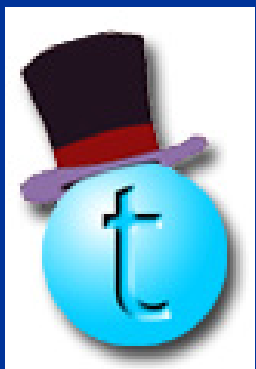


W-t-b at the ILC

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Snowmass 2005
Top & QCD
8/24/2005

Outline

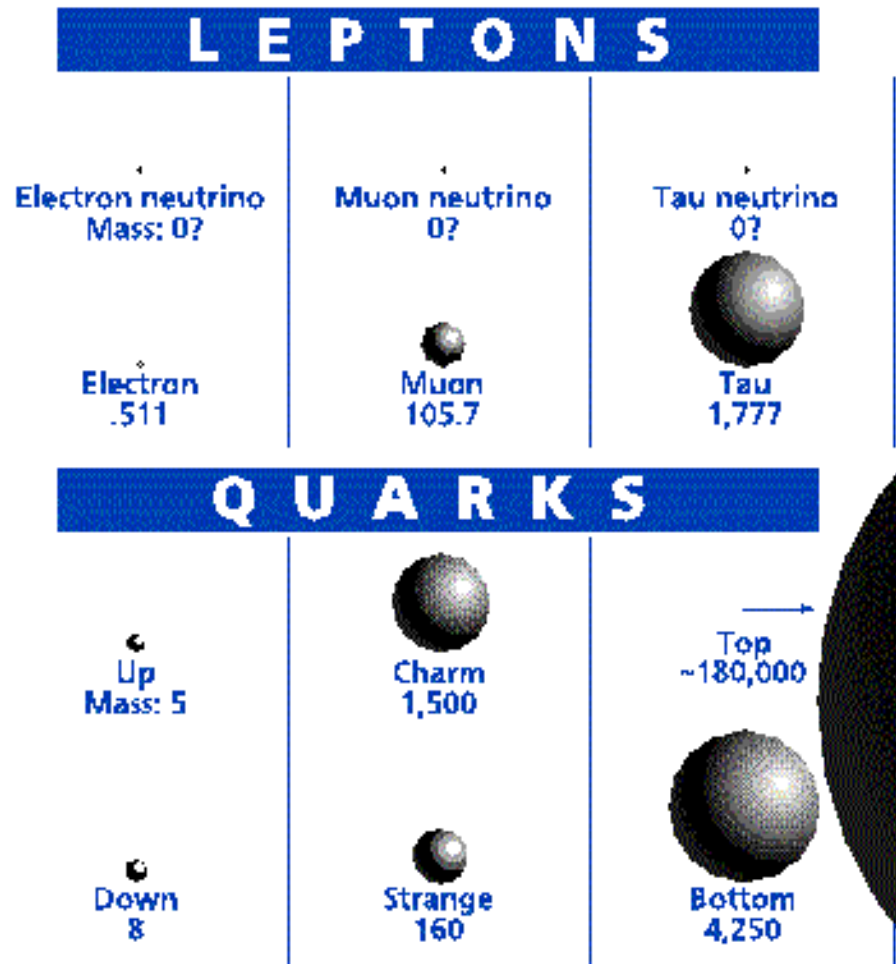
- Introduction: Why measure W-t-b?
- What quantities are we trying to pin down?
- How do we measure them?
- Outlook

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.
- Weak interactions are the obvious place to look!

SM Fermions

| LEPTONS | | |
|-------------------------------|---------------------|--------------------|
| Electron neutrino Mass: 0? | Muon neutrino 0? | Tau neutrino 0? |
| Electron .511 | Muon 105.7 | Tau 1,777 |
| QUARKS | | |
| Up Mass: 5 | Charm 1,500 | Top ~180,000 |
| Down 8 | Strange 160 | Bottom 4,250 |





W-t-b in the SM: V_{tb}



- In the SM, the CC interactions are described by V_{tb} , V_{ts} , and V_{td} .
- V_{ts} and V_{td} are measured indirectly from b physics.
- V_{tb} can be constrained using unitarity.
- This assumes the SM, with 3 generations.
- Physics beyond the SM can easily modify these results (in a big way).
 - I.e. a Fourth generation

$$\text{CDF: } \frac{\text{BR}(t \rightarrow Wb)}{\text{BR}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24}$$



$$V_{tb} \gg V_{ts}, V_{td}$$

CDF PRL86, 3233 (2001)

$$\begin{bmatrix} 0.9739 - 0.9751 & 0.221 - 0.227 & 0.0029 - 0.0045 \\ 0.221 - 0.227 & 0.9730 - 0.9744 & 0.039 - 0.044 \\ 0.0048 - 0.014 & 0.037 - 0.043 & 0.9990 - 0.9992 \end{bmatrix}$$

$$V^\dagger V = 1 \Rightarrow |V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

$$\begin{bmatrix} 0.9730 - 0.9746 & 0.2174 - 0.2241 & 0.003 - 0.0044 & \dots \\ 0.213 - 0.226 & 0.968 - 0.975 & 0.039 - 0.044 & \dots \\ < 0.08 & < 0.11 & 0.07 - 0.9993 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

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

New Interactions

- A model independent way to study new physics is provided by effective Lagrangians, adding interactions beyond those in the SM.
- The SM already contains all renormalizable interactions (with couplings of mass dimension 4 or less); we must include non-renormalizable terms.
- Couplings for ‘higher dimensional’ operators have negative dimension so that the Lagrangian stays at dimension 4:

| Counting Dimension | |
|--------------------|-------|
| Ψ | : 3/2 |
| H, V_μ | : 1 |
| ∂_μ | : 1 |

$$\underbrace{g}_{\text{dimension 0}} \times \underbrace{\overline{\Psi} \gamma_\mu \Psi V^\mu}_{\substack{\text{dimension 4} \\ \underbrace{\overline{\Psi}}_{3/2} \underbrace{\gamma_\mu}_{1} \underbrace{\Psi}_{3/2} \underbrace{V^\mu}_{1}}} \underbrace{\frac{1}{\Lambda^2}}_{\text{dimension -2}} \times \underbrace{\overline{\Psi} \gamma_\mu \overline{\Psi} \gamma^\mu \Psi}_{\substack{\text{dimension 6} \\ \underbrace{\overline{\Psi}}_{3/2} \underbrace{\gamma_\mu}_{1} \underbrace{\overline{\Psi}}_{3/2} \underbrace{\gamma^\mu}_{1} \underbrace{\Psi}_{3/2}}}$$

- This theory makes sense as an expansion in energy. Observables depend on E^n / Λ^n , so provided $E \ll \Lambda$, the expansion makes sense.
- Gauge symmetries of the Standard Model such as SU(3) invariance, etc. are still respected by the new interactions.
- They can be understood as residual effects from very heavy particles.

Non-standard W-t-b

- Thus, to describe generic new physics effects in the W-t-b interaction, we should write down all of the lowest dimensional operators beyond the SM which can contribute to this interaction.

- The dimension six operators which can contribute are:

| |
|---|
| Cao, Wang, Yang, Zhang PRD58, 094004 (1998) hep-ph/9804343 |
|---|

$$O_{qW} = \left[\bar{q}_L \gamma^\mu \tau^I D^\nu q_L + \overline{D^\nu q_L} \gamma^\mu \tau^I q_L \right] W_{\mu\nu}^I,$$

$$O_{\Phi q}^{(3)} = i \left[\Phi^\dagger \tau^I D_\mu \Phi - (D_\mu \Phi)^\dagger \tau^I \Phi \right] \bar{q}_L \gamma^\mu \tau^I q_L,$$

$$O_{Db} = (\bar{q}_L D_\mu b_R) D^\mu \Phi + (D^\mu \Phi)^\dagger (\overline{D_\mu b_R} q_L),$$

$$O_{bW\Phi} = \left[(\bar{q}_L \sigma^{\mu\nu} \tau^I b_R) \Phi + \Phi^\dagger (\bar{b}_R \sigma^{\mu\nu} \tau^I q_L) \right] W^I,$$

$$O_{t3} = i \left[(\tilde{\Phi}^\dagger D_\mu \Phi) (\bar{t}_R \gamma^\mu b_R) - (D_\mu \Phi)^\dagger \tilde{\Phi} (\bar{b}_R \gamma^\mu t_R) \right],$$

$$O_{Dt} = (\bar{q}_L D_\mu t_R) D^\mu \tilde{\Phi} + (D^\mu \tilde{\Phi})^\dagger (\overline{D_\mu t_R} q_L),$$

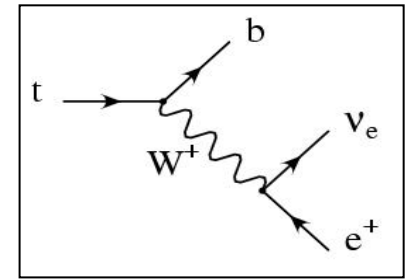
$$O_{tW\Phi} = \left[(\bar{q}_L \sigma^{\mu\nu} \tau^I t_R) \tilde{\Phi} + \tilde{\Phi}^\dagger (\bar{t}_R \sigma^{\mu\nu} \tau^I q_L) \right] W_{\mu\nu}^I,$$

- Replacing the Higgs with its VEV gives us effectively lower dimensional operators involving only W, t, and b:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left[W_\nu^- \bar{b} (\gamma_\mu F_1^L P_- + F_1^R P_+) t - \frac{1}{2M_W} W_{\mu\nu} \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+) t \right] + \text{h.c.}$$

- Recall that the effects of higher dimensional operators on observables grow with energy: this, and perhaps unusual polarization effects are the best way to extract them from the SM contributions.
- In specific theories of physics beyond the SM, we can compute how large the coefficients of these operators are expected to be.

Top Decay and Width



- The W-t-b interaction is actually the dominant feature in top phenomenology today, because it leads to the characteristic decay into W b.
- The width is directly proportional to $|V_{tb}|^2$ in the SM:

$$\Gamma_t = \frac{G_F M_{\text{top}}^3}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{M_{\text{top}}^2}\right)^2 \left(1 + 2 \frac{M_W^2}{M_{\text{top}}^2}\right)$$

- The width, while huge for a quark (~ 1.5 GeV) is still narrow compared to experimental resolutions. Some observables have a mild dependence on it, mostly arising from the tails of off-shell top production which can be observable with high enough statistics.
- Because $\Gamma_t \gg \Lambda_{\text{QCD}}$, polarization can be described within perturbative QCD and offers a unique chance to study the structure of the W-t-b interaction.
- CDF used single versus double b-tagged top events to measure:

CDF PRL86, 3233 (2001)

$$\frac{\text{BR}(t \rightarrow Wb)}{\text{BR}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.94^{+0.31}_{-0.24} \implies V_{tb} \gg V_{ts}, V_{td}$$

- The decay is telling us that W-t-b is important. But it is not practically accessible as a precision measurement of the magnitude of the W-t-b interaction.

W Polarization



• W Polarization

- SM: Depends on m_t & m_W :

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

- This is a direct test of the left-handed nature of the W - t - b vertex.

- Physics beyond the SM such as mixing with mirror quarks could introduce a right-handed component.

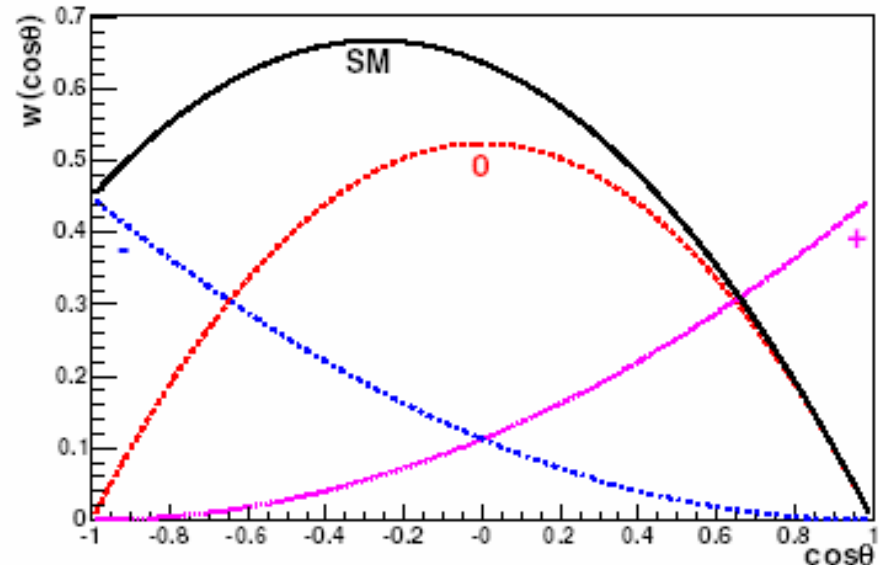
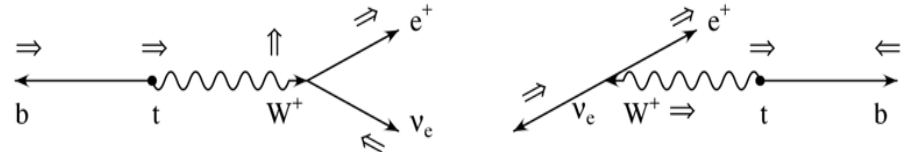
- λ_W correlated with the direction of p_e compared with the direction of p_W in the top rest frame.

CDF: $f_+ < 0.18$ (95% CL)

CDF PRD71, 031101 (2005)

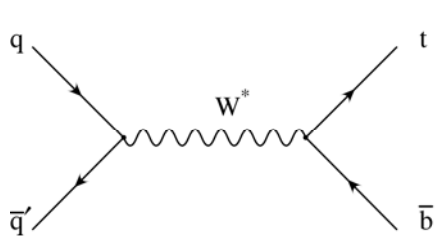
D0: $f_+ < 0.25$ (95% CL)

D0 hep-ex/0505031

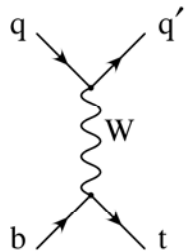


What will hadron machines tell us?

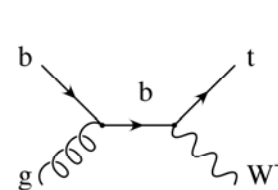
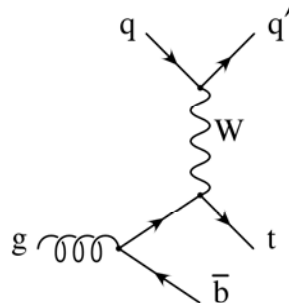
- Hadron machines directly measure W-t-b through single top production.



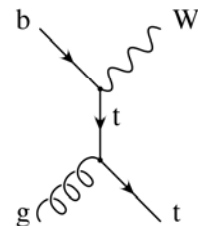
s-channel



t-channel



tW associated



- The production rates are all proportional to the W-t-b interaction ($|V_{tb}|^2$), and thus are a sensitive probe of this (and perhaps other) physics.
- The t-channel rate dominates both at Tevatron and LHC
- The ability to extract V_{tb} is limited on the theory side by uncertainties in PDFs, μ_F , m_t , etc and on the experimental side by the ability to **measure backgrounds**, **statistics**, etc.
- Theoretical studies have estimated the sensitivity to be:
 - At the Tevatron, (2 fb^{-1}) $\delta V_{tb} \sim \pm 10\%$
 - At the LHC (statistics unimportant), $\delta V_{tb} \sim \pm 8\%$

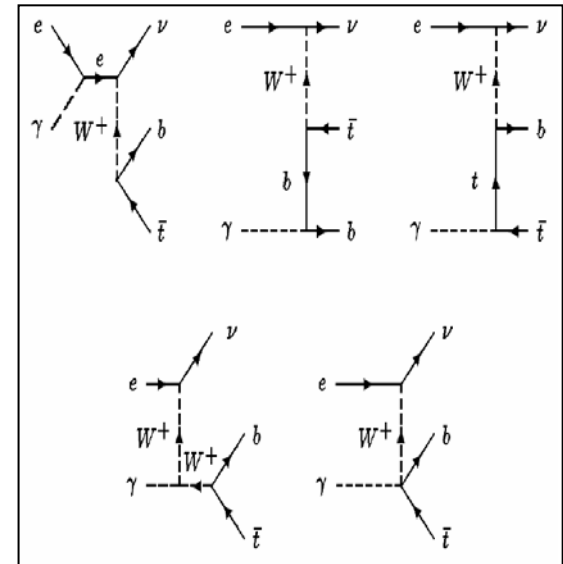
Stelzer, Sullivan, Willenbrock
PRD58, 094021 (1998) hep-ph/9807340

ILC

- An e^+e^- initial state is **not** ideal to measure W - t - b (unlike Z - t - t).
- Higher order processes are suppressed by weak couplings, and thus have tiny rates.
- The width can be inferred from a $t\bar{t}$ threshold scan. The width can be measured to $\sim\pm 10\%$, implying an error on V_{tb} of order $\sim\pm 5\%$.

Murayama, Sumino PRD47, 82 (1993)
 Fujii, Matsui, Sumino PRD50, 4341 (1994)
 Tesla TDR

- More promising is a $e\gamma$ collider, which can produce single tops through the process $e\gamma \rightarrow \bar{t} b \nu$.
- Both from the inclusive rates as well as angular distributions, limits can be placed on the “effective” anomalous interactions of order **0.1** or better.



$$\mathcal{L} = \frac{g}{\sqrt{2}} \left[W_\nu^- \bar{b} (\gamma_\mu F_1^L P_- + F_1^R P_+) t - \frac{1}{2M_W} W_{\mu\nu} \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+) t \right] + \text{h.c.}$$

| $\sqrt{s_{e^+e^-}}$, TeV | 0.5 | 1.0 | 1.5 | 2.0 |
|----------------------------|-----------|-------------|-------------|-------------|
| \mathcal{L} , fb $^{-1}$ | 50 | 200 | 300 | 500 |
| δF_2^L | -1./1 | -0.20/.065 | -0.01/.05 | -0.008/.035 |
| δF_2^R | -1./1 | -0.035/.035 | -0.022/.022 | -0.016/.016 |
| δF_1^R | -0.20/.35 | -0.12/.25 | -0.09/.22 | -0.08/.20 |

Off-shell tops?

- While looking at the webpage for the top/QCD WG, I saw ran across the proposal to let the top go off-shell in $e^+e^- \rightarrow t\bar{t}$, by running the collider below the $t\bar{t}$ threshold.
- That's a good idea! When the top goes off-shell, the rate becomes proportional to the W-t-b coupling squared:

$$M_{total} \propto M(e^+e^- \rightarrow t\bar{t}) \otimes \frac{1}{M_{Wb}^2 - m_t^2 + im_t\Gamma_t} \otimes M(t \rightarrow Wb)$$

(This is schematic only! The top spin is hooked from production to decay!)

- Perhaps a good place to start would be at center of mass energies:

$$m_t + m_W + m_b < E \ll 2m_t$$

for which we expect the rate to be dominated by one real top and one virtual one. If we push the top far off-shell, the dependence on Γ_t will be small.

As a sanity check I ran compHEP (with help from P Batra) for the process $e^+e^- \rightarrow \bar{t}W^+b$

at center of mass energy 320 GeV. No cuts, efficiencies, backgrounds, etc were included.

The rate is 4.3 fb, indicating that at least from the statistics point of view, with 100fb^{-1} this could lead to W-t-b measurements on the order of **3%**. Of course, many improvements need to be included before this is realistic, but it is encouraging.

Outlook

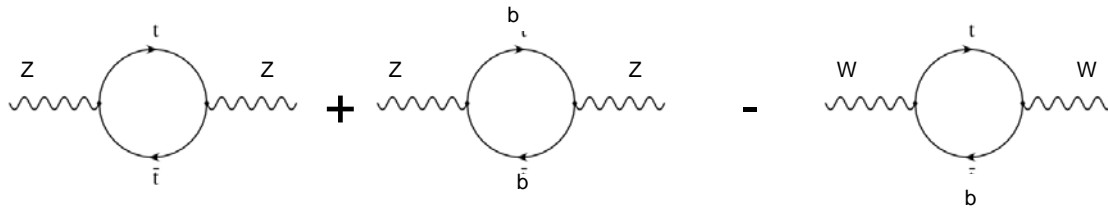
- Top's EW interactions are of great interest. If top's large mass is a clue that it plays some special role in electroweak symmetry breaking, the weak interactions are a likely place to look for physics beyond the SM.
- Anomalous interactions are parameterized by a series of higher dimensional operators. These potentially lead to different energy and spin dependences in observables compared to the SM. They are generic and can be used to bound any model predicting modification of top's interactions.
- Hadron colliders will probe W - t - b through single top at the 10% level.
- W - t - b is somewhat challenging for an e^+e^- collider. The $t\bar{t}$ threshold leads to similar precision to that expected from hadron colliders.
- An $e\gamma$ collider running at ~ 500 GeV and collecting $\sim 50 \text{ fb}^{-1}$ can probe the anomalous interactions to the level of 0.1.
- Off-shell top production looks like it at least has the rate to possibly be interesting. In the very least I would say that this is something that should be improved so we know for sure!

Supplementary Slides

Top's Role in the SM

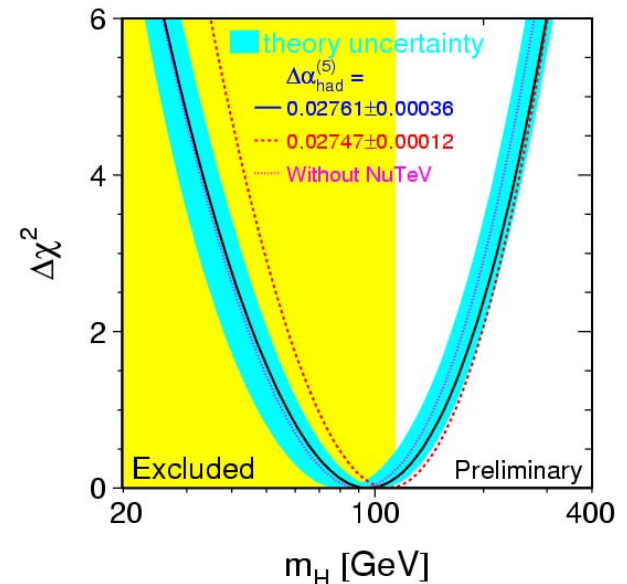
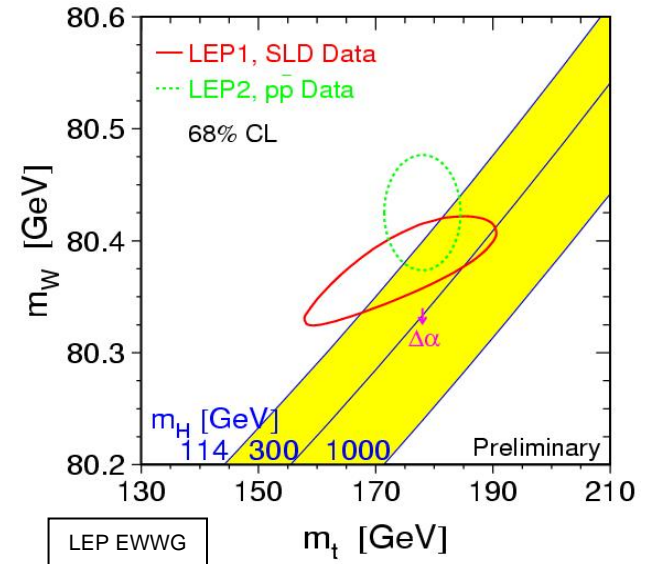
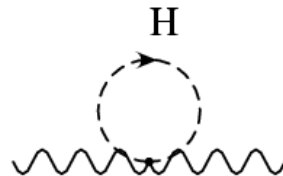
- Precision EW Physics:

- 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 $\Delta\rho$ (ΔT).



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

- The one loop corrections are so sensitive to the top mass that precision measurements at LEP/SLD could predict 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:

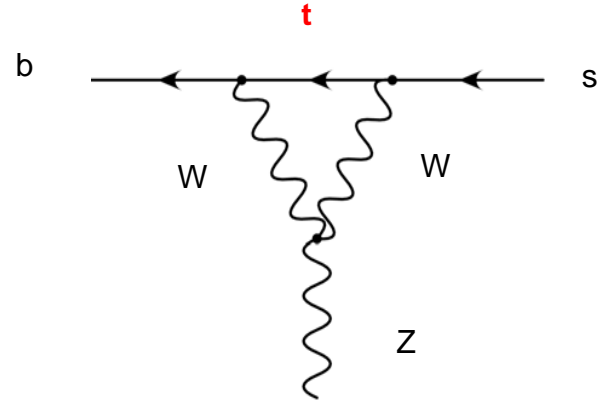
- $B \rightarrow X_s \nu \bar{\nu}$

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

- $B_s \rightarrow \mu^+ \mu^-$

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

i.e.:



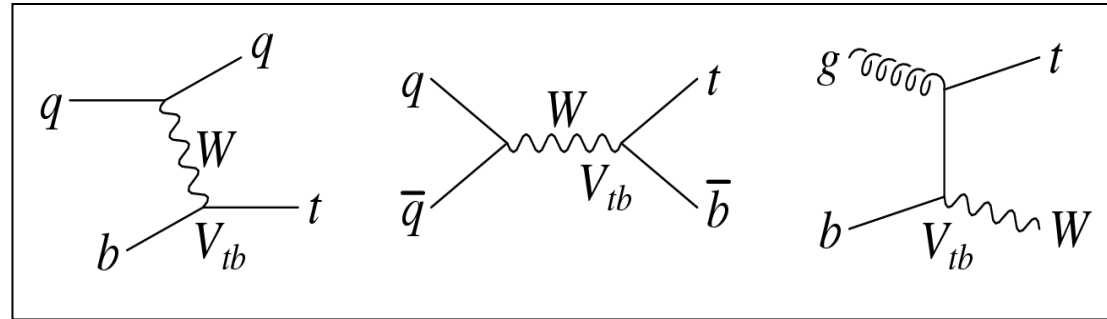
Buchalla, Buras, Lautenbacher RMP68,1125 (1996)

Precision inputs from the top sector for precision SM predictions.

Top's large mass disrupts the GIM mechanism!

Single Top Production

- Top's EW interaction.
 - Three modes:
 - T-channel: $q b \rightarrow q' t$
 - S-channel: $q \bar{q}' \rightarrow t \bar{b}$
 - Associated: $g b \rightarrow t W^-$



Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024
 Tait, PRD 61 (00) 034001; Belyaev, Boos, PRD 63 (01) 034012

Coming soon to Run II!

| σ | Tevatron Run I | Tevatron Run II | LHC |
|--------------------|--------------------------------------|--------------------------------------|-----------------------------------|
| σ_t (NLO) | 1.45 ± 0.08 pb | 1.98 ± 0.13 pb | 247 ± 12 pb |
| σ_s (NLO) | 0.75 ± 0.07 pb | 0.88 ± 0.09 pb | 10.7 ± 0.9 pb |
| σ_{tW} (LL) | 0.06 ± 0.01 pb | 0.09 ± 0.02 pb | 56 ± 8 pb |
| Total | 2.26 ± 0.11 pb | 2.95 ± 0.16 pb | 314 ± 15 pb |

Run I Limits

< 13.5 pb

< 12.9 pb

CDF PRD65, 091102 (2002)
 DØ PLB517, 282 (2001)