TOP QUARK FLAVOR PHYSICS ISSUES AT 8500′

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- $|V_{tb}|$
- Rare decays
- ~~CP~~

TOP FLAVOR PHYSICS:

$|V_{tb}| = 0.9990$ to 0.9993 in the Standard Model.

This constraint is <u>ENTIRELY</u> from unitarity

Our only "direct" measurement of $|V_{tb}|$ is from

$BR(t \to Wb) \gtrsim 0.7$ at CDF/DØ.

$\Rightarrow$ All this tells us is $|V_{tb}|^2 \gg |V_{ts}|^2 + |V_{td}|^2$.

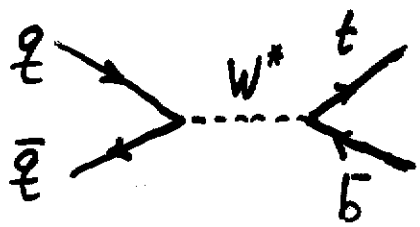
WITHOUT UNITARITY:

$|V_{tb}|$ is essentially unconstrained.

Only direct probe of $|V_{tb}|$ is

Single top production.

At hadron colliders, cleanest probe is "s-channel"

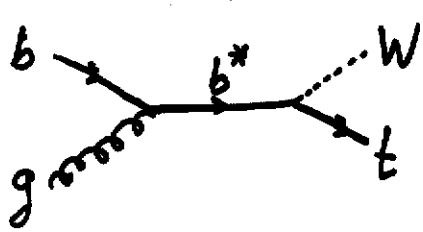


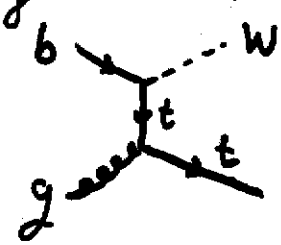
882 fb (TeV Run II)
10215 fb (LHC) ← higher backgr.

Given acceptances, backgrounds, we can expect a few hundred events at Run 2a ⇒ ~10% cross-sec. measurement

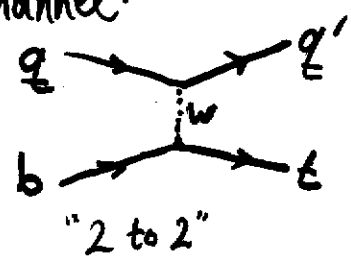
Other diagrams contribute too — but final states are distinguishable:

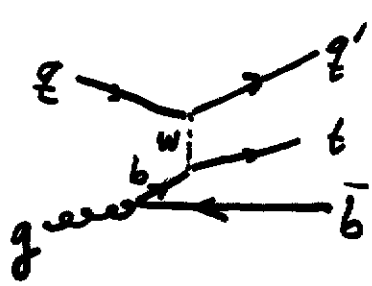
"W-t associated production" of beauty sea — depends on b,g pdf's:





t-channel:

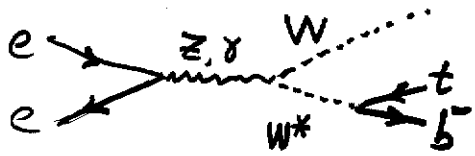




These processes dominate the s-channel at LHC — $|V_{tb}|$ fr these will be QCD-limited.

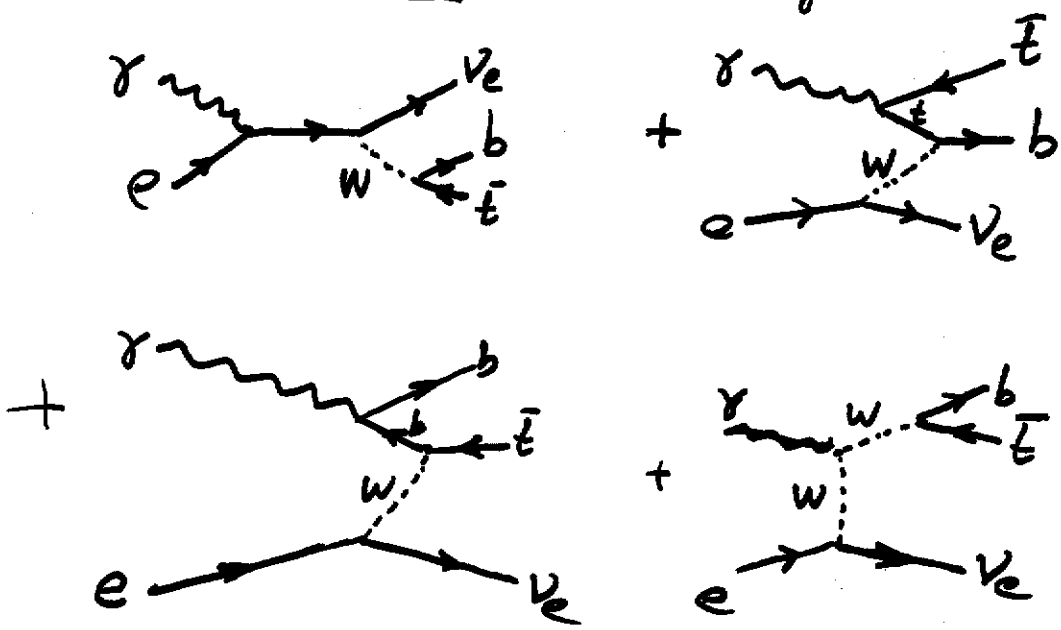
ELECTRON COLLIDERS offer a theoretically cleaner probe of the W-t-b vertex:

e^+e^- → Cross-sections low ($\ll 1$ fb)
same final state as $e^+e^- \to t\bar{t}$



+ many similar diagrams.

$e^-\gamma$ → <u>Much</u> more promising!



$\sigma \approx 40$ fb ($\sqrt{s} = 400$ GeV, unpolarized)
doubles for polarized beams.

$\lesssim 1\%$ measurement of $|V_{tb}|$ possible!

New physics observable in single top production:

DEFINE $$R_t \equiv \frac{\sigma(\text{single top})_{\text{observed}}}{\sigma(\text{single top})_{SM, V_{tb} \approx 1}}$$

(Note that R_t could be different for different production channels.)

- 4th quark generation:

$$R_t < 1 \quad (|V_{tb}| < 1)$$

(Different 1-top channels give <u>same</u> R_t)

- Heavy gauge bosons (W') a la Technicolor:

$$R_t > 1 \quad (|V_{tb}| \approx 1)$$

(Different 1-top channels are at different $Q^2 \Rightarrow$ different R_t)

Sensitivity at TeV to $M_{W'} \sim 1$-3 TeV depending on mixing.

Tait & Yuan

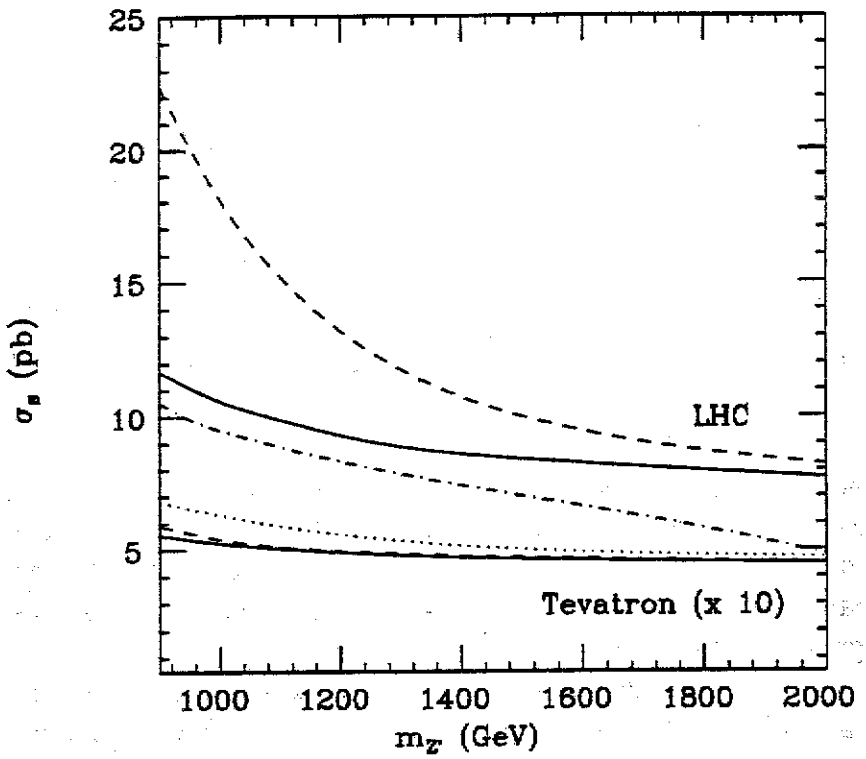


FIG. 7. The NLO rate of $q\bar{q}' \to W, W' \to t\bar{b}$ (σ_S) in pb at the Tevatron (lower curves) and CERN LHC (upper curves), for the top-quark-flavor model with $\sin^2\phi=0.05$ (solid curves) and $\sin^2\phi=0.25$ (dashed curves), as a function of $M_{Z'}=M_{W'}$. The Tevatron cross sections are multiplied by a factor of 10. At the Tevatron, the $\bar{t}$ production rate is equal to the t rate. At the CERN LHC the $\bar{t}$ rates are shown for $\sin^2\phi=0.05$ (dotted curve) and $\sin^2\phi=0.25$ (dot-dashed curve).

RARE TOP DECAYS – $W+q$

In the SM, rare decays probably not observable:

$$t \to Ws \qquad 1.6 \times 10^{-3}$$
$$t \to Wd \qquad 10^{-4}$$

Certainly produced copiously at TeV, LHC but background from mistagged b jets prohibitive.

- 4th Generation: Unitarity constraints on $\Gamma(t \to Wb)$ disappear
  $\Longrightarrow$ only limits on $\left(\frac{\Gamma(t \to Ws, Wd)}{\Gamma(t \to Wb)}\right)$ are from direct searches (CDF, DØ).

$$BR(t \to Ws) < 0.25$$
$$BR(t \to Wd) < 0.01 \quad \text{(from loop-process limits on } |V_{td}|\text{)}$$

b' may be light enough to show up in t decay:

$$BR(t \to W\underset{\hookrightarrow W^- c}{b'}) \sim 10^{-3} \text{ for } m_{b'} \sim 100\ \text{GeV}/c^2$$

RARE TOP DECAYS — FCNC

$t \to c g$

$t \to c \gamma$

$t \to c Z$

Only proceed at loop level in SM —
$BR \sim 10^{-13} - 10^{-12}$.

THESE DECAYS ARE ENHANCED IN NEW PHYSICS MODELS:

- MSSM: All these decays factor of $\sim 10^5$ above SM.
  $\Rightarrow$ Still not observable at TeV, LHC
- MSSM $\not{R}$: Decays increase $10^8 - 10^9$ above SM.
  $\Rightarrow$ $t \to c\gamma$ may be observable at LHC; others within 1 order of magnitude.
- Multiple Higgs Doublets: "Type III" models - Decays increase by factor of $10^6 - 10^7$ above SM. Not observable soon.

RARE TOP → HIGGS DECAYS:

DECAYS TO NEUTRAL HIGGS:

SM: • $BR(t \to Wbh^0) \lesssim 7 \times 10^{-8}$ for $m_H \gtrsim 100$ GeV/c^2 IN SM

→ DROPS RAPIDLY FOR HIGHER m_H; W or h^0 OFF-SHELL ALREADY.

• $BR(t \to ch^0) = 10^{-12} \sim 10^{-14}$ for $M_H = 100 \sim 160$ GeV/c^2 in SM.

MSSM: • $BR(t \to ch^0)$ UP TO 10^{-4}

2 HIGGS • $BR(t \to ch^0)$ UP TO 10^{-2} IN MODEL III

(due to tree-level tcH coupling $\propto \sqrt{m_t m_c}$)

DECAYS TO CHARGED HIGGS:

MSSM: • $BR(t \to h^+ b)$ potentially large (0.1) for large or small $\tan\beta$

→ perhaps observable at TeV.

2 HIGGS: • $BR(t \to h^+ b)$ potentially large

RARE t DECAY MATRIX

Decay	Predicted Rates								Sensitivity		
	SM	MSSM RPC	MSSM RPV	4th Gen	2 Higgs Doubl's	Ext. Dim.	Anom. Coupl.	Topcolor Asst. TC	TeV Run 2	LHC[b]	LC
Wb	> 0.99									$0.002^{p,C}$	
Ws	$1.6 \cdot 10^{-3}$ [B]			< 0.25 [B]							
Wd	$1.0 \cdot 10^{-4}$ [B]			< 0.01 [B]							
h^+b	0	$< 1^c$	$< 1^c$		$\leq \mathrm{BR}(Wb)$				11%[a]	$0.03^{d,C}$	?
cg	$5 \cdot 10^{-11}$ [B]	10^{-6}	10^{-3} [e]		10^{-5} [f,B]					$.0074^{g,C}$	
$c\gamma$	$5 \cdot 10^{-13}$ [B]	10^{-8}	10^{-4} [e]		10^{-7} [f,B]				$\sim 0.1^b$	$.0001^{g,C}$	
cZ	$1.3 \cdot 10^{-13}$ [B]	10^{-8}	10^{-5} [e]		10^{-6} [f,B]					$.0002^{g,C}$	
ch^0	$< 10^{-7}$ [A]	$\sim 10^{-4}$ [i]	$\sim 10^{-5}$ [e,j]		< 0.01						
ch^0	10^{-12} [k]										
ch^0	10^{-15} [l]										
WbZ	$\sim 10^{-6}$ [B]				$0.01^{f,m,B}$					10^{-3} [C]	
Wbh^0	$7 \cdot 10^{-8}$ [k,B]										
cWW	10^{-13} [B]										
Wb'	0			10^{-3} [n,B]							

[a]Integrated luminosity 2 fb^{-1}.
[b]Integrated luminosity 10 fb^{-1}.
[c]Can be large for large or small values of $\tan\beta$.
[d]Limited by systematic uncertainty in τ ID eff and fake t's.
[e]In models with baryon number violating couplings.
[f]In Type III models (FCNC couplings allowed)
[g]Integrated luminosity 100 fb^{-1}.
[i]For CP-even higgs h^0.
[j]Using 2s bounds on relevant R-parity violating couplings. (??)
[k]$M_h = 100\ \mathrm{GeV}/c^2$
[l]$M_h = 160\ \mathrm{GeV}/c^2$
[m]Extension of 2HDM model to include Higgs triplets
[n]$M_{b'} = 100\ \mathrm{GeV}/c^2$
[p]Statistical sensitivity only; systematics may dominate.
[A]hep-ph/9802305.
[B]B.Mele, hep-ph/0003064.
[C]Atlas Detector and Physics Performance Technical Design Report (1999).

$\not{CP}$ IN $t \to Wb$ decay

Two-Higgs doublet models predict a CP-violating polarization of the W in $t \to Wb$ decay.

$\Longrightarrow$ Manifested experimentally as an asymmetry $A^t \equiv \dfrac{N^{up} - N^{down}}{N^{up} + N^{down}}$

where N^{up}, N^{down} are the number of W-decay leptons emitted, respectively, above and below the $t \to Wb$ decay plane.

A^t has no tree-level contribution in SM

$\Longrightarrow$ vanishingly small.

In favored 2HDM regions with $\tan\beta \ll 1$,

$$|A^t| = 10^{-5} \sim 10^{-3}.$$

CONCLUSIONS —

- RICH PROGRAMS OF FLAVOR PHYSICS WITH THE TOP QUARK WILL BE POSSIBLE AT NEW FACILITIES, INCLUDING A LINEAR COLLIDER (ESPECIALLY ONE WITH $e^-\gamma$ COLLISIONS).

- 4th GENERATION SEARCHES LOOK MOST PROMISING IN SINGLE TOP PRODUCTION AND Ws, Wd DECAYS

- SUSY, 2-HIGGS-DOUBLET PHYSICS COULD APPEAR IN $t \to$ HIGGS DECAYS

- FCNC DECAYS WITHOUT HIGGS IN FINAL STATE LOOK VERY DIFFICULT EVEN WITH NEW PHYSICS.

- $\not{CP}$ IN 2HDMs INTERESTING WITH $> 10^6$ t DECAYS.