Measuring $|V_{tb}|$ at Hadron Colliders *

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ABSTRACT

In the context of 3 generations V_{tb} is the most constrained of all the CKM matrix elements. However, if one allows for the possibility of a fourth generation V_{tb} is almost completely unconstrained. Single-top-quark production offers the best opportunity to measure V_{tb} at hadron colliders. The s-channel or W^* mode has relatively small theoretical uncertainties and should be able to measure V_{tb} with a statistical uncertainty of 10% with 2 fb^{-1}. The t-channel or Wg fusion mode has higher statistics, however the current uncertainty in the gluon distribution function limits the precision available through this channel.

I. INTRODUCTION

V_{tb} is unique in the CKM matrix because it is the only diagonal element which has not been directly measured. Despite this lack of measurement, in the context of three generations $|V_{tb}|$ is the most constrained CKM element. [1] This constraint is the result of the small values of $|V_{ub}|$ and $|V_{cb}|$, combined with the unitarity requirement $|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$. If one allows for the possibility of a fourth generation then the lower limit on V_{tb} from unitarity is relaxed, and V_{tb} becomes almost entirely unconstrained, $0 < |V_{tb}| \leq 0.9993$. [1] A direct measurement of $|V_{tb}|$ can explore the possibility of a fourth generation. Furthermore, a measurement of $|V_{tb}|^2 > 0.5$ will confirm that the top quark discovered at the Tevatron is indeed the SU(2) partner of the bottom quark.

II. $t\,\bar{t}$ MEASUREMENTS

The discovery of the top quark at CDF and D0 has provided the opportunity to directly investigate V_{tb}. [2] The first analysis, done by CDF, focused on $t\bar{t}$ pairs since these dominated the top-quark data sample. In $t\bar{t}$ production V_{tb} determines the fraction b of top quarks which decay into b quarks compared with other kinematically allowed decays:

$$b = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}. \tag{1}$$

The unitarity of the CKM matrix requires the denominator to be less than or equal to one even if there are more than three generations. Therefore the CDF measurement of b provides an upper bound on V_{tb}: $|V_{tb}|^2 \leq b$. If b is measured to be less than one, this would be a major discovery since limits from three generation constraints require $|V_{tb}| > .9989$.[1] The $t\bar{t}$ measurement does have limitations because if b is measured to be $\simeq 1.0$, V_{tb} remains unconstrained and could be significantly less than one.[1]

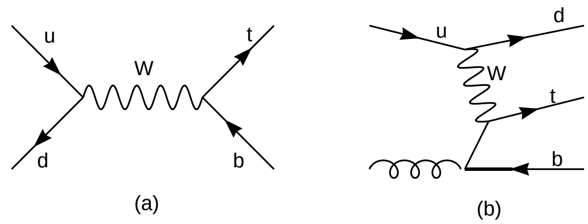

Figure 1: Representative Feynman diagrams for Single-top-quark production mediated via (a) s-channel W, and (b) t-channel W.

III. $|V_{tb}|$ IN SINGLE-TOP PRODUCTION

The total cross section for single-top production at the Tevatron is approximately $\frac{1}{3}$ that of $t\bar{t}$ production. Figure 1 shows the leading diagrams for single-top production via W* and Wg fusion. Notice that the production cross section is proportional to $|V_{tb}|^2$, so a measurment of the single-top-quark production cross section provides a direct measurement of $|V_{tb}|$. Since the top quark decays before it can be detected, experiments actually measure $\sigma(t) * B(t \to W^+b)$. The branching ratio is at most 1.0 and therefore measuring $\sigma(t) * B(t \to W^+b)$ provides a lower limit on $|V_{tb}|$. This lower limit can be changed to an equality by combining a measurement of $B(t \to W^+b)$ from $t\bar{t}$ events with the single-top analysis. In addition to strengthening the lower limit to an equality, this combination tends to reduce systematic effects such as uncertainty in the top-quark mass and the luminosity.

Because of the different theoretical uncertainties, it is useful to consider single-top production through an s-channel W (figure 1a) as distinct from single-top production mediated through a t-channel W (figure 1b). Single-top production through an s-channel W has several nice theoretical qualities.[3, 4] First, the process proceeds primarily via valence quarks in the proton at moderate values of $x \simeq m_{top}/\sqrt{s} \simeq 0.1$. The quark distribution functions in this range are relatively well constrained. Furthermore, partonic fluxes may be measured during the run using s-channel W and Z production thereby reducing the uncer-

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[1] Since $b \neq 0$, $|V_{tb}| \neq 0$. However, if $|V_{tb}|$ turns out to be small, then the 'top quark' discovered at the Tevatron would not be the SU(2) partner of the bottom quark. In this case one would interpret the quark discovered as a fourth generation t'.

tainty. Second, the next-to-leading order corrections for s-channel production have been computed [5]. At a 2 TeV Tevatron $\sigma(t)+\sigma(\bar{t}) = .88\pm.06$pb. The relatively small error of 6% corresponds to a 3% error in $|V_{tb}|$ which is below the expected statistical uncertainty.

The statistical resolution is limited not only by the relatively small cross section of 0.9 pb, but also by cuts required to reduce the backgrounds. Details of these cuts can be found in the literature [4, 6]. These papers conclude that with 2 fb^{-1} of data from run II at the Tevatron, $|V_{tb}|$ can be measured to $\simeq$10% statistical accuracy. If the integrated luminosity is increased to 30 fb^{-1} at TeV33 the accuracy would increase to 3%. At the LHC the top quark is relatively light, and gluon initiated processes dominate $q\bar{q}$ initiated processes. This results in a large background from misidentified $gg \to t\bar{t}$ events overwhelming the s-channel signal. Therefore it is unlikely the LHC will be able to improve upon the Tevatron results in the s-channel mode.

The primary advantage of t-channel single-top production is the increased cross section.[7, 8, 9] At the 2 TeV Tevatron the cross section for t-channel production is $\simeq$ 2 pb, twice as large as s-channel. By including the leading logs, the cross section is relatively insensitive to the choice of scale. However, this process depends on the gluon distribution function at $x \simeq 0.1$. This parton distribution is relatively unconstrained, and therefore provides a large source of uncertainty in the calculation. Since currently there are no error estimates provided with the parton distribution functions, it is difficult to quantify this uncertainty. Discussions with members of CTEQ suggest an uncertainty of order 20% may be a reasonable estimate.

If these theoretical uncertainties can be overcome, Wg fusion offers a significant statistical advantage. Preliminary work suggests a factor of 2 greater resolution for a given luminosity. This would result in a measurment of $|V_{tb}|\pm 10\%$ (statistical) with only 1 fb^{-1} of integrated luminosity. Unlike s-channel production, t-channel production benefits from the increased gluon luminosity at the LHC. The statistical significance of this is currently being investigated. Since the signal cross section increases by roughly a factor of 100, one may anticipate that statistical uncertainties will become negligible after a very short time running.

IV. CONCLUSIONS

Measuring $|V_{tb}|$ is important since it is currently unconstrained, and can confirm that the top-quark discovered at the Tevatron is indeed the SU(2) partner of the bottom quark. Single-top-quark production can place a lower bound on $|V_{tb}|$. Including information from $t\bar{t}$ events can turn this bound into an equality. s-channel production has the advantage of depending only on large x valence quarks. These distributions are well constrained, and the partonic fluxes can be directly measured during the run from Drell-Yan production. Furthermore, the next-to-leading order corrections have been done and the combined theoretical uncertainty is expected to be around 6% which corresponds to an uncertainty in $|V_{tb}|$ of 3%. The limiting factor for s-channel production will therefore be statistics. With 2 fb^{-1} of luminosity the statistical uncertainty on $|V_{tb}|$ will be 10%. Because this is a $q\bar{q}$ initiated process, and backgrounds are gg initiated, it is unlikely the increased energy of the LHC will allow for a more accurate measurement.

t-channel single-top-production has twice the cross section, and therefore better statistical resolution. Given 2 fb^{-1} of luminosity the statistical uncertainty on $|V_{tb}|$ will be 5%. The primary drawback here is the theoretical uncertainty. In particular the dependence of this cross section on the gluon distribution function may introduce an uncertainty of order 20%. Hopefully progress in constraining the gluon distribution, or at least quantifying its uncertainty, will permit the enhanced statistics of t-channel single-top production to accurately determine $|V_{tb}|$. Furthermore, the increased energy of the LHC will greatly enhance the statistics emphasizing the need to reduce the systematic uncertainty associated with the gluon distribution function.

V. REFERENCES

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