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The Future Collider Physics Program at Fermilab: Run II and TeV33

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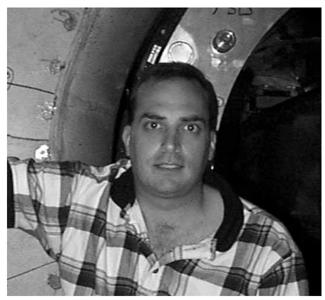

High luminosity collider running at Fermilab is scheduled to occur during the period 2000-2005. Requisite collider detector upgrades are underway. An outline of the physics that can be realized with the upgraded Tevatron and CDF/DØ detectors is presented.

1 Introduction

During the period 1992-1996 (Run I) the Fermilab Tevatron supplied the CDF and DØ detectors with a combined integrated luminosity of $\sim$ 200pb^{-1}. This data set has provided a wealth of information[1] on the Standard Model (SM). Examples of which are the observation of the top quark and measurement[2] of its mass m_t=173.8 $\pm$ 5.2 GeV/c^2; the most precise single measurement of the W boson mass to date, M$_W$=80.44 $\pm$ 0.12 GeV/c^2; limits on extensions to the SM and new particle masses; and the inclusive jet cross section to E_T = 450 GeV.

With the addition of the Main Injector to the Tevatron, integrated luminosities of between 1-10fb^{-1}/year/detector will be possible. The nominal scenario calls for accumulating 2fb^{-1}/detector during 2000-2002, followed by higher luminosity running at 5-10fb^{-1}/year/detector. These two periods are referred to as Run II and TeV33. Additionally, the beam energy will be increased from $\sqrt{s}$ = 1.8 to 2.0 TeV. Extensive upgrades to the CDF and DØ detectors[3,4] are underway. The combination of luminosity and detector improvements will significantly extend and expand the physics results of Run I.

2 Physics Goals

To date, the SM $SU(3)_C \times SU(2)_L \times U(1)_Y$ theory of strong and electroweak interactions has been extremely successful, withstanding all experimental challenges; the outstanding issue being observation of the spin-zero neutral Higgs boson. It is, however, widely felt that extensions to the current SM are needed to ameliorate certain problems. A number of proposed extensions predict new physics effects just above the currently probed energy scale. Deviations between high precision measurements and SM predictions may, at some point, indicate these extensions. Our program is to make use of the broad physics spectrum of $p\overline{p}$ collisions to test the SM at the level of its quantum corrections in search of any deviations, and to directly search for new physics.

The physics menu can generally be organized along five fronts:

- Top Quark Physics
- Electroweak Physics
- New Phenomena
- QCD, and
- B Physics.

The following sections discuss various aspects of each program. The top quark and W mass measurements are covered in somewhat greater detail given their importance in future SM electroweak fits, along with other aspects of top quark physics that become statistically significant with future data sets.

3 Top Physics

The large top quark sample provided by the Run II and TeV33 data sets will lead to a broad range of top quark studies. The TeV2000 [5] report provides an extensive survey of possible measurements, including the mass, $\sigma_{t\bar{t}}$, Wtb coupling, decay width, limits on $|V_{tb}|$, CP asymmetries, and searches for SUSY and other rare decays. The following short survey is drawn from that document and others.

3.1 Yields, Mass and Cross Section Measurements

Top quarks will be produced both in pairs via the strong interaction, and singly via the electroweak interaction. The dominant single top modes are $qb \to q't$ (W-gluon fusion), and $q'\overline{q} \to t\overline{b}$ (W^* production). The event yields are of order [a] (7000, 3300)/fb^{-1} for $t\bar{t}$ and single t production respectively. Extrapolating from CDF's Run I experience for lepton and b-jet tagging, [b] yields of $\sim$600 reconstructed $t\bar{t}$ (l+jets+1b-tag) events/fb^{-1} can be expected. Single top events (decaying leptonically) must pass tighter cuts on lepton identification and b-tagging due to the high W+jets background. The TeV2000 report estimates a BR $\times$ reconstruction efficiency of $\sim$3.5%, which yields about 115 reconstructed events/fb^{-1}, with a signal to background ratio of 1:2.

An accurate measurement of the top quark mass is a prime objective. In Run I, the l+jets+1b-tag sample produced the most accurate measurement of m_t. With the large event samples of Run II/TeV33, the error on m_t from the dilepton, l+jets+2b-tag, all-hadronic, and single top channels are all expected to become competitive with the l+jets+1b-tag channel. Estimates of δm_t in Run II typically use the l+jets+1b-tag channel as a benchmark. Table 1 shows the expected values of δm_t for this channel based on $t\bar{t}$ and calibration data for 2 and 30 fb^{-1}. At 2fb^{-1}, δm_t is expected to be $\sim$ 3 GeV/c^2 per detector. When all of the decay modes from CDF and DØ are combined, the precision of the top quark mass may be known to $\leq$ 2 GeV/c^2. Beyond Run II, the challenge will be to trigger on and reconstruct top quark and calibration events in the presence of multiple underlying minimum bias events. The situation is

[a] $\sigma_{t\bar{t}}$ from ref.[8] with m_t=174 GeV/c^2, $\sqrt{s}$=2 TeV, σ_t from ref.[9]

[b] from refs.[5,6] assuming $\not\!\!E_T \geq$ 20GeV, $l_{p_T} \geq$ 20 GeV/c, single b-jet tagging efficiency = 65%

addressed in the TeV2000 study and others,[6,7] and the expectation is that with 30fb^{-1}, $\delta m_t \leq 1$ GeV/c^2 is achievable.

With the large data samples of Run II and TeV33, systematic uncertainties will dominate δm_t. The dominant sources are the jet energy scale, background shape, and event reconstruction. Of these, the jet energy scale is the largest. Large statistics $Z{+}j$ ($Z \rightarrow e^+e^-$), $W \rightarrow jj$, and $Z \rightarrow b\bar{b}$ event samples will be used to calibrate the Monte Carlo jet model and detector response. In general, the various systematics, in particular the jet energy scale, are expected to scale[5] as $1/\sqrt{N}$.

Measurement of the production cross section, $\sigma_{t\bar{t}}$, provides a check of QCD and is sensitive to new physics. Non Standard Model processes could show up as an enhancement or reduction of the cross section, or as a modification to the event kinematics. Heavy resonances decaying into $t\bar{t}$ pairs could be seen as a peak in the $t\bar{t}$ invariant mass distribution. Table 1 lists the expected measurement precision of $\sigma_{t\bar{t}}$ for 2 and 30fb^{-1}. The dominant uncertainties are in the total acceptance for $t\bar{t}$ and background, and a constant 3.5% uncertainty in the integrated luminosity measurement. As data samples increase, the precision of the $\sigma_{t\bar{t}}$ measurement is expected to converge to ~5%. The expected sensitivities [5,10] to a topcolor Z', decaying into a $t\bar{t}$ pair are also given in Table 1.

3.2 Wtb Vertex, $|V_{tb}|$, $t \rightarrow H^{\pm}$

The structure of the Wtb vertex can be probed using top quark decays. In the SM, the Wtb vertex has only V−A couplings; as a result, top quarks decay only into longitudinal and left-handed W's, with branching ratios of about 70(30)% respectively. Non-universal top couplings can be probed by studying the polarization of decay W's. The polarization state of a W from top decay can be probed experimentally using the angular distribution of the charged lepton[11]. As shown in ref.[5] this measured distribution can be used to extract the longitudinal and left-handed branching ratios and to set limits on a right-handed W component. The expected sensitivities are shown in Table 1.

Lower limits on the CKM matrix element $|V_{tb}|$ can be extracted from the single top production cross sections. Under the assumption of three generations and unitarity of the CKM matrix, $|V_{tb}|$ is ~1. If a fourth generation exists, $|V_{tb}|$ could lie anywhere between ≈0-1, depending on the mixing with the fourth generation. Given this, a measurement of $|V_{tb}|$ appreciably less than 1 would be of great interest. The measurement of $|V_{tb}|$ is best accomplished using the cross section for single top production, $\sigma_t \propto |V_{tb}|^2$. From various studies [13,14], it appears that isolating the cross section of the W^* s-channel process is possible and will yield the best limits on $|V_{tb}|$, as it is free of theoretical uncertainties on the gluon distribution. With the assumption of no V+A coupling, limits of $|V_{tb}| \geq 0.86(0.95)$ with 2(30)fb^{-1} are expected. In ref.[15], the implications of a V+A contribution to the cross section and the impact on the $|V_{tb}|$ measurement are explored.

A charged Higgs boson, H^+, could be produced in top quark decays, $t \rightarrow H^+ b$. The coupling will depend on tanβ and the H^+ mass. With a subsequent decay, $H^+ \rightarrow c\bar{s}$ or $\tau\nu$, direct searches can be made by looking for a τ excess or a dijet mass bump. In general, limits on non-W top decays can be set using the ratio $\sigma_{l+jets}/\sigma_{dilepton}$. Non-$W$ decays will deplete the dilepton sample, increasing the ratio. With an understanding of the $H^+ \rightarrow c\bar{s}$, $\tau\nu$ contribution to the single and dilepton cross sections, this ratio can be used to set limits on a charged Higgs component in top decays. This sensitivity, given in Table 1, is estimated in the TeV2000 study for the $c\bar{s}$ decay with the pessimistic assumption of $M_{H^+} \approx M_W$, giving no dijet mass separation.

Table 1: Selected parameters and sensitivities for the FNAL top physics program. Results are for each detector in the nominal Run II and TeV33 scenario.

Int. Lum./experiment, fb^{-1}	2	30
Produced, # events		
$t\bar{t}$	14000	21×10^4
single top	6000	9×10^4
Reco. Yields, # events		
$t\bar{t}$: decay channel		
$l+\geq 3$ jets+1b-tag	1200	18000
$l+\geq 4$ jets/2b-tag	450	6600
dilepton	156	2350
all-hadronic[16]	1000	15000
single top		
(W-gluon fusion) $qb \rightarrow q't$	170	2500
(W^* production) $q'\bar{q} \rightarrow t\bar{b}$	21	320
δm_t^a,(GeV/c^2)	2.8	$\leq$1
statistics	1	0.3
jet energy scale	2.3	0.6
Σ other systematics	1.2	0.43

	2	30
Cross Section Precision, (%)		
$\delta\sigma_{t\bar{t}}$	8	6
$\delta\sigma_t$(all σ_t, W^* only)	25,27	7,8
(X$\rightarrow t\bar{t}$) Resonance Search		
$\sigma\times BR(\Gamma_X=1.2\% m_X)$, (fb)	<80	<5
m_X, (GeV/c^2)	>920	>560
Wtb Couplings		
δB(t$\rightarrow bW_{long}$)	4.6%	1.2%
δB(t$\rightarrow bW_{right}$)	1.8%	0.5%
$\lvert V_{tb}\rvert$ Precision		
from $\sigma_t(W^*)$	14%	5%
Top H^+ Decay		
B($t\rightarrow H^+ b$)	< 11%	< 3%

[a]for l+jets+1b-tag channel only.

4 The Precision Electroweak Program

The mass of the W boson, M_W, is a fundamental parameter in the SM. Precise knowledge of M_W and m_t place constraints on the Higgs boson mass via electroweak radiative corrections. Eventually, with M_H in hand, these corrections may place the most stringent constraints on the SM. In addition to the measurement of M_W, a number of other electroweak measurements can be made which yield useful SM comparisons/constraints. This program of measurements is already established from Run I, and future analyses are, in general, straightforward extensions. The Run II/TeV33 CDF and DØ analyses will however benefit greatly from detector improvements. Electron and muon triggering is extended to higher η with improved purity and efficiency (see refs.[3,4]) resulting in an expected factor of 2-3 improvement in acceptance. Yields of approximately 2×10^6 $W\rightarrow l\nu$ (e,μ) and 3×10^5 $Z\rightarrow ll$ events/fb^{-1}/detector are expected.

The extraction/precision of M_W in Run II is discussed in the following section. Below some of the highlights of the future electroweak program are summarized:

- Uncertainty of the W mass, $\delta M_W \leq 30$ MeV/c^2 per detector with $2fb^{-1}$;
- $\delta M_H \approx 40\% M_H$, from a global fit with δM_W=30 MeV/c^2, δm_t=2 GeV/c^2;
- The W width can be measured to a precision of 15 MeV; The leptonic branching ratio B($W\rightarrow l\nu$) can be measured to about the 1% level;
- The forward-backward asymmetry (A_{FB}) in $q\bar{q}\rightarrow e^+e^-$ at the Z pole can be used to measure $\sin^2\theta_W$ in the light quark sector, ($\delta\sin^2\theta_W = 0.00023$ with $10fb^{-1}$);
- The W charge asymmetry will be measured using the high lepton pseudorapidity coverage and will be used to further distinguish different PDF's, which will lead to improvements in the M_W and A_{FB} measurements;
- Searches for CP violation in W production and decay will be pursued;
- Present limits on anomalous WWV and $Z\gamma V$ couplings will be extended - a factor of 10

Table 2: Extrapolated future uncertainty on W mass measurement based on current statistical and systematic uncertainties.

	traditional M_T analysis		W/Z transverse mass ratio	
Int. Luminosity (fb^{-1})	2	30	2	30
Interactions/crossing	2	6	2	6
δM_W(MeV/c^2), statistical	20	5	30	8
systematic	21	10	9	4
Total δM_W(MeV/c^2)	29	11	31	7

increase in $\int Ldt$ leads to a factor of $\approx$ 2 increase in sensitivity.

4.1 Future W Mass Measurements

In Run I, M_W was extracted from leptonic W decays by comparing the measured transverse mass spectrum, which sharply peaks in the vicinity of M_W, to Monte Carlo results with M_W as an input. The results for Tevatron measurements[18] through Run Ib are M_W=80.41±0.09 GeV/c^2. Combined with the recent LEPII result the current world average is M_W=80.375±0.065 GeV/c^2. The analysis of the uncertainties in the M_W fit and their extrapolation to Run II data sets is covered in detail in refs.[5,17] Currently the error is dominated by statistics of the event sample and the lepton energy/momentum scale, both of which will scale as $1/\sqrt{N}$. With Run II data sets, δM_W will be dominated by the W production model.

Another method for measuring M_W employs ratios of the distributions of relevant quantities in W and Z events,[19,20] in particular the lepton p_T or transverse mass. Due to similarities in $W(Z)$ production and decay, many of the systematics cancel in the ratio. DØ has presented a preliminary M_W ratio analysis[20] using $W \rightarrow e\nu$ and $Z \rightarrow ee$ events. The Z decays are transformed into W decays by treating one of the electrons as a ν, adding its energy to the residual $\not{E}_T$ in the event, and appropriately modifying the overall event parameters. The Z transverse mass distribution is then scaled down to the W distribution. The W mass is then determined from the scale factor times the Z mass. Using 14pb^{-1}, the uncertainty from the DØ analysis is $\delta M_W = \pm 0.36$(stat)± 0.075(sys) GeV/c^2, and is dominated by low Z statistics. An extrapolation to future data sets can be made by assuming the statistical uncertainty will scale as[5,17] $\sqrt{I_C/N}$, where I_C is the number of interactions/crossing.

Table 2 shows the estimated future errors based on the current DØ uncertainties[18], $\delta M_W = \pm 95$(stat)± 70(sys) MeV/c^2 (from 90 pb^{-1}), using the M_T method and the uncertainties given above for the ratio method. It may be optimistic to assume that the systematics will continue to scale with statistics in the future high luminosity environment, however $\delta M_W \sim 30$ MeV/c^2 from Run II seems feasible.

5 QCD

QCD studies in Run II and TeV33 will benefit from copious statistics, improved theoretical calculations, and an improved understanding of the detector response; thus broadening the scope and increasing the precision of QCD tests. Some of the main goals of the future QCD program are:

- With a 2fb^{-1}sample, simultaneously determine α_S and parton distribution functions, and measure the running of α_S to Q^2 of $(500 GeV)^2$;

• The large data set will allow for measurement of differential cross sections with respect to an increased number of event parameters; triple differential cross sections can be chosen that are particularly sensitive to the partonic and gluonic content of the proton;

• New Phenomena searches include quark compositeness, excited quarks, rare diffractive processes, vacuum polarization, and new objects which decay into combinations of jets, bosons, or neutrinos;

• The statistics of the W/Z+jet sample will be comparable to the present di-jet sample, making it feasible for use in the entire QCD menu.

6 B Physics

Within the next few years, precision tests of the Standard Model of weak quark mixing and CP violation are going to be carried out by experiments at SLAC, KEK, DESY, Cornell, and Fermilab. The current CDF and DØ B physics programs[1] will be greatly enhanced in Run II/TeV33. The upgraded CDF and DØ detectors will be well suited for triggering on and reconstructing B hadrons. Both feature new stereo silicon vertex detectors, high bandwidth trigger systems, and hardware upgrades that will allow lower $e(\mu)$ trigger thresholds, with triggering extended to higher η.

A primary objective of the program will be the search for CP violation in neutral B meson decays and constraining the CKM matrix via a measurement of B_s mixing. Additionally, many other B physics studies are feasible, such as extraction of α^2 and α^3 processes, searches for rare $B_0 \rightarrow l^+ l^-$ decay modes via dilepton triggers, and B_c spectroscopy[21].

With 2fb^{-1}, each detector will collect between $10-15\times10^3$ $B_0 \rightarrow J/\psi K_s$ decays, with flavor tagging efficiencies[c] between 3-8%. An asymmetry in the B_0 and $\overline{B_0}$ decay rates would indicate CP violation and can be used to extract $\sin(2\beta)$. Using 2fb^{-1} the estimated $\delta\sin(2\beta)$ is 0.16-0.08.

For the $B_0 \rightarrow \pi^+\pi^-$ decay and extraction of $\sin(2\alpha)$, CDF will trigger on pairs of isolated tracks in its Level 1 trigger with an expected accept rate of 16kHz. Using curent estimates of the $B_0 \rightarrow \pi^+\pi^-$ branching ratio and with flavor tagging efficiency of 6%, this leads to $\delta\sin(2\alpha)$=0.1.

The observable range of the B_s mixing parameter x_s will be $\lesssim 20$ using fully reconstructed hadronic decays. Triggering and background suppression will be crucial to maximize the reach and precision of the x_s measurement.

7 New Phenomena: SUSY and Direct Higgs Searches

Future SUSY/Higgs searches at the Tevatron are an active area of research[22]. The Supersymmetry/Higgs workshop[23] at Fermilab has been formed with the purpose of organizing and cataloging the possible SUSY variants and their associated detector signatures, along with SM backgrounds. Given the various SUSY scenarios, and number of unknown parameters, there are a number of possibilities, and over two dozen discovery channels are under study.

Most analyses to date have assumed R-parity conserving scenarios in which supersymmetric particles (sparticles) are pair produced and the lightest sparticle (LSP) is stable. Models with the neutralino as the LSP, χ_1^0, lead to final states with $\not\!\!E_T$. A channel often discussed in the literature is chargino-neutralino pair production $q\bar{q} \rightarrow \chi_1^{\pm}\chi_2^0$ with subsequent decays $\chi_1^{\pm} \rightarrow l\nu\chi_1^0$ and $\chi_2^0 \rightarrow l\bar{l}\chi_1^0$, leading to a salubrious tri-lepton + $\not\!\!E_T$ final state. Both CDF and DØ have searched[24] for this signature using $\sim$100pb^{-1} from Run I data with negative results and have set limits on $\sigma\times$BR as a function of model parameters. Ref.[25] studies this mode for a TeV33 scenario and concludes that with 25fb^{-1}, the maximum chargino mass we can probe is 250

[c] CDF is considering a number of detector improvements to enhance this measurement including a time of flight system to discriminate between π's and K's.

GeV/c^2. Other TeV33 sensitivities, from ref.[22], are gluino/squark masses >450 GeV/c^2 via the classic (multijets + $\not\!\!E_T$) and light stop masses out to 180 GeV/c^2 via $\tilde{t_1} \rightarrow b\chi_1^\pm$ (dilepton + $\not\!\!E_T$).

Searches for the Higgs boson are an obvious priority. LEPII has excluded M$_H$<77.5 GeV/c^2, and by the start of Run II should have excluded(discovered) the Higgs up to M$_H$~95 GeV/c^2. At the LHC, $t\bar{t}$ backgrounds will make observation difficult for M$_H$<130 GeV/c^2. Higgs searches at the Tevatron have been studied in some detail,[5,26,27,28] and detection up to M$_H$≈130 GeV/c^2 should be possible with 30fb^{-1}.

SM Higgs production at the Tevatron would proceed via $q\bar{q}\rightarrow$ $(W,Z)H$ with $H \rightarrow b\bar{b}$, $\tau^+\tau^-$ or $c\bar{c}$, with branching fractions $\sim$ 85, 8, 8% respectively. Of the various decay scenarios, triggering on leptonic W, Z decays with $H \rightarrow b\bar{b}$ is the most promising. A signal would be seen as an enhancement in the invariant mass distribution of the two b-tagged jets over background. From the studies cited above, using the combined W and Z channels, the signal to background ratios are (310/1284, 168/834)/detector for M$_H$=(100,120) GeV/c^2 with 30fb^{-1}.

It should be noted that beyond Run II, the physics justification for the TeV33 era will be SUSY and Higgs searches. Given that current SM electroweak fits favor a light Higgs, M$_H$<250 GeV/c^2, and that within the MSSM the lightest Higgs, h_0, is SM-like with $m_{h_0} < 130$ GeV/c^2, the Higgs search in Run II/TeV33 will be one of the highest priorities.

8 Conclusion

The data from $p\bar{p}$ collisions are applicable to a wide range of physics issues. Over the period 2000-2005 the CDF and DØ detectors will make use of the expected large integrated luminosity supplied by the Tevatron. The measurements made during this period will provide valuable and continued input to the Standard Model.

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