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The TeV2000 Workshop

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The TeV2000 Workshop is studying the potential of upgrades to the Tevatron collider for physics at the electroweak scale. We review the physics program, focusing on top, light Higgs, supersymmetry, W/Z and QCD physics. Detector requirements and triggering at high luminosities are discussed; no insurmountable problems have been found. We feel that the accumulation of integrated luminosities of several tens of inverse femtobarns at the Tevatron collider offers considerable physics potential, and is possible on a reasonable timescale.

INTRODUCTION

TeV2000 [1] is a continuing workshop devoted to studying the promise of upgrades to the Fermilab Tevatron collider for high-p_T (electroweak scale) physics. An initial meeting was held at the University of Michigan in October 1994; a written report will be available in the summer of 1995. The accelerator conditions considered are:

- Run II, with the Main Injector upgrade now under construction giving a luminosity of $\mathcal{L} = 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and with $1-2\,\mathrm{fb}^{-1}$ accumulated using the already planned CDF and DØ detector upgrades;
- "Run III", which might follow after a few years with a further luminosity upgrade to $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $30-100\,\mathrm{fb}^{-1}$ accumulated, using an unspecified future detector(s) or upgrade(s).

We will show that datasets of the order of those assumed for Run III have significant physics potential.

PHYSICS PROGRAM

The Top Quark

The top quark represents a new state at the electroweak scale, and it is the most strongly coupled to the symmetry-breaking sector. Indeed, its coupling to the standard-model Higgs is of order 1. It therefore offers a window into new physics, yet it is produced at an existing facility, and the cross sections and yields are known,

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enabling us to plan a physics program: we expect about 6500 tagged $t\bar{t}$ events in $10\,\mathrm{fb}^{-1}$, with about 2800 of these being double-tagged events with 4 jets.

For the t mass measurement, present CDF precision suggests $\delta m_t \sim 3\,\mathrm{GeV}/\sqrt{\mathcal{L}}\,(\mathrm{fb}^{-1})$. The systematic limitations from the calorimeter and jet energy scale (including gluon radiation) will be hard to beat down, but calibration on $W \to jj$ and $Z + jets$ will help. The $W + jets$ background shape can be pinned down using $Z + jets$ events, as can the b-tagging efficiency and biases. Knowledge of the background shapes and mass-fitting systematics will benefit from the huge control samples available. We also expect that theoretical uncertainties will be reduced over time. We therefore estimate that the top mass will be measureable to $3-5\,\mathrm{GeV}$ with $1\,\mathrm{fb}^{-1}$ and $1-2\,\mathrm{GeV}$ with $10\,\mathrm{fb}^{-1}$ of integrated luminosity. Other mass-determination techniques also deserve investigation: fitting the $t\bar{t}$ system mass, measuring the b-decay length distribution, or the branching ratio of top to longitudinal W's.

The $t\bar{t}$ production cross section will be measured to 13% with $1\,\mathrm{fb}^{-1}$ of integrated luminosity; this will fall to 5% and 3% for $10\,\mathrm{fb}^{-1}$ and $100\,\mathrm{fb}^{-1}$ respectively. (The present theoretical uncertainty is of the order of 20% but this should fall.) It will be possible to place limits of much less than 1 pb on the product of cross section and branching ratio for new particles decaying into $t\bar{t}$, as predicted in models of multiscale technicolor, V_8 color octet mesons, *etc* [2]. The single top cross section will be measured to 14% with $1\,\mathrm{fb}^{-1}$ of integrated luminosity, again falling to 5% and 3% for $10\,\mathrm{fb}^{-1}$ and $100\,\mathrm{fb}^{-1}$ respectively. The single top cross section enables extraction of Γ_t, the top quark's total width, which is not measureable in t decays; currently this extraction would be theoretically limited to an accuracy of about 30%, but theoretical progress should reduce this uncertainty.

The branching ratio for top to decay into longitudinally polarized W bosons may be determined from the center of mass angular distribution of the lepton from the W decay [3]. Its value (about 0.7 in the standard model) may be measured to 4%, 1.3% and 0.4% with $1\,\mathrm{fb}^{-1}$, $10\,\mathrm{fb}^{-1}$ and $100\,\mathrm{fb}^{-1}$ of integrated luminosity. The same measurement may be used to set limits on a $(V+A)$ contribution to the $t \to Wb$ vertex at the level of 2% ($1\,\mathrm{fb}^{-1}$), 0.6% ($10\,\mathrm{fb}^{-1}$) and 0.2% ($100\,\mathrm{fb}^{-1}$). The branching ratio for $t \to b$ can be measured from the ratio of single to double-b-tagged events to 3% ($1\,\mathrm{fb}^{-1}$), 1% ($10\,\mathrm{fb}^{-1}$) and 0.3% ($100\,\mathrm{fb}^{-1}$). This in turn can be used to constrain the CKM matrix element V_{tb}.

It should be emphasized that the precision of almost all of these top quark parameters is significantly improved with integrated luminosities of $10\,\mathrm{fb}^{-1}$ or $100\,\mathrm{fb}^{-1}$ compared with $1\,\mathrm{fb}^{-1}$, showing the physics potential of further Tevatron upgrades beyond Run II.

Associated Production of Light Higgs

A number of recent phenomenological papers [4] have suggested that the Tevatron collider is sensitive to standard model Higgs bosons with masses up to about 120 GeV given an integrated luminosity of $\sim 30\,\mathrm{fb}^{-1}$. The channels of interest are associated production of the Higgs H with a W or Z, where $H \to b\bar{b}$ and $W/Z \to$ leptons; or $H \to \tau^+\tau^-$ and $W/Z \to$ jets. Studies including detector simulations are currently in progress to investigate these channels. For the $b\bar{b}$ mode, the necessary b-tagging efficiencies seem reasonable, and no insurmountable difficulties have appeared; on the other hand, the $\tau^+\tau^-$ mode seems rather harder than has been claimed (given the large $Z \to \tau^+\tau^-$ background) and may not be feasible at the Tevatron.

It should be noted that the Higgs search relies upon b-tagging and jet-jet mass reconstruction. The feasibility of these techniques was first demonstrated in the top quark discovery and they will undoubtedly benefit from refinements as large statistics top samples are studied.

Supersymmetry

Supersymmetry at the electroweak scale is theoretically appealing as it avoids unnatural fine-tuning and ensures gauge coupling unification. In the framework of the constrained minimal supersymmetric standard model [5] some general predictions may be made: there is a light, almost standard-model Higgs, with mass less than 140 GeV; and most of the parameter space has low-mass superpartners detectable at the Tevatron. Experimentally, Tevatron searches will look for a light Higgs, charginos and neutralinos, and squarks and gluons. With about $30\,\mathrm{fb}^{-1}$ of integrated luminosity, it will be possible to discover — or to severely constrain — supersymmetry at the electroweak scale.

Weak Vector Bosons

With integrated luminosities of several inverse femtobarns, extremely large samples of W and Z production will be available. For example, per fb^{-1}, we expect one million $W \to \ell\nu$, 80,000 $Z \to \ell^+\ell^-$, 9000 $Z + jet$, and 200 $Z + 4\,jets$ events. We expect an error on the W mass of about 50 MeV for $1\,\mathrm{fb}^{-1}$, dropping to perhaps 30 MeV for $10\,\mathrm{fb}^{-1}$, though it will certainly be challenging to keep systematics below this level. With a top mass uncertainty of 3 GeV and a W mass uncertainty of 50 MeV, the standard model Higgs mass is constrained to approximately $\delta m_H/m_H = \pm 0.8$; for 1 GeV and 30 MeV, this improves to $\delta m_H/m_H = \pm 0.5$.

The forward-backward asymmetry for $Z \to \ell^+\ell^-$ will enable a determination of $\sin^2\theta_W$ (for light quarks) to 0.00036 ($10\,\mathrm{fb}^{-1}$), which is comparable to the present LEP precision, but without any fragmentation systematics. The W asymmetry will also determine parton distributions. For $10\,\mathrm{fb}^{-1}$, limits on anomalous vector boson couplings from $W\gamma$ production will be $\lambda < 0.05$ and $\Delta\kappa < 0.20$, which are comparable with LEP2 ($500\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 190$ GeV).

QCD

W/Z and Drell-Yan production offer clean probes of QCD without any final state interactions. However, large luminosities are needed because the cross sections are small. In $10\,\mathrm{fb}^{-1}$, there will be approximately one million $Z \to \ell^+\ell^-$ events, giving statistics comparable with present jet samples. It will, for example, be possible to determine α_S and its running from Drell-Yan plus jets events as a function of dilepton mass. The differential cross sections for W/Z and Drell-Yan processes will also serve to constrain parton distributions, especially at the extremes of phase space.

New Physics

Hadron colliders are very powerful in their sensitivity to a wide variety of new physics beyond the standard model. The Tevatron collider is no exception. For many such objects (axigluons, new gauge bosons, excited quarks, color octet technirhos, leptoquarks, *etc.*) the mass reach increases monotonically with increasing luminosity up to at least $100\,\mathrm{fb}^{-1}$ [6].

DETECTOR SYSTEMS

The physics signatures described above place rather well-defined requirements on the detector needed at an upgraded Tevatron. We feel that the requirements, though quite stringent, are all technically achievable. The recent discovery of the top quark at the Tevatron has re-emphasized the feasibility of lepton and jet identification, b-tagging, measurement of $\not\!\!E_T$ and reconstruction of a massive state from its decays into jets, in a hadron collider environment. These techniques will continue to be refined as more Tevatron collider data is accumulated, and this gives us confidence that the detector systems and analysis techniques required represent a reasonable extrapolation of the present state of the art.

Tracking and Vertex-tagging

A magnetic central tracking system is needed in order to measure and trigger on isolated high momentum charged tracks. This will form part of the electron and muon identification and will allow detection of one and three-prong hadronic tau decays.

The tracker should also incorporate a silicon vertex detector capable of identifying a displaced vertex from b-decay up to $|\eta| \leq 2$ with an efficiency of 50% and a mistag rate of $\leq 1\%$. It is crucial to understand whether this b-tagging efficiency is still achievable at the high luminosities envisaged. We have compared the performance of four silicon detector designs:

- The CDF SVX detector as currently operating in Run 1B.
- The DØ Silicon detector under construction for Run 2.
- The ATLAS and CMS silicon detector systems for LHC.

The CDF SVX at $\mathcal{L} = 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has a b-tagging efficiency, ϵ_b, of about 60% per jet (within the fiducial region), and a rejection, R, of about 200 against light quark jets. The DØ Silicon detector for Run 2 has been simulated to give $\epsilon_b = 0.5$ or 0.35 for $R = 50$ or 100 respectively, at $\mathcal{L} = 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The CDF and DØ silicon detectors are broadly similar, with 4 or 5 layers of silicon arranged close to the beampipe (the DØ detector covers a larger range of rapidity). The LHC detectors both propose to use many more layers of silicon, covering a larger range of radius from the beam, and to employ finely segmented pixel detectors close to the beam to enhance the tagging capabilities in the high-ocupancy environment. The ATLAS simulations claim a performance of $\epsilon_b = 0.6$ for $R = 200$ at $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and $\epsilon_b = 0.5$ for $R = 50$ at $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The CMS design is somewhat more conservative, and its expected performance is $\epsilon_b = 0.5$ or 0.4 for $R = 50$ or 150 at $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The present performance of the CDF SVX seems adequate for the Higgs search in the $b\bar{b}$ channel — the challenge is to maintain this performance at much higher luminosity. The LHC designs have chosen to add more silicon layers and to use pixel detectors in order to increase redundancy and reduce occupancy; their performance is also quite adequate for the Higgs search (though at greater cost). An evolution in a similar direction may be expected for the detector(s) at an upgraded Tevatron. We are confident that the necessary b-tagging performance can be obtained, though the design and optimization of the detector will require detailed studies.

Calorimetry

Electromagnetic calorimetry is required for the identification and measurement of isolated electrons (from $W \to e$ decays) and of soft electrons as b-tagging technique. Ultra-precise energy resolution is not called for (typical EM resolutions of $\sim 15\%/\sqrt{E}$ should be sufficient). The EM calorimeter must cover the pseudorapidity range up to $|\eta| \leq 2.5$ in order to have adequate acceptance. The EM calorimeter should provide an isolated electron trigger; in principle one could also attempt to trigger on soft electron b-tags but this has not been assumed in the trigger rate estimates.

Electron and photon identification will be degraded by the extra energy from minimum bias pileup events, which will make isolation cuts less efficient. It is found [7] that an electron efficiency of 90% may still be obtained in the presence of nine pileup events with a cut of $E_T \leq 4\,\mathrm{GeV}$ in a cone of $R = 0.4$.

The EM calorimeter must be backed with a hadronic section capable of identification and measurement of jets and measurement of missing transverse energy. Again, ultra-precise energy resolution is not called for (typical hadronic resolutions of $\sim 70\%/\sqrt{E}$ should be sufficient) but emphasis should be placed on the performance of the calorimeter for jet-jet invariant mass reconstruction. Studies for the LHC suggest that transverse segmentation of $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$ is desirable in order to reconstruct boosted $W \to jj$ decays but that segmentation finer than this is not called for. The hadron calorimeter should cover at least the range up to $|\eta| \sim 3.5$ in order to be efficient for jets up to $|\eta| = 2.5$ and in order to provide a good measurement of $\not{E}_T$. The hadronic calorimeter must be capable of triggering on jets and on $\not{E}_T$.

Pileup will also degrade the $\not{E}_T$ resolution. It is found [7] that ten minimum bias pileup events give an average contribution to $\not{E}_T$ of about 10 GeV but do not yield any extra events with $\not{E}_T \geq 20\,\text{GeV}$.

Muon Detection

A muon detector is required for the identification and measurement of isolated muons (from $W \to \mu$ decays) and of soft muons as a b-tagging technique. The muon system must cover the pseudorapidity range up to $|\eta| \leq 2.5$ and should provide an isolated muon trigger at moderate momenta ($p_T \geq 15 - 20$ GeV/c); one could also attempt to trigger on soft muon b-tags but this has not been assumed in the trigger rate estimates. The most precise measurement of muon momentum will most likely come from the central tracker, so the muon system should concentrate on tagging and triggering fuctions.

In addition to the physics requirements, the detector systems must operate and be triggerable in the high-rate, high-radiation environment of the upgraded Tevatron collider.

TRIGGER AND DATA ACQUISITION

In order to obtain some semi-realistic estimates of trigger rates for a detector running at $\mathcal{L} = 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$, we have assumed a three-level trigger system. The first level is assumed to be analogue hardware (e.g. a calorimeter tower above threshold); the second level programmable digital hardware (e.g. isolation or track-matching using a DSP chip); and the third level a software trigger running on general purpose cpu's with access to full event information.

The following primitives should be available to the trigger:

- **Isolated Electrons** based on the EM calorimeter up to $|\eta| \leq 2.5$. In principle one could also attempt to trigger on soft electron b-tags but this has not been assumed in the rate estimates.
- **Isolated Muons** using the muon system up to $|\eta| \leq 2.5$. Again, soft muon b-tags could also be added to the trigger but this has not been assumed in the rate estimates.
- **Charged Tracks**. An isolated high momentum charged track trigger will be needed to trigger on one and three-prong hadronic tau decays.
- **Jets** based on EM+hadronic calorimeter up to $|\eta| \leq 2.5$. At trigger level 2 or 3 a jet-jet invariant mass requirement could be used but this has not been assumed in the rate estimates.
- **Missing** E_T based on the sum of towers in the EM+hadronic calorimeters. At trigger levels 2 or 3 this estimate can be refined by inclusion of muons, use of fitted vertex z-position, etc.
- **Displaced Vertex**. A silicon vertex tracking trigger capable of a displaced vertex b-tag up to $|\eta| \leq 2$ at trigger level 2 or 3 may be useful but has not been assumed in the rate estimates.

A Toy Trigger Menu

We have surveyed current and proposed experiments regarding trigger bandwidths at each level. The rates that we have assumed as limits are 50 kHz accepted by Level 1, 5–10 kHz accepted by Level 2, and 100–200 Hz

Mode	$L1 \to L2$	$L2 \to L3$	$L3 \to host$
Top	7.2 kHz	4.0 kHz	50 Hz
$W/Z \to \ell$	8.0 kHz	3.4 kHz	28 Hz
$\not\!\!E_T$ + jets	1.3 kHz	1.3 kHz	30 Hz
$(W/Z)H \to q\bar{q}\tau^+\tau^-$	15 kHz	5.8 kHz	37 Hz
Total	23.5 kHz	11.1 kHz	145 Hz
(Limit)	50 kHz	5–10 kHz	100–200 Hz

TABLE I. Rates for an illustrative mix of triggers at $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

passed to the host computer. These rates are audacious but consistent with being technically achievable on the timescale of an upgraded Tevatron.

In Table 1, estimated rates are listed for an illustrative mix of triggers:

- *top*: single and dilepton top triggers based on the current DØ menu.
- $W/Z \to e, \mu$: unprescaled single lepton plus $\not\!\!E_T$ trigger for W's and uprescaled dilepton trigger for Z's.
- $\not\!\!E_T$+jets: for supersymmetry and $ZH \to \nu\nu b\bar{b}$. The $\not\!\!E_T$ threshold would be about 40 GeV for a pure $\not\!\!E_T$ trigger, and could be lowered to about 25 GeV if two jets were also required.
- $(W/Z)H \to qq\tau\tau$: charged track tau trigger for Higgs.

The rate estimates use measured (Run 1b) DØ calorimeter trigger cross sections, estimates for DØ charged track and muon trigger cross sections for Run 2, and measured rejection factors at level 2 and 3. The rates include allowance for the overlap between the electron and muon triggers for top, W/Z and $\tau \to \ell\nu\bar{\nu}$.

The immediate conclusion is that the situation does not look too bad. The rates at all levels are consistent with the limits assumed. Some more rejection at level 2 may be desirable, but there are a number of tools available that have not been assumed to be used so far — triggering for top on soft lepton tags or displaced vertex b-tags at level 2 or 3, for example.

Two points must be emphasized. Firstly this is, of course, only a very first look at trigger rates. Many factors such as multiple interactions at higher luminosity may dramatically increase the rates over what is quoted here. Secondly the bandwidths listed, while achievable, represent a large increase over the capabilities of the present DØ and CDF data acquisition systems and will be expensive and technically challenging to implement.

OFFLINE PROCESSING

If the rate of events out of Level 3 is 200 Hz, this cannot be spooled to tape (unless the event size is tiny or a large number of drives is used). It is more reasonable to imagine a 'near-line' processing farm where the reconstruction is performed in quasi-real-time. The present DØ and CDF reconstruction programs requires of the order of 15–20 seconds per event on a $\sim$ 30 MIPS machine, i.e. 500 MIPS-sec. If we assume the same reconstruction time per event then a reconstruction facility of 10^5 MIPS will be required to keep pace with the events being written. This could be thought of as a farm of two hundred workstations, each with 500 MIPS of cpu(s), which is quite conceivable on the timescale required.

CONCLUSIONS

There is interesting physics to be done with data samples of $10\,\mathrm{fb}^{-1} - 100\,\mathrm{fb}^{-1}$ at the Tevatron — 50,000 tagged top events, one million Z's — plus discovery potential for light Higgs and supersymmetry. The CDF and DØ detector 'configurations' are adequate, and a hypothetical future detector (or upgrade) would be triggerable and could be read out; processing the resulting large stream of data would not be a problem.

An interesting analogy may be made with CESR: in about 1983, there were $\sim$ 15 reconstructed B's in all modes, while by 1995 about 15 $b \rightarrow s\gamma$ rare decays had been observed. At the Tevatron, in 1995 we have $\sim$ 15 reconstructed t's in all modes; if the pattern could be repeated, we may hope for 15 rare top decay events in 2005!

REFERENCES

1. For more details of the TeV2000 workhsop, and a complete list of participants, please refer to `http://www.pa.msu.edu/hep/tev2000/`. The material presented here includes contributions from D. Amidei, R. Brock, P. Baringer, U. Baur, J. Butler, D. Cutts, K. De, M. Demarteau, J. Ellison, S. Errede, R. Harris, A. Heinson, U. Heintz, J. Hylen, T. Kamon, S. Kuhlmann, G. Ladinsky, T. LeCompte, T. Liss, W. Merritt, S. Vejcik, H. Weerts, S. Willenbrock, D. Winn, J. Womersley and others.
2. E. Eichten and K. Lane, Phys. Lett, **B327** (1994) 129; K. Lane, 'Top Quarks and Flavor Physics,' Boston University BUHEP-95-2, January 1995.
3. D. Winn and D. Amidei, 'Study of the $t \rightarrow Wb$ vertex at CDF,' CDF/PHYS/TOP/CDFR/2914, March 1995.
4. A. Stange, W. Marciano and S. Willenbrock, Phys. Rev. **D50** (1994) 4491; S. Mrenna and G.L. Kane, 'Possible Detection of a Higgs Boson at Higher Luminosity Hadron Colliders,' University of Michigan UM-TH-94-24, June 1994; A. Belyaev, E. Boos and L. Dudko, Mod. Phys. Lett. **A10** (1995) 25.
5. S. Mrenna *et al.*, 'Possible Signals of Constrained Minimal Supersymmetry at a High Luminosity Fermilab Tevatron Collider,' University of Michigan UM-TH-95-14, May 1995.
6. R. Harris *et al.*, 'Prospects for Exotic Physics at the Tevatron,' CDF/PUB/EXOTIC/PUBLIC/2900, April 1995.
7. T. Kamon, private communication.