Physics with the Main Injector

Hugh E. Montgomery
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, U.S.A.

The Main Injector is a new rapid cycling accelerator at Fermilab which is a source of protons to be used in antiproton production to enhance the luminosity of the Tevatron Collider and to provide extracted beams for use in a range of fixed target experiments. We discuss the current status of the accelerator and the physics which it enables. The physics ranges broadly over the standard model and beyond, from the search for neutrino mass to collider physics at the highest energy available today.

I. INTRODUCTION

Since its construction the protons and anti-protons used in the Tevatron Collider have been produced and injected into the Tevatron, by the Main Ring which was the original 400 GeV proton synchrotron constructed during the 1970's. The Main Injector is a new 120-150 GeV rapid cycling synchrotron in a tunnel separate from that of the Tevatron. The Main Injector improves significantly the anti-proton production capability of the complex. The new 8 GeV permanent magnet storage ring, the Recycler, in the Main Injector tunnel, permits reuse of the anti-protons that remain in the Tevatron at the end of a store. Since most of the luminosity degradation results from beam dilution rather than anti-proton loss, this effectively doubles the available anti-protons for collisions.

The greatly increased luminosity of the Tevatron Collider opens up windows on new physics. The production rate for heavy objects such as the top quark will be greatly enhanced. Perhaps most strikingly the increased luminosity may eventually provide sensitivity to the Higgs boson system which is thought to generate the mass of the observed particles, the W boson, the Z boson, and the quarks and leptons.

The Main Injector is constructed with extracted beams that can be used for fixed target experiments. The operational possibilities are sufficiently flexible to interleave anti-proton production and fixed target physics with modest impact on either. One of the primary uses of the high intensity extracted proton beam will be to produce a beam of neutrinos which will then be directed towards the Soudan mine in Minnesota where a distant detector can make measurements on the evolution of the neutrino species in the beam.

The couplings of the three generations of quarks are described using the Cabibbo-Kobayashi-Maskawa flavor mixing matrix. A complete understanding this matrix does not yet exist. For example, the violation of Charge-Parity symmetry has been observed in the decay of neutral long-lived K_L^0 mesons but nowhere else. Kaon beams from the Main Injector promise key measurements in that system. The analogous investigation of the b-quark system is only beginning. The collider experiments CDF and DØ or/and a new dedicated experiment, BTeV, have ready access to large numbers of B hadrons, thus permitting extensive measurements beyond those being made at electron-positron B factories.

The varieties of physics in these different sectors are all at or beyond the edge of our theoretical understanding and offer new insight on our world. In the rest of this paper we explore the machine and the enabled physics in a little more detail.

II. THE MACHINE

The Main Injector is a rapid cycling proton synchrotron with a circumference half that of the Tevatron. Protons are injected from the Booster machine to the Main Injector at 8 GeV and are accelerated to 120 GeV for either extraction to the anti-proton production target or to an external physics target. For injection of either protons or anti-protons into the Tevatron, the Main Injector ramps to 150 GeV.

The machine performance parameters of interest for the particle physicist are given in Table I. In mixed modes of operation, the Main Injector can deliver 2.5 10^{13} protons to the experimental target and 5.0 10^{12} protons to the anti-proton production target every 2.87 secs. This causes a 15-20% reduction of anti-proton production as a result of the increased cycle time. There are also potential improvements which could ultimately yield $5 - 10$ 10^{13} protons per cycle.

TABLE I. Main Injector Performance Characteristics.

	$\overline{p}$ Production	Fast Spill	Slow Spill
Energy(GeV)	120	120	120
Protons per Cycle	5.0 10^{12}	3.0 10^{13}	3.0 10^{13}
Flat Top(secs)	0.01	0.01	1.00
Cycle Time(secs)	1.47	1.87	2.87

The Collider luminosity is controlled by the total number of anti-protons available to accelerate and store. The anti-protons are produced by the 120 GeV protons incident on a nickel target. The produced anti-protons are focussed with a Lithium lens and collected in a debuncher ring at 8 GeV. From the debuncher they are transferred to the accumulator ring, also at 8 GeV, where they are cooled, thus producing stored anti-proton bunches. These are transferred to the 8 GeV Recycler ring before acceleration in the Main Injector, and eventually the Tevatron, to the full energy.

During a store, nuclear collisions cause some attrition while the beam-beam effects lead to an increase in the emittance of the beams. This effect dominates the reduction in luminosity over a period of hours. The effect is most strong on the anti-protons since the proton bunches are, in general, more intense than those of anti-protons. At the end of a store, which is usually defined by the luminosity having dropped to a few tenths of its initial value, the number of anti-protons has only reduced by a factor of two or less. These survivors can be decelerated through the Tevatron and Main Injector and captured in the Recycler. This is an 8 GeV permanent magnet machine equipped with stochastic cooling. It permits the recovery of emittances suitable for reinjection into the Tevatron and thus results in an effective factor of two enhancement to the number of available anti-protons under normal operation. The Tevatron Collider will operate with the luminosities indicated in Table II

TABLE II. Tevatron Collider Operating Characteristics.

	Bunch Spacing(nsec)	Inst. Luminosity(10^{31}cm^{2}sec^{-1})	Interactions per crossing	Luminous Region(cm)
Run Ib (1994-6)	3500	1.6[a]	1-2	30
Run II (2000-3)	396/132	10/20	1-2/1-2	30/15
Run III(2004-7)	132	50	5	15

[a]This was typical, the absolute record exceeded 2.5 10^{31}cm^{2}sec^{-1}.

Further enhancements can be expected from the introduction of electron cooling in the Recycler and from the use of tune compensation in the Tevatron. A possible accumulation of integrated luminosity as a function of time is shown in Table III. Before the full operation of the Large Hadron Collider at CERN, more than 10 fb^{-1} could be expected.

TABLE III. Tevatron Collider Integrated Luminosity.

Year	2000	2001	2002	2003	2004	2005	2006	2007
Peak Luminosity($10^{31} cm^2 sec^{-1}$)	5	10	20		40	50	50	50
Integrated Luminosity(fb^{-1})	0.5	1.0	2.0		4.5	5.5	5.5	5.5
Accumulated Luminosity(fb^{-1})	0.5	1.5	3.5		8.0	13.5	19.0	24.0

The Main Injector was being commissioned [1] at the time of the conference and that process has gone extremely well. In particular the machine is being operated with parameter values near those of the design and with relatively minimal use of correction elements. As for performance, it is already close to its intensity and cycle time goals. Meanwhile the Recycler is still in the final stages of installation. Beam has been passed through a fraction of its circumference.

III. THE PHYSICS

A. Neutrino Mixing and mass

Over the years there have been speculations about whether or not neutrinos have identically zero mass. If not, one expects the weak eigenstates states to mix so that a pure beam of neutrinos of one species will evolve to contain an admixture of neutrinos of one or more other species. This phenomenon is called neutrino oscillation. The probability that a transition takes place is proportional to $\sin^2(1.27\Delta m^2 L/E)$ where the difference in mass squared between the two neutrino states, Δm^2, is measured in $(eV)^2$, the path length, L, in kilometres and the energy, E, in GeV. The strength of the oscillations is usually described by a factor $\sin^2 2\theta$.

At the present time there are a number of observations [2] from experiments which could be explained had the the neutrinos a finite mass. However the picture is quite complicated. The observation of a deficit of neutrinos from the sun suggests oscillations with very low Δm^2. The experiments measuring the fluxes of atmospheric neutrinos, including the recent results from Kamiokande [3], suggest $\Delta m^2 \simeq 10^{-3} - 10^{-2}(eV)^2$ with maximal strength. The LSND experiment at Los Alamos has observed a hint of oscillations with $\Delta m^2 \simeq 10^{-2} - 10^{0}(eV)^2$ with $\sin^2 2\theta$ as low as 10^{-3}. These observations are indicated in Fig. 1 [5].

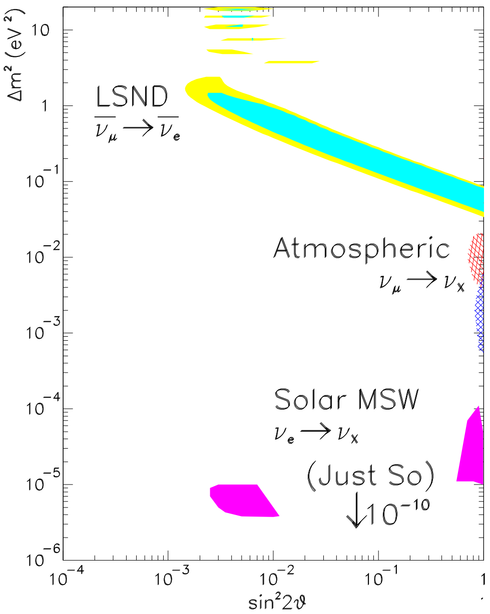

FIG. 1. Hints of neutrino oscillations from present measurements. Note that the most recent atmospheric measurements, reported at this conference, suggest a region of Δm^2 somehwat higher than indicated in this figure from the summer of 1998.

The NuMI project, Neutrinos at the Main Injector, will construct a neutrino beam with energies peaking in the 10-25 GeV range. These neutrinos will be directed at two detectors, one on the Fermilab site, the other 740 km further north in the Soudan mine in Minnesota, see Fig. 2.

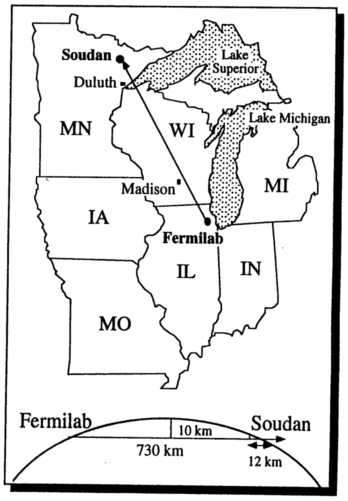

FIG. 2. Map indicating the trajectory of the neutrino beam from Fermilab to the Soudan mine in Minnesota. Inset at the bottom is a "section" of the earth showing the penetration of the neutrino trajectories through the earth's crust.

The MINOS experiment [4], Main Injector Neutrino Oscillation, will comprise two detectors one on the Fermilab site which monitors the neutrino beam interactions close to the source and one at the Soudan mine. The far detector sketched in Fig. 3 will consist of iron toroid plates and solid scintillator sheets. The goals of the experiment are unequivocally to observe the oscillations indicated by the SuperKamiokande and other experiments and to identify the mode(s) of oscillation. Neutral current events are distinguished from charged current events using measurements of the shapes of the neutrino induced showers. This technique gives some promise of positive identification of oscillations into ν_τ. This capability could be enhanced by a supplementary emulsion detector should the existing measurements continue to suggest that the ν_τ mode is the relevant one. The sensitivity of the experiment is primarily at high values of $\sin^2 2\theta$ and with $\Delta m^2 \geq 10^{-3}(eV)^2$.

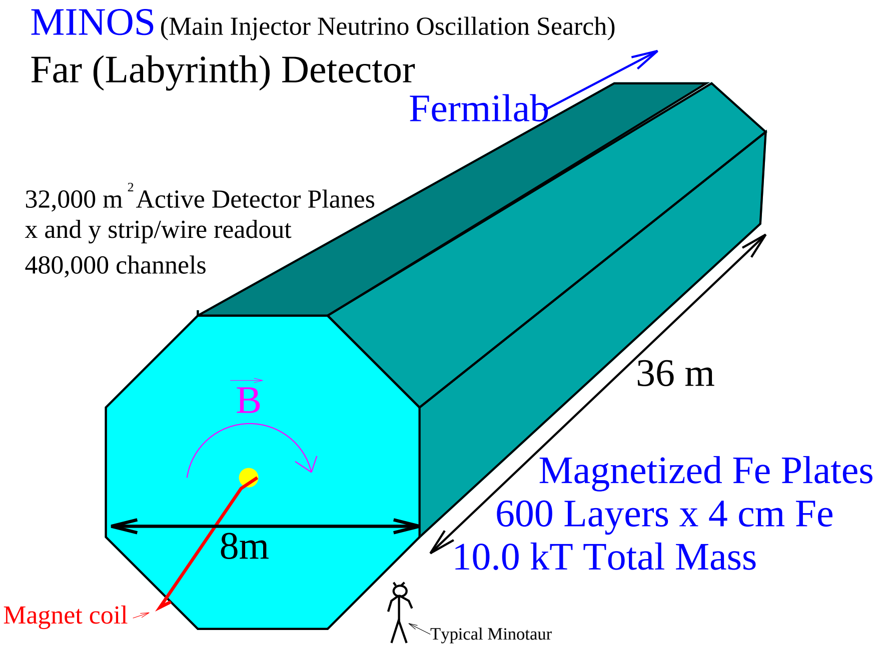

FIG. 3. Layout of the MINOS "Far Detector" which will be situated in the Soudan mine.

The mini-BooNE experiment [6], Booster Neutrino Experiment, is not a Main Injector experiment. Rather it uses protons from the 8 GeV proton Booster machine to generate low energy neutrinos. Using an apparatus derived from that of LSND and situated about 1 km from the source, it aims definitively to cover that region of parameter space corresponding to the LSND observations. The systematic uncertainties would be significantly different from those of LSND.

B. Physics of the Kaon System

The Cabbibo-Kobayashi-Maskawa(CKM) matrix has nine elements that can be described using four real parameters of which one is a phase angle. In turn, if the matrix is unitary, these parameters can be represented by a triangles. The lengths of the sides are controlled by the various transition amplitudes. The magnitude of Charge-Parity(CP) symmetry violation is controlled by the phase angle. This description of the quarks and their couplings may or may not hold in nature. It is one of the highest priorities of high energy physics to explore the CKM matrix in more detail and to determine whether or not the conjectures about its properties are true.

At present the single indication of CP symmetry violation, which is what requires the complex matrix element, occurs in the K_L^0 system [7]. At present CP violation has not been observed in any other system containing strange quarks nor yet definitively observed in the b-quark sector [8].

The conditions for existence of CP violation in any given system may be quite involved. In the K_L^0 system, for example, at the time of the conference it was still possible for the observed CP violation to be completely described by the mixing effects which are controlled by the parameter ϵ. The search is for CP violation in the decay, " direct CP violation", which is controlled by the parameter ϵ'. The new measurement [7,9], which appeared since the time of the conference, give $\mathcal{R}\rceil(\epsilon'/\epsilon) \simeq (28 \pm 4) \times 10^{-4}$

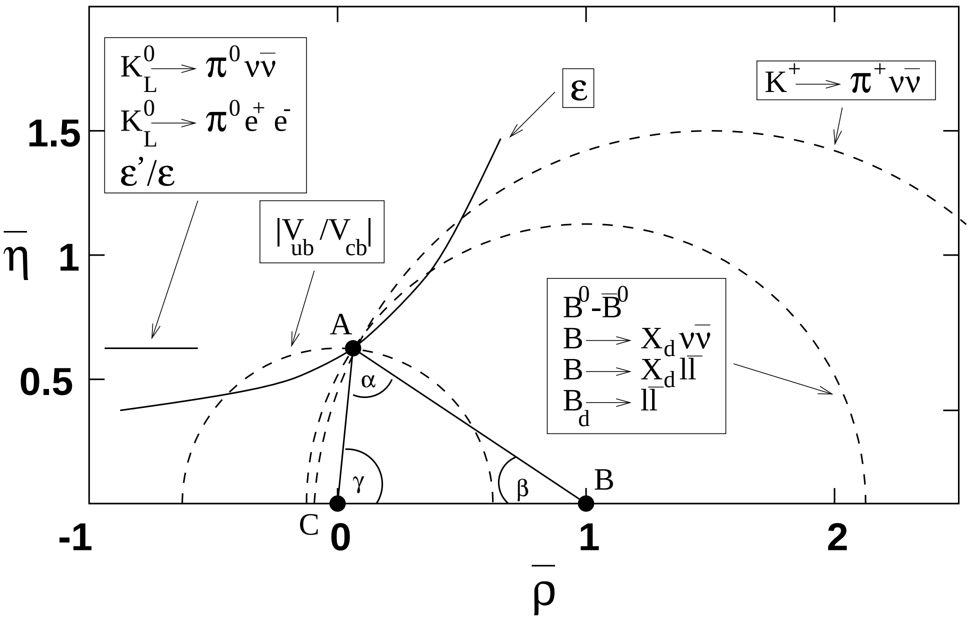

FIG. 4. The Unitarity Triangle associated with the Cabbibo-Kobayashi-Maskawa flavor mixing matrix and the measurements possible in the kaon system.

In order to make progress, thoughts have turned to other possibilities [11]. A version [10] of the unitarity triangle is shown in Fig. 4. In principle it is possible to over-constrain the triangle and hence to test the theory using only measurements with kaons. As indicated, a measurement of the branching fraction for $K_L^0 \to \pi^0 \nu\overline{\nu}$ would directly constrain the height of the triangle while a similar measurement of the charged decay $K^+ \to \pi^+ \nu\overline{\nu}$ determines the radius of an arc which should also pass through the apex of the triangle, if the theory is correct.

The charged kaon decay has been sought [12] at Brookhaven national Laboratory in the decays of stopped kaons with one event observed. Recently a proposal [13], the "CKM" experiment, has been made to use decays in flight. The apparatus is shown in Fig. 5; the beam would be a 22 GeV radiofrequency-separated beam of charged kaons at the Main Injector. It is interesting to look carefully at the aspect ratio of the experiment. It is very long and very narrow approximating an instrumented sewer pipe. The goal is to fully identify and measure the incident kaon and the outgoing charged pion, the only two measurable particles in the process.

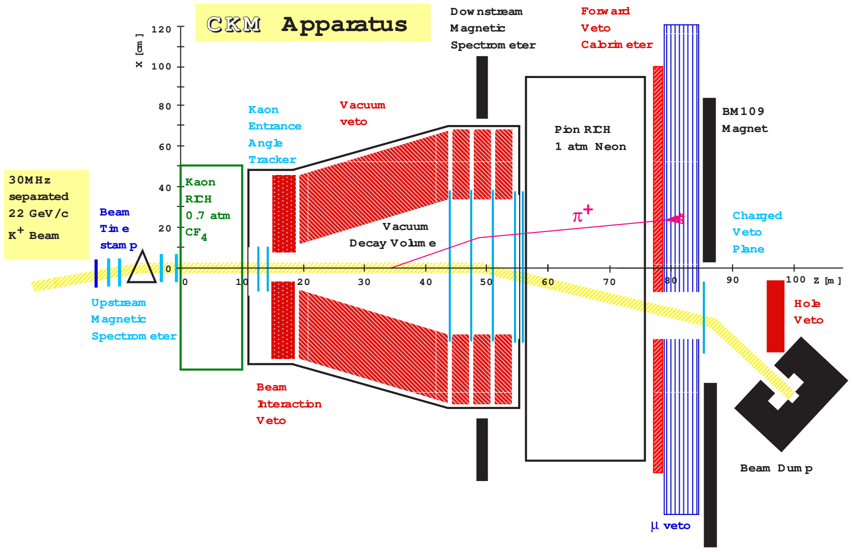

FIG. 5. Layout of the CKM Experiment.

The equivalent neutral kaon experiment [14], "KaMI", which would search for $K_L^0 \to \pi^0 \nu \overline{\nu}$ could be derived from the KTeV experiment making the recent measurements of ϵ'/ϵ at Fermilab. The key elements are the electromagnetic calorimeter and the photon vetos which are crucial to the background suppression. As with the charged kaon decay, this would be a very difficult measurement.

KAMI DETECTOR LAYOUT

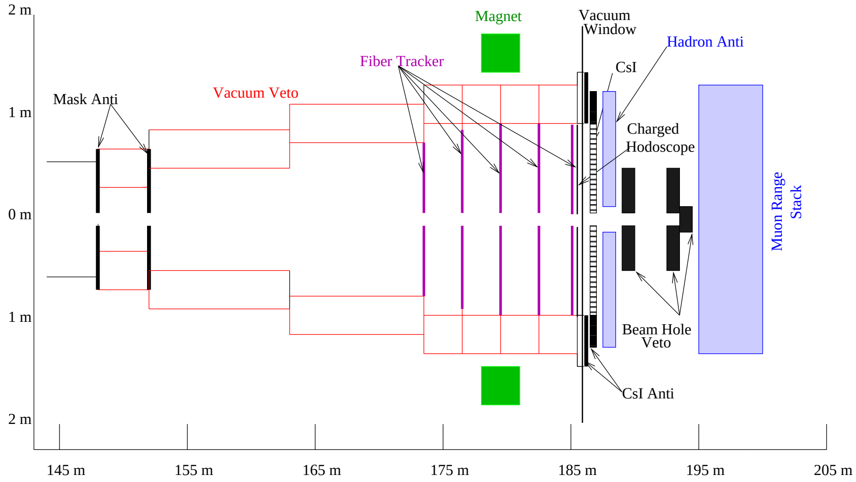

FIG. 6. Layout of the KAMI Experiment

Completing the suite of kaon proposals is the "CPT" Experiment [15]. The goal is to measure CP violation in a number of modes especially in K_S^0 decays. It also gives the opportunity to measure the phase of the charged pion decays which in conjunction with the measurement of ϵ'/ϵ gives a check on CPT symmetry with a sensitivity which corresponds to the Planck scale. It should be noted, see Fig. 7, that since it is necessary to measure the interference terms between K_L^0 and K_S^0, the apparatus would be significantly shorter than either of the other two experiments. The K^0 beam is derived from the same RF-separated K^+ beam that is used for the "CKM" experiment.

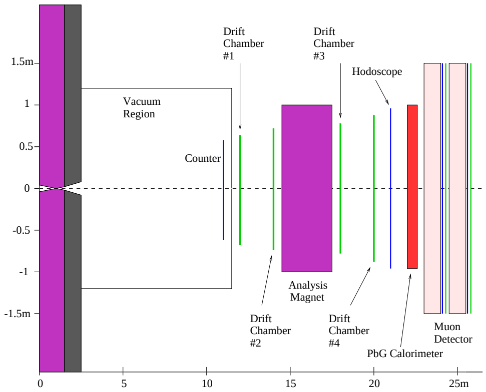

FIG. 7. Layout of the CPT Experiment.

C. Physics of the B System

In order to access large numbers of b quarks at Fermilab, it is necessary to turn to the Tevatron Collider. The existing two detectors, CDF, see Fig. 8, and DØ see Fig. 9, are being upgraded for operation in the Main Injector era. The upgrades [16,17] are extensive and are driven by the physics goals and by the changed operating characteristics of the Tevatron; the decreased spacing between bunch crossings has forced a rework of all the front-end eleectronic systems to introduce pipelines. A particular region of improvement is in the tracking in which each detector is being substantially modified. DØ has installed a central solenoid and both experiments are constructing new outer trackers. The inner, silicon, systems will have upward of 600,000 channels each. These will provide high quality b-quark tagging and B meson reconstruction. In addition to enhancing the B-physics capabilities, b-quark tagging is recognised as an important tool in the exploration of and search for higher mass states. This was demonstrated in top-quark physics and is expected to be true for Higgs, SUSY or technicolor states.

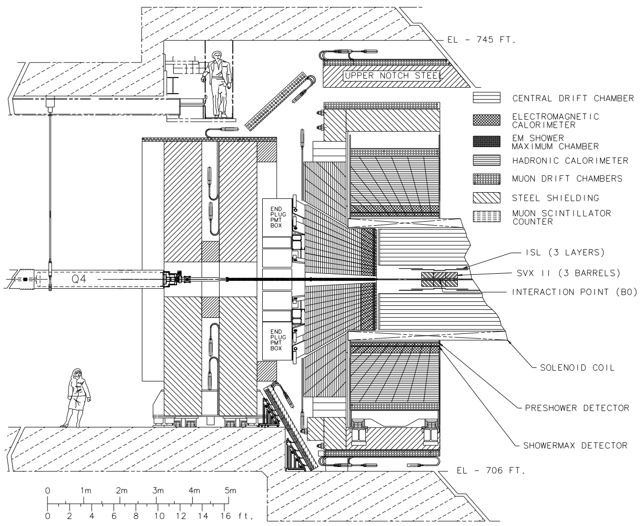

FIG. 8. The upgraded CDF detector.

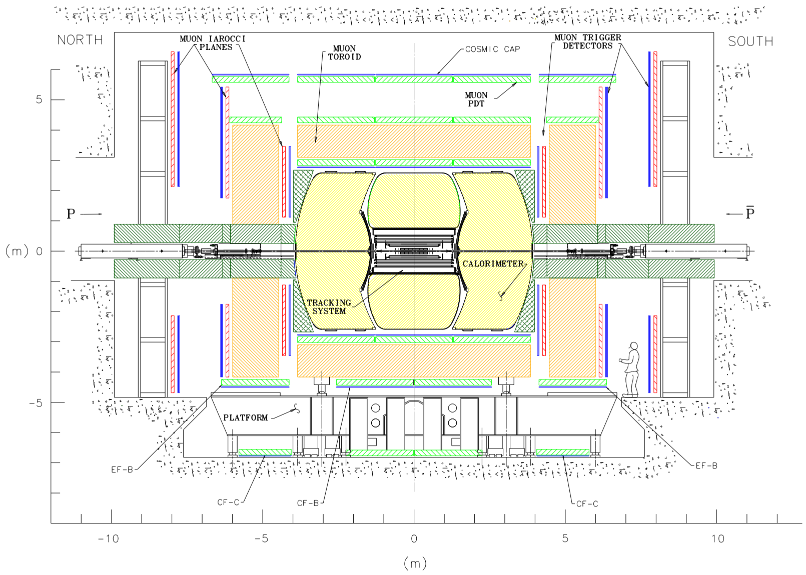

FIG. 9. The upgraded DØ apparatus.

The physics which will be addressed by CDF and DØ is wide ranging. In later sections electroweak studies and physics beyond the standard model will be addressed but in this section we will concentrate on B physics. Recent results from CDF presage a bright future for the general purpose detectors at the Tevatron and for B physics at hadron colliders more generally. There is also an initiative to consider a dedicated detector [18].

The BTeV proposal is motivated by the enormous production rate for b quarks and the potential of a detector which accentuates the forward and backward directions in order to exploit the favorable mapping of rapidity to solid angle and to benefit from the relatively larger decay lengths for b quarks of a given transverse momentum. The planned detector is shown in Fig. 10. It consists of two spectrometer arms. Each arm is equipped with a silicon detector system inside the beam pipe and ring imaging Cherenkov counters. It is expected that the latter will be especially important.

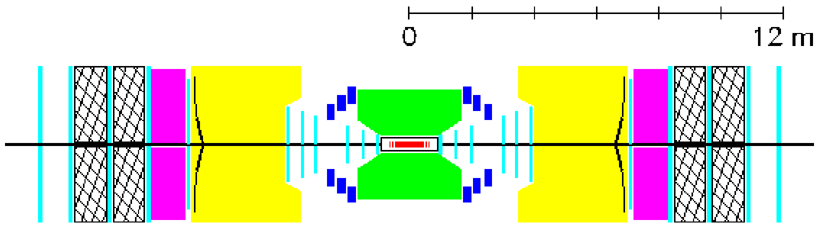

FIG. 10. The BTeV apparatus.

If the standard model is correct, the same triangle in Fig. 4 should describe the b-quark system. Measurements of the CP violating asymmetry in the decay $B \to J/\psi K^0_S$ would determine $\sin 2\beta$. The recent measurement [8] from CDF finds $\sin 2\beta = 0.79^{+0.41}_{-0.44}$ suggesting a positive value at about the 90% C.L. A feature of this measurement is the use of several different flavor tagging techniques. With approximately 2fb^{-1} and the upgraded detectors, the uncertainty on $\sin 2\beta$ will be reduced below 0.1 for each experiment. Similar uncertainties are projected for $\sin 2\alpha$ although the interpretation for this case is considered to be more difficult. Measurement of the third angle, γ, will be a challenge.

During the last year, there have been a number of results from CDF on various aspects of higher mass B hadron states. The measurements of B_s mixing [19] are competitive with those from LEP and SLD. Extrapolating to Run II, we expect sensitivities in the range $x_s \geq 25$ from each experiment thus comfortably covering the expected range. The observation [20] of the B_c meson has further demonstrated that sophisticated studies of B physics are possible at a hadron collider. One should note that the final state used for this observation was semi-leptonic. Despite the incomplete reconstruction the backgrounds were manageable. Given the enormous rates, the Tevatron is arguably the best place to do B physics. This is especially true for states which are not decay products of the Υ_{4S} and are therefore difficult to access with an electron-positron B factory.

D. Electroweak Physics

The hadron colliders have for some time contributed to the suite of measurements which provide stringent cross-checks of the electroweak model. The initial measurements from the CERN $Sp\overline{p}S$ observation of the W and Z bosons paved the way. The current measurements [21] from the Tevatron keep pace in precision with those from LEP and at each new level of precision we see ways to constrain the details of the production measurements from the data themselves. For example in the recent DØ measurement it was found that the constraint from the rapidity distribution of the bosons is only marginally weaker than that from the parton distribution function measurements from the worlds experiments. The current errors are 80-90 MeV per experiment. Already the latter are strongly influenced by measurements of the W asymmetry at the Tevatron. The constraints from the data themselves will scale with statistics to higher integrated luminosity. This means that the current estimates of about 40 MeV per channel and per experiment are indeed possible.

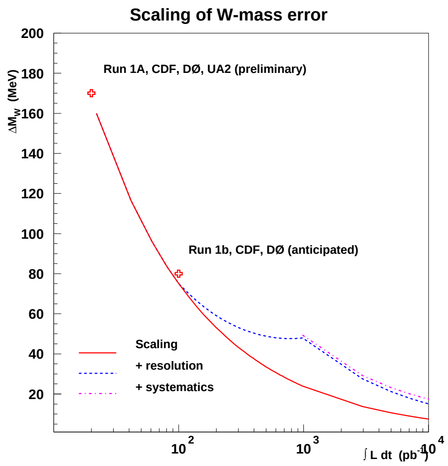

FIG. 11. Expected evolution of the precision of a measurement of the W-boson mass at the Tevatron Collider.

TABLE IV. Uncertainties in a single experiment top mass determination.

Uncertainty(GeV)	Run I	Run II
Statistical	5.6	1.3
Jet Energy Calibration	4.0	0.4
Gluon ISR/FSR	3.1	0.7
Detector Noise etc	1.6	0.4
Fit Procedure	1.3	0.3
All Systematic	5.5	0.9
Total	7.8	1.6

This kind of evolution as expressed in an earlier study [22] is illustrated in Fig. 11. That study considered particularly the effects of the underlying event on the technique which uses the transverse mass of the event (lepton plus neutrino) as the primary measure of the boson mass. This leads to a relative deterioration as the number of interactions per bunch crossing increases. What is also shown is the subsequent evolution as we decrease the bunch spacing in the machine to 132 nsecs. Fora given luminosity this decreases the number of interactions per crossing. We are also learning to take advantage of all the measures of the boson mass, the lepton transverse momentum, and the neutrino transverse momentum. It is gratifying that this projection made some four years ago holds good through the 100 pb^{-1} of data from which the recent measurements are derived.

A very powerful newcomer to precision measurements is the top mass. It enters into the electroweak parameters through its dominance of the quark loops. From the existing data, the 3% uncertainty makes the top-quark mass the best known of all quark masses. The 5 GeV uncertainty in the top-quark mass is equivalent to about 30 MeV uncertainty in the W mass in terms of its its sensitivity to the Higgs mass.. Currently the dominant error [23] comes from the calibration of the jets. Recently CDF observed the $Z \to b\bar{b}$ decay. Extrapolating to the luminosities and upgraded detectors with silicon track triggers to enhance the sensitivity to this channel, a very precise calibration of the jet energies becomes possible. This will be used in conjunction with the W-boson decays to jets which are present in the top signal data themselves. The resulting evolution of a single experiment in the lepton-plus-jets channel is illustrated in Table IV. An uncertainty of less than 2 GeV appears to be possible.

A number of other electroweak studies are possible including the comparison of the W width as determined by direct and indirect methods and a study of the Z asymmetry. The latter may serve either as a determination of $\sin^2\theta_W$ for the light quarks or another constraint on the parton distribution functions. Taken together, the masses of the W boson and the top quark lead to constraints on the mass of the Higgs boson either in the standard model or in the supersymmetric variants. This is illustrated in Fig. 12 where, in the plane of the W mass and the top-quark mass, the various measurements including the latest from CDF and DØ at the Tevatron. We can anticipate that these indirect measurements will determine the Higgs mass to about 50% of its value.

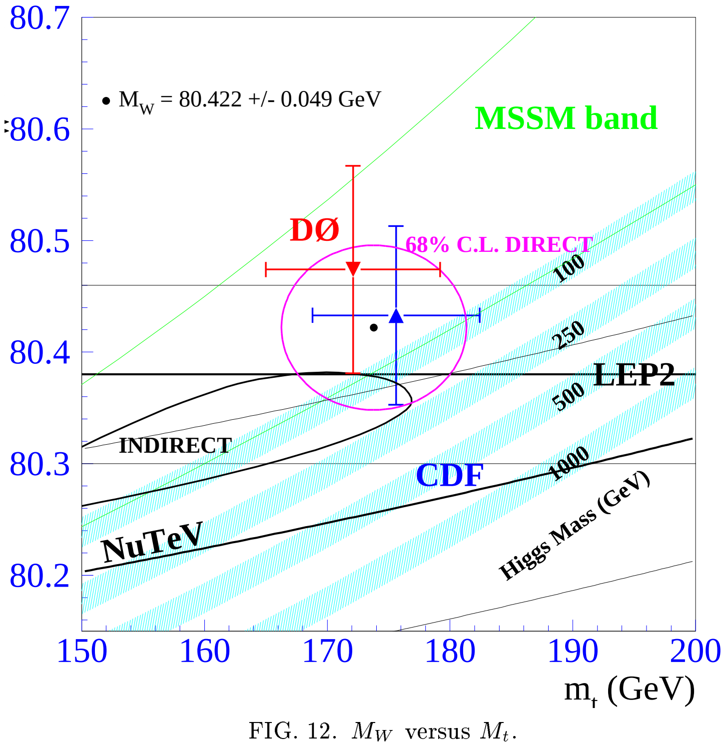

FIG. 12. M_W versus M_t.

E. Physics beyond the Standard Model

There are as many searches for new physics as can be generated by the imagination of physicists. In the search for compositeness, structure, higher mass bosons, leptoquarks, the present limits are in the few-hundred-GeV range. With 2 fb^{-1} these searches will be sensitive close to the 1 TeV range. Indirect searches as exemplified by the measurement of the Drell-Yan, lepton pair cross section and the dijet mass spectrum, are sensitive, through possible contact terms to the 5 TeV range.

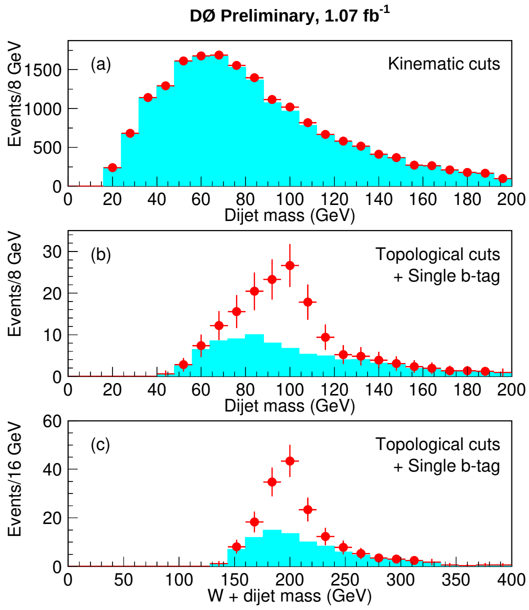

FIG. 13. Mass spectra expected for technicolor signals for the π_T and the ρ_T .

1. Technicolor

A longstanding candidate to explain the origin of electroweak symmetry breaking is a new strong interaction, technicolor, analogous to QCD. Such a strong interaction would lead to massive electroweak bosons in a manner analogous to the way the masses of the pion and ρ meson are generated by QCD. There are complications with the simplest forms of such a theory but variations [24] of the original scheme continue to be explored.

TABLE V. Mass ranges covered for a 5σ discovery in SUSY models.

Model	SUSY Particle	Run I(0.1 fb^{-1} Mass Limit(GeV)	Run II(2.0 fb^{-1} Mass Limit(GeV)
SUGRA			
	$\tilde{\chi}_1^{\pm}$	70[a]	210
	$\tilde{g}$	270[b]	390
	$\tilde{t}_1(\to b\tilde{\chi}_1^{\pm})$		170
GMSB			
	$\tilde{\chi}_1^{\pm}$		265
	$\tilde{\tau}$		120

[a]95% CL.
[b]95% CL.

The production cross section for the some of the states can be quite substantial [25]. Analysis of Monte Carlo simulations of technicolor signals using a basic signature of a W, seen through its leptonic decay, along with two jets gives a dijet mass spectrum as shown in the upper plot of Fig. 13. Some topological requirements are then applied and a b-quark tag is requested. This leads to the middle of the three plots. The dijet spectrum clearly shows an excess which corresponds to the technipion decaying to two b-quark jets. In the bottom plot, the mass of the combined W boson and the two-jet system shows a peak over background corresponding to the technirho. Once again the importance of b-quark tagging techniques is demonstrated.

2. SUSY

The mainstream of theoretical thinking with respect to the physics of electroweak symmetry breaking and the physics above 100 GeV is dominated by those who consider that supersymmetry, SUSY, should play a strong role. SUSY comes in may guises but always leads to a proliferation of postulated particles differing in spin by one half unit with respect to the "standard particles". Thus there is a spin-one-half gluino, the partner of the gluon, a spin-one-half photino, the partner of the photon and a host of squarks and sleptons. The simplest assumption is that these sparticles can only be produced in pairs, a restriction that is usually formulated as conservation of a quantum number R-parity.

Given R-parity conservation there is always a stable lightest supersymmetric partner(LSP) which is neutral in most theories. This leads to the presence of missing transverse energy as the most generic of SUSY indicators. As with technicolor, the use of b-quark tagging also can be a useful discriminator against background. Since we have not seen supersymmetric partners with the same masses as the ordinary particles, SUSY, if it exists must be a broken symmetry. The mechanism by which it is broken at very high mass scales distinguishes different models. Very commonly considered is the super gravity(SUGRA) class. In the last few years, alternatives such as gauge mediated models(GMSB) have been prominent. The latter are characterised by the gravitino($\tilde{G}$) being the LSP and cascades of decays such as $\chi_1^0 \rightarrow \gamma\tilde{G}$ which generate final states with one or more photons and missing transverse energy.

As indicated in Table V, the present limits for different sparticles range up to a couple of hundred GeV for some but around 100 GeV for others. The afficionados of SUSY tend to expect that it would appear with sparticle masses in the range below 1 TeV if it is to be relevant to the electroweak symmetry breaking problem. The recent studies [26], also summarised in Table V suggest that with 2 fb^{-1} of integrated luminosity, these ranges can be considerably extended to cover a large fraction of the "interesting" region.

F. The Higgs Boson

Without looking beyond the physics of the standard model, it is necessary to postulate some mechanism to break the electroweak symmetry and to give mass to the W and Z bosons. The simplest thing to do is to assume a single complex Higgs field which in turn leads to a single neutral Higgs boson. As we have seen earlier the mass of such an object is predicted through the radiative corrections to the electroweak parameters and with the mass of the top quark and that of the W boson measured we should find the Higgs boson at the appropriate place.

The search for the standard-model Higgs boson is the most widely used benchmark for the potential of planned collider experiments. Recent studies [27] have put the estimates for the Tevatron Collider experiments, DØ and CDF, on a more solid footing. While gluon-gluon fusion has the highest Higgs production cross section, the associated , WH and ZH, production channels offer distinctive experimental signatures through the leptonic decays of the bosons and have received much attention. The $b\bar{b}$ decay of the Higgs also adds powerful discrimination especially at low masses, below about 130 GeV, where that decay dominates. A more thorough study of the channels involving b-quark tagging was conducted. Further, the use of the WW decay modes in conjunction with the dominant gluon-gluon fusion has been reconsidered [28]. The branching fractions for the latter rise strongly, see Fig. 14, with increasing Higgs mass and also are distinctive experimentally.

The combined sensitivity for all channels and two experiments is shown in Fig.15. The figure shows the required luminosity to obtains a signal at different levels of significance, 5 σ, 3 σ, and the 95% exclusion limit, as a function of Higgs mass. We see that with both experiments and 30 fb^{-1} of luminosity for each experiment the sensitivity extends up to Higgs massses of 190 GeV. If the Higgs does not exist in this mass region, with 10 fb^{-1} this whole region could be excluded experimentally at the 90% C.L.

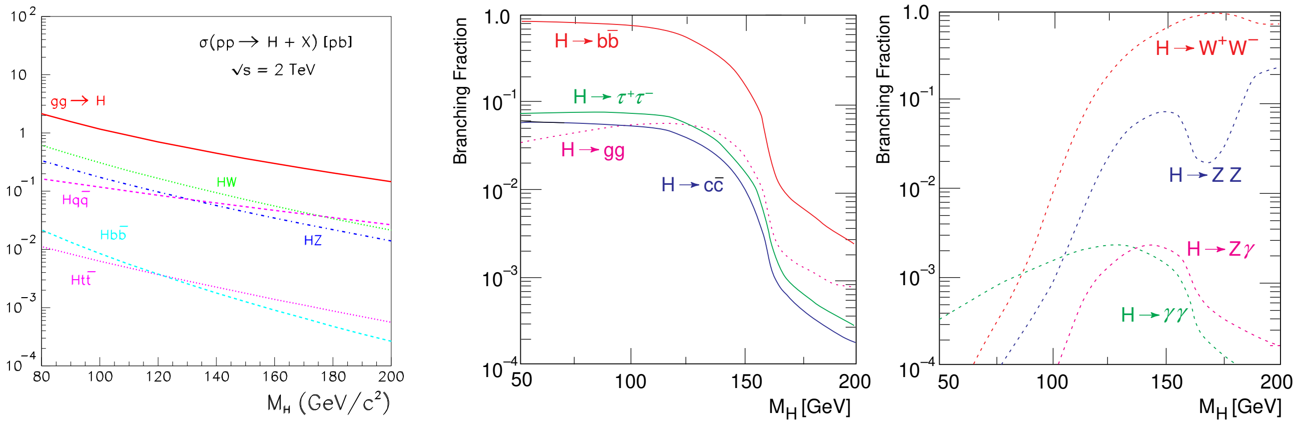

FIG. 14. Higgs-boson production cross sections and branching fractions for fermions and bosons as a function of Higgs-boson mass.

Other studies concentrated on the extensions of the Higgs sector, in particular the SUSY-Higgs two-doublet model. There are three neutral and two charged Higgs states and, depending on the value of the ratio of the vacuum expectation values of the two doublets, very strong coupling of the Higgs to the b-quark may be expected. Again the rôle of the b-quark tagging is important and similar sensitivities to the SUSY Higgs are achieved as in the standard-model-Higgs case.

As we discussed earlier, an integrated luminosity of 20-30 fb^{-1} before the startup of the LHC is anticipated. There is a considerable challenge for the experiments but even the fierce conditions may be mitigated by operating the machine in such a way as to maintain the instantaneous luminosity at or less than $5. \times 10^{32} cm^2 sec^{-1}$.

It is clear that maximizing the exploitation of the Tevatron Collider to search for the Higgs and other new high-mass physics should be one of the highest priorities of the U.S. high energy physics program.

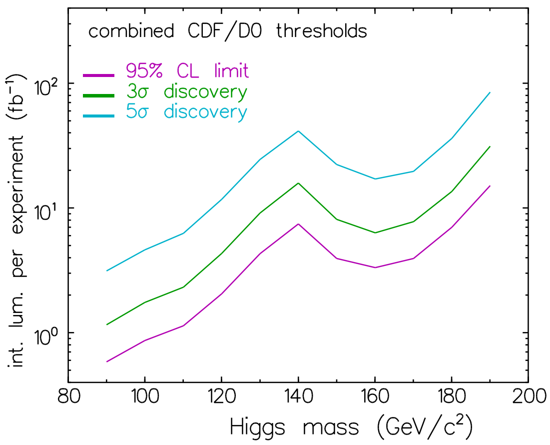

FIG. 15. Luminosity required as a function of Higgs mass to achieve different levels of sensitivity to the standard-model Higgs boson.From the upper curve corresponds to a 5 σ discovery, the middle a 3 σ signal and the lower a 95% exclusion limit. These limits require two experiments, Bayesian statistics are used to combine the channels and include the improved sensitivity which would come from multivariate analysis techniques.

IV. THE EXPERIMENTAL PROGRAM

We have seen in the above discussion that the physics reach of the accelerator complex which we label with its newest component, The Fermilab Main Injector, is phenomenal and diverse. Full exploitation of every aspect could swallow resources in excess of what appears to be available. The attempts to construct a realistic program has so far left the various components in states of varying certitude. While some pieces are well on their way to completion of construction others remain glints in the eyes of the proponents. In order to give a sense of perspective, I have chosen to give the briefest of summaries of the status of each of the components of the Main Injector physics program.

- The Main Injector: the commissioning of the machine is well advanced; the ancillary Recycler storage ring will be completed in the coming months.
- The Tevatron Collider and the CDF and DØ Detectors: the Tevatron will operate in fixed target mode during 1999 and will convert to collider operations for early 2000. The upgrades of the two detectors CDF and DØ are in the middle of construction and completion and roll-in is expected in 2000.
- The NuMI Project: the project has approval from the appropriate authorities and a baseline for the scope, cost, funding and schedule has been approved by a Department of Energy review with funds for civil construction allocated.
- The mini-BooNe Experiment: this initial phase of a potentially longer program is an approved experiment expected to run in 2002.
- The Kaon-CP Violation experiments: these experiments, labelled, CKM, CPT and KaMI, have submitted proposals or letters of intent to the laboratory; research and development projects associated with different aspects of them have been established.
- The dedicated collider-B Experiment, BTeV: a letter of intent has been submitted and an experimental hall has been constructed; a research and development program is under way.
- A 120 GeV QCD Program: a number of groups have submitted proposals [29] in response to the potential offered by extracted hadron beams from the the Main Injector. The primary thrust of such a program would be to emphasize QCD studies. Thus far there is no action on these proposals.

V. CONCLUSIONS

The Main Injector enables a phenomenally broad and imposing array of physics and we, the field, must be wise in choosing which pieces to emphasize. Many physicists are determined to exploit the potential of this program. I am very excited to be among those physicists.

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[1] Fermilab Beams Div. OperationsDepartment Page, *http://www-bd.fnal.gov/operations/operations.html*
[2] Gary Feldman, Neutrino Physics, Plenary Review Talk presented at this conference.
[3] Mark Messier, "Atmospheric Neutrinos at Super-Kamiokande", Paper presented at this conference.
[4] The MINOS Experiment Technical Design Report, NuMI-L-337, April 1998.
[5] Janet Conrad, Rapporteur's Talk at ICHEP the International Conference on High Energy Physics, ICHEP'98, Vancouver, British Columbia, Canada, August, 1999.
[6] E. Church *et al.* A proposal to measure $\nu_\mu \to \nu_e$ oscillations and ν_μ disappearance at the Fermilab Booster, December 7, 1997.
[7] Ed. Blucher, CP Violations and Rare Decays, Plenary Review Talk presented at this conference.
[8] K. Pitts, Seminar, Fermilab, February, 1999, CDF/PUB/BOTTOM/CDF/4855, Feb. 5, 1999, *http://www-cdf.fnal.gov/physics/new/bottom/cdf4855/cdf4855.html*
[9] Peter Shawhan, Seminar, Fermilab, February 24, 1999.*http://fnphyx-www.fnal.gov/experiments/ktev/ktev.html*
[10] A. Buras, TUM-HEP-255-96, Sep 1996, hep-ph/9609324.
[11] A Kaon Physics Program at the Fermilab Main Injector, FERMILAB-TM-2032, Ed. P.Cooper, November 1997.
[12] L. Littenberg, hep-ex/9802014.
[13] Charged Kaons at the Main Injector: A Proposal for a Precision Measurement of the Decay $K_L^+ \to \pi^+\nu\overline{\nu}$ and other Rare K^+ Processes at Fermilab Using the Main Injector, May 15, 1998.
[14] An Expression of Interest to Detect and Measure the Direct CP Violating Decay $K_L^0 \to \pi^0\nu\overline{\nu}$ and Other Rare Decays at Fermilab Using the Main Injector, September 27, 1997.
[15] The CP/T Experiment: An Experimental Program to Study CP Violation and Search for CPT Violation in the $K_L - K_S$ System.
[16] The CDF II Detector Technical Design Report, FERMILAB-Pub-96/390-E, November 1996.
[17] The DØ Upgrade: The Detector and its Physics, FERMILAB-Pub-96/xxx-E, July 1996.
[18] A. Kulyatsev *et al.*, The BTEV Program at Fermilab, Paper #92 submitted to the International Conference on High Energy Physics, ICHEP'98, Vancouver, British Columbia, Canada, August, 1999; *http://www-btev.fnal.gov/btev.html.*
[19] Ting Miao, CDF Collaboration, Fermilab Seminar, February 1999, *http://www-cdf.fnal.gov/physics/new/bottom/cdf4485/cdf4485.html*
[20] F. Abe *et al.*, CDF Collaboration, Phys. Rev. D 58, 112004 (1998).
[21] Ashutosh Kotwal, DØ Collaboration Fermilab Seminar, February 26 1999, *http://www-d0.fnal.gov/~skulik/Public/wmass/index.html*;
Young-Kee Kim, CDF Cololaboration, Talk to Run II QCD/EW Working Group, March 4 1999, *http://www-cdf.fnal.gov/physics/ewk/*
wmass global.html
[22] Future ElectroWeak Physics at the Fermilab Tevatron: Report of the tev-2000 Study Group, FERMILAB-PUB-96/082, Editors D. Amidei and R. Brock.
[23] A Silicon Track Trigger for the DØ Experiment in Run II - Further Physics Benefit Studies, Addendum to the proposal(P908). January 1999.
[24] Workshop on New Strong Dynamics for Run II of the Fermilab Tevatron, *http://www-d0.fnal.gov/~womersle/strongdynamics.html*
[25] Estia Eichten, Kenneth Lane, John Womersley, Phys. Lett. B 405 305 (1997)
[26] Mario Roco Talk prepared for The Hadron Collider Physics conference, Mumbai, January, 1999, talk delivered by P.Grannis; Work done at the Tevatron Run 2 SUSY/Higgs Workshop, Fermilab, November 1998.*http://fnth37.fnal.gov/susy.html*
[27] J. Conway, " Higgs Working Group Experimental Studies, Summary Talk at the Tevatron Run 2 SUSY/Higgs Workshop, Fermilab, November 1998.*http://fnth37.fnal.gov/susy.htmlhttp://fnth37.fnal.gov/funnelweb/conway summary/*
[28] Tao Han, Andre S. Turcot, Ren-Jie Zhang, Fermilab,MADPH-98-1094 November 1998, hep-ph/9812275, 1998.
[29] Workshop on Fixed Target Physics at the Main Injector, May 1-4, 1997, *http://www.fnal.gov/projects/numi/workshop/summaries/summaries.html* ,
Strong interactions, *http://www.fnal.gov/projects/numi/workshop/summaries/strong.txt*