PHYSICS HIGHLIGHTS

FROM THE DØ EXPERIMENT

1992 - 1999

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1. INTRODUCTION

The DØ experiment was proposed for the Fermilab antiproton-proton Tevatron Collider in 1983 and approved in 1984. After 8 years of design, testing, and construction of its hardware and software components, the experiment recorded its first antiproton-proton interaction on May 12, 1992. The data-taking period referred to as "Run 1" lasted through the beginning of 1996. Collisions were studied mainly at an energy of 1800 GeV in the center of mass (the world's highest energy), with a brief run taken at 630 GeV. The total luminosity collected during Run 1 was equivalent to 125 events/pb of cross section. All results summarized below are based on these data, and on the dedicated and imaginative efforts of the undergraduate and graduate students, postdoctoral fellows and senior scientists involved in the program. Currently, the DØ Collaboration consists of more than 500 scientists and engineers from 60 institutions in 15 countries (see some of them in Fig. 1). Over 110 Ph.D. dissertations have been written so far on various aspects of DØ, and more are anticipated over the next two years, as the analyses of data from Run 1 wind down, and the next run, with both an upgraded detector and improved accelerator, commences.

Fig. 1: Members of the DØ collaboration gathered near the detector in early 1996.

Among the highlights from Run 1 described in the following sections are the discovery of the top quark and measurements of its mass and production cross section; the precise determination of the mass of the W boson and the couplings of the electroweak bosons (photon, W and Z); numerous searches for new physics; measurements of bottom quark production; and extensive studies of the strong "color" force, quantum-chromodynamics (QCD). We have already published most of our results from the past six years; to date, over 80 papers have appeared in refereed journals. In addition, our publications are reprinted in annual collections that are available from the library at Fermilab. The published papers, as well as work presented in conferences, can be accessed from our web pages (see http://www-d0.fnal.gov/). In this summary, we only discuss some of the highlights of the results of Run 1. We have also prepared "plain English" summaries, intended for a more general audience, that can be found on the web at http://www-d0.fnal.gov/public/pubs/d0_physics_summaries.html.

Much of our research benefited from insights and friendly competition within our scientific community. In particular, interactions with our colleagues at CDF (the other major Fermilab Collider experiment), as well as SLD (at SLAC), the LEP experiments (at CERN in Geneva, Switzerland), the HERA experiments (in Hamburg, Germany), and theorists around the world have been both intellectually stimulating and productive.

This summary of the highlights from Run 1 can only provide a flavor of some of the most interesting results. To gain a better understanding of their significance, and for greater detail, we invite the reader to consult our public web pages, as well as the members of the DØ collaboration.

2. THE DØ DETECTOR

For many years, our understanding of nature revolved around four separate, unrelated forces -- gravity (familiar to us all), the electromagnetic force (involved in everything from the formation of molecules to the pointing of the arrow of a compass northward), the weak force (responsible for radioactivity), and the strong force (which holds the nuclei of atoms together). Over the past three decades, many experimental and theoretical advances have led to a coherent and predictive picture of the strong, electromagnetic and weak forces called the Standard Model (SM). In the SM, the elementary constituents of matter, quarks and leptons, interact through forces, which are transmitted through the exchange of particles called gauge bosons. Each of these three microscopic forces is described by a gauge theory, in which the interactions are invariant under changes in the complex phase of the constituent fields at every point in space-time, thus requiring the presence of a spin-1 massless gauge boson. Gravity remains outside the SM framework.

During the 1960s and 70s, it was recognized that the electromagnetic and weak forces could be described through a unified picture, and the theory of electroweak interactions was born. A set of four gauge bosons with zero mass was introduced in the SM, together with two pairs of spin-0 "Higgs" particles, to provide the observed breaking of the symmetry in the underlying electroweak force. As a result of the symmetry breaking, two of the mediators of the electroweak force, the W and Z bosons, acquire mass, while the photon remains massless. Three of the Higgs particles are absorbed in giving the W and Z their masses, while the last one remains to be discovered; its mass is not predicted, but can be inferred in the framework of the SM from precision measurements of other quantities.

The strong force is mediated by a set of eight massless gauge bosons called gluons, and is described by Quantum Chromodynamics (QCD). Of the matter particles, only the quarks experience the strong force. In the SM, the strong and electroweak interactions are specified separately, but are not unified. There are compelling reasons to believe that the SM, though remarkably predictive and extremely well tested, is only an approximate theory to nature. Theories have been postulated that extend the SM, provide unification of the forces, and give deeper understanding of the Higgs particles. Seeking evidence for the path beyond the SM is the major theme of future experimentation.

According to the SM (see Fig. 2), the particles created at the Tevatron fall into two broad classes: leptons (electron, muon, tau, and neutrinos associated with each) and hadrons (protons, pions, kaons, etc.), the latter being composed of combinations of the six quarks. The quarks and leptons are mirrored by their respective antiparticles. In addition, the gauge bosons transmit the fundamental forces; these include the photon (electromagnetic force), the gluons (QCD strong force), and the W and Z bosons (weak force). Other particles, outside this framework, could exist and are the subject of many of our searches. Most collisions produce quarks or gluons, which evolve into collimated sprays of hadrons called jets. These jets usually do not contain leptons, and many of the studies of rare processes -- such as the production of the top quark, W and Z bosons, or searches for new phenomena -- that would be swamped by backgrounds from copious QCD processes with jets, can be realized only by using decays of the interesting objects into leptons. Neutrinos and certain newly proposed particles do not interact with matter often enough to be detected, but can be inferred by an apparent imbalance in momentum conservation. Because of such considerations, the detector was optimized to measure jets, leptons, and "missing" transverse momentum.

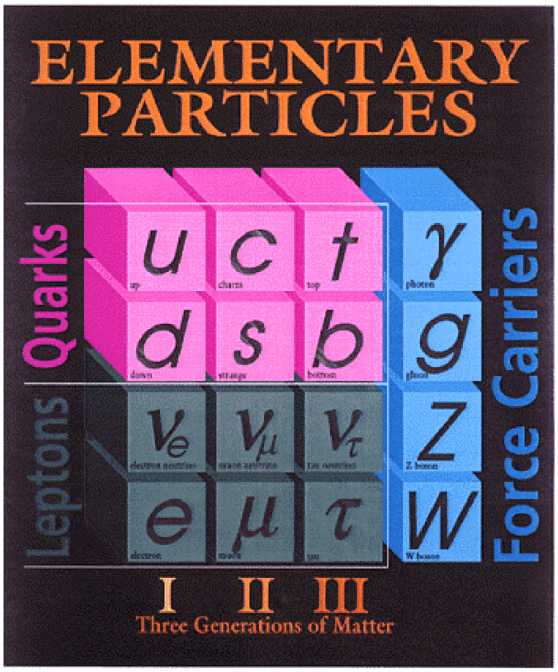

Fig. 2: A table of the elementary particles and force carriers in the Standard Model.

The physics results from DØ rest on the technical achievements of many scientists and engineers. The Fermilab accelerator complex, with its eight distinct major components, provides high intensity proton and antiproton beams at the world's highest energy (900 GeV for each beam). These beams collide at two locations in the Tevatron ring, where experiments are performed by the CDF and DØ collaborations. The DØ experiment contains many sophisticated components, which include not only the particle detectors, but also the electronics needed to select and digitize events, and the software necessary to monitor the experiment and reconstruct events written to magnetic tape. Although a full description is not appropriate in this note, it is useful to provide a brief overview of the detector.

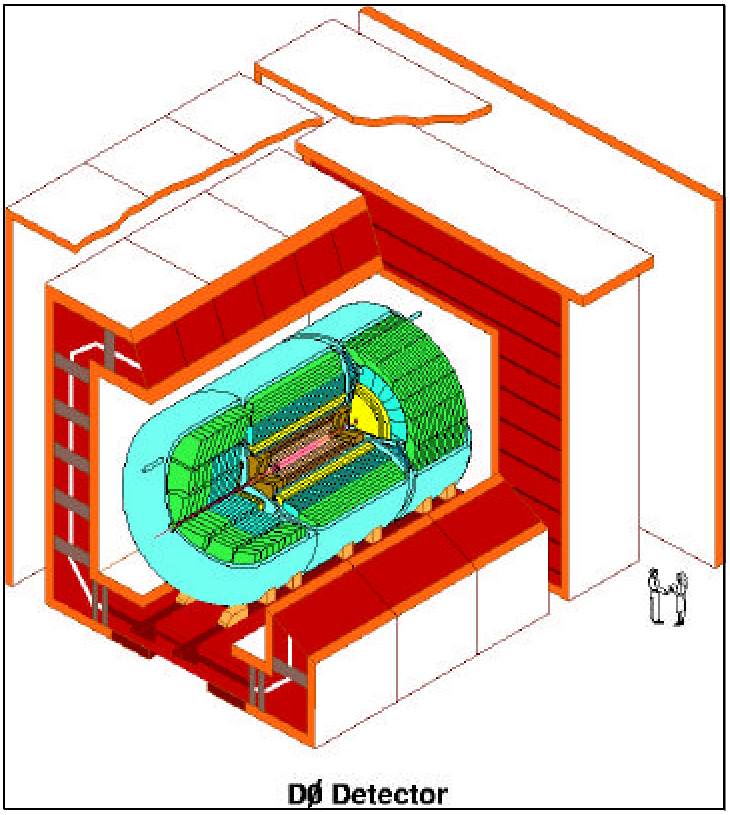

Fig. 3: A schematic view of the DØ detector during Run 1. The tracking chambers near the beam are shown in purple, gray and pink. The calorimeters are shown in yellow, blue, and green. The muon chambers are shown in orange, and surround the iron magnets (in red).

The DØ detector, as it existed in Run 1, is shown in Fig. 3. There were three major subsystems: a collection of tracking detectors extending from the beam axis to a radius of 30 inches; energy-measuring calorimeters surrounding the tracking region; and, on the outside, a muon detector that deflected muons using solid iron magnets. The entire detector was about 65 feet long, about 40 feet wide and high, and weighed 5500 tons. It rested on a moveable platform that permitted detector assembly and commissioning in accessible areas, prior to positioning in the collision hall for operation. The umbilical cord of cables for carrying signals and services followed the detector, and allowed the sensitive electronics for triggering and digitization to be housed in outer control rooms. The detector was operated around the clock by teams of about six physicists and technicians, working from the control room, and using the hundreds of available displays to monitor the flow and quality of data. In all, the detector had over 120,000 channels of individual electronic signals.

Some of these were used to take a fast "snapshot" of the properties of an event, and to decide whether it was a candidate for further study. This "triggering" process proceeded in stages: the first level was completed within 4 microseconds, before the next accelerator beam-bunches arrived at DØ. A second level of trigger decision followed the digitization of all information in a farm of dedicated microprocessors. Events that survived this screening process were written to tape and reconstructed in detail for subsequent analysis.

Figure 4 shows a “typical” event as observed in the DØ detector. The directions of all charged particles were measured in tracking chambers surrounding the collision point. These detectors relied upon the ionization of a gas caused by the passage of charged particles; the produced ionization was focussed electrically onto sensors that recorded the amount of charge and its time of arrival, and permitted reconstruction of the particle trajectory. In addition, the tracking region contained a stack of hundreds of thin foils, called a transition radiation detector. Particles traversing this detector emitted x-rays with intensity that depended upon their velocity. This device was used to enhance electron identification.

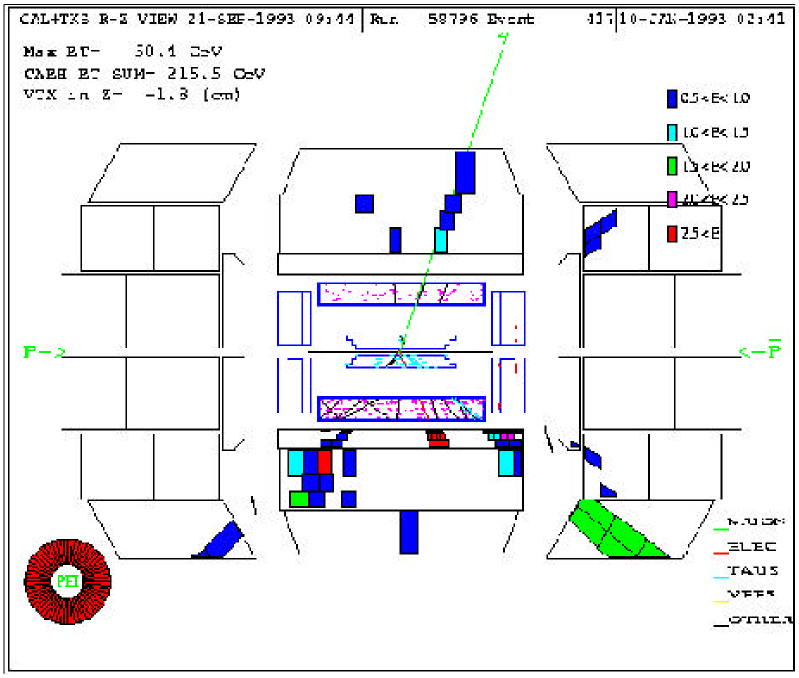

Fig. 4: A side view of "Event 417" referred to in Section 3. The muon track is shown as a green line, the electron track is shown as a short red line, and the two main jet energy depositions in the calorimeters are shown in different colors that represent the energies in the contributing cells.

The energy of most particles (all but muons and neutrinos) was measured in the three calorimeters that surrounded the tracking volume. Each was composed of a stack of heavy metal plates (uranium, steel or copper) interspersed between gaps containing liquid argon. Particles hitting upon the calorimeters interacted, yielding secondary particles, which also interacted, leading to a shower of particles that ultimately ended when all the secondary particles lost energy and stopped. The passage of the full set of showering particles through the argon gaps produced ionization electrons that were collected on localized electrodes. The observed signal was proportional to the incoming particle energy. The pattern of energy deposition along the shower was used to distinguish electrons or photons from hadrons. Clusters of deposited energies were used to reconstruct the jets associated with quarks and gluons.

Muons penetrated the calorimeters, typically without a substantial change in their energy or direction. They were detected in the outer region of the detector using gas-filled tracking chambers, positioned before and after magnetized blocks of iron. These chambers provided the muon trajectories before and after the bend in the magnet, and thus yielded the momentum or energy of the muons.

The computer software for DØ was almost completely custom-written. It was required for monitoring and control of the experiment, for the microprocessors in the trigger system, for controlling the data flow to the ultimate logging to tape, for the reconstruction of particles from the signals measured in the detector, and for managing the large data samples (70 million events, 3 Terabytes of data) acquired over the run. Special attention was paid to graphical displays of events and detector performance. Many millions of simulated events were created for study of detector performance and specific physics processes through "Monte Carlo" programs that mimicked the response of the detector.

3. PHYSICS OF THE TOP QUARK

The four lightest quarks (called "up", "down", "strange", and "charm") have been known to us for over 25 years; they come in pairs, with members of each doublet having internal "weak isospin" quantum numbers of $\pm 1/2$. In 1977, the "bottom" (or " b") quark was discovered, and found to have weak isospin of $-1/2$, thus requiring a partner called the "top" quark. Prior to the start of Run 1, the lower limit on the mass of the top quark had been pushed up to about 90 GeV by experiments at CERN and early data from CDF. Physicists had already begun to puzzle over what the large mass difference between the b quark (at about 5 GeV) and the top quark implied, suggesting the possibility of a special role for the top quark in the scheme of particle phenomena.

From the beginning, the search for the top quark was a very high priority at DØ. The Standard Model was explicit in predicting top-production and decay characteristics. Specifically, the production rate for top-antitop pairs could be calculated reliably from on QCD theory, once the top-quark mass was specified. Similarly, the decays of a top (or antitop) quark could be predicted because the top was expected to decay nearly all the time to a W boson and a b quark, giving rise to a final state with two Ws and two b-quark jets. The decays of W bosons (either into charged leptons and their neutrinos or into quark-antiquark pairs) were already well established. Thus the basic classes of final states arising from top and antitop production were the following: (a) six quark jets (four from the Ws and two from b quarks); (b) a lepton and neutrino, accompanied by four quark jets (two from one W and two b jets); or (c) two leptons and neutrinos and two b quark jets (see the diagram in Fig. 5). Other final-state particles were expected from the interactions of the rest of the quarks and gluons in the colliding proton and antiproton, and also from the radiation of gluons from the interacting quarks. Neutrinos could be sensed only through the missing transverse momentum in the detector. Tau leptons are difficult to identify, and consequently the electron and muon channels turned out to be the preferred channels for studying leptonic final states.

The experimental challenges differ for the three classes of events: the six jet class, with no leptons, is the most likely, but suffers from huge backgrounds due to ordinary strong production of jets; the two-lepton class has relatively little background but a small rate. The single lepton class is intermediate in both rate and background. The measurement of jet energies and directions is crucial to the determination of the mass of the top quark; this measurement is complicated by the spatial spreading of particles in the jet, and by the possibility of gluon radiation. It was generally believed that a measurement of the mass could not be performed to better than 10% accuracy, both because of the jet problems and the presence of missing transverse momentum carried by the invisible neutrinos.

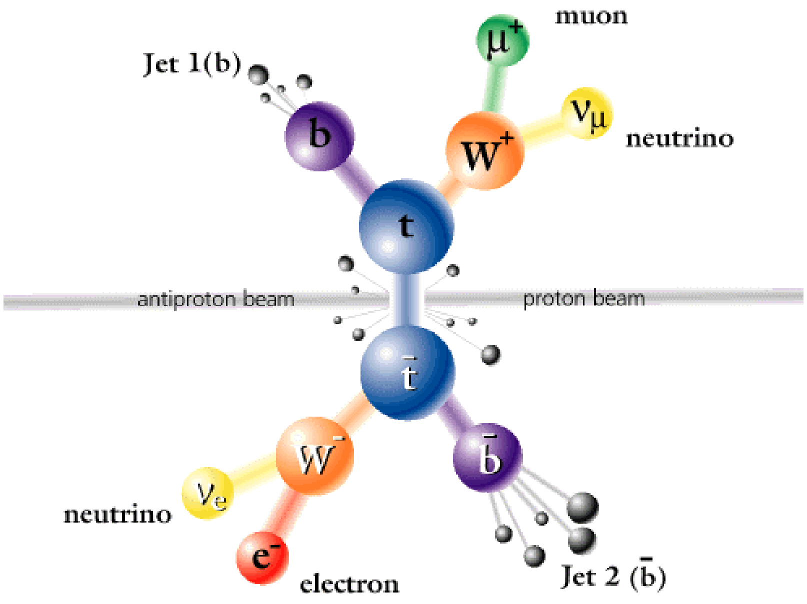

Fig. 5: A schematic of top-quark pair production, where both Ws decay leptonically

The first portion of Run 1 (Run 1a) was completed in mid-1993 and yielded an accumulated collider luminosity corresponding to 14 events per 1 pb of production cross section (usually referred to as 14 pb^{-1}). From these data, DØ published its first search for the top quark in early 1994, using the single lepton, electron (e) and muon (μ) channels, and the ee and eμ channels. The selection criteria were set to optimize the discovery of a top quark with a mass of about 100 GeV. Three events were found: one eμ candidate, one ee candidate and one single-electron candidate, all with accompanying jets. The expected backgrounds were comparable to the number of observed events. Hence, a lower limit of 131 GeV at the 95% confidence level was set on mass of the top quark, based upon the SM calculations for the expected yield as a function of mass. This was the highest mass limit at the time (and, as it turned out, the last lower limit reported on the mass of the top quark!). There was a spectacular event ("Event 417") in this sample, containing an electron, a muon, and missing transverse momentum, all above 100 GeV, together with two well-identified jets and a small third jet. The probability for background processes to produce this event was extremely small. Our publication reported an analysis of the mass, based on the assumption that this event was a top-antitop production, stating that: "The likelihood distribution is maximized for a top mass of about 145 GeV, but masses as high as 200 GeV cannot be excluded." This event, shown in Fig. 4, survived subsequent signal-selection criteria that were even more restrictive and ended up in our final Run 1 top-quark sample.

With this mass limit in place, and in anticipation of much larger data samples from Run 1b later in 1994, DØ optimized the search for top at higher masses, and developed powerful techniques for determining its mass. Several useful variables were developed to aid in separating signal events from background. One was the "aplanarity" variable that measured the isotropy of energy flow. Top quark pairs are expected to be produced nearly at rest in the center of mass frame and to spray their decay products uniformly in all directions, in contrast to the more back-to-back topology of multi-jet background processes. Another variable was the scalar sum of the transverse momenta of jets and lepton in the event. This variable, resembling a measure of event temperature, distinguished the energetic decay fragments of massive top quarks from typically lower energy background from jet production. Refined methods for estimating background rates were established using the observed rates of background samples, and which decreased exponentially as the number of jets in the sample increased. Simultaneously, methods were developed for determining the mass of the top signal. Using data for background events and Monte Carlo simulation of the top-antitop signal events with a given assumed top mass, templates were made for the expected distributions of reconstructed top masses. The template with which the data agreed best gave the best estimator of true top quark mass.

In late spring of 1994, the CDF experiment submitted for publication a publication showing evidence that the top quark may exist, with a mass near 175 GeV. The CDF excess of events corresponded to a cross section of more than a factor of two above the expected (and currently accepted) value. Although suggestive, these data were insufficient to claim discovery. At the same time, DØ presented its updated results at conferences. New features of the DØ analyses included the use of additional variables and channels in which the b quark was tagged through its decay to a muon (and its accompanying neutrino and other particles). The techniques were now tuned to optimize the discovery of top in the mass range above 160 GeV. The sensitivities of both the CDF and DØ experiments to possible top signal were very similar, but the DØ sample contained only a modest excess over background estimates (7 events with an expected background of 3.2 events), and the top-antitop production rate inferred was consistent with that predicted (and now confirmed) by the Standard Model.

At the beginning of 1995, data samples had increased by a factor of nearly three. On February 24, 1995, DØ and CDF simultaneously submitted papers announcing the discovery of the top quark. The DØ sample had 17 events with an expected background of 3.8, and the odds for the background to fluctuate to the observed sample were only 2 in 1 million. For this sample, the mass of the top quark was estimated to be between 167 and 231 GeV. The cross section was measured to be 6.3 ± 2.2 pb for a mass of about 200 GeV. The CDF results were consistent with those from DØ, favoring a somewhat larger cross section and a lower mass. The discovery of the top quark completed the roster of SM particles comprising matter, and underscored the special nature of the top quark -- an elementary particle as heavy as a gold atom, and with a mass commensurate with the energy scale of electroweak symmetry breaking. These CDF and DØ papers on the discovery of the top quark have now become the second most cited result in experimental high energy physics (after the papers on the J/ψ discovery).

By the end of Run 1 in early 1996, DØ had recorded about 125 pb^{-1} of data. From the full data set, several more improvements were made in understanding the top quark. Searches for anomalous behavior in top production were sought, but none found. Searches for new particles in top decay, such as charged Higgs bosons, came up empty-handed. But several important advances were made in the measurement of the top-antitop production cross section and the mass of the top quark. A comprehensive new study of top production was carried out in the single and two-lepton classes using carefully optimized selection criteria to minimize the uncertainty on the cross section. A sophisticated analysis of the cross section was completed in the six-jet channel, making extensive use of neural networks that were sensitive to the differences between signal and background. The backgrounds were determined from data, without recourse to Monte Carlo simulations. The combination of all analyses of the top-antitop cross section yielded 5.9 ± 1.6 pb, for a top mass of 172 GeV, in excellent agreement with the theoretical prediction from QCD.

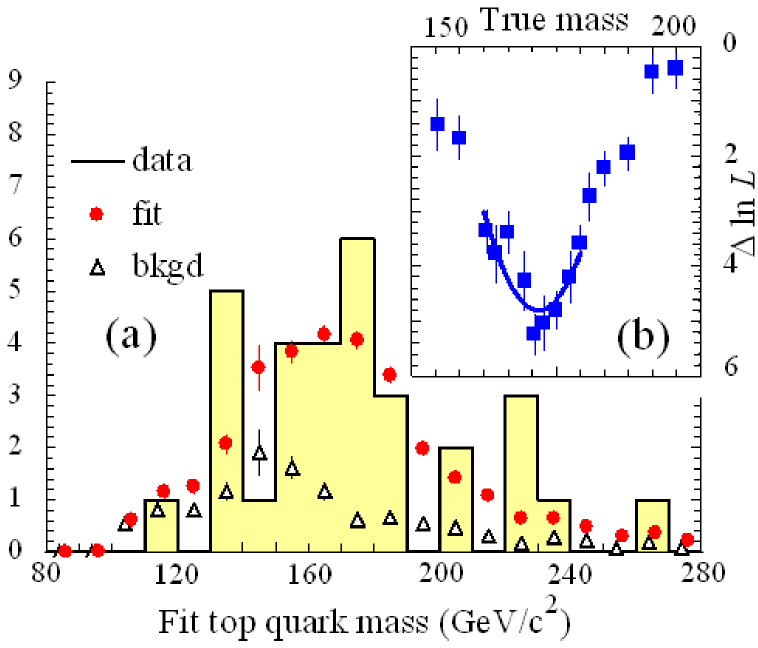

Fig. 6: The mass reconstructed for the top-candidate events with one lepton, four jets and missing transverse momentum (yellow histogram). The triangular symbols represent the expected backgrounds, whereas the red circles represent the sum of signal and background for the best fitted value of the top mass. The inset shows the quality of the fit as a function of top mass, with the best value of 173 GeV being at the minimum.

The mass analysis was improved in several ways. For the single-lepton channels, neural networks and a likelihood discriminant were developed to distinguish signal and background without biasing the mass distribution. The final data sample is shown in Fig. 6, where the separate contributions for expected background and total (signal and background) are compared with the observed mass distribution. From this channel alone, the mass was found to be 173.3 ± 7.8 GeV.

Powerful new methods were also devised to estimate the mass for the dilepton samples, where the presence of two neutrinos precluded the direct calculation of a mass. These new techniques were pioneered in DØ at the beginning of 1993, following the excitement over the observation of "Event 417". Probabilities for dilepton events to originate from top production were calculated as a function of the assumed top mass, and a maximum likelihood fit was then used to extract the best value. Taken together with the single lepton channels, the final top mass from DØ analyses is 172.0 ± 7.1 GeV (an uncertainty of about 4%), far exceeding the initial expectation for precision, and making the top mass the most precisely known of all quark masses. Combining all mass measurements from both CDF and DØ, yields a mass of 174.3 ± 5.1 GeV (< 3% uncertainty) for the top quark.

The discovery of the top quark was a major achievement and the highlight of the DØ program in Run 1. Its very large mass suggests that it may well play a special role in the breaking of the electroweak symmetry, and could be partially responsible for the mechanism by which all particles acquire mass. It provides a probe for seeking new forces in which top and antitop quarks combine (annihilate) to make new particles, and a vehicle for the search for new massive particles in its decays. These are the themes that will dominate top-quark studies in the forthcoming Run 2, where at least forty times more top events are expected in a substantially improved detector with greater capability for deciphering these complex signals.

4. ELECTROWEAK PHYSICS

One consequence of the unification of the electromagnetic and weak forces was the prediction of the existence of two new particles: the W and Z gauge bosons. After several years of search by experiments around the world, two collaborations at CERN, using the world's most powerful accelerator at the time, announced in 1983 the first direct observation of these elusive particles. With a total of ten W bosons and four Z bosons, the experiments measured the masses of the particles to be ~ 80 GeV and ~ 90 GeV respectively, with an uncertainty of 5–10 %. While the number of events was relatively small, the importance of this observation was immense because the W and Z bosons were essential ingredients in the SM.

One of the primary goals of DØ was to measure accurately many of the properties that characterize these fundamental particles. The high energy and the intensity of the proton and antiproton beams at Fermilab make the Tevatron an ideal place to produce large samples of W and Z events. During Run 1, DØ and CDF collected the world's largest sample of W bosons, with DØ accumulating over 100,000 W particles, a far cry from the handful observed in their discovery. With such a large sample, DØ has made some of the best measurements of the properties of the W boson, including its mass and couplings to other particles, as we briefly describe below.

W bosons are produced at the Tevatron mainly when a quark from a proton and an antiquark from an antiproton collide head-on at the DØ detector. Almost immediately after being produced, the W decays into other particles within about 10^{-24} seconds. Roughly 10% of the time a W decays into an electron and a neutrino, and it is this decay mode that DØ uses to measure the W mass. While only one W boson with this decay signature is produced for about every forty million collisions, processes that mimic this decay are about 50 times less likely. Thus, although it took three years to accumulate the W events, the sample is nearly pure.

To extract the mass of the W boson, DØ first measures the momenta of its decay particles. The energy of the electron is measured in the liquid-argon calorimeter. Since neutrinos rarely interact with matter, their momenta must be measured indirectly by invoking momentum conservation. The sum of the momenta of all the particles produced in the collision (in the plane transverse to the proton and antiproton beam directions) must be balanced by the transverse momentum of the neutrino. A quantity called the transverse mass of the W boson is then calculated by combining the transverse momenta of the electron and neutrino, and the mass of the W is extracted from the shape of this transverse mass distribution. The DØ value for the W mass is 80.482 ± 0.091 GeV, the world's most accurate measurement of this important parameter published to date from any single experiment.

The experimental uncertainty of 0.091 GeV, or 0.11%, represents an improvement of about a factor of 100 compared to the original set of measurements, and required an extremely detailed understanding of the experimental apparatus. For example, the mean calorimeter response to the electron had to be known to better than one part in a thousand, and energy depositions as small as 100 MeV had to be taken into account in collisions with up to 1.8 TeV ($1\text{TeV}=10^6\text{MeV}$) of total available energy. To put this in perspective, it is as if you had to know whether you had several grains of sand under each of your fingernails when you weighed yourself on the bathroom scale. Luckily, Z bosons are produced in nearly the same way as Ws, and their decay particles can be used to calibrate the detector. With 10,000 Zs available, DØ was able to understand the apparatus to the required level of accuracy.

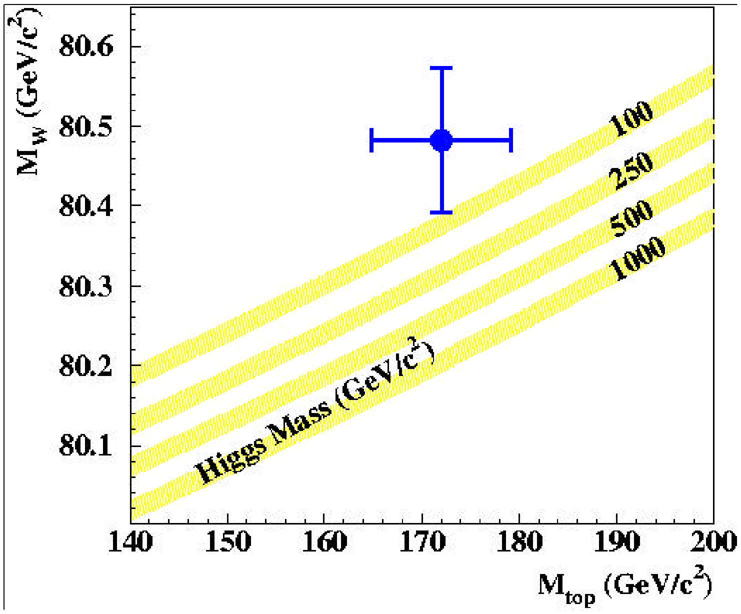

Fig. 7: Measured values of the top and W mass at DØ are shown superimposed upon predictions from the Standard Model in which the Higgs mass is varied between 100 and 1000 GeV.

The precision determination of the W mass, together with the mass of the top quark discussed above, can be combined to estimate the mass of the Higgs particle. The W mass receives contributions from its virtual disassociations to top and antibottom quarks or to W boson and Higgs. The properties of the Z boson, accurately measured at the CERN and SLAC e^+e^- colliders, also provide sensitivity to the mass of the Higgs. The full set of these measurements thus constrains the Higgs mass in the context of the Standard Model. Figure 7 shows the result of the DØ measurements. The indirect measurements using the Z, obtained mainly at LEP and SLC, and the directly measured top quark and W masses from DØ and CDF agree well, and suggest that the Higgs boson has a mass below 200 GeV – perhaps within reach of the next run at the Tevatron.

In addition to measuring the W mass, DØ used its large sample of Ws and Zs to probe the strength of the couplings between these gauge bosons and the photon. The unified theory of electroweak interactions makes unique predictions for these couplings, which are quite different from predictions one would derive from separate electromagnetic and weak theories. By studying events containing both a W boson and a photon, DØ was able to show directly for the first time that the unified theory was indeed needed to describe the results. In addition, analyzing events produced with a W boson and two jets allowed DØ to demonstrate directly that Ws and Zs interact with each other as predicted by the Standard Model. Such tests of the couplings between the bosons probe the very heart of the electroweak theory, and any deviations from the predictions would provide direct evidence of new physics. With some of the most sensitive measurements to date, DØ has been a world leader in studying these couplings, but so far has found no sign of anything new beyond the SM.

While Run 1 was quite successful, the future for DØ is even brighter. When improvements to the Fermilab Tevatron and the DØ apparatus are completed, DØ will begin to take data and expects to collect over 2.5 million W events. The uncertainty on the W mass will be reduced by at least a factor of two, and significant improvements will be made in the measurements of the gauge boson couplings. Along with many other interesting W and Z physics topics, the DØ experiment should be able to confront the electroweak sector of the Standard Model with unprecedented sensitivity and with the hope and possibility of discovering something new.

5. QCD PHYSICS

Quantum Chromodynamics (QCD) is the part of the Standard Model that describes the strong interaction responsible for the nuclear force. The quarks that make up the proton and all hadrons interact with gluon force carriers by virtue of their "color" quantum number. Though the proton can be viewed simplistically as a collection of three quarks, when examined closely, it reveals substantially more complex internal structure. The additional quarks and gluons appear with increasing magnification, or at larger momentum transfers, commensurate with smaller distances, and are described by phenomenological functions called parton distribution functions (PDFs). These PDFs are derived from data, and therefore have uncertainties that have to be taken into account in any QCD-based prediction. Moreover, the basic coupling strength between quarks and gluons, α_s, decreases as the momentum transfer in a process increases. Hence, perturbative calculations of strong-interaction processes become more precise at large values of the square of four-momentum transfer (q^2), whereas at low q^2 such calculations are extremely difficult, and often not reliable.

Because of the excellent coverage for jets provided by the calorimeter, DØ has made detailed and accurate measurements of strong interaction processes that test the predictions of QCD in many domains. We have already remarked on the great success of QCD in predicting the production of top quarks, and we focus here on only a few processes that pertain to the production of jets (quarks and gluons) and W and Z bosons.

The elastic scattering of quarks (or gluons) within the colliding proton and antiproton resembles classic Rutherford scattering of alpha particles by gold nuclei. Both processes are well described by the exchange of a spin 1 quantum (a photon or a gluon) for the case when the interacting objects display no substructure. The inclusive production of jets at very large transverse energy (E_T) can be calculated with confidence in QCD, given knowledge of the PDFs. Using Run 1 data, DØ has published the inclusive jet E_T spectrum in the range $60 < E_T < 560$ GeV. In this measurement, jets were detected in the central region of the detector. Figure 8 shows the observed cross section, which drops by six orders of magnitude over the measured range. Taking account of the statistical and systematic uncertainties, DØ finds that the QCD prediction, including its higher order corrections (and using standard PDFs), agrees well with the data. This result attracted considerable attention because CDF had published an inclusive jet cross section, which showed possible excess above theoretical predictions at the high-E_T end of the spectrum. If such excess were confirmed, it could be interpreted as providing evidence for quark compositeness or the presence of other new physics beyond the Standard Model. The DØ result showed that Standard Model calculations do not need to be augmented with new physics beyond expectations from QCD.

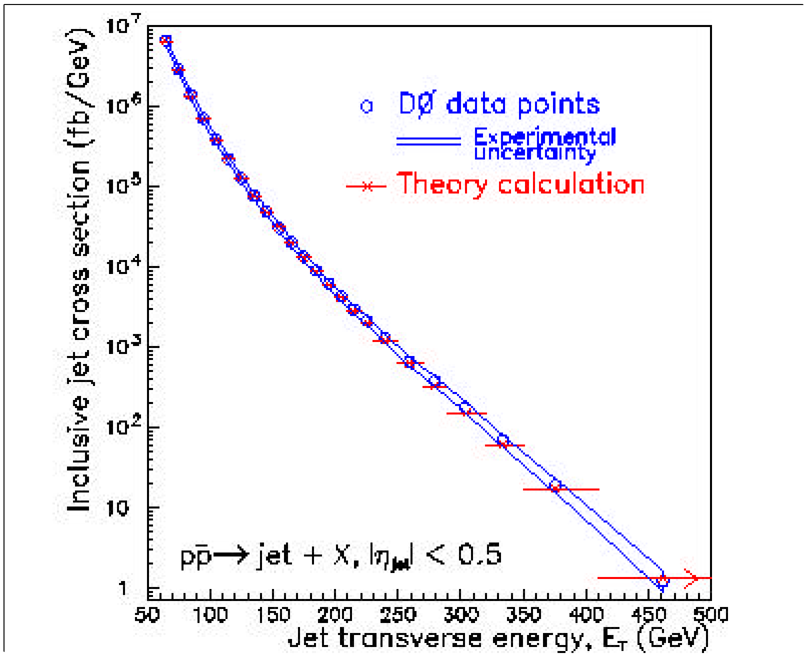

Fig. 8: The measured DØ inclusive jet cross section compared with QCD calculations.

The inclusive jet cross section was also measured during a special Tevatron run at lower center of mass energy of 630 GeV (where the earlier CERN measurements had been made). Taking the ratio of the inclusive jet cross sections at 630 and 1800 GeV cancels many experimental and theoretical uncertainties. DØ measured this ratio to be about 20% lower than expected. However, better agreement can be obtained if the energy scales for the perturbative calculations are defined differently at the two center of mass energies.

Using the two highest-E_T jets among those reconstructed in any event; DØ calculated an invariant mass to search for possible new particles that might decay into two jets. Such a state would appear as a bump above the smooth background of ordinary QCD production. The slope of the falling dijet mass distribution is also sensitive to possible substructure of quarks and gluons. DØ has published the dijet mass spectrum for the range of 200 to 1,400 GeV, and found no structures. A quantitative limit on quark compositeness was determined from the shape of this distribution. A possible substructure can be characterized by a mass-scale parameter Λ, corresponding to bound states of any subunits within quarks. For $\Lambda < 2.4$ TeV, the slope of the predicted mass spectrum would be inconsistent with DØ's measured result. This limit on Λ indicates that there is no substructure within quarks or gluons down to the attometer scale (10^{-18} m), and is the most stringent limit on quark substructure determined by experiments to date.

W and Z bosons are created primarily through the annihilation of valence quarks and antiquarks, and so a comparison of measured W and Z production cross sections with theoretical predictions provides test of QCD that is complementary to jet production. Using W and Z decays in both electron and muon channels; DØ has measured the ratio of the W/Z cross section multiplied by their respective branching fractions to leptons. The resulting ratio of 10.49 ± 0.25 is in excellent agreement with the QCD calculation to order α_s^2 of $R = 10.73 \pm 0.11$, where the theoretical uncertainty stems from choice of input PDF and variations due to the uncertainty in M_W and energy reference-scale factors used in the theory. The measurement of R was also used to extract the total decay width of the W ($\Gamma_W = 2.152 \pm 0.066$ GeV), and to determine that no more than 8% of W decays could proceed into unexpected final states. DØ has also measured the transverse momentum spectra for the production of the W and Z bosons. The comparison of these distributions is the most sensitive to non-perturbative effects from multiple gluon radiation present in low-q^2 QCD.

In data that contain at least two high-E_T jets, DØ has observed that a small fraction of events have the striking feature of sizeable gaps in energy deposition between the two jets, or between jets and the beam direction. The gaps are characterized by the absence of particles in extended regions of polar angle in the tracking detectors, calorimeters or forward trigger counters. Such events are termed "rapidity-gap" events (the rapidity variable is related to the polar angle), and fall into three topological categories: jet-gap-jet, gap-jet-jet, and gap-jets-gap, depending on the location of the gaps in the detector. Events in the first two categories (jet-gap-jet and gap-jet-jet) were observed about 1% of the time of events with similar jet topologies. Events of the third category (gap-jets-gap) were observed about 1% of the time of events in category 2 (gap-jet-jet). Dijet events of all three topologies have been observed at both 1800 GeV and 630 GeV. Similar topologies have also been reported at the e-p collider experiments at HERA in Hamburg Germany.

Explanations for the gap events are based on the supposition of the existence of a color-free object called the Pomeron. The Pomeron has long been postulated as the exchanged object and force carrier responsible for elastic and diffractive scattering of two hadrons. The colorless property of the Pomeron is used to explain the presence of rapidity gaps. Ordinary hadrons are produced due the color carried by their constituents, hence their emission from the color-free Pomeron is suppressed. The jets produced in these events have E_T distributions similar to those in standard QCD (quark and gluon exchange) processes. This leads to the view that the Pomeron may have an internal structure, consisting at least partly of normal quarks and gluons arranged in such a way as to make the Pomeron colorless. DØ's study of rapidity-gap events will be enhanced during Run 2, when a set of detectors very close to the beams will enable the experiment to intercept diffractively scattered beam particles on either side of the interaction point. These detectors will provide the full kinematic reconstruction of certain gap-jet-jet and gap-jets-gap topologies, shedding more light on the Pomeron's structure and dynamics.

6. PHYSICS OF THE BOTTOM QUARK

Within the family of known quarks, the bottom (or b) quark is characterized by a set of rather peculiar and often intriguing properties, sufficiently so as to warrant dedicated facilities for its study. Discovered in an experiment at Fermilab in 1977, its unexpected appearance created an imbalance in the internal organization of the existing quarks. The absence of a "weak isospin" partner represented a theoretical discomfort that was only dispelled with the later discovery of its missing companion, the top quark (see Section 3).

When confronted with its earlier known siblings, the bottom quark is considered heavy, with a mass about four times that of its next heaviest colleague, the charm quark. Such relatively high mass grants the bottom quark special status in the studies of QCD. Bottom quarks are produced in proton-antiproton collisions dominantly by the strong QCD interactions of gluons and light quarks that reside within the colliding beam particles.

The large value of α_s and the non-abelian nature of QCD are responsible for the difficulty of making quantitative predictions. However, the higher the mass of the involved quark, the more reliable are the calculations. The mass of the bottom quark is high enough for obtaining reliable QCD calculations, but still low enough to have copious production at the Tevatron. This balance is one of the aspects that single out bottom quarks as an excellent source of data for confrontation with theory, a true "laboratory" for QCD studies. Consequently, one of the ways we test the reliability of QCD in DØ is by measuring the rate at which bottom quarks are produced. An added bonus of heavy quark production is that the dependence of the production rates has a direct correlation to the internal gluon distributions within the colliding protons, which are not well measured, and can be extracted from such data.

DØ has measured the production of bottom quarks in various kinematic regimes, and through the observation of different reactions and final configurations. DØ is especially well equipped for such studies, partly because of its extensive angular coverage. Once produced, free colored quarks do not exist for very long, but immediately initiate a process of pulling light quarks from the vacuum and "dressing" themselves into colorless bound-state hadrons. Bottom quark hadronization usually leads to the production of an unstable B hadron that subsequently decays. Muons are produced in such decays about 11% of the time, and can be used to tag b quarks. DØ has a good muon detector, and the extended muon coverage near the incident beams, the so-called forward rapidity region, is unique to DØ, and has provided measurements of bottom-quark production in new kinematic regions.

The process starts with a selection of collisions that contain one or more muons, a promising signature of something interesting having happened in that event. Weeding out background leaves a sample that can be classified according to the number of muons present in the final state, and how they relate to each other (if two are present) and to the remainder of the collision products. For example, a muon moderately close to the hadrons comprising a b jet provides a signature for a b quark.

Such studies have yielded a wealth of valuable measurements. Resonant and non-resonant final states, in different physical configurations and kinematic regions, have been traced back to their origins in bottom-quark production, enabling a multifaceted focus on production rates, correlations, and confrontations with predictions of QCD.

The results of such measurements are intriguing. While the general aspects of the QCD predictions are in agreement with DØ observations, the calculated production rates systematically fall short of the observed yields by roughly a factor of three. The data from several related studies are shown in Fig. 9, and indicate the level of agreement between theory and experiment as a function of transverse momentum. Similar results have been obtained by CDF. Although there are uncertainties in theory and experiment, the present status represents an exciting challenge that is currently being addressed by theorists, and motivates the program of increasingly accurate measurements for the next Tevatron run.

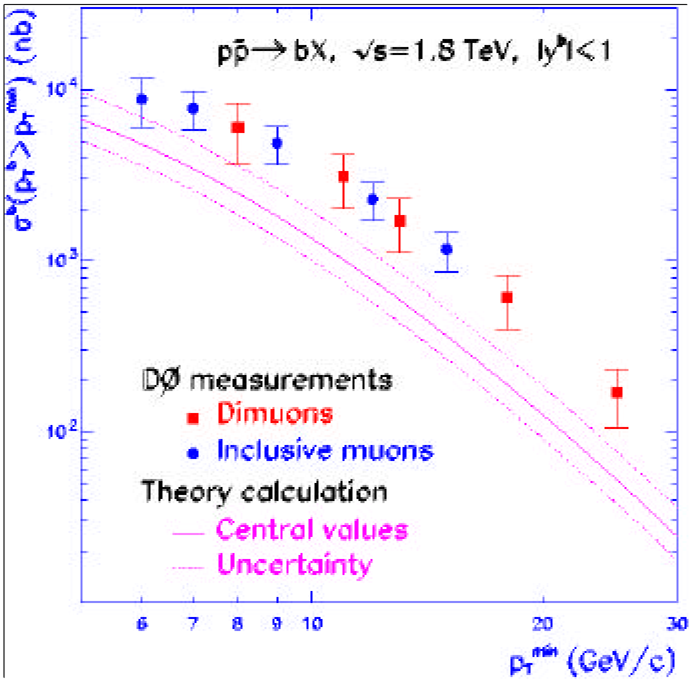

Fig. 9: The DØ inclusive b-quark cross section compared to theoretical calculations.

We noted that the bottom quark is a heavy object when compared with its earlier known siblings; in striking contrast, when confronted with its companion top it is in fact remarkably light. This delicate placement in the mass scale, together with the tendency of quarks to interact mainly with their weak isospin partners, conspire to give the bottom quark yet another set of very welcome properties. The b quark has an unusually long lifetime (hadrons containing b quark travel typically a few millimeters before decay), and clear signatures associated with its decay products. Once an experiment is equipped to observe and analyze specific bottom-quark decay modes, another entirely new and rich chapter of physics is opened, which includes such fundamental topics as CP violation, and windows of exploration into particle physics phenomena beyond the scope of the Standard Model.

The installation of a superconducting solenoid and precision tracking sensors in its interior, are two important features of the upgraded DØ detector for the next Tevatron run. They will give us access to specific bottom quark decay modes and an opportunity to focus on some of these new topics.

7. SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL

It is an amazing feature of the Standard Model that, despite its extraordinary predictive power, it is almost surely incomplete. There are 26 parameters needed to specify the SM, and these can only be supplied by experiment. The strong and electroweak interactions that jointly make up the SM are seemingly unrelated entities; we would prefer to see a unification of these forces but the SM does not do this. The mechanism that breaks the underlying symmetry of the electroweak interaction, and thereby provides disparate masses to W/Z bosons and the photon, is not understood; in the SM the Higgs boson is inserted to provide the symmetry breaking, but its mass is expected to be 10^{14} times larger than that of the W and Z bosons unless some fantastic "fine tuning" is at work. Beyond these defects, the SM offers no clue as to why there are three generations of quark and lepton families with nearly identical properties apart from their mass. It can accommodate, but not explain the existence of CP violation, or why the cosmological constant that should be of order 10^{100} GeV is close to zero, or how to get gravity into a unified framework with the other forces.

Twenty years of precision tests of this model have resulted in an enormous number of successful comparisons of data and theory, with no verified departure from the SM. Despite this impressive predictive power, we firmly believe that the SM is nothing more than a low-energy approximation to a more general theory, the one that explains our world in its completeness and puzzling beauty. This is a very interesting situation, comparable to instances in the past that foreshadowed a major shift of paradigm. Are we completely blind in our search for this more complete theory? The answer is "probably not". We have several hypotheses that we consider as strong candidates for extensions beyond the SM. At the same time, it is imperative that we look for any possible deviations from predictions of the SM, and the DØ experiment has been a pioneer in such studies.

One set of possible extensions of the SM, usually associated with a postulated new super-strong force involving new massive families similar to the quarks, require the presence of particles called leptoquarks. The leptoquarks would have the properties of both leptons and quarks, and thus would let quarks and leptons interact in a non-SM way. In 1997, the possibility of existence of leptoquarks got a boost from experiments at HERA. By colliding positrons and protons, the HERA experiments could produce single leptoquarks. In February 1997, the experiments H1 and ZEUS announced an excess of events over SM expectations at large q^2, with an invariant mass around 200 GeV, which could be interpreted as due to leptoquark production. The evidence was not compelling, but the possible sighting could have had revolutionary implication, and it therefore set the Tevatron experiments in motion to add information.

At DØ and CDF, leptoquarks can be produced in pairs via the strong interaction. This mechanism is well understood and is relatively model independent. The high energy of the Tevatron offers the possibility of searching for leptoquarks to masses higher than accessible at HERA. DØ physicists immediately teamed up for the search. It took three months of analysis to unambiguously establish that the excess that HERA saw was not due to leptoquarks. DØ used advanced data-analysis techniques, such as neural networks and other methods of multivariate analysis, introduced earlier in top-quark studies at DØ. These novel techniques allowed DØ to establish the world's best limits on the existence of leptoquarks that could decay into electrons and quarks. The lower limit on mass of the leptoquark from the DØ experiment alone was 225 GeV, more than enough to rule out the possibility for the HERA event-excess of being interpreted as evidence for leptoquark production. Combined with the 213 GeV limit obtained by CDF, the two Tevatron experiments were able to rule out the existence of these particles with masses below 242 GeV. More general DØ limits on the mass of the first generation leptoquarks (M_{LQ}), as a function of the probability that these particles decay into electron and quark (β), are shown on the left side of Fig. 10.

Supersymmetry (SUSY) has been suggested as a possible cure for many of the shortcomings of the Standard Model. Space-time symmetries such as those of translation or rotations of coordinates lead to momentum and energy conservation. Supersymmetry postulates a further symmetry between bosons (integer-spin particles) and fermions (half-integer-spin particles), thereby generalizing the Poincare group describing space and time. This radical reshaping of our understanding of space-time is also a key ingredient in the theory of strings in multiple dimensions. When used as a phenomenological ingredient of physics at the scale of present-day experiments, it provides a natural solution to the shortcomings of the SM involving the instability of the mass of the Higgs boson, and permits the unification of the strong and electroweak forces. Supersymmetry predicts that each known fermion and boson should have a mirror "superpartner" of the opposite type. Clearly, supersymmetry is broken, since there is no spin-zero superpartner for the electron at 0.511 MeV. But to be self-consistent, supersymmetry predicts that the superpartners should be found with masses below 1000 GeV, and some could be within reach of discovery at the Tevatron.

The DØ experiment has searched for traces of supersymmetry in a variety of processes. So far, these searches have not been successful, and have resulted only in limits on the existence of superpartners. Depending on the model parameters, squarks and gluinos (the superpartners of quarks and gluons, respectively) with masses less than about 260 GeV have been excluded. The right side of Fig. 10 shows the region of supersymmetry parameter space over which the DØ results have ruled out squarks and gluinos. The parameters M_0 and $M_{1/2}$ refer to the unified masses of the spin zero and spin one-half superpartners at the scale of unification of forces. Limits were also set on masses of charginos and neutralinos, the superpartners of the W, Z, and Higgs bosons. Despite these negative results, hopes are high as capabilities for discovering supersymmetry improve dramatically in the next Tevatron collider run. The mass reach will be about 100 GeV higher than present limits on superpartner masses, bringing DØ into a very interesting range of SUSY parameter space.

Among other fundamental symmetries probed by the DØ experiment is the "broken" symmetry between the electric and magnetic charges. We know that free carriers of electric charge exist, but there is no trace of a free magnetic charge, or magnetic monopole. If monopoles exist, one would expect pairs of high-energy photons to be produced at the Tevatron at a much higher rate than predicted by the Standard Model. This indirect search, though unsuccessful, yielded the most restrictive limit on the mass of a possible magnetic monopole.

Recently, a novel idea was introduced for physics beyond the SM. It originates from string theory that views all known particles as vibrations of tiny “strings” of energy. The recent success of string theory in explaining entropy flow in black holes has drawn much attention. String theory, or its subsequent elaboration as membrane or M-theory, seeks to explain all physical phenomena using structures in a universe with 10 or 11 spatial dimensions and time. The extra (beyond the usual four) dimensions are believed to be "curled up" at a scale of at most 10^{-19} cm. However, recent suggestions predict that some of these extra dimensions may be confined to a much larger scale, perhaps of the order of one millimeter. If this is correct, then the highest energy scale we know of, the so-called Planck scale might be much lower than initially realized (~ 1 TeV, and not 10^{16} TeV). DØ is currently looking for possible manifestations of this predicted signal in several channels.

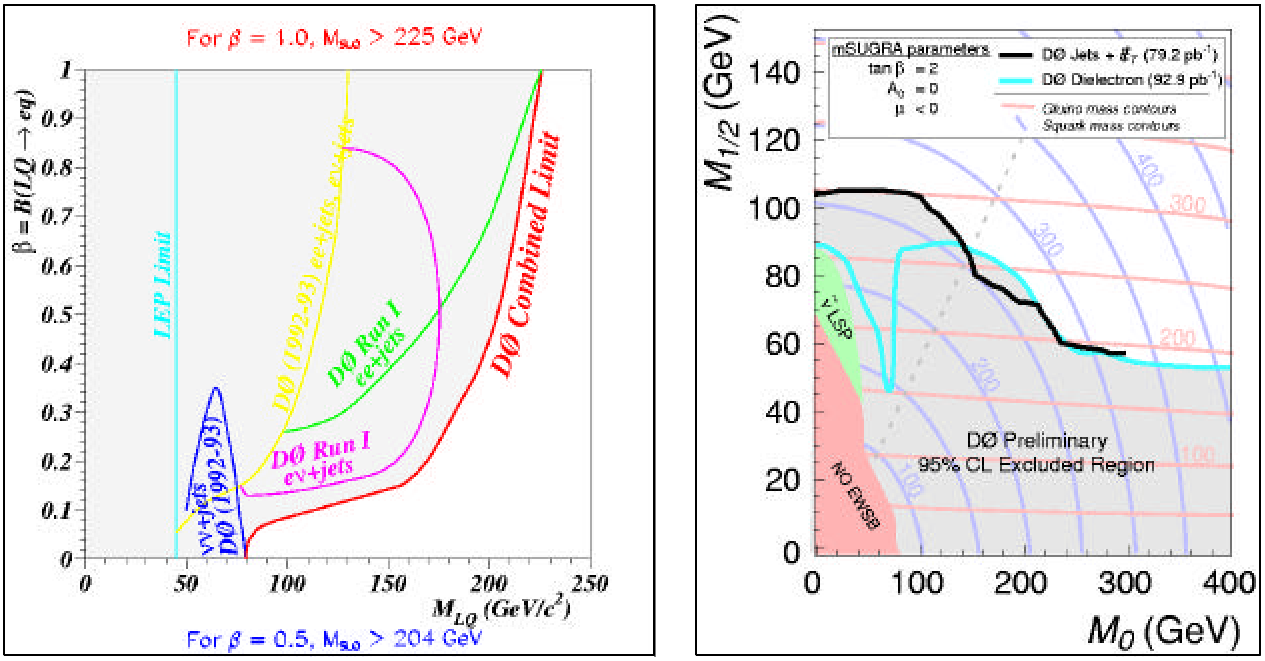

Fig. 10: Highlights of searches for new physics at DØ: limits on the mass of first-generation leptoquarks (left), and limits on squarks and gluinos in SUSY models (right).

The searches discussed above are just highlights of the many that DØ has performed in its very successful first run. DØ has also looked for leptoquarks of other generations, additional quarks and vector bosons, quark-lepton compositeness, technicolor, non-standard Higgs bosons, and more. We are closely following recent developments in theory, and several searches for the manifestations of new theoretical concepts are still ongoing. Although no new physics has as yet been observed, DØ will continue hunting for the unknown.

8. CONCLUSIONS

The studies by DØ, together with those by our companion experiment CDF at the Tevatron, and the experiments at LEP, SLC, HERA, and other accelerators, have taught us much about the character of particles and forces at smallest-distance scales. These results have given a qualitatively new understanding of the properties of matter, and have thus far demonstrated the surprising resilience of the Standard Model of particle physics. But the puzzles that this research has created make us eagerly anticipate the next round of experiments. There is an almost agreed expectation that the experiments of the coming several years will make breakthrough discoveries. There are pointed questions that have arisen from the past work that cry out for answers. Why is the top quark so heavy in comparison with its partners? Where is the Higgs boson, or whatever else nature has chosen to be the agent of electroweak symmetry breaking? Can we find evidence for supersymmetry and thus pave the way to unification of all the microscopic forces? Or, are the solutions to the questions before us to be found in some hitherto unexpected quarter? From the vantage point of the understanding obtained from the past run at DØ, we look forward with eager anticipation to the enhanced possibilities of the next run.

We note with pride the efforts of the many in the DØ collaboration whose ingenuity and hard work have made the results presented in this overview possible. We appreciate also the many contributions to our understanding that have come from our experimental and theoretical colleagues worldwide. And we are most grateful to our governments for the support that has made this research possible. The new results have brought not only new understanding of the structure of matter, but have also benefited society through the novel techniques that have been developed, and that over the course of time will enrich society in ways that are presently unforeseen.