Fermi National Accelerator Laboratory

FERMILAB-Conf-99/056-E
CDF and D0

Recent Results from the Tevatron Collider

Hugh E. Montgomery
For the CDF and D0 Collaborations

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

April 1999

Published Proceedings of the *Conference of Nuclear Physics Division of Russian Academy of Science*, I.T.E.P., Moscow, Russia, November 16-20, 1998

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Recent Results from the Tevatron Collider

Hugh E. Montgomery*
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, U.S.A.
For the CDF and DØ Collaborations

April 12, 1999

*e-mail:mont@fnal.gov

Abstract

In as much as space permits we discuss some examples of interesting recent results obtained by the CDF and DØ experiments at the Tevatron Collider.

1. Introduction

The Fermilab Tevatron Collider currently provides the highest energy collisions in the world. Data taken by the CDF and DØ experiments from 1992 to 1996 are based on an integrated luminosity of slightly more than 100 pb^{-1}. In 1995 the top quark was discovered and a number of other incisive results have been published in the time since. The data continue to yield interesting results across almost all aspects of the standard model of high energy physics. In this paper we will briefly review a few selected aspects of the results from the last year or so.

We start with some results concerning the third generation of quarks; the bottom quark is discussed in section 2 and the top quark in section 3. In section 4 we consider some results in the electroweak sector. In section 5 we look to the unknown, the searches for the Higgs boson and signs of other physics beyond the electroweak scale.

Although the most common of the interactions there is still a lot to be learned about QCD. In section 6, we will discuss some of the recent high precision measurements and also the use of the data to explore higher mass scales through searches for compositeness.Finally we will draw a few conclusions.

The approach in several instances will be to choose results from either CDF or DØ in order to illustrate the points we wish to make rather than to show every result from each experiment. For those readers interested in pursuing other aspects of the data from these two experiments the world wide web home pages[1, 2] of the experiments provide a good starting point.

2. b-quark Physics

The basic production mechanisms for b quarks at the Tevatron are in principle well known. With its relatively high mass, the perturbative QCD calculations should provide a fairly good description. However, as illustrated in Fig. 1 the production cross section as measured in the central region is higher than

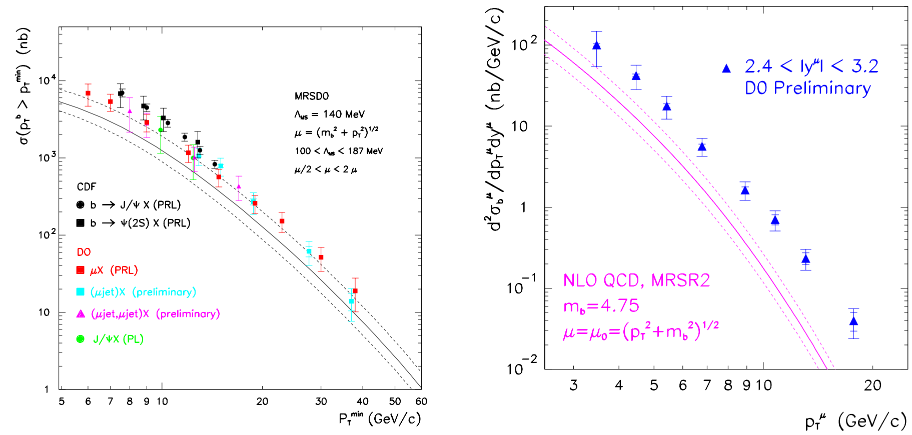


Figure 1. b-quark production as a function of transverse momentum. On the left are results from the central region from both DØ and CDF, on the right are results at high rapidity from the DØ experiment.

that calculated. The measurements come from both CDF and DØ and are made by a number of different techniques. Recently measurements[3], by the DØ experiment, of the muons from the decay of b quarks at large rapidity, have appeared. They show, see Fig. 1, a similar excess with respect to the predictions, in this case by perhaps a factor four rather than the factor two which is observed in the central region. This is clearly seen in Fig. 2 in which the dependence on rapidity is displayed.

In the study of any quark system a basic parameter is the lifetime which is controlled by the mix of amplitudes that are operative in the decay and by their interference. For example in the charm system the difference between the lifetimes of the neutral and charmed mesons presaged an understanding that the spectator-quark mechanism did not dominate. Several B-hadron lifetimes have been measured at the Tevatron by the CDF experiment and these are displayed in Fig. 3. We see that, in contrast to the charm system, the neutral and charged mesons have very simlar lifetimes, about 1.5 ps, and that the b baryon(Λ_b) has a lifetime only slightly less than that of the mesons.

One of the features of the Tevatron for b-quark physics is the ready access

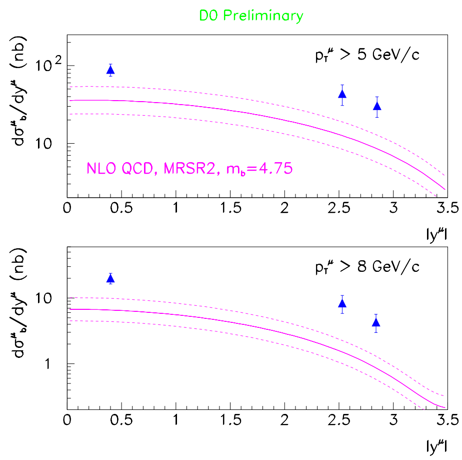


Figure 2. b-quark production as a function of rapidity from the DØ experiment.

to heavy states. During 1998, the B_c^+ bottom-charm meson was observed[4] by CDF. The relevant decay was the semi-leptonic $B_c^+ \rightarrow J/\psi l^+ \nu$. Since there is a missing neutrino, the reconstructed mass of the system, see Fig 4, is less than that of the meson, but nevertheless shows a characteristic peak. Indeed a mass measurement for the state results. A key element to the observation is the use of the displaced vertex of the J/ψ with respect to that of the primary vertex. The measurement of this vertex as illustrated in Fig 4; the decay length leads to a measurement of the lifetime of the B_c at about 0.5 psec. It is interesting to note that this is remarkably close to the expectations[5].

The advent of measurements in the b-quark system which might be sensitive to CP violation has been eagerly awaited. Recently CDF presented the first attempt[6] at such measurements. In order to be sensitive to the CP-violating evolution of a neutral B meson, the initial identity of the state must be known. This is achieved by tagging either the state itself or the partner B state. Same-side tagging involves the observation of a co-produced soft charged pion. Depending on the charge of the pion accompanying a $B^0 \rightarrow J/\psi K_S^0$ decay the initial neutral state could be identified as either B^0 or $\overline{B^0}$. This initial measurement led to a determination of the relevant pa-

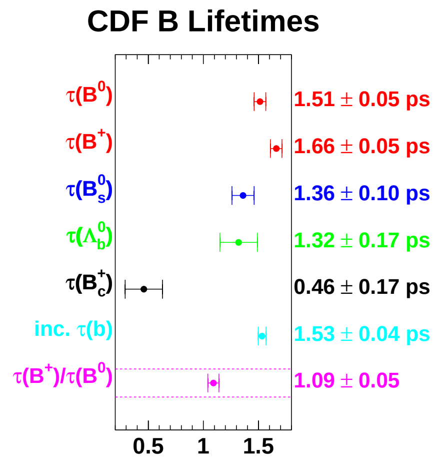


Figure 3. A compilation of B hadron lifetime measurements from CDF.

rameter of the unitarity triangle of the Cabibbo-Kobayashi-Maskawa(CKM) matrix, $\sin 2\beta = 1.8 \pm 1.1(stat) \pm 0.3(stat)$ which limits $\sin 2\beta > -0.2$ with 95% confidence level. Since the time of this conference, CDF has presented a new measurement[7] using several different tagging techniques with the result $\sin 2\beta = 0.79^{+0.44}_{-0.41}$.

3. t-quark Physics

The cross section for top-quark production is expected to be very well described by perturbative QCD and, in contrast to the b quark, this is indeed the case. The predictions are in the range 4.6-5.5 pb. The measurements from DØ range from 5.6±1.8 pb., in the leptonic channels[8], to 7.1±3.2 pb. in the all-hadronic channel[9] in which there are six final state jets. CDF measures[10] all three channels for a mean of $7.6^{+1.8}_{-1.5}$ pb.

The mass is an important property of the top quark and, since it is large, it is also an important parameter in the calculation of the electroweak radiative corrections which contain quark loops. On the left of Fig 5 we display the reconstructed mass for different samples of events from CDF. The samples are labelled by the discriminators, displaced vertex and soft lepton, used to tag the b

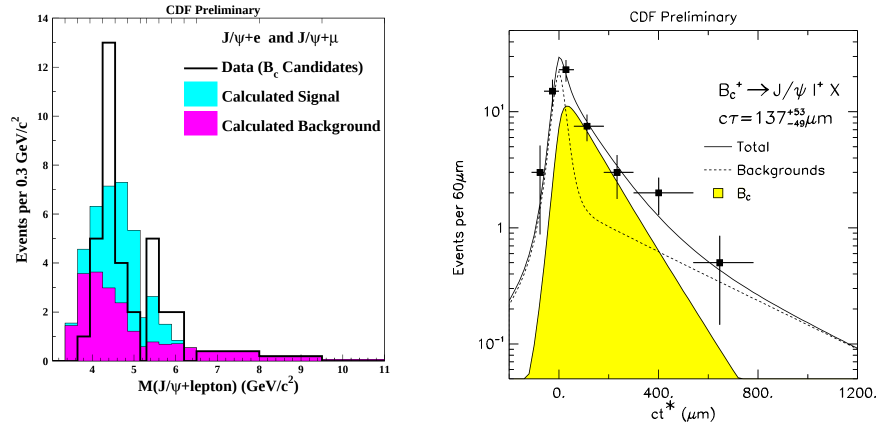


Figure 4. Left: the effective mass of the J/ψ and lepton indicating the B_c signal; right: B_c decay length distribution measured from the displacement of the J/ψ vertex.

quarks from the top-quark decay. The insets show the corresponding likelihood plots for the mass fit to each sample. DØ uses analogous methods but different discriminators; their measurement is illustrated in the right-hand plot of Fig 5; the insets are the fit for a sample dominated by background and the likelihood distributions for two different fits. The measurements in all channels, see Fig. 6, and from each of the experiments are in good agreement and are combined[11], properly taking into account all the correlations, to give $m_t = 174.3 \pm 5.1$ GeV. Quite remarkably, given its youth, this makes the top-quark mass the best known by far of all the quark masses.

4. Electroweak Physics

A fundamental feature of the electroweak theory is that it is non-Abelian; there are couplings between the bosons of the theory. In this sense it is similar to QCD in which the gluons carry color charge and unlike the pure U(1) electromagnetic theory in which the bosons, the photons, are not charged. In the electroweak theory the non-Abelian couplings lead to cancellations among the different diagrams. For example, without them the production cross section

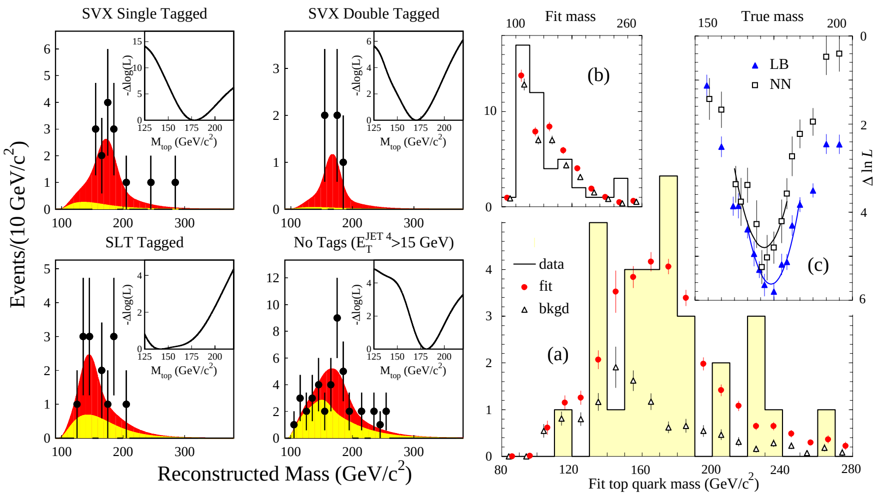


Figure 5. Top mass distributions and the maximum likelihood fits for the leptons + jets channel from CDF(left) and DØ (right).

for several diboson final states would diverge at high energy and would violate unitarity. As they used to say in history books, "this would be a bad thing".

At the Tevatron we are sensitive to the triple boson gauge couplings through the production of boson pairs. Some of the cross sections are very small, indeed within the standard model the cancellations lead to the standard model predicting the smallest possible production cross sections. This means that non-observation gives a limit on any anomalous coupings. The presence of anomalous couplings would also lead to the bosons being produced with a harder transverse momentum spectrum. We therefore search for high transverse momentum boson pairs. So far all the measured cross sections match to the standard model expectations. The results of the measurements are therefore limits.

In Fig. 7 we display an event from DØ which illustrates rather well the distinct signature of a WZ event. The presence of three leptons and the absence of transverse momentum balance is visually very clear. On the other hand only a few tenths of an event were expected in the 100 pb^{-1} of integrated luminosity so if it is a WZ event we were fairly lucky. Further it is very difficult to argue with any certainty that a given event comes from a particular process. On a

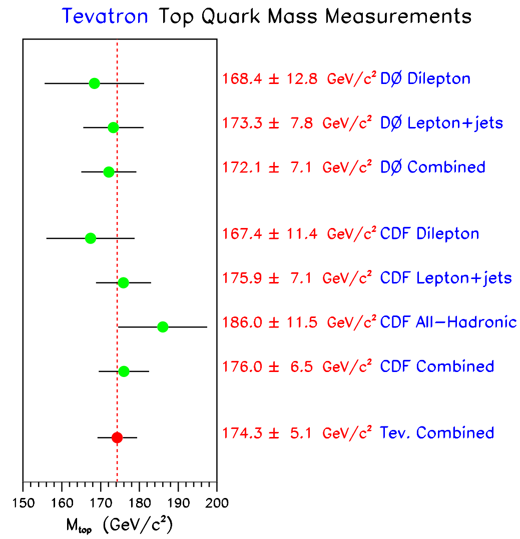


Figure 6. Top mass Measurements from both CDF and DØ and the average which is constructed taking into account correlations.

scale in which the magnetic moment of the W boson is unity, the limits obtained are of the order of a few tenths at 95% confidence level. The mass scale for new physics probed by these measurements is 1.5- 2 TeV.

In order to fully determine the electroweak theory, three parameters are required, for example we often choose the elecromagnetic coupling, the Fermi weak interaction coupling, and the mass of the Z boson. In addition, the masses of the fermions, the quarks and leptons enter through loops. These masses are in some sense trivial aspects of electroweak theory, however its large value promotes the mass of the top quark to great importance. Finally, in order to generate masses for anything, but in particular the W and Z bosons, we postulate a Higgs mass. Given the chosen three measurements, we can predict the mass of the W boson. A measurement of the W boson mass of sufficient precision therefore leads to a check of the self consistency of the theory we are using and, given the mass of the top, can lead to a constraint on the Higgs-boson mass. This is true of other electroweak observables but is particularly transparent in the case of the W boson; we can draw the loops which clearly show how the mass of the top quark and the mass of the Higgs boson should

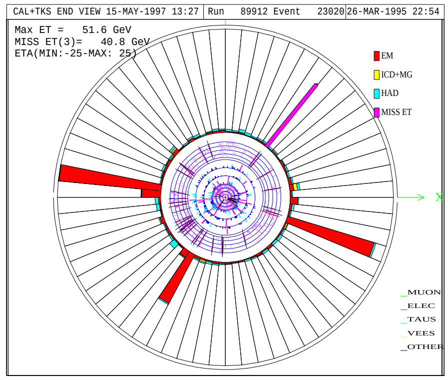


Figure 7. Candidate WZ event from DØ containing three high E_T electrons and missing transverse energy.

contribute.

CDF and DØ have therefore invested some effort in this measurement. At the time of this conference, final measurements existed from DØ using central electrons and preliminary measurements from CDF using muons. Since that time DØ has completed the measurement[12] using the end calorimeters to reduce the measurement uncertainty to less than 100 MeV. This was followed immediately by a CDF result[13] using both electrons and muons. Taken together the measurements from these two experiments and that from UA2 give a combined mass of 80.448 ± 0.062 GeV. This precision, better than 1% from apparati as large as the collider experiments, was predicted, but there is an enormous satisfaction in seeing it achieved. Along with the LEP measurements, which may themselves soon improve, the uncertainty on the W mass is reduced to 44 MeV! The various measurements are shown graphically in the upper part of Fig. 8.

Taken together with the top-quark mass from the previous section, the current picture of the status of the measurements and the constraints on the elec-

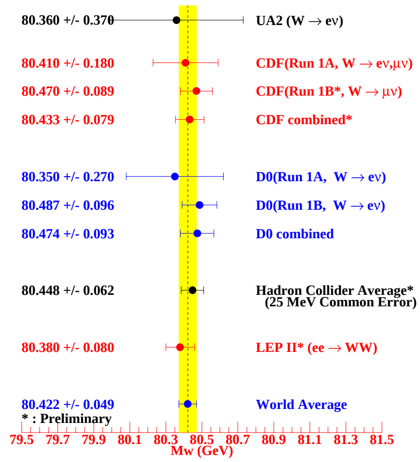


Figure 8. W mass measurements from different experiments.

troweak theory is given in Fig. 9. The optimistic among physicists will rejoice that the Higgs is maybe just around the corner, perhaps behind us, but the serious will notice that the uncertainties on the Higgs-boson mass are still substantial.

5. Searches for the Higgs Boson and New Physics

As we have seen in the previous section, the indications from the current precision measurements of electroweak parameters suggests that the Higgs boson may have a rather low mass. It is also a widely held prejudice that this and other features of the mechanism for electroweak symmetry breaking will become manifest between 100 GeV and 1 TeV. This belief is more general than belief in any of the specific models. CDF and DØ have therefore conducted rather wide ranging searches for new physics, signs of the Higgs boson, supersymmetry and/or technicolor; so far all results have been negative. In this section we only discuss a selected few of these results.

The Higgs boson may be produced by a gluon-gluon fusion mechanism with the subsequent decay to vector boson pairs. For low mass Higgs states this means the decay to photon pairs which has a very low branching ratio and the signal has significant backgrounds associated. An alternative is to search for

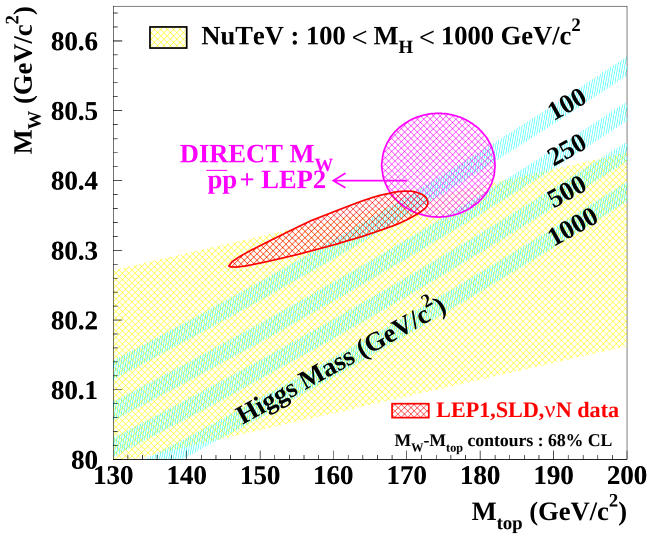


Figure 9. The plane of M_W vs M_t showing the results from indirect measurements dominated by those at the Z pole, the direct measurements from LEP and the Tevatron and the measurement of $\sin^2\theta_W$ from the NuTEV experiment at Fermilab.

associated production of a W boson and the Higgs. If we look for the Higgs decay to a pair of b quarks, the decay of the b quarks may be manifest as either a displaced vertex or as a semi-leptonic decay. The leptonic decays of the W boson then provide further discrimination against background. Such searches have been performed by both CDF and DØ and a collection of the results[15] is shown in Fig. 10. All of the searches look for b-quark decays while different signals are used for the W-boson decay. The upper limits are in the 20 fb range for masses of the putative Higgs boson up to 110 GeV. This is considerably above the standard model expectations, on the other hand there is no-one to say that the standard model is correct. There are those who suggest that there may be a Higgs boson whose decays are entirely to bosons. At low masses this then is 100% to photons. Searches[16] show no sign of such an object and set lower mass limits of about 80 GeV.

As a result of data from HERA(H1 and Zeus) suggesting a possible deviation from expectations at high Q^2, there were some focussed efforts to find evidence for leptoquark states. These have all turned out to be negative[17] and the

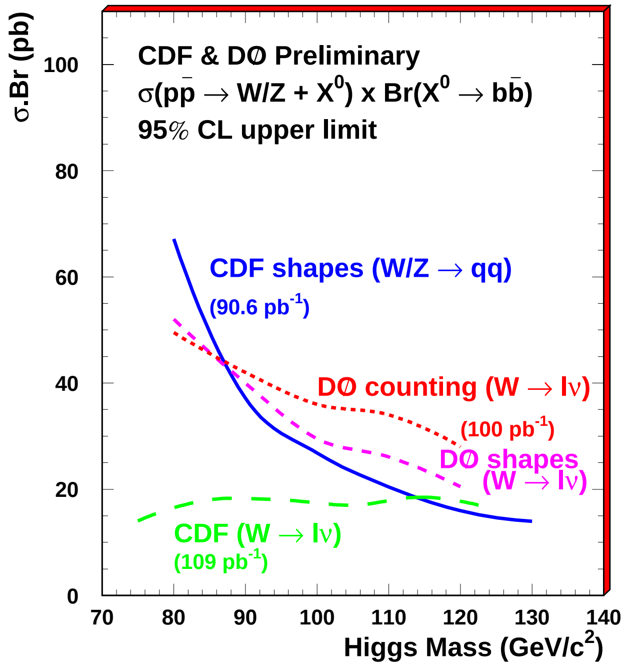


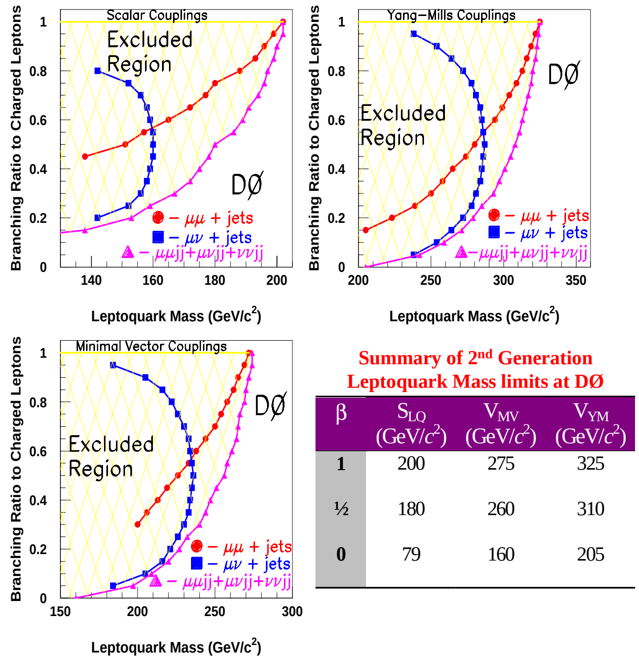
Figure 10. A number of cross section upper limits for associated Higgs boson production from the DØ and CDF experiments.

present lower limits for scalar first generation leptoquarks stand at 242 GeV for the combined CDF and DØ data at 95% confidence level. For second generation leptoquarks the limits are only slightly weaker[18]. The limits from DØ for second generation leptoquarks are collected in Fig. 11.

Reviews of some of these and a number of other measurements have been presented[17] at the ICHEP'99 conference in Vancouver. The briefest of summaries is that with the present reach of the Tevatron Collider data, the lower mass limits for higher mass vector bosons, Z' and W' of different varieties, are in the range of 6-700 GeV.

6. QCD and Compositeness

A couple of years ago, CDF published their measurement[19] of the inclusive jet cross section in the central region. This year DØ completed the reanalysis[20] of their jet energy scale which considerably reduced their uncertainties. The



Summary of 2nd Generation Leptoquark Mass limits at DØ

β	S_{LQ} (GeV/c^2)	V_{MV} (GeV/c^2)	V_{YM} (GeV/c^2)
1	200	275	325
½	180	260	310
0	79	160	205

Figure 11. Second generation leptoquark mass limits from the DØ experiment.

new results[21] of their measurement of the inclusive jet cross section are shown in the upper plot of Fig. 12. On the semilogarithmic scale the description provided by next to leading order perturbative QCD is excellent. A more detailed comparison using three different parton distribution sets is given in the lower half of Fig. 12. We plot the difference between the data and the theory, normalised to the theory as a function of the transverse energy. Again in all cases the description is excellent. In quantitative terms, using all the correlations between the component uncertainties, this conclusion survives.

The excellent agreement between the data and the perturbative QCD predictions can be turned around to search for deviations which might signal the existence of higher scale physics. If one postulates composite quarks at high scales, they could lead to modifications of the interaction Lagrangian at present energies. In particular they could lead to "contact terms" which would modify the observed angular distributions. This possibility was investigated by DØ using the dijet mass distribution measured[22] in two ranges of pseudorapidity, η. The results[22] are illustrated in Fig. 13. The higher mass scale Λ may appear

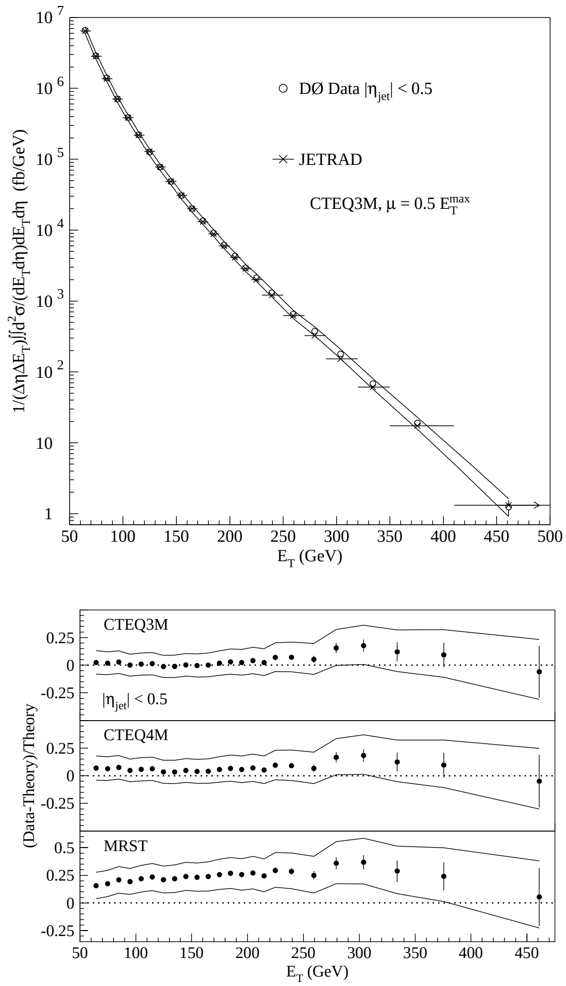


Figure 12. Inclusive jet cross section measured by the DØ experiment compared to a perturbative QCD prediction. The lower plot shows the difference between data and several predictions which are distinguished by different choices of parton distribution functions.

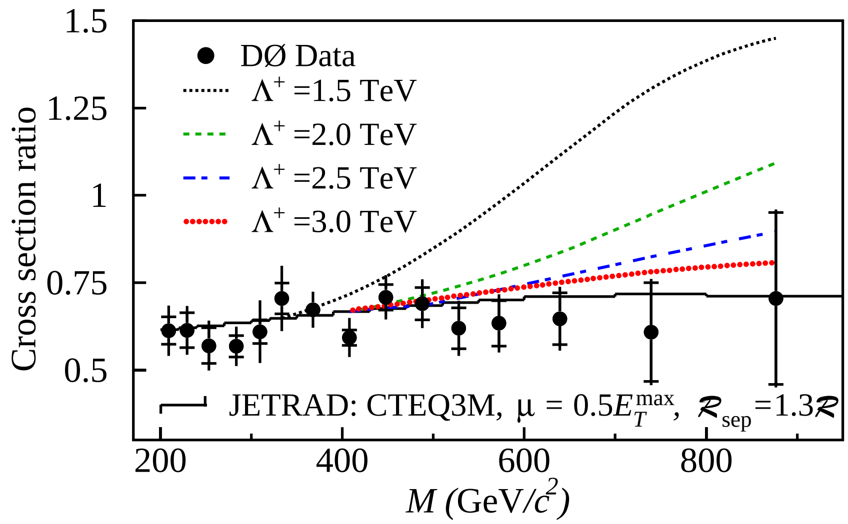


Figure 13. Ratio of the dijet mass cross sections in two different η regions as measured by the DØ experiment. Also shown are the expectations for deviations as a result of putative contact terms arising from higher scale interactions

with different coupling forms of which only one is illustrated here. We can see that low scales, for example $\Lambda = 1.5$ TeV are easily excluded by the data but as the mass increases, its influence becomes less and less and eventually the data cannot distinguish between the original QCD and the modified theory. These studies set lower limits in the range $\Lambda \simeq 3$ TeV depending on the detailed form of the coupling.

A similar approach can be taken to the production of lepton pairs. This process is usually known as "Drell-Yan" production. In order for the process to be sensitive to the postulated higher scale interaction or compositeness scale that compositeness must lead to some of the constituents of the lepton and of the quark being in common. The data from CDF are shown in Fig. 14 and those from DØ in Fig 15. In each case the Z peak is prominent and there is the long tail and the Drell-Yan cross section at high masses. We also display the expected deviations as a result of the higher scale interactions. Using these data lower mass limits of $\Lambda \simeq 5 - 6$ TeV are obtained

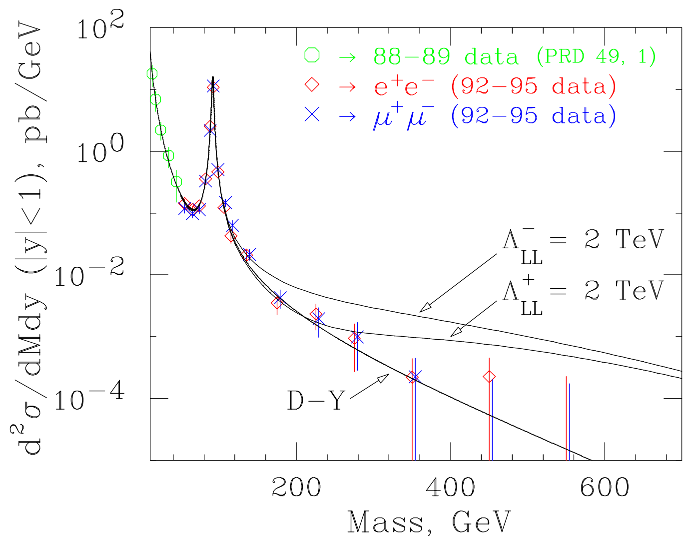


Figure 14. Drell-Yan measurements from CDF.

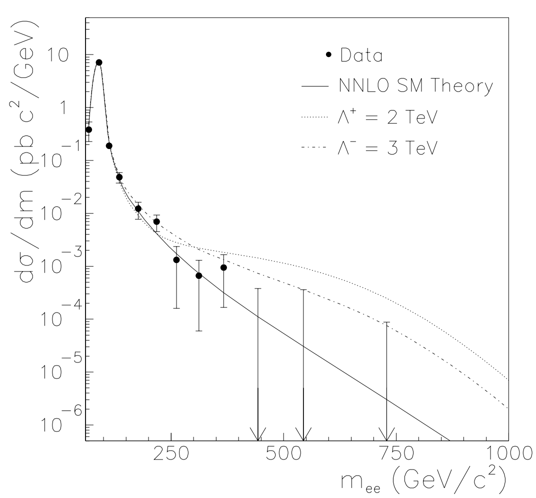


Figure 15. Drell-Yan measurements in the electron channel from DØ .

7. Conclusions

In this paper we have covered some of the more recent of the continuing series of results from the enormously successful data taking period from 1992-96 at the Fermilab Tevatron Collider. The continued production of results has to compete with frenzied preparations of the machine and the upgraded detectors for operation in the year 2000. The initial plans are for running at higher luminosity with a goal of integrating 2-4 pb^{-1}. There are also intentions to fully exploit the potential of both the detectors and the machine in the period between 2000 and at least the start of operation of the Large Hadron Collider. Extrapolation of the present experience promises major advances in both the precision of mass measurements, those of the W boson and the top quark, and the extension of searches to cover the region up to 1 TeV. For low cross section processes such as Higgs production the reach is thought to extend beyond 150 GeV.

Acknowledgements

I would especially like to thank my Russian colleagues on both DØ and and CDF and the organisers of this very enjoyable and interesting conference. This work was supported by the United States Department of Energy under Contract No. DE-AC02-76CHO3000.

References

1. CDF Collaboration Home Page, *http://www-cdf.fnal.gov/*
2. DØ Collaboration Home Page, *http://www-d0.fnal.gov/*
3. DØ Collaboration, " Forward Rapidity Muon and b-quark Production in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV, Paper #453 submitted to the XXIX Inter-

national Conference on High Energy Physics - ICHEP98, July 23-29, 1998, Vancouver, B.C., Canada.

4. F. Abe *et al.*, CDF Collaboration, Phys. Rev. Lett. 81, 5513 (1998).
5. S.S.Gershtein, V.V. Kisilev, A.K. Likhoded, A.V. Tkabladze, Uspeki Phys. Nauk. 165 (1995) pp 3-40. IHEP 94-81, 1994.
6. F. Abe *et al.*, The CDF Collaboration, Phys. Rev. Lett. 81, 5513 (1998).
7. CDF Collaboration, *http://www-cdf.fnal.gov/physics/new/bottom/cdf4855/cdf4855.html.*
8. B. Abbott *et al.*, DØ Collaboration, Phys. Rev. Letters 79 1203 (1997).
9. B. Abbott *et al.*, DØ Collaboration, FERMILAB PUB-98/130-E, hep-ex/9808034, to be published in Phys. Rev. D.
10. F. Abe *et al.*, The CDF Collaboration, Phys. Rev. Lett. 80, 2773 (1998).
11. *http://www-d0.fnal.gov/public/top/top_public.html.*
12. Ashutosh Kotwal, DØ Collaboration Fermilab Seminar, February 26 1999, *http://www-d0.fnal.gov/~skulik/Public/wmass/index.html.*
13. Young-Kee Kim, CDF Colaboration, Fermilab Seminar, March 19 1999, *http://www-cdf.fnal.gov/physics/ewk/wmass global.html*
14. F. Abe *et al.*, The CDF Collaboration, Phys. Rev. Lett. 81, 5748 (1998).
15. J. Hobbs, private communication.
16. B. Abbott *et al.*, DØ Collaboration, Phys. Rev Lett. 15, 2244 (1999).
17. C. Grosso-Pilcher, The CDF Collaboration, FERMILAB-CONF-98/306-E. Published Proceedings 29th International Conference on High Energy Physics (ICHEP 98), Vancouver, British Columbia, Canada, July 23-29, 1998.

18. D. Karmgard, Talk presented to the Division of Particles and Fields Conference, U.C.L.A., January, 1999.

19. F. Abe *et al.*, The CDF Collaboration, Phys. Rev. Lett. 77, 438 (1996).

20. B. Abbott *et al.*, DØ Collaboration,Nucl. Instr. and Methods A424, 352 (1999).

21. B. Abbott *et al.*, DØ Collaboration, Phys. Rev. Lett. 82 2451 (1999).

22. B. Abbott *et al.*, DØ Collaboration,Phys. Rev. Lett. 82 2457 (1999).