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Tevatron: Recent results and prospects at the upgrade

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Abstract. In this article, we review some of the recent results from CDF and DØ experiments at the Tevatron and their prospects at the upgrade. Among the topics discussed are top quark physics, electroweak physics, qcd physics and new physics beyond standard model.

Keywords. Tevatron; top quark mass; W-boson; QCD jets; supersymmetry.

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1. Top quark physics

In $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\text{TeV}$, top and anti-top quarks are predominantly pair produced through $q\bar{q}$ annihilation ($\approx 90\%$) or gluon fusion ($\approx 10\%$). The predicted theoretical cross section for $t\bar{t}$ production at Tevatron is estimated to be around 4.75–5.5 pb. In the run I covering the period 1992–1996, both DØ and CDF have collected data exceeding $100\,\text{pb}^{-1}$ of integrated luminosity each. One therefore expect about 500 $t\bar{t}$ pairs produced in each experiment. In the standard model, due to their large mass, they decay before they can even hadronize to a W boson and a b quark. The subsequent W decay determines the signature of $t\bar{t}$ decay. In the dilepton channel both W bosons decay either to $e\nu$ or to $\mu\nu$. The branching fraction for this channel is only $4/81$, however has the advantage of small backgrounds. In the lepton + jets channel, one W boson decays to $e\nu$ or $\mu\nu$ and the other hadronically. The branching fraction is $24/81$. The dominant source of background for this channel is $W+$jets production. In the all jet channel, both W decay hadronically. Although this channel has the largest branching fraction, it also has a much larger background contribution.

1.1 *Top cross section*

The $t\bar{t}$ production cross section for each channel is given by

$$\sigma = \frac{N - B}{\varepsilon_{\text{total}} L},$$

where N is the number of observed events, B is the number of expected background events, L is the integrated luminosity and $\varepsilon_{\text{total}}$ is the total acceptance consisting of the b-tagging efficiency, the geometric and kinematic acceptances as well as the branching fraction and the trigger efficiency. The signature of the dilepton channel consists of two isolated high p_T leptons, two or more jets, and large $\not{E}_T$. The signature of the lepton + jets channel consists of one isolated high p_T lepton, $\not{E}_T$ due to the neutrino and several jets. In these events, jets are produced by the hadronization of two b quarks and the two quarks from the hadronic W decay. In addition, both DØ and CDF puts additional criteria to suppress the $W+$ jets background. CDF identifies jets coming from b quarks either by identifying a secondary vertex using the silicon vertex detector (SVX tagging) or by identifying an additional lepton (e or μ) due to the semileptonic decay of one of the b quarks (SLT). DØ also puts two additional criteria to suppress the $W+$ jets background. In one method, it requires a jet to be associated with a taged muon as evidence of the semileptonic decay of a b-quark. In the second method, it exploits the difference in event topology and kinematics between $t\bar{t}$ and background. In table 1, we present the summary of the current measurement of $\sigma_{t\bar{t}}$ by CDF and DØ [4] in various channels.

1.2 *Top quark mass*

DØ and CDF have measured the top quark mass in the lepton + jets [1], dilepton [2] and all hadronic channels [3]. The lepton + jets final states give the most precise value. The event selection criteria for the mass analysis are slightly different than those used for cross section measurement. Also the detailed criteria have some differences among the various channels and between DØ and CDF. The important criteria are listed here. Lepton + jets candidates must have a single, isolated electron or muon with high transverse momentum ($P_T > 20\,\text{GeV/c}$), large $\not{E}_T$ ($> 20\,\text{GeV}$), and at least four jets. Dilepton final state candidates must have at least two isolated high-P_T leptons, large $\not{E}_T$, and at least two jets. All jet events must have at least six jets, at least one of which is tagged.

1.2.1 *Lepton + jets analysis*: The top mass analysis rely on kinematic fitting to assign a mass value for each top candidate. A likelihood fit is then performed to extract a top mass from the observed distribution of mass values. CDF divide the event samples into four non-overlapping subsample: events with two SVX tags, events with single SVX tag, events

Table 1. Summary of current CDF and *DØ* measurements on $\sigma_{t\bar{t}}$ in various channels.

Experiment	Channel	$\varepsilon\times$ BR(%)	Data	Background	$\sigma_{t\bar{t}}$ (pb)
CDF	Dilepton	0.74 ± 0.08	9	2.1 ± 0.4	$8.5 + 4.4 - 3.4$
	$l+$jets (SVX)	3.5 ± 0.7	34	8.0 ± 1.4	$6.8 + 2.3 - 1.8$
	$l+$jets (SLT)	1.7 ± 0.3	40	24.3 ± 3.5	$8.0 + 4.4 - 3.6$
	Combined	—	83	33.4	$7.5 + 1.9 - 1.6$
	Had^1	4.4 ± 0.9	187	142 ± 12	$9.6 + 4.4 - 3.6$
	Had^2	3.0 ± 0.9	157	120 ± 18	$11.5 + 7.7 - 7.0$
	Had^{1+2}	—	—	—	$10.1 + 4.5 - 3.6$
DØ	ll (with $e\nu$)	0.91 ± 0.17	9	2.6 ± 0.6	6.4 ± 3.4
	$l+$jets (topol.)	2.17 ± 0.46	19	8.7 ± 1.7	4.1 ± 2.1
	$l+$jets/μ	0.96 ± 0.15	11	2.4 ± 0.5	8.3 ± 3.6
	Combined	4.14 ± 0.69	39	13.7 ± 2.2	5.6 ± 1.8
	All jets	1.8 ± 0.4	44	25.3 ± 3.1	7.9 ± 3.5

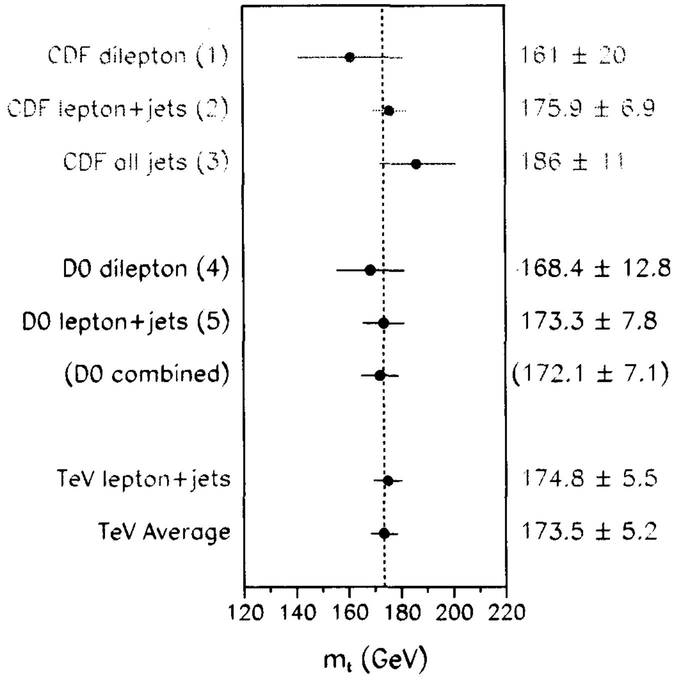

Figure 1. Summary of the top mass measurements from DØ and CDF.

with an SLT tag and no SVX tag and events with no tag. These four subsets are analysed independently. Combining the likelihoods gives an overall top mass of 175.9 ± 4.8 ± 4.9 GeV. DØ uses a 2-dimensional likelihood fit to extract the top mass. One axis of the 2-dimensional distribution is the best 2-C fit mass and the other is a multivariate top discriminant. To show the robustness of the analysis, two different top discriminant D_{LB} (low bias) and D_{NN} (neural network) are used for the above mentioned 2-dimensional likelihood fits. From the 90 DØ top candidates, 77 are used for the mass fit, of which 5 are μ tagged and $\approx 65\%$ are background. The LB and NN results m_t^{LB} and m_t^{NN} are mutually consistent. The combined result, which has $88 \pm 4\%$ correlation, is $173.3 \pm 5.6 \pm 6.2$ GeV/c^2.

1.2.2 *Dilepton results*: CDF and DØ has 8 and 6 dilepton top candidates respectively used for mass analysis. CDF use two methods to extract top mass from the dilepton events. The first method fits the distribution of jet energies for the two highest E_T jets in the event. The other method fits the distribution of the lepton $+b$-jet invariant mass. The combined top mass from these two methods is $161 \pm 17 \pm 10$ GeV/c^2. DØ also use two different methods (MWT and νWT) and use the zero constraint kinematic calculation to get a weighted mass plot for each candidate event. The two methods differs in the way the weights are calculated. In the MWT method, one calculates the weight using the parton distribution functions and the probability density of the lepton energy in the top rest frame. In νWT method, the weight depends on the phase space of the two neutrinos. The combined DØ dilepton top mass from the above two methods is $168.4 \pm 12.3 \pm 3.6$ GeV

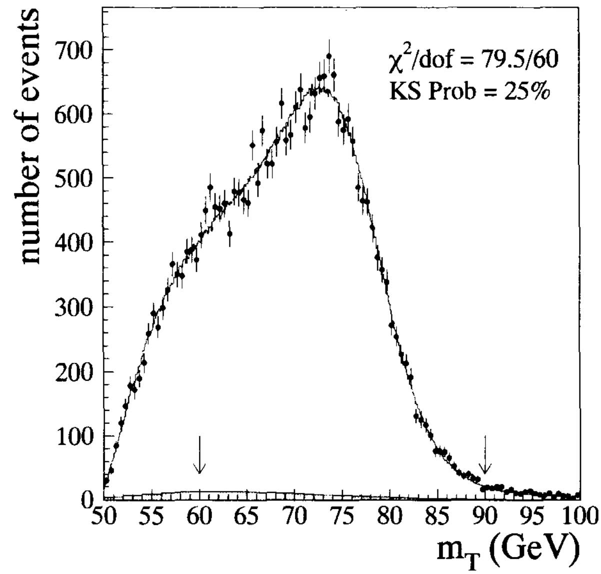

Figure 2. DØ transverse mass distribution of $W \rightarrow e\nu$ decays collected during the 1994–1995 run. The points are the data and the line is the best fit.

1.2.3 *All jets results*: CDF all jet sample consists of 136 events of which the estimated background is 108 events. The likelihood fit to the best mass distribution gives a top mass of $186 \pm 10 \pm 12$ GeV/c^2.

In figure 1 we summarize all the measurements on top mass from DØ and CDF.

2. Electroweak physics

2.1 *Measurement of W mass*

Both CDF and DØ W mass analysis presented here are based upon the run 1 data, with CDF analysis based on W decay into muons and the DØ analysis based on electrons. In the CDF W mass analysis the momentum scale of the central magnetic tracker is set by scaling the measured J/ψ mass to the world average value using $J/\psi \rightarrow \mu^+\mu^-$ decays. At DØ currently the W mass is measured from $W \rightarrow e\nu$ decays and the corresponding electromagnetic scale is determined by calibrating to the $Z \rightarrow ee$ resonance in conjunction with the reconstruction of π^0 and J/ψ decays. After the energy scale has been set, the W mass is determined from a maximum likelihood fit of Monte Carlo generated templates in the transverse mass to the data distribution. Both CDF and DØ use only central leptons to determine the W mass. Figure 2 shows the transverse mass distribution for the data together with the best fit of the Monte Carlo for the run 1B electron data for DØ. The W mass is determined to be 80.450 ± 0.070 (stat) ± 0.100 (syst) GeV/c^2 by DØ and 80.430 ± 0.100 (stat) ± 0.120 (syst) GeV/c^2 by CDF. Combining these measurements with previous W mass measurements gives a combined Tevatron average W mass $M_W = 80.41 \pm 0.09$ GeV/c^2. Figure 3 summarizes the current status of the W mass measurements.

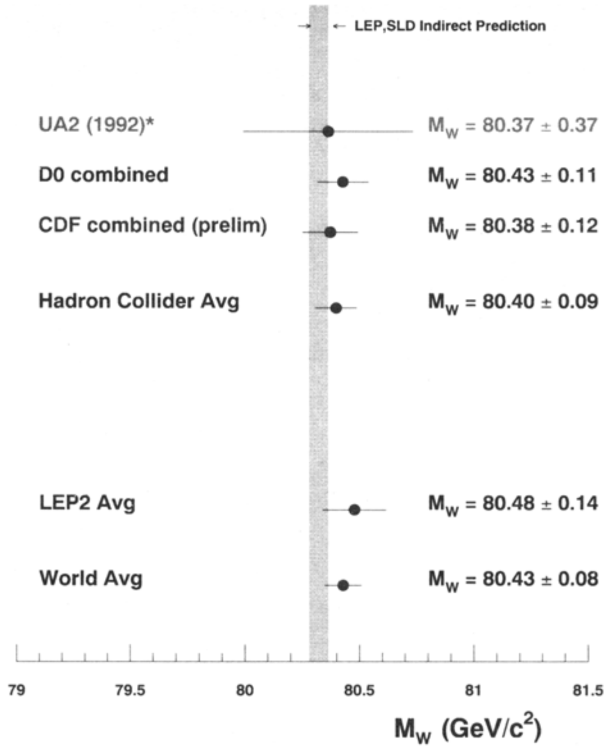

Figure 3. Summary of the W mass measurement.

3. QCD physics

3.1 *Inclusive jet cross section*

In 1996 CDF collaboration published the inclusive jet cross section measurement using run 1A data [5]. It shows an excess of events at high E_T. The preliminary CDF run 1B measurement also shows the same feature. Both measurements are compared with theoretical predictions in figure 4. However during 1997, DØ collaboration presented their new inclusive jet cross section measurement which include a new jet energy scale and significantly reduced systematic uncertainties [6]. DØ data (figure 5) shows good agreement with theory. Since CDF and DØ experiments have used different η ranges (CDF measurement is in the $|\eta|$ range $0.1 \leq |\eta| \leq 0.7$ while DØ measurement covers $|\eta| < 0.5$) and have different choices for the theoretical parameters, it is difficult to compare the two results directly. In order to determine, if the DØ and CDF data agrees with one another, DØ has redone the jet analysis in the rapidity range (0.1–0.7) used by CDF and fit the results to a smooth curve. This was then compared to the CDF Run 1B measurement. The two measurements seem to be consistent in shape as well as in normalization to one another within the experimental systematic uncertainties (figure 6). It is to be noted that the theoretical calculation itself has several uncertainties (renormalization and factorization scales, clustering algorithem, parton distributions) and also it is possible to accomodate the CDF high E_T

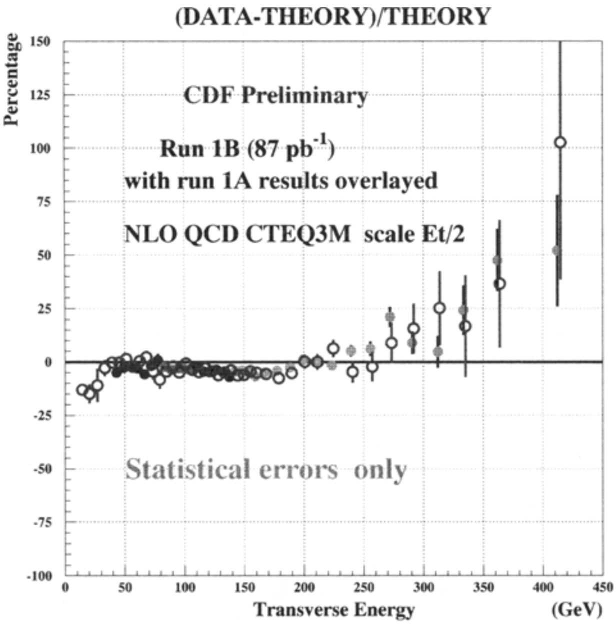

Figure 4. CDF measurements of the inclusive jet E_T spectrum at $\sqrt{s} = 1.8\,\text{TeV}$, for $0.1 \geq |\eta| \geq 0.7$.

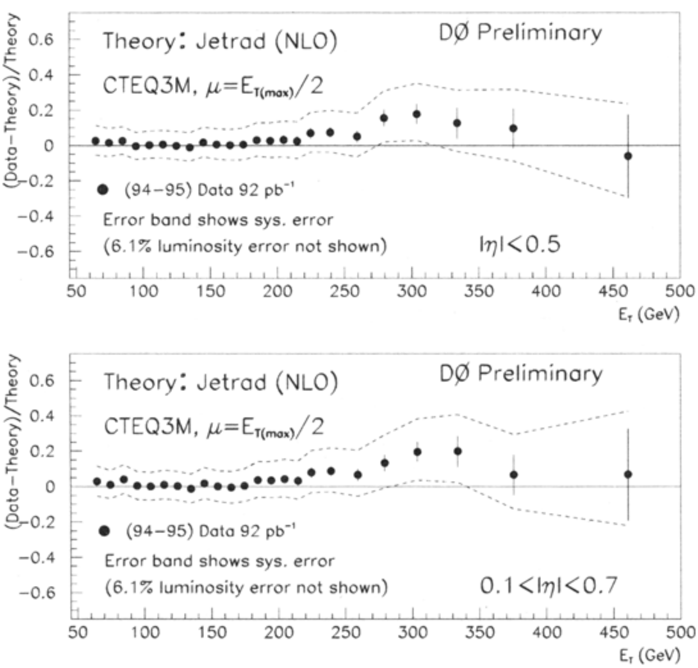

Figure 5. 5. DØ measurements of the inclusive jet E_T spectrum at $\sqrt{s} = 1.8\,\text{TeV}$, for $|\eta| \geq 0.5$ (top) and $0.1 \geq |\eta| \geq 0.7$ (bottom).

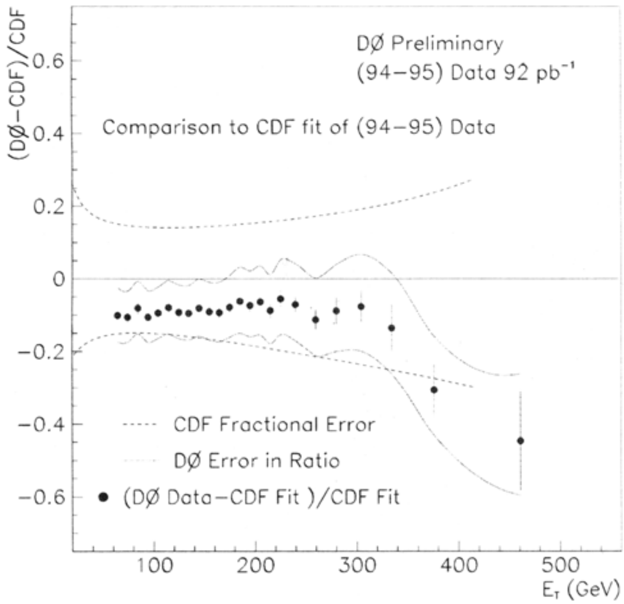

Figure 6. Direct comparison of the measured CDF and DØ inclusive jet E_T spectra at $\sqrt{s} = 1.8\,\mathrm{TeV}$.

excess by a modification of the gluon distribution function at large x. Such a modification would not be incompatible with other experimental data entering global parton distribution fits. This has been shown by the CTEQ collaboration's CTEQ4HJ fit [7].

3.2 *Dijet angular distribution*

CDF [8] and DØ [9] have both measured the dijet angular distribution. This shape is dominated by the t-channel exchange and is nearly identical for all the dominant subprocesses. Both experiments use the variable $\chi = 1 + |\cos\theta^*|/1 + |\cos\theta^*|$ for this measurement as the angular distribution is expected to be flat for this variable. Most new physics however predict an angular distribution which would produce a peak at low χ. Figure 7 shows DØ data compared to JETRAD predictions for different mass bins. CDF dijet angular distribution data exclude at the 95% C.L. a contact interaction scale of $\Lambda^+_{ud} \leq 1.6\,\mathrm{TeV}$ and $\Lambda^-_{ud} \leq 1.4\,\mathrm{TeV}$. For a model where all quarks are composite $\Lambda^+ \leq 1.8\,\mathrm{TeV}$ and $\Lambda^- \leq 1.6\,\mathrm{TeV}$. The corresponding results from DØ with μ (jet energy scale) $= E_{T\max}/2$ are $\Lambda^-_{ud} \leq 2.2\,\mathrm{TeV}$, $\Lambda^- \leq 2.4\,\mathrm{TeV}$, $\Lambda^+ \leq 2.3\,\mathrm{TeV}$.

3.3 $W + 1$ *jet to* $W + 0$ *jet cross section ratio*

A preliminary measurement of the ratio of the production cross sections for $W + 1$ jet to $W + 0$ jet as a function of the mimimum jet E_T ($E_T^{\min}$) has been made by the DØ collaboration [10]. Figure 8 compares the result to predictions using the CTEQ4M and MRSA parton distribution function. The theoretical predictions are however all consistently

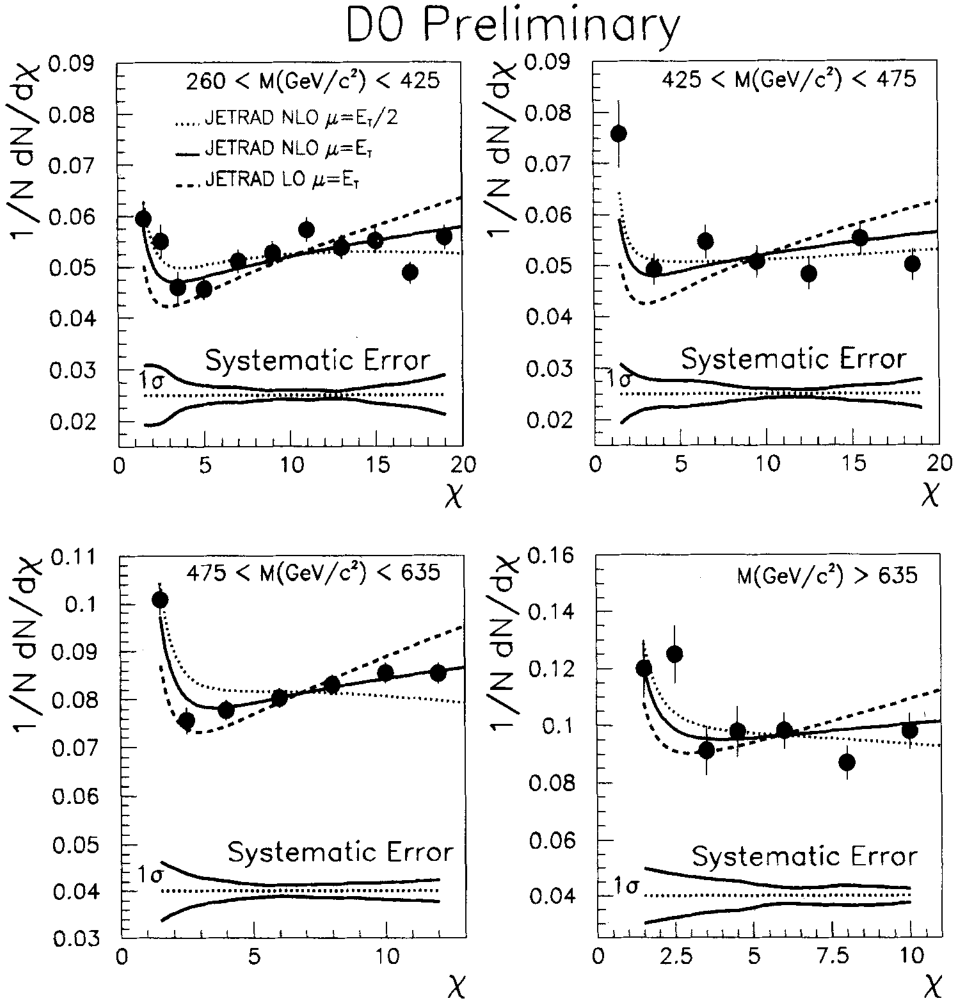

Figure 7. Dijet angular distribution as measured by DØ for different mass ranges as compared to LO and NLO QCD predictions.

below the data. Recently CDF [11] has completed a similar analysis by measuring the ratio of inclusive cross sections $R_{10} \equiv \sigma\ (W+ \geq 1\ \text{jet})/\sigma(W)$ as a function of minimum E_T requirement on the jet. CDF measurement agrees with the prediction for $E_T^{\min} > 25$ GeV. The difference between the CDF and DØ measurement include the jet cone radius (0.4 for CDF, 0.7 for DØ) and also CDF measurement is inclusive where as DØ measurement is exclusive.

4. New physics

4.1 *Search for leptoquarks*

Leptoquarks are particles having both lepton and color quantum numbers; they are color triplet bosons with fractional charge. Recently, leptoquarks came into prominence due to

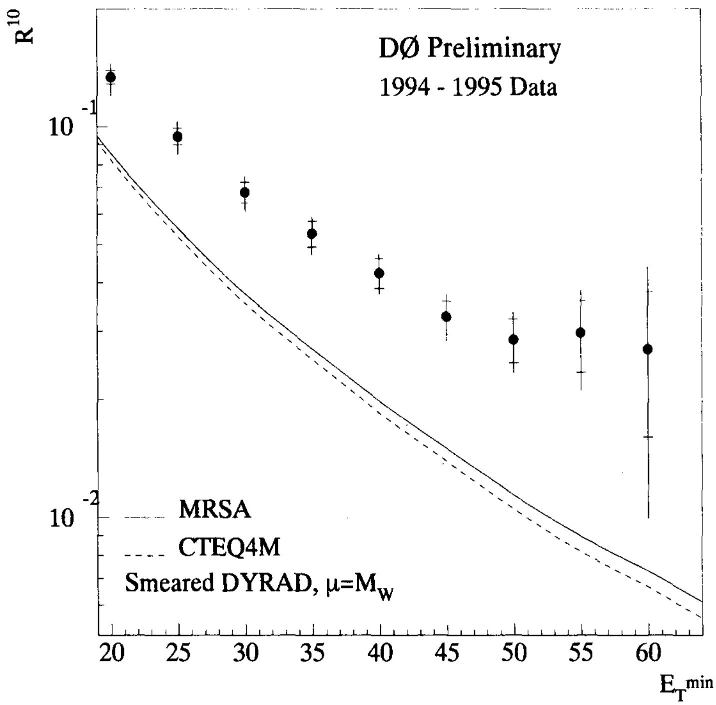

Figure 8. $W+1$ jet to $W+0$ jet cross section ratio at $\sqrt{s}=1.8$ TeV as measured by DØ compares to DYRAD predictions using CTEQ4M and MRSA′ pdf's.

Table 2. Summary of current CDF and DØ mass limits on scalar leptoquarks for various values of β.

Experiment	β	Channel	Mass limit (GeV/c^2)
		First generation scalar	
CDF	1	*eejj*	213
CDF	$\frac{1}{2}$	$e\nu jj$	180
DØ	1	*eejj*	225
DØ	$\frac{1}{2}$	*eejj* and $e\nu jj$	204
Combined	1	*eejj*	242 GeV
		Second generation scalar	
CDF	1	$\mu\mu jj$	197
CDF	$\frac{1}{2}$	$\mu\mu jj$	133
DØ	1	$\mu\mu jj$	184
DØ	$\frac{1}{2}$	$\mu\mu jj$	140
		Third generation scalar	
CDF	1	$\tau\tau jj$	99
DØ	0	$\nu\nu bb$	94

the observation of several high mass events at Hera, which could be explained due to the production of leptoquarks. At Tevatron collider, leptoquarks are expected to be pair produced. A leptoquark will decay with an unknown coupling, λ to a lepton and a quark. It is normally assumed that the leptoquarks follow the quark-lepton generation index or in other words, leptoquarks of one generation couple exclusively to leptons and quarks of the same generation. At Tevatron, since the leptoquarks are produced in pairs, their signature would be two leptons plus two or more jets. The branching fraction of the leptoquarks to charge lepton plus quark, β is assumed to be a free parameter. Both CDF [13] and DØ [12] have searched for all the three generations of leptoquark. Summary of current Tevatron leptoquark 95% C.L. mass limits for scalar leptoquarks are shown in table 2 as a function of leptoquark generation and the branching fraction β into charge lepton plus quark. DØ has also obtained 95% C.L. mass limits on the mass of a first generation vector leptoquark. These limits are 200, 325 and 340 $\mathrm{GeV/c^2}$ for $\beta = 0.0$, 0.5 and 1.0 respectively.

4.2 *Search for supersymmetry*

DØ has recently reported two new searches, one using the dielectron data [14] and the other using the multijet data, for SUSY particles within the SUGRA-GUT framework, which has only five free parameters. These five parameters are: a common SUSY breaking scalar mass (m_0), a common gaugino mass ($m_{1/2}$), a common value for all trilinear coupling (A_0), the ratio of the vacuum expectation values of the two Higgs fields ($\tan\beta$) and the sign

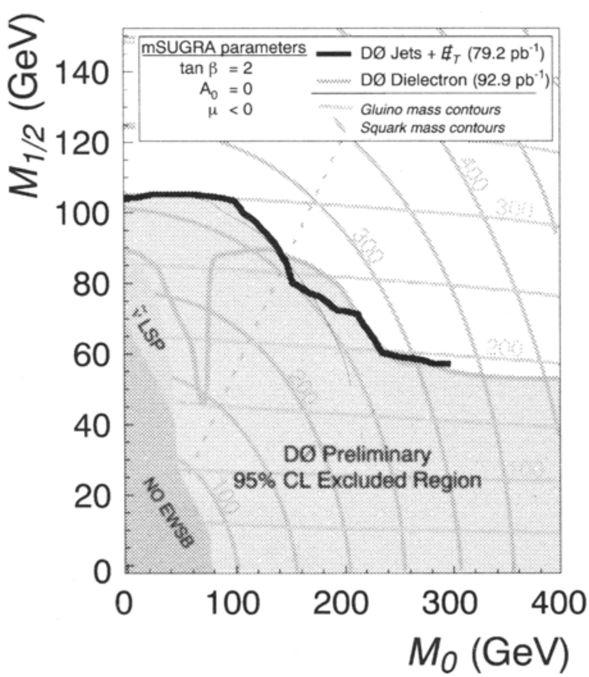

Figure 9. The exclusion contour in the $m_0 - m_{1/2}$ plane with A_0, $\tan\beta$, and $\mathrm{sgn}(\mu)$ fixed at 0, 2, and -1 respectively from DØ dielectron as well as multijet analysis.

of μ, where μ is the Higgsino mass mixing parameter. Squarks and gluinos are normally expected to decay to final state quarks and LSPs. This will give rise to canonical multijet $+\not{E}_T$ signature. However for higher mass squarks and gluinos, there are additional decay channels through chargino and neutralino intermediate states. In addition to hadronic decays, these charginos and neutralinos can also decay leptonically. Leptonic SUSY searches, using isolated leptons, jets and $\not{E}_T$ therefore compliments the SUSY particle searches using only jets and $\not{E}_T$. Till now both the searches mentioned above have produced null results which are used to exclude the SUSY parameter space in the m_0–$m_{1/2}$ plane for fixed values of A_0 (0), tanβ(2) and μ (negative). Figure 9 shows the exclusion coutours at 95% C.L. for the dielectron as well as for the all-jet channel.

5. Future prospect

The Tevatron collider have produced a wealth of physics results over the last several years including the discovery of top quark. The next Tevatron run is scheduled to start in March 2000. The Tevatron collider is now being upgraded for the next run. The C.M. energy will be increased from 1.8 to 2 TeV. This will enhance the $\sigma_{t\bar{t}}$ by about 35%. The integrated luminosity to be collected by each experiment will be increased from the present $100\,\text{pb}^{-1}$ to about $2\,\text{fb}^{-1}$. Both CDF and the DØ detectors are presently going through major upgrades. As a result of all these, both the experiments are expected to pursue many exciting physics in run II. In top quark physics with about 40 times more data sample, it is expected that its mass will be measured to $\Delta M_{\text{top}} < 4\,\text{GeV/c}^2$ and $\Delta\sigma/\sigma \approx 9\%$ and will perform detailed survey of top quark properties. In electroweak sector, each experiment will collect about 4 M $W \to l\nu$ and 600 K $Z \to l^+l^-$ events and is expected to measure the W mass to an accuracy of $40\,\text{GeV/c}^2$. In QCD physics, CDF and DØ are expected to test higher order QCD calculations using the production and fragmentation properties of jets, probe the Drell–Yan lepton production, direct photons and W/Z production to higher precision. Upgraded DØ and CDF detectors will also address many issues in B physics ranging from QCD tests involving production dynamics through the mass spectrum of the B_c system, rare decay modes, B_s mixing and CP violation. In particular one is expected to measure $\sin 2\beta$ to $\Delta \sin 2\beta \approx 0.13$ using the $B^0 \to \psi K_s^0$ events and $\sin 2\alpha$ to $\Delta \sin 2\alpha \approx 0.14$. In new physics, it is expected to probe the SUSY particles and leptoquarks of masses of up to $300\,\text{GeV/c}^2$ and W' and Z' masses to up to 1 TeV. It is therefore certain that the next Tevatron run will be as exciting as the last one.

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