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Quarks and Gluons at Hadron Colliders

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Data from proton-antiproton collisions at high energy provide important information on constraining the quark and gluon distributions in the nucleon and place limits on quark substructure. The W asymmetry data constrains the slope of the d/u quark distributions and significantly reduces the systematic error on the extracted value of the W mass. Drell-Yan data at high invariant mass provides strong limits on quark substructure. Information on α_s and the gluon distributions can be extracted from high Pt jet data and direct photons.

1 Introduction

The significant increase in the quantity and quality of data from run 1 at the Fermilab collider implies that collider data can now place strong constraints on α_s, and provide new information on quark and gluon distributions in the nucleon. The high Q^2 collider data also is sensitive to quark substructure and provides limits on quark compositeness.

2 W Charge Asymmetry, W mass, and the Slope of d/u

W^+ (W^-) bosons are produced in $p\overline{p}$ collisions primarily by the annihilation of u (d) quarks from the proton and $\overline{d}$ ($\overline{u}$) quarks from the antiproton. Because the u quark tends to carry a larger fraction of the proton's momentum than the d quark the W^+ (W^-) tends to be boosted in the proton (antiproton) direction. The charge asymmetry in the production of W's, as a function of rapidity, is therefore related to the difference in the quark distributions at very high Q^2 ($\approx M_W^2$) and low x ($0.007 < x < 0.24$).

The W decay involves a neutrino, whose longitudinal momentum is undetermined. Therefore the quantity measured is the charge asymmetry of the decay leptons, which has an added contribution due to the V-A decay of the W. This portion of the asymmetry has been well measured by muon decay experiments; thus in comparisons to theory, one can attribute any deviations (between prediction and measurement) to the parton distributions used in the calculations. The asymmetry is defined as:

$$A(y_l) = \frac{d\sigma^+/dy_l - d\sigma^-/dy_l}{d\sigma^+/dy_l + d\sigma^-/dy_l} \tag{1}$$

where $d\sigma^+$ ($d\sigma^-$) is the cross section for W^+ (W^-) decay leptons as a function lepton rapidity (positive rapidity is defined in the proton beam direction). As long as the acceptance and efficiencies for detecting l^+ and l^- are equal, this ratio of cross sections becomes simply the difference in the number of l^+ and l^- over the sum. Further, by CP invariance, the asymmetry at positive η is equal in magnitude and opposite in sign to that at negative η. Therefore the value at positive η is combined with that at negative η reducing the effect of any differences in the efficiencies for l^+ and l^-.

The asymmetry is sensitive to the ratio of d and u quark distributions to $x < 0.01$ at $Q^2 \approx M_W^2$, where nonperturbative effects are minimal.

The charge asymmetry as a function of lepton rapidity, $A(y_l)$, has been previously measured by the CDF collaboration [3] at $\sqrt{s} = 1.8$ TeV for $|y_l| < 1.8$, using the W decays to electrons and muons recorded by CDF during the Run 1A run of the Tevatron Collider [4]. The integrated luminosity used in the published run 1A analysis, approximately 20 pb^{-1}, and detector improvements resulted in a seven fold increase in statistics relative to the 1988-89 data [5]. The increased statistics in the Run 1A data allowed for the first time to use collider data for the discrimination between sets of modern parton distribution functions. It was found at that time that of the two sets of of parton distributions, those of Martin, Roberts and Stirling (MRS [6]) were favored over the sets produced by the CTEQ [7] collaboration. This difference was observed even though both sets were found to agree, at the level of the nuclear shadowing corrections, with the recent measurements of F_2^n/F_2^p performed by NMC [8]. The W asymmetry data provided a stronger constraints on d/u ratio than the recent measurements of $F_2^{\mu n}/F_2^{\mu p}$ which are limited by uncertainties originating from deuteron corrections. The results of this analysis have demonstrated the value of collider data in the measurement of the proton's structure. The most recent parton distribution fits by both Martin, Roberts, and Stirling (MRS [6]), and CTEQ [7] now include the CDF 1A data in their fits.

In the most recent measurement by CDF, the dataset used in the W lepton charge asymmetry analysis has been significantly increased. First, data from Run 1B (94/95) corresponding to an additional 91 pb^{-1} of integrated luminosity has been included. Secondly, the data sample in the forward pseudorapidity region between 1.2 to 1.8 has been doubled, and extended to higher values of η. This was accomplished by including, in addition to events for which charge of the electron is measured using the standard central tracking information, events in the forward direction for which the electron charge was measured using a combination of stand-alone silicon SVX track finder in conjunction with a shower cluster centroid position from the strips and pads in the plug electromagnetic calorimeter. In addition, data from the forward muon detector has been included.

In CDF, positively charged particles are bent in the increasing ϕ direction, and negatively charged particles are bent in the decreasing ϕ directions. Thus the charge of electrons can then determined by comparing the ϕ_{SVX} measured with Silicon Vertex Detector, with ϕ_{PEM} measured with the Plug Electromagnetic Strips. Figure 1 shows the distribution of $\delta\phi_{measured}/|\delta\phi_{expected}|$ the plug W electron sample. The charge mis-identification for η between 1.2 and 1.8 is estimated to be on average $0.80 \pm 0.2\%$. Above η of 1.8 it is about 5%.

These new preliminary W charge asymmetry results are compared with theoretical predictions of various parton distribution functions (PDFs) using a NLO calculation [13] in Figure 2. The reduced statistical errors have greatly increased the differentiating power between modern PDFs. However, there are differences between the NLO theory and that data in the forward direction, and indicate the need for further tuning of the d/u ratio at smaller value of x. Note that the difference between data and theory in the forward direction becomes even worse when a resummation [14] calculation is used. Figure 3. shows a comparison of the data with the predictions of the MRSA parton distribution using both the NLO and the resummed calculations. A comparison between data and the resummation calculation for other structure functions is currently being performed.

By restricting the shape of PDF's, the W asymmetry measurement has significantly reduced the systematic uncertainty in the W mass measurement. The fitted W mass is strongly correlated with the W charge asymmetry. The CDF results for the W asymmetry from the Run 1A data have been used as a guide in determining the uncertainty due to the PDF's. Fig. 4 shows the correlation between the ΔM_W (in MeV) and $\Delta\sigma_{\overline{A(\eta)}}$, the deviation between average measured asymmetry and the NLO PDF predictions. The W mass extracted from the run 1A data is 80.41 ± 0.18 GeV from the combined electron and muon data. The asymmetry measurement allowed the CDF to reduce systematic uncertainty on M_W due to PDF's to 50 MeV for Run 1A. This error is included in the overall 180 MeV error for run 1A. Smaller errors on the W mass are expected when the analysis of the run 1B data is completed.

The comparison of W asymmetry measurement with predictions of various PDF's in NLO (DYRAD) is shown in Table 1. A comparison using the resummation calculation is currently being done.

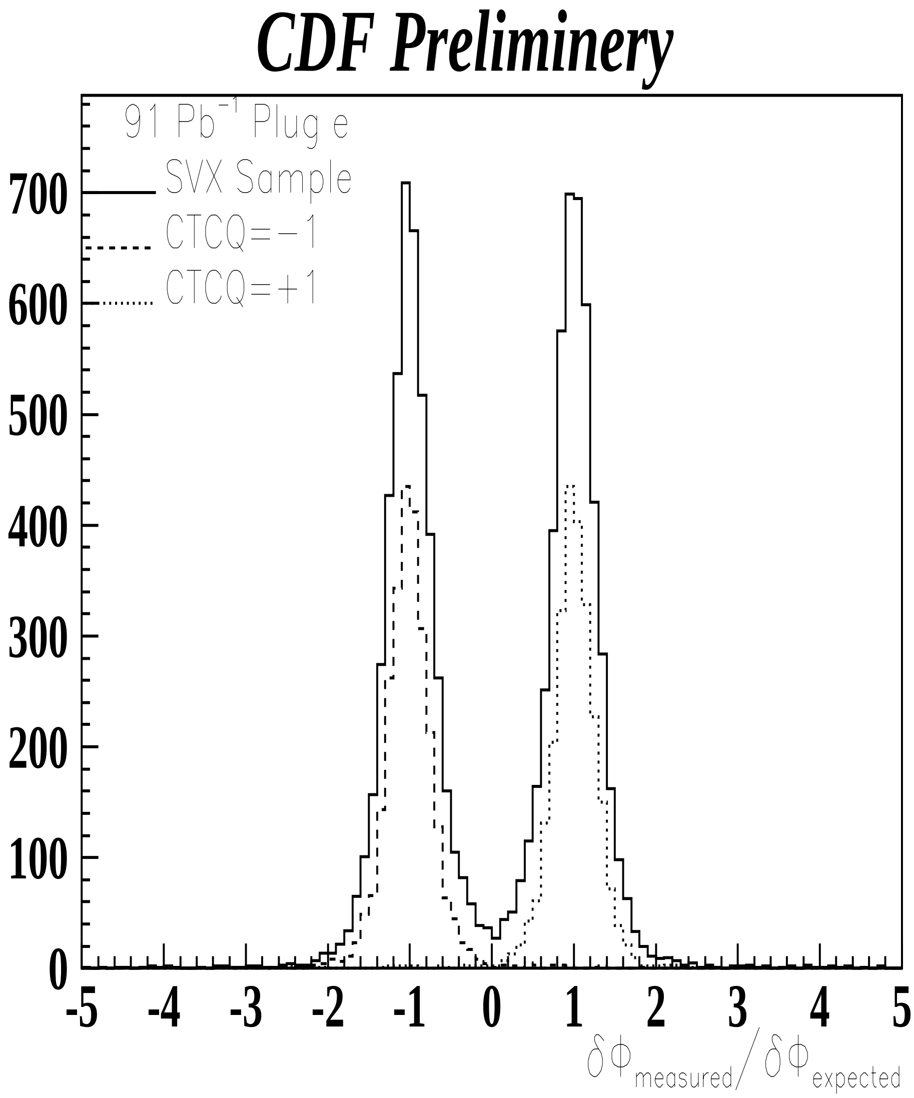

Figure 1: The distribution of $\delta\phi_{measured}/|\delta\phi_{expected}|$ for the plug W electron sample. The CTC charge mis-identification rate is $0.5 \pm 0.2\%$ and $0.2 \pm 0.1\%$ for plus and minus charges, respectively.

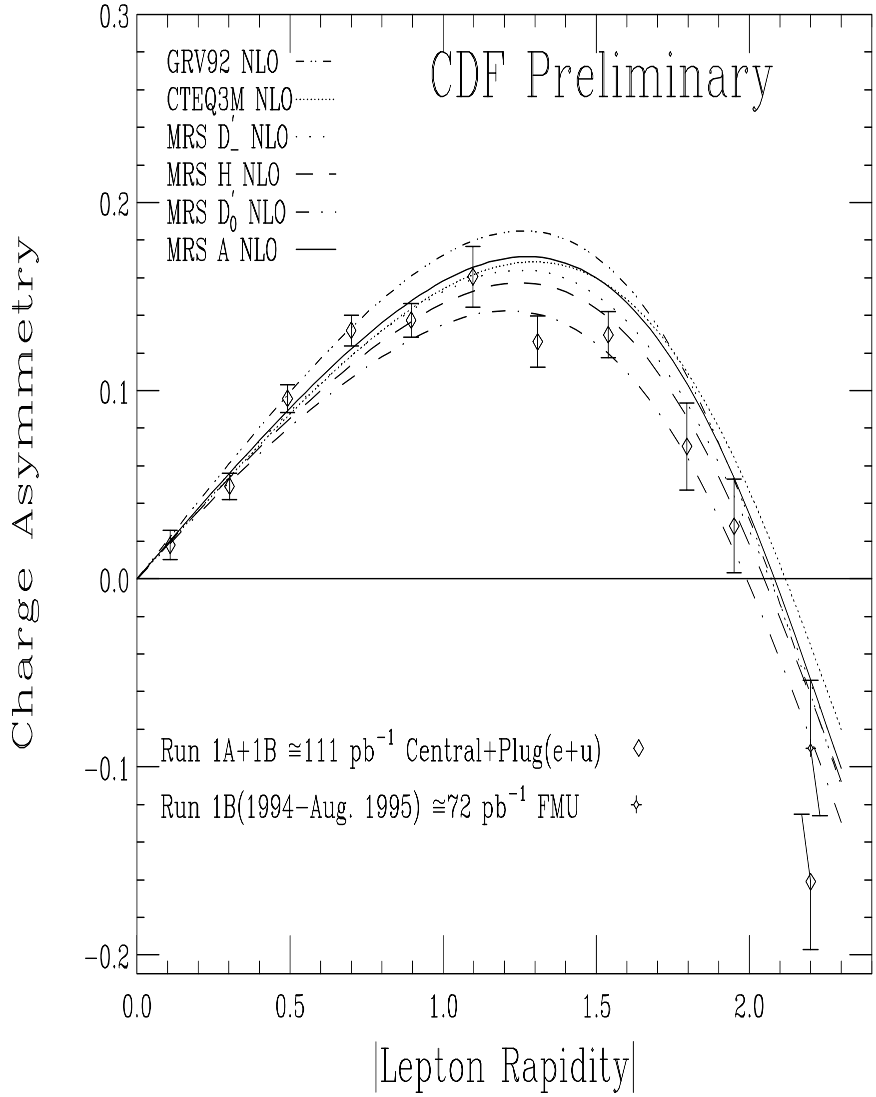

Figure 2: Comparisons of W asymmetry measurement with Recent PDF's Predictions. The charge asymmetry measured by CDF, compared to predictions of the latest PDF's (using NLO DYRAD). The data includes the Run 1A Central and Plug data sets (PRL, 74 (1995)) and additionally the Run 1B Central+Plug data set (CDF Preliminary).

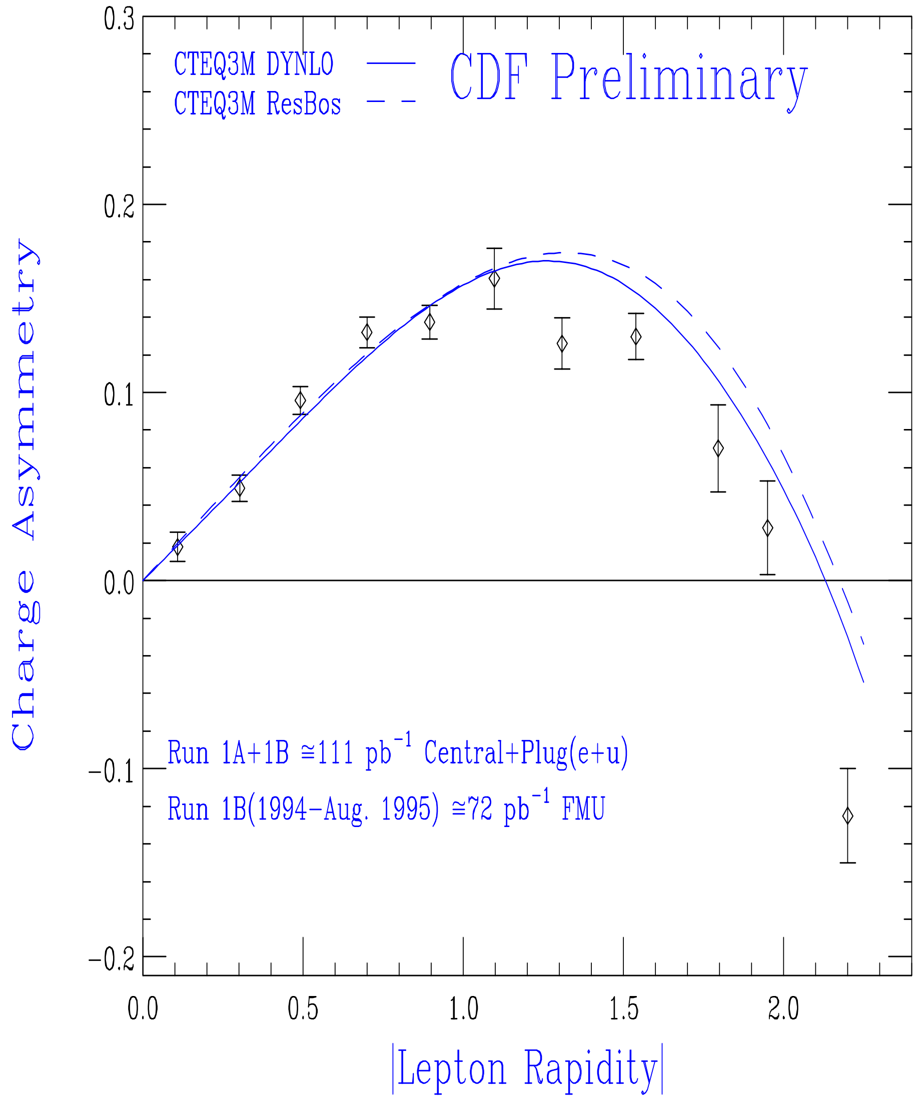

Figure 3: Comparisons of W asymmetry measurement with two theories using the same parton distributions. Shown are the theoretical curves using the NLO (DYRAD) calculation and also the Resummation (RESBOS).

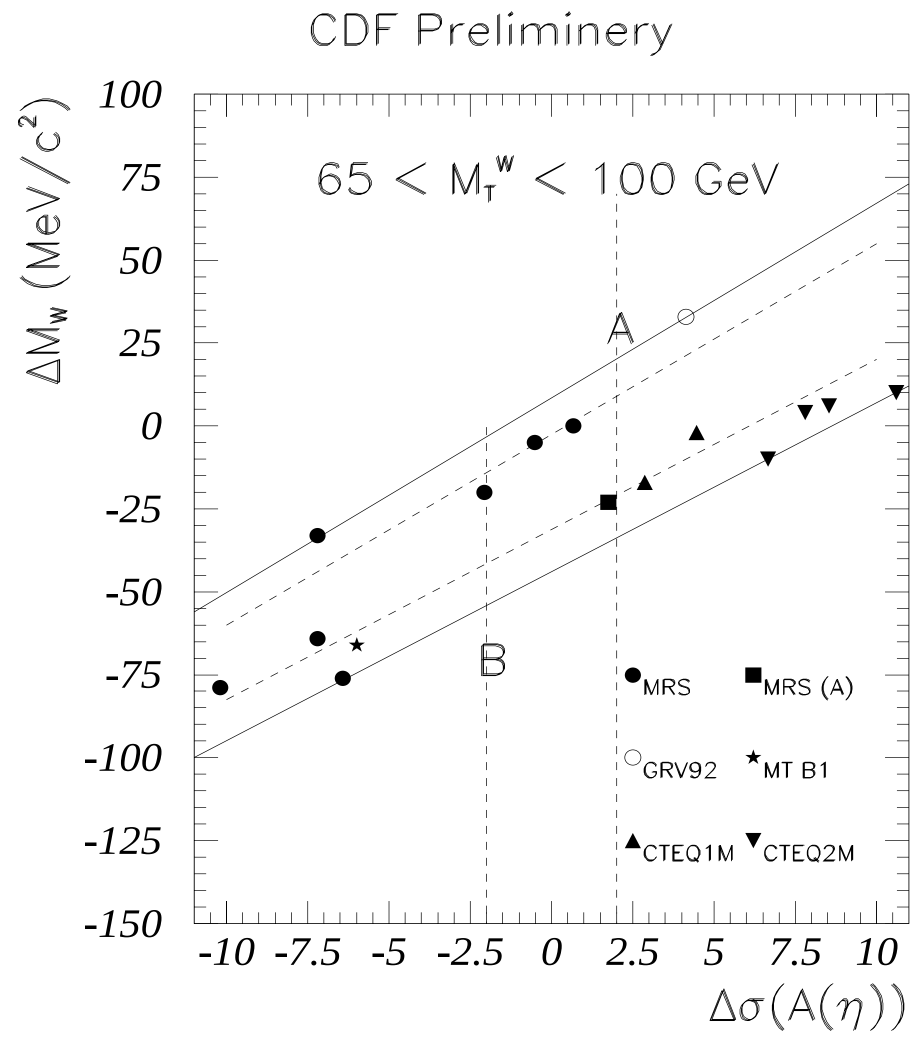

Figure 4: The correlation between the ΔM_W (in MeV) and $\xi = \Delta\sigma_{\overline{A(\eta)}}$, the deviation between average measured asymmetry and the PDF predictions. The M_T^W regions for the W mass fitting is $65 < M_T^W < 100$ GeV. The area between solid lines covers all the points and the dashed lines denote $\pm\ 2\ \Delta\sigma_{\overline{A(\eta)}}$. The W mass measurement uncertainty due to PDF's is taken to be half of the two extreme values in the area within $\pm\ 2\ \Delta\sigma_{\overline{A(\eta)}}$. This analysis was performed using the DYRAD NLO calculation. The data sample includes all central and forward 1A and 1B electron and muon W events.

CDF Preliminary

PDF	$\Delta\sigma_{\overline{A(\eta)}}$	ΔM_W^e (MeV/c^2)	ΔM_W^μ (MeV/c^2)
CTEQ 2M	+10.60	+10	+ 15
CTEQ 2MF	+ 8.53	+ 6	+ 6
CTEQ 2ML	+ 7.80	+ 4	+ 12
CTEQ 2MS	+ 6.67	−10	− 8
CTEQ 1M	+ 4.46	− 2	− 8
GRV 92	+ 4.13	+33	+ 50
CTEQ 1MS	+ 2.86	−17	− 28
MRS A	+ 1.75	−23	− 28
MRS D'_-	+ 0.68	0	0
MRS H	− 0.51	− 5	− 7
MRS D'_0	− 2.06	−20	− 19
MT B1	− 5.99	−66	− 79
KMRS B_0	− 6.43	−76	− 87
HMRS B	− 7.20	−33	− 35
MRS B'	− 7.20	−64	− 74
MRS E'	−10.20	−79	−100

Table 1: Dependence of the W charge asymmetry and the W mass on PDF choice. The Monte Carlo error is 15 MeV/c^2. MRS D'_- is the default choice of the Run 1A+1B analysis. $\Delta\sigma_{\overline{A(\eta)}}$ is defined as $(A_{PDF} - A_{DATA})/\delta A_{DATA}$. The theory used here is the NLO DYRAD calculation. The data sample includes all central and forward 1A and 1B electron and muon W events.

3 High Mass Drell Yan and limits on Z' bosons and quark substructure

The Drell-Yan events are easily reconstructed from the measured properties of the decay leptons. The differential Drell-Yan cross section provides information on the magnitude of the quark distributions in the x range 0.006-0.03 over a Q^2 range of 121-3600 GeV^2. The CDF experiment has measured [9] the differential cross section $d^2\sigma/dMdy_{|y|<1}$, over the mass range $11 < M < 150$ GeV/c^2 using dielectron and dimuon data from 1988-89 collider run (≈ 4 pb^{-1}). The results showed $1/M^3$ dependence as is expected from naive Drell-Yan model. The measurement favored those distributions which have the largest quark contribution in the x interval 0.006 to 0.03, in particular the sets which used the most recent DIS data. However, as was the case for the 1988-89 W asymmetry data, the statistics were limited.

Recently, CDF has presented [18] a preliminary measurement of the Drell-Yan cross-section using the combined Run 92/93 and 94/95 data corresponding to the total integrated luminosity of 110 pb^{-1}. Figure 5 shows results of the combined dielectron and dimuon Drell-Yan cross-section measurement using high mass events collected during Run 1A+1B. The data is consistent with the earlier published Drell-Yan measurement by CDF [9] and agrees well with the NLO calculations.

The high mass Drell-Yan data is ideal for searching for an additional heavy gauge boson ($Z^{'}$) decaying to dileptons.

The CDF experiment has published the results on $Z^{'}$ mass limits using 88/89 data [10] and more recently the extended limits for $Z^{'}$ decaying into dielectron channel [11] using the Run 1A data. Preliminary results on $Z^{'}$ mass limit using the CDF Run 1A+1B data have been recently presented at 1996 APS Meeting. Figure 6 shows the $Z^{'}$ mass limits extracted from the dimuon samples of the combined 1A+1B samples (≈ 110 pb^{-1}). Combining both dielectron and dimuon channels using Run 1A+1B, we set $Z^{'}$ lower mass limit of 690 GeV/c^2. We also set limits for the production of sequential neutral vector bosons within the framework of E_6 superstring inspired supersymmetric models, as shown on Figure 7. The CDF mass limits at the 95% CL range from 550 GeV to 620 GeV, when supersymmetric and exotic decays of the Z' are not considered.

The measurement of the dilepton invariant mass spectrum is also sensitive to the possible existence of an additional contact term interaction between quarks and leptons characterized by the compositeness scale Λ. If quarks and leptons are composite particles that share constituents, an effective contact interaction arises between them [12]. This interaction would result in an en-

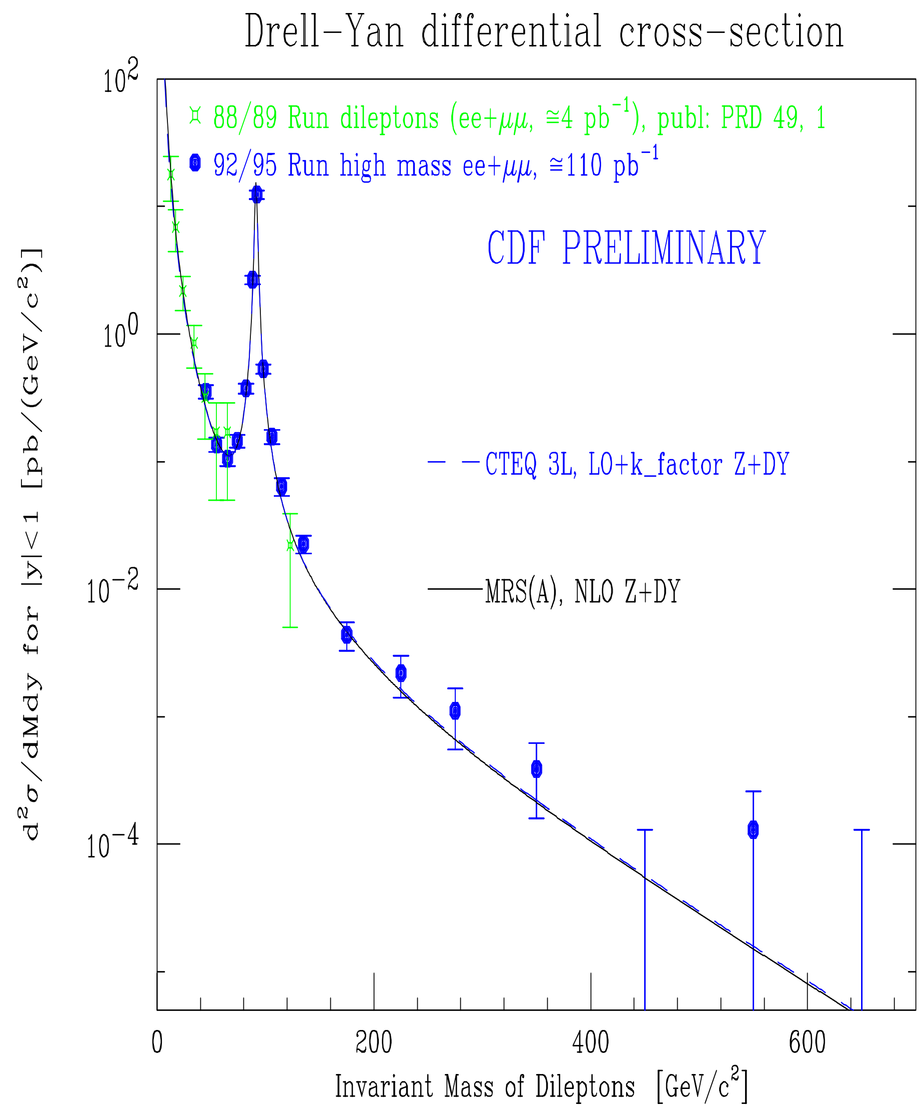

Figure 5: Drell-Yan dielectron+dimuon combined (dark circle symbols) pair production cross section from Run 1A+1B corresponding to 108 ± 7.1 pb^{-1} of data. For comparison we also show results from Run 88/89. At high mass, both the NLO and LO+Kfactor QCD calculations agrees with the data.

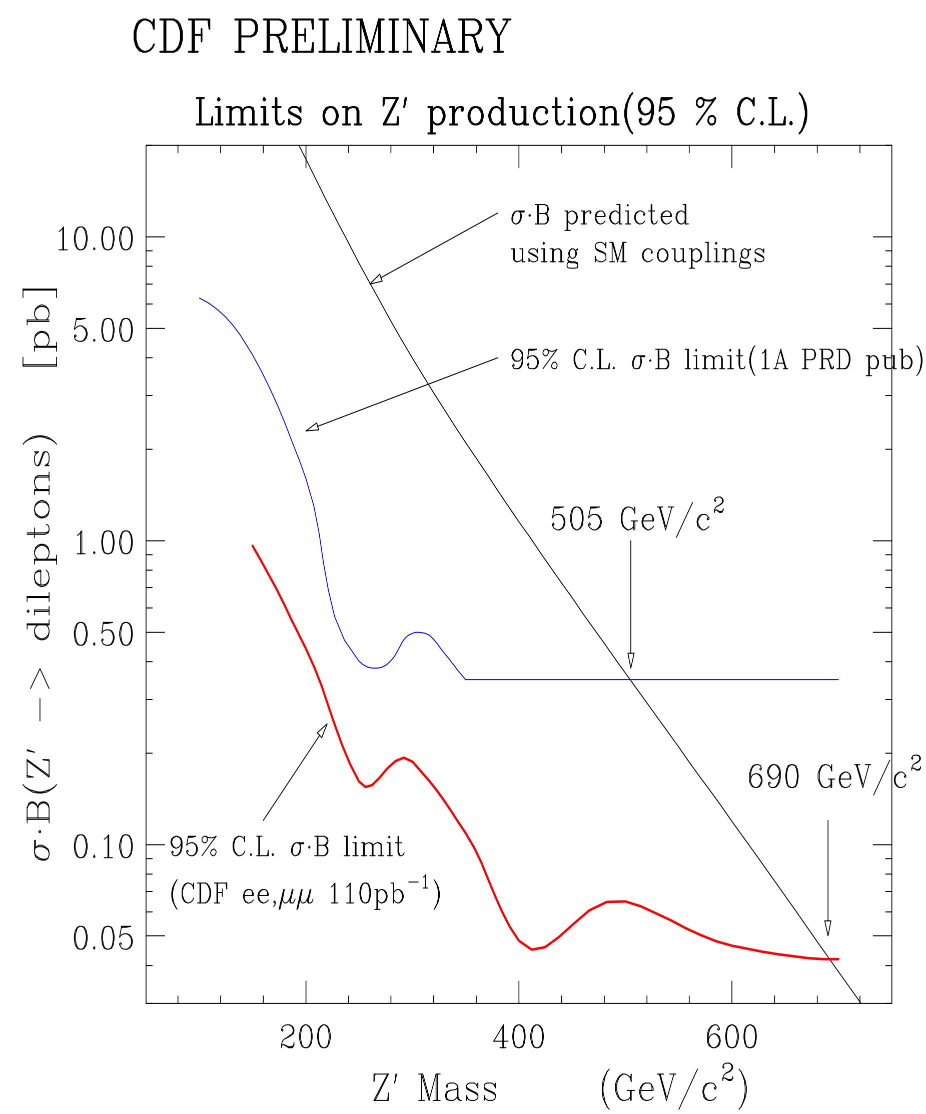

Figure 6: The Z' mass limits (95% CL) extracted from the CDF combined dielectron and dimuon samples of the Run 1A+1B sample ($\approx$ 110 pb^{-1})

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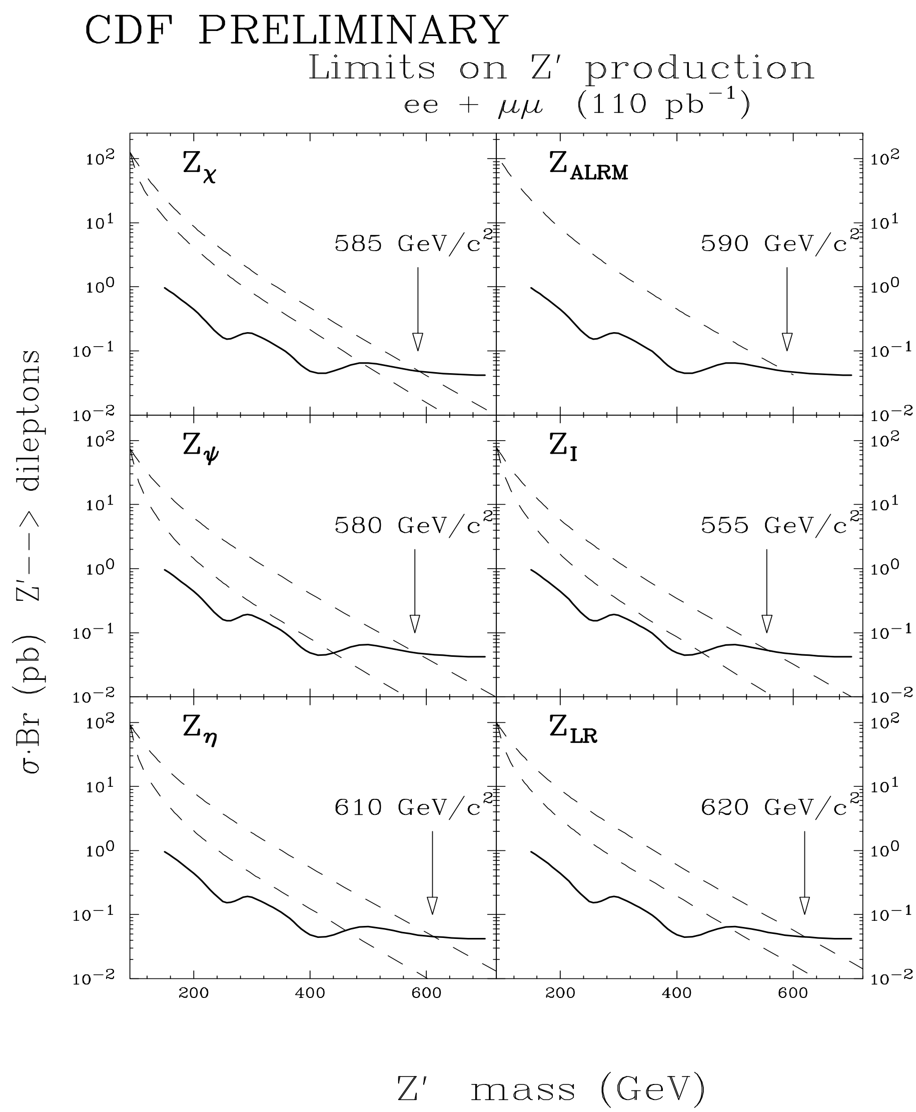

Figure 7: The Z' mass limits (95% CL) for the production of sequential neutral vector bosons within the framework of E_6 superstring inspired supersymmetric models extracted from the CDF dimuon samples of the combined Run 1A+1B sample ($\approx$ 110 pb^{-1}).

hancement of the dilepton differential cross section at high invariant mass. Earlier [15] CDF 95% CL limits on the scale of such an effective contact interaction were extracted from the 88/89 dataset. The limits (on contact terms for $qq-\mu\mu, qq-ee$ interactions) based on the absence of high mass dilepton events in the ≈ 4 pb^{-1} of data were:

$$\Lambda^{-}_{LL}(ee, CDF-4pb^{-1}) \geq 2.2\ TeV, \quad (2)$$

$$\Lambda^{+}_{LL}(ee, CDF-4pb^{-1}) \geq 1.7\ TeV, \quad (3)$$

$$\Lambda^{-}_{LL}(\mu\mu, CDF-4pb^{-1}) \geq 1.6\ TeV, \quad (4)$$

$$\Lambda^{+}_{LL}(\mu\mu, CDF-4pb^{-1}) \geq 1.4\ TeV. \quad (5)$$

Within the Eichten's Left-Left (LL) model - (+) corresponds to constructive (destructive) interference with the photon amplitude and Λ_{LL} refers to the scale parametrizing the interaction between left-handed currents.

Theoretical models of quark and lepton compositeness have recently gained considerable attention, especially after the publication recently submitted to PRL [16] by the CDF Collaboration. There, we have reported that above 200 GeV, the jet cross section is significantly higher than the NLO predictions. The excess of high p_T jets could be explained [17] by a modified gluon distributions inside the proton. The presence of quark substructure could also appear as an enhancement of the inclusive differential jet cross-section at high E_T. The best agreement between inclusive jet cross-section data above $E_T \geq 200\ GeV$ and the LO QCD calculation including compositeness is achieved for value of compositeness scale $\Lambda(qq)$ ($qq-qq$ contact term interaction), $\Lambda(qq) \approx 1.6\, TeV$. However, as described in the next section, a much more likely explanation is that the data require some tuning of of the gluon distribution at large x and a somewhat higher value α_s, within the range allowed by previous experiments.

At the 1996 Electroweak Moriond Conference [19], the CCFR/NuTeV Collaboration has presented the 95% CL limits on compositeness scale ($\nu\nu-qq$ contact term interaction). These limits have been recently updated (July 1996) as follows:

$$\Lambda^{-}_{LL}(\nu_\mu\nu_\mu, CCFR-NuTeV) \geq 3.5\ TeV, \quad (6)$$

$$\Lambda^{+}_{LL}(\nu_\mu\nu_\mu, CCFR-NuTeV) \geq 3.8\ TeV. \quad (7)$$

CDF has presented new preliminary limits on the compositeness scale Λ at the 1996 Moriond Conference [18]. The analysis was performed using the observed dilepton events with mass above 150 GeV and the bin likelihood technique.

Figures 8 and 9 show comparison between the Drell-Yan cross-section measurement and theoretical predictions for various values of compositeness scale $\Lambda^-_{LL}(ee)$ and $\Lambda^+_{LL}(ee)$ respectively. The 95% CL limits (on contact terms for $qq-\mu\mu, qq-ee$ interactions) based on the absence of high mass dilepton events in the ≈ 110 pb^{-1} of data are:

$$\Lambda^-_{LL}(ee, CDF-110pb^{-1}) \geq 3.4\ TeV, \tag{8}$$
$$\Lambda^+_{LL}(ee, CDF-110pb^{-1}) \geq 2.4\ TeV, \tag{9}$$
$$\Lambda^-_{LL}(\mu\mu, CDF-110pb^{-1}) \geq 3.5\ TeV, \tag{10}$$
$$\Lambda^+_{LL}(\mu\mu, CDF-110pb^{-1}) \geq 2.9\ TeV. \tag{11}$$

The process $u\overline{u}$ and $d\overline{d}$ going to quarks, or to dimuons or dielectrons may have different compositeness scales. If one assumes that the scales are the same for electrons and muons, the combined CDF electron and muon data yield compositeness scale limits of $\Lambda^-_{LL}(ll)$ are:

$$\Lambda^-_{LL}(ll, CDF-110pb^{-1}) \geq 3.8\ TeV, \tag{12}$$
$$\Lambda^+_{LL}(ll, CDF-110pb^{-1}) \geq 2.9\ TeV. \tag{13}$$

4 Direct Photons, Diphotons, and K_T Effects from Multigluon Emission in the Initial State

A comparison of the NLO QCD calculations with all direct photon data did not agree with either fixed target or collider data. When ratio of data to theory are plotted versus P_T, each data set shows a slope (high at low P_T and low at higher P_T). The CDF and Dzero direct photon data (mean photon X_T of 0.02), the UA2 data (mean photon X_T of 0.08), The ISR data (mean photon X_T of 0.2) and the FNAL E706 fixed target data (mean photon X_T of 0.35) disagree with the NLO theory by up to $\pm 20\%$, $\pm 50\%$, $\pm 80\%$. and $\pm 100\%$, respectively. However, when one includes multi-gluon initial state radiation, using a Monte Carlo like PYTHIA, there is good agreement between he collider data and theory. The steep P_T dependence of the direct photon cross sections results in a great sensitivity to intial state transverse momentum of the quarks. At collider energies, the P_T is the gluons is high enough, such that the effects of initial state multigluon radiation can be described perturbatively using a initial state parton shower Monte Carlo. At fixed target energies, the gluon energies are low, and the perturbative calculation is not valid. However, the non-perturbative effects may be handled by including and "effective" initial state K_T.

An experimental handle on the magnitude of the initial state transverse momenta of the quarks may be obtained from the di-photon data. Here, the

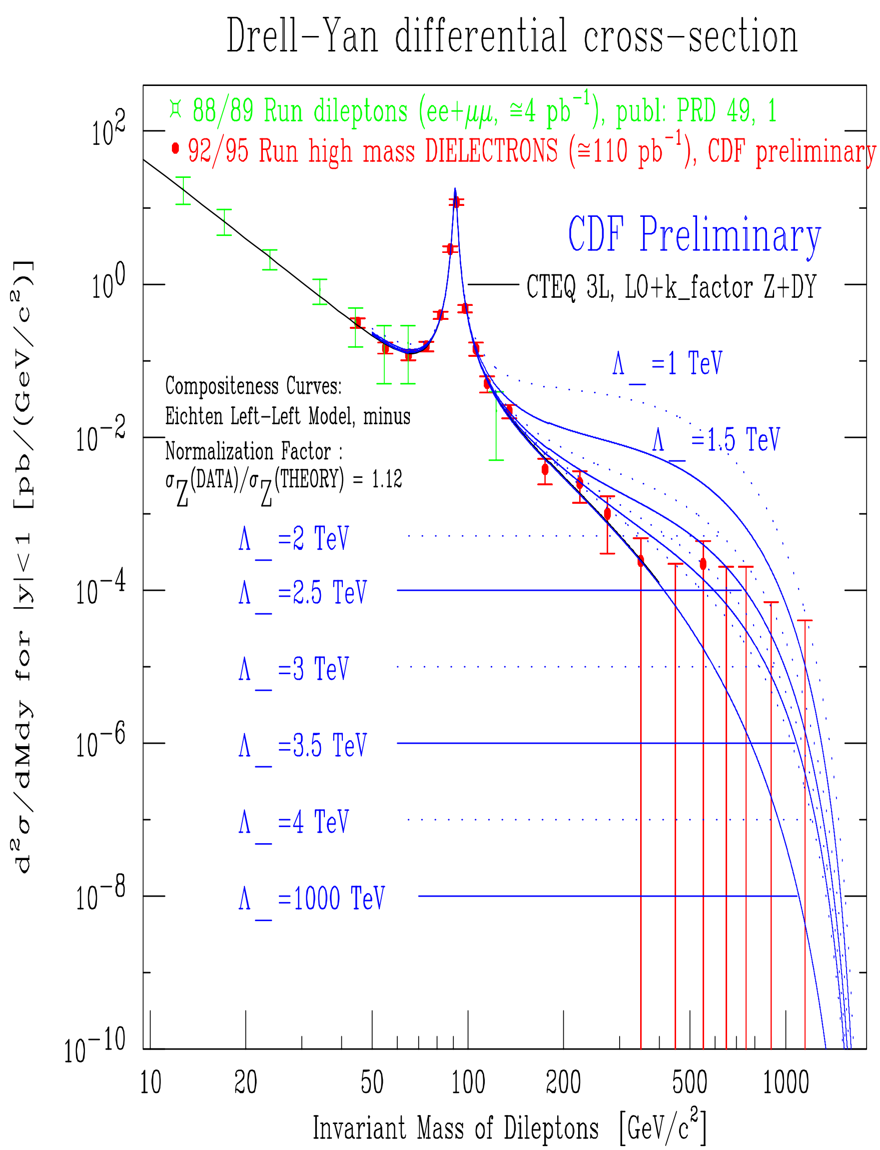

Figure 8: Comparison between the CDF Drell-Yan cross-section measurement and theoretical prediction for various values of compositeness scale $\Lambda^-_{LL}(ee)$, for dielectron channel.

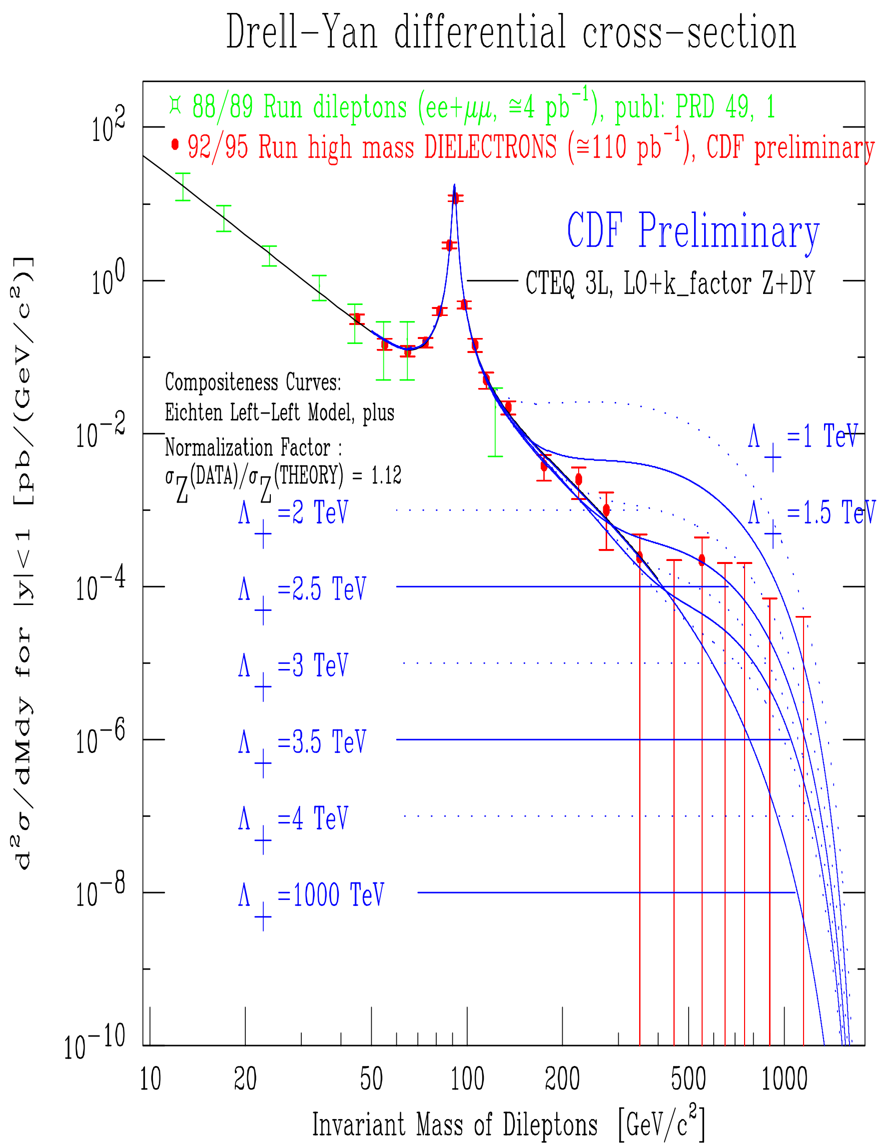

Figure 9: figure= Comparison between the CDF Drell-Yan cross-section measurement and theoretical prediction for various values of compositeness scale $\Lambda^+_{LL}(ee)$, for dielectron channel.

final state should reflect the P_T of the initial quarks, since both photons are observed. The P_T distributions of diphotons in both fixed target and collider experiments are consistent with the mean K_T values that are need to make data an theory agree in the single direct photon case.

5 High P_T jets and the Gluon Distribution at Large x

The high P_T jet data for CDF and Dzero are described in several contributions to these proceedings. In addition, fits to these data by both the MRS and CTEQ groups are also described in several contributions to this proceedings. Rather than duplicate the plots, I will only summarize the conclusions. The jet cross section versus Pt varies from a value of 10^4 at Pt of 20 GeV to 10^{-6} at Pt of 450 GeV. There is good agreement between data and theory over a range of 10 order of magnitude. At the very highest values of P_T, the CDF cross section was about 30% higher than the NLO QCD calculation using standard parton distributions. The Dzero data are consistent with the CDF data. Note that the high Pt region is sensitive to gluons at large values of x (between 0.3 and 0.4) where the distribution is not well known. This is the region where fixed target direct photon experiments (which in principle could measure the gluon distribution) are sensitive to non-perturbative initial state K_T. However, both the fixed target direct photon experiments, and the CDF data favor a larger value for the gluon distribution at large x. A new fit by the CTEQ collaboration, in these proceedings, yields good agreement between the collider data and all other experimental data. The fit yields a somewhat larger value of α_s and a larger gluon distribution at high x, and indicates the value of the jet collider data to our improved determinations of the gluon distributions and α_s.

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