RECENT CDF AND DØ RUN I RESULTS

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We summarize some of the the most recent CDF and DØ results from the 1992-1995 collider run at the Fermilab Tevatron. These include a detailed examination of the heavy flavor content of W+jet data made by CDF. We found in this study that the rate and the kinematic properties of the event subsample, featuring soft lepton and secondary vertex in the same jet, are statistically difficult to accommodate with the Standard Model simulation. CDF has also searched for new physics in events with a photon, a lepton and $\not{E}_T$. Finally, the results of the two collaborations in their search for the first, second and third generations leptoquarks are presented.

1 Introduction

In this paper, we describe some of the most recent results obtained by the CDF and DØ collaborations in the search for physics beyond the Standard Model. Both experiments operate at the Tevatron $p\bar{p}$ collider at Fermilab. The results are based on the analysis of data samples collected during the 1992-1995 run known as Tevatron Run I, and are based on an integrated luminosity exceeding 100 pb^{-1} per detector.

The CDF and DØ Run I detectors are described in Ref. [1] and Ref. [2] respectively.

2 CDF detailed examination of the heavy flavor content of W+jet data

A study of the properties of events containing a W boson and associated jets (W+jet sample), provides a good opportunity to test our understanding of the standard model (SM) QCD and electroweak predictions. This event sample was used to establish the top quark discovery [3]. The whole sample was also exploited to perform a measurement of the top quark mass [4] and

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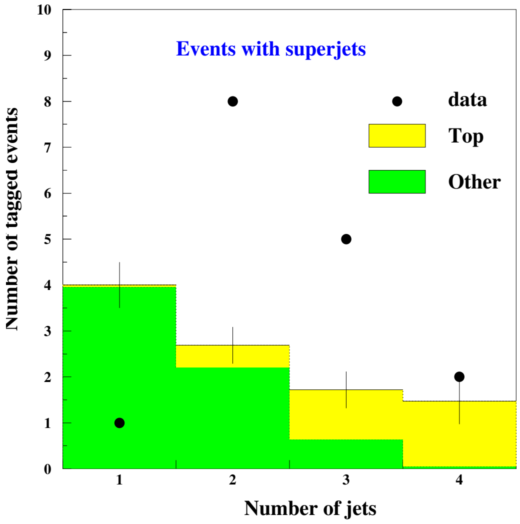

Figure 1: Comparison between observed and predicted number of W+jet events with a supertag as a function of the number of jets in the event.

	W+1jet	W+2jets	W+3jets	W+$\geq$4jets
		SECVTX events		
SM (ST)	64.4 ± 6.5	29.6 ± 2.7	12.9 ± 1.9	8.9 ± 2.0
SM (DT)		2.4 ± 0.6	3.2 ± 0.8	4.0 ± 1.0
Data (ST)	66	35	10	11
Data (DT)		5	6	2
		SLT events		
SM (ST)	137.75 ± 11.29	46.1 ± 5.7	12.9 ± 1.9	8.9 ± 2.0
SM (DT)		0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
Data (ST)	146	56	17	8
Data (DT)		0	0	0
		Superjet events		
SM (SJ)	4.00 ± 0.50	2.7 ± 0.4	1.7 ± 0.4	1.5 ± 0.5
SM (DT)		0.3 ± 0.1	0.4 ± 0.1	0.5 ± 0.1
Data (SJ)	1	8	5	2
Data (DT)		2	3	0

Table 1: Observed and predicted number of W events with SECVTX tag (top lines), soft lepton tag (center lines) and the events with a supertag (bottom part).

of its production cross section [5] after assuming that any observed excess of beauty-tagged data was due to $t\bar{t}$ production. In this study a complementary approach is adopted [6]. We use the theoretical estimate of $\sigma_{t\bar{t}}$ and we test the compatibility of the SM prediction with the observed number of different tags [a] as a function of jet multiplicity.

The top part of Table 1 summarizes the number of observed and predicted W events with one (ST) or (DT) two SECVTX tags in the accompanying jets. The comparison for SLT tags is shown at the center. The probability that the observed numbers of events with at least one SECVTX (SLT) tag are consistent with the prediction in all jet bins is 80% (56%) [6].

Studying the correlation between the taggers we found that the SM simulation does not predict well the number of events with a SLT and a SECVTX tag in the same jet. We called these tags and jets supertags and superjets, respectively. The comparison between the observed number of events with supertag and the SM prediction is summarized in the bottom lines of Table 1 and is shown in Fig. 1 The probability that the observed numbers of events with at least one superjet fluctuate to the prediction in all four jet bins is 0.4%. The *a posteriori* probability of observing no less then 13 in the W+2,3 jet bins, where 4.4 ± 0.6 are expected from SM sources, is 0.1%.

We selected a complementary data sample which have a close composition to the superjet sample. This sample consists of W+2,3 jet events with a SECVTX tag, but no SLT tag in the same jet. However, we require that at least one of the SECVTX tagged jets contains a soft lepton candidate track. After all of requirements we left with 42 W+2,3 jet events, while 41.2 ± 3.1 events are expected from the SM processes.

When we examined the additional jets in the superjet sample we found 5 events with an additional SECVTX tag. If the 13 events are a fluctuation from SM processes, we can expect to find 1.8 ± 0.3 events with double SECVTX tag. Taking into account the high probability of finding a SECVTX tag in the additional jets, we decided to name them conventionally as b-jets.

If the 13 events are a statistical fluctuation, their kinematics would be consistent with the SM simulation and with the kinematics of the complementary sample. We choose two sets of 9 variables to compare the samples [6]. The first set includes: $d\sigma/dp_T$ and $d\sigma/d\eta$ of the lepton,

[a] CDF uses two different methods for identifying (tagging) heavy quark jets [3]. The first technique uses the silicon microvertex detector (SVX) to locate secondary vertices from b and c-hadron decays (SECVTX tag). The second one (SLT) searches for a relatively soft lepton (e or μ) contained in the jet cone and produced by these semileptonic decays.

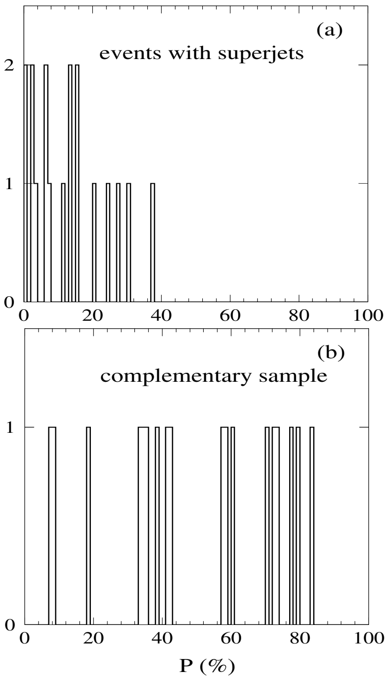

Figure 2: Distribution of the probabilities $\mathcal{P}$ that the 13 superjet events (a) and the complementary sample (b) are consistent with SM prediction.

Variable	Events with superjet		Complementary sample	
	δ^0	$\mathcal{P}$ (%)	δ^0	$\mathcal{P}$ (%)
E_T^{ℓ} ($\not{E}_{\mathrm{T}}$)	0.47(0.31)	2.6(27.1)	0.14(0.14)	70.9(57.1)
η^{ℓ} (M_T^W)	0.54(0.36)	0.1(13.1)	0.12(0.16)	72.7(38.2)
E_T^{suj} (M^{suj+b})	0.38(0.36)	11.1(4.0)	0.15(0.12)	43.0(58.9)
η^{suj} (y^{suj+b})	0.36(0.35)	15.2(7.1)	0.13(0.14)	73.4(34.9)
E_T^{b}(E_T^{suj+b})	0.36(0.28)	6.7(24.0)	0.18(0.10)	8.6(60.1)
η^{b} ($M^{l+suj+b}$)	0.38(0.31)	6.8(21.0)	0.11(0.15)	80.0(33.6)
$E_T^{\ell+suj+b}$ ($\theta^{suj,b}$)	0.39(0.26)	2.5(30.1)	0.17(0.15)	18.8(41.1)
$E^{\ell+suj+b}$ ($\phi^{suj,b}$)	0.31(0.31)	13.8(15.3)	0.19(0.10)	7.8(83.8)
$\phi^{\ell,suj+b}$ ($\theta^{\ell,suj+b}$)	0 43(0.25)	1.0(37.3)	0.12(0.16)	77.9(35.7)

Table 2: Summary of the KS comparison between data and simulation. The results for the two sets of kinematical variables are presented.

superjet and additional "b-jet(s)" [b]; the transverse energy and the rapidity of the system $(\ell + suj + b)$, which is strongly correlated with the missing transverse energy and the rapidity of the object producing $\not{E}_{\mathrm{T}}$; and the azimuthal angle $\phi^{\ell,suj+b}$ between the primary lepton and the superjet-additional jet(s) (b-jet(s)) system. These 9 variables are sufficient to describe the kinematics of the final state with relatively modest correlations.

A second set of 9 variables was also tried, including: the corrected transverse missing energy ($\not{E}_{\mathrm{T}}$); the W transverse mass (M_T^W); the invariant mass, rapidity, and transverse energy of the system $suj + b$ (M^{suj+b},y^{suj+b} and E_T^{suj+b}); the invariant mass of the system $l + suj + b$ ($M^{l+suj+b}$); the angle and the azimuthal angle between the superjet and b-jets ($\theta^{suj,b}$,$\phi^{suj,b}$); and the angle between the primary lepton and the $suj + b$ system ($\theta^{\ell,suj+b}$).

The data of the superjet and of the complementary samples are compared to SM montecarlo distributions using a Kolmogorov-Smirnov (KS) test. The Kuiper's definition of the test was applied: $\delta = max(F(x_i) - H(x_i)) + max(H(x_i) - F(x_i))$. For each variable, the probability distribution of the KS distance δ is determined with the ensemble of montecarlo experiments. In each montecarlo experiment, temporary templates are constructed. They account for the Poisson fluctuations in the number of events in the SM processes and for the Gaussian uncertainties in the SM cross sections. From these temporary templates, we randomly generated a distribution with the same number of entries as in the data and evaluated the KS distance with respect to the nominal SM template.

The results of the KS comparison between data and simulation for the 18 kinematic distributions are summarized in Table 2 and presented in Fig 2. The complementary sample probabilities are flatly distributed which indicates consistency with the SM simulation. On the other hand, one can notice that the distribution for the superjet events cluster at low probabilities. This indicates the difficulty of the SM simulation to describe the kinematics of the supperjet events. Additional studies, combining all 18 probabilities, and determining the statistical significance of the observed discrepancies, were done in the Ref. [7].

An extensive study of the properties of the superjets and/or superjet events was done[6]. This includes a detailed examination of the soft lepton tag parameters, a check of the primary lepton isolation and lifetime, an investigation of the superjet properties (lifetime, hadronization) using generic QCD data and SM montecarlo. In addition, a number of background and acceptance studies were performed and no anomalous behavior was found. However, removing the second

[b] In the sub-sample of W+3jet events the same variables with two entries per event are used.

level of the primary muon trigger requirement and extending the acceptance for the primary electrons up to $|\eta|$ <1.5 [c], 4 additional W+2,3 jet events with superjets were found, while 0.42 ± 0.06 are expected from the SM.

3 Search for a new physics in events with a photon and a lepton

The inclusive production of a photon and a lepton (e or μ+γ+X) at large P_T provides the opportunity to test many SM predictions. Indeed, the observation of an anomalous production rate of these events, possibly associated with additional photons, leptons, and large missing transverse energy ($\not{E}_{\mathrm{T}}$) would be a clear indication of new processes beyond SM.

The interest to these events originates from the appearance of the ee$\gamma\gamma\not{E}_{\mathrm{T}}$ event recorded by CDF. A supersymmetric model [8] designed to explain this event predicts the production of photons from the radiative neutralino decay and of leptons from the chargino decay featuring $\ell\gamma\not{E}_{\mathrm{T}}$ events as a signal. In addition, these events can be explained by resonant smuon production with a single dominant R-parity violating coupling, in a model where gravitino is the lightest supersymmetric particle [9].

Inclusive photon-lepton events are selected by CDF by requiring an isolated [10] central photon and lepton with $\mathrm{E}_{\mathrm{T}}^{\gamma} > 25$ GeV and $\mathrm{E}_{\mathrm{T}}^{e,\mu} > 25$ GeV respectively. The selection criteria for lepton and photons identification are described in detail in Ref. [11]. A total of 77 events satisfied this selection: 29 photon-muon and 48 photon-electron candidates. Figure 3 summarizes the selections criteria and shows the breakdown of the inclusive sample into the final categories.

Rather than looking for the specific characteristics of the events, like we did in the case of superjet events, here we simply compare the number of observed events to expected events. Without a specific model and assuming that our null hypothesis (the SM) is correct, the significance of an observed excess is calculated as a probability $\mathcal{P}$ to obtain at least the observed number of events (N_0). This probability $\mathcal{P}(\mathrm{N}\geq\mathrm{N}_0/\mu_{SM})$ is computed from a large ensemble of montecarlo experiments in which each quantity used in the determination of SM photon-electrons contribution is varied randomly with a Gaussian distribution, and the resulting event number is fluctuated according the Poisson law. The fraction of cases in the ensemble when $\mathrm{N}\geq\mathrm{N}_0$ gives $\mathcal{P}(\mathrm{N}\geq\mathrm{N}_0/\mu_{SM})$.

The predicted and observed number of events for two-body and multi-body selection are compared in Table 3 [10]. The most important SM contributers are Zγ production, where one of the Z-decay leptons escaped the detector, Wγ production, misidentified jets and electrons.

The most significant deviation from the SM is observed in $\ell\gamma\not{E}_{\mathrm{T}}$X sample (it is outlined with bold box on Fig. 3.) where 16 events are detected and 7.6 ± 0.7 are expected from SM sources. The *a priori* probability of observing no less than 16 is 0.7%, equivalent to 2.7σ for a Gaussian distribution.

4 CDF and DØ leptoquark searches

Many extensions, for example see Refs. [12,13,14], of the SM predict the existence of the leptoquarks (LQ), hypothetical color-triplet bosons with fractional electric charge that couple directly to leptons and quarks. Their masses are not predicted from the models. They are assumed to be pair-produced at the Tevatron through a virtual gluon in the process $\mathrm{p}\bar{\mathrm{p}} \to g + X \to \mathrm{LQ}\overline{\mathrm{LQ}} + X$. For the scalar [13] LQ, a production cross section is independent of the coupling between leptoquark, lepton and quark. In case of vector [12] LQ, the two specific possibilities of the coupling are assumed which result in minimal vector coupling (MV) and Yang-Mills coupling

[c] This was done by including the electrons not only from the central calorimeter $|\eta|$ <1.0 but from the CDF plug calorimeter too.

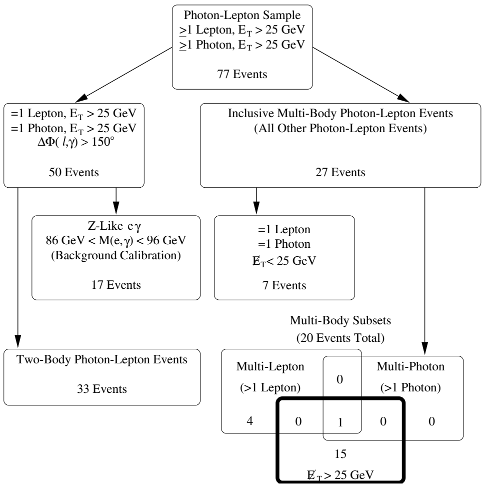

Figure 3: The diagram summarizes the selection criteria for the inclusive photon-lepton subsets. The bold box represents the sample with the largest deviation from SM prediction.

Process	Two-Body	Multi-body		
	$\ell\gamma$X	$\ell\gamma$X	$\ell\gamma\not{E}_T$X	$\ell\ell\gamma$X
W+γ	2.7 ± 0.3	5.0 ± 0.6	3.9 ± 0.5	-
Z+γ	12.5 ± 1.2	9.6 ± 0.9	1.3 ± 0.2	5.5 ± 0.6
ℓ+jet,jet$\rightarrow\gamma$	3.3 ± 0.7	3.2 ± 0.6	2.1 ± 0.4	0.3 ± 0.1
Z$\rightarrow$ee,e$\rightarrow\gamma$	4.1 ± 1.1	1.7 ± 0.5	0.1 ± 0.1	-
hadron+γ	1.4 ± 0.7	0.5 ± 0.3	0.2 ± 0.1	-
π/K decay+γ	0.8 ± 0.9	0.3 ± 0.3	0.1 ± 0.1	-
b/c decay+γ	0.1 ± 0.1	< 0.01	< 00.1	-
Predicted μ_{SM}	24.9 ± 2.4	20.2 ± 1.7	7.6 ± 0.7	5.85 ± 0.6
Observed N$_0$	33	27	16	5
$\mathcal{P}$(N$\geq$N$_0$/μ_{SM})	9.3%	10.0%	0.7%	68.0%

Table 3: The number μ_{SM} of events predicted by the SM, the number N$_0$ of observed events and probability $\mathcal{P}$ that SM predictions fluctuate to no less then N$_0$ are presented.

(YM). In most models LQ are expected to couple only within a single generation because of the experimental limit imposed by the non-observation of flavor-changing neutral currents.

Using the Run 1 Tevatron data, CDF and DØ have performed an extensive search for pair production of LQ of first, second and third generation [d].

DØ has made a search for LQ pairs decaying to $\nu\nu$+jets [15]. The $\nu\nu$+jet candidate events are selected by requiring at least two jets with $E_T > 50$ GeV, $\not{E}_T > 40$ GeV, $\delta\phi(jet, \not{E}_T) > 30^o$, and jet-jet separation greater than 1.5 [e]. The main SM backgrounds are coming from the W and Z boson production associated with jets, where the final states correspond to only neutrinos and jets, or to undetected charged lepton(s) and jets, or to an electron from W, which is misidentified as a jet, and an extra jet. The number of events surviving all of the selection cuts is 231($242 \pm 18.9^{+23.3}_{-19.0}$ are expected from SM processes).

A further step included a neural network optimization of the selection criteria for the production of 100 GeV/c^2 scalar LQ and for 200 GeV/c^2 vector LQ with minimal vector coupling. After applying the new criteria, 58(10) events for the scalar(vector) LQ are expected and $56^{+8.1}_{-8.2}$ ($13.3^{+2.8}_{-2.6}$) are expected from the SM. This null result yields the 95% C.L.upper limit on the cross section (Fig. 4) versus the leptoquark mass. LQ are excluded with mass below 98 GeV/c^2 for scalar LQ, and 238 GeV/c^2 and 298 GeV/c^2 for vector LQ with minimal vector coupling and Yang-Mills coupling, respectively.

All the current Tevatron LQ limits are summarized in Table 4.

5 Conclusions

The most recent results of the searches for new physics beyond the Standard Model in the Tevatron Run I data have shown some anomalies but no solid evidence for new physics was found.

CDF performed a detailed examination of the heavy flavor content of the jets produced with W bosons. An excess was found in events with a superjet, featuring both a SECVTX and SLT tags in the same jet. In the W+2,3 jet subsample, 4.4 ± 0.6 events are expected from the SM processes, while 13 are observed. By releasing some cuts and extending the search region 4 more superjet events were recovered bringing to an effect of 17 observed and 4.8 ± 0.7 expected events. A detailed examination of the kinematical properties of the first 13 events shows that it is

[d] Since no evidence for the LQ production has been observed, all the results are reported as excluded limits at 95% CL.

[e] Jet-jet separation is defined as $\sqrt{(\delta\eta)^2 + (\delta\phi)^2}$, where η and ϕ are the jet pseudorapidity and azimuthal angle, respectively.

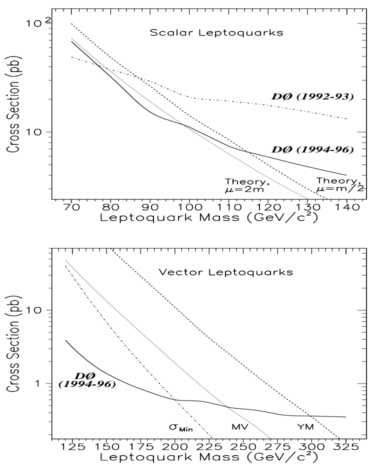

Figure 4: DØ limits on the cross section at 95% C.L. vs. LQ mass, for scalar (top) and vector (bottom) LQ. Different theoretical predictions are shown in the plots.

BR(LQ→ $\ell^{\pm}$q)	Scalar	Vector with Minimal Coupling	Vector with Yang-Mills Coupling
	First Generation LQ		
1.0	225 (220)	292(280)	345(330)
0.5	204 (202)	282(265)	337(310)
0.0	98	238	298
	Second Generation LQ		
1.0	202 (208)	275(228)	342(265)
0.5	170 (180)	270(230)	310(290)
0.0	98	238	298
	Third Generation LQ		
1.0	94 (148)	148(199)	216(250)
0.0	98 (99)	238(170)	298(225)

Table 4: Combined lover mass limits for LQ pair production for DØ . The CDF limits are presented in the brackets.

statistically difficult to reconcile them with a simulation of the SM processes. The same SM simulation models well the complementary W+jet sample and other larger generic-jet samples of data. There is not known model which could incorporate the production and decay properties of these events. One is forced to conclude that either they are a rare fluctuation, or a hint for something totally new.

Properties of the CDF events with photon and lepton have been studied. An excess of events equivalent to 2.7 standard deviations has been found in one subsample which features additional large $\not{E}_T$. This is also an intriguing result which needs more data for confirmation.

Finally, we summarize the CDF and DØ searches for first, second and third generations leptoquarks and present the mass limits for scalar and vector LQ's.

Both CDF and DØ are eagerly looking forward to more data in the upcoming Fermilab Tevatron Run II.

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