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Electroweak and QCD Results from the Tevatron

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1 Introduction

The Tevatron collider has been remarkably successful and has so far delivered more than 11 fb^{-1} of data to both the CDF and D0 experiments. Though the LHC has replaced the Tevatron as the world's most powerful collider, years of detector calibration, the huge size of the dataset and the nature of $p\overline{p}$ collisions will keep the Tevatron competitive in many selected topics in the near future. More than 10 fb^{-1} of data has been collected by each experiment. Good understanding of the detector performance has been demonstrated by the high precision W boson mass ($\Delta M_W = 31$ MeV) and top quark mass ($\Delta M_t = 1.06$ GeV) measurements.

We report the latest electroweak and QCD results from both experiments. Most analyses presented here used 4 - 6 fb^{-1} of data.

2 Electroweak Physics

Large production cross sections of single W and Z bosons at the Tevatron allow precise measurements of the properties of intermediate weak bosons and determinations of fundamental parameters such as M_W and $\sin^2\theta_W$ etc. Studies with dibosons ($V\gamma$, VV' with $V, V' = W$ or Z) can provide better understanding of the diboson production processes and extraction of anomalous triple gauge couplings (aTGCs).

The presence of both vector (g_V^f) and axial-vector (g_A^f) couplings of fermions to the Z boson gives rise to an asymmetry in the distribution of the polar angle θ^* of the negatively charged lepton relative to the incoming quark direction in the rest frame of the decayed lepton pair. The forward-backward charge asymmetry, A_{FB}, is defined by $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$, where $\sigma_F(\sigma_B)$ is the cross section for process with $\cos\theta* > 0$ ($\cos\theta* < 0$). The couplings g_V^f and g_A^f depends on the charge and isospin of the fermion, and $\sin^2\theta_W$. At the Tevatron, the Z/γ^* bosons are mainly produced via $u\overline{u}$ ($d\overline{d}$) annihilation. A precise measurement of the A_{FB} distribution thus can be used to extract $\sin^2\theta_W$ and the $Z-$light quark couplings (g_V^u, g_A^u, g_V^d, g_A^d). About 5 fb^{-1} of data collected by the D0 experiment are used to measure the A_{FB} distribution

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using $Z/\gamma^* \to ee$ events [1]. The Z/γ^* candidates are selected using the requirement of two isolated electrons in the fiducial calorimeter region. The number of selected forward (backward) events is corrected for detector acceptance and selection efficiency in order to get the inclusive cross section for forward (backward) process. The A_{FB} are measured in 15 M_{ee} bins in the range $50 < M_{ee} < 1000$ GeV. Good agreement has been found between the measured A_{FB} distribution and two theoretical predictions using PYTHIA and ZGRAD2. The individual $Z - u(d)$ couplings are extracted by comparing the measured A_{FB} distribution to templates generated with RESBOS for different values of the Z-light quark couplings. World's best direct measurements of the $Z - u(d)$ couplings have been achieved. Events in the Z pole region are also used to determine $\sin^2\theta_W = 0.2309 \pm 0.0008(stat.) \pm 0.0006(syst.)$.

A precise measurement of the distribution of ϕ^*_η has been performed using 7.3 fb^{-1} of data collected by the D0 detector [2]. The variable, ϕ^*_η, is defined as $\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$, where ϕ_{acop} is the acoplanarity angle, given by $\phi_{acop} = \pi - \Delta\phi^{\ell\ell}$, and $\Delta\phi^{\ell\ell}$ is the difference in azimuthal angle between the two lepton candidates. The variable θ^*_η is defined as $\cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2]$, where η^- and η^+ are the pseudorapidities of the negatively and positively charged leptons, respectively. The ϕ^*_η probes the same physical effects as the Z/γ^* boson transverse momentum, but is less susceptible to the effects of experimental resolution and efficiency. 455k dielectron events and 511k dimuon events are used. The observed ϕ^*_η distribution is corrected for experimental effects using Z/γ^* simulated MC events. The corrected particle level ϕ^*_η distributions are compared with the RESBOS predictions in two (three) Z/γ^* rapidity bins, using dimuon (dielectron) events. Predictions from RESBOS are found to be unable to describe the detailed shape of the corrected data, and a prediction that includes the effect of small-x broadening is strongly disfavored.

A first measurement of the angular distributions of final state electrons in $Z/\gamma^* \to ee$ events has been performed by the CDF experiment using 2.1 fb^{-1} of data [3]. The angular distributions (the polar θ and azimuthal ϕ angles in the Collins-Soper frame) are studied and compared with predictions from several MC event generators. Good agreement has been observed for dependencies of four angular coefficients as a function of the dilepton transverse momentum. The relations of these angular coefficients are found to agree with the Lam-Tung relation, which is based on a spin-1 description of the gluon. This study demonstrates that at high values of the transverse momentum, Z bosons are produced via $q\bar{q}$ annihilation and quark-gluon Compton processes.

A $W\gamma$ cross section measurement has been performed in muon channel using 4.2 fb^{-1} of data collected by the D0 detector [4]. The cross section times branching ratio for the process $W\gamma \to \mu\nu\gamma$ is determined for $p_T^\gamma > 8$ GeV and $\Delta R_{\mu\gamma} > 0.7$ The $\mu\nu\gamma$ events are selected by requiring one isolated muon and photon with large missing transverse energy. Photons are required to not be spatially matched to tracker activity. An artificial neural network discriminant is used to separate jets from photons. The dominant background is due to W+jet process, its contribution

is estimated using a data-driven method. The $W\gamma$ cross section is measured to be $15.2 \pm 0.4(stat) \pm 1.6(syst)$ pb, which agrees with the SM expectation of 16.0 ± 0.4 pb. The photon p_T distribution is used to set limits on the anomalous $WW\gamma$ couplings. The one dimensional 95% C.L. limits are $-0.14 < \Delta\kappa_\gamma < 0.15$ and $-0.02 < \lambda_\gamma < 0.02$.

A study of the invariant mass distribution of two jets produced in association with a W boson has been reported by the CDF experiment using 4.3 fb^{-1} of data [5]. Events are selected with one isolated electron or muon, large missing transverse energy and exactly two jets reconstructed with a fixed-cone algorithm with radius $\Delta R = 0.4$. The dominant background due to W+jets and Z+jets processes are estimated using MC event generators and a GEANT-based CDF detector simulation. The generators used are ALPGEN with an interface to PYTHIA providing parton showering and hadronization. The observed distribution has an excess in the 120-160 GeV mass range which is not described by current theoretical predictions within the statistical and systematic uncertainties. Assuming only background contributions, the probability to observe an excess larger than in the data is 7.6×10^{-4} corresponding to a significance of 3.2 standard deviations from a Gaussian distribution.

Both CDF and D0 experiments have measured the production cross section of $\sigma(p\overline{p} \to ZZ)$ with four charged lepton final state $\ell^+\ell^-\ell'^+\ell'^-$ ($\ell, \ell' = e$ or μ) [6, 7]. Ten candidate events are observed by the D0 experiment with an expected background of 0.37 ± 0.13 events. Fourteen candidates events are observed by the CDF experiment with an expected ZZ signal of 10.4 events. The cross section is found to be $1.40^{+0.43}_{-0.37}(stat) \pm 0.14(syst)$ pb (D0) and $2 \pm 0.58(stat) \pm 0.32(syst) \pm 0.12(lumi)$ pb. CDF also performed a ZZ cross section measurement using $ZZ \to \ell\ell\nu\nu$ events [8]. Larger branching ratio and backgrounds are expected compared with the four lepton channel. A neural network discriminant is trained to separated the ZZ signal from the dominant Drell-Yan background. The cross section is measured to be $1.45^{+0.45}_{-0.42}(stat)^{+0.41}_{-0.30}(syst)$ pb. The results from all three measurements are in agreement with a NLO prediction of 1.4 ± 0.1 pb.

3 QCD Physics

Studies with inclusive jets, jets in association with a vector boson (V+jets), and photon pair ($\gamma\gamma$) provide powerful probes of the dynamics of hard QCD interactions. These studies can be used to make precision tests of QCD calculations in different regions of parton momentum fraction x and hard-scattering scales Q^2, determine strong coupling constant α_s, provide stringent constraints on PDFs, test and tune phenomenological models. The V+jets and $\gamma\gamma$ processes are also major backgrounds to many new phenomena searches. A better understanding of their production mechanisms will be useful to improve the new physics search sensitivities.

A first measurement of the inclusive three-jet differential cross section as a func-

tion of the invariant mass of the three jets ($d\sigma_{3jet}/dM_{3jet}$) has been performed by the D0 experiment [9]. The three-jet cross section is directly sensitive to the perturbative QCD (pQCD) matrix element of $O(\alpha_s^3)$, and therefore has a higher sensitivity to α_s as compared to inclusive jet and dijet cross sections, while having a similar sensitivity to the PDFs. Jets are defined by the Run II Midpoint jet algorithm with a cone of radius $\Delta R = 0.7$. The measurement is made in different rapidity regions and for different jet transverse momentum requirements. The data are compared to theoretical predictions which have been obtained from NLO pQCD calculations with non-perturbative corrections applied. The non-perturbative corrections (including corrections due to hadronization and underlying event) are determined using PYTHIA with "tune DW". The best description of the data is obtained for the MSTW2008NLO and NNPDFv2.1 PDF parameterizations which describe both the normalization and the shape of the observed M_{3jet} spectra. The PDF parameterizations from ABKM09NLO give a reasonable description of the data, although with a slightly different shape of the M_{3jet} spectrum. The central results from the CT10 and HERAPDFv1.0 PDF sets predict a different M_{3jet} shape and are in poorer agreement with the data.

A first study of the substructure of jets with transverse momentum greater than 400 GeV has been performed by the CDF experiment using 6 fb^{-1} of data [10]. Massive boosted jets constitute an important background in searches for various new physics models, the Higgs boson, and highly boosted top quark pair production. Jets are reconstructed using the Run II Midpoint cone algorithm using the FASTJET program and the anti-K_T algorithm. The distributions of the jet mass, angularity, and planar flow are measured and compared with the pQCD calculations. Good agreement between PYTHIA predictions, the NLO QCD jet function predictions, and the data for the jet mass distribution above 100 GeV for Midpoint and anti-k_T jets has been observed. The Midpoint and anti-k_T algorithms are found to have very similar jet substructure distributions for high mass jets. Results also show that high mass jets coming from light quark and gluon production are consistent with two-body final states from a study of the angularity variable, and that further rejection against high mass QCD jets can be obtained using the planar flow variable.

D0 experiment used 4.2 fb^{-1} of data and measured the inclusive and differential cross sections of $W(\rightarrow e\nu)+n$ jet process ($n = 1-4$) [11]. The background-subtracted data are corrected for detector resolution effects using a regularized inversion of the resolution matrix as implemented in the program GURU, with ensemble testing used to derive statistical uncertainties and unfolding biases. Considerably smaller uncertainties on W+jets production cross sections than previous measurements are achieved. The differential cross section is measured as a function of jet transverse momentum for jet multiplicities $n = 1 - 4$, normalized to the inclusive $W \rightarrow e\nu$ cross section. The measurements are compared to NLO pQCD calculations (ROCKET+MCFM and BLACKHAT+SHERPA) in the $n = 1 - 3$ jet multiplicity bins and to LO pQCD calculations in the 4-jet bin. The measurements are generally in agreement with pQCD

predictions, although certain regions of phase space are identified where the calculations could be improved.

CDF experiment used 8.2 fb^{-1} of data and measured the inclusive and differential cross sections of $Z(\rightarrow \ell\ell)+ \geq n$ jet process ($\ell = e$ or μ and $n = 1 - 3$) [12]. Jets are reconstructed using the Run II Midpoint algorithm with a cone of radius $\Delta R = 0.7$. The measurements are corrected to the hadron level and compared to NLO pQCD predictions for $n = 1, 2$ and LO pQCD predictions for $n = 3$. The theoretical predictions have non-perturbative corrections applied. Good agreement for both the normalization and shape between data and theoretical predictions has been found for $n = 1, 2$. For $n = 3$, good agreement for the shape has been found between data and the LO predictions. D0 experiment performed a measurement of the ratio of the cross section of a Z boson and at least one b-quark jet to the inclusive Z+jet cross section [13]. The $Z + b$ jet(s) process is a major background to the SM Higgs boson search in $ZH(H \rightarrow b\bar{b})$ associated production. This process is also sensitive to the b-quark PDFs. A discriminant that exploits the properties of the tracks associated to the jet is used to separate $Z + b$ jet(s) events from $Z+$ charm and light jet(s) events. The measurement ratio is 0.0193 ± 0.0027 for events having a jet with transverse momentum greater than 20 GeV and pseudorapidity less than 2.5, which is the most precise to date and is consistent with theoretical predictions of 0.0192 ± 0.0022. The dominant experiment uncertainties come from the uncertainty on the discriminant efficiency and on the shape of the discriminant templates used for the extraction of the b jet fraction. Other important sources of uncertainty are the b tagging efficiency, the b jet energy scale and reconstruction efficiency.

D0 experiment measured the differential cross sections of direct photon pair process using 4.2 fb^{-1} of data [14]. The direct photon pair production constitutes a large and irreducible background to searches for the SM Higgs boson search in diphoton channel and also new phenomena searches such as new heavy resonances and extra spatial dimensions. A requirement on the photon isolation distribution is used to suppress the contributions from photons produced in the fragmentation processes. The dominant backgrounds from γ+jet and jet+jet are estimated using a data-driven 4×4 matrix method. The single differential cross sections are measured as a function of the diphoton mass, the transverse momentum of the diphoton system, the azimuthal angle between the photons, and the polar scattering angle of the photon. In addition, double differential cross sections considering the last three kinematic variables in three diphoton mass bins are also measured. The results are compared with different pQCD predictions and event generators as RESBOS, DIPHOX and PYTHIA, showing the necessity of including higher order corrections beyond NLO as well as the resummation to all orders of soft and collinear initial state gluons. Similar measurement has been performed by the CDF experiment using 5.4 fb^{-1} of data [15]. The overall systematic uncertainty is limited to about 30%. Similar conclusions have been made. Results also show that the inclusion of photon radiation in the initial and final states

can significantly improve the PYTHIA parton shower calculation.

4 Conclusion

Recent electroweak and QCD results from the Tevatron experiments are presented here. These measurements allow us to have better understanding of the electroweak and QCD processes at hadron colliders. Most analyses shown here used 4-6 fb^{-1} of data. With more than 10 fb^{-1} collected by each experiment, we expect to see more individual and combined results from two Tevatron experiments.

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