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Electroweak physics at the Tevatron

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Recent measurements of processes involving the electroweak bosons, Z and W, performed at the Fermilab Tevatron Collider are summarized. The large integrated luminosities collected by both the D0 and CDF Collaborations enable precise measurements of differential single boson production cross sections, the determination of the W mass with unprecedented precision, and the observation of diboson production including ZZ.

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1. Introduction

The analysis of single and pair production of the weak vector bosons Z and W in hadron-hadron collisions provides not only insight into the electroweak interaction (e.g. through the measurements of the couplings of quarks and leptons to the Z boson) but also allows to study the strong interaction (e.g. with measurements of differential boson production cross sections) or even to possibly detect new phenomena beyond the Standard Model (SM, e.g. via an observation of anomalous triple-gauge couplings). Furthermore, a precise measurement of the W boson mass M_W provides an indirect constraint on the mass of the long-sought Higgs boson given the radiative corrections to M_W.

In $p\overline{p}$ collisions at the Fermilab Tevatron collider, the weak boson decays in leptonic final states exhibit very clear experimental signatures. In fall 2008, both the CDF and D0 experiments have collected data sets with integrated luminosities beyond $4\,\text{fb}^{-1}$ at the collision energy of $\sqrt{s} = 1.96\,\text{TeV}$. In the following, we summarize recent results of both collaborations on differential single boson production cross sections, on the mass of the W boson and on diboson production.

2. Single boson production

Inclusive cross sections for the production of Z and W bosons decaying into final states with e, μ or τ were previously published or presented as preliminary results [1, 2]. The D0 collaboration has recently updated their measurement of the inclusive Z boson production cross section in the $Z \rightarrow \tau\tau$ decay channel using a $1\,\text{fb}^{-1}$ data set collected with an inclusive muon trigger [3]. In this analysis, one of the two τ candidates is reconstructed as a decay muon whereas the second is identified as a hadronically or electronically decaying τ using neural networks. The measurement yields $\sigma_Z \cdot Br(Z \rightarrow \tau^+\tau^-) = 237 \pm 15(\text{stat}) \pm 18(\text{syst}) \pm 15(\text{lum})\,\text{pb}$, which is in good agreement with the SM prediction. Furthermore, it verifies the capability to identify isolated τ leptons, which is critical in the search for the Higgs boson in supersymmetric extensions of the SM.

The large data sets being accumulated by both experiments enable precise measurements of differential weak boson production cross sections, which allow to set additional constraints on parton distribution functions (PDFs) and to test corrections to the lowest-order predictions of Quantum Chromodynamics (QCD).

2.1 Z boson transverse momentum distribution

QCD corrections to vector boson production manifest themselves in the radiation of additional quarks or gluons in the final state which gives rise not only to the production of associated jets, but also to a substantial transverse momentum p_T of the produced boson. At large p_T, fixed-order calculations in perturbative QCD (pQCD) are applicable and have been derived up to next-to-next-to-leading order (NNLO) [4]. For low p_T, where the emission of multiple soft gluons becomes important, the leading logarithms in the perturbative expansion can be resummed. The Monte Carlo generator RESBOS accounts for additional non-perturbative corrections using a form factor [5].

The D0 collaboration has recently published a measurement of the p_T distribution in $Z/\gamma^* \rightarrow e^+e^-$ events based on a data set with $1\,\text{fb}^{-1}$ [6]. The NNLO pQCD calculation is found to describe the shape of the distribution at $p_T > 30\,\text{GeV}$, but underestimates the measured rate by $\sim 25\%$.

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The data in the low p_T region is well modeled by RESBOS and disfavors a recently suggested modification of the form factor (small-x broadening) [7].

The D0 collaboration has also presented a preliminary measurement of g_2, a parameter in the non-perturbative form factor, using a data set of $2\,\text{fb}^{-1}$ and both e^+e^- and $\mu^+\mu^-$ decay signatures [8]. A new method with a reduced sensitivity to the lepton p_T resolution is applied, which yields a measurement of g_2 as precise as the previous world average. Future measurements of M_W would benefit from an increased precision on the form factor as the systematic uncertainty due to the modeling of weak boson production would decrease.

2.2 Z boson rapidity distribution

At leading order the boson rapidity y is directly related to the momentum fraction of the scattering partons $x_{1,2} = M_Z/\sqrt{s} \cdot e^{\pm y}$. Thus, its distribution at large $|y|$ probes the PDFs at high momentum transfer $Q^2 \approx M_Z^2$ and at both very large and low x. Similar to a previous D0 publication [9] a preliminary measurement by the CDF collaboration [1] finds a good agreement with higher-order pQCD. The data is compared to various predictions using different PDF sets, but its current precision does not provide significant additional constraints on PDFs.

2.3 W boson charge asymmetry

As u quarks carry on average a higher momentum fraction x than d quarks, W^+ (W^-) bosons are preferentially boosted along the p ($\bar{p}$) direction, thus resulting into a charge asymmetry

$$A(y_W) = \frac{\mathrm{d}\sigma^+/\mathrm{d}y_W - \mathrm{d}\sigma^-/\mathrm{d}y_W}{\mathrm{d}\sigma^+/\mathrm{d}y_W + \mathrm{d}\sigma^-\mathrm{d}y_W}$$

in the W boson rapidity distribution. In leptonic W decays y_W cannot be directly determined since the longitudinal momentum of the decay neutrino is unmeasured. However, the pseudorapidity η_ℓ of the charged lepton from the W decay is correlated with y_W given the $V-A$ coupling of the weak interaction. In addition, for the lepton asymmetry

$$A(\eta_\ell) = \frac{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell - \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell + \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}$$

the systematic uncertainty related to lepton reconstruction largely cancels.

Fig. 1 shows $A(\eta_e)$ as measured by the D0 collaboration in two bins of electron transverse energy E_T^e, which probe different regions of y_W (and thus x) for fixed η_e [10]. For nearly all data points and in particular for $E_T^e > 35\,\text{GeV}$ the experimental uncertainties are significantly smaller that the PDF uncertainty band on the theoretical prediction, which is calculated using the CTEQ6.6 error PDF sets [11].

The CDF collaboration has developed a method to directly measure the W boson asymmetry $A(y_W)$ by reconstructing the y_W distribution using a constraint on M_W [12]. The two possible solutions for the neutrino momentum are weighted with a probability which is iteratively determined from simulation. This new method has an improved statistical sensitivity compared to the measurement of $A(\eta_\ell)$, but since for fixed values of $y_{W^\pm}$ the corresponding lepton pseudorapidities η_ℓ^+ and η_ℓ^- are distinct, the geometric acceptances to reconstruct W^+ or W^- bosons, respectively, can differ by large amounts and the systematic uncertainty due to the lepton reconstruction is increased.

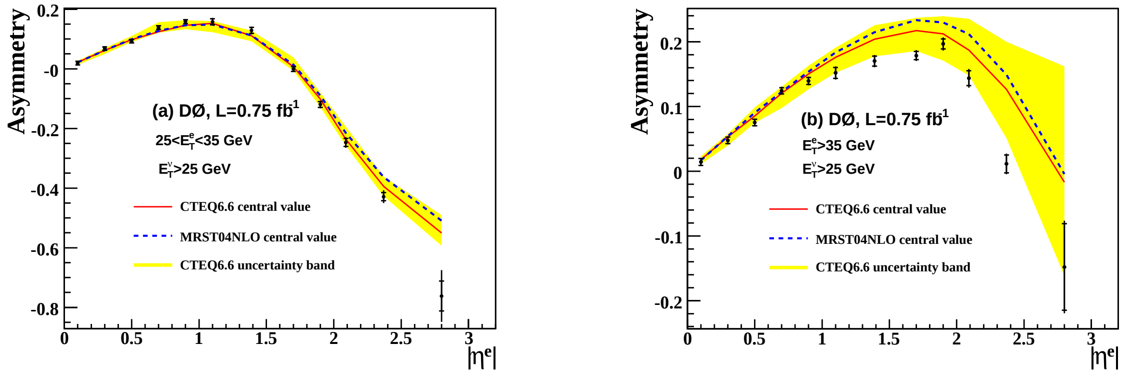

Figure 1: The electron charge asymmetry distribution $A(\eta_e)$ in two E_T^e bins: $25\,\text{GeV} < E_T^e < 35\,\text{GeV}$ for (a) and $E_T^e > 35\,\text{GeV}$ for (b) compared to the predictions based on the CTEQ6.6 (including uncertainty band) and MRST04NLO PDF sets [10].

Similar to the D0 result on $A(\eta_e)$, CDF's preliminary measurement of $A(y_W)$ based on $W \to e\nu$ decays and an integrated luminosity of $1\,\text{fb}^{-1}$ has a higher precision than the PDF uncertainty on the prediction [12].

2.4 Forward-backward charge asymmetry in $Z/\gamma^* \to e^+e^-$ events

A measurement of the forward-backward charge asymmetry A_{FB} as function of the dilepton mass $M_{\ell^+\ell^-}$ in $Z/\gamma^* \to \ell^+\ell^-$ events probes the interference between the γ^* and Z propagators and is sensitive to the vector and axial-vector couplings $g_V^{u,d,\ell}$ and $g_A^{u,d,\ell}$ of the u and d quarks and the final-state lepton to the Z boson. Therefore, A_{FB} also constrains the effective weak mixing angle $\sin^2\theta_W^{\text{eff}}$ and a hypothetical heavy Z' boson would alter A_{FB} for $M_{\ell^+\ell^-} \approx M_{Z'}$.

A previous measurement of A_{FB} based on only $72\,\text{pb}^{-1}$ of integrated luminosity performed by the CDF collaboration put constraints on $g_V^{u,d}$ and $g_A^{u,d}$ complementary to the results from LEP and HERA [13]. The D0 collaboration recently published a measurement of A_{FB} up to dielectron masses $M_{ee} > 300\,\text{GeV}$ using their $1\,\text{fb}^{-1}$ data set and extracted $\sin^2\theta_W^{\text{eff}}$ with a precision comparable to that of the LEP measurements of the inclusive hadronic charge asymmetry [14].

3. Measurement of the W boson mass and width

The new combination of the measurements of the W mass M_W and width Γ_W from the Tevatron Runs and LEP [15] is shown in Fig. 2. The Run I results have been corrected to account for their outdated assumptions on PDFs and Γ_W or M_W, respectively.

The most precise single measurement of M_W has been achieved by the CDF collaboration using $W \to e\nu$ and $W \to \mu\nu$ events collected in a data set with $200\,\text{pb}^{-1}$ integrated luminosity [16]. For this result, the W mass is derived from distributions of the transverse mass m_T, the lepton p_T and the missing transverse energy $\not{E}_T$. The statistical and systematic uncertainty contribute equally to the precision on the measured W boson mass $\Delta M_W = 48\,\text{MeV}$.

A preliminary CDF analysis based on a more than tenfold integrated luminosity L shows that the statistical uncertainty on M_W scales with approximately $\sqrt{L}$, which demonstrates that the measurement of M_W does not degrade with the larger energy pile-up in the calorimeter due to the

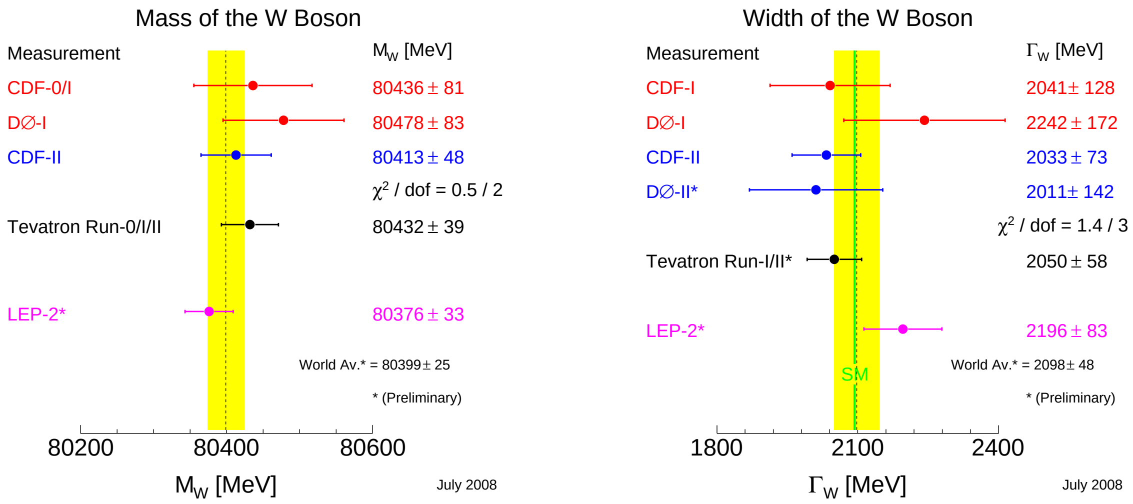

Figure 2: Comparison of the measurements of the W boson mass (left) and width (right) together with their averages [15].

increasing instantaneous luminosity [1]. Whereas the lepton energy scale of the published measurement is mostly constrained by J/ψ and Υ decays due to the limited number of Z boson decays, the improved statistical precision on M_Z with increasing data sets is expected to significantly reduce the scale uncertainty, which is one of the dominating systematic errors in the measurement of M_W.

4. Diboson production

The pair production of the electroweak bosons, W, Z, and γ, probes the trilinear gauge boson couplings predicted by the non-Abelian structure of the SM. Any deviation from the expected couplings, commonly referred to as anomalous couplings, would indicate the presence of new physics beyond the SM. The Tevatron measurements are complementary to those performed at LEP, since the former probe higher energies and are sensitive to different combinations of couplings. As a compilation of all diboson measurements of both CDF and D0 collaborations can be found elsewhere [1, 2], only a few recent results will be presented below.

4.1 Observation of ZZ production

Following CDF's measurement of ZZ production with a significance of 4.4σ [17], the D0 collaboration has reported the first observation of this process with a significance of 5.7σ [18]. Two selections are applied. For $ZZ \to \ell\ell\ell'\ell'$ ($\ell, \ell' = e$ or μ) production, three candidate events, with an expected background of 0.14 events are found in 1.7 fb^{-1} of data corresponding to a significance of 5.3σ. Fig. 3 shows the four lepton invariant mass for these events compared to the expected signal and background distributions. For the other channel, $ZZ \to \ell\ell\nu\nu$, a new estimator for the missing transverse energy with a reduced sensitivity to instrumental mismeasurements resulting in an improved background rejection has been developed (Fig. 3) [19]. After the signal is discriminated from the dominating WW background using a likelihood a significance of 2.7σ is observed. The combined ZZ production cross section is $\sigma = 1.60 \pm 0.63(\mathrm{stat})^{+0.16}_{-0.17}(\mathrm{syst})\,\mathrm{pb}$, consistent with the SM prediction of 1.4 ± 0.1 pb derived at NLO.

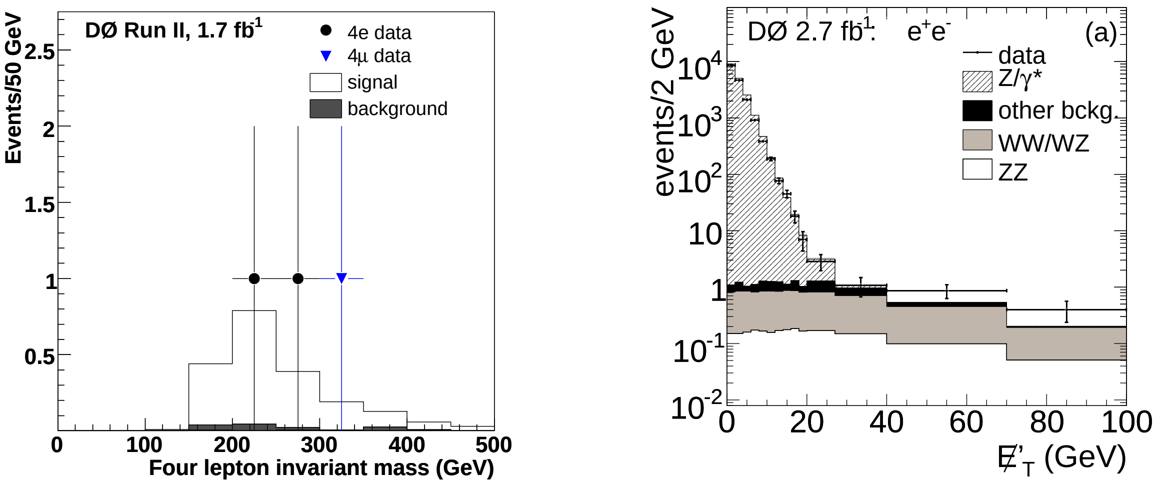

Figure 3: Left: Distribution of four lepton invariant mass in the $ZZ \to \ell\ell\ell'\ell'$ selection [18]. Right: Distribution of the missing transverse energy estimator $\not\!\!E_T{}'$ in the $\to \ell\ell\nu\nu$ selection before applying the $\not\!\!E_T{}'$ requirement [19].

4.2 Limits on anomalous triple gauge couplings

The analysis of WZ production allows to study the WWZ triple gauge coupling independently of the $WW\gamma$ vertex contribution. For the WWZ vertex three CP conserving coupling parameters are defined, which take the following values in the SM: $g_1^Z = 1$, $\kappa_Z = 1$, $\lambda_Z = 0$. In a recent preliminary measurement the CDF collaboration utilizes the p_T distribution of Z bosons in WZ events (Fig. 4) to constrain anomalous contributions to the WWZ triple gauge coupling [1]. As an example, the one and two-dimensional limits on g_1^Z and κ_Z are shown in Fig. 4.

5. Conclusions

The increasing luminosities at Tevatron enable the precise study of single and diboson production as well as the measurement of fundamental parameters like M_W. Furthermore precise measurements are expected from the continuously increasing data sets which are collected by both the CDF and D0 experiments.

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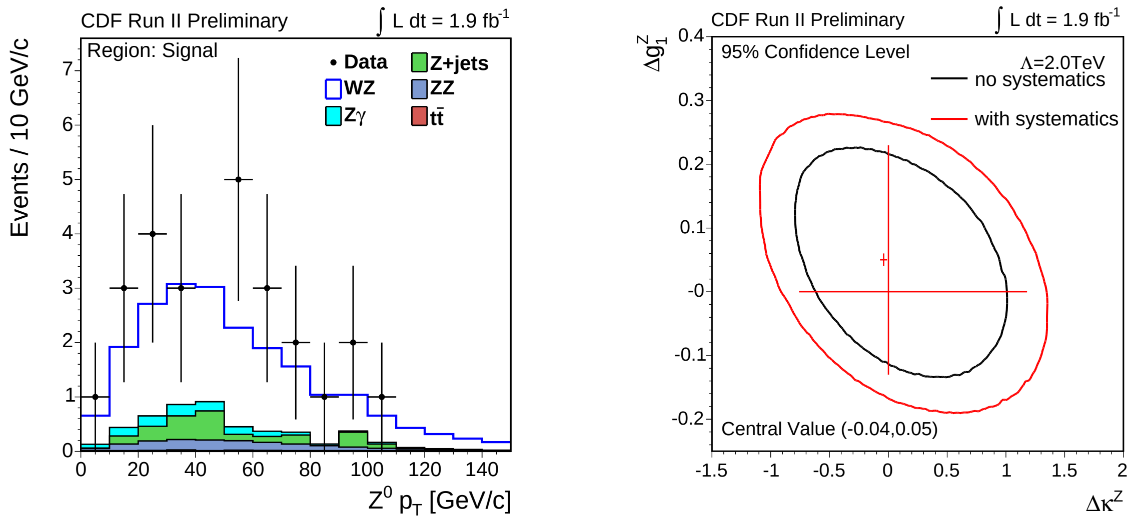

Figure 4: Left: The p_T distribution of the Z boson in WZ candidate events. Right: The one and two-dimensional limits on Δg_1^Z and $\Delta\kappa_Z$ (deviations from SM values) derived from the distribution shown on the left side [1].

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