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Top, electroweak and recent results from CDF and combinations from the Tevatron

D. Lucchesi(1)(2) on behalf of the CDF and D0 Collaborations

(1) *INFN, Sezione di Padova - Padova, Italy*
(2) *Dipartimento di Fisica e Astronomia, Università di Padova - Padova, Italy*

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Summary. — Data collected at the Tevatron proton-antiproton collider are still producing interesting results. Measurements of QCD, top and electroweak quantities are competitive to LHC because of the low center of mass energy, $\sqrt{s} = 1.96\,\text{GeV}$ and due to the fact that this is proton-antiproton data. This report describes the CDF measurement of the prompt photon cross section and the determination of the effective leptonic electroweak mixing angle by CDF and D0 experiments. The combination of the two results gives a precise measurement of $\sin^2\theta^{lep}_{eff}$ from which the W mass is inferred by using standard model calculations.

1. – Introduction

CDF and D0 experiments took data until 2011 at the Tevatron collider at an energy in the center of mass of $\sqrt{s} = 1.96\,\text{TeV}$. Data was produced in proton anti-proton collisions and nowadays its analysis can still give useful physics insight. The precision determination of fundamental standard model observables, like the W mass and the study of quantities which depend on the forward-backward asymmetries, can compete to LHC experiments results. These measurements have intrinsic limitation at LHC due to the high background and the symmetric initial state collisions. In addition to that the low momentum or low invariant mass process are accessible with Tevatron data.

2. – Measurement of the inclusive photon cross section at CDF

Prompt photons are defined as photons produced in the beam particle collisions and not originating from secondary hadron decays. The determination of the production cross section is an important test of the perturbative Quantum Chromodynamics enabling to probe parton distribution functions (PDFs) and the parton-to-photon fragmentation functions. CDF has analyzed the full photon dataset corresponding to $9.5\,\text{pb}^{-1}$ of data collected by requiring photon with a pseudorapidity $\eta < 1$ and minimum transverse

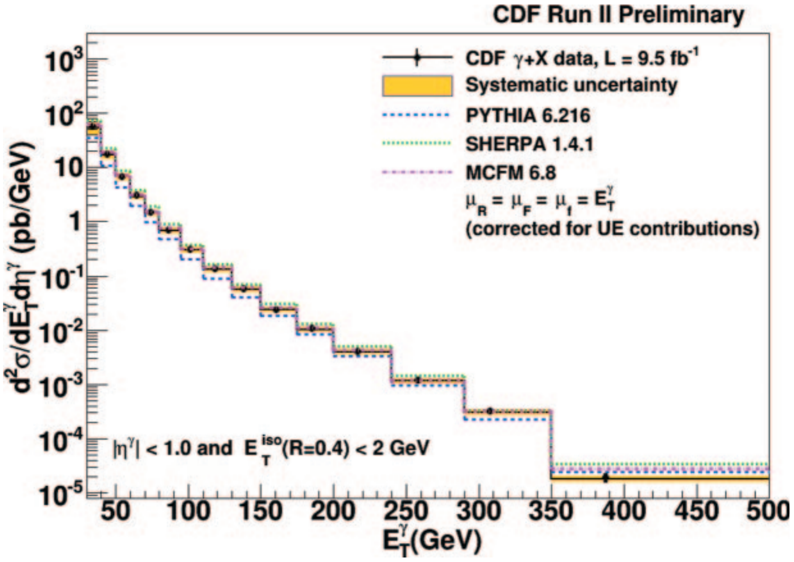

Fig. 1. – Inclusive γ cross section as function of E_T with the theoretical predictions superimposed. The vertical error bars show the statistical uncertainties, while the shaded areas show the systematic uncertainties.

(respect to the beam axis) energy $E_T = 25\,\mathrm{GeV}$. The main background is constituted by photons coming from π^0 and η decay and dijets events. The sample composition, namely the signal fraction, is obtained for each photon in E_T bins by fitting the output distribution of the Artificial Neural Network which was trained to discriminate between prompt photons and QCD background events. By using Pythia [1] Monte Carlo, inclusive photons are generated and then simulated through the detector with CDFSim to determine acceptance and efficiency in bin of E_T. Data is unfolded back to hadron level taking into account the systematic errors that are dominated by the photon energy scale determination and PDF used to produce simulated data. The cross section at hadron level as a function of photon E_T, shown in fig. 1, is compared to three theoretical models: Pythia leading order generator with CTEQ5L PDFs; SHERPA [2], whose calculation includes Matrix Elements with one photon and up to three jets in CDF kinematic region, with CT10 PDFs; MCFM [3], fixed-order NLO calculation including non-perturbative fragmentation at leading order.

In fig. 2, where data is represented by points centered at 1 and data/theory ratio by lines, the reasonable agreement of Sherpa predictions with the measured cross section within theoretical and experimental uncertainties is visible. Pythia predictions underestimate the measured cross sections. MCFM predictions have an overall good agreement with respect to data.

3. – Measurement of the electroweak mixing angle at Tevatron

The production of Drell-Yan lepton pairs at the Born level proceeds through two parton-level processes

$$q\bar{q} \to \gamma^* \to \ell^+\ell^-, \qquad q\bar{q} \to Z^0 \to \ell^+\ell^-,$$

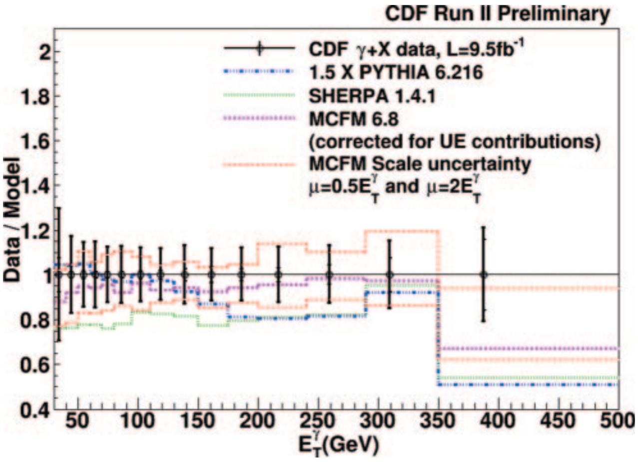

Fig. 2. – Data points centered at 1 and Data/Theory ratio (lines) of the inclusive prompt photon cross section as a function of the photon transverse energy.

where $q\bar{q}$ are the quark and anti-quark of the colliding beams. An interaction vertex of a fermion with a Z^0 contains a vector current and axial current term which depend on $\sin^2\theta_W$. In the standard model at Born level and in all orders of the on-shell renormalization scheme [4] the W mass and the Z^0 mass are related to $\sin^2\theta_W$ by the relationship

$$\sin^2\theta_W = 1 - M_W^2/M_Z^2. \tag{1}$$

By using the well-known Z^0 mass is possible to infer the W mass by measuring $\sin^2\theta_W$. Radiative corrections alter the strength of the Born-level couplings into effective couplings $\sin^2\theta_{eff}^{lep}$. The two most precise determinations of $\sin^2\theta_{eff}^{lep}$ show a tension, the combined LEP-1 and SLD b-quark forward-backward asymmetry bring to $\sin^2\theta_{eff}^{lep} = 0.23221 \pm 0.00029$ [5, 6] while the SLD left-right polarization asymmetry of Z-boson production yields $\sin^2\theta_{eff}^{lep} = 0.23098 \pm 0.00026$ [5,6]. They differ by 3.2 standard deviations.

3˙1. *Electroweak mixing angle and the forward-backward asymmetry.* – The lepton invariant mass is studied in the Collins-Soper framework(CS) [7] with θ being the polar angle of the negatively charged lepton respect to the $q\bar{q}$ interaction direction. The angular distribution in the boson rest frame depends on several terms [8] which reduces just to one, A_4, when the lepton-pair transverse momentum is zero. The $A_4\cos\theta$ term generates the forward-backward ℓ^- asymmetry and it is due to the interference between the Z^0 boson vector and axial-vector amplitudes and the interference of $\gamma^* - Z^0$ amplitudes. The forward-backward cross section asymmetry is given

$$A_{fb} = \frac{\sigma^+(M) - \sigma^-(M)}{\sigma^+(M) + \sigma^-(M)} = f(A_4),$$

where M is the lepton invariant mass, σ^+ (σ^-) is the total cross section for $\cos\theta \geq 0\,(\cos\theta < 0)$. Figure 3 shows the dependence of the asymmetry as a function of the leptons invariant mass from a Drell-Yan QCD calculation. Away from the Z^0

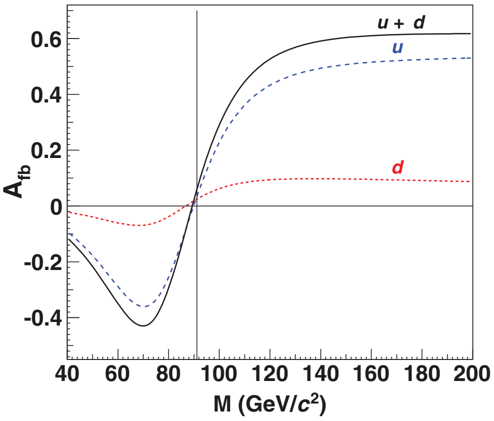

Fig. 3. – Dependence of the A_{fb} on the two leptons invariant mass. The vertical line marks $M = M_{Z^0}$, where is visible the deviation from zero.

mass, the asymmetry is dominated by the component from $\gamma^* - Z^0$ interference, the offset from zero at the Z^0 mass is related to $\sin^2\theta_W$.

3˙2. *Measurement of the leptonic electroweak mixing angle.* – The strategy to perform the measurement is the same for CDF and D0. It consists of:

- Determination of the raw asymmetry background subtracted. The backgrounds are from the production of QCD dijets, W+jets, $\gamma^*/Z^0 \rightarrow \tau\tau$, diboson and $t\bar{t}$. QCD dijets are estimated using data, other backgrounds are evaluated with Monte Carlo simulation.
- Removal of the effects of detector resolution and QED final state radiation (FSR) to get the asymmetry in bin of dilepton invariant mass. Drell Yan events simulated with Pythia + PDF (CTEQ5L for CDF and NNPDF 2.3 for D0) + corrections for final state radiation losses are used to unfold experimental effects.
- Fit the A_{fb} to theory templates generated with different values of $\sin^2\theta^{lep}_{eff}$ in order to determine it.

D0 has used the decay $Z^0 \rightarrow e^+e^-$, the measurement using muon pairs is not yet available, to extract [9]

$$\sin^2\theta^{lep}_{eff} = 0.23147 \pm 0.00043(stat) \pm 0.00019(sys);$$

CDF performed the measurement in both decay channels, the $Z^0 \rightarrow e^+e^-$ [10] and $Z^0 \rightarrow \mu^+\mu^-$ [11], obtaining, respectively,

$$\sin^2\theta^{lep}_{eff} = 0.23248 \pm 0.00049(stat) \pm 0.00019(sys),$$
$$\sin^2\theta^{lep}_{eff} = 0.2315 \pm 0.0009(stat) \pm 0.0004(sys).$$

The systematic error is dominated by the knowledge of the PDF for both experiments.

Table I. – *Summary of the uncertainties for the CDF and D0 measurement of the electroweak-mixing angle.*

Sources	CDF Inputs	D0 Inputs
Statistics	±0.00043	±0.00043
NNPDF PDF	±0.00016	±0.00017
Uncorrelated	±0.00007	±0.00008
Correction		±0.00005

3·3. *Combination of* $\sin^2\theta_{eff}^{lep}$ *measurements.* – The CDF and D0 measurements are combined using the Best Linear Unbiased Estimate (BLUE) method [12]. Table I summarizes the uncertainties of both experiments used as inputs. Statistics refers to the statistical error of the CDF combined measurements and the D0 one. The PDF used in the combination is NNPDF [13] and the uncertainties are treated as 100% correlated. All other input systematic uncertainties are uncorrelated, and put together into a single combination category denoted as uncorrelated. The "Correction" row in the table includes the uncertainty due to the corrections applied to D0 measurement in order to standardize the PDF usage and the radiative corrections. CDF already used the NNPDF 3.0 framework and ZFITTER [14] electroweak radiative corrections.

The result of the combination is

$$\sin^2\theta_{eff}^{lep} = 0.23179 \pm 0.00030(stat) \pm 0.00017(sys).$$

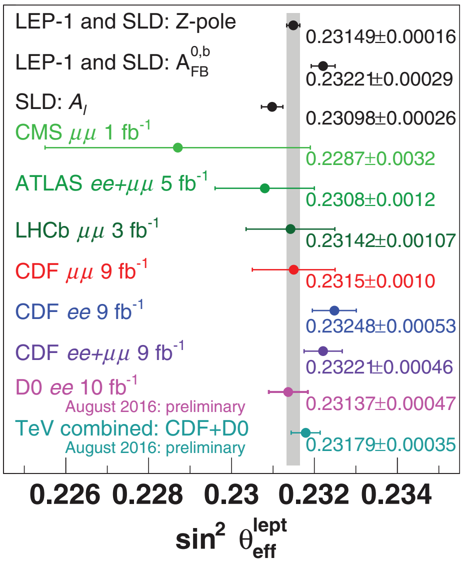

Fig. 4. – Comparison of $\sin^2\theta_{eff}^{lep}$ that includes the best measurements as of this time. Z-pole entry is the standard model analysis using all Z-pole measurements. $A_{FB}^{0,b}$ is the b-quark asymmetry based measurement, and A_l measurement corresponds to pure leptonic couplings [5, 6]. The latest LHC results are also included [15-17]. The Tevatron measurements [9-11] are those used in the combination.

Figure 4 shows a comparison of the most precise measurements of $\sin^2\theta^{lep}_{eff}$. The Tevatron combination has high precision but still not enough to solve the tension between the b-quark forward-backward asymmetry and the left-right polarization asymmetry of Z^0-boson production based measurements.

3·4. *Inference of* $\sin^2\theta_W$ *and* W *boson mass.* – The ZFITTER standard model calculation is used to infer $\sin^2\theta_W$ from $\sin^2\theta^{lep}_{eff}$ exploiting the relationship

$$\sin^2\theta^{lep}_{eff} = Re[\chi_e(M_Z^2)]\sin^2\theta_W .$$

The form factor that multiply $\sin^2\theta_W$ is calculated to be 1.037, it is particularly sensitive to the top quark and Higgs boson mass. The relation reported in eq. (1) is used to determine the W boson mass. The D0 results are

$$\begin{aligned}\sin^2\theta_W &= 0.22313 \pm 0.00041(stat) \pm 0.00020(sys),\\ M_W &= 80.373 \pm 0.021 \pm 0.010\,\mathrm{GeV}/c^2\end{aligned}$$

and for CDF

$$\begin{aligned}\sin^2\theta_W &= 0.22400 \pm 0.00041(stat) \pm 0.00019(sys),\\ M_W &= 80.328 \pm 0.021 \pm 0.010\,\mathrm{GeV}/c^2.\end{aligned}$$

The results of the combination are

$$\begin{aligned}\sin^2\theta_W &= 0.22356 \pm 0.00029(stat) \pm 0.00019(sys),\\ M_W &= 80.351 \pm 0.015 \pm 0.010\,\mathrm{GeV}/c^2.\end{aligned}$$

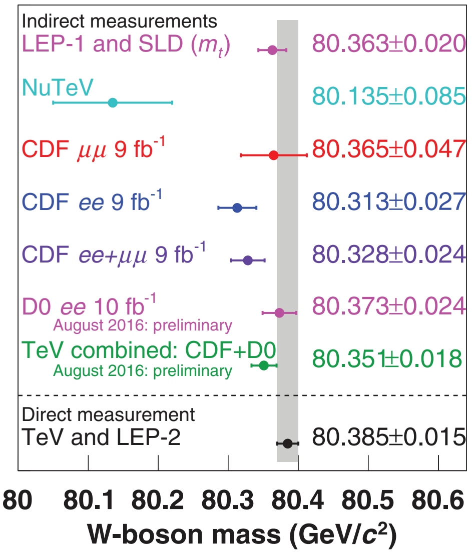

Fig. 5. – The direct W mass measurement is compared to the indirect measurements obtained exploiting the standard model with Tevatron, LEP and SLD data. NuTeV is the neutrino neutral current measurement [18].

In fig. 5 the direct W boson mass measurement is compared to the indirect determinations obtained with ZFITTER that uses the on-shell renormalization scheme [4]. The combined Tevatron measurement is as precise as the direct one, fact that tests the electroweak sector of the standard model.

4. – Conclusions

Two measurements have been presented here demonstrating how Tevatron data can still be useful to determine fundamental quantities of the standard model. In particular the angular distribution of Drell-Yan lepton pairs provides information on the electroweak-mixing parameter, $\sin^2\theta_W$ and therefore the W boson mass. The results are

$$\begin{aligned} \sin^2\theta_W &= 0.22356 \pm 0.00035, \\ M_W &= 80.351 \pm 0.018\,\mathrm{GeV}/c^2. \end{aligned}$$

The current precision can still be improved by adding the D0 dimuons decay channel measurement.

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