IL NUOVO CIMENTO Vol. 33 C, N. 6 Novembre-Dicembre 2010
DOI 10.1393/ncc/i2011-10747-7

Colloquia: IFAE 2010

Top, W and Z: Experimental results

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(ricevuto l' 8 Ottobre 2010; pubblicato online il 18 Gennaio 2011)

Summary. — In this paper we will review the most recent experimental results obtained at Tevatron (Fermilab) on top and electroweak physics.

PACS 14.65.Ha – Top quarks.
PACS 14.70.Fm – W bosons.
PACS 14.70.Hp – Z bosons.

1. – Introduction

Top and electroweak physics are two of the main research fields at the Tevatron accelerator at Fermilab: the precise knowledge of t, W and Z properties is a powerful test of the Standard Model (SM) and can open a window to new physics phenomena. In some cases, like diboson associated production, final states involving these particles represent an irreducible background to Higgs searches. The Tevatron, with more than $7.2\,\text{fb}^{-1}$ of data collected per experiment and the perspective of acquiring $5\,\text{fb}^{-1}$ more by the end of 2011, is currently the ideal place where these particles can be studied in detail. In this paper we will review the most recent CDF and D0 results on t, W and Z physics, obtained with data samples ranging from 0.36 to $5\,\text{fb}^{-1}$.

2. – Top

The t-quark, discovered at Tevatron in 1995 [1, 2], can be considered special among the 6 quarks: it is the heaviest and according to the SM it decays with a branching ratio (BR) of almost 100% in a W-boson and a b-quark without hadronizing; as a consequence, its properties can be measured directly from its decay products.

At Tevatron, where $p\bar{p}$ interactions occur at a center-of-mass energy $\sqrt{s} = 1.96\,\text{TeV}$, it is mainly produced in $t\bar{t}$ pairs via strong interaction through $q\bar{q}$ annihilation (BR $\sim$ 85%) or g-g fusion (BR $\sim$ 15%). Top can also be produced singly via electroweak interaction, though with a cross section much smaller than pair production.

At CDF and D0 experiments $t\bar{t}$ pairs are observed and studied in all possible final states: *dileptonic*, when both W's decay into leptons, *lepton + jets*, where one W decays leptonically and the other into jets of particles, and *all hadronic*, where both W's

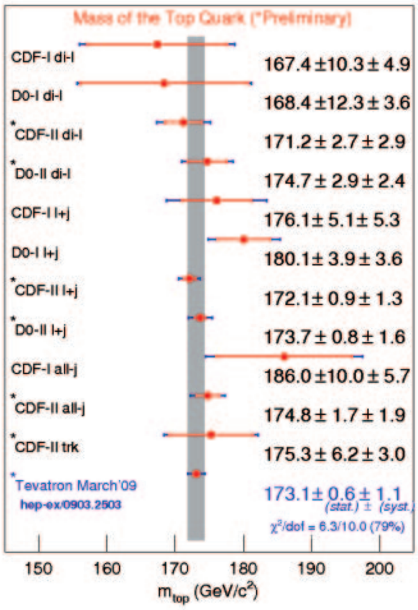

Fig. 1. – Tevatron t mass combination (March 2009).

decay hadronically. The golden channel for t studies is the lepton+jets, which has the highest branching ratio (38%) and a clean signature thanks to the leptonic decay of the W-boson.

2˙1. *Top mass*. – The t-quark mass is a fundamental parameter of the SM and its precise knowledge is necessary to calculate physics observables involving t-quark quantum loops to high precision. In combination with a precise W mass determination, it helps to constrain the Higgs boson mass.

The t mass has been measured at both CDF and D0 experiments in all final states and with different techniques, the Matrix Element [3] and the Template methods [4] being the most used. In fig. 1 we report the most recent combination of CDF and D0 results, together with all the values entering the combination. The measurements are in good agreement and their combined value is $m_t = 173.1 \pm 0.6\ (stat) \pm 1.1\ (syst)\,\mathrm{GeV}/c^2$ [5]. The t mass is now known with a relative precision of 0.75%, limited by the systematic uncertainties which are dominated by the jet energy scale uncertainty. This systematic is expected to improve as larger data samples are collected since the jet energy scale can be constrained *in-situ* using $W \to q\bar{q}$ decays. Both collaborations expect to reach a precision of $1\,\mathrm{GeV}/c^2$ each.

Recently CDF has performed the single most precise top-quark mass measurement ever done: the analysis is performed in the lepton+jets channel on a sample of $4.8\,\mathrm{fb}^{-1}$ applying the Matrix Element technique. Key ingredients of the measurement are the use of a Neural Network discriminant to better distinguish the $t\bar{t}$ signal from the background and an increased acceptance on t events thanks to the inclusion of new muon categories. The result is $m_t = 172.8 \pm 1.3\,\mathrm{GeV}/c^2$: this measurement alone has a precision comparable to the world average [6] and will be soon included in the Tevatron combination.

A very interesting measurement related to the t mass is the determination of the mass difference between t and $\bar{t}$, a direct test of the CPT theorem. D0 has performed the first measurement of this quantity in the lepton+jets channel on $1\,\mathrm{fb}^{-1}$ of data, using the charge of the lepton to infer if the quark is a t or $\bar{t}$. The measured mass difference is $3.8 \pm 3.7\,\mathrm{GeV}/c^2$ [7], consistent with the equality of t and $\bar{t}$ masses.

2·2. *$t\bar{t}$ spin correlations.* – Due to its short lifetime, t quark decays weakly before any hadronization process takes effect, thus enabling its spin information to be transmitted to its decay products. SM $t\bar{t}$ pair production shows a characteristic spin correlation which can be modified by new production mechanisms such as Z' bosons or Kaluza-Klein gluons. The spin correlation coefficient k can be defined as $k = (N^S - N^O)/(N^S + N^O)$ where N^S and N^O are the number of $t\bar{t}$ pairs with parallel and antiparallel spin, respectively. CDF measures this coefficient in the lepton+jets channel on $4.3\,\mathrm{fb}^{-1}$ of data in the helicity basis. The result is $k = 0.60 \pm 0.50$ $(stat) \pm 0.16$ $(syst)$ [8] to be compared with a SM expected value of $k^H_{SM} = 0.40$ in the same basis. D0 performs the same measurement in the dilepton channel on $4.2\,\mathrm{fb}^{-1}$ of data in the beam axis basis: the correlation coefficient is measured to be $k = -0.17^{+0.65}_{-0.53}$ $(stat + syst)$ [9], to be compared with a SM expected value of $k^{BA}_{SM} = 0.78$.

2·3. *Top-quark charge.* – Exotic models of a fourth generation of quarks predict that the t-quark decays to a W^- and a b-quark, hence having a charge of $-4/3$, rather than to a W^+ and a b quark as predicted by the SM. CDF has recently performed a measurement of the t charge in the lepton plus jets channel in $2.7\,\mathrm{fb}^{-1}$. Two b-jets are required to be present in the event: one is identified looking for tracks displaced with respect to the primary vertex; the second looking for soft leptons from the semileptonic decay of the b-quark. The charge of the two W's and two b-quarks is determined for each data event using a kinematic fitter to select the best jet to parton assignment compatible with the t-quark decay. CDF observes 29 events consistent with the SM and 16 events consistent with a $-4/3$ charge t-quark. This results in a 95% confidence level exclusion of the $-4/3$ charge hypothesis [10].

2·4. *Top-quark width.* – In the SM the theoretical t-quark lifetime is very short, of the order of $5 \cdot 10^{-25}$ s, which corresponds to a decay width of 1.5 GeV. Deviations from the predicted value could signal contributions from decays to non-SM particles, for example $t \to H^+ b$. A t-quark width of 1.5 GeV is out of reach of current experiments and direct measurements can only result in upper limits. Recently D0 explored a new technique and measured the t-quark width *indirectly* on $2.3\,\mathrm{fb}^{-1}$ as a function of the theoretical and experimental single-top t-channel cross sections, the theoretical t width and the measured branching ratio of $t \to Wb$. The result, $\Gamma_t = 2.05^{+0.57}_{-0.52}\,\mathrm{GeV}$ [11], is the first indirect and most precise determination of the t-quark width.

2·5. *Single top.* – The search for t-quark produced singly via the electroweak interaction is very challenging due to the small cross section and a less distinctive signature with respect to $t\bar{t}$ pair production. Nevertheless the reasons for studying single t-quark are compelling: its production cross section is proportional to the square of the CKM matrix element $|V_{tb}|$ and it is sensitive to various new physics phenomena. Both CDF and D0 have searched for this signal using sophisticated multivariate techniques (neural networks, boosted decision trees, matrix element and log likelihood methods). In 2009 both collaborations claimed the observation of single t at the 5.0 standard deviations

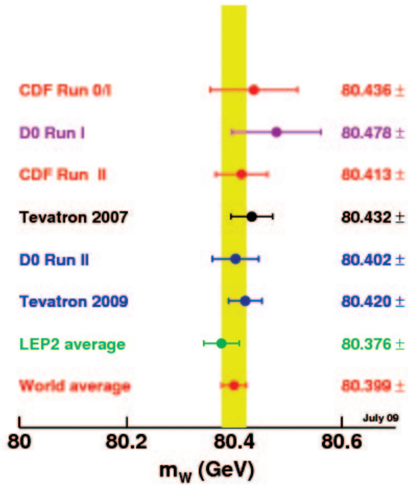

Fig. 2. – W mass world average, along with all the measurements entering the combination.

level of significance. Recently, two CDF measurements and one from D0 have been combined in order to reduce the statistical error on the cross section and provide a stronger constraint on $|V_{tb}|$. The results are $\sigma = 2.76^{+0.58}_{-0.47}$ pb (s-channel and t-channel combined) and $|V_{tb}| = 0.88 \pm 0.07$: combining the three measurements the uncertainty on the cross section is reduced from 22% to 19% while for $|V_{tb}|$ the error is reduced from 14% (CDF) and 11% (D0) to 8% [12].

2˙6. *Search for new physics in the top sector*. – Among the different searches for new physics in the top sector we mention the search for a heavy t, the t', predicted by Little Higgs models and fourth generation theories. According to those theories, this new quark is pair-produced strongly, it has a mass greater than the t and it decays promptly to a W-boson and lighter quarks. CDF has searched for $t'\bar{t}'$ pairs in 4.6 fb^{-1} of data in the lepton+jets final state. A 2-dimensional fit to the reconstructed transverse mass of t' and the scalar sum of all transverse energies of the event showed no evidence for $t'\bar{t}'$ signal. A t' quark with mass below 335 GeV/c^2 has been excluded at 95%CL, given a t mass $M_t = 172.5$ GeV [13].

3. – W mass and width

The precise measurements of W-boson mass and width are of particular importance as a powerful test of the SM and to constrain the SM Higgs boson mass. The measurements are performed in the channel where the W decays leptonically, using a template method applied to the transverse mass and the transverse momenta of the lepton and the neutrino. A very accurate measurement of lepton momentum and hadronic recoil (to estimate the neutrino momentum) is critical to improve the precision of the measurements which is currently limited by the systematic uncertainties on the lepton energy scale and on the parton distribution functions (PDFs). The best and most recent single measurement of the W mass has been made by D0 on 1 fb^{-1} of data in the electron channel. The result is $M_W = 80.402 \pm 0.043$ GeV/c^2 [14]. Combining this measurement with the CDF result Tevatron obtains the value $M_W = 80.376 \pm 0.031$ GeV/c^2 [15] (fig. 2), more precise than LEP2 direct measurement. Both CDF and D0 are analyzing more data and working to further reduce the systematic error: larger $Z \to ll$ ($l = e/\mu$) samples will help to improve the lepton momentum determination, while ongoing measurements of W charge asymmetry and Z rapidity will allow a better knowledge of the PDFs. Tevatron expects to reduce the total uncertainty on the W mass down to 25 MeV. As far as the W width is concerned, both experiments have produced measurements consistent with each other and with the SM: CDF measures $\Gamma_W = 2.032 \pm 0.073$ GeV [16] and D0 $\Gamma_W = 2.034 \pm 0.072$ GeV [17]. In this case both measurements are separately more precise than the LEP2 determination and combined with Run I results give a Tevatron average $\Gamma_W = 2.046 \pm 0.049$ GeV [18].

4. – Diboson production

The diboson production is sensitive to new physics through anomalous trilinear gauge couplings (aTGCs): the presence of anomalous couplings would increase the diboson production cross sections and alter the production kinematics, so any deviation from the expected values could indicate the presence of physics beyond the SM. Moreover, the diboson production is also an important and irreducible background to the search of SM Higgs boson and SUSY.

D0 searches for $Z\gamma$ production, sensitive to $ZZ\gamma$ and $Z\gamma\gamma$ aTGCs, in 3.6 fb^{-1} of data in the channel $Z \to \nu\nu$. It observes 51 signal events with a predicted background of 17.3 and measures a cross section value $\sigma = 39 \pm 9$ $(stat+syst) \pm 2$ $(lumi)$ fb for photons with transverse energy greater than 90 GeV [19]. This measurement, which corresponds to a statistical significance of 5.1 σ and is in good agreement with the theoretical value ($\sigma_{th} = 39 \pm 4$ fb) represents the first observation of $Z\gamma \to \nu\nu\gamma$ at Tevatron. Another interesting diboson state is WW, which is the main background to $H \to WW$ searches, as well as a final state sensitive to $WW\gamma$ and WWZ aTGCs. At Tevatron it has first been observed in the final state with two leptons: thanks to the clean signature and the high statistics, CDF measures a cross section $\sigma(pp \to WW) = 11.5 \pm 2.1 (stat+syst) \pm 0.7$ $(lumi)$ pb [20] and D0 measures $\sigma(pp \to WW) = 12.1 \pm 0.9$ $(stat)$ $^{+1.6}_{-1.4}(syst)$ pb [21], both compatible with the theoretical value $\sigma^{NLO} = 11.7 \pm 0.7$ pb. D0 combines this measurement with other searches for $W\gamma \to l\nu\gamma$, $WZ \to l\nu ll$ and $W(W/Z) \to l\nu + jets$ and obtains the first high-statistics combination of limits on WWZ and γWW aTGCs across different diboson production mechanisms [22]. Both CDF and D0 are working on a future combination of results on 5 fb^{-1} of data to improve the sensitivity to be competitive with LEP.

Finally, in the recent past new challenging signatures have started being explored: CDF looks for a very general final state characterized by missing transverse energy and jets; this search is sensitive to both $l\nu qq$ and $\nu\nu qq$ final states and has acceptance on WW, WZ and ZZ production. In 3.5 fb^{-1} of data, CDF extracts 1516 events with a statistical significance of 5.3 σ, making this measurement the first observation of this diboson final state at a hadron collider [23].

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