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Top and electroweak measurements at the Tevatron

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Summary. — In this report, we summarize the latest results of the top-quark mass and electroweak measurements from the Tevatron. Since the world combination of top-quark mass measurements was done, CDF and D0 experiments improved the precision of several results. Some of them reach the relative precision below 1% for a single measurement. From the electroweak results, we report on the WW and WZ production cross-section, measurements of the weak mixing angle and indirect measurements of W boson mass. The Tevatron results of the weak mixing angle are still the most precise ones of hadron colliders.

1. – Top-quark mass measurements

In the standard model (SM) of particle physics, the top quark is the heaviest elementary particle. The fact that top-quark Yukawa coupling is close to one implies the top quark can play a special role in electroweak (EW) symmetry breaking. The large mass of the top quark constrains its lifetime to become shorter than time needed for hadronization. This allows a precise study of pure quantum-chromodynamic (QCD). Since the top-quark mass (m_{top}) is linked to the W boson and Higgs boson masses through radiative corrections, a precise measurement of the top-quark mass provides a test of EW sector of the SM. In addition, the assessment of the stability of the EW vacuum depends critically on the value of m_{top}.

At Tevatron, the top-quark mass is measured in events containing $t\bar{t}$ pairs. According the SM the top quark decays into W boson and bottom quark in almost 100% of the time, while the W boson decays leptonically ($l\nu$) or hadronically ($q\bar{q}$). Depending on number of W bosons decaying leptonically, we distinguish three different topologies of $t\bar{t}$ events: *dilepton*, *lepton+jets*, and *all-hadronic* decay channel. In the lepton+jets decay channel, only one W boson decays leptonically —into electron or mion and corresponding antineutrino. In dilepton (all-hadronic) decay channel, both W bosons decay leptonically (hadronically).

There are several methods used to measure top-quark mass, however the most common ones are *matrix method* and *template method*.

The matrix method is based on evaluating probability of event with the certain input m_{top} leading to the measured variables. The probability depends on fraction of signal

$t\bar{t}$ events and the probabilities of event representing a signal $t\bar{t}$ event with a given m_{top} or background event. The signal probability can be expressed using parton distribution functions of the colliding proton and anti-proton, the detector response, and the differential partonic cross-section, which is defined by matrix element. The method takes into account event-by-event differences. The final result of measured m_{top} is extracted from global likelihood.

The template method uses variable sensitive to m_{top}, which is reconstructed from top-quark decay products. The templates of the variable are obtained from Monte Carlo (MC) samples generated with different top-quark masses. The top-quark mass is extracted from a likelihood fit of the measured distribution of the sensitive variable to various MC templates. The method is fast, but the statistical uncertainty is worse than the ones obtained from the other methods.

The top-quark mass measured by the methods described above cannot be used directly as an input for precise NLO/NNLO theoretical predictions. The measured m_{top} reflects the mass parameter used in the MC generator. Identifying the nature of the parameter and relating it to common mass schemes, like the pole mass, is a non-trivial problem [1]. However, there are alternative methods to measure top-quark mass. One of them is the extraction of the top-quark pole mass, m_t^{pole}, from the total cross-section measurement. As the total inclusive $t\bar{t}$ cross-section depends on theoretically well-defined top-quark mass (m_t^{pole}, top-quark $\overline{\mathrm{MS}}$ mass, ...), the measured cross-section can be used to constrain it.

1·1. *World combination.* – To get as precise measurement of m_{top} as possible, the experiments combine their results using analytic BLUE method [2, 3]. The method determines the weights to be used in a linear combination of the input measurements by minimizing the total uncertainty of the combined result. In March 2014, the CDF, D0, ATLAS and CMS collaborations performed a combination of their most precise individual m_{top} results. In the combination, six measurements from the Tevatron collider, based on Run II $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$, and five from the LHC, based on pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, are used. Details of the inputs measurements can be found in [4]. The combined $m_{\mathrm{top}} = 173.34 \pm 0.76\,\mathrm{GeV}/c^2$. The relative uncertainty is 0.44% [4].

1·2. *Tevatron combination.* – Since performing the world combination, Tevatron collaborations updated their measurements using the full Run II data. The CDF collaboration updated results from dilepton and all-hadronic decay channels, while D0 collaboration updated result in lepton + jet decay channel. Using the BLUE method, the combination of the Tevatron Run I and Run II measurements supersedes the world combination. The results of the individual measurements used in the combination can be found in [5]. The combined $m_{\mathrm{top}} = 174.34 \pm 0.64\,\mathrm{GeV}/c^2$ is obtained with the relative uncertainty of 0.37% [5].

1·3. *D0 measurement in dilepton.* – After the mentioned combinations were done, the D0 collaboration updated the m_{top} measurement using the full Run II data in dilepton decay channel. The selected events are required to contain two opposite sign leptons (e or μ) and at least two jets, where at least one of the two jets must be iniciated by a b quark. Due to the presence of the neutrinos, additional criteria on the missing transverse energy

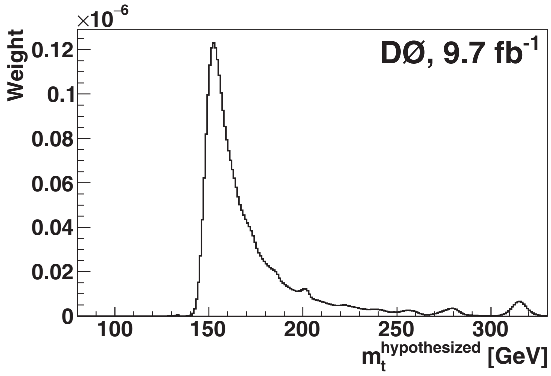

Fig. 1. – Distribution of the weight, $w(m_{\rm top})$, characterizing the level of agreement between the measured and calculated $\not\!\!E_{\rm T}$ for a typical event [7].

($\not\!\!E_{\rm T}$) are applied to ee and $\mu\mu$ events, while a criteria on $H_{\rm T}$([1]) is applied to $e\mu$ events.

As it is impossible to fully constrain the event kinematics due to the presence of the neutrinos, the neutrino weighting method is applied [6]. By scanning the neutrino rapidities, a weight characterizing the level of agreement between the measured and calculated $\not\!\!E_{\rm T}$ is obtained for chosen values of hypothesized top-quark mass in each event. A weigh distribution for a typical event is shown in fig. 1. The most of the information about $m_{\rm top}$ can be extracted from the first two moments (μ_w, σ_w) of the weight distribution $w(m_{\rm top})$.

The selection criteria and parameters of the recontrsuction are optimized to minimize the statistical uncertainty. In the measurement, the template method is used. Different templates of the μ_w are shown in fig. 2. The result is extracted by performing the maximum likelihood fit to the extracted moment distributions [μ_w,σ_w] in data. The observed $m_{\rm top} = 173.32 \pm 1.36({\rm stat.}) \pm 0.85({\rm syst.})\,{\rm GeV}/c^2$. The systematic uncertainty is dominated by jet energy scale and higher-order effects. The relative uncertainty of 0.93% makes the measurement the most precise dilepton measurement at the Tevatron [7].

1˙4. *Top-quark pole mass.* – To extract the top-quark pole mass from the inclusive $t\bar{t}$ cross-section measurements, the D0 collaboration use the full Run II data of lepton+jet and dilepton decay channels. The measurement uses various Multi Variate Analysis (MVA) techniques described in [8]. In order to determine the inclusive $t\bar{t}$ cross-section a simultaneous log-likelihood fit to the lepton+jets and dilepton decay channel MVA discriminants, is performed. The procedure is repeated for different top-quark mass and the dependence is parametrized with a cubic fit. Comparing the top quark mass dependence of the measured inclusive $t\bar{t}$ cross-section with the expected dependency yields a theoretically well-defined $m_t^{\rm pole}$ (see fig. 3). The extracted value is $169.6^{+3.3}_{-3.4}\,{\rm GeV}/c^2$. The relative precition of the measurement is 1.9% [8].

([1]) The H_T is the scalar sum of the transverse momenta ($p_{\rm T}$) of the two highest-$p_{\rm T}$ jets and of the lepton with the highest $p_{\rm T}$.

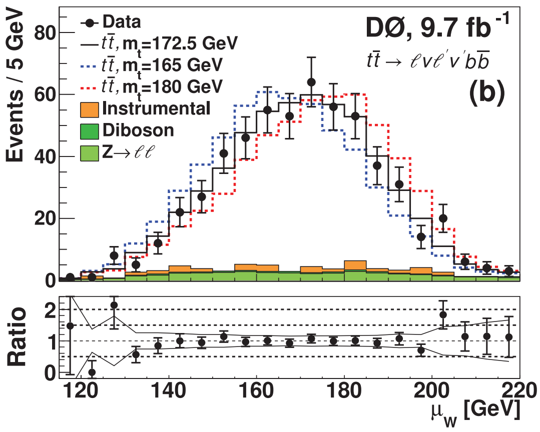

Fig. 2. – The distribution in the mass estimator μ_w. The ratios show the total number of observed events divided by the MC number of expected events in a given bin of μ_w for $m_{\text{top}} = 172.5\ \text{GeV}/c^2$ [7].

2. – Electroweak measurements

2·1. *WW and WZ production cross sections*. – The measurements of the cross-sections directly probe triple gauge coupling terms of the SM. Using the full Run II data, the CDF selects events with one W boson decaying leptonically ($l\nu$) and the other boson decaying hadronically ($q\bar{q}$, *e.g.*, $W^+ \to c\bar{s}$, $Z \to c\bar{c}$, $b\bar{b}$). A jet originated from the b- or c-quark is identified by a Heavy Flavour (HF) tagger, which is based on the presence of the secondary vertex. The sample is then divided into two subsamples: with single or double HF-tags. A Flavour-separator Neural Network (NN) is optimized to distinguish the b-, c-, and light-quark jet. The output of the NN together with a distribution of

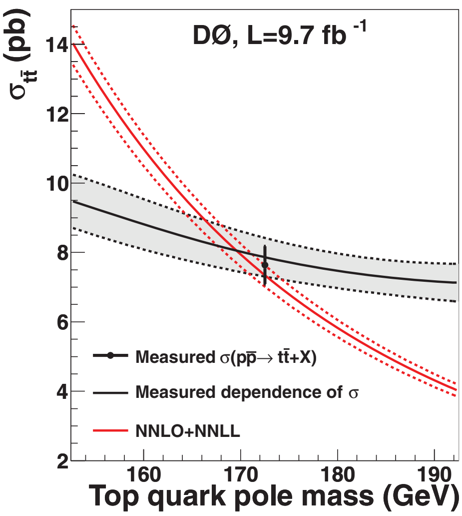

Fig. 3. – The measured $t\bar{t}$ production cross-section dependency on the top quark mass compared to the one provided by the NNLO pQCD calculation [8].

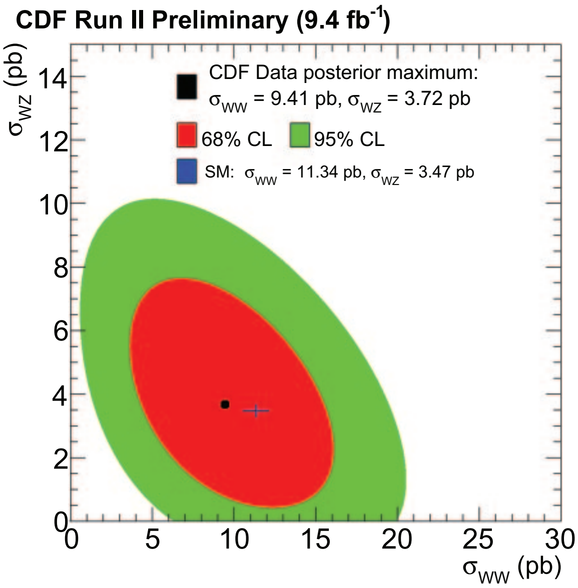

Fig. 4. – The Bayesian posterior shown in the σ_{WW}-σ_{WZ} plane. The measured cross-sections correspond to the maximum value of $\sigma_{WW} = 9.4$ pb and $\sigma_{WZ} = 3.7$ pb. The red and green areas represent the smallest intervals enclosing 68% and 95% of the posterior integrals, respectively [9].

the dijet invariant mass, M_{jj}, are used to distinguish WW and WZ production. To discriminate signal from background, two-dimensional distribution of the NN output and M_{jj} is used in events with one HF-tag, while only M_{jj} distribution is used in events with two HF-tags.

The final result is extracted by a Bayesian statistical analysis, which use systematic uncertainties as a nuisance parameters. The observed cross-section of $\sigma_{WW+WZ} = (13.7 \pm 3.9)$ pb is consistent with an evidence (significance of 3.69σ) for $WW + WZ$ associate production and with the SM expectation [9].

As the WW and WZ processes can be distinguished by the NN output and M_{jj} distributions, the CDF measures the production cross-section of two processes separately. The values of $\sigma_{WW} = 9.4 \pm 4.2$ pb and $\sigma_{WZ} = 3.7^{+2.5}_{-2.2}$ pb are observed with a significances of 2.87σ adn 2.12σ for WW and WZ production, respectively. The results are consistent with the SM predictions [9], as shown in fig. 4.

2·2. *Weak mixing angle*. – The weak mixing angle is measured very precisely. However, the two most precise measurements differ by 3.2σ and the LHC Run 1 measurements have higher uncertainties (see fig. 5).

The latest CDF measurement uses the full Run II data of e^+e^- pairs from Drell-Yan process. The electron angular distribution is affected by fermion coupling to a virtual photon and Z boson and a forward-backward asymmetry, A_{FB} can be measured. There are two sources of the asymmetry: $\gamma^\star$-Z interference and Z self-interference. The former mentioned affects the shape of the A_{FB} as a function of lepton-pair invariant mass, while the latter is a product of fermion vector couplings from lepton and quark vertices and is directly related to the electroweak mixing angle, $\sin^2\theta_W$. The coupling strength is altered by a few percent due to the loop and radiative corrections, so the measured quantity is an effective mixing angle at lepton vertex, $\sin^2\theta^{lept}_{eff}$.

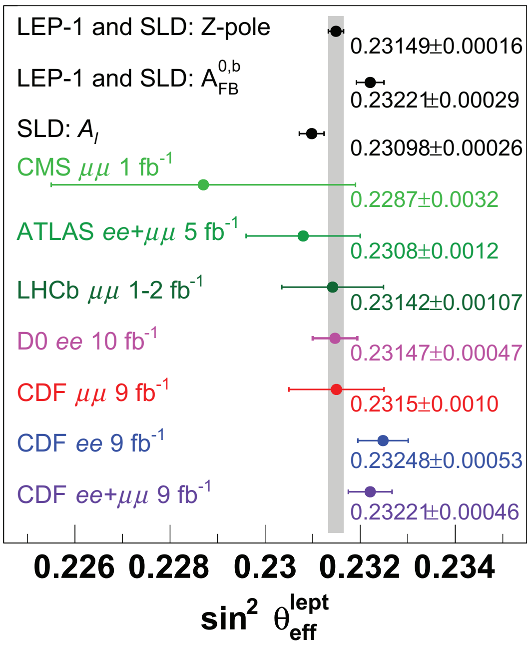

Fig. 5. – Comparison of experimental measurements of effective weak mixing angle at lepton vertexes [10].

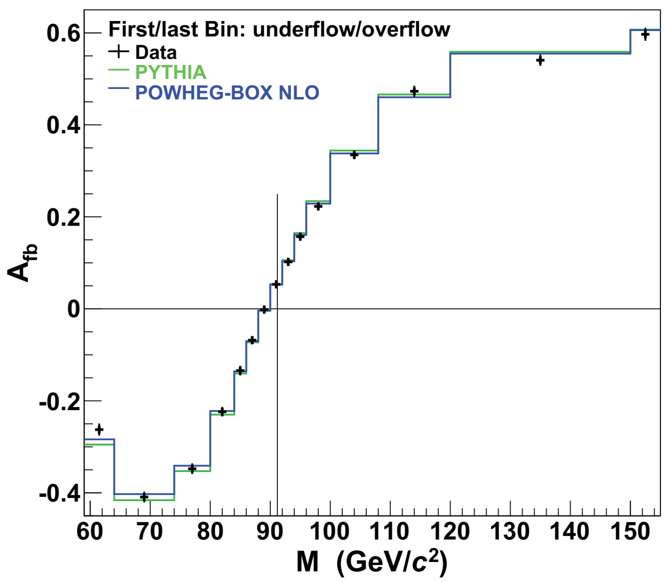

Fig. 6. – Fully corrected forward-backward asymmetry of produced electron pairs [10].

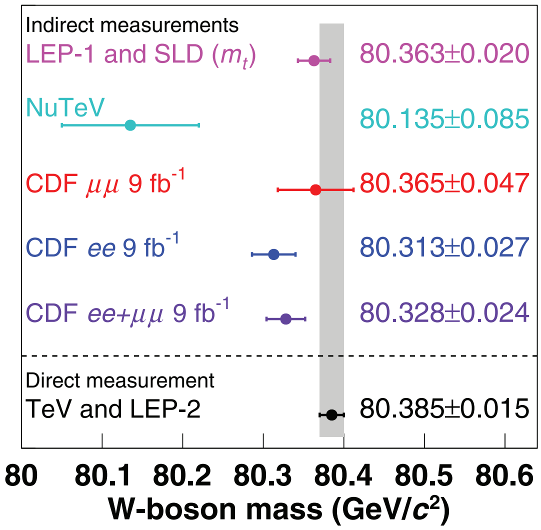

Fig. 7. – Comparison of experimental determinations of the W-boson mass [10].

The CDF measures the A_{FB} in 15 bins of lepton-pair invariant mass. The distribution obtained after performing corrections on the resolution unfolding, acceptance, and detector non-uniformities, is shown in fig. 6. The measured distribution is compared to Monte Carlo templates calculated with different values of $\sin^2\theta_W$. The final results of $\sin^2\theta^{lept}_{eff} = 0.23248 \pm 0.00049(\text{stat}) \pm 0.00019(\text{syst})$ and $\sin^2\theta_W = 0.22428 \pm 0.00048(\text{stat}) \pm 0.00020(\text{syst})$ are obtained by evaluating χ^2 for each template. The higher source of the systematic uncertainty comes from parton distribution functions [10].

The most precise measurement of the effective mixing angle from hadron colliders is obtained by combining the above CDF measurement with the one based on muon pairs [11]. The combined result is $\sin^2\theta^{lept}_{eff} = 0.23221 \pm 0.00043(\text{stat}) \pm 0.00018(\text{syst})$ [10].

2·3. *Indirect measurement of W boson mass.* – Using the result of the measurement of the weak mixing angle and the on-shell renormalization scheme, it is possible to derive the W-boson mass from the equation

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

where $M_Z = 91.1875\,\text{GeV}/c^2$ [12] and M_W are the Z- and W-boson masses, respectively. The W-boson mass obtained from the measurement is $80.328 \pm 0.024\,\text{GeV}/c^2$ [10]. The comparison to the other indirect measurements of M_W are summarized in fig. 7.

3. – Conclusions

The Tevatron experiments finalize measurements with the full Run II data. There are many top-quark-mass measurements updated since the World combination. More optimized analysis with an improvements in the systematic treatment helped also to increase the precision of the latest Tevatron combination. The measurement of the top-quark pole mass is the most precise one at the Tevatron. From the electroweak measurements, the WW and WZ production cross-sections are compatible with the SM predictions and the latest result of the weak mixing angle is more precise than the results from the LHC experiments.

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