SELECTED PHYSICS RESULTS FROM THE D0 EXPERIMENT AT THE TEVATRON

PNPI participants of the D0 Collaboration:
G.D. Alkhazov, S.V. Evstyukhin, V.T. Kim, A.A. Lobodenko, P.V. Neustroev,
G.Z. Obrant, V.A. Oreshkin, Yu.A. Shcheglov, L.N. Uvarov, S.L. Uvarov

1. Introduction

D0 is an international collaboration of about 670 physicists from 83 institutions, who have designed, built and operated a collider detector at the Fermilab Tevatron.

Main physics goals are precision tests of the Standard Model (SM), the weak bosons physics, top quark physics, Quantum ChromoDynamics (QCD), *B* physics, a search for the Higgs boson, and a search for particles and forces beyond the SM: super-symmetric particles, gravitons, candidates for the cosmic dark matter, and a search for extra dimensions.

During Run II, the Tevatron was operated at an increased $p\bar{p}$ centre-of-mass energy of 1.96 TeV. The luminosity was increased by a factor more than ten, to $\geq 10^{32}$ cm^{-2} s^{-1}. Originally, the Tevatron operation and data taking was planned up to 2009. However, the Tevatron operation was extended to 2011. By the end of September 2011, the data taking was completed, and the Tevatron was shut down. The data, corresponding to about 11 fb^{-1} of an integrated luminosity, have been collected by the D0 experiment. Analyses of the collected data will continue a few more years.

PNPI was involved in the D0 project through the design and programming of the electronic readout for mini drift tubes (50000 channels) and operation of the Forward Muon System [1]. PNPI physicists took part in the data analysis, including QCD, *B* physics, and Electroweak and New phenomena physics studies. Among main D0 physics results are the top-quark mass, B_s mixing frequency, cross section for single top-quark production, discovery of the cascade Ξ_b baryon. This report presents several D0 results obtained in 2007–2012 years.

2. D0 detector

The Run II D0 detector (Fig. 1) [2] consists of a central tracking system, a liquid-argon/uranium sampling calorimeter and an iron toroid muon spectrometer.

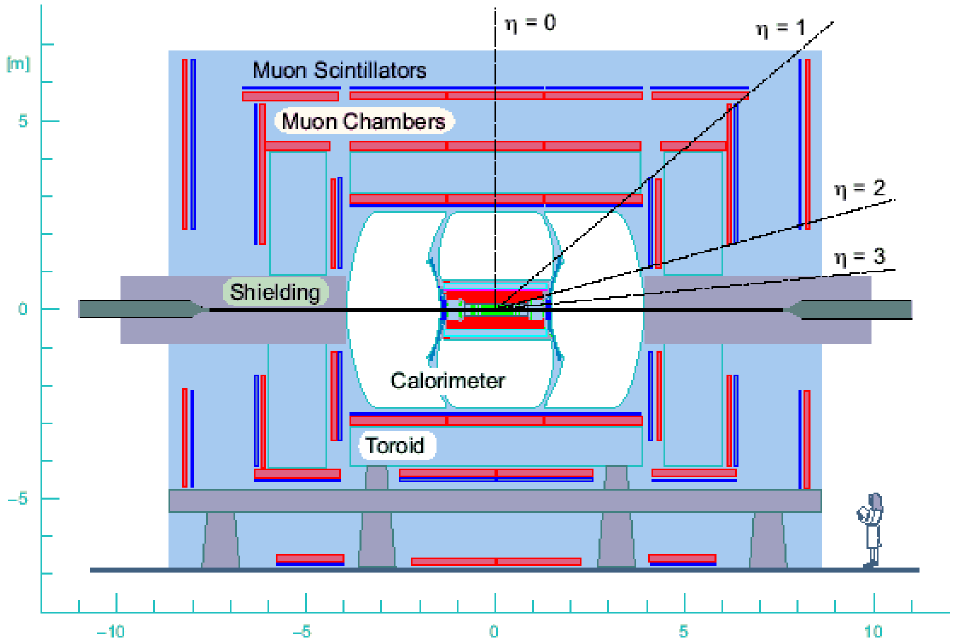

Fig. 1. Schematic view of the D0 detector

The central tracking system is composed of a Silicon Microstrip Tracker (SMT) and a central fiber tracker, both located into a 2 T superconducting solenoidal magnet. The SMT detector has about 800000 individual strips, and its design is optimized for tracking and vertexing capabilities allowing heavy flavour tagging. The calorimeter is longitudinally segmented into electromagnetic and hadronic layers and is housed into three cryostats. The muon system [3] resides beyond the calorimeter and consists of a layer of tracking detectors and scintillation counters before the toroidal magnet, followed by two similar layers after the toroid. Tracking in the muon system relies on wide or mini drift tubes depending on the acceptance. The Run II D0 detector allows to work at the luminosity of > 10^{32} cm^{-2} s^{-1}. The D0 detector is described in detail in [2].

3. Top quark production cross section and mass

The t quark, the heaviest particle known, was discovered at the Tevatron in 1995. Since then, the study of the top quark was one of important directions of investigations at D0. In the triggering and analysis, the event selection was done with high p_T leptons, high E_T multiple jets, a large missing energy E_T and displaced vertices for b-jets. The cross section for the $t\bar{t}$ production was measured by several methods [4]. The determined $t\bar{t}$ production cross section is $\sigma_{t\bar{t}}$ = $= 7.6 \pm 0.6$ pb [5]. Note that within the SM the measured $t\bar{t}$ production cross allows one to predict the top-quark mass: M_t = 168 ± 6 GeV/c^2 [6], which agrees with the results of direct top-quark measurements presented below.

The top-quark mass is a fundamental SM parameter. Together with the W mass, it provides a constraint on the Higgs boson mass. Different methods were used at D0 to derive the top-quark mass. The combined result for the top-quark mass, obtained by the D0 and CDF Collaborations from the data of Run I and Run II, is [7]: $M_t = 173.2 \pm 0.9$ GeV/c^2 (Fig. 2). This is the most accurate measurement of the top-quark mass by now.

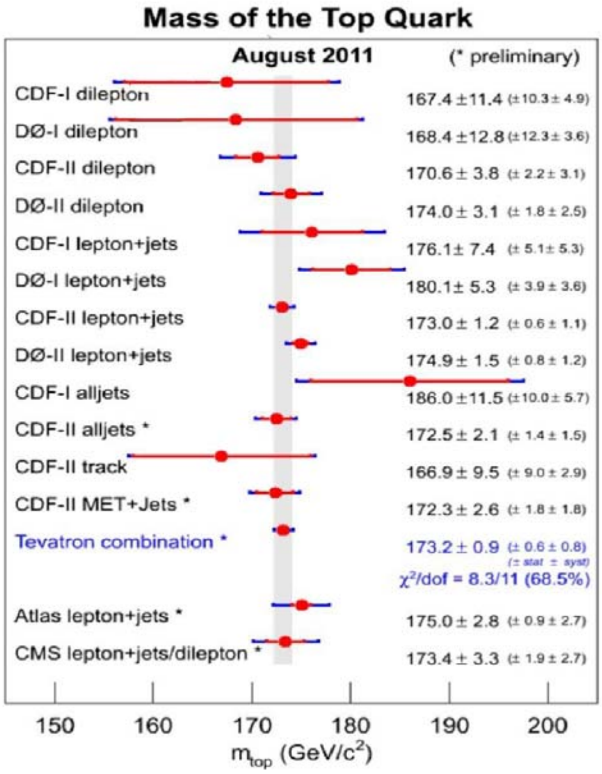

Fig. 2. Results of the t-quark mass measurements in the experiments D0 and CDF

4. Single top-quark production

The top quarks are produced mainly in their $t\bar{t}$ production mode. The single top-quark production with the tb or tqb final states is also possible via the electroweak interaction. However, the cross section for single top-quark production is smaller, while the contribution of background is larger. A measurement of this cross section can be used to constrain the magnitude of the CKM matrix element V_{tb} and to study the Wtb coupling. The event selection in the search for single top quarks is similar to that for the search for top-quark pairs in the l + jets mode.

For the first time, the production of single top quarks was observed by the D0 Collaboration. Using events containing an isolated electron or muon and missing transverse energy, together with jets originating from the fragmentation of b quarks, the cross section for the production of single top quarks in the reactions $p\bar{p} \rightarrow tb + X$, $p\bar{p} \rightarrow tqb + X$ was measured to be 3.43 ± 0.74 pb [8]. The probability to measure a cross section at this value or higher in the absence of signal is about $2.5 \cdot 10^{-7}$, corresponding to a 5.0 standard deviation significance for the observation. The measured cross section was used to determine the CKM matrix element that describes the Wtb coupling. The found value of V_{tb} is $0.79 < |V_{tb}| \leq 1$ at 95% C.L., which agrees with the SM.

5. Mass difference of the top and anti-top quarks

According to the CPT theorem, the mass of an elementary particle should be equal to that of its anti-particle. This is one of the most fundamental principles of the SM, which refers also to the masses of the quarks and antiquarks. The top quark is the only quark which mass can be determined experimentally. Indeed, no bound states are formed before decay of produced top quarks, thereby providing a unique opportunity to measure directly the mass difference between a quark and its antiquark. The difference between the masses of the top and antitop quarks were measured by the D0 experiment with high accuracy, the determined mass difference being $\Delta M = 0.8 \pm 1.8$ (stat) ± 0.5 (syst) GeV/c^2 [9]. Figure 3 shows the two-dimensional plot for the results of mass measurements for the top and anti-top quarks. The performed measurements are compatible with no mass difference at the level of ≈ 1 % of the mass of the top quark.

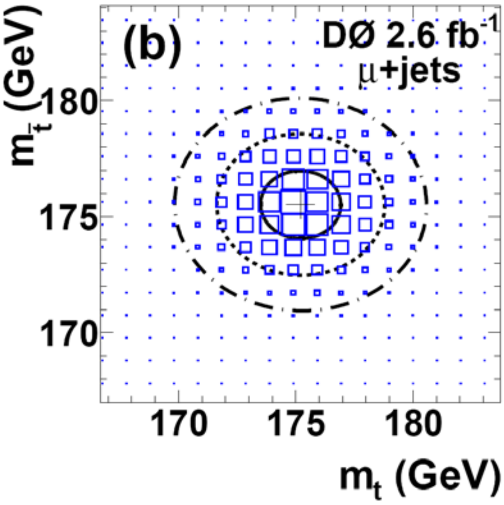

Fig. 3. Two-dimensional plot for the masses of the top and anti-top quarks

6. Top quark pair spin correlation

Although top and antitop quarks are produced unpolarized at hadron colliders, their spins can be correlated, and a significant correlation is expected in the SM. The strength of the spin correlation depends on the production mechanism and differs, for example, for top quark pair production at the Tevatron, where the $q\overline{q}$ production mechanism dominates, and for top quark pair production at the LHC, where the gg production mechanism dominates. The SM predicts that the top quark decays before its spin flips. The spin of the top quark is therefore reflected by its decay products, which allows one to measure the correlation between the spins of pair-produced top and antitop quarks. The D0 Collaboration has measured the top pair quark spin correlation, and for the first time has provided evidence for the presence of spin correlation in $t\overline{t}$ events with a significance of more than three standard deviations. The measured spin correlation coefficient is $A = 0.66 \pm 0.23$ (stat + syst) [10]. This value is consistent with the SM prediction of $A = 0.78$.

7. QCD studies

Motivations of the QCD studies are to use the strong interaction processes for an investigation of the internal proton structure, a search for the quark substructure, a study of the diffractive and heavy flavour production, a study of new objects, like $X(3872)$, and for the understanding of backgrounds to the physics beyond the SM.

The D0 Run II results [11] cover the QCD cross section for inclusive jets production which changes up to 8 orders of magnitude (Fig. 4). The next-to-leading order (NLO) QCD predictions describe the data within the experimental uncertainties for different rapidity $|y|$ intervals in the whole p_T range considered.

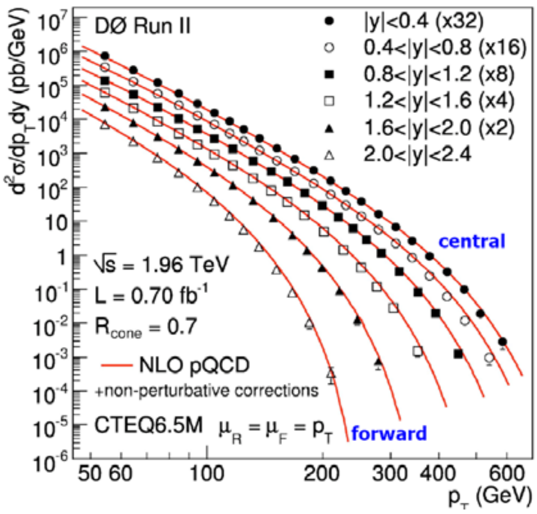

Fig. 4. Cross sections for jet production for different rapidity intervals versus p_t

8. Anomalous like-sign dimuon charge asymmetry

Studies of particle production and decay under the reversal of discrete symmetries (charge, parity and time) have yielded considerable insight into the structure of theories that describe high energy phenomena. Of particular interest is the observation of CP violation, a phenomenon well established in the K^0 and B_d^0 systems, but not in the B_s^0 system, where the effect of the CP-violation is expected to be small in the SM. The violation of CP symmetry is a necessary condition for baryogenesis, the process for the matter-antimatter asymmetry in the universe. However, the observed level of CP violation in the K^0 and B_d^0 systems is not sufficient to accommodate this asymmetry, suggesting the presence of additional sources of CP violation beyond the SM.

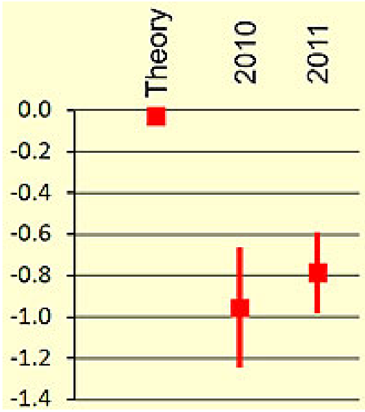

Fig. 5. Asymmetry A_{sl}, measured at D0 in 2010 and 2011, in comparison with theory

The D0 experiment is well suited to the investigation of the small effects of CP violation because the periodic reversal of the D0 solenoid and toroid magnetic field polarities results in a cancellation of most detector-related asymmetries. The charge asymmetry A for like-sign muon pairs was measured by the D0 experiment in 2010 using the data corresponding to an integrated luminosity of 6.1 fb^{-1} [12], and in 2011 using the data of an integrated luminosity of 9 fb^{-1} [13]. The like-sign dimuon charge asymmetry A is defined as $A = (N^{++} - N^{--}) / (N^{++} + N^{--})$, where N^{++} and N^{--} represent the number of events in which the two muons of highest transverse momentum, satisfying the proper kinematic selections, have the same positive or negative charges. After removing contributions from background and from remaining detector effects, any residual asymmetry A_{sl} is assumed to arise solely from the mixing of B_q^0 ($q = d, s$) mesons (via $B_q^0 \leftrightarrow \overline{B}_q^0$ oscillations) that later decay semileptonically. The result of 2010 measurement was $A_{sl} = -(0.96 \pm 0.25\ \text{(stat)} \pm 0.15\ \text{(syst)})$ % (Fig. 5). This asymmetry is significantly larger than that predicted by the SM, and disagrees with the SM prediction $A_{sl} = -0.02$ % by 3.2 standard deviations. The analysis of 2011 has confirmed the result of 2010, the measured asymmetry being equal to $A_{sl} = -(0.79 \pm 0.17 \pm 0.09)$ % . This result differs by 3.9 standard deviations from the prediction of the SM and provides evidence for anomalously large CP violation in semileptonic neutral B decay.

9. Forward-backward asymmetry in top quark-antiquark production

At lowest order in QCD, the SM predicts that the kinematic distributions in $p\overline{p} \to t\overline{t} + X$ production are charge symmetric. However, NLO calculations predict forward-backward asymmetries of (5–10) %, but next-to-next-to leading order calculations predict additional significant corrections for $t\overline{t}$ production. Processes beyond the SM can modify the $t\overline{t}$ production asymmetry. Therefore, the small asymmetries expected in the SM make this a sensitive probe for new physics.

For the first time, the forward-backward production asymmetry defined as $A_{fb} = (N_f - N_b) / (N_f + N_b)$, where N_f (N_b) is the number of events with a positive (negative) rapidity difference between the top and antitop quarks $\Delta y = y_t - y_{\overline{t}}$ was measured in the D0 experiment in 2007 [14]. A relatively small sample of 0.9 fb^{-1} of data, collected at that time by the D0 experiment, was used to determine the asymmetry. The obtained result was consistent within relatively large errors with the SM prediction. In 2010, the forward-backward production asymmetry was measured by the CDF experiment using a larger data sample. A rather large asymmetry, several times larger than that predicted by the SM, was obtained in that new measurement.

In 2011, the D0 experiment presented a new forward-backward asymmetry measurement based on a dataset corresponding to an integrated luminosity of 5.4 fb^{-1}. When corrected for detector acceptance and resolution, the asymmetry in top quark-antiquark production in proton-antiproton collisions was found to be (19.6 ± 6.5) % [15], to be compared with the SM NLO prediction of (5.0 ± 0.1) %. A forward-backward asymmetry was also determined in an alternative approach that does not depend on a full reconstruction of the $t\bar{t}$ system – a measurement of a forward-backward asymmetry based only on the rapidity of the lepton in the final state. The determined asymmetry for this case was (15.2 ± 4.0) %, to be compared with the SM NLO prediction of (2.1 ± 0.1) %. The asymmetries measured in D0 data disagree with the SM NLO-based predictions, with the most significant discrepancy above three standard deviations.

10. *W*-boson mass

Since the masses of the W boson, top quark, and the Higgs boson are related via radiative corrections, the Higgs mass M_H can be constrained with the precision measurements of the W-boson and top-quark masses M_W and M_t. Knowledge of M_W is currently a limiting factor in our ability to tighten the constraints on the Higgs-boson mass. Improving the measurement of M_W is an important contribution to our understanding of the electroweak interaction, and, potentially, of how the electroweak symmetry is broken. The previous world-average measured value was $M_W = 80.399 \pm$ $\pm\, 0.025$ GeV/c^2 from a combination of measurements from ALEPH, DELPHI, L3, OPAL, D0 and CDF Collaborations.

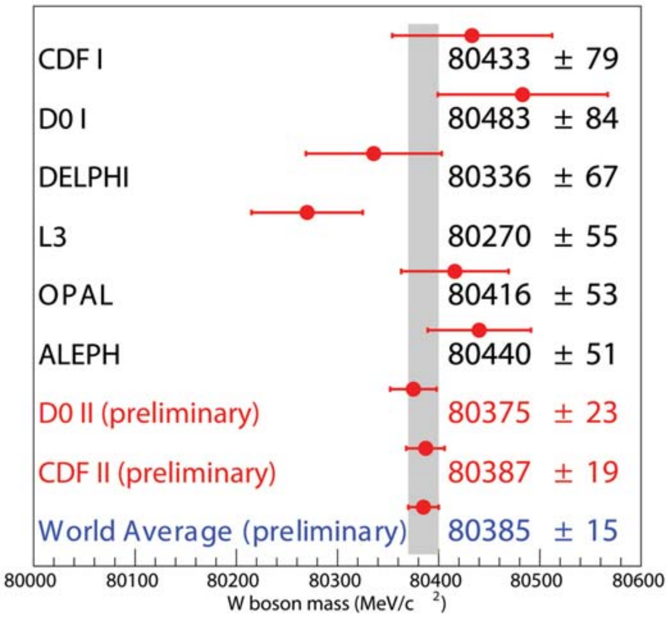

Fig. 6. Previous and new values of the *W* boson mass

The D0 and CDF Collaborations have performed a new measurement of the W boson mass. The collaborations measured the particle's mass in six different ways, which all match and combine for a result that is twice as precise as the previous measurement. The D0 Collaboration measured the W boson mass to be 80.375 ± 0.023 GeV/c^2 [16], while the CDF Collaboration measured the particle's mass to be 80.387 ± 0.019 GeV/c^2. The two new measurements, along with the addition of previous data from the earliest operation of the Tevatron, combine to produce a measurement of $M_W = 80.387 \pm 0.017$ GeV/c^2, which has a precision of 0.02 percent (Fig. 6). The new W mass measurement and the latest precision determination of the mass of the top quark from Fermilab triangulate the location of the Higgs particle and restrict its mass to less than 152 GeV/c^2, this result being in agreement with direct Higgs boson searches.

11. Standard Model Higgs search

In the SM, the Higgs boson is crucial to the understanding of electroweak symmetry breaking and the mass generation of electroweak gauge bosons and fermions. However, this particle has not been observed yet. The mass of the Higgs boson is not predicted in the SM. Precision measurements in particle physics constrain the Higgs mass to $114 < M_H < 152$ GeV/c^2. The low mass region of 120–130 GeV/c^2 is available to a search for the Higgs at the Tevatron. Therefore, a search for the Higgs boson was one of the most important goals of the D0 experiment.

In 2011, new Higgs boson searches including more data, additional channels, and improved analyses techniques compared to previous analyses were performed by both the D0 and CDF Collaborations [17]. All available D0 and CDF results on SM Higgs boson searches, based on luminosities ranging from 4.3 to 10.0 fb^{-1}, were combined. Figure 7 shows (by the solid line) the ratio of the cross section for Higgs production, which is excluded at the confidential level (C.L.) of 95 % by the common data analyses of the D0 and CDF experiments, to that predicted by the SM for different assumed values of the Higgs mass. It is seen that the Higgs masses M_H from 147 to 179 are excluded at the 95% C.L. At the same time, an excess of the data events with respect to the background estimation is observed in the mass range $115 < M_H < 135$ GeV/c^2. At $M_H = 120$ GeV/c^2, the probability value for a background fluctuation to produce this excess is ~ $3.5 \cdot 10^{-3}$, corresponding to a local significance of 2.7 σ. The global significance for such an excess anywhere in the full mass range is approximately 2.2 σ. The observed excess in the data might be interpreted as coming from a Higgs boson with a mass in the region of 115 to 135 GeV/c^2.

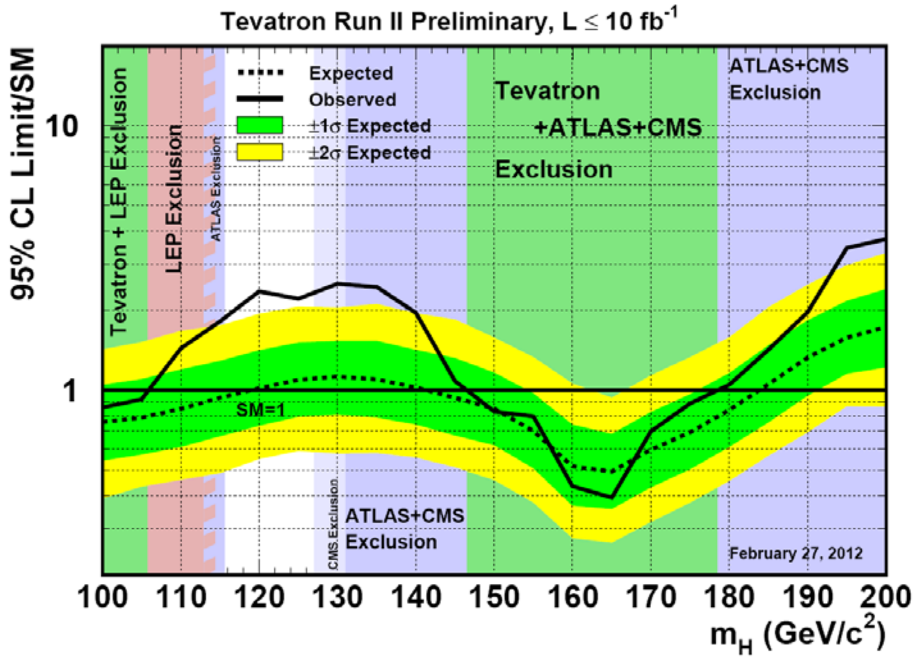

Fig. 7. Ratio of the Higgs production cross section excluded by the data of the D0 and CDF experiments to the cross section predicted by the SM (solid black curve)

In 2012, searches for the Higgs boson by the CDF and D0 Collaborations were continued, in particular, searches for the associated production of a Higgs boson with a W or Z boson and subsequent decay of the Higgs boson to a bottom-antibottom quark pair. The searches were conducted for a Higgs boson with mass in the range 100–150 GeV/c^2. An excess of events in the data compared with the background predictions has been observed, which is most significant in the mass range between 120 and 135 GeV/c^2 [18]. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations. This result is interpreted as evidence for the presence of a new particle consistent with the SM Higgs boson, which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair.

12. Conclusion

The D0 detector was working well with a high data taking efficiency. A number of physics results have been obtained recent years. Tevatron experiments discovered the top quark, discovered several new elementary particles predicted by the SM, made precision measurements of the top-quark and W boson masses, observed B_s mixing and set many limits on potential new physics theories. In a number of data analyses, only a part of the collected data statistics has been analyzed by now. The data analyses will be continued several forthcoming years.

References

1. G.D. Alkhazov, V.L. Golovtsov, V.T. Kim, A.A. Lobodenko, P.V. Neustroev, G.Z. Obrant, Yu.A. Scheglov, N.K. Terentyev, L.N. Uvarov, S.L. Uvarov and A.A. Vorobyov, in *PNPI XXX, High Energy Physics Division*, *Main Scientific Activities*, *1997–2001*, Gatchina, 2002. p. 124.
2. V.M. Abazov *et al*., Nucl. Instr. Meth. A **565**, 463 (2006).
3. V.M. Abazov *et al*., Nucl. Instr. Meth. A **552**, 372 (2005).
4. V.M. Abazov *et al*., Phys. Rev. D **76**, 072007, 092007, 052006 (2007), Phys. Rev. Lett. **100**, 192004 (2008), Phys. Lett. B **679**, 177 (2009), Phys. Rev. D **82**, 071102 (2010), Phys. Rev. D **84**, 012008 (2011).
5. V.M. Abazov *et al*., Phys. Lett. B **704**, 403 (2011).
6. V.M. Abazov *et al*., Phys. Rev. D **82**, 032002 (2010).
7. T. Aaltonen *et al*., Phys. Rev. D **86**, 092003 (2012).
8. V.M. Abazov *et al*., Phys. Rev. D **84**, 112001 (2011).
9. V.M. Abazov *et al*., Phys. Rev. D **84**, 052005 (2011).
10. V.M. Abazov *et al*., Phys. Rev. Lett. **108**, 032004 (2012).
11. V.M. Abazov *et al*., Phys. Rev. D **85**, 052006 (2010).
12. V.M. Abazov *et al*., Phys. Rev. Lett. **105**, 081801 (2010), Phys. Rev. D **82**, 032001 (2010).
13. V.M. Abazov *et al*., Phys. Rev. D **84**, 052007 (2011).
14. V.M. Abazov *et al*., Phys. Rev. Lett. **100**, 142002 (2008).
15. V.M. Abazov *et al*., Phys. Rev. D **84**, 112005 (2011).
16. V.M. Abazov *et al*., Phys. Rev. Lett. **108**, 151804 (2012).
17. The Tevatron Working Group for the CDF and D0 Collaborations, arXiv:1203.3774[hep-ex].
18. T. Aaltonen *et al*., Phys. Rev. Lett. **109**, 071804 (2012).