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The Tevatron legacy

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Summary. — The Tevatron $p\bar{p}$ collider was shut down in 2011, after almost 10 years of high-performance operation at a center-of-mass energy of 1.96 TeV. The two experiments, CDF and D0, continue to analyze the collected data, aiming to extract all possible information on validation of the standard model and on searches for new physics. A short review of some legacy measurements at the Tevatron, and of the impact of the Tevatron program in high-energy physics, is presented.

PACS `14.80.Bn` – Standard-model Higgs bosons.
PACS `14.70.Fm` – W bosons.
PACS `14.65.Ha` – Top quarks.

1. – Introduction

The Tevatron proton-antiproton collider at the Fermi National Acceleraor Laboratory (Fermilab) in US was shut down on September 30, 2011, after nearly ten years of operations at a collision energy of 1.96 TeV during Run II. The collider delivered 12 fb^{-1} of integrated luminosity and each experiment, CDF and D0, acquired data corresponding to approximately 10 fb^{-1}. These samples are now intensively analyzed by the CDF and D0 Collaborations. They are well understood and, based on the mature analysis knowledge developed by both Collaborations, they provide an enormous potential for physics within and beyond the standard model.

2. – Outstanding physics results

Both Tevatron experiments have completed their program of searches for the standard model Higgs boson in all possible channels, using the full luminosity in almost all channels [1]. The left panel of fig. 1 shows the exclusion limits of the combination at the 95% confidence level (CL) as a function of the Higgs boson mass hypothesis. The dashed line shows the expected limit, with the one- and two-standard-deviation uncertainty bands. The solid line shows the observed limit. The Higgs boson is excluded between 150 and 180 GeV/c^2, mainly by the $H \to WW$ channel, while there is an observed excess over

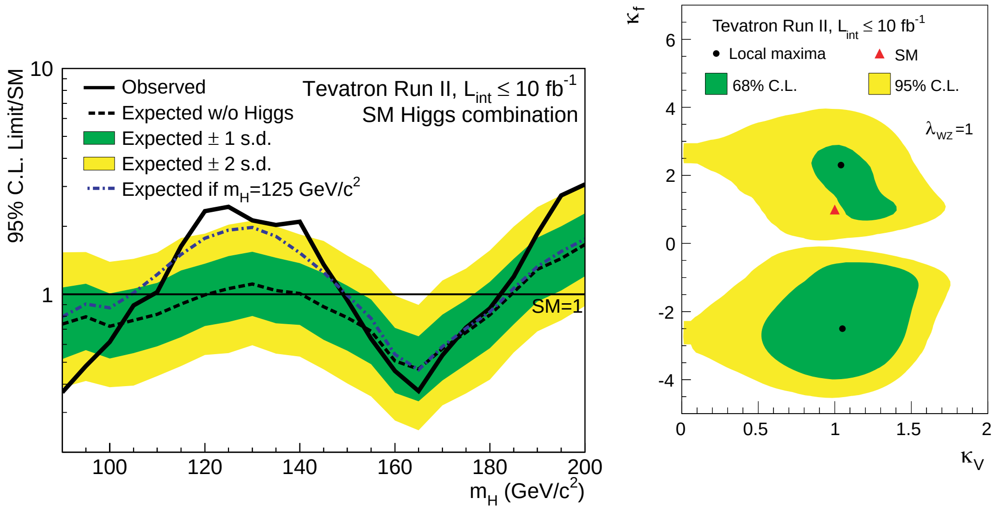

Fig. 1. – Left: Exclusion limits of the standard model Higgs boson from the Tevatron. Right: Constraints on the standard model Higgs boson couplings from the Tevatron.

the standard model expectation between 115 and 150 GeV/c^2 with an observed significance of 3.0 standard deviations at 125 GeV/c^2, mainly from the $H \rightarrow b\bar{b}$ channel. The dash-dotted line shows the expectation for a Higgs boson with a mass of 125 GeV/c^2. The solid line of the observed limit shows a clear preference for this hypothesis against the no Higgs boson hypothesis (dashed line).

The couplings of the standard model Higgs boson to the weak bosons and to fermions were derived from the measured cross sections times branching ratios in all production and decay channels. The right panel of fig. 1 shows the measured fermionic and bosonic couplings with the one- and two-standard deviation uncertainty regions, compared to the standard model prediction. The sign degeneracy arises from the quadratic dependence of the cross sections and branching ratios on the couplings. The measurement is consistent with the prediction.

The left panel of fig. 2 shows the expected exclusion limit from the search for a $Z' \rightarrow t\bar{t}$ decaying boson at CDF [2], as a function of the Z' boson mass, compared with corresponding limits from other experiments. The CDF limit is derived from $t\bar{t} \rightarrow$ lepton + jets events and it is currently the World best up to a mass of 700 GeV/c^2. The right panel of fig. 2 shows the expected exclusion limit from the search for a $W' \rightarrow t\bar{b}$ decaying boson at CDF [3], as a function of the W' boson mass, compared with corresponding limits from other experiments. The CDF limit is derived from $t\bar{b} \rightarrow \not\!\!E_T b\bar{b}$ events and it is currently the World best up to a mass of 700 GeV/c^2.

CDF and D0 measured the cross section for single top-quak production in the s-channel (through the decay of a time-like W boson into a $t\bar{b}$ quark pair) using their full data sets and both reported evidence for this process, with an observed significance of 4.2 standard deviations for CDF [4] and of 3.8 standard deviations for D0 [5]. D0 measured the cross section in the $t\bar{b} \rightarrow$ lepton + $b\bar{b}$ topology, whereas CDF measured the cross section in both the $t\bar{b} \rightarrow$ lepton + $b\bar{b}$ and the $t\bar{b} \rightarrow \not\!\!E_T b\bar{b}$ topologies and combined the two results. A top-quark mass of 172.5 GeV/c^2 was assumed in all measurements. The

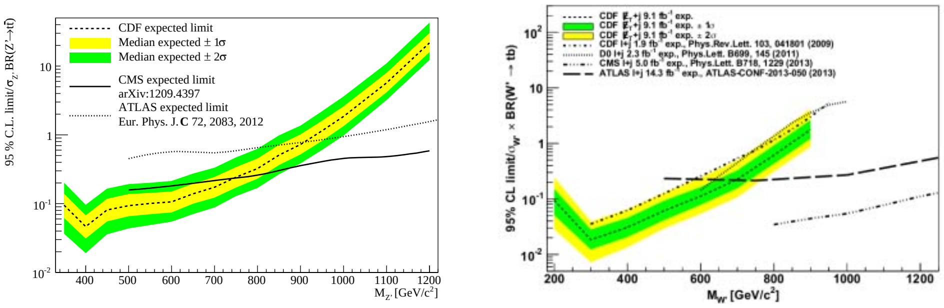

Fig. 2. – Left: Expected exclusion limit of a $Z' \to t\bar{t}$ decaying boson from CDF. Right: Expected exclusion limit of a $W' \to t\bar{b}$ decaying boson from CDF.

two experiments combined their results to obtain the first observation of this process [6], with an expected significance of 5.1 standard deviations and an observed significance of 6.3 standard deviations. The left panel of fig. 3 shows the distribution of the signal-to-background ratio logarithm, which is used as the final discriminant and manifests the sensitivity to the single top-quark signal in the signal-rich bins. The right panel of fig. 3 shows the probability density of the log-likelihood ratio for the null (background only) and test (standard model signal plus background) hypotheses, derived from pseudo-experiments, from which the expected and observed significance are measured.

A subtlety observed in the Tevatron data concerns the forward-backward asymmetry in the production of top-quark pairs, *i.e.* how many top quarks are produced closer to the direction of the initial-state protons *vs.* how many are produced closer to the direction of the initial-state antiprotons. This asymmetry depends on the initial state, which is CP-invariant at the Tevatron, and it originates from the interference of the leading-order (LO) $t\bar{t}$ production mechanisms with next-to-leading order (NLO) mechanisms, but also with possible mechanisms beyond the standard model (BSM). Figure 4 on the left shows the differential cross section for $t\bar{t}$ production as a function of the top-quark angle about the initial-state proton direction in the $t\bar{t}$ rest frame, measured at CDF

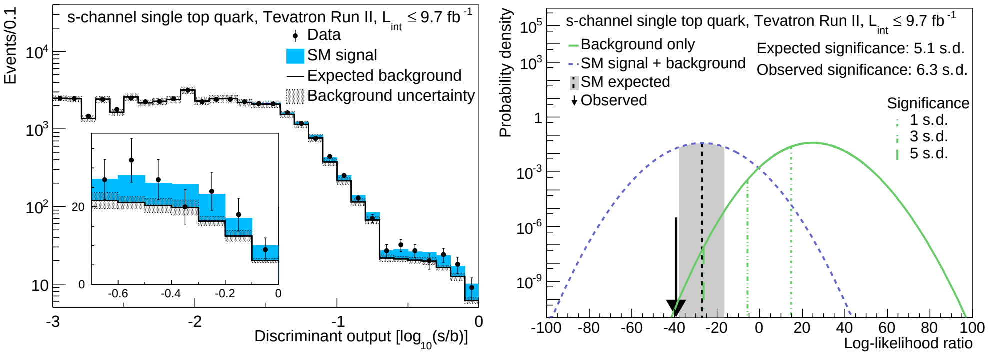

Fig. 3. – Left: The final discriminant of the s-channel single top-quark events from the background. The inset figure shows the most sensitive bins with the highest signal-to-background ratio. Right: The log-likelihood ratio distributions for the background-only and signal-plus-background hypotheses.

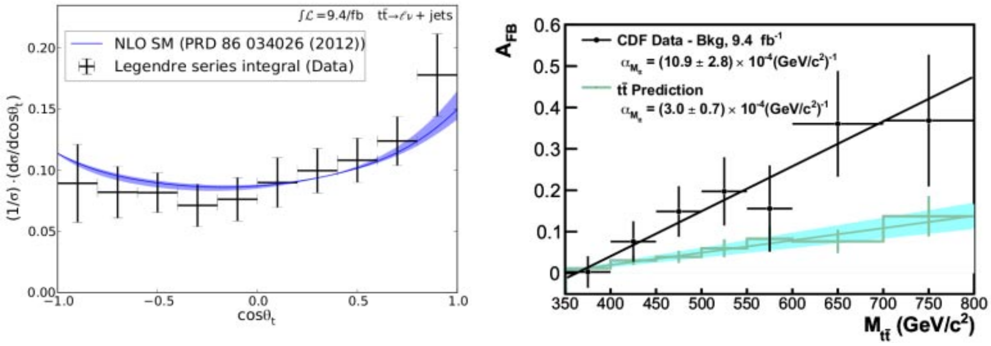

Fig. 4. – Left: The differential cross section for $t\bar{t}$ production at CDF, as a function of the top-quark angle in the $t\bar{t}$ rest frame. Right: The forward-backward $t\bar{t}$ production asymmetry at CDF, as a function of the $t\bar{t}$ invariant mass.

from $t\bar{t} \rightarrow$ lepton + jets events [7]. The cross section is clearly asymmetric, with an asymmetry stronger than the NLO standard model prediction. The asymmetry itself, measured at CDF from $t\bar{t} \rightarrow$ lepton + jets events [8], is shown in the right panel of fig. 4 as a function of the $t\bar{t}$ invariant mass, in comparison with the corresponding NLO standard model prediction [9]. Both the measured and the predicted asymmetries are well parametrized by a linear function, but the measured slope is about 2.7 standard deviations stronger than the predicted slope. The tension between the measured and predicted asymmetry, if not an extreme statistical fluctuation, could be a signature either of missing higher-order corrections in the standard model calculation or of some exotic $t\bar{t}$ production mechanism.

The potential for high precision measurements using the Tevatron data is fully manifest in the measurement of the W boson mass. The last update from the Tevatron used CDF data corresponding to $2.2\,\text{fb}^{-1}$ of integrated luminosity for both electrons and muons and D0 data corresponding to $4.3\,\text{fb}^{-1}$ for electrons [10]. The resulting Tevatron average of $(80387 \pm 16)\,\text{MeV}/c^2$ dominates the World average of $(80385 \pm 15)\,\text{MeV}/c^2$, as shown in fig. 5 on the left side. The figure also shows the consistency of all measurements included in the World average. The precision in the W boson mass of 0.02% thus achieved allows for testing the internal consistency of the standard model through the relation of the W boson and top-quark masses to the Higgs boson mass, as shown on the right side of fig. 5. In this figure, the World average measurements of the W mass [10] and the top mass [11] are compared with 1- and 2-standard-deviation contours of global electroweak parameter fits, with and without the constraint of the direct Higgs-boson mass measurement at the LHC [12]. The constrained fit shows a consistency of all three measured masses at the 1-standard deviation level, indicating no effect from possible new physics at this level of precision of the three measurements.

High-precision measurements with photons and jets using the full luminosity are testing state-of-the-art quantum chromo-dynamical (QCD) calculations. Figure 6 on the left shows the distribution of the azimuthal distance of the photons in diphoton events measured at CDF [13] and on the right it shows the distribution of the azimuthal distance of the two highest transverse-momentum jets in $W(\rightarrow e\nu)$+jets events measured at D0 [14]. The comparison of the measurements with various calculations shows that corrections beyond leading-order QCD are required to describe the data with sufficient accuracy.

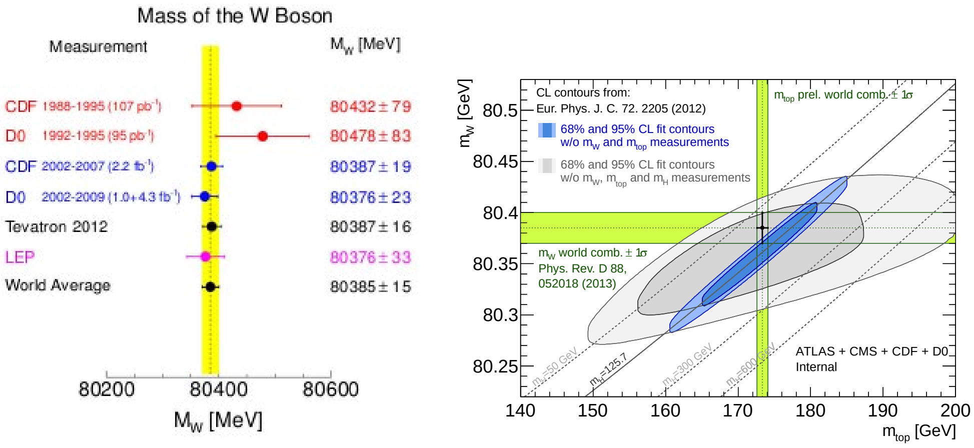

Fig. 5. – Left: Comparison of W boson mass measurements. Right: Global electroweak fits showing the consistency of the standard model with the measured W boson, top-quark, and Higgs boson masses.

The Tevatron data are ideal for high-precision heavy-quark flavor physics, especially due to the technology of silicon detectors developed at the two Tevatron experiments. Figure 7 shows perhaps the most characteristic example of a measurement that would not be possible without the technological achievement it was based on. This is the observation of oscillation of the B_s^0 meson with its anti-particle $\bar{B}_s^0$, conducted with data

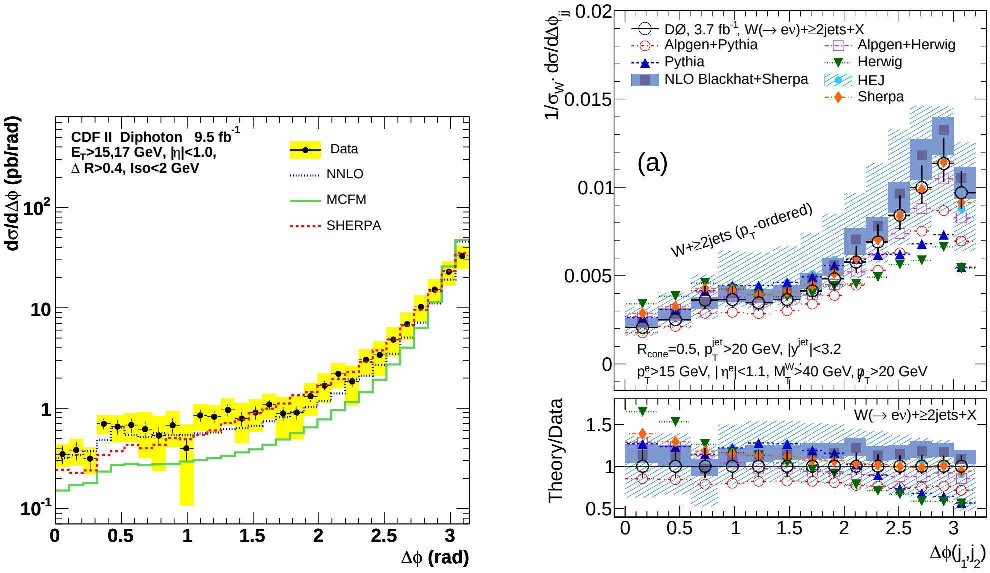

Fig. 6. – Left: Azimuthal distance between the photons in diphoton events measured at CDF. The shaded area depicts the systematic uncertainty of the measurement. Right: Azimuthal distance between the two leading jets in W + jets events measured at D0. The shaded areas depict systematic uncertainties of the predictions.

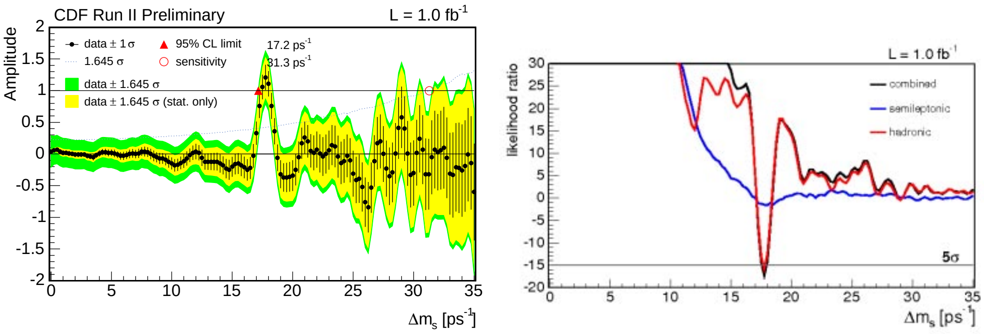

Fig. 7. – Left: B_s^0-$\bar{B}_s^0$ oscillation in the frequency domain measured at CDF. Right: Log-likelihood ratio of the oscillation hypothesis in the frequency domain, from pseudo-experiments of the various B_s^0 decay modes.

corresponding to only $1\,\mathrm{fb}^{-1}$ of integrated luminosity [15, 16]. The measurement used many B_s^0 hadronic decay modes whose observation was made possible only by using the secondary vertex trigger (SVT) that allowed to trigger the events on the displaced (secondary) vertex reconstructed online by the silicon detector, which gives the signature of those decay modes. The figure shows on the left the frequency of the oscillation and on the right the log-likelihood ratio for the oscillation hypothesis as a function of the frequency. The right plot clearly shows that the observation would be impossible by using only the semileptonic decays of B_s^0. It was the inclusion of the hadronic decays, made possible by the use of the SVT, which allowed for the oscillation to be observed with a significance greater than 5 standard deviations.

3. – Outline of the Tevatron legacy

The Tevatron has been leading high-energy physics for two decades, ontributing to all relevant areas of science and technology. In physics, it was the place were the top quark, the heaviest known particle, was discovered and its properties were measured for the first time. It provided the first evidence for the standard model Higgs boson in fermionic final states. Precision measurements in the electroweak and QCD sector were performed, including measurements of jets, photons, vector boson plus jets, and diboson cross sections, as well as the most precise measurement of the W boson mass to date. Substantial progress was made in heavy flavor states and mixing, while several cases of subtle behavior have been spotted and studied in detail, such as CP violation in heavy hadrons and the forward-backward asymmetry in top-quark pair production.

In hardware developments, tracking and vertex reconstruction using silicon detectors were taken to a whole new level. Heavy flavor tagging was widely developed and used. The entire trigger concept in a hadron collider environment was re-considered and advanced, including the secondary vertex trigger and out-of-time triggers for the detection of long-living or slow particles. In the domain of data analysis, the importance of multivariate techniques was established in cases such as the search for the standard model Higgs boson and the observation of single top-quark production, where the signal is tiny relative to the irreducible background. Innovative physics methods were applied for the first time, such as the *in situ* jet-energy scale (JES) calibration in top-quark mass measurements, making use of the precisely know W boson mass to constrain the energy scale of jets originating from W decays.

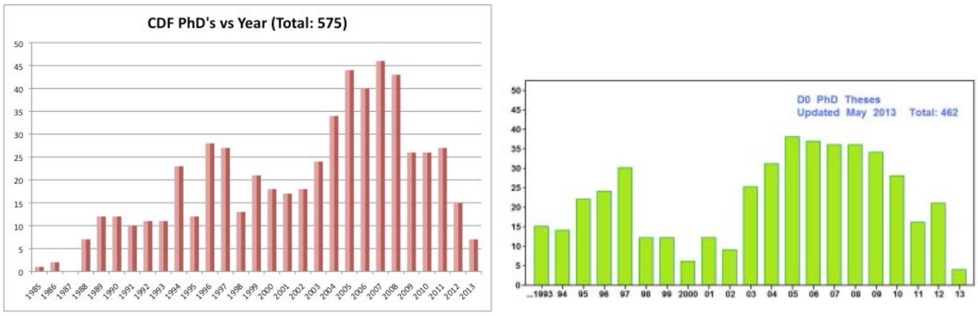

Fig. 8. – Left: PhD theses per year from CDF. Right: PhD theses per year from D0.

In the accelerator technology, major advances were the anti-proton recycler, the anti-proton cooling with electrons, as well as many innovations in cryogenic technology. The Tevatron was the first installation of mass-produced super-conducting magnets on an industrial scale.

An major part of the Tevatron legacy is the impact on the LHC. The Tevatron was the place where it was first demonstrated that a wealth of precision measurements can be made at hadron colliders. Advanced analysis techniques were brought to full maturity, allowing for tiny signals to be extracted from huge —often complex mixtures of— backgrounds, as for example in the single top-quark and Higgs boson cases. The Tevatron proved that a huge gain in sensitivity can be achieved with data, painstaking experimental work, and a lot of ingenuity. Most important impact was the transfer of a huge amount of knowledge and experience through Tevatron accelerator experts and physicists from the Tevatron experiments joining the LHC experiments.

Perhaps the most important part of the Tevatron legacy was the formation of a new generation of scientists in physics and in the society at large, through the graduation of more than one thousand PhD students in 25 years so far (1988–2013), whose work was based on either of the Tevatron experiments, as fig. 8 shows.

4. – Conclusions

The Tevatron experiments, CDF and D0, two and a half years after the shutdown of the collider, keep producing high-quality physics results, with emphasis to precision and to measurements that are difficult to conduct at the LHC. A huge legacy in science and technology is inherited after more than 25 years of operations, research, and development, which is reflected in more than 1000 publications in peer-reviewed journals and more than 1000 PhD theses from both experiments. The huge impact on new-generation experiments seals the full success of the Tevatron and paves the way for greater advances in physics in the future.

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This article is dedicated to Giorgio Bellettini, one of those people who essentially founded the Tevatron and played a major role throughout its long history. Together with Alvin Tollestrup and Kuni Kondo, Giorgio transformed CDF into an international Collaboration in 1980. He was the father of the ideas of projective-tower calorimetry and of the use of silicon detector to reconstruct collision vertices. He was the leader of one of the analyses that resulted in the discovery of the top quark in 1995. He served CDF as a spokesperson in 1995–97. He has been the driving force of the INFN–Fermilab Summer Student program, which has provided CDF with an excellent pool of new scientists. He has been organizer of the *Rencontres de Physique de la Vallée d'Aoste* since its start, 28 years ago, where all new Tevatron results are constantly presented every year. This year he celebrates 80 years of life, 35 of them in CDF. On behalf of present and past members of the CDF Collaboration, I would like to express a deep gratitude to him for his enormous contribution to this historical experiment.

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