

Tevatron legacy^(*)

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Summary. — Several major milestones and discoveries were attained during the lifetime of the Tevatron proton-antiproton collider at Fermilab, from 1987 to 2011. One of the most important was the discovery of the top quark in 1995, followed by an intense program to study that particle in greater detail. In this article, I give an overview of the history of the top quark, its current status as well as the still to be completed legacy measurements at the Tevatron.

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1. – Introduction

The heaviest fundamental particle ever known, the top quark, was discovered at the Tevatron proton-antiproton ($p\bar{p}$) collider at Fermilab in 1995. Since then, intensive studies continue to be performed at the two general purpose detectors at the Tevatron, CDF and D0, to gain a better understanding of the production mechanisms and properties of that particle. With the start of operations of the Large Hadron Collider (LHC) at CERN in 2010, a top quark factory has opened, where top-antitop quark pairs ($t\bar{t}$) are currently produced at cross sections a factor of about twenty higher than at the Tevatron, raising the question about the legacy of the Tevatron, *i.e.*, the heritage the Tevatron leaves to the physics community. In this article, I offer a brief review of the history of the Tevatron and of the top quark, an overview of the current status of the understanding of the top quark, as well as a perspective of what measurements are still important to complete in top-quark physics at the Tevatron in view of the onset of the LHC-era.

2. – The past

From its start, until the turn-on of the LHC, the Tevatron $p\bar{p}$ collider has been the highest-energy frontier of the world. During the lifetime of the Tevatron, which was

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commissioned in 1983, and switched off on September 30th, 2011, several important milestones have been attained, as, for example, the observation of the top quark [1, 2] and the detailed study of its properties, the observation of B_S oscillations, the precise measurement of the mass of the W boson and the extensive hunt for the Higgs boson, that led to stringent limits over a wide range of Higgs-boson mass values. All of these discoveries and studies have enhanced our understanding of nature. In this section, I briefly review the history of the Tevatron and that of the top quark.

2.1. A brief history of the Tevatron. – With the goal to double the energy of the existing accelerator at Fermilab, and thereby explore new regions of phase space, the planning to build the Tevatron $p\bar{p}$ collider using superconducting magnets was initiated in the late 1970s [3,4]. In summer 1983, the Tevatron was completed and commissioned as fixed-target accelerator, while the completion of the antiproton source and therefore the initialization of first $p\bar{p}$ collisions in the Tevatron took until 1985. In October 1985, the partially finished CDF detector observed its first collisions. At this time, the D0 detector was still under construction. In 1987, Run0 of the Tevatron started, at a center of mass (CM) energy of 1.8 TeV. During Run0, only the CDF detector was in operation, recording about 5 pb^{-1} of data. To increase luminosity, the Tevatron and accelerator complex were upgraded through a new LINAC, introduction of transverse stochastic cooling in the antiproton source, and installation of electrostatic separators in the Tevatron. These improvements were associated with RunI of the Tevatron, that lasted from 1992 to 1996, at a CM energy of 1.8 TeV, but now with both CDF and D0 detectors, in operation. During this time, namely in 1995, the top quark was discovered. In total, CDF and D0 each recorded about 120 pb^{-1} of data during RunI. After the end of RunI, the complex was upgraded again, now with the introduction of the Main Injector and Recycler. The invention and further development of electron cooling in the Recycler enabled the storage of large numbers of antiprotons, resulting in luminosities well beyond initial expectation. At the same time, both CDF and D0 detectors underwent upgrades. With an instantaneous luminosity goal of a factor of about five greater than that of RunI, as well as a higher CM energy of 1.96 TeV, RunII of the Tevatron started in March 2001, lasting until September 2011. Both detectors collected about 10 fb^{-1} of data, that are currently being analysed.

All in all, for many years the Tevatron was not only the highest-energy particle collider in the world, but also a great symbol of technological innovation and breakthroughs that included the construction of superconducting magnets and the introduction of stochastic cooling, and development of major particle-detection and triggering schemes, all of which form part of the legacy of the Tevatron.

2.2. A brief history of the top quark. – One of the major achievements of the Tevatron was the discovery of the top quark [5]. The previous discoveries of the u -quark and thereby the b -quark at Fermilab in 1977, together with the τ -lepton at SLAC in 1976, initialized the extension of quark generations in the Standard Model (SM) of particle physics to three families. As the pattern for the SM suggested that a quark of the third generation was missing from an expected doublet, in particular, the up-type partner of the b -quark, a race to find this predicted particle, named the top quark, was started. Based on the ratio of masses of the partners in the two known families, it was widely believed that the top quark would have a mass about a factor of three to four that of the b -quark. Several searches were performed based on the expectation of a heavy new particle in a $t\bar{t}$ bound state, such as the search at the PETRA experiment at the e^+e^- collider at DESY, where

a lower limit was set on $m_t > 23.3 \text{ GeV}$ in 1984. With the construction of the $S\bar{p}\bar{p}S$ at CERN, and its start-up in 1981, a new energy frontier was explored with the UA1 and UA2 experiments searching for the top quark in W -boson decays. Both collaborations set new lower limits on m_t , almost ruling out the possibility of $W \rightarrow t\bar{b}$ decay. With the start-up of Tevatron RunI, CDF and D0 joined the hunt for the top quark in 1992. Because the detectors in RunI were quite different—CDF being strong on tracking, while D0, not having a solenoid magnet in the tracking system, had a better calorimeter than CDF—the strategy to search for the top quark was also different at the two experiments: CDF focused on b -jet identification to reduce background, D0 used topological information. The first lower limits from CDF in 1992 of $m_t > 91 \text{ GeV}$ finally eliminated the possibility of $W \rightarrow t\bar{b}$ decay. With the data collected up to 1993, D0 also was able to set lower limits, now at $m_t > 131 \text{ GeV}$, with a search focusing on $t\bar{t}$ production. In 1994, CDF published first evidence for $t\bar{t}$ events, where a small excess of top-like events was observed. Although D0 observed a few top-like events (at the predicted level), the luminosity was deemed insufficient to establish the existence of a top quark. Finally, in winter 1994/1995, the data samples were large enough to reach a conclusive result. On February 24th, 1995, CDF and D0 simultaneously submitted papers to Physics Review Letters [1, 2], based on 50 pb^{-1} at D0, and 67 pb^{-1} at CDF, that announced definitive observations of $t\bar{t}$ production. On March 2nd 1995, the discovery was announced publicly in a joint session held at the Fermilab auditorium.

With the discovery of the top quark a large program was initiated to study the particle's characteristics in detail—from its production mechanism to its inherent properties, as well as its connection to possible physics beyond the standard model. An impressive understanding of the top quark has been achieved over the past 16 years, some of which will be summarized in the following section.

3. – The present

While the top quark discovery took place with just a handful of events, the amount of data available today corresponds to thousands of analyzable $t\bar{t}$ events per experiment, thereby enabling a precise measurement of the $t\bar{t}$ production cross section, a detailed study of top quark properties, and the performance of sensitive searches for new physics in the top quark sector. Furthermore, the observation of electroweak single top-quark production in 2009 [6, 7], also simultaneously by CDF and D0, provided another milestone in the understanding of the top quark and the SM. Almost everything we know about the top quark has been achieved through pioneering studies performed at the Tevatron. These relied not only on the large amount of data, but also on the development and refinement of new ideas and analysis techniques. For example, the in-situ calibration of the JES using the hadronically decaying W -boson and the Matrix Element (ME) method first realized at D0, has yielded the most precise measurements of the mass of the top quark, the establishment of multivariate analysis techniques was crucial in the search for single top quarks, and measurements of the $t\bar{t}$ production cross section have reached uncertainties comparable to the uncertainty on the corresponding theoretical quantum-chromodynamics predictions. Furthermore, several analyses have reached a precision where systematic uncertainties are comparable or even larger than their statistical components, as, for example, in measurements of the top-quark mass and in studies of the W helicity fractions in $t\bar{t}$ decays.

All in all, the measurements performed show that the particle discovered in 1995 agrees well with the top quark predicted by the SM. The production and properties are

in full accord with their predicted values, and a vast field of searches for signs beyond the SM in states involving top quarks indicate no behaviour beyond the SM. Recently, a deviation of measurements from prediction in $t\bar{t}$ events was reported in the $t\bar{t}$ forward-backward asymmetry, showing higher measured asymmetries than expected. While the LHC top-quark factory now provides more data than the Tevatron, many D0 and CDF analyses are still competitive, and some are complementary—one being the $t\bar{t}$ forward-backward asymmetry. In the next section, I discuss these competitive and complementary analyses. A more detailed overview of the current understanding of top-quark production and its properties is given in several review papers, *e.g.*, refs. [8], as well as in the articles in these proceedings.

4. – The future

Despite that the Tevatron collider is switched off and the LHC experiments are collecting large amounts of data, the Tevatron analyses are proceeding at full pace. In the field of top-quark physics, the analyzed data corresponds to about half of the collected data of about 10.5 fb^{-1} at both CDF and D0. To decide which analyses are still competitive with the new top quark factory, it is important to understand the differences between the two colliders. Because a proton and an antiproton are made to collide at the Tevatron, the initial $p\bar{p}$ states are CP -eigenstates, which is not true for two protons undergoing collisions at the LHC. Furthermore, the energies in the center of mass are different, with 1.96 TeV at the Tevatron and currently 7 TeV at the LHC. At these energies and respective types of interactions, the fraction of $t\bar{t}$ events that are produced via $q\bar{q}$ annihilation and via gluon-gluon fusion is about inverse: the former process happens about 85% at the Tevatron, while it only contributes about 15% at the LHC. On the basis of these differences we can define the legacy measurements that appear to be important to pursue with the full Tevatron data. These comprise, in particular, the measurement of the production cross sections—differential and inclusive—that will not be repeated at the same energy and incident states, the measurement of $t\bar{t}$ spin correlations, which are different in $q\bar{q}$ annihilation and gluon-gluon fusion, as well as the $t\bar{t}$ forward-backward asymmetry, which does not appear in the process $gg \rightarrow t\bar{t}$. Besides these complementary studies, the measurement of the mass of the top quark forms one of the legacy measurements of the Tevatron, as it benefits from a well understood environment and is limited by systematic uncertainty. In the following, I offer a brief perspective on each of these analyses.

4.1. Complementarity resulting from the difference in energy and type of collisions: Production kinematics. – Although the $t\bar{t}$ production cross section at the LHC is a factor of twenty larger than at the Tevatron, a precise measurement of the $t\bar{t}$ production cross section as well as production kinematics, are important to check the reliability of perturbative calculations in quantum chromodynamics (QCD) as well as to search for possible deviations from prediction that could suggest contributions from beyond the SM (BSM). While differential distributions have thus far been measured only with small statistics and for few variables, the extracted inclusive $t\bar{t}$ cross sections for 5.6 fb^{-1} of data are highly dominated by systematic uncertainties. It is likely therefore that measurements of the inclusive $t\bar{t}$ cross section will not be repeated in all final states. The issue of electroweak production of single top quarks is quite different, in that single top production can occur via s -channel, t -channel or the Wt -channel. The latter has a negligible cross section at the Tevatron, and will therefore not be measured separately. The initial observation of

single top quarks was realized through the sum of s - and t -channel contributions. But since BSM could affect the contributions differently in the different production modes, it is important to disentangle the individual channels. D0 recently reported the separate observation of the t -channel process [9]. The production in this channel has also been reported recently by the LHC experiments ATLAS and CMS [10, 11], where the production cross section is a factor of about 29 higher. For s -channel single-top production, the enhancement factor at the LHC is only about 4.5, and there is far more background. The relatively small s -channel cross section at the LHC and the fact that it has not yet been observed separately, suggests this measurement for priority at the Tevatron.

4'2. Complementarity resulting from the difference in the type of collisions: $t\bar{t}$ Spin Correlations. – By studying $t\bar{t}$ spin correlations, the full chain from production to decay can be probed for consistency with the SM. Predictions for $t\bar{t}$ spin correlations depend on the production mechanism, and on whether the top quarks are produced at threshold. At the Tevatron, the main contribution is from $q\bar{q}$ annihilation, where the spin of the top and antitop quarks are parallel in the beam basis, while at the LHC, events especially with low $m_{t\bar{t}}$ are expected to have spins of top and antitop mostly in like-helicity configurations. The $t\bar{t}$ spin correlation at the Tevatron is therefore complementary to that at the LHC. Both CDF and D0 have explored $t\bar{t}$ spin correlations using both template and Matrix-Element techniques. Recently, first evidence for non-vanishing $t\bar{t}$ spin correlations was reported by D0 in 5.4 fb^{-1} of data in dilepton and lepton+jets final states [12]. As this measurement is still limited by statistics, the full data sample should improve the precision of the result by a factor of $\sqrt{2}$, not counting expected improvements in the analyses.

4'3. Complementarity resulting from the difference in the type of collisions: $t\bar{t}$ Forward Backward Asymmetry. – One of the most interesting results this year is the forward-backward asymmetry of top and antitop production, where measured asymmetries are consistently larger than predicted from effects of QCD color charge. A particularly striking feature is the enhanced asymmetry at large $m_{t\bar{t}}$ reported by the CDF collaboration. Besides trying to accommodate this apparent discrepancy with theory, it is important to repeat the statistically limited measurements using all available data. Furthermore, this kind of effect is harder to measure at the LHC, as it is easy to define the directions of the incoming quark and antiquark by just assuming the proton and antiproton flight directions, respectively, but the asymmetry also appears mainly in $q\bar{q}$ annihilation—with far smaller contributions from qg states—and not at all in gluon-gluon fusion, which dominates at the LHC. Measurements at LHC are so far based on the difference in absolute rapidities of top and antitop quarks, reflecting the widths of the two symmetric distributions, and these effects are far more subtle and smaller than the predictions at the Tevatron. By using the full data sample, the uncertainty on the measurement can be reduced by a factor of $\sqrt{2}$, again ignoring additional improvements expected in the analysis. The observed, unexpected behaviour puts the study of the $t\bar{t}$ forward-backward asymmetry as a high priority for continued top-quark analyses at the Tevatron.

4'4. Competitive because of a well understood environment: Mass of the top quark. – The mass of the top quark, m_t , is a free parameter in the SM, and, together with the mass of the W boson, constrains the mass of a SM Higgs boson. It is therefore important to measure m_t precisely. A variety of methods have been invented at the Tevatron to provide the most precise mass measurements, as, for example template methods using neutrino or matrix weighting, or the ME method. By performing measurements in all

possible final states, using the wealth of techniques, and combining the different results from CDF and D0, the uncertainty on m_t has reached < 1 GeV for the first time this year [13], yielding $m_t = 173.2 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})$ GeV. As this result is limited by systematic uncertainties, the main task for the experiments at LHC and Tevatron is to improve the understanding of systematic contributions, in particular, through studies of differences in jet energy scale (JES) for quark and gluon jets, as well as heavy-flavors, and initial and final-state radiation. Including some of the expected improvements on systematic uncertainties, especially those related to JES, can reduce the uncertainty on the combined Tevatron m_t to about 0.6 GeV in the final mass measurement from the Tevatron.

5. – Summary

The Tevatron has provided many technological innovations and analysis techniques that have led to a huge advancement in the understanding of fundamental particle physics, all of which define the legacy of the Tevatron. A crucial part of the legacy is the discovery and detailed characterization of the heaviest known elementary particle, the top quark, and the understanding of its production and properties achieved in the past 16 years of top quark physics at the Tevatron. The future of the top-quark program at the Tevatron requires a prioritization of measurements that are complementary and competitive with the LHC. Besides the effort to improve the analyses using all the collected data, the results from each of the two Tevatron experiments must be combined to provide the legacy of the Tevatron.

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