ELECTROWEAK AND TOP PHYSICS AT THE TEVATRON AND THE LHC

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In the last decades electroweak processes were studied at hadron and lepton colliders. By exploiting the large statistics and the c.o.m. energy available, hadron colliders played a significant role in performing precision measurements of standard model parameters and in observing rare processes. Besides, in the last decade of the XX century, the last fermion predicted -the top quark- was discovered at the Tevatron collider. We are now at the start of a new hadron collider, the LHC, and in this paper, I will review recent results from the Tevatron and compare perspectives for experiment taking data at the two accelerators.

1 Introduction

The Tevatron Collider, where protons and antiprotons collide at $\simeq 2\text{ TeV}$ of c.o.m. energy, operated at Fermilab (in the outskirts of Chicago) since the mid-eighties of the last century. Since then it has played a key role in studying the electroweak processes, and is also the place where, in 1994-1995 the first observation, and then the discovery of the top quark, took place. After a long shutdown, the machine and the two detectors (CDF and D0) were upgraded to run at increased luminosities. Since 2001 CDF and D0 have been steadily taking data. Here I will present results obtained with an integrated luminosity of $2\div 4\text{ fb}^{-1}$.

The Large Hadron Collider (LHC) was built at CERN, and will collide protons on protons, starting in fall 2009. In the first year of operation, collisions will take place at a c.o.m. energy of 7 TeV. After a shutdown it will increase the beam energy to reach its design goal of 14 TeV. Unlike the Tevatron, aimed to generically study processes predicted in the standard model of elementary particles (SM) framework, the LHC goal is to specifically explore the electroweak symmetry breaking process and to look for new physics. In order to fulfill this task, two full purpose detectors (ATLAS and CMS) were built, along with two dedicated ones (LHCb, to flavour physics and TOTEM to diffraction and elastic processes). Finally, as the LHC will also collide ions to study high-density states of matter, a fifth detector -ALICE- was built to this scope. In the following, when discussing LHC perspectives, I will limit myself to future measurements by ATLAS and CMS.

2 The Environment

Both Tevatron and LHC share the common ground of colliding hadrons (proton and antiprotons at the Tevatron, protons at the LHC). This implies that in the hard scattering between partons only the fraction of energy carried by the interacting quarks and gluons, is available to produce

\begin{footnote}
1 fb = $10^{-39}\text{ cm}^2$
\end{footnote}
interesting events. Most of the energy is lost into peripheral ("soft") interactions. Moreover the soft interactions between the hadrons is also responsible for most of the cross section. At the Tevatron, the total inelastic cross section is about 50 mb, while, for example, single-top production has a cross section of $\sim 3$ pb, or $\sim 3 \times 10^{-9}$ mb (see figure 1 for a comparison of several production cross section). It is obvious that, in order to study processes at the pb rate, a trigger system, capable of rejecting more than 99.999% of the events, without introducing dead-time, is needed. The LHC, with its even higher energy and instantaneous luminosity, provides similar challenges to ATLAS and CMS in order to fulfill their physics goals.

2.1 The Tevatron

The Tevatron collider started operation in October 1985, recording an handful of events at CDF (back then the only operational detector) at $\sqrt{s} = 1.6$ TeV. After a first data taking period ("Run 0") in 1988-1989 at 1.8 TeV, the two detectors collected $\simeq 120$ pb$^{-1}$ of data during the long (1992-1996) Run I. In this period a number of striking measurements and discoveries were made. Most and foremost the top quark was first observed (1994) and then discovered in 1995, but I would also like to mention the precision measurements of the $W$ mass and many QCD and B-physics results.

It was clear that, while originally designed to provide a maximum luminosity of $10^{30}$ cm$^{-2}$ s$^{-1}$, an upgrade of the luminosity could extend the physics reach of D0 and CDF and provide the chance to explore in deep the structure of the electroweak processes as well as the nature of the ElectroWeak Symmetry Breaking (EWSB). The improvement of the machine and, in parallel, the upgrades of the two detectors, brought to the start of Run II (2001) with new expectations. Soon became clear that, instead of the 2 fb$^{-1}$ per experiment, as originally foreseen, more data could be available by the time the LHC went into operation. We are now in the eighth year of Run II and, after a shaky startup, the Tevatron is now routinely colliding proton and antiproton at $\sqrt{s}=1.96$ TeV and instantaneous luminosity in excess of $10^{32}$ cm$^{-2}$ s$^{-1}$. These outstanding performances already delivered to each detector about 5 fb$^{-1}$ of data or (to put things in perspectives) more than 33K $t\bar{t}$ pairs, 30millions $W$, more than 20,000 $WW$ etc. The current plan of the Laboratory foresees running until the end of FY 2011, in figure 2 I show the past history and the current prediction for the integrated luminosity.

2.2 The LHC

The LHC, built at CERN in the LEP tunnel, is a 23 Km diameter machine designed to collide protons on protons at $\sqrt{s} = 14$ TeV at an instantaneous luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. The increase in c.o.m. energy, together with the very short interbunch (25 ns) set an harsh environment for
the detectors: each bunch crossing at design luminosity is expected to see the overlap of (on the average) \( \sim 20 \) soft interactions. ATLAS and CMS are designed to, first of all, detect the needle in the haystack and write to tape only a very tiny fraction of events where the hard scattering took place. The first data taking run is expected to start in Fall 2009, at a c.o.m. energy of 7 TeV (each beam at 3.5 TeV) and last until about 100 \( \text{pb}^{-1} \) have been recorded by each experiment\(^2\).

3 \ Electroweak Physics

The cornerstones of electroweak physics are \( Z \) and \( W \) bosons. Copiously produced at the Tevatron, they are routinely used as monitoring tools, both during data taking and in testing the offline algorithms. Their leptonic decays in \( e, \mu \) and \( \nu \) provide easy trigger signatures. Moreover, the very large number of events, allow the precision study of their properties.

3.1 \( W \) and \( Z \) production

An interesting milestone is the measurement of the cross sections and the comparison of data and theoretical prediction. In figure\(^3\) I show the compilation of the measurements at hadron colliders. It will be interesting to compare the NNLO prediction with the LHC results as large increases are predicted as a function of \( \sqrt{s} \). \( W \) cross section is predicted to be 20(12) nb at 14 (10) TeV, while \( Z \) production is 2 (1.2) nb at 14(10) TeV. Figure\(^4\) shows the expected \( E_T \) distribution at CMS in 10 \( \text{pb}^{-1} \) at 10 TeV. Expectation, after all cuts, is of the order of 10,000 events per experiment in 50 \( \text{pb}^{-1} \) at 10 TeV. ATLAS, with as few as 50 \( \text{pb}^{-1} \) at 14 TeV, predicts \( \Delta \sigma/\sigma \simeq 5 \) (3) \% in the \( e (\mu) \) channel\(^3\).

As \( W \) and \( Z \) cross sections brings information about the parton distribution functions (p.d.f.) of quarks and gluons, the \( W \) asymmetry and the \( \text{d}\sigma/\text{d}y \) for \( Z \) events provide constraint for the p.d.f. Those measurements, to be useful, need a good understanding of the backgrounds and of systematic effect. In a first phase, at LHC, might be more useful to perform a measurement of the ratio of forward-to central cross sections that can be directly compared to NNLO calculation and provide early information on the p.d.f.\(^4\).

3.2 \( \) Diboson Production

A special role in electroweak processes, is played by diboson production and decay. Necessary in the theory to guarantee unitarity, they represent a window on the unknown as \( WW \) and \( WZ \) are produced through diagrams involving trilinear gauge couplings. However, at the Tevatron, their tiny cross sections set them at the boundary of the observable \( \sigma(pp \rightarrow WZ) \simeq 4 \) pb at 1.96 TeV. In figure\(^5\) you can see the most recent Tevatron results for \( WW \) production. Recently
CDF measured $\sigma(ZZ) = 1.56^{+0.80}_{-0.63} \pm 0.25 \text{ pb}$ in 4.8 fb$^{-1}$ and $\sigma(WW) = 14.4 \pm 3.1 \pm 2.2 \text{ pb}$ in 3.9 fb$^{-1}$.

The large statistics available at the LHC will allow to set strong limits, after a few years, on new physics. As an example figure 6 shows the ATLAS expectations for anomalous couplings in the $WW$ channel, looking for anomalous couplings in the $WWZ$ and $WW\gamma$ vertices.

3.3 $W$ mass

This (free) parameter of the SM has a specific relevance as, combined with the mass of the top quark, it is related, through loop diagrams, to the mass of the Higgs particle.

The $W$ mass in measured in events where the boson decays into $\nu$ and $e$ or $\mu$. CDF, in 0.2 fb$^{-1}$ measures $80.431 \pm 0.034(stat) \pm 0.034(syst) \text{ GeV/c}^2$, D0 in 1 fb$^{-1}$ $80.401 \pm 0.021(stat) \pm 0.038(syst) \text{ GeV/c}^2$ (see figure 7). Their combined result ($80.420 \text{ GeV/c}^2$) has an uncertainty of only 31 MeV/c$^2$, an improvement over LEP uncertainty (33 MeV/c$^2$) where, however, four experiments were involved. This brings the World Average to $80.399 \pm 0.023 \text{ GeV/c}^2$. CDF is working to update its result with $\sim 2 \text{ fb}^{-1}$. The expected statistical accuracy is $\sim 16 \text{ MeV/c}^2$ per each channel ($e, \mu$).

Both ATLAS and CMS plan on determining $W$ mass with an accuracy of $\sim 10 \text{ MeV/c}^2$. At the moment, it looks like this measurement is a long way to go for the LHC. A tough systematics, to be thoroughly understood, forces to reject most of the events. As an example the recent D0 result uses only $\approx 20\%$ of the $W$’s produced. A recent estimate by ATLAS (15 pb$^{-1}$ at 14 TeV) predicts uncertainties, statistical and systematics combined, $O(200) \text{ MeV/c}^2$, still far from the Tevatron results while CDF and D0 project a $\approx 10 \text{ MeV/c}^2$ limit for a run with 10 fb$^{-1}$. A prediction that, however, seems very ambitious at this time.
4 Top Physics

Since its discovery in 1995, top is a real focus for the Tevatron physics programme as Fermilab is the only place where it can be studied. Thanks to its large mass, top decays before hadronization, therefore provides the two experiments with a unique place to test QCD prediction. Its peculiarity eases the comparison of measured production cross section with predictions and makes the top quark mass one of the most accurate measurement of the SM parameters.

At LHC $t\bar{t}$ pairs are produced with a cross section of $500(800) \text{ pb}$ at $10(14) \text{ TeV}$. Therefore tens of thousands of events will be available soon after the start of operation. While many studies focus on the use of those events to improve understanding of the detectors, there are physics measurements that will exploit at best this ”top factory”. Indeed we will see that the large event yield opens interesting perspectives to shed light on the 3rd family couplings.

4.1 Production and decays

Until recent times, top quark has been observed only in strong production of $t\bar{t}$ pairs. This process proceeds for about $85(15)\%$ through quark (gluon) fusion at the Tevatron. The situation, thanks to the larger energy available at parton level, reverses at the LHC.

As $t$ decays $\simeq 100\%$ in $W$ and a $b$ quark, different channels for $t\bar{t}$ are classified (and named) after the $W$ decays. The most important ones, thanks to a combination of branching fractions, and of signal over background ratio, are the dilepton channel (where both $W$’s decay into leptons) and the lepton+jets channel, where one of the $W$ decays into two jets. To improve $S/B$ in the latter case, $b$-tagging (i.e. the positive identification of at least one jet as coming from the hadronization of a $b$ quark) is applied. Charged leptons mostly used for those measurements are $e$ and $\mu$, with $\tau$ playing a lesser role.

CDF recently updated its results in the dilepton and lepton+jets (and $b$ tagging) channels with $\approx 5 \text{ fb}^{-1}$. The measured cross section (assuming $M_{\text{top}} = 172.5 \text{ GeV/c}^2$) is $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{Z th. + residual lum.}) \text{ pb}$. The Tevatron results already challenge the theoretical predictions as you can see in figure 9 where most recent NLO calculations (uncertainty $O(10\%)$) are compared to the CDF experimental determination.

Both ATLAS and CMS studied different channels in various scenarios. At CMS, for the dilepton channel, a $10\%$ precision on $\sigma_{t\bar{t}}$ is predicted with as little as $10 \text{ pb}^{-1}$ at $14 \text{ TeV}$. Figure 10 shows the expected $W$+jet distribution for this channel ($ee, e\mu, \mu\mu$). ATLAS predicts an accuracy $\Delta\sigma/\sigma \simeq 4.5(\text{stat}) \oplus 8(\text{syst})\%$ using $b$-tagging with $100 \text{ pb}^{-1}$ of data at $14 \text{ TeV}$. These preliminary figures are very encouraging. Besides, while channels with $\tau$ were of little use at the Tevatron, the large statistics might allow them to play a more significant role at the LHC. A possibility to be explored is to determine $M_{\text{top}}$ from a precise cross section determination as there is a mild dependence of $\sigma$ upon the top mass.
The large statistics can be very helpful also in exploring aspects of top physics linked to the decay channels. CDF pioneered the search for FCNC currents \((t \rightarrow Zq)\) setting limits \(\simeq 3 \div 4\\%\). While these channels are, of course, suppressed at tree level in SM, in some theories they appear at the \(O(10^{-4})\) level. In figure 11 the result of ATLAS study using 1 fb\(^{-1}\) of data compared to current limits. FCNC decays were also studied by CMS as a function of the collected integrated luminosity (figure 12). With the large statistics available, these decays represent a real window on scenarios beyond the SM.

### 4.2 Top Mass

As mentioned earlier, \(W\) mass is linked, through (logarithmic) loop corrections involving the mass of the top quark, to the Higgs sector. Therefore, within the SM, these two measurements provide an hint on the Higgs mass and can suggest the emergence of new physics (if direct and indirect measurements show some strain).

The measurements of the top mass typically proceed through the comparison of mass-sensitive observables in data and MC. At the end of Run I, D0 pioneered a technique which, using as additional information the dynamics of \(t\bar{t}\) events, improved the statistical accuracy 5. Nowadays this path is largely exploited by both experiments.

At the Tevatron both CDF and D0 measure \(M_{\text{top}}\) in various channels: dilepton, l+jets and all-hadronic. Only the latter has a fully-reconstructed final state, the others contain at least one neutrino with an unknown \(P_z\). In all cases, as top and \(W\) decays in quarks, hadronization corrections are needed to go back from the (measured) jet energies to the initial parton energies. Together with other energy-related uncertainties, they are dubbed Jet Energy Scale (JES) and represent the most important systematics to measure \(M_{\text{top}}\). In order to obtain an \textit{in situ} calibration of the JES, \(W\rightarrow jj\) in \(t\bar{t}\) events is used as an additional constraint. This reduces this systematic error as a function of increased luminosity 6. In figure 13 I present a full compilation of the results obtained in various channels. The current Tevatron average, obtained with 3.6 fb\(^{-1}\) of data, is 173.1±0.6(stat)±1.1(syst) GeV/c\(^2\). A striking determination with an accuracy of better than 1 % which makes \(M_{\text{top}}\) the best known of all quark masses. However, at this level, there is a debate among theorists on how to interpret this accuracy. Nevertheless, when put together with the mass of the \(W\) it sets a strong constraint on the Higgs sector (see figure 14).

As of today, the 95 % C.L. limit obtained by indirect EWK fits is: \(M_H < 157\) GeV/c\(^2\). The future looks still bright for the Tevatron as shown in figure 15, where you can see CDF expectations as a function of the collected integrated luminosity. Even without improvements in the analysis, luminosity will provide a chance to possibly reach the 1 GeV/c\(^2\) limit.

The LHC experiment will exploit techniques and studies performed at the Tevatron. As the current predictions by CMS (see figure 16) and ATLAS are \(\delta M_{\text{top}} \approx 1\)GeV/c\(^2\) with 10 fb\(^{-1}\) at
14 TeV, I expect that the top mass will be a lasting heritage of the Tevatron.

### 4.3 Single Top

One of the most interesting electroweak processes is the production of events containing one top quark. There are three relevant Feynman diagrams: s-channel, t-channel, associated production. In the s-channel one W is produced by two light quarks and decays in a t and a b quark. In the t channel the top quark is produced in association with a light quark and finally the associated production produce a final state containing a t quark and a W. At the Tevatron the latter has a negligible (≈ 0.3 pb) cross section, while the s channel is σ = 0.88 ± 0.11 pb and the t channel 1.98 ± 0.25 pb at NLO. One of the reason why this channel is interesting is that, due to its peculiar production, \( \sigma_{\text{single-}t} \propto |V_{tb}|^2 \), therefore a direct measurement of this CKM matrix element can be performed.

The tiny cross section is a formidable problem at the Tevatron. Despite the large integrated luminosity in Run II, it still took 14 years from \( tt \) to s-top discovery. Indeed the final state of single top events is represented by events containing a W and 2 jets (containing one or two b jets). We know that the large \( W + b\bar{b} \) and \( Wjj \) generic events constitutes a significant background. Moreover the standard \( tt \) production constitutes another source of background. Overall, even after all selection requirements, the signal is a fraction of background (S/B ≈ 1/16) and a counting experiment is not possible. CDF and D0 used a number of multivariate separation techniques that, exploiting the excellent knowledge of the detectors response and of the backgrounds, allow to statistically separate signal-like events from the overwhelming background. As an example I show in figure 17 and 18 the distribution of the invariant mass of the system lνb for all events and for events selected as signal-like by a Neural Network. It is clear that, in the second plot, data favours the presence of events containing single top. CDF published \( \sigma = 2.3^{+0.6}_{-0.5} \) pb and D0 \( \sigma = 3.94 \pm 0.88 \) pb. The combined Tevatron result is \( 2.76^{+0.58}_{-0.41} \) pb. From these measurements one can solve for the CKM element \( V_{tb} = 0.88 \pm 0.07 \).
or $|V_{tb}| > 0.77$ at 95% C.L..

At the LHC single top is produced through the same mechanisms but the cross sections are quite different: s-channel: 11 pb, t-channel: 250 pb, associated production: 66 pb. t-channel appears to be the best candidate for observation, however the large background due to $W$+jets events requires $b$-tagging to improve S/B. A recent study by ATLAS found the original TDR to be optimistic and, with a cut based selection they now estimate $S/B \approx 1/3$ in 1fb$^{-1}$. In the same amount of data, using ”multivariate methods” as D0 and CDF, it improves to be $\approx 1.3$ with an expected accuracy $\Delta \sigma/\sigma \sim 22\%$, more or less the same as obtained at the Tevatron.

5 Conclusion

Precision electroweak measurements and top physics are the basics of physics at hadron colliders. However, despite they belong to the realm of standard model physics, many interesting topics can be covered and new physics can be explored. Their full understanding is the key to proceed forwards in the realm of the unknown. Tevatron experiments showed that unexpected accuracies can be obtained thanks to the ingenuity of the physicists involved. Measurements of $M_{top}$ and $M_W$ are good examples.

As there are still many results which are statistically limited, we expect significant contribution by ATLAS and CMS ”soon”. They will operate at the border of the standard model where we are now testing fundamental aspects of the theory.

Be ready for surprises as we move to new energies.

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References

1. F. Abe et al., Phys. Rev. Lett., 74 (2626)1995; S. Abachi et al., Phys. Rev. Lett., 74 (2626)1995.
2. S. Bertolucci, this Conference.
3. G. Aad et al. arXiv:0901.0512.
4. F. Abe et al., Phys. Rev. Lett., 98 (251801)2007.
5. V. M. Abazov et al. Nature, 429, 638 (2004)
6. A. Abulencia et al., Phys. Rev. Lett., 96 (022004)2006;
7. LEP EWK Working Group.