

Single top quark events at Fermilab

B. Ananthanarayan, Rituparna Chakrabarti and Monalisa Patra

According to a press release dated 9 March 2009, the two experiments CDF (Collider Detector at Fermilab) and DZero have announced the discovery of 'single top quark' events, which represent a spectacular discovery and confirmation of the standard model of elementary particle physics. The results of their findings are now available as preprints which have been submitted for publication in *Physical Review Letters*^{1,2}.

The top quark is the heaviest of all elementary particles, and is a very heavy counterpart of the more familiar *u* and *d* quarks, which are the constituents of such known matter as protons and neutrons (nucleons). Quarks are particles which participate in the strong interactions which are mediated by particles known as gluons. The familiar forces between nucleons, for instance, are a residue of the strong interactions, after the strong interactions bind quarks in stable particles such as the nucleons. The precise mechanism by which quarks and gluons bind is still not understood completely and remains one of the great open challenges in the field of elementary particle physics. The other unstable quarks are the *s*, *c* and *b* quarks which are significantly lighter than the top quarks. The instability of the quarks is due to the weak interactions which among other things, is responsible for nuclear beta decay as well as the instability of the free neutron, to cite some familiar examples.

As a result of their instability, these can only be produced in special laboratory conditions where particles are collided against one another, leading to a fireball in which typically these particles and their corresponding anti-particles are produced in pairs. All prior observations of the top quark, also at the Fermilab, were made when top and anti-top quark pairs were produced. Indeed, at the Tevatron, proton and anti-proton beams are collided at the highest energies reached so far corresponding to a 'centre of mass energy' of 1.96 TeV, where TeV stands for teraelectronvolt, a fact which gives the Tevatron its name. In these collisions, not all the energy is available in a particular collision event; the participating constituent of the protons and anti-

protons carry only a certain fraction of the available energy. Note that at Tevatron energies, the other constituents of the proton and anti-proton, which are the gluons, also carry significant fractions of the available energy and also have a significant collision cross-section. The pair production, through the annihilation of the constituent quarks and gluons, proceeds essentially through the strong interactions.

The new events are very rare, as the production mechanism for these proceeds through quanta associated with the weak interactions, the *W* bosons. The corresponding production cross-section and associated event rates are therefore much smaller than those for pair production. It is possible to represent the underlying process that leads to the single top production pictorially, which is exhibited in Figure 1.

There has already been some evidence in the past couple of years for single top quark events. For instance, single top quark event was first reported by DZero in 2006. At that time, CDF was unsuccessful as its method of analysing the signal did not work. While it expected a 2.6σ (where σ denotes the standard deviation) significance signal, in practice it actually obtained an even lower value. Later on, by increasing the amount of data analysed along with refining the event selection techniques, CDF reported its first single top event within one year with a 3.1σ effect.

According to the current preprints released^{1,2}, they each report that the signal they observed had a statistical signifi-

cance of 5σ . The integrated luminosity of the CDF and DZero were 3.2 and 2.3 fb^{-1} (where the symbol fb^{-1} is to be read as 'inverse femtobarn' a unit of 'integrated luminosity', a measure of the total accumulated data) respectively. The CDF collaboration had already reported a signal last year but not at the 5σ level; in fact they had reported a 3.7σ result based on an integrated luminosity of 2.2 fb^{-1} (ref. 3). Even earlier, DZero in 2006 announced a 3.6σ result based on an integrated luminosity of 0.9 fb^{-1} (ref. 4). Note here the present sensitivity of CDF and DZero are quoted at 5.9 and 4.5σ respectively according to their reports submitted to *Physical Review Letters*.

The events are studied through the decay of the top quark into mainly a *W* boson and a *b* quark as shown in Figure 1. The *W* boson further decays leptonically into electrons/muons or hadronically. To select the data sample, the method that both collaborations make use of most frequently is standard lepton, missing transverse energy and jet reconstruction algorithms: the search focusses on the final state consisting of one high transverse momentum isolated lepton and missing transverse energy, together with a *b*-quark jet from the decay of the top quark. Moreover, there is an additional contribution of a *b*-quark in the *s*-channel production, whereas in the *t*-channel production, there is an extra light quark along with a *b*-quark. Besides the signal cross-section being small, the presence of only one top quark in the final state makes the process of separation of the signal from the large background chal-

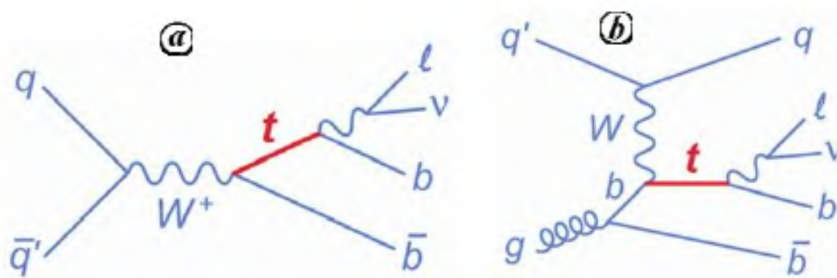


Figure 1. Figures depicting the single top production from Fermilab web-site through (a) the *s*-channel, and (b) *t*-channel. Here $q(\bar{q})$ is the constituent quark (anti-quark) in the collision, and g is the gluon in the collision as the case may be.

linging as its kinematics is not very different from that of the signal. The most serious background for single top quark event is pair production. The other major background sources are W bosons produced along with jets and a multi-jet background. This calls for some advanced techniques to extract a small signal out of a large background. In the course of discovery of the single top quark, the analysis techniques have gone a long way with background model improvements, neural network b-tagging and splitting analysis channels by a number of jets, to name a few.

CDF selects its candidate events using a 'W + 2 jets' signature. Its detector works on the principle of accurately tracking the path of individual particles in a magnetic field, so as to measure the momenta. Therefore, it is not hard for it to recognize the high energy electrons and muons, along with the energetic neutrino coming from the W signal. The DZero's analysis on the data on the other hand is divided into 12 orthogonal channels, to increase its sensitivity since there is a significant variation in the signal to background ratio from channel to channel. It uses an extremely precise segmented calorimeter which measures the energy from each collision. The channels are selected based on the lepton flavour, jet multiplicity and tagged b jets. Each event is examined carefully, by taking the kinematics of all measured objects and noting the probability of it matching with any of the possible configuration and energies of the single top events. The neural network b tagger in this case identifies those jets originating from the hadronization of the b-quarks, thereby pointing to the single top signal yielding a W and 2 b-quark jets. After this, the decision tree is used to study the data, which with the help of many kinematical variables differentiates the signal from all background sources. The collected data is enriched by imposing a cut on the above output till a required number of events is observed. The selected events are then again individually scrutinized by the decision tree method but with the

lesser number of most distinguishing kinematical variables, thereby only leaving the events produced by single top production. After all this selection procedure, the cross-section is computed by taking into account the amount of data analysed.

Recall here that an important missing piece in the standard model is the discovery of the Higgs particle: in the standard model the quanta such as the W boson as well as all the particles such as the quarks become massive through the so-called Higgs mechanism, which implies the existence of the Higgs particle. At the Tevatron the single top quark and Higgs signals have backgrounds in common, with the single top itself being a background for the Higgs particle. Thus the observation of single top quark events is tied to the search for the Higgs particle.

The collaborations have also reported first direct measurement of the modulus of an important parameter of the standard model, viz. value of one of the elements of the so-called Cabibbo–Kobayashi–Maskawa matrix, denoted by $|V_{tb}|$. It may be recalled here that Kobayashi and Maskawa were honoured with the 2008 Nobel Prize for introducing precisely this matrix, which is also at the heart of the phenomenon known as CP violation in the standard model, where C stands for the discrete symmetry known as charge conjugation (particle–antiparticle symmetry) and P for the discrete symmetry known as parity (reflection or mirror symmetry), and CP for the combined action of these symmetries. CP invariance is by and large respected by nature (the further action of time-reversal symmetry denoted by T leads to so-called CPT symmetry, under which all natural laws remain invariant as a consequence of the special theory of relativity). See ref. 5, for a review of this Nobel prize in *Current Science*. Returning to the CDF and DZero results on the measurement, they report the values 0.91 ± 0.11 and 1.07 ± 0.12 respectively, which agree within the errors. Note that there is a theoretical upper bound of unity on this parameter.

The pressing importance of the single top events is that it is also a window to the discovery of elementary particle interactions that may be present in nature which are yet to be discovered. Such interactions are present in many extensions of the standard model, each of which has as an objective of addressing one or several of its (theoretical) drawbacks or shortcomings. For instance, why the parameters of the standard model are what they are, or what the actual mechanism of the electroweak symmetry breaking is, or why the mass of the W and Z bosons is 17 orders of magnitude lower than the Planck scale (the natural scale involving Planck's constant and Newton's universal constant of gravitation). The single top events would be sensitive to phenomena coming from such extensions which might induce for instance (1) exotic phenomena that change particle type, (2) the possible existence of even heavier counterparts of, say, the top quark, (3) existence of heavy W bosons, and (4) charged Higgs bosons present in models with extended Higgs sectors.

To summarize, the important discovery of single top quark events at Fermilab is crucial for testing the experimental predictions of the standard model. One of the elements of the Kobayashi–Maskawa matrix elements has also been measured.

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3. Aaltonen, T. *et al.*, CDF Collaboration, *Phys. Rev. Lett.*, 2008, **101**, 252001 (arXiv:0809.2581 [hep-ex]).
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B. Ananthanarayan and Monalisa Patra are in Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India; Rituparna Chakrabarti is with St Stephen's College, Delhi 110 007, India. *e-mail: anant@cts.iisc.ernet.in*