Still the mystery of the hidden order in $URu_2Si_2$ continues. The experiments of Wiebe *et al.*[3] point to the clear importance of an itinerant picture: $URu_2Si_2$ supports an anisotropically paired density wave, which raises many issues; for example, the incommensurate nature of the collective mode strongly suggests that the heavy-electron Fermi surface must contain 'nested' surfaces, separated by the observed incommensurate wavevector. Another concept also comes to mind. In $UPd_2Al_3$, a similar collective mode has been identified as the 'glue' responsible for superconductivity[8]. It would be fascinating if an analogous situation occurs in $URu_2Si_2$, for then we may have a link between anisotropic pairing in hidden order and in exotic superconductivity.

References
1. Palstra, T. T. M. *et al. Phys. Rev. Lett.* **55,** 2727–2730 (1985).
2. Broholm, C. *et al. Phys. Rev. B* **43,** 12809–12822 (1991).
3. Wiebe, C. *et al. Nature Phys.* **3,** 96–100 (2007).
4. Matsuda, K. *et al. Phys. Rev. Lett.* **87,** 872031 (2001).
5. Kiss, A. & Fazekas, P. *Phys. Rev. B* **71,** 054415 (2005).
6. Tripathi, V., Chandra, P. & Coleman, P. *J. Phys.* **17,** 5285–5311 (2005).
7. Varma, C. M. & Zhu, L. *Phys. Rev. Lett.* **96,** 0364051 (2006).
8. Sato, N. K. *et al. Nature* **410,** 340–343 (2001).

HIGH-ENERGY PHYSICS

# Top quarks go it alone

The first, long-sought evidence for the production of single top quarks, by the weak interaction, has been reported from a sophisticated analysis of a large number of proton–antiproton collisions at the Tevatron.

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The top quark's enormous mass, approximately that of a gold atom, makes it the heaviest known elementary particle. The top quark was first observed[1,2] in 1995 by the CDF and DØ collaborations in experiments at the Tevatron collider at the Fermi National Accelerator Laboratory, and — until CERN's Large Hadron Collider turns on at full energy in the next year or so — the Tevatron remains the only laboratory in the world in which top quarks can be produced and studied. The fact that the top quark is so much more massive than the other quarks may be a hint that it plays a special role in the mechanism for mass generation. Studies of the interactions of the top quark — including that of single-top production now published by the DØ collaboration[3] — might also uncover possible exotic interactions that may be felt more weakly by the lighter quarks.

Most top quarks are produced in top–antitop pairs by the strong force. The production rate for this process is substantial (it has a cross-section of about 7 picobarns) and the presence of two massive top quarks in each event provides a clear signature to separate them from the background. The weak interaction, on the other hand, can change a quark of one flavour into another, enabling massive quarks to decay into lighter ones. The dominant decay mode of the top quark is into a charged $W$ boson and a bottom quark, but the lifetime is expected to be very short and has not been measured. But if this decay process is run backwards, it becomes a production process: a sufficiently energetic collision of a $W$ boson with a bottom quark is expected to produce a top quark some of the time (Fig. 1a). Alternatively, a $W$ boson with enough energy may produce a top quark and an anti-bottom quark together (Fig. 1b). Both of these processes are expected to occur in proton–antiproton collisions at the Tevatron, with a combined cross-section of about 3 picobarns, assuming standard interaction couplings.

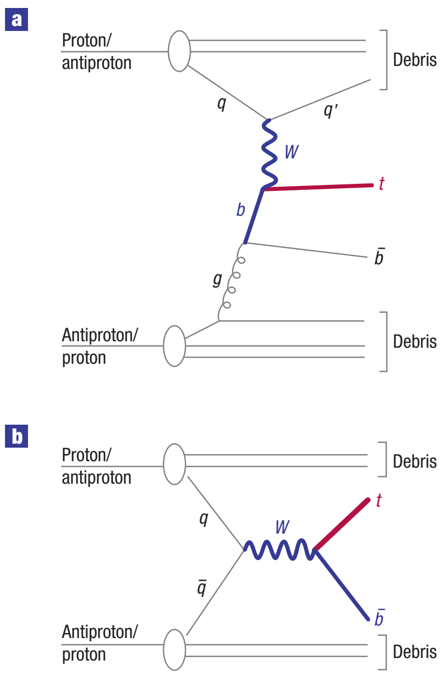


**Figure 1** Production of single top quarks in proton–antiproton collisions. **a**, A single top quark ($t$) can be created in the collision of a $W$ boson and a bottom quark ($b$). In this example, the $W$ boson is emitted from a quark in the proton, changing the quark's flavour ($q \rightarrow q'$); the bottom quark is pair-produced from a gluon ($g \rightarrow b\bar{b}$). **b**, A single top quark can also result from the annihilation of a quark and antiquark ($\bar{q}$).

However, nature may not be wholly described by the Standard Model, with its three generations of fermions (Fig. 2). If a fourth generation of particles exists, its members are too heavy to have been seen yet, but they may share weak couplings with the three generations we already know about. If the coupling between a $W$ boson, a top quark and a bottom quark were measured to be lower than predicted, a possible explanation is that a heavy fourth generation could be sapping coupling from the lighter three. If the measured coupling is higher than predicted, it could be a sign that the $W$ boson has a heavy cousin, a $W'$ boson, which can also contribute to single-top production; some other new interaction could also be at work.

The DØ collaboration has now reported evidence for the production of single top quarks[3]. The search for this process is a technical *tour de force*, with far-reaching implications. Compared with the top–antitop process, the production of a single top has a smaller cross-section, and the presence of only one heavy top quark in the events makes this process much more difficult to separate from the background processes that are inescapable in collisions of protons and antiprotons. Much of the work of the analysis is devoted to understanding the absolute rates expected of the signal and of each background process. Many of the background rates are calibrated with collider data, as the theoretical predictions have large uncertainties.

After preliminary event selection, the ratio of signal to background is just 5%, and the uncertainties on the background rates are at the level of 20%. To test for the presence of a signal under these challenging circumstances, the DØ collaboration has put to use three sophisticated analysis techniques — boosted decision trees, bayesian neural networks, and a matrix-element analysis — to select purer samples of single-top candidate events. These three techniques take advantage of the many features that are reconstructed for each candidate event, comparing them against what is expected for signal, and what is expected for background. For example, the mass of the top quark is known, and its polarization in single-top events, expected to be close to 100%, can be used to advantage. Information is also extracted from the debris recoiling from the top quark. In all, DØ uses 49 different quantities measured on each event to help separate the signal from the background.

One reason these searches are important is that they can be refined for use as Higgs boson searches. Higgs production in association with a *W* boson has the same final state as single-top-quark production. Backgrounds for single-top searches are therefore also backgrounds for Higgs searches, and single-top events themselves are a background for a Higgs search. The Higgs search is expected to require more data, because the signal production cross-section is lower, and the signal is less distinct from the backgrounds.

| 1st | 2nd | 3rd | 4th? |
|---|---|---|---|
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | ? |
| $e$ | $\mu$ | $\tau$ | ? |
| $u$ | $c$ | $t$ | ? |
| $d$ | $s$ | $b$ | ? |

**Figure 2** Three generations, or more? The elementary fermions — electrons, muons, taus, their associated neutrinos, and the six quarks, up, down, charm, strange, top and bottom — line up in three 'generations'. A fourth, heavier generation may exist, and its presence might detectably influence the interactions of the lighter generations.

DØ's decision-tree analysis is its most sensitive, with an expected excess over the background of 2.1 standard deviations in the data sample analysed (amounting to 0.9 inverse femtobarns). An excess of 3.4 standard deviations is seen in the data. This excess is sufficient to report 'evidence' for single-top production, but does not yet meet the five-standard-deviation criterion to report a 'discovery'. The chances of observing an excess as large as that seen by the DØ collaboration, assuming single top quarks are produced at their Standard-Model rate, is 11%. The other two analyses agree with the decision-tree result, with excesses of 2.9 standard deviations for the matrix-element method and 2.4 standard deviations for the neural network analysis. The three results are highly correlated, as they involve different interpretations of the same selected events. They are not 100% correlated, however, and a future combination of the results is expected to provide an even more sensitive result. For now, the DØ measurement of the cross-section for single-top production is 4.9 ± 1.4 picobarns, somewhat higher than the prediction of 3 picobarns.

The CDF collaboration at the Tevatron has also sought single top quarks with multiple analyses with similar expected sensitivity, but does not yet have evidence for single-top production. Both collaborations expect to have data samples in excess of 2 inverse femtobarns — more than twice the current data sample size — analysed by the summer of 2007. The new data will bring a large increase in the expected sensitivity, allowing firmer conclusions to be drawn about the production of single top quarks, and tighter constraints to be placed on new interactions.


### References

1. Abe, F. *et al.* (CDF Collaboration) *Phys. Rev. Lett.* **74,** 2626–2631 (1995).
2. Abachi, S. *et al.* (DØ Collaboration) *Phys. Rev. Lett.* **74,** 2632–2637 (1995).
3. Abazov, V. M. *et al.* (DØ Collaboration) Preprint at <http://arxiv.org/abs/hep-ex/0612052> (2006).


ASTROPARTICLE PHYSICS

# Neutrinos and quantum spacetime

Spacetime might seem smooth, but it could, at very short length scales, be quantized. Energetic neutrinos from gamma-ray bursts could provide a useful means to investigate further, and probe the nature of quantum gravity.

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Research into 'quantum gravity', a unified description of gravitational and quantum phenomena, has led to many hints that the fundamental description of spacetime should not be based on the familiar concept of a classical, smooth geometry, but on a new, somehow quantized picture. The length scale at which this spacetime quantization is expected to appear is very small — the so-called Planck length, $L_P \sim 10^{-35}$ m — so it is extremely difficult to test this prediction. But, as Jacob and Piran[1] discuss on page 87 of this issue, observations using neutrino telescopes could present a rare opportunity for such a test — and perhaps the most powerful test among the few that have been proposed over recent years.

When we describe the motion of planets, using general relativity, and when we describe the properties of microscopic elementary-particle systems, which are governed by quantum mechanics, our formalisms refer to a smooth classical spacetime. However, when we attempt to unify general relativity and quantum mechanics in a theory of quantum gravity,