

## Celebrating 20 years of the discovery of the Top Quark

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An historical recount of the events leading to the discovery of the top quark in 1995 by the CDF and D0 experiments at the Tevatron.

### 1 Introduction

This presentation brings us back to the early nineties. It is interesting to picture ourselves without iphone and laptops, working on DEC VAX and having to stay in the office to work because there was no internet at home. The programming language was Fortran and plots were made with PAW. Detectors were becoming bigger and more complex, but no Silicon detector had been tried in a hadron collider yet. To put things in perspective for the LHC physicist of today: the MonteCarlo programs of the time did not differentiate between heavy and light quarks (VECBOS), there were no b-tagging algorithms, it was not clear that a Silicon detector could survive the radiation environment of an hadron collider such as the Tevatron and collecting data took a long time (one year for  $20 \text{ pb}^{-1}$ ). Nonetheless, working at the most powerful accelerator of the time was as exciting as it today.

### 2 History of particles discoveries

From the sixties onward the story of particle physics went through a phase of reorganization. First the idea that quarks would be the building bricks of mesons and baryons, then the appearance of the fact that quarks and leptons seemed to be organized in some sort of families. Discoveries kept confirming this pattern: quark charm in 1974, tau lepton in 1976 and the bound state of the quark b in 1977. By the year 2000 also the tau neutrino was discovered and only one piece seemed missing, the top quark, companion of the bottom quark with charge  $2/3$ . The historical vision gives the impression of necessity of the existence of this quark but that was not the feeling at the time. On the experimental side the search kept giving null result and mass limits increased.

### 3 The search in Run0 and the hints from EWK fits

Initially the search was based on the hypothesis that the quark top was so light to be produced in the process of W boson decay,  $W \rightarrow tb$  followed by  $t \rightarrow b\nu_\ell$ . This was the strategy used during 1988/1989 during the so called Run0 of the Tevatron, only the CDF experiment was running and did not have a silicon detector yet. A new limit of  $M(top) \geq 91$  GeV was established that took out of the game the CERN hadronic machines.

However, once the LEP lepton collider started taking data it became clear that there was a great power in measuring precisely some of the fundamental Electroweak variables so that they could be used to constrain unknown ones, such as the mass of the top quark or the mass of the Higgs boson. As we can see in Fig.1, from the evolution of the value of the top mass as predicted from the result of electroweak fits as a function of time, there is a trend toward high values. A few weeks before the announcement of the CDF evidence for top production, the result of the electroweak fits extrapolation was presented in Moriond EWK 1994 and it corresponded to  $M(top) = 174 \pm 11 \pm 18$  GeV.

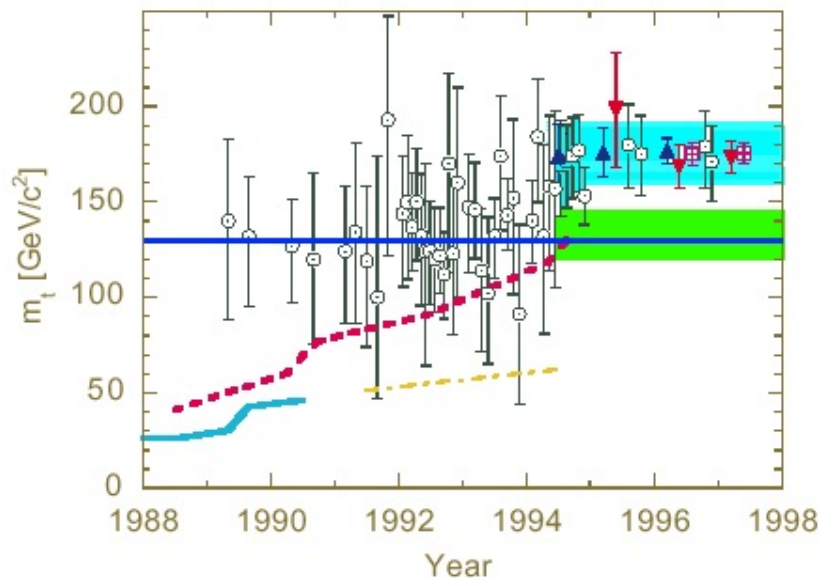


Figure 1 – Top mass from electroweak fits as a function of time

### 4 The Tevatron and its detectors

The Tevatron was a  $p\bar{p}$  collider equipped with superconducting magnets that can provide a centre of mass energy of 1800 GeV. Two general purpose detectors were built around the interaction points: CDF and D0. Each detector a bit complementary to the other: D0 strong in jet and missing energy resolution thanks to its fully hermetic calorimeter, while CDF with better tracking and an innovative vertex silicon detector to identify displaced vertices from b-quark decays.

The top quark would be mainly produced at the Tevatron in pair of  $t$  and  $\bar{t}$  either initiated by quarks (85% of the time) or by gluons (15% of the time). This is the opposite of what happens at a higher energy collider such as the LHC where the production cross section is dominated by the gluon fusion process. Another interesting comparison is that given the production cross section and the luminosity of the Tevatron there would be about ten  $t\bar{t}$  produced per day, while at the LHC at 8 TeV there is about one  $t\bar{t}$  event per second. This implies that at the end of Run I the Tevatron produced only about 100  $t\bar{t}$  pairs in each experiment. Not a very large statistic for

discovering a new particle in such a difficult environment.

The top would decay almost 100% in a W boson and a b quark that would hadronize into a jet. The final states of a top pair production can be classified based on the decay of the two W bosons: lepton plus jets (one W to leptons), dileptons (both Ws to leptons) or all-hadronic. Decays with  $\tau$  leptons are treated separately in case of  $\tau$  hadronic decays, but enter the (di)lepton category in the other cases.

### *The Silicon Vertex Detector of CDF*

The Silicon Vertex Detector of CDF is the first ever microstrip silicon detector being installed in a hadron collider environment. The initial idea, by a professor from Pisa, Aldo Menzione, was not considered a viable option. However, in 1992 the detector was installed on the beam pipe at the heart of the CDF experiment and started taking data with excellent performance throughout its life. At the time, it was the largest detector of this type, built of two cylinders of four layers of silicon microstrip detectors with 2D reconstruction capability, see Fig.2.

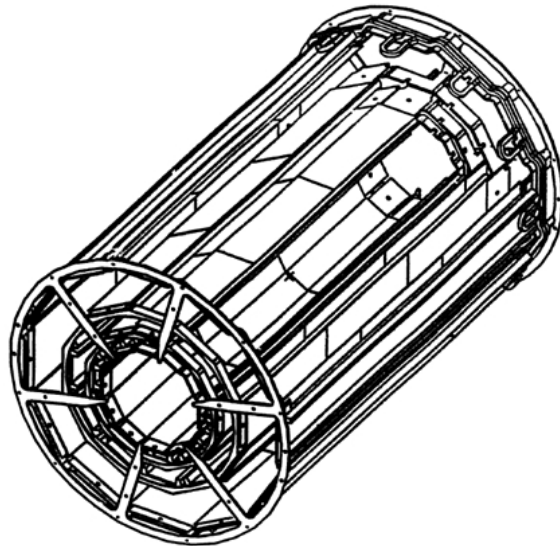


Figure 2 – The CDF Silicon Vertex Detector(SVX) Barrel module

## **5 The road to discovery**

The Tevatron Run I started in 1992 and continued until 1996. During that time the race for the discovery was fierce. Very quickly both experiments were blessed by very spectacular events. For CDF, it was the 1992 "DPF event", a dilepton  $e-\mu$  event with two jets one of them b-tagged by both SVX and a soft lepton. For D0 it was the "event 417", another dilepton  $e-\mu$  event consistent with coming from the decay of an object with a mass between 145 and 200 GeV. The analyses strategies for both collaborations were organized in groups following the different final states topologies: dilepton, with the smallest branching ratio but highest signal over background ratio and the lepton plus jets channel, with a larger branching ratio but a higher background from W/Z+jets production, that could be reduced significantly with the identification of a b-jet. However, the initial performance of the Tevatron was disappointing. By the end of 1994 CDF manages to obtain "evidence" for a top signal with a handful of events, dominated by the presence of lepton plus jets events that would all cluster around the mass of 175 GeV.

Things changed during a technical stop of the accelerator, when a misplaced magnet was found, and after that the beam intensities doubled. The competition grew even more. The

concept of "blind analysis" was born: in order to be able to claim a discovery, the experiments decided a set of selection cuts a priori, using the early part of the data, to maintain unchanged until the whole statistics would be collected. A posteriori, since all the optimization was done with the hypothesis of a smaller top mass, the cuts chosen were not so optimal for a heavier object. A fun fact of the period was the fear of leaks of information across the Tevatron ring, the paranoia of the Top Physics groups from both experiments forced people to swear complete secrecy and to hide paper drafts in secret directories. Of course all these effort were useless as the information leaked anyway.

Finally on February 24th 1995 the two collaborations submitted back to back the two discovery papers that are published on April 3rd of the same year<sup>2</sup>. The new particle proved to be indeed very heavy, with a reconstructed mass in the lepton plus jets channel of  $M(top) = 176 \pm 13$  GeV for CDF, see Fig.3, and  $M(top) = 199 \pm 30$  GeV for D0, see Fig.4.

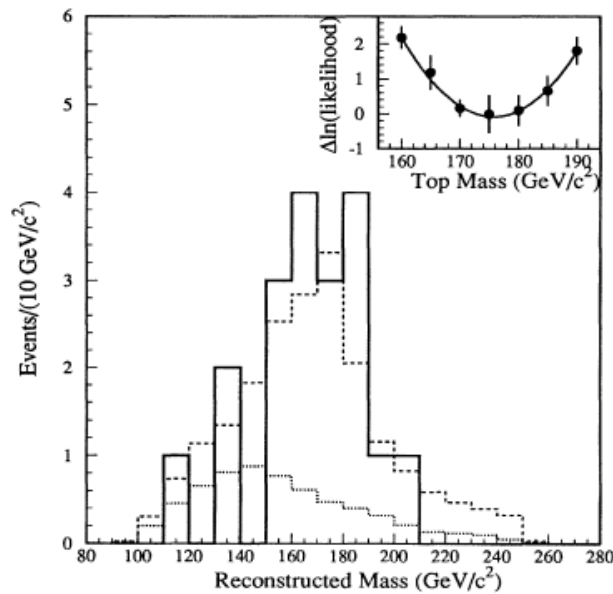


Figure 3 – Reconstructed mass distribution for the b-tagged W+4-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus  $t\bar{t}$  Monte Carlo simulations for  $m_t=175$  GeV (dashed), with the background constrained to the calculated value. The inset shows the likelihood fit used to determine the top mass.

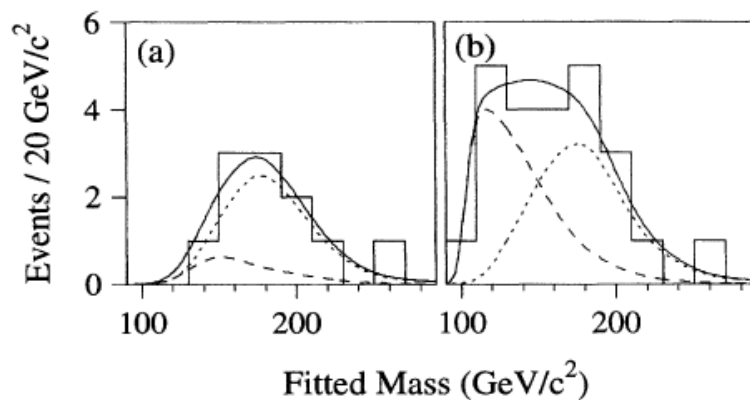


Figure 4 – Fitted mass distribution for candidate events (histogram) with the expected mass distribution for 199 GeV top quark events (dotted curve), background (dashed curve), and the sum of top and background (solid curve) for (a) standard and (b) loose events selection.

### *Other analyses*

As the discovery of the new particle was based only on two final state topologies and very simple analysis strategy, soon enough the experiment were in need of a wider exploration of the properties of the top quark. Two main avenues were pursued, the one of more sophisticated analyses and the extraction of the signal in the remaining final state topologies. Some analyses existed that were indeed able to see a signal during the period before discovery, but using very innovative techniques that could not be fully verified to the satisfaction of the collaboration in the short time available, could finally be published<sup>3</sup>. Some other groups focused first on the more challenging all hadronic final state in order to confirm the expected behaviour of the new particle. For the all jets channels where the signal was submerged by a background several orders of magnitude larger, new ideas for background reduction and estimate were developed that brought to the evidence paper in this final state about one year after the announcement of the discovery<sup>4</sup>. The observation of the remaining decays including hadronic taus followed later on to complete the whole picture.

## **6 Conclusions**

The discovery of the top quark has been one of the major enterprises of particle physics and it was achieved pushing to the extreme the limits of technology and creativity of the particle physics community. After 20 years, the interest in the top quark has not faded as, due to its large mass, it is possibly one of the best handles to find what new physics lies beyond the Standard Model.

## **References**

1. "Evidence for top quark production in  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV", CDF Collaboration (Abe, F. et al), *Phys. Rev. Lett.* **73**, 1994 (225-231)
2. "Observation of top quark production in  $p\bar{p}$  collisions", CDF Collaboration (Abe, F. et al), *Phys. Rev. Lett.* **74**, 1995 (2626-2631) "Observation of the top quark", D0 Collaboration (Abachi, S. et al.), *Phys. Rev. Lett.* **74**, 1995 (2632-2637)
3. "Kinematic evidence for top quark production in W+multijets events in  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV", *Phys. Rev. D* **51**, 1995 (4623)
4. "First observation of the all hadronic decay of  $t\bar{t}$  pairs", CDF Collaboration (Abe, F. et al.), *Phys. Rev. Lett.* **79**, 1997 (1992-1997)

