

A TEVATRON TESTAMENT

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A quarter-century of experimentation has come to a close for Fermilab's Tevatron Collider, a pioneering instrument that advanced the frontiers of accelerator science and particle physics alike, setting the stage for the Large Hadron Collider at CERN. The world's first high-energy superconducting synchrotron, the Tevatron served as the model for the HERA proton ring at DESY and as a key milestone toward the development of the LHC. In its final months of operation, the Tevatron's initial luminosity for proton-antiproton collisions at 1.96 TeV has averaged over 350 Hertz per microbarn. The integrated luminosity delivered at 1.96 TeV approaches 12 inverse femtobarns, with approximately 10 inverse femtobarns recorded by the CDF¹ and D0² experiments. A long line of innovations and much perseverance made possible the evolution of luminosity shown in Figure 1.³

The legacy of the Tevatron experiments includes many results for which the high energy of a hadron collider was decisive. Chief among these is the discovery of the top quark, which for fifteen years could only be studied at the Tevatron. Exacting measurements of the masses of the top quark and W boson and of the frequency of B_s oscillations punctured the myth that hadron colliders are not precision instruments. Remarkable detector innovations such as the first hadron-collider silicon vertex detector and secondary vertex trigger and multilevel triggering are now part of the standard experimental toolkit. So too are robust multivariate analysis techniques that enhance the sensitivity of searches in the face of challenging backgrounds. CDF and D0 exemplify one of the great strengths of particle physics: the high value of experimental collaborations whose scientific interests and capabilities expand and deepen over time, responding to new opportunities and delivering a harvest of results not imagined when the detectors were proposed.

A Brief Chronology

The CDF logbook records the first collision event in the Tevatron at 2:32 am on October 13, 1985, at an energy of 800 GeV per beam. The estimated luminosity was $2 \times 10^{25} \text{ cm}^{-2} \text{ sec}^{-1}$, more than seven orders of magnitude below the machine's performance in 2011.⁴ By afternoon, the Tevatron complex was shut down for eighteen months to construct the D0 interaction region and complete the CDF detector. CDF's pilot run in 1987 yielded the first wave of physics papers, including both measurements and searches. During 1988 and 1989, CDF accumulated 4 inverse picobarns, now at 1.8 TeV (c.m. energy). [Two special-purpose experiments also published results from this run. Experiment 710 measured elastic scattering and the total cross section; Experiment 735 sought evidence of a deconfined quark-gluon plasma.] The peak luminosity delivered to CDF surpassed 1 Hertz per microbarn in collisions of six proton bunches on six antiproton bunches. Papers from these early runs are worth rereading as reminders of how little we knew, and how a tentative but growing respect for the standard model brought coherence to

the interpretation of results. It is also interesting to see how the experimenters went about gaining confidence in their detector and their analysis techniques.

Both D0 and CDF took data at 1.8 TeV in the extended “Run 1” between 1992 and 1996, recording 120 inverse picobarns. An important enabler of increased luminosity was the move to helical orbits, which eliminated collisions outside the two interaction regions. During this period, a small test experiment called MiniMax (T864) searched for disordered chiral condensates and other novel phenomena in the far-forward region.⁵ This was a time of high excitement, not only for the drama of the top-quark search, but also for the stimulating conversation among the Tevatron experiments and those at the CERN and SLAC Z factories and the HERA electron-proton collider, all breaking new ground.

Fermilab next constructed the Main Injector and Recycler in a new tunnel, while the experiments undertook ambitious detector improvements. Improvements to the cryogenic system made it possible to lower the operating temperature of the superconducting magnets, and so to raise the collision energy to 1.96 TeV. CDF installed a new central tracker and improved silicon vertex detector and enhanced its forward calorimetry and muon detection. D0 added a solenoid magnet, silicon vertex detector, and scintillating-fiber tracker, and improved forward muon detection. Run 2 began slowly in 2001, but attention to detail and many accelerator improvements, including 36-bunch operation and electron cooling of antiprotons in the recycler, contributed to the outstanding performance of the mature machine.

Let us survey some of the areas in which the Tevatron experiments have delivered results of enduring importance.

Quantum Chromodynamics

The Tevatron experiments have probed the proton with a resolution of about one-third of an attometer, greatly expanding the kinematical range over which we can test the theory of the strong interactions. Perturbative QCD is extremely well validated in studies of hadron jets and other observables. The jet cross section displayed in Figure 2 shows the agreement between calculation and observation over eight orders of magnitude in rate.⁶ Such measurements established the importance of gluon-gluon scattering as a mechanism for jet production and helped constrain the gluon parton distribution functions. Values of the strong coupling constant extracted from jet studies exhibit the running behavior characteristic of asymptotic freedom at higher scales than accessible in other experiments. The strong coupling at the Z-boson mass has been determined with an uncertainty of about 4%.

Other jet studies have not only tested QCD, but also probed for physics beyond the standard model. Measurements of the angular distribution of dijet production confirm the Rutherford-scattering-like expectation of QCD, and place upper bounds on the size of extra spatial dimensions. They also validate, at a resolution of nearly $1/(3 \text{ TeV})$, a key idealization that underpins the standard model—the working

hypothesis that quarks are pointlike and structureless. Measurements of the dijet mass spectrum that extend beyond 1.2 TeV (roughly 2/3 of the center-of-mass energy of the proton-antiproton collisions) are likewise in accord with next-to-leading-order QCD calculations. No evidence is seen for unexpected dijet resonances.

Electroweak Physics

In the final data set of 10 inverse femtobarns, each experiment should have approximately 5 million W bosons in each leptonic decay channel, and perhaps 400 thousand Z bosons. These large samples have made possible many important measurements. The production cross sections agree with QCD predictions, to such a degree that electroweak gauge-boson production is under study as a primary luminosity monitor for LHC experiments. Studies of Z production, with or without accompanying jets, are immensely valuable for testing simulations of standard-model physics. The forward-backward asymmetry of the electrons or muons produced in W decay, which arises from the V-A structure of the charged weak current, provides important information about the up-quark and down-quark parton distribution functions.

Given what we know from many sources, the masses of the W boson and top quark are key elements in the standard-model network that constrains the properties of the Higgs boson. A stellar accomplishment of the Tevatron experiments has been the determination of the W -boson mass as 80.420 ± 0.031 GeV, better than 4 parts in ten thousand. Figure 3 summarizes the Tevatron measurements and their impact on the current world average. The combined uncertainty at the end of Run 2 may approach 15 MeV.

The growing data samples available at the Tevatron, along with the evolution of experimental techniques, have made it possible to observe cross sections times branching ratios well below 0.1 picobarn. All the electroweak diboson pairs ($W\gamma$, $Z\gamma$, WW , WZ , and ZZ) have been detected at the rates predicted by the standard model, as indicated in Figure 4. Mastery of these channels is a prerequisite to the Higgs-boson search at moderate and high masses, but they carry their own physics interest as well: the possibility of validating the standard-model structure of the triple-gauge couplings and searching for anomalous couplings incompatible with the standard model. So far, the three-gauge-boson interactions are consistent with the electroweak theory in every particular.

Heavy Flavors

CDF and D0 have exerted a broad impact on our knowledge of states containing heavy quarks. Studies of the production and decay dynamics of quarkonium states have repeatedly challenged phenomenological models, while measurements of b - and t -quark production have made possible sharp tests of QCD calculations at next to leading order. The Tevatron experiments account for nearly all of our knowledge of the B_c meson, with very precise measurements of the mass and lifetime. The

Tevatron contributes world-leading measurements of masses and lifetimes of B mesons and baryons and has been the unique source of information on many of the B -baryons. With CDF's recent observation of Ξ_b^0 , all the spin-1/2 baryons containing one b quark have been observed at the Tevatron, except for Σ_b^0 , as shown in Figure 5. We also owe to the Tevatron our knowledge of orbitally excited B and B_s mesons, constraints on the mass and quantum numbers of $X(3872)$, important evidence on $D^0 - \bar{D}^0$ mixing, and high-sensitivity searches for rare decays into dimuons.

The Tevatron experiments met one of the key targets for Run 2 by determining the frequency of $B_s - \bar{B}_s$ oscillations. Following a two-sided limit published by D0, the CDF Collaboration determined the oscillation frequency as $17.77 \pm 0.13 \text{ ps}^{-1}$.⁷ The oscillation signal is shown in Figure 6. This beautiful measurement, in line with standard-model expectations, constrains the manner in which new physics might show itself in B physics.

The Top Quark

The discovery of the top quark by the Tevatron Collaborations in 1995 was a landmark achievement.⁸ By 1990, searches by CDF had raised the lower bound on the top-quark mass to 91 GeV, excluding decays of W into top + bottom. A heavy top decays so swiftly that it cannot be observed directly, but must be inferred from its disintegration into a bottom quark and a W boson—both unstable particles themselves. The hunt took off with the growing data sets available to both CDF and D0 in 1992-1993, and soon the possibility of observing top was in the air. D0 subsequently raised the lower bound to 131 GeV. Moreover, a growing body of observations that probed quantum corrections to the electroweak theory pointed to a top-quark mass in the range 150 - 200 GeV. Finding top there emerged as a critical test of the understanding built up over two decades.

Eighteen months of deliciously intense activity culminated in a joint seminar on March 2, 1995, demonstrating that top was found in the reaction $p\bar{p} \rightarrow t\bar{t} + \text{anything}$. CDF gauged the top-quark mass at $176 \pm 13 \text{ GeV}$, while D0 reported $199 \pm 30 \text{ GeV}$. Since the discovery, larger event samples, improved detectors, and sophisticated analysis techniques have led to a very detailed dossier of top-quark properties.⁹ Tevatron measurements of the top mass have reached 0.54% precision, at $173.2 \pm 0.9 \text{ GeV}$,¹⁰ a level that demands scrupulous attention to the theoretical definition of what is being measured. A compilation of the Tevatron measurements is shown in Figure 7. CDF and D0 now aim for an uncertainty of $\pm 1 \text{ GeV}$ per experiment; to reach this level of precision will require a better understanding of b -jet modeling and of uncertainties in the signal and background simulations.

The $t\bar{t}$ production characteristics are in good agreement with QCD expectations for the total rate, transverse-momentum dependence, and invariant-mass distribution. Tevatron studies support a top-quark charge of $+2/3$, and show that the tbW interaction is left-handed. Approximately 70% of the W bosons emitted in top decay

are longitudinally polarized, while the rest are left-handed. The top-quark lifetime is close to 0.3 yoctosecond, as the electroweak theory anticipates. Because top decays before hadronizing, it can be studied as a bare quark. To this point, exploratory studies of spin correlations among the $t\bar{t}$ decay products are in accord with the standard model. Both experiments have observed a forward-backward production asymmetry that is considerably larger than the standard-model predictions, as currently understood. This tantalizing result—which could point to new physics—challenges theorists to create more robust, detailed, and credible simulations of the standard model.

Important information about the weak interactions of top comes from the detection of single-top production through the decay of a virtual W boson or the interaction of an exchanged W boson with a b quark. Using an array of multivariate analysis techniques, CDF and D0 have observed single-top production at a rate consistent with the standard model. The D0 Collaboration has succeeded in isolating the t -channel exchange process. These measurements allow the a determination of the strength of the $t\bar{b}W$ weak coupling that is consistent with the standard-model prediction of a value near unity, and with other indications that $t \rightarrow bW$ is the dominant decay mode of the top quark.

The Higgs Boson

The search for the standard-model Higgs boson is the ultimate challenge for the Tevatron. The straightforward strategy, to detect a light Higgs boson produced in gluon-gluon fusion that decays into the dominant $b\bar{b}$ mode is foreclosed by the overwhelming rate of b -quark pair production by the strong interactions. Thus CDF and D0 have had to seek signals in several production channels and decay modes, and to master many sources of background. Current searches consider gluon-gluon fusion, associated production of a Higgs boson and W or Z boson, and vector-boson fusion. The decay modes examined are $b\bar{b}$, W^+W^- , ZZ , $\gamma\gamma$, and $\tau^+\tau^-$, leading to many dozens of distinct final states.

So far, the Tevatron experiments have given information on where the standard-model Higgs boson is not. The Summer 2011 combined analyses, based on up to 8.6 inverse femtobarns of data, exclude standard-model Higgs-boson masses between 156 and 177 GeV, as shown in Figure 8.¹¹ Parallel work has restricted the allowed parameter space for the lightest Higgs boson of supersymmetric models. According to projections informed by current experience, the full Tevatron data set should yield 95% confidence level exclusion limits up to 185 GeV, should no signal be present, and “evidence” at the three-standard-deviation level below 120 GeV and in the range 150 – 175 GeV.

The Search for New Phenomena

During more than two decades as the world’s highest-energy machine, the Tevatron has had unparalleled capability to search for direct manifestations of physics beyond the standard model. Broad explorations and searches for specific

hypothetical phenomena have been major activities for the experiments. The Tevatron constraints on conjectured extensions to the standard model are impressive in number and scope: CDF and D0 have set limits on supersymmetric particles, many varieties of extra spatial dimensions, signs of new strong dynamics, carriers of new forces of nature, magnetic monopoles, and many more exotica. The null searches compel us to contemplate with greater intensity the unreasonable effectiveness of the standard model.

To be sure, some observations do not square with conventional expectations. In addition to the suggestion of a larger-than-foreseen forward-backward asymmetry in top-pair production noted above, it is worth mentioning two other surprising effects now in play. D0 reports an anomalous like-sign dimuon charge asymmetry in semileptonic decays of $b\bar{b}$ pairs that suggests unexpectedly large CP violation in b -hadron decays. CDF sees a yield of jet pairs in association with a W boson that exceeds expectations in the dijet mass interval between 120 and 160 GeV. D0 does not confirm the excess, but the degree of disagreement remains to be quantified. We should find out soon, from further work at the Tevatron and from new analyses at the LHC, whether any of these results holds up and changes our thinking.

A Final Thought

The last events have been recorded at the Tevatron collider, but the interpretation of data, now enriched by conversation with LHC experiments, goes on. I would like to thank the CDF and D0 collaborators not only for the results they have put in the books, but also for the demands they have placed on theorists to calculate more processes ever more accurately, to make more reliable simulations, and to think in new ways.

Figure 1. Initial luminosity for all stores in the Tevatron Collider. The peak luminosity reached 430 Hz per microbarn—about 30 million collisions per second. (HistoricalPeakLuminosity.png) [source:<http://www-bd.fnal.gov/pplot/today/HistoricalPeakLuminosity.png>]

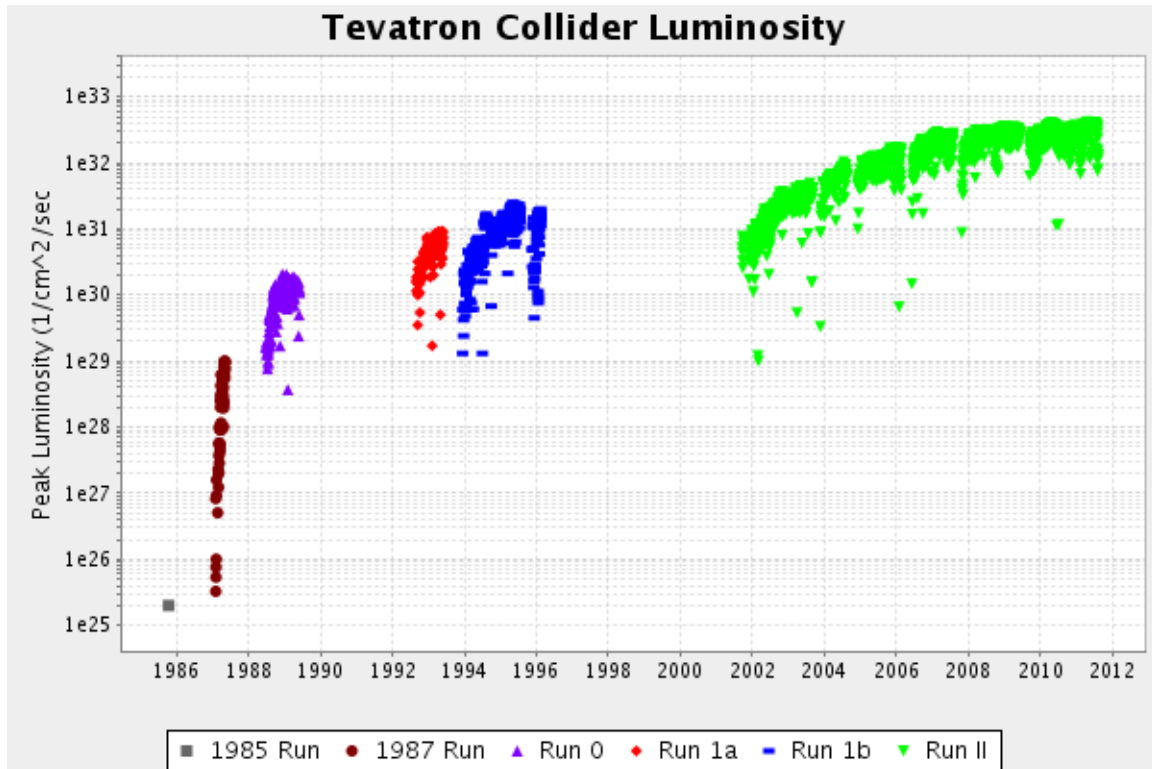


Figure 2. The inclusive jet cross section measured by the D0 Collaboration in proton-antiproton collisions at 1.96 TeV as a function of transverse momentum in six rapidity bins. Solid curves show next-to-leading-order (one-loop) perturbative QCD predictions. (D0jetsr.pdf)

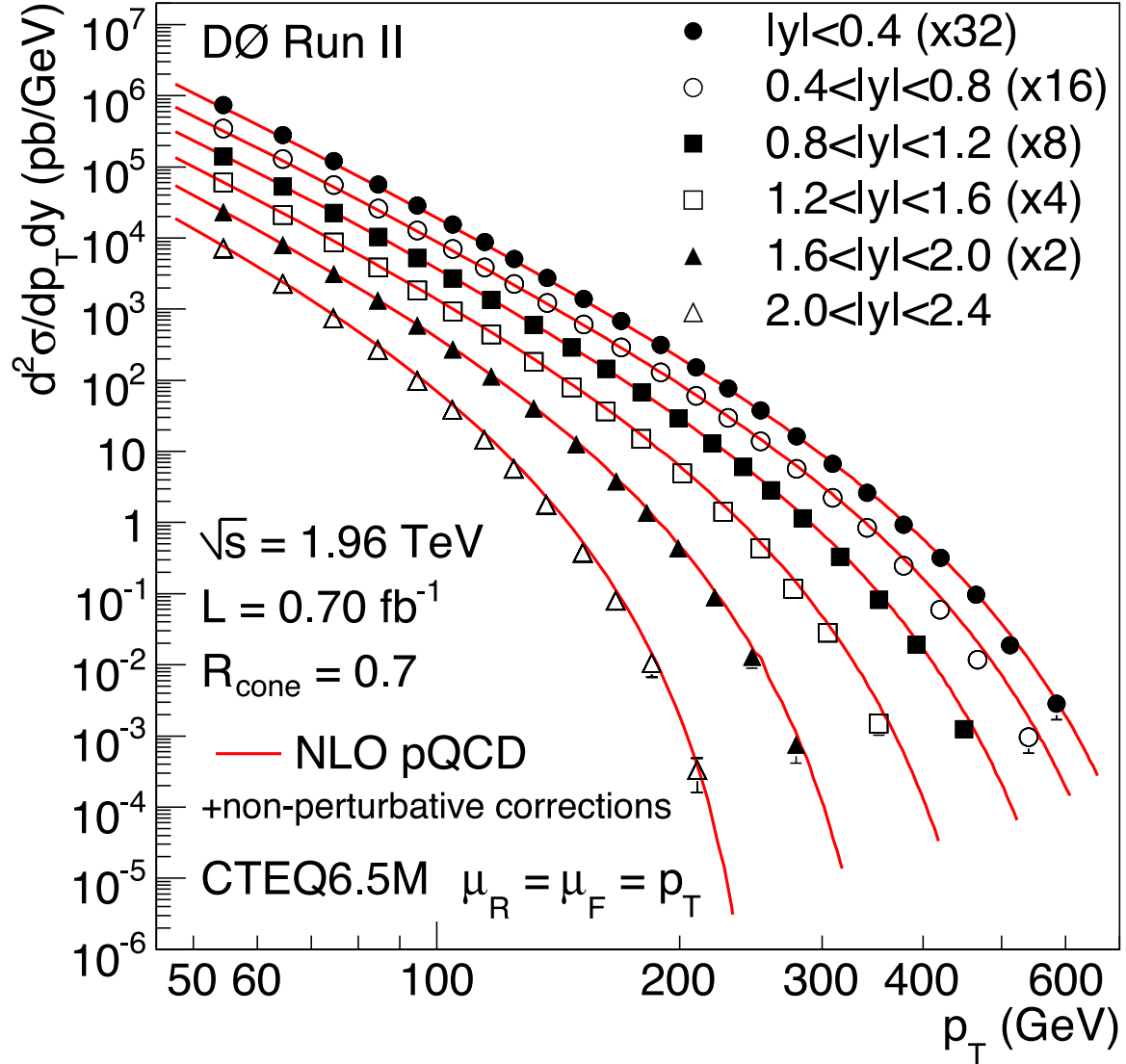


Figure 3. Tevatron measurements of the W-boson mass, compared with the average from the four LEP experiments and the world average. (MWTeV.pdf)

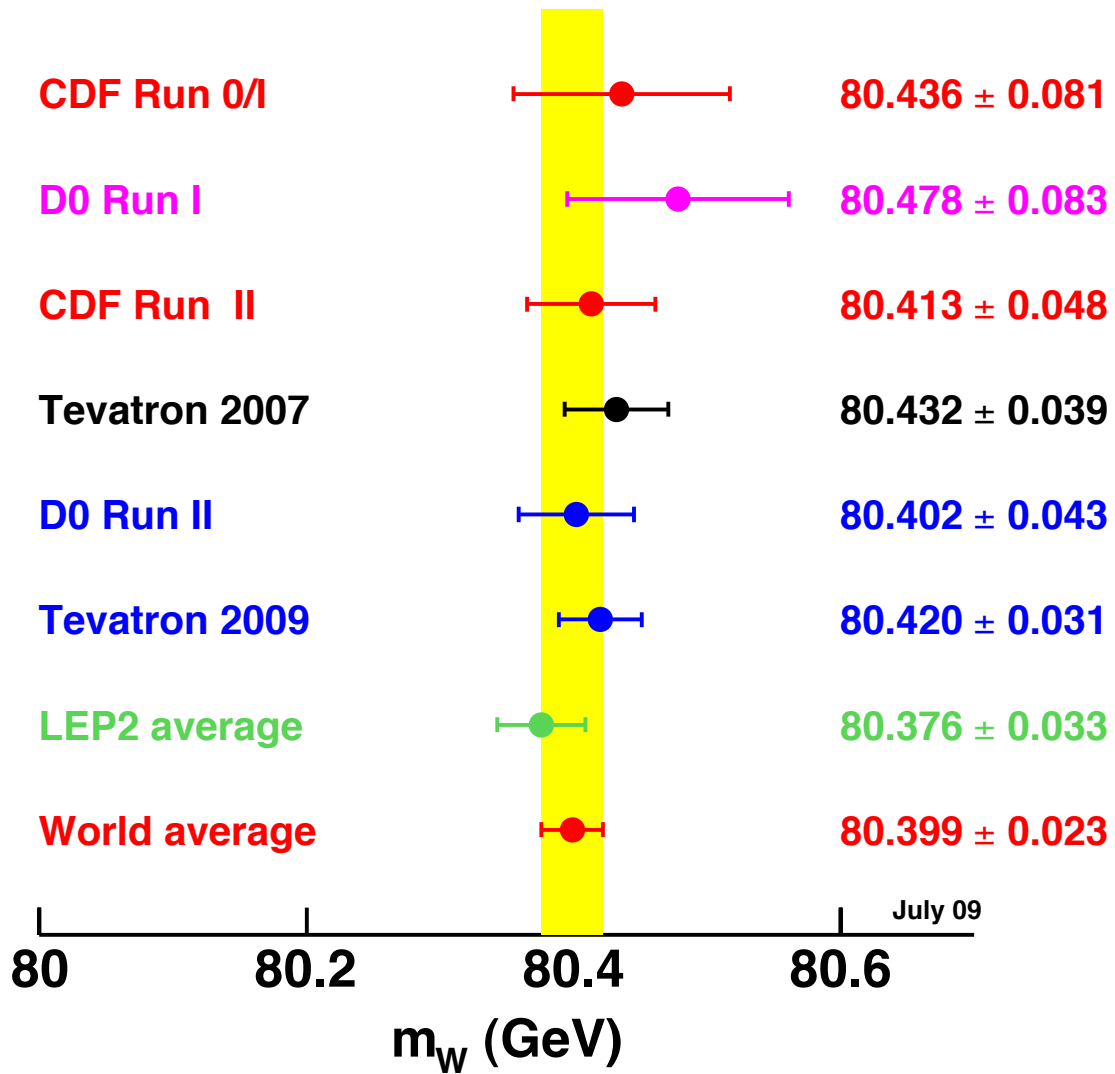


Figure 4. Calculated and observed production rates for key final states in Tevatron Run 2. (tev_xsec.pdf)

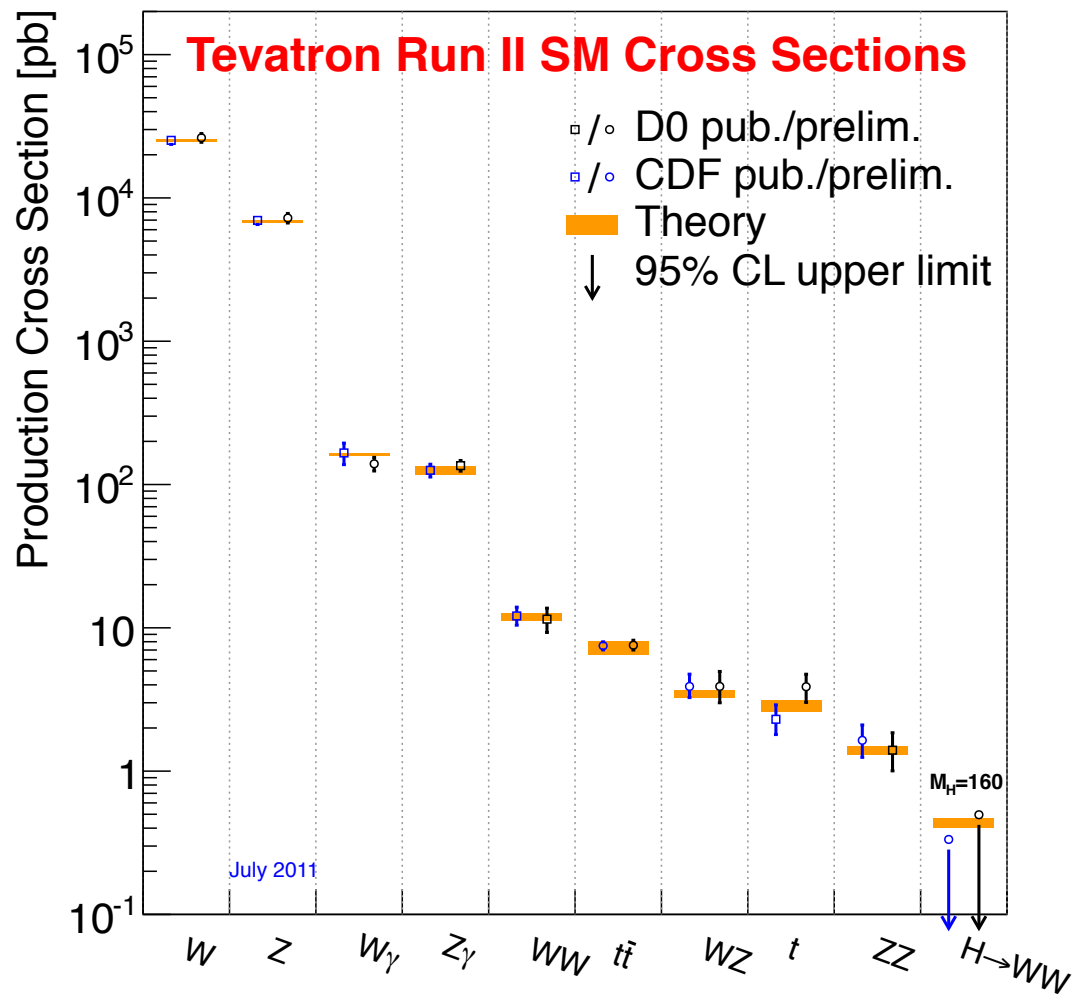


Figure 5. Spin-1/2 baryons containing 0, 1, or 2 bottom quarks. (BaryonsIllustrations.pdf)

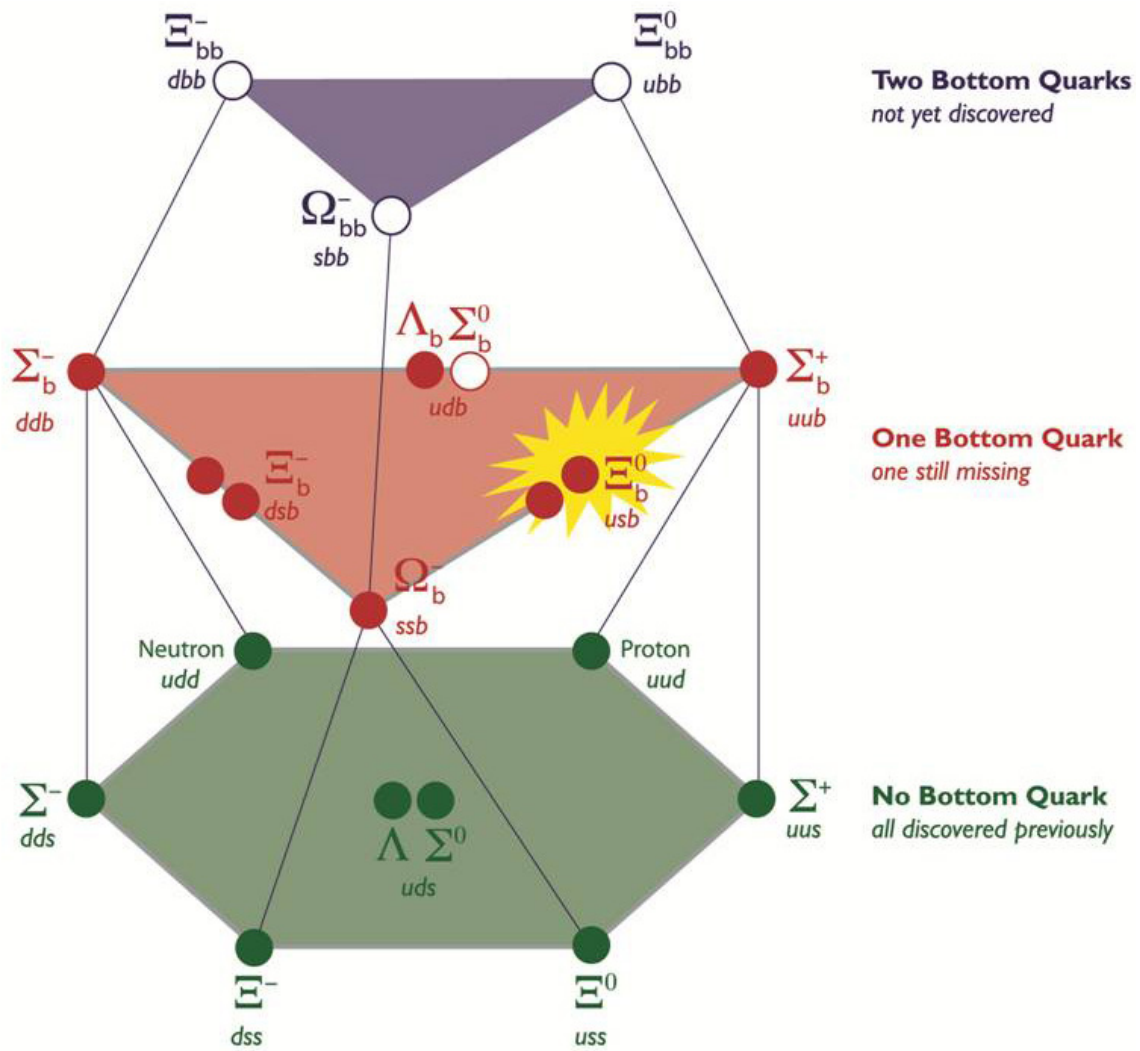


Figure 6. The $B_s - \bar{B}_s$ oscillation signal measured in five bins of proper decay time modulo the measured oscillation period. (BsAsymmetry.pdf)

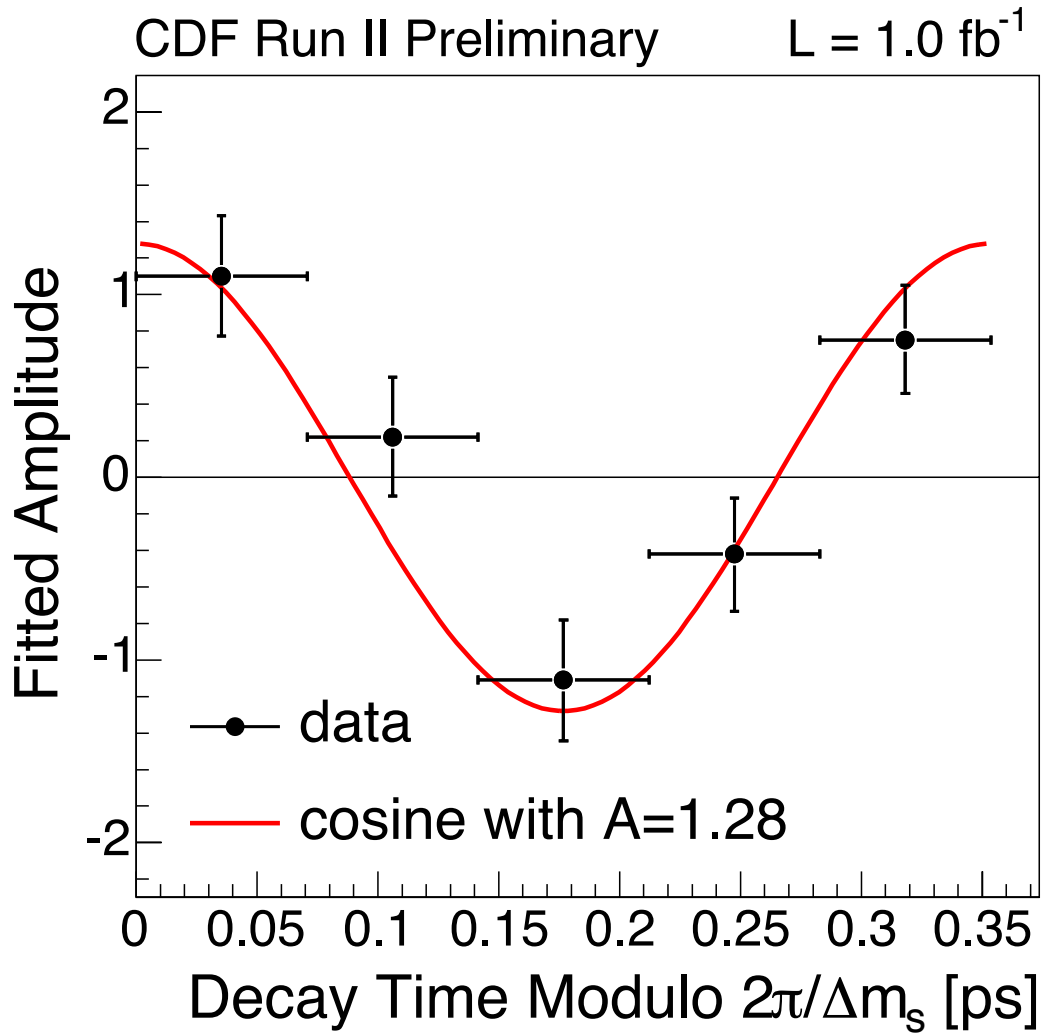


Figure 7. Tevatron measurements of the top-quark mass. (TevMtSum.pdf)

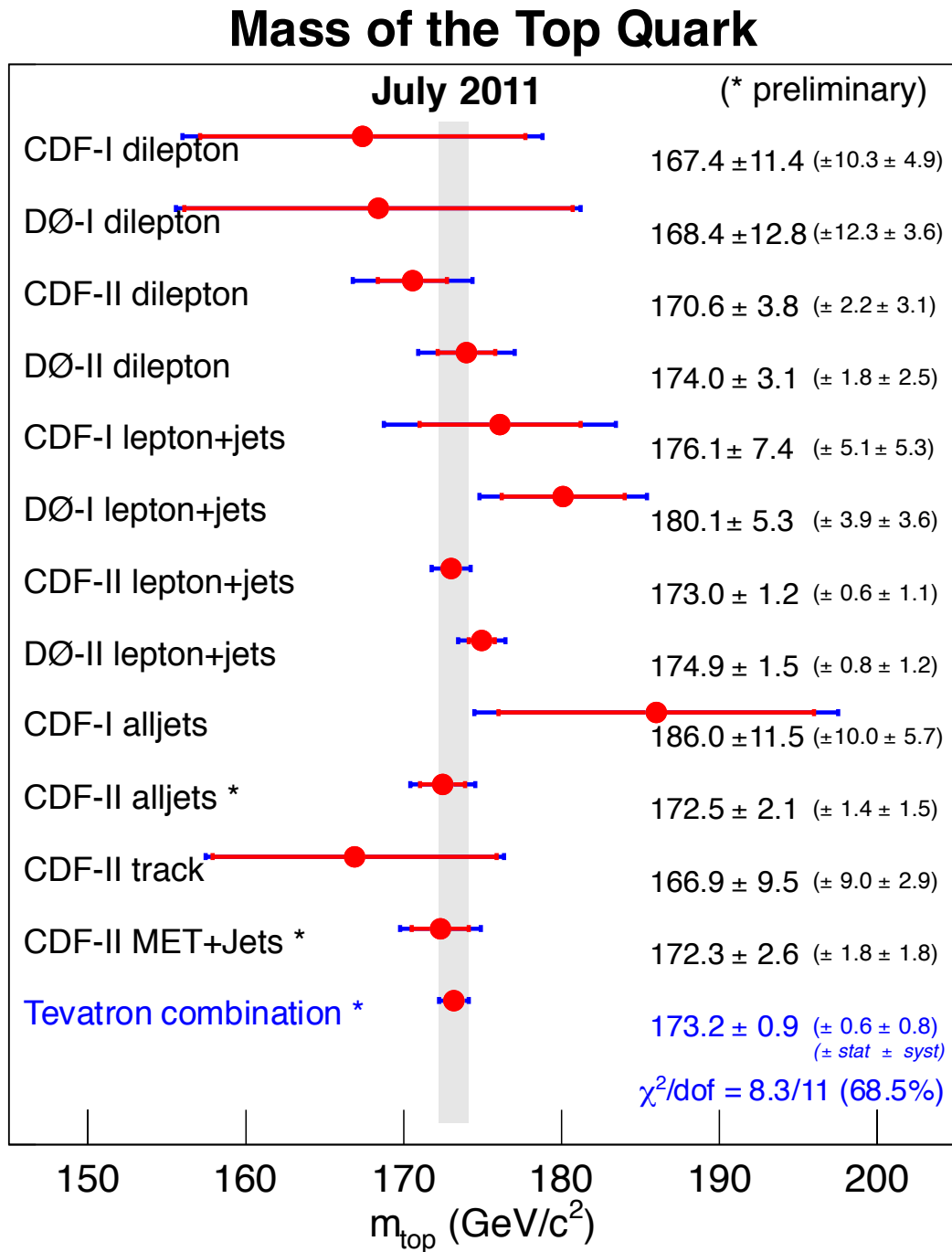
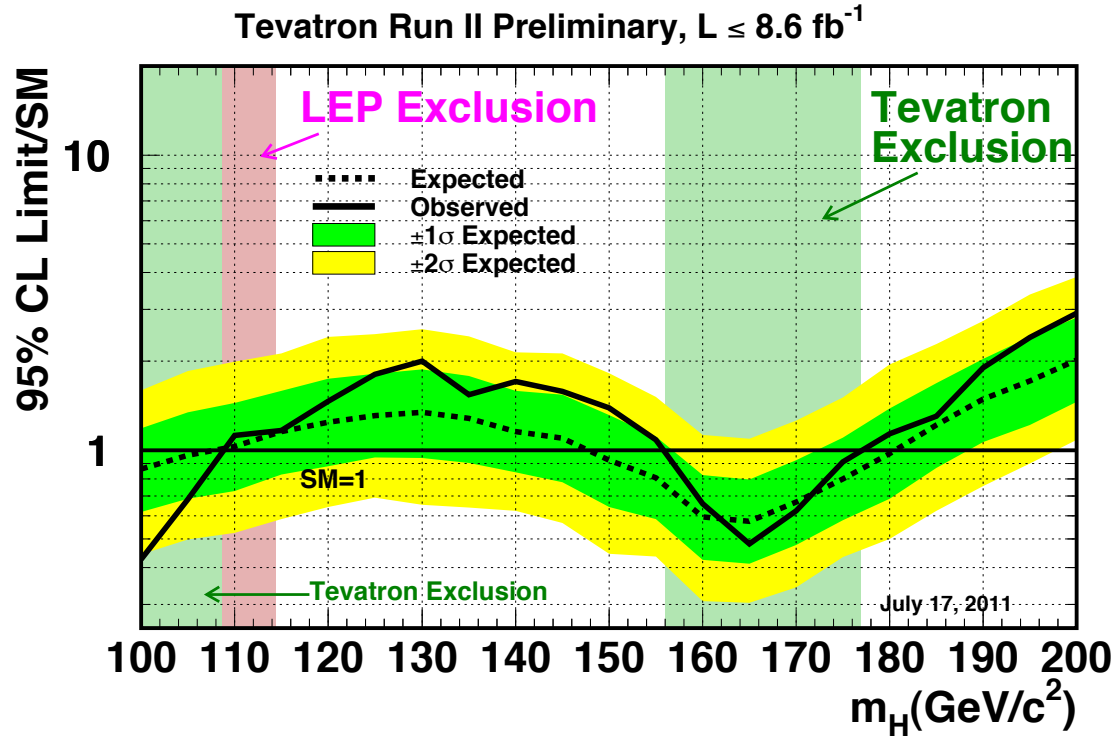


Figure 8. Observed and expected 95% C.L. upper limits on the ratios to the standard-model cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses. The bands represent 68% and 95% probability regions for fluctuations in the absence of signal. (TevHiggsCombo.pdf)



¹ <http://www-cdf.fnal.gov>.

² <http://www-d0.fnal.gov>.

³ The early history of the Tevatron is reported in H. Edwards, *Ann. Rev. Nucl. Part. Sci.* **35**, 605 (1985). For an up-to-the-minute overview, see S. Holmes, R. S. Moore, and V. Shiltsev, *JINST* **6**, T08001 (2011). Anecdotal accounts are given by V. Shiltsev, “Accelerator Breakthroughs, Achievements and Lessons from the Tevatron Collider,” 2010 John Adams Lecture, <http://j.mp/qndsb5>; J Peoples, Wilson Prize Lecture, “The Tevatron Collider: A Thirty Year Campaign,” <http://j.mp/ohzgih>. S. Holmes, DPF 2011 Lecture, “Celebrating the Tevatron: the Machine(s),” <http://j.mp/mRCPsQ>.

⁴ The logbook page, event displays, and other artifacts are at <http://j.mp/pvaez>

⁵ <http://www-minimax.fnal.gov>.

⁶ For example, V. M. Abazov, *et al.* [D0 Collaboration], *Phys. Rev. Lett.* **101**, 062001 (2008); T. Aaltonen, *et al.* [CDF Collaboration], *Phys. Rev. D* **78**, 052006 (2008); **79**, 112002 (2009).

⁷ A. Abulencia, *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **97**, 242003 (2006).

⁸ F. Abe, *et al.* (CDF collaboration), *Phys. Rev. Lett.* **74**, 2626 (1995); S. Abachi, *et al.* (D0 collaboration), *ibid.* **74**, 2632 (1995). For a first-person account, see B. Carithers and P. Grannis, “Discovery of the Top Quark,” *SLAC Beam Line* **25**, (3) 4 (1995), <http://j.mp/qumHer>.

⁹ F. Deliot and D. A. Glenzinski, [arXiv:1010.1202 [hep-ex]].

¹⁰ Tevatron Electroweak Working Group and CDF and D0 Collaborations, arXiv:1107.5255 [hep-ex].

¹¹ The Tevatron New-Phenomena and Higgs Working Group for the CDF and D0 Collaborations, arXiv:1107.5518 [hep-ex].