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TOP QUARK MEASUREMENTS AT THE TEVATRON

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We present recent top physics results from the CDF and D0 collaborations. The data were collected at the Fermilab Tevatron over the years 1992-1995 and correspond to approximately 110 pb^{-1} of $p\overline{p}$ collisions. Both experiments present determinations of the $t\bar{t}$ production cross section using a variety of top decay channels, and refined measurements of the top mass.

The 1996 Physics In Collision conference coincides roughly with the one year anniversary of the discovery of the top quark. Today the top sector is still largely uncharted territory, though the way is becoming clearer with new techniques. The results discussed here represent a nearly two-fold increase in data since the discovery announcements [2 3] and initial evidence paper.[1] The principle quantities within reach at this time are the top mass M_{top} and the top quark pair production cross section $\sigma_{t\bar{t}}$. In the higher statistics future, detailed studies of the top's production kinematics ($M_{(t\bar{t})}$, $P_{T(t\bar{t})}$, W polarization) and of its decay ($V_{|tb|}$ and rare decays) will enable further probes for physics beyond the Standard Model. We must first perfect the art of extracting M_{top} and $\sigma_{t\bar{t}}$, since these quantities form the foundation for all the other measurements. An excellent, comprehensive review of the history and discovery of the top quark can be found in the Review of Modern Physics [4]. A recent summary can also be found in the Annual Review of Nuclear and Particle Science [5].

The top quark game is still one of low statistics. Given our current measured cross section, we expect of order 600 top quark pairs produced in 100 pb^{-1} of data at the Tevatron. This rate is some ten orders of magnitude below the total inelastic cross section, and three orders of magnitude below the inclusive W cross section, so background rejection is essential. In the end, the small sample size limits both the statistical accuracy of our measurements and also our ability to understand some of the systematics.

1 Top Quark Production at the Tevatron

At the Tevatron, top quark pairs are produced either by gluon fusion or quark-anti-quark annihilation. Although the matrix element for the ($gg \rightarrow t\bar{t}$) process is several times larger than the ($q\overline{q}' \rightarrow t\bar{t}$) process, the later dominates because $t\bar{t}$ production probes the large x part of the parton distribution functions where

Table 1: Categories for $t\bar{t}$ decay.

Decay Channel	Branching Fraction
Dilepton ($ee, \mu\mu, e\mu$)	4/81
Lepton + Jets ($e + jets, \mu + jets$)	24/81
All Hadronic ($alljets$)	36/81

quarks are more prevalent than gluons. If the Standard Model is correct, the top quark has a lifetime of roughly 4×10^{-25} seconds, corresponding to a width of nearly 2 GeV/c^2. In this brief time, the top is not expected to hadronize [6], and so what we see in our detectors is truly the result of the decay of a "free" quark. Measurement of the production cross-section therefore provides a good test of perturbative QCD and the Standard Model (SM). Theoretical calculations have been performed to order α_s^3 and extended to include leading logarithm corrections corresponding to initial state gluon bremsstrahlung. There is some disagreement among the predictions, which range from 4.75 pb to 5.5 pb for $M_{top} = 175$ GeV/c^2, and quote uncertainties on the order of 15 %. [7 8 9]

2 Top quark decays

In the SM, the top quark decays almost exclusively to a W boson and a b-quark. The two W bosons subsequently decay either to a lepton and a neutrino or to a quark and an anti-quark. We characterize the decay as a "dilepton" if both W's decay leptonically, "lepton + jets" if one decays leptonically and the other to quarks, or "all hadronic" if both W's decay to quarks. In this context, a lepton refers to an electron or a muon; analyses which seek to identify tau's are underway, but are not discussed here. Table 1 lists the relevant branching fractions.

3 The Dilepton channel

The dilepton decay mode has a small branching fraction of approximately 5% but offers a clean signature with small backgrounds. The final state contains two high momentum leptons, two jets (from the b-quarks) and large missing energy ($\not\!\!E_T$) from the two neutrinos. Background processes which can result in two leptons are $b\bar{b}$ or $c\bar{c}$ production, Drell-Yan production of dilepton pairs (mediated by a Z or photon), diboson (WW) production or "fake" leptons.

Table 2: Summary of CDF Results. The expected yield is taken from the calculations of Laenen *et al.* [7] assuming a top mass of M_{top}= 175 GeV/c^2

Channel	Data	Background	Expected Yield
Dilepton			
$(e\mu)$	7	0.76 ± 0.21	1.7
$(ee, \mu\mu)$	3	1.23 ± 0.36	2.4
Lepton + Jets			
(Soft Lepton Tag)	40	24.3 ± 3.5	9.3
(Displaced Vertex Tag)	34	8.0 ± 2.2	18.9
All Hadronic			
	192	137.1 ± 11.3	25.4

Table 3: Summary of D0 Results. The expected yield is taken from the calculations of Laenen *et al.* [7] assuming a top mass of M_{top}= 180 GeV/c^2

Channel	Data	Background	Expected Yield
Dilepton			
$(e\mu)$	3	0.36 ± 0.09	1.69
(ee)	1	0.66 ± 0.17	0.92
$(\mu\mu)$	1	0.55 ± 0.28	0.53
Lepton + Jets			
(Soft Lepton Tag)	11	2.58 ± 0.57	5.2
(Event Shape)	21	9.23 ± 2.83	12.9

Of particular concern is the $Z \to \tau\tau$ process which can give two leptons and large $\not{E}_T$. Both experiments require two high P_T leptons accompanied by two jets. CDF requires that the leptons have opposite charge. D0 requires opposite charge dimuon channel only. In most cases, significant $\not{E}_T$ is also required. D0 further rejects background by using a quantity called H_T which is the scalar sum of the transverse energy of jets and the leading electron (where present) in the event. H_T is a rough indicator of the mass of the event, and so tends to be larger for signal events than background. Tables 2 and 3 list the number of candidate events, the backgrounds and the expected yields in each channel.

4 The Lepton + Jets Channel

In this channel the final state contains a single high momentum lepton, four jets (two from the W and two b-quark jets) and missing energy from the neutrino.

After requiring a lepton, four jets, and significant $\not\!\!E_T$ the inclusive production of W+4 jets still looms several times larger than the expected rate for top quarks. The background can be further reduced by requiring the presence of a b-quark or applying additional topological or "event shape" requirements.

D0 performs an event shape analysis using the event *Aplanarity* (which distinguishes between planar and spherical event topologies), H_T (here defined simply as the sum of jet E_T in the event), and the total leptonic transverse energy ($E_T^{lepton} + \not\!\!E_T$). The cut values are chosen to optimize signal to background using a Monte Carlo method.

There are two principle methods for indentifying jets likely to contain a b-quark. The first is to search for an additional lepton in the event from the decay ($b \to \ell$) or ($b \to c \to \ell$). The leptons are soft, with 45 % having P_T below 4 GeV/c. Nonetheless, the leptons are in ample supply; considering soft electrons and muons, there should be on average one per event. The CDF analysis looks for soft electrons and muons with $P_T > 2$ GeV/c^2 and has an acceptance twice as large as the CDF dilepton analysis. In the CDF analysis the largest background comes from hadrons misidentified as leptons, electrons from unremoved photon conversions, and muons from pion or kaon decay-in-flight. The resulting signal to background is less than 1:1.

The D0 lepton-tag analysis looks for soft muons with P_T >4 GeV/c. D0 also applies cuts on Aplanarity and H_T, and has smaller decay-in-flight and punch-through backgrounds than CDF because of their compact drift volume and well shielded muon chambers. This results in a very clean analysis with a signal to background better than 3:1.

At CDF, b-jets may also be identified with the silicon vertex detector (SVX) by searching for a displaced vertex characteristic of the long lifetime of the b-quark. The b lifetime is ≈ 1.5 ps, and is given a large boost in the top decay. On average $P_T^b = 40$ GeV/c, in which case the b travels 3.4 mm transverse to the beam before decaying. In a typical top event, the SVX can resolve the displaced vertex to about $130\mu m$ and so is an extremely effective tool for selecting b's while rejecting non-heavy flavor jets. The major background to this analysis is the production of real heavy flavor in W events, such as $Wb\bar{b}$ or $Wc\bar{c}$. Displaced vertex tagging is a powerful tool, and achieves twice the tagging efficiency of the CDF soft lepton analysis with a third the background. Tables 2 and 3 summarize the results.

5 The All Hadronic Channel

The all hadronic channel has the advantage of a large branching fraction, but lacks the distinctive lepton or $\not\!\!E_T$ native to the dilepton or lepton + jets channels. The signature is 6 jets, two of which originate from b-quarks. The large background from multijet production can be reduced by requiring a b-tag and applying event-shape cuts. CDF uses aplanarity and H_T to select events and further requires an SVX tagged jet. This leaves a sizeable background, but preserves a discernable top signal. The results are summarized in Table 2.

6 Measurement of the Top Production Cross Section

The best measurement of the top cross section will come from combining information from all top decay channels. CDF combines their SVX, soft lepton and dilepton analyses and obtains a $t\bar{t}$ production cross section of $\sigma_{t\bar{t}} = 7.5^{+1.9}_{-1.6}$ pb, assuming a top mass of 175 GeV/c^2. D0 combines results from all their analyses and reports a cross section of $\sigma_{t\bar{t}} = 5.2\pm$ 1.8 pb assuming a top mass of 170 GeV/c^2. Figure 1 compares the results from each channel with the predictions from theory.

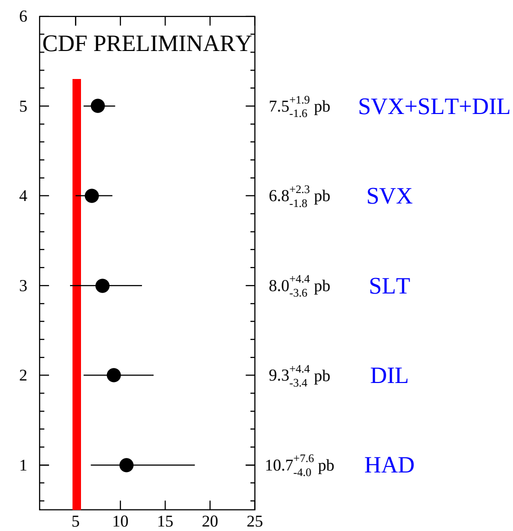
7 Top Mass Measurement in the Lepton + Jets Channel

The top mass is most easily reconstructed in the lepton + jets channel. Here, four jets are required, so that one may be matched to each of the four final state quarks (two b's, and two light quarks). Each event is reconstructed assuming the decay chain:

$$
\begin{array}{ll}
(1) & p\overline{p} \rightarrow t_1 + t_2 + X \\
(2) & t_1 \rightarrow b_1 + W_1 \\
(3) & t_2 \rightarrow b_2 + W_2 \\
(4) & W_1 \rightarrow q + \overline{q}' \\
(5) & W_2 \rightarrow \ell + \nu
\end{array}
$$

The two top masses in the event are required to be equal, and the W masses constrained to the measured world-average. These requirements, combined with energy and momentum conservation at each vertex gives 20 equations. There are 18 unknowns, so the system is overconstrained. The largest stumbling block is deciding how to reconstruct the event. Without any further information, we do not know which jet to assign to which parton. Combinatoric woes are further compounded by a quadratic ambiguity which arises in solving for the component of the neutrino momentum along the beam axis, increasing the possible combinations two-fold.

If, however, we can identify one or two jets as coming from a b-quark, the situation is significantly ameliorated. With no b-tagged jets there are 24 possi-



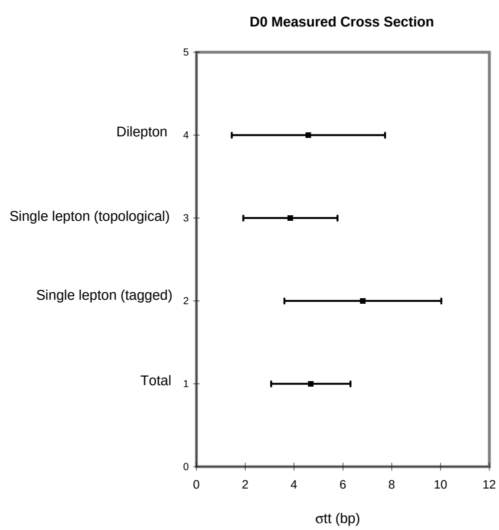


Figure 1: Top Cross Section Measurements from CDF (upper plot) and D0 (lower plot). The line in the CDF plot shows the range of theoretical predictions taken from three recent calculations. [7 8 9]. CDF assumes a top mass of M_{top}= 175 GeV/c^2, D0 takes M_{top}= 180 GeV/c^2.

ble ways to reconstruct the event, but with one b-tag this is reduced to 12, and with two tags there are only four possible solutions. Once a particular configuration is assumed, a global fit is performed for the event which minimizes a chi-square based on the equations of constraint given above.

The chi-square contains valuable information about the consistency of the kinematics of the event fit with the top hypothesis, and can be used to choose among the various possible configurations for a particular event. CDF has chosen to take the solution with the best chi-square. D0 averages the top three solutions, weighted by their chi-square probability. In either case, there results one *fitted mass* for each event.

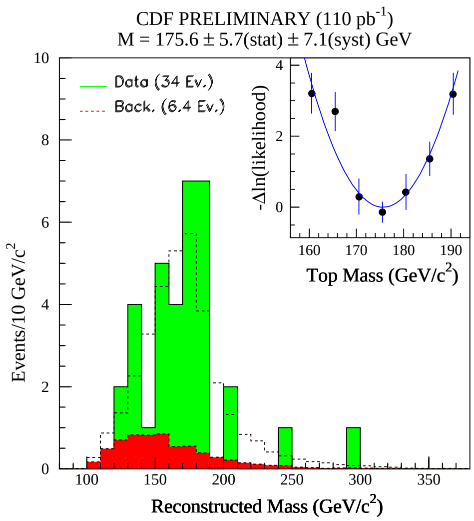
To enhance the top purity of the W+4 jet sample, CDF requires the presence of at least one b-tag (soft lepton or SVX). This leaves a sample of 34 events which are expected to be $\approx$ 80 % pure. D0 applies event shape cuts which are selected so that they do not bias the reconstructed mass distribution for background. The final D0 sample contains 30 events and is expected to be $\approx$ 50 % pure.

Finally the reconstructed masses are fit using a log-likelihood method to a combination of top and background shapes. The top shape is taken from a HERWIG based Monte Carlo simulation, and the background from a VECBOS based Monte Carlo simulation. The results of the fit are shown in Figure 2. D0 obtains a value of M_{top} = 170 $\pm$ 15 (stat) $\pm$ 10 (syst) GeV/c^2. CDF obtains M_{top} = 175.6 $\pm$ 5.7 (stat) $\pm$ 7.1 (syst) GeV/c^2. CDF has also performed a fit to the 9 events which contain two b-tags. The expected background is only 0.4 events, and the fit mass is M_{top} = 174.8 $\pm$ 7.6 (stat) $\pm$ 5.6 (syst) GeV/c^2. The dominant systematic uncertainties are due to uncertainties in the gluon radiation and the jet energy corrections.

7.1 Top mass in the Dilepton Channel

In the dilepton channel, too few quantities are measured to allow direct reconstruction of the top mass. However, the top mass can be inferred by other means. CDF chooses to fit the E_T spectrum of the two jets in the event, which tend to be stiffer for top than background, and obtains a value of M_{top} = 150 $^{+24}_{-22}$ (stat) $\pm$17 (syst) GeV/c^2.

D0 employs more involved technique to extract the top mass. The procedure obtains the most likely top mass for an event by effectively trying out the entire phase space of solutions. If one assumes a top mass for the event, the event can be reconstructed, although there remains a four-fold ambiguity in the solution for the neutrino momenta and two possible pairings for the b-jets with the leptons. For each configuration, a likelihood is calculated which



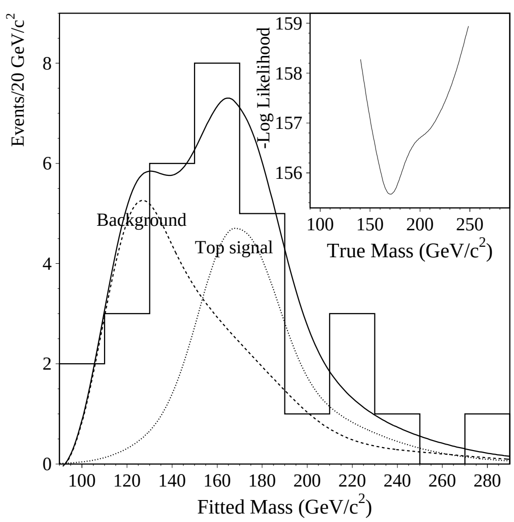


Figure 2: Top Mass measurements in the lepton + jets channel. The upper plot shows the CDF fit with background (dark histogram) and the background combined with top shape (open histogram). The lower plot shows the D0 fit.

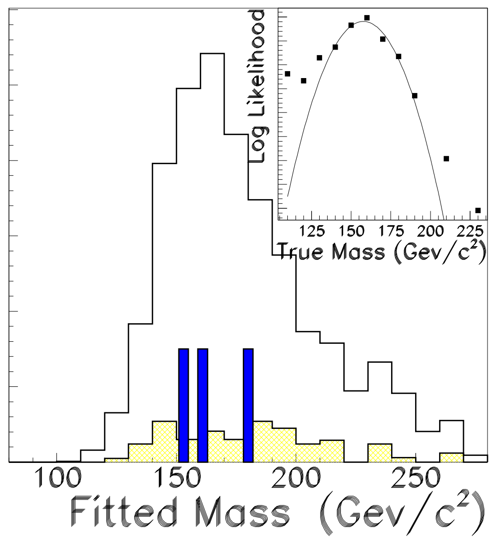


Figure 3: D0 measurement of the top mass in the dilepton channel. The solid histogram shows the fitted mass for the 3 $e-\mu$ events, the hatched histogram shows the background shape, and the open histogram shows the expected shape for top (M_{top}= 150 GeV/c^2) combined with background.

takes into account the parton distribution functions and the momentum of the leptons. The likelihood peaks at some top mass which is taken to be the fitted mass for the event. The procedure is repeated for each dilepton event, and the results fit to a combination of background and top shapes as in the lepton+jets channel. D0 chooses to use only the three $e\mu$ events since this channel has smaller backgrounds than the ee and $\mu\mu$ channels. The resulting mass is $M_{top} = 158 \pm 24$ (stat) $\pm$ 10 (syst) GeV/c^2. The fit is shown in Figure 3.

7.2 Top mass in the All Hadronic Channel

CDF has extracted a top mass from events in their all hadronic analysis. In the all hadronic channel there are no neutrinos and so, in principle, all the decay products of the $t\bar{t}$ system are observed. With one jet b-tagged there are 30 possible configurations of jet-parton assignments to choose from. CDF chooses to take the solution with the best chi-square as the fit mass for the event. After fitting all candidate events, the resulting masses are fit to a combination of signal and background shapes with a likelihood technique similar to the that used in the lepton+jets channel. Here the background shape is determined from a top depleted sample selected with the same kinematic cuts, but where no jets are b-tagged. The resulting mass is $M_{top} = 187 \pm$ 8 (stat) $\pm$ 13 (syst) GeV/c^2. The fits are shown in Figure 4

8 Measurment of V_{tb}

In the SM, the unitarity of the CKM matrix implies that $V_{tb} \approx 1$. We can constrain V_{tb} by measuring the relative branching fraction $b = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$. CDF has done this with a maximum likelihood method which compares the number of single and double b-tagged lepton+jets events, and the tagged and non-tagged dilepton events. Assuming unitarity and three generations (in which case the denominator $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2=1$) CDF finds $|V_{tb}| = 0.97 \pm 0.15 \pm 0.07$. Relaxing this assumption, and allowing a fourth quark generation which couples only to the third, however, one can only set a lower limit, $|V_{tb}| > 0.022$ (95% C.L.).

9 Conclusions

Both CDF and D0 have updated their techniques and measurements of the top mass and cross section since the discovery announcement. There is still progress to be made in understanding some of the systematics, and additional improvements are likely as we begin to combine more information from the different decay channels to make more optimal use of the data. Currently, CDF quotes a top cross section of $\sigma_{t\bar{t}}= 7.5^{+1.9}_{-1.6}$ pb and a top mass of $M_{top} =$ 175.6 $\pm$ 5.7 $\pm$ 7.1 GeV/c^2. D0 obtains $\sigma_{t\bar{t}}= 5.2 \pm 1.8$ pb and $M_{top}=$ 170 $\pm$ 15 $\pm$ 10 GeV/c^2. As shown in Figure 5, the results are consistent with predictions from the Standard Model.

The top quark mass lies suggestively close to the electroweak scale. Whether this is a clue or mere coincidence will likely have to wait for the Tevatron Run II which promises at least an order of magnitude more data.

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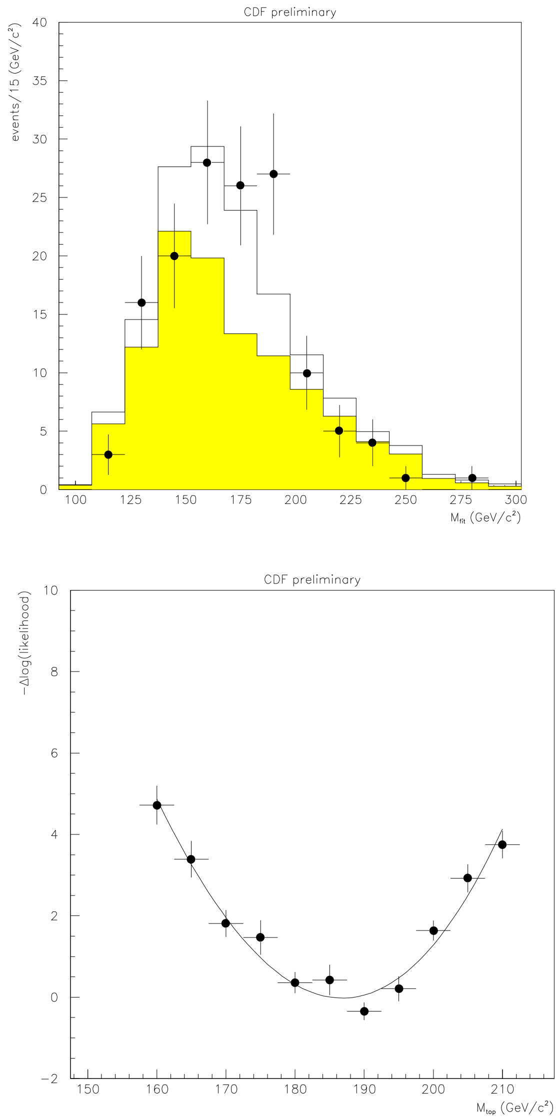

Figure 4: The Top Mass Measured in the All Hadronic Channel (CDF). The upper plot shows the fitted mass for the candidate events (points), the expected background shape (solid) and the combined background and top shape for M_{top} = 175 GeV/c^2. The lower plot shows the fit likelihood as a function of top mass.

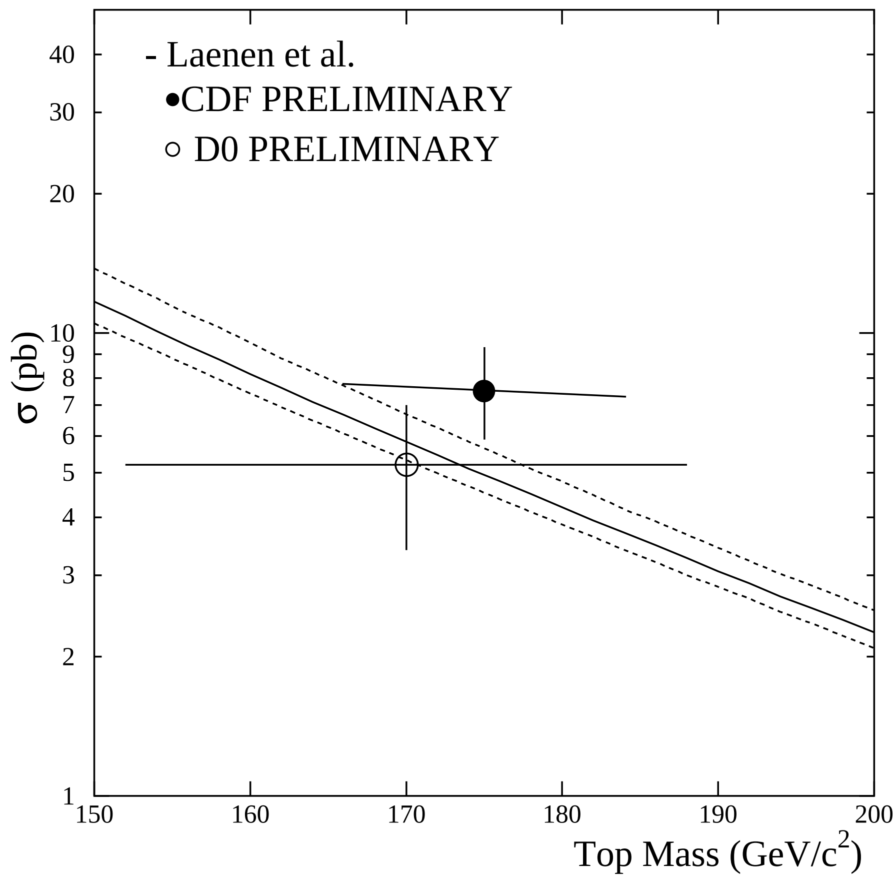

Figure 5: Top Mass and Cross Section Measurements Compared to Theoretical Calculations

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