January 14, 1999
Version 1.1

What *Isn't* Anomalous in CDF Run I Top Data, and What *Is* [1]

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Abstract

There has been much discussion, both in the theoretical community and inside the experimental collaborations, of possible anomalies in the top quark data samples. I give a brief and frankly pedagogical[2] discussion of what I think is and isn't anomalous, with specific emphasis on why the CDF combined measurement of the $t\bar{t}$ cross-section should *not* be taken by theorists as an indication of new physics. The top 'trilepton' event *is* proffered as an (another) anomalous event.

1 Introduction

From the first evidence for the existence of the top quark[1] there has been speculation[2] about the cross-section being 'high', and hence the question 'Is it only top?'. In addition the first dilepton event (dubbed 'the DPF event') did not fit the kinematics of top decay well. Two more of the dilepton events have been analyzed as not from top decay[9]. Historically the existence of the 2nd-generation lepton and the first-generation quarks at similar masses caused confusion, and similarly with the 3rd-generation lepton and the charmed quark. Run I reached a cross-section sensitivity where it is reasonable to be interested in new mechanisms for producing top quark pairs and the possible production of new particles which give signatures that fall in top samples. Physics beyond the Standard Model will first show up, most likely, as a few events that are not likely in the SM.

2 What Isn't Anomalous: the $t\bar{t}$ Production Cross-section

2.1 The CDF Combined Top Cross Section

Figure 1 shows the comparison of the final cross-section for $t\bar{t}$ production measured by CDF [3], compared to theoretical predictions. The experimental value of $7.6^{+1.8}_{-1.5}$ pb is in

[1] Brief talk at ***Thinkshop, Top Quark Physics for Run II***, Fermi National Accelerator Laboratory, October 16 - 18, 1998

[2] This talk is at the level of first-year graduate students who may be interested in working on Run II data. To paraphrase Robert Park, "Opinions are the author's and are not necessarily shared by CDF, but they should be."

reasonable agreement with the predictions of 5-6 pb, although it was (and still is, by many) generally perceived to be 'high' (the predictions were lower in the past- see the talk by Keith Ellis at this workshop for a very sensible summary of the present status[4].)

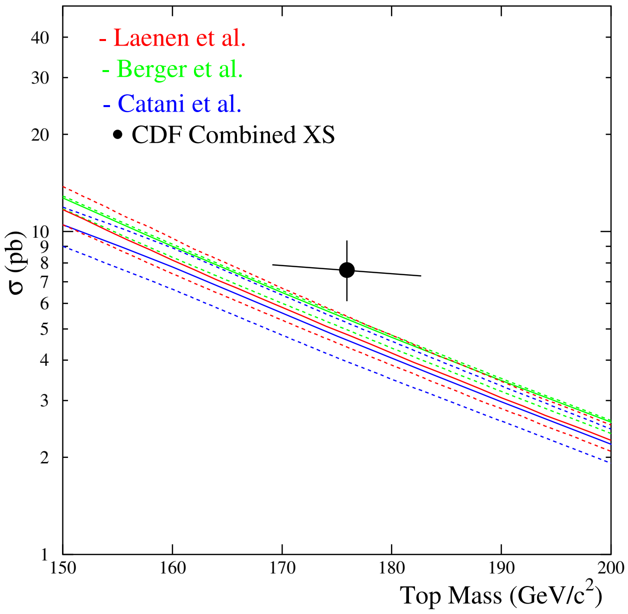

Figure 1: The combined cross-section as measured in the e/μ+jets, e/μ-dilepton, and all-hadronic modes by CDF. Also shown is the theoretical prediction. The two are normalized differently as discussed in the text.

Figure 2 shows the individual cross-sections measured for the three channels of 'Lepton+jets'[3], 'Dilepton', and 'All-hadronic' modes. The efficiencies, acceptances, backgrounds, and number of events for each of these are given in Table 1.

Lastly, all of the channels measured by both CDF and D0 are displayed in Figure 3, along with the theoretical prediction. This plot in fact makes no sense (it's internally inconsistent): CDF and D0 are using different values of the $\bar{p}p$ total cross-section to normalize these cross-sections. The CDF cross section is normalized to the CDF measurement[5] of 80 mb, and the D0 top cross section is normalized to the world average, which at this time is 4% lower. Many things are not certain, but it is a good bet that protons have the same total cross-section at B0 and D0. Differences in the total cross-sections reflect themselves in the top (and all other) cross-sections linearly: a higher total cross-section makes the top and all other cross-sections higher by the same percentage.

[3]CDF uses the word 'lepton' to mean first and second generation lepton; dilepton means that there are two of these (i.e. tau's are excluded and dealt with separately). This should change in Run II.

2.2 The Denominator: the $\bar{p}p$ total cross-section

The total cross-section in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV has been measured three times, with values of 72.8 $\pm$ 3.1 mb (E710), 80.03 $\pm$ 2.24 mb (CDF), and, recently, 71.71 $\pm$ 2.02 mb (E811) (the misuse of significant figures is CDF's and E811's, and not mine). Taking the two most precise (CDF and E811), the average is 75.4 mb, but with a chisquared for 1 degree-of-freedom of 7.6. This corresponds to a confidence level of 0.005. The situation is shown in Figure 4.

Given a situation like this one can average, and inflate the uncertainty by an S factor[6], or one can use one's experimental judgement and theoretical biases. to decide that one of the numbers is wrong. In this case there *is* such a deciding factor, and that is that the same CDF data were analyzed twice, by two independent groups. The first result[7] gave 72.0 $\pm$ 3.6 mb, in good agreement with the E710 and E811 measurements, and in conflict (remember, these are the same data so uncertainties are presumably correlated) with the later CDF number.

So we will use the E710 and E811 numbers, which give 72.0 mb instead of 80.0 mb for the central value CDF normalization of the top cross section. Calculating the uncertainty is problematic; the uncertainty on the combined E710 and E811 numbers is $\pm$1.7 mb, but the cross- normalization to the CDF cross section has other systematics in it. Given that the central value is most-likely wrong, it's not clear what to do with the uncertainties. We advocate a way around this whole problem below.

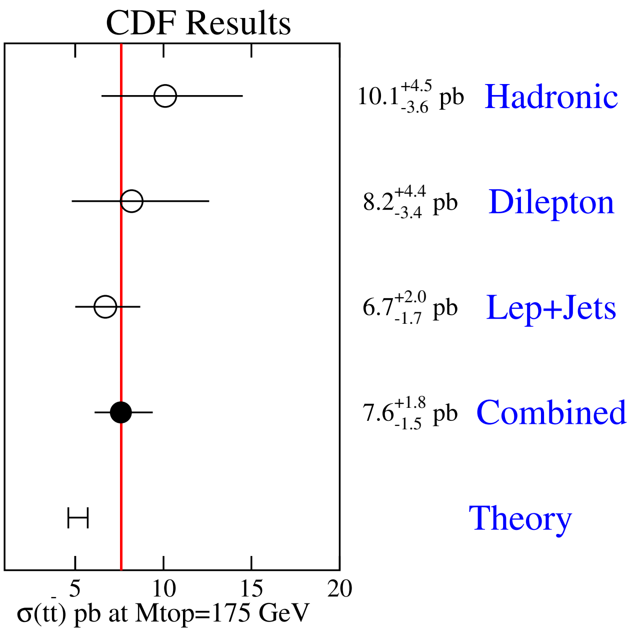

Figure 2: The individual cross-sections in the e/μ+jets, e/μ-dilepton, and all-hadronic modes. Also shown are some theoretical predictions.

	Lepton+Jets		Dilepton	All-Hadronic	
Tag	SVX	SLT	not req.	SVX	2 SVX
ϵ_{tag}	0.39±0.03	0.18±0.02	–	0.42±0.04	0.11±0.02
geo·kin	0.104±0.010		0.0076±0.0008	0.106±0.021	0.263±0.045
trigger	0.90 ± 0.07		0.98±0.01	$0.998^{+0.002}_{-0.009}$	
A_{total}	0.037±0.004	0.017±0.002	0.0074±0.0008	0.044±0.009	0.030±0.009
Obs. Events	34	40	9	187	157
Background	9.2 ±1.5	22.6 ±2.8	2.4 ±0.5	142 ±12	120 ±18
$\sigma(t\bar{t})$	$6.2^{+2.1}_{-1.7}$pb	$9.2^{+4.3}_{-3.6}$pb	$8.2^{+4.4}_{-3.4}$pb	$9.6^{+4.4}_{-3.6}$pb	$11.5^{+7.7}_{-7.0}$pb

Figure 3: The details of the calculations of the individual cross-sections in the e/μ+jets, e/μ-dilepton, and all-hadronic modes.

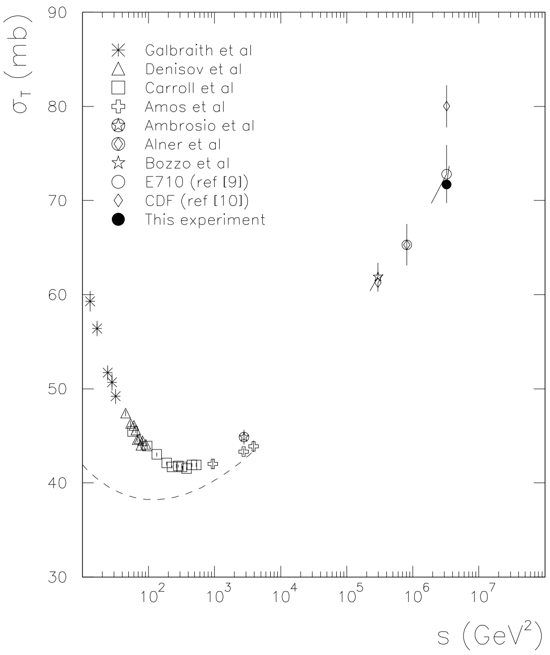

Figure 4: A compilation of total cross section measurements from E811, including their latest result.

2.3 The Numerator: the $\bar{p}p$ total cross-section

I do not address questions of correctness of the values for the individual top cross sections here, but address what is the most precise measurement of the numerator (the number of

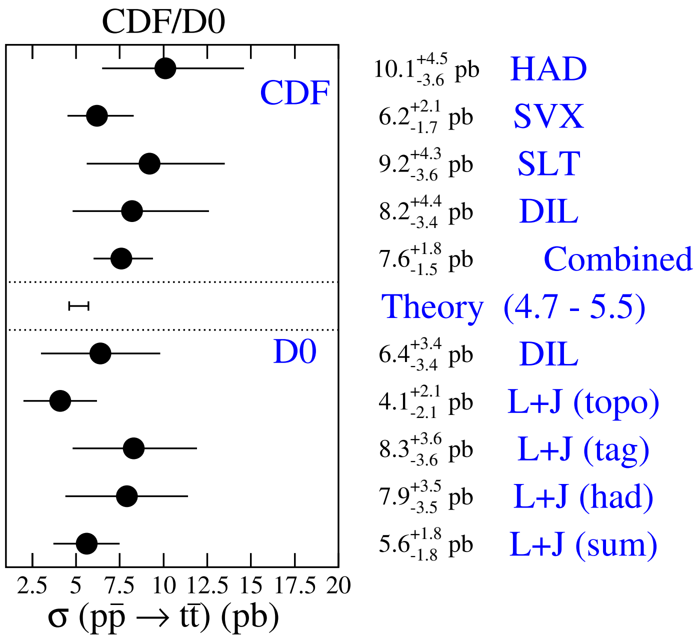

Figure 5: The individual cross-sections in the e/μ+jets, e/μ-dilepton, and all-hadronic modes by. Also shown is the range of theoretical predictions.

top events). This is again pedagogical: in a perfect world, with perfectly understood systematic errors, the prescription is that one would combine *all* measurements taking account of correlated uncertainties, etc. In the real world, where systematics errors are by nature themselves uncertain, one should chose the technique with the smallest systematics as long as the loss in statistical power does not compromise the usefulness of the measurement (this is in fact the reason for tossing out low-statistics channels- one cannot begin to measure the systematics if the statistics are low).

CDF combines three channels to get the 'final' top cross-section, the e/μ+jets, e/μ-dilepton, and all-hadronic modes (the $e/\mu\tau$ channel is not included). Is this the right number to quote?

Of these 3 measurements one has significantly better signal-to-background ratio and statistical power. The 'lepton + jets' measurement with a b-jet identified with the SVX detector is the cleanest channel we have. The dilepton channel has low statistics (the argument used to exclude the lepton-tau channel, in fact); the all-hadronic mode has a large background from W+jets that has to be subtracted (see Table 1). When making a precision measurement, it is poor practice to combine measurements from techniques of different quality; what one wants to do is select (*a priori*, of course) the preferred method.

In fact, the combining of the measurements is also not what one wants to do from a physics point of view. The comparison of an average top cross-section with the SM prediction obscures the comparison of the individual signatures with their SM expectations. The lepton+jets+SVX measurement gives the best measurement of the top cross-section; the *ratio* of the dilepton cross-section, for example, to the lepton+jets cross-section is a more incisive number than an average.[4]

Thus a better way to ask the question about compatibility of the measured top cross-section and theoretical predictions is to divide it into the two questions: 1) Is the $t\bar{t}$ cross section in agreement with theory? and 2) are each of the signatures in which we are looking for top in the expected ratio?

2.4 A More Robust Cross-section Measurement and A More Incisive Comparison of Decay Modes

2.4.1 The Cross-section Measurement

A measurement that is more robust than the ratio of the top cross-section to the 'beam-beam counter' cross-section (that's what is used to normalize the luminosity) is the ratio of the top cross-section to the $W^{\pm} \rightarrow e^{\pm}\nu$ cross-section[10]. The W cross-section is easy to measure; the total cross-section is difficult. Moreover the ratio of top/W is measured at the same time with the same detector; the ratio of top/(total cross-section) is the ratio of two different experiments. The W cross-section is directly related to the structure functions used to make the theoretical predictions of the top cross-section; the $\bar{p}p$ total cross-section is at most tenuously related. This is the number that we should be measuring, and theorists should be predicting[5]

Actually we suggest using the inverse of the ratio, *i.e.* the ratio of the W to top cross-section, as is done with the quantity R, defined as the ratio of the W to the Z cross-section. Using the CDF measured W cross-section[11] of 2.49 ± 0.02 (stat)± 0.08 (syst)± 0.09 (lum) nb as the denominator, and the CDF 'lepton+jets+SVX' cross-section of $6.2^{2.1}_{1.7}$ pb as the numerator, and treating only the luminosity uncertainty as common (this is conservative), we find the best value for the ratio of the W to top cross-sections, R^{top}, of:

$$R^{top} \equiv \sigma^{W}/\sigma^{top} = 400^{+130}_{-105}. \tag{1}$$

It is this ratio that should be calculated for comparison to the much more precise measurements in Run II.

To get back to an absolute cross-section requires a value for the W cross-section. For this one could use a measured cross-section[6] (tieing it back to the total cross-section), for example, or a theoretical calculation. I will use the measured CDF cross-section lowered by 10% for the change from 80 mb to 72 mb for the total cross-section. This gives a 'best-practice' top cross-section of:

$$\sigma^{top} = 5.6^{+1.9}_{-1.5}\ pb. \tag{2}$$

The reader is invited to draw this on Figure 1 and draw her/his own conclusions.

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[4]Because the branching ratios into lepton pairs for $t\bar{t}$ pairs is so small, the relative effect of new physics in the dilepton channel could be a larger relative effect than in some other channels such as the all-hadronic mode, for example.

[5]There may be in the future some gains in the the precision of the theoretical predictions as well, which at present are dominated by gluon radiation in the top cross-section.

[6]This can and should be measured in special runs with special care for conditions (e.g., low enough luminosity so there are not many multiple collisions per crossing, etc.)

2.4.2 The Comparison of Decay Modes

The expected ratio of branching ratios in the dilepton modes to the lepton+jets mode is 4/81 : 24/81 = 1/6. The ratio of the dilepton cross-section to the 'lepton+jets+SVX' is only an approximation of the numbers one would really like, which are the branching ratios themselves. There is cross-talk between the channels and so the cross-section measured in a given signature (e.g. two leptons + 2 jets + missing Et) does not map exactly onto the process of top decay with both W's decaying leptonically (see Ref [8] for a detailed discussion). The branching ratio measurement needs to be a separate (optimized) analysis; here I make the approximation that a given signature is dominated by the corresponding decay mode, and so the ratio of the measured cross-sections is a measure of the ratio of the branching ratios.

$$\sigma^{\ell\bar{\ell}+2jet}/\sigma^{\ell jetsSVX} = 1.3^{+0.8}_{-0.7}. \quad (3)$$

The ratio of the all-hadronic cross-section to the 'lepton+jets++SVX' is

$$\sigma^{6jet}/\sigma^{\ell jetsSVX} = 1.6^{+0.9}_{-0.8}. \quad (4)$$

Both of these are statistically compatible with the expectation of 1.0 (the SM branching ratios have been assumed in the cross-section calculations.)

3 What Is Anomalous: the Top Dilepton 'Trilepton' Event

It has long been noticed[12, 9] that one of the CDF 'dilepton' events, Event 129896 of Run 67581, has *three*, clean, isolated, high–p_T leptons, large $\not{E}_t$, and a high-E_T jet. In addition, the most energetic of the leptons is a positron with $E_T \simeq 200$ GeV, significantly larger than is typical for top events (0.06 ± 0.02 events are expected). The corrected $\not{E}_t$ is over 100 GeV, also large for top decay (0.6 ± 0.1 events are expected). The event contains a jet with $E_T \simeq 100$ GeV; the total transverse energy plus $\not{E}_t$ is about 450 GeV. The other two leptons are an isolated electron with $E_T = 27$ GeV and an isolated muon (μ^-) with $p_T = 27$ Gev. The invariant mass of the e^+e^- pair is 130 GeV, well away from M_Z; the pair has very high p_T. In the SM top quark analysis, the event is classified as a dilepton+2 jet event, because the lower E_T electron fails the fiducial cut by 4 mm and is thus defined to be a jet; however, the electron passes all other standard electron criteria and is a "golden" electron in all other ways.[7] The kinematics of the event are unusual: the invariant mass $M_{e\mu j}$ is on the order of m_t, while the other hemisphere contains only the high-E_T positron. The three isolated leptons and the kinematics make the event unlikely[13] to come from SM top production and decay. The event is a high–mass trilepton $+\not{E}_t$ event, and is consequently anomalous for top decay.[9].

[7] In the top quark analysis the fiducial volume was conservatively chosen to be the same as for the precision electroweak measurement of the ratio of W to Z cross sections. The 4 mm miss does not affect the electron identification.

4 What We Think May Be Anomalous, But Won't Know Until Run II

The τe and $\tau\mu$ channels[8] are interesting. Four events are observed versus an expectation (signal plus background, but mostly background) of 3.6 ± 0.5. However, if one requires a jet to be 'tagged' as a b-jet, one finds that three events are tagged. One event has an SVX tag, one has an SLT tag, and one has a jet that is tagged by both SVX and SLT. The expectation is 0.91 ± 0.16. There is a 7% chance of this happening, and consequently, while interesting, it is not unusual.

Other features of the dilepton sample, such as the number of $e\mu$ events with the leptons close in ϕ, and the number of events with high thrust, are unusual, but not statistically significant. They are described in detail in References [8].

5 Conclusions and Some Predictions

My conclusions are:

- CDF and D0 should use the same normalization for cross-sections.
- The normalization should a process measurable by both collaborations, and should be robust with respect to backgrounds and efficiencies.
- When the CDF top cross-section is normalized this way (specifically, to the measured W cross-section), it has no hint of being anomalously high. I find:

$$R^{top} \equiv \sigma^W/\sigma^{top} = 400^{+130}_{-105}. \tag{5}$$

  and, using the measured CDF W cross-section normalized to 72 mb:

$$\sigma^{top} = 5.6^{+1.9}_{-1.5}\ pb. \tag{6}$$

- The measurements that best span the space of unknowns in searching for new physics in the top samples are the total cross-section and the branching ratios, rather than the average cross-section of several of the channels. These are the numbers that will go into PDG tables, e.g.
- The top trilepton event was recognized early on within CDF [12] and later by others[9] as being anomalous. It satisfies my criteria: there are at least two rare qualities, and the relevant quantities that make it rare are well-measured (electrons, muons, photons, and not jets or met). The real test will be in Run II, where we should see many such events if this one is typical.
- The dilepton sample has several mildly anomalous features, such as a preponderance of $e\mu$ events with the two leptons close to each other, high values of thrust, etc.[8], but these are not statistically significant. We will watch these closely with Run II data.

6 Acknowledgments

We thank Marcus Hohlmann, Rob Roser, and David Toback, for help and advice. Win Baker from E811 very kindly supplied Figure 4.

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[13] In a Monte Carlo sample of 80,000 $t\bar{t}$ pairs there were zero trilepton events (this is more than 100 times our data sample). There were 34 electrons from b decay that passed the 25 GeV threshold. More details on the expected number of such events can be found in Ref [8].

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