Top Quark Physics: New Experimental Results and Open Questions

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on Particle Physics

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Sound bites:

$t \to H^+ b$ limits

W boson helicity

Analyses waiting for Run II

Analyses related to $m(t)$:

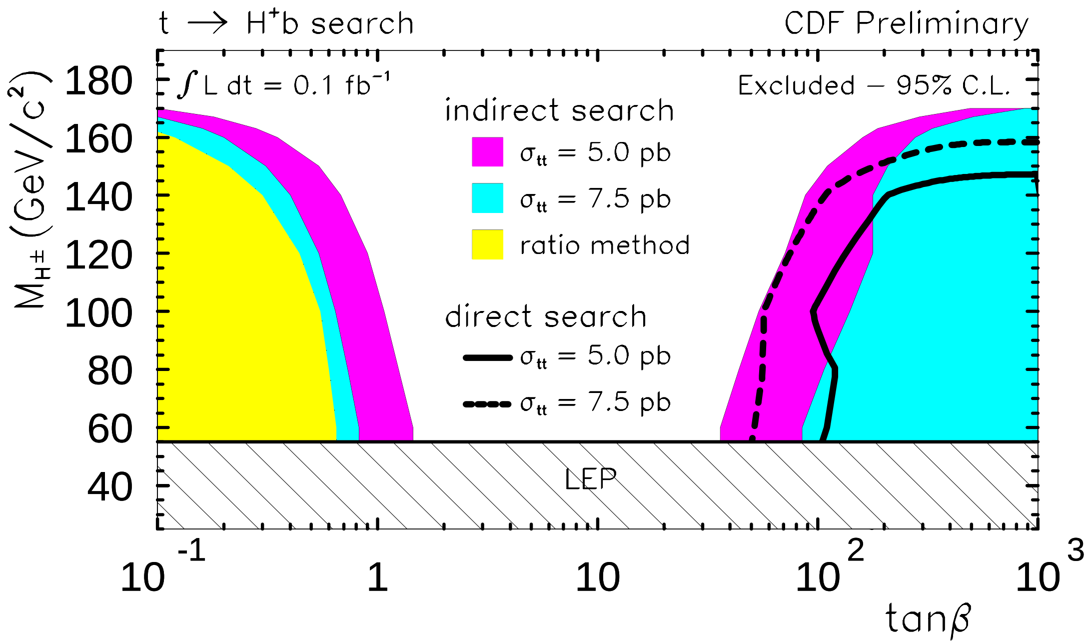
$\bar{t}t$ system: M, y

$m(t)$ from dileptons; new $\langle m(t) \rangle$

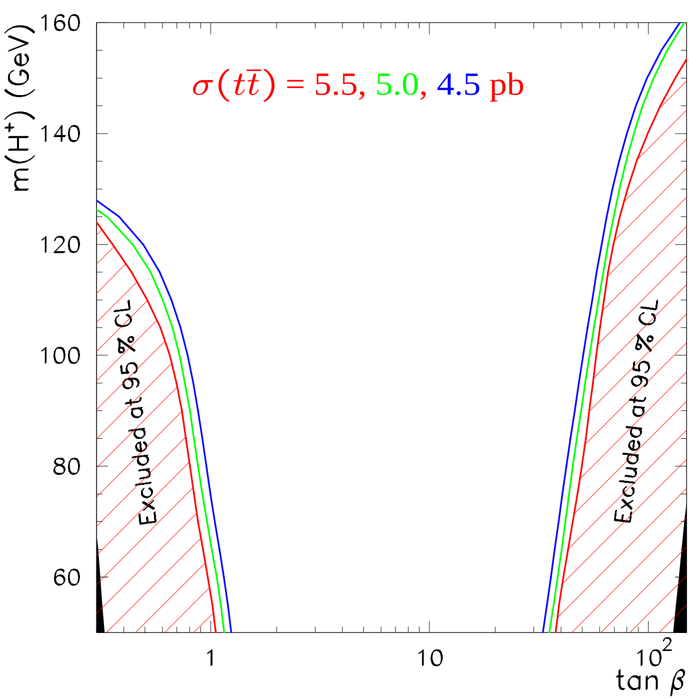
Unusual dilepton events

URL for this talk: `http://www-d0.fnal.gov/~strovink/`

$t \to H^+ b$ limits from $\bar{t}t$ disappearance and τ appearance



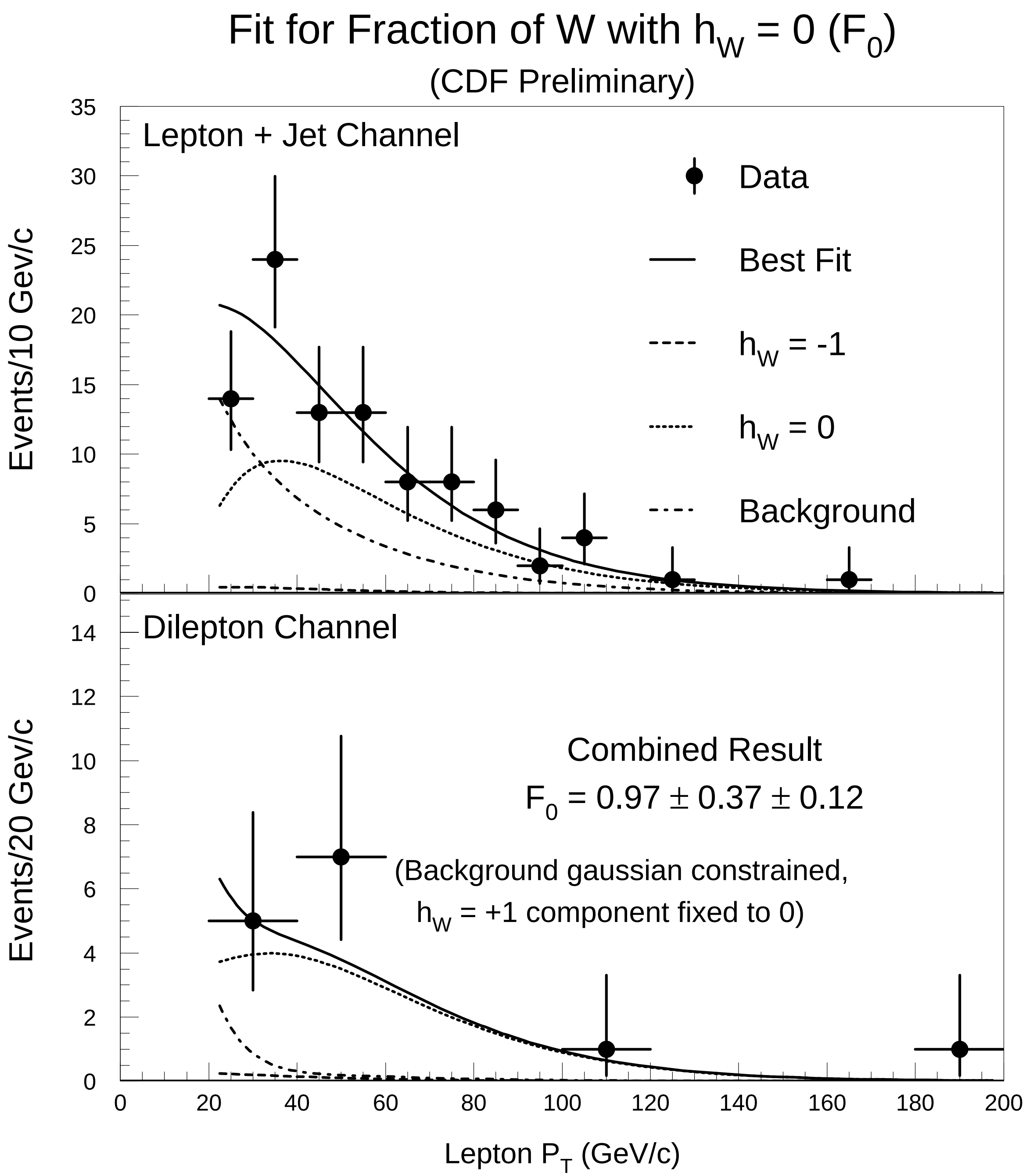
CDF sets limits on $t \to H^+ b$ at low values of tan β (where $H^+ \to \bar{s}c$) or high tan β (where $H^+ \to \tau\nu$) via $\bar{t}t$ disappearance (shaded areas), and at high tan β via τ appearance (lines).



D0 sets limits on $t \to H^+ b$ at both low and high tan β via $\bar{t}t$ disappearance, taking into account:

- $H^+ \to \bar{b}bW^+$ as well as $H^+ \to \bar{s}c$ and $H^+ \to \tau\nu$.
- Acceptance in SM $\bar{t}t$ modes for H^+ decay channels.
- Upper bound on Yukawa couplings of t and b to H^+ set by validity of leading-order calculations, restricting the search to ~0.3 < tan β < ~150.
- Upper bound on $\Gamma(H^+)$ set by validity of leading-order calculations when $|m(t)-m(H^+)|$ is small, restricting the search to $m(H^+)$ < 160 GeV.
- Upper bound on $\Gamma(t)$ set by validity of leading-order calculations (excludes dark regions).

W boson helicity in top decay



CDF measures the helicity of *W*'s produced in $t\bar{t}$ decay by fitting the lepton p_T spectrum in both lepton+jets and dilepton final states.

The unbinned maximum likelihood fit assumes that the *W* is polarized either longitudinally (~70% in the SM) or left-handed.

The measured fraction of longitudinally polarized *W*'s is

$F_0 = 0.97 \pm 0.37 \pm 0.12$.

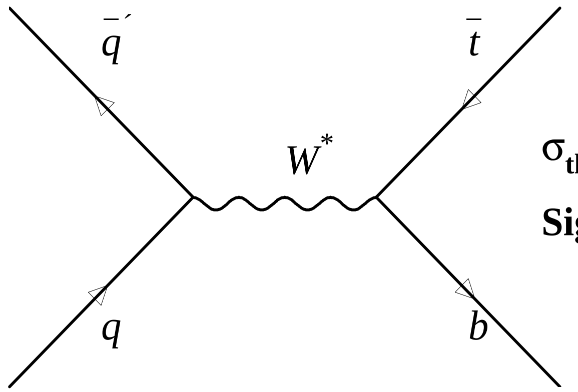
If F_0 is fixed to 0.75 and the remaining *W*'s are free to be either left- or right-handed, the fit right-handed fraction is

$F_+ = 0.11 \pm 0.15 \pm 0.06$.

Analyses waiting for Run II

Single top

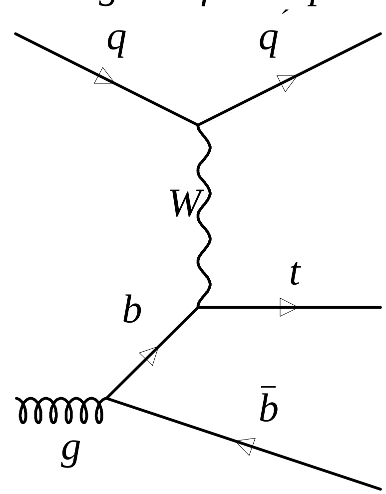
s-channel W^* process



σ_{theory} = 0.7 pb

Signal is W+b+$\bar{\text{b}}$

W-gluon fusion process

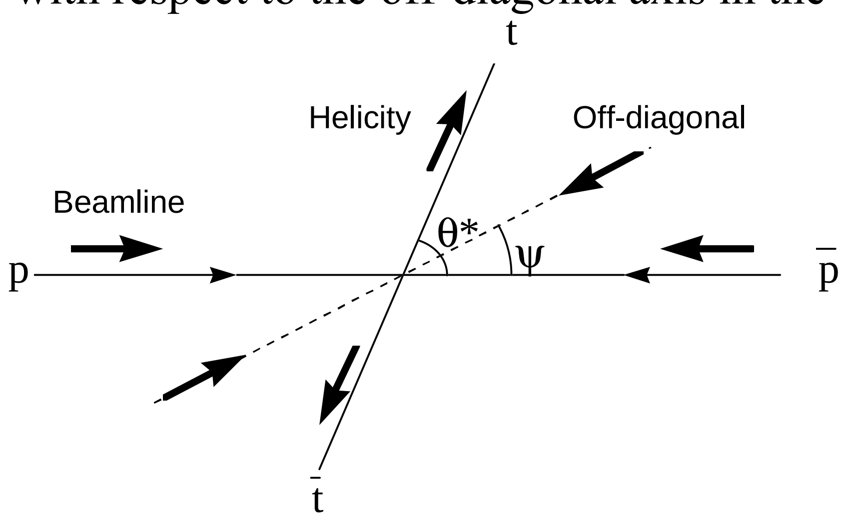


σ_{theory} = 1.7 pb

Signal is W+b+q

In each channel, CDF sets a 95% CL upper limit of ~15-16 pb on the cross section for single top production in $\bar{p}p$ collisions. This is ~10-20 × the level expected in the SM.

$\overline{tt}$ spin correlations. D0 uses the "off-diagonal" basis described by Mahlon and Parke. In the SM, $d\Gamma / d\cos\theta_+ \, d\cos\theta_- \propto 1 + \kappa \cos\theta_+ \cos\theta_-$ with $\kappa \sim 0.9$, where $\theta_\pm$ is the lepton angle with respect to the off-diagonal axis in the top rest frame.



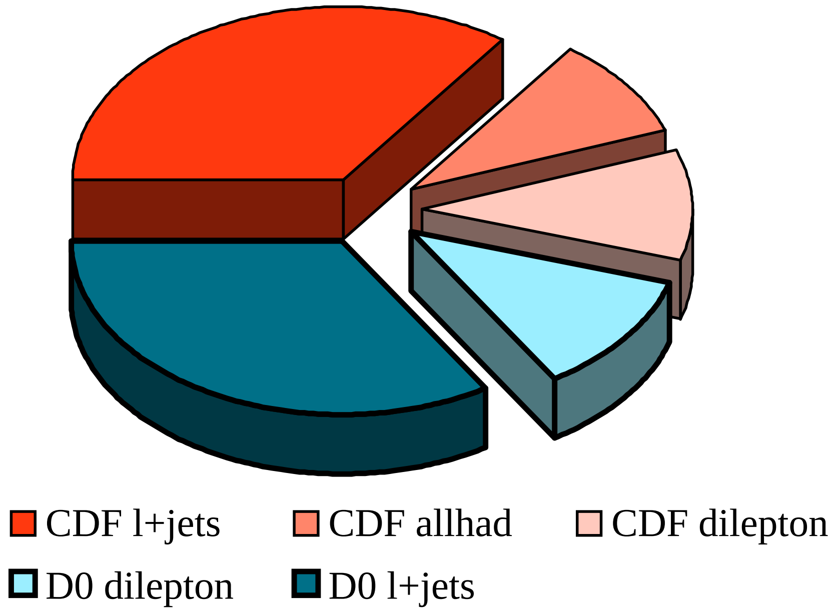
The best fit to the data is $\kappa = 1$, but the betting odds ($\kappa = 1$) : ($\kappa = 0$) are only ~ 1.2 : 1.

A factor ~3 in sensitivity is sacrificed to the missing constraint in the dilepton channel, and to combinatorics and backgrounds.

Also, D0's particular six events yield ~ half the typically expected sensitivity -- the first such example in the history of top quark analysis.

What's new in measurements related to the top quark mass

Relative weight in top mass average



Including the progress mentioned below, the world average directly measured top quark mass is

$m(t)$ = 174.3 ± 3.2(stat) ± 4.0(syst) GeV/c^2.

The two lepton+jets measurements contribute ~35% each to the overall error, and the two dilepton analyses and one all-hadron analysis contribute ~10% each.

Lepton+jets

On *m(t)* not much is new. Widely presented, will not review here.

New plots of kinematic quantities relevant to $\bar{t}t$ production are sharpened by assigning jets to quarks and applying *m(t)* and *M(W)* constraints. $M(\bar{t}t)$ and $y(\bar{t}t)$ discussed here.

This channel also dominates measurement of $\sigma(\bar{t}t)$. There is no evidence for a cross section excess relative to SM expectation [*cf.* H. Frisch, Top Thinkshop (Oct 98)]. This issue not discussed here.

All hadronic

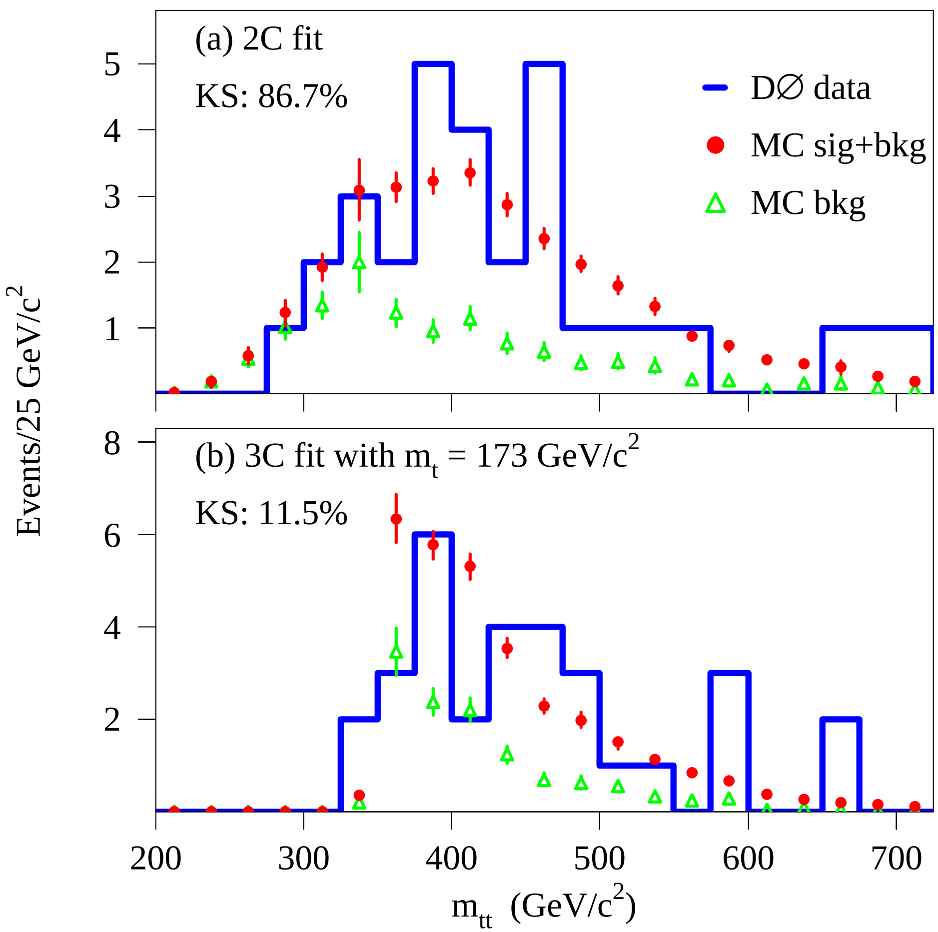
CDF has ~halved its systematic error on *m(t)*. Details available soon.

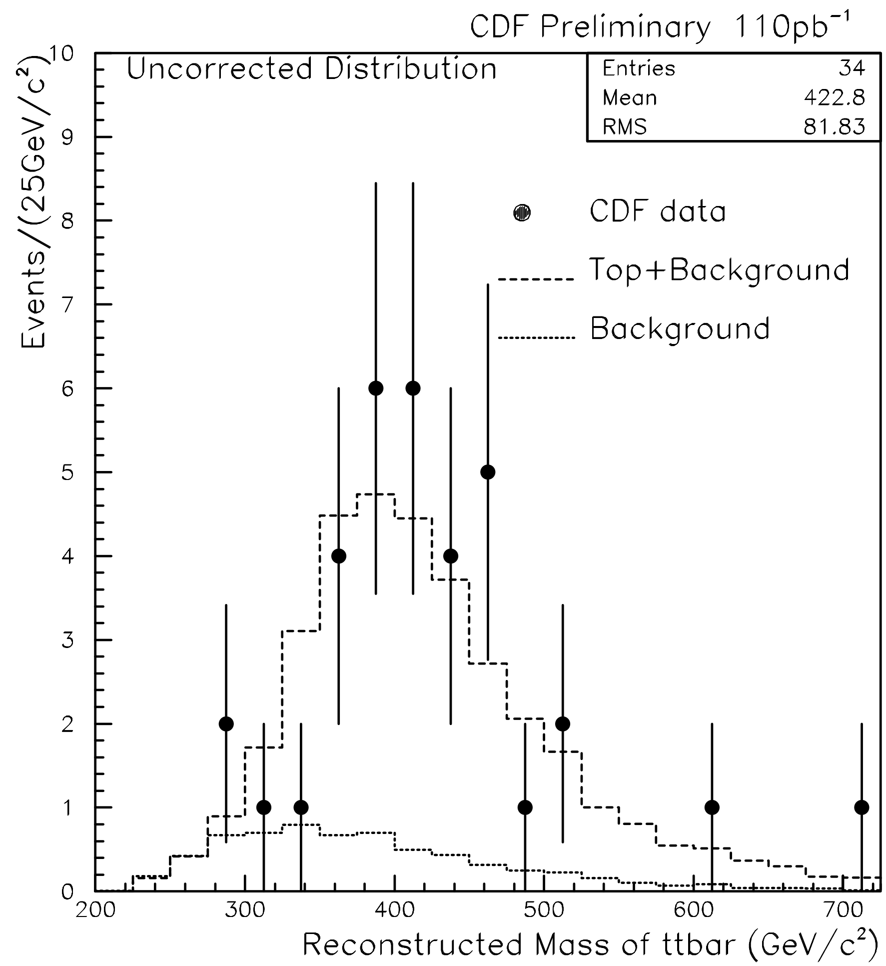
Dilepton

CDF has ~halved its total error on *m(t)* using D0's "neutrino phase space weighting" technique.

Two of CDF's eight events seem more interesting than top. Both topics discussed here.

$M(\bar{t}t$ system) for lepton+jets top mass events



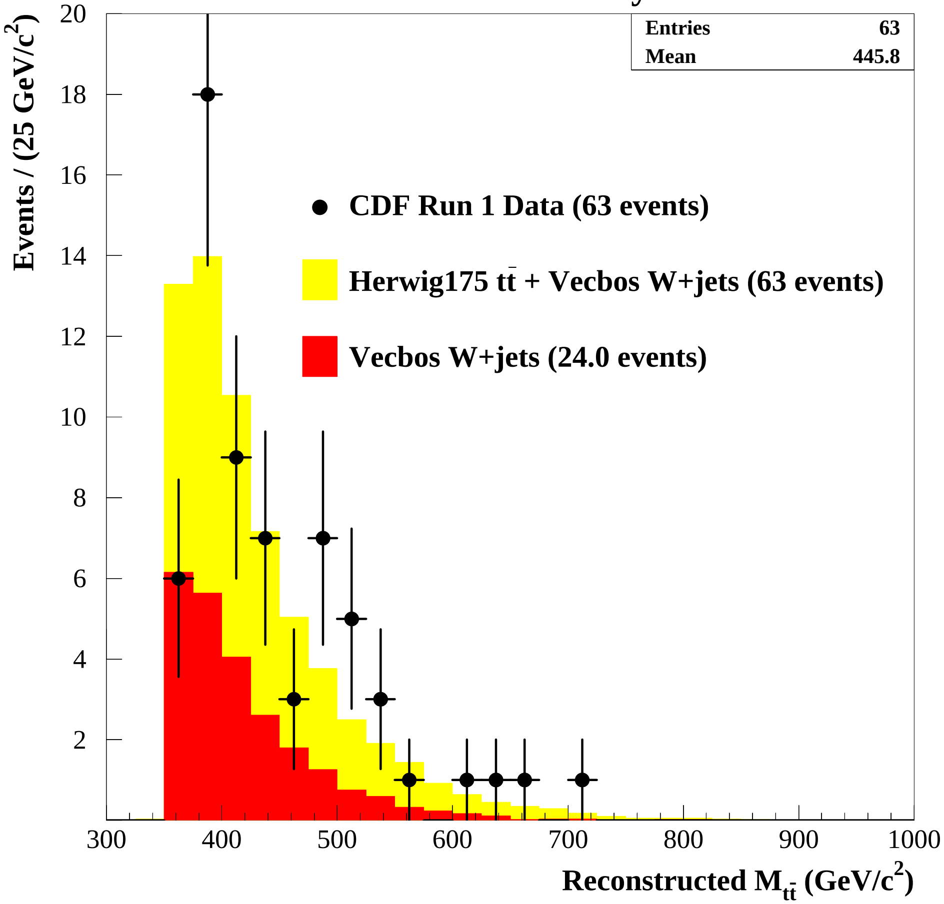


D0 (left) has published the $\bar{t}t$ invariant mass distribution of the events used for its lepton+jets top mass measurement. Results were obtained for events after both a 2C fit (to the top mass) and a 3C fit (with the top mass constrained to 173 GeV).

Until recently, CDF (right) exhibited the results of an analogous 2C fit to the $\bar{t}t$ invariant mass of their SVX tagged top mass subsample. (Data points with 0 counts are unplotted.)

None of these plots furnished evidence for a deviation from expectation.

$M(\bar{t}t$ system) for lepton+jets top mass events (cont'd)



Recently CDF increased the statistics in this plot (from 34 to 63 events) by including SVX untagged events and by relaxing the χ^2 cut on the 3C fit to 50.

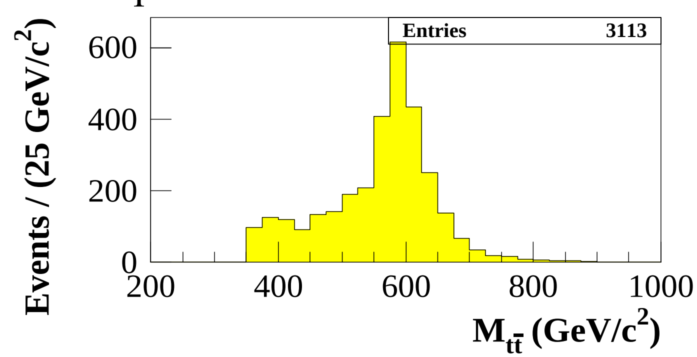
At left is the result of 3C fits to these events with the top mass constrained to 175 GeV.

To guard against wrong combinations, a 2C fit is then performed using the same jet assignments as in the best 3C fit, but with the 175 GeV constraint lifted. The event is rejected unless the $l\nu j$ and jjj masses both lie between 150 and 200 GeV.

When there is a true systematic discrepancy between data and expectation, it usually is reflected in the mean or rms of an appropriately chosen kinematic variable. For the above plot,

$$\langle m(\bar{t}t)\rangle = 446 \pm 55 \text{ GeV (data)}$$
$$= 430 \text{ GeV (expected)}$$

Below is the lineshape that would be expected if all $\bar{t}t$ pairs were the decay products of a 600 GeV Z'.



$y(t\bar{t}$ system) for lepton+jets top mass events

Top Thinkshop (Fermilab, Oct 98)

Working group "Is it top? Is it only top?": many parallel talks, including

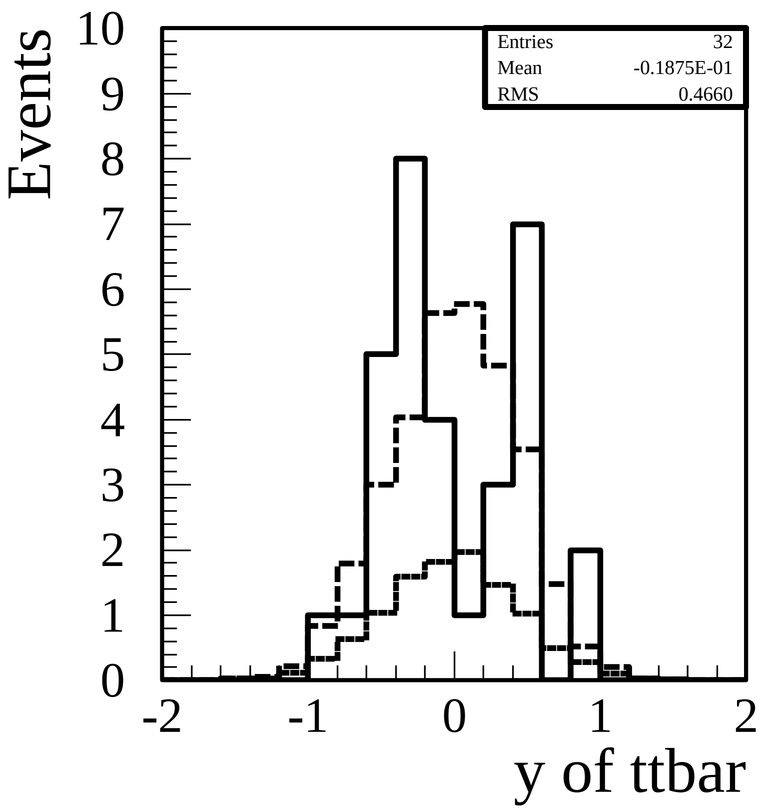
H. Frisch "Things that are, are not, and may be anomalous" (later)

K. Sliwa "Top search and top mass measurements in CDF: is everything consistent?":

$p_T(t\bar{t}$ system) "harder than expected from the... simulations used in the mass measurement... may reflect new physics..."

$y(t\bar{t}$ system)

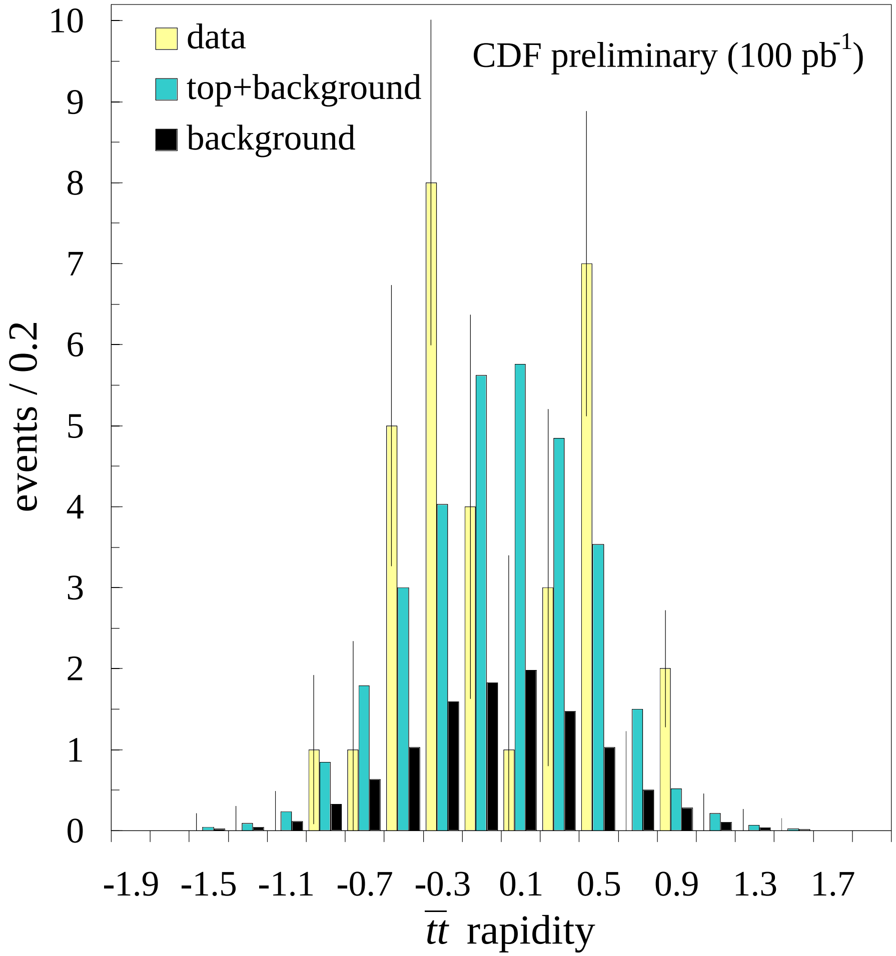
Among the distributions discussed informally by Sliwa, we focus on $y(t\bar{t}$ system), which appears to be the most discrepant. Sliwa's own interpretation of this plot:



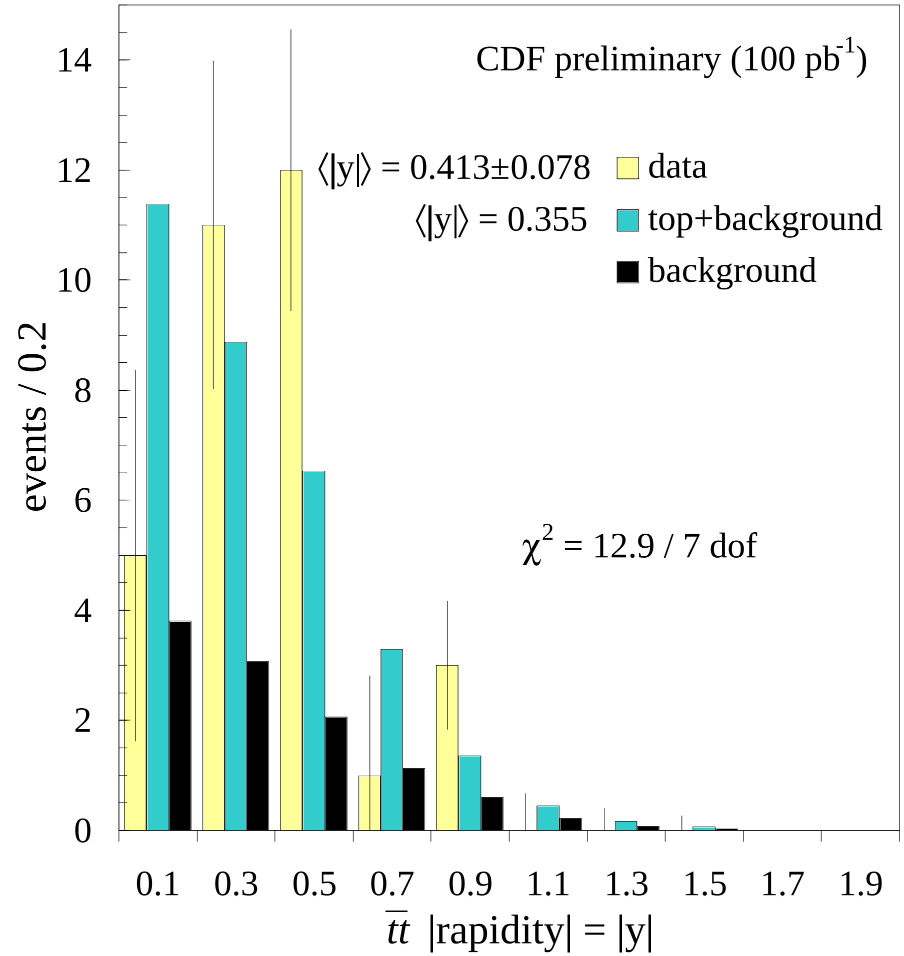
"The variable probes directly the longitudinal component of the $t\bar{t}$ system... The discrepancy, unless a statistical fluctuation (which does not seem very likely), indicates most likely that the original hypothesis about the nature of the top candidate events made while performing the [top quark mass] fits is incorrect. It was assumed that two objects of the same mass were produced, and then decayed as expected of top quarks in the SM, *i.e.* there is only one missing neutral particle... Obviously, new physics would alter this picture (*e.g.* light gluinos in SUSY) and the fits would be erroneous... I would like to know how this plot looks in the D0 lepton+jets sample!"

$y(\,\bar{t}t$ system) for lepton+jets top mass events (cont'd)

How the same data might look in an annual report:



Any new physics would be symmetric about y=0, so we fold the plot:

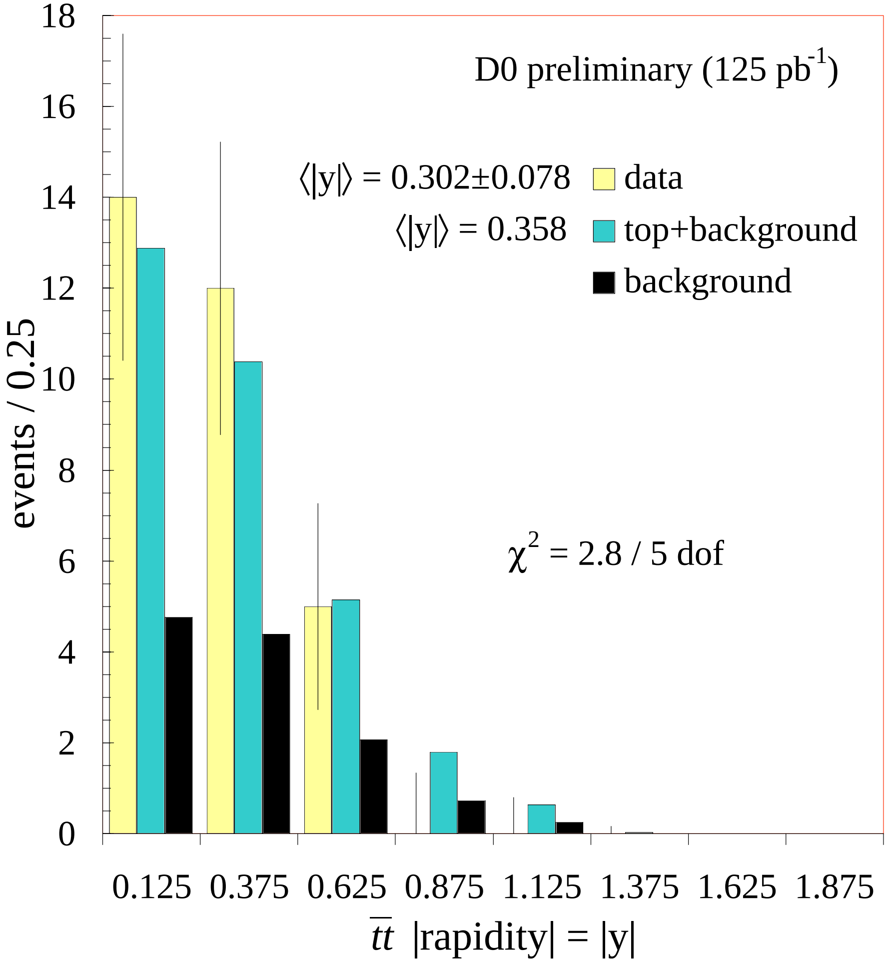


For the folded plot, the χ^2 is somewhat high compared to expectation.

However, if a discrepancy is truly systematic, it usually is reflected by a significant deviation in the mean or rms of an appropriate variable. The deviation in $\langle|y|\rangle$ is less than 1σ.

$y(\,\overline{t}t$ system) for lepton+jets top mass events (cont'd)

Here is the analogous D0 plot:



This χ^2 is >50% probable.

The deviation in $\langle|y|\rangle$ is also less than 1σ, and it is in the opposite direction.

The combined data provide no evidence for any departure from expectation for the rapidity of the $\overline{t}t$ system.

Top quark mass analysis in the dilepton channel

We discuss two aspects of this topic:

CDF has ~halved its total error on *m(t)* using D0's "neutrino phase space weighting" technique.

Two of the eight top dilepton candidates used by CDF for this analysis seem more interesting than top.

We use the first aspect as an introduction to the second.

In the top-to-dilepton channel, the system is once underconstrained. If a top mass is assumed, the system can be reconstructed via a quartic equation with 0, 2, or 4 real solutions.

Usually solutions exist for a wide range of $m(t)$. More discrimination can be gained by asking "if $m(t)$ had a certain value, how likely is it that the top decay products would appear in the detector as they did?"

The factors in this likelihood $L(m(t))$ are:

A. $(1/\sigma)$ $(d\sigma$ / d LIPS$)$ for $\bar{t}t$ production.

B. Probability density for energy of l in t rest frame.

C. Jacobian $|\partial$ LIPS / $\partial\{o\}|$ [$\{o\}$ = observed variables].

D0 (hep-ex/9706014; PRL **80**, 2063) made two independent approximations to $L(m(t))$:

- Matrix element weight (*M*WT)

  Ignores **C**, includes **B**, approximates **A** using product of proton pdf's with empirical $m(t)$ dependent factor.

  Extension of Kondo; Dalitz & Goldstein ideas.

- Neutrino phase space weight (νWT)

  Ignores **A** and **B** and approximates **C.** Predicts missing E_T after fixing both ν rapidities to many different values. Compares to measured missing E_T and increments a likelihood sum.

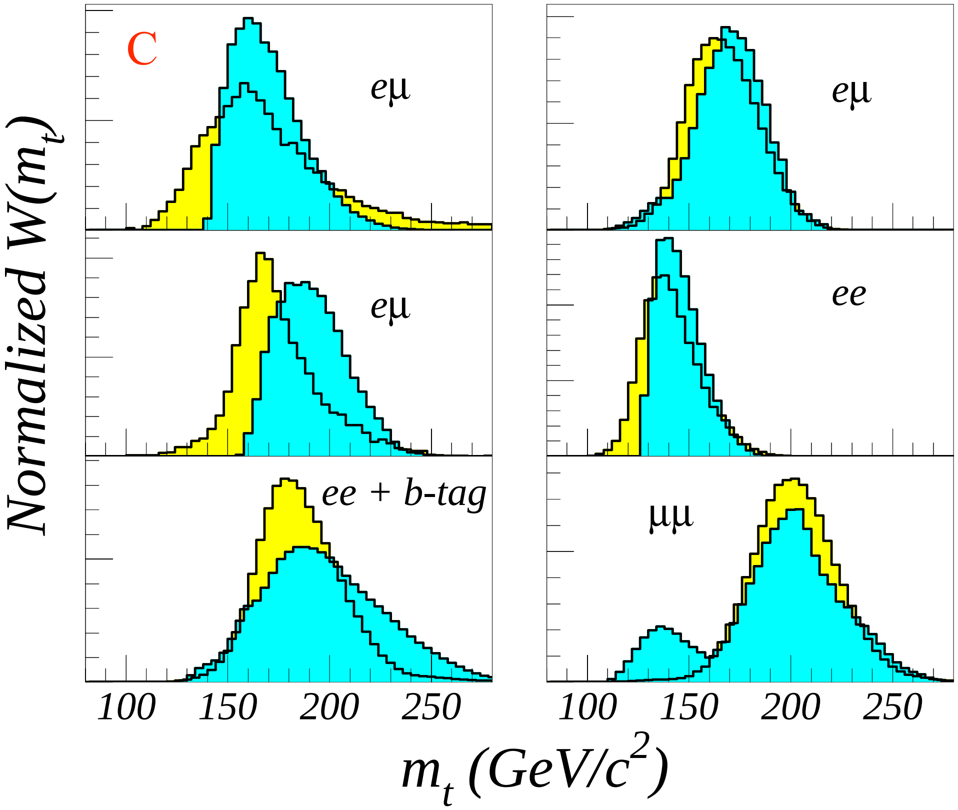
To obtain their final weight, both methods sum over

Quartic solutions

Jet assignments (including isr and fsr)

Many resolution-smeared versions of the same event

Top quark mass analysis in the dilepton channel (cont'd)

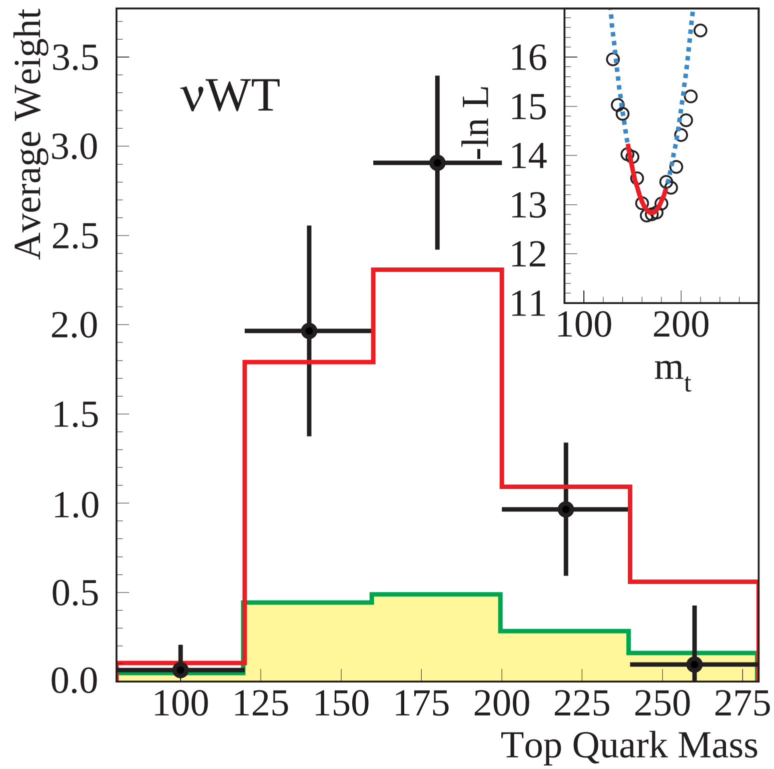


At left is the weight vs. top mass for 6 D0 dilepton events (dark = matrix element method; light = ν phase space method).

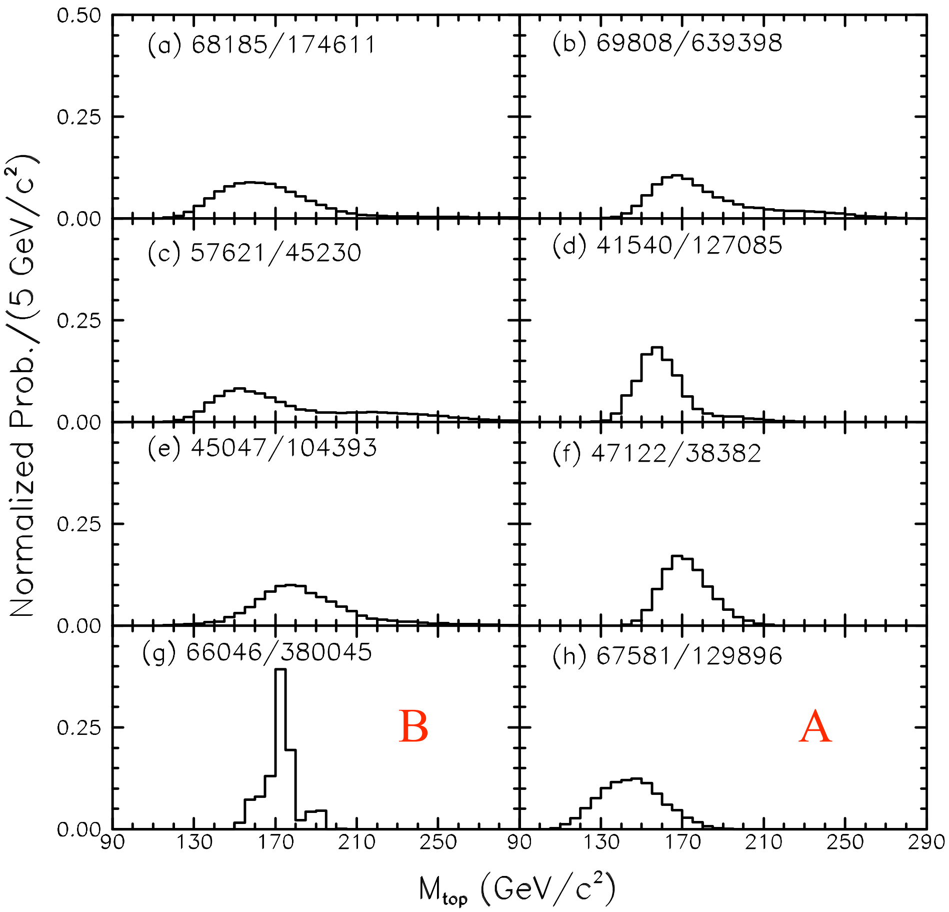
These distributions are not top mass probability densities. To extract the top mass, they are compared to distributions from a mixture of expected signal and background for many MC top masses, using a likelihood fit.

The weight distribution for each event is stored as a vector whose components are the fraction of the weight found in each of 5 mass bins.

Plotted for each of 5 regions is the average weight for data, best fit mixture, and background. The inset shows the result of the likelihood fit for the ν phase space weighting method. Both methods agree and yield **$m(t)$ = 168.4 ± 12.3(stat) ± 3.6(syst) GeV/c^2**.

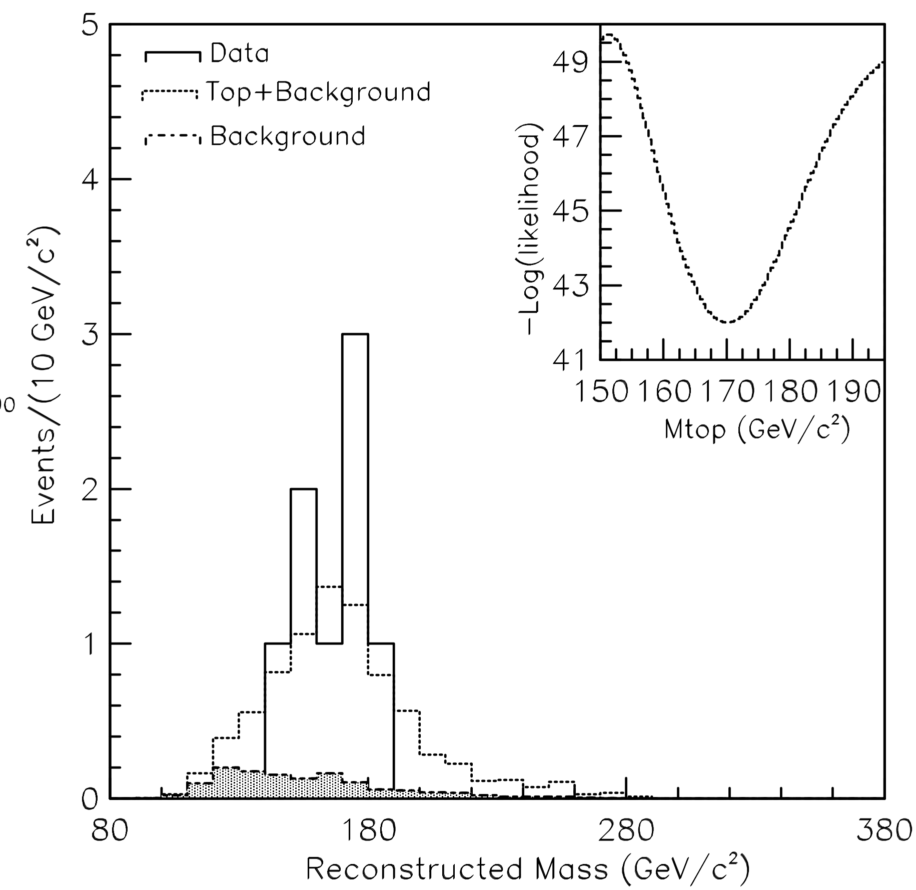


Top quark mass analysis in the dilepton channel (cont'd)



Recently (hep-ex/9810029; accepted by PRL) CDF applied the same ν phase space weight to 8 dilepton candidates.

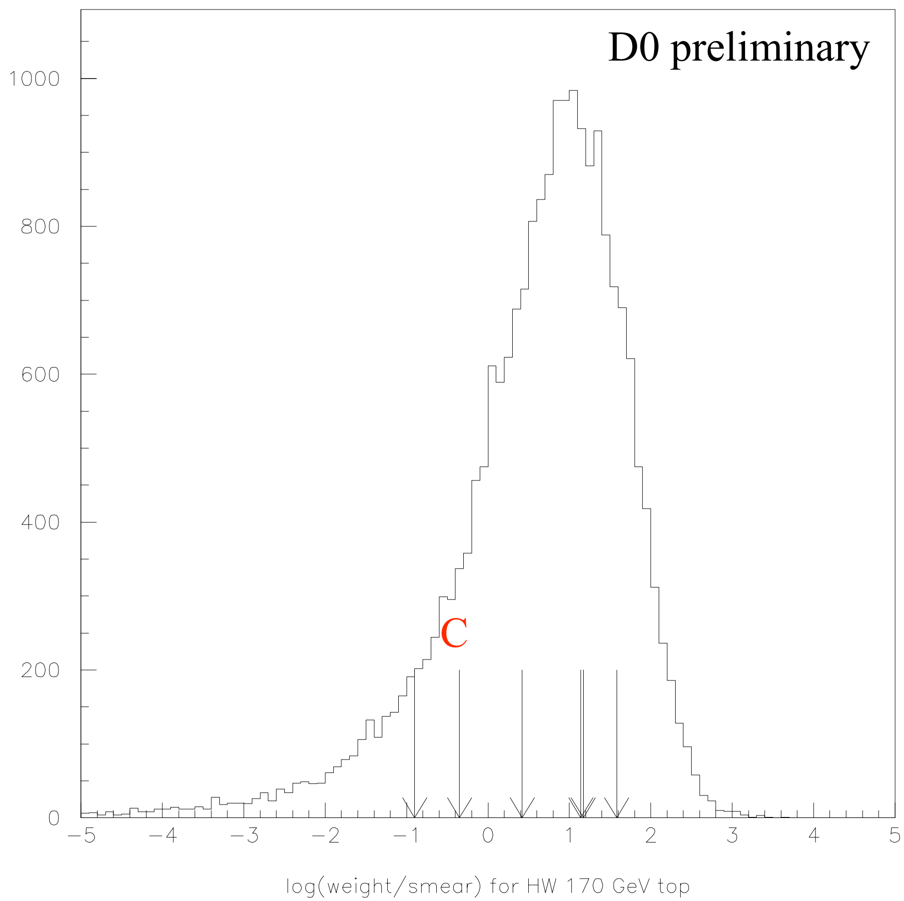
The weight vs. top mass distribution for one event ("B") has low statistics compared to the others; for that event, after resolution smearing, most $t\bar{t}$ solutions had low weight.

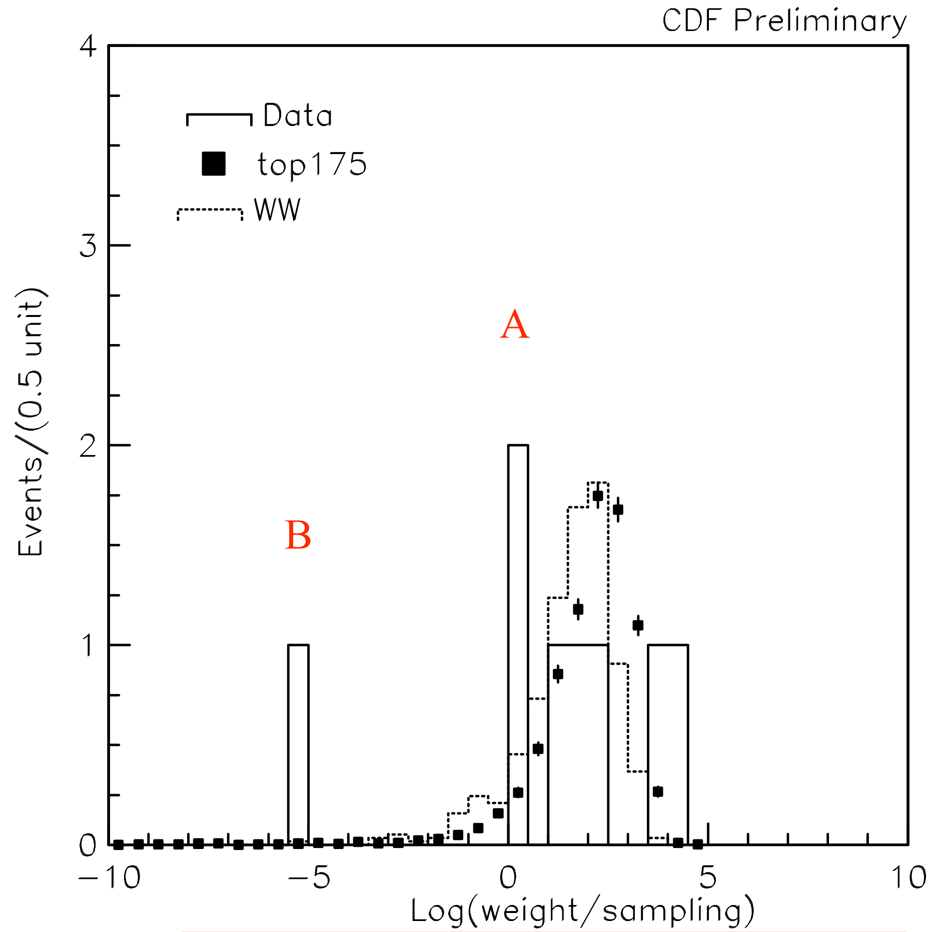


At right is the reconstructed top mass for the 8 dilepton events, compared to expectations for background and background + top signal.

The likelihood fit result is shown in the inset: ***m*(*t*) = 167.4 ± 10.3(stat) ± 4.8(syst) GeV/c²**.

Unusual events in the top dilepton channel

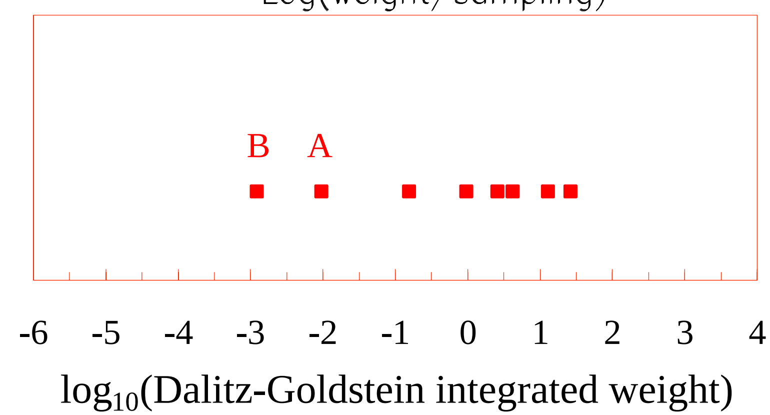




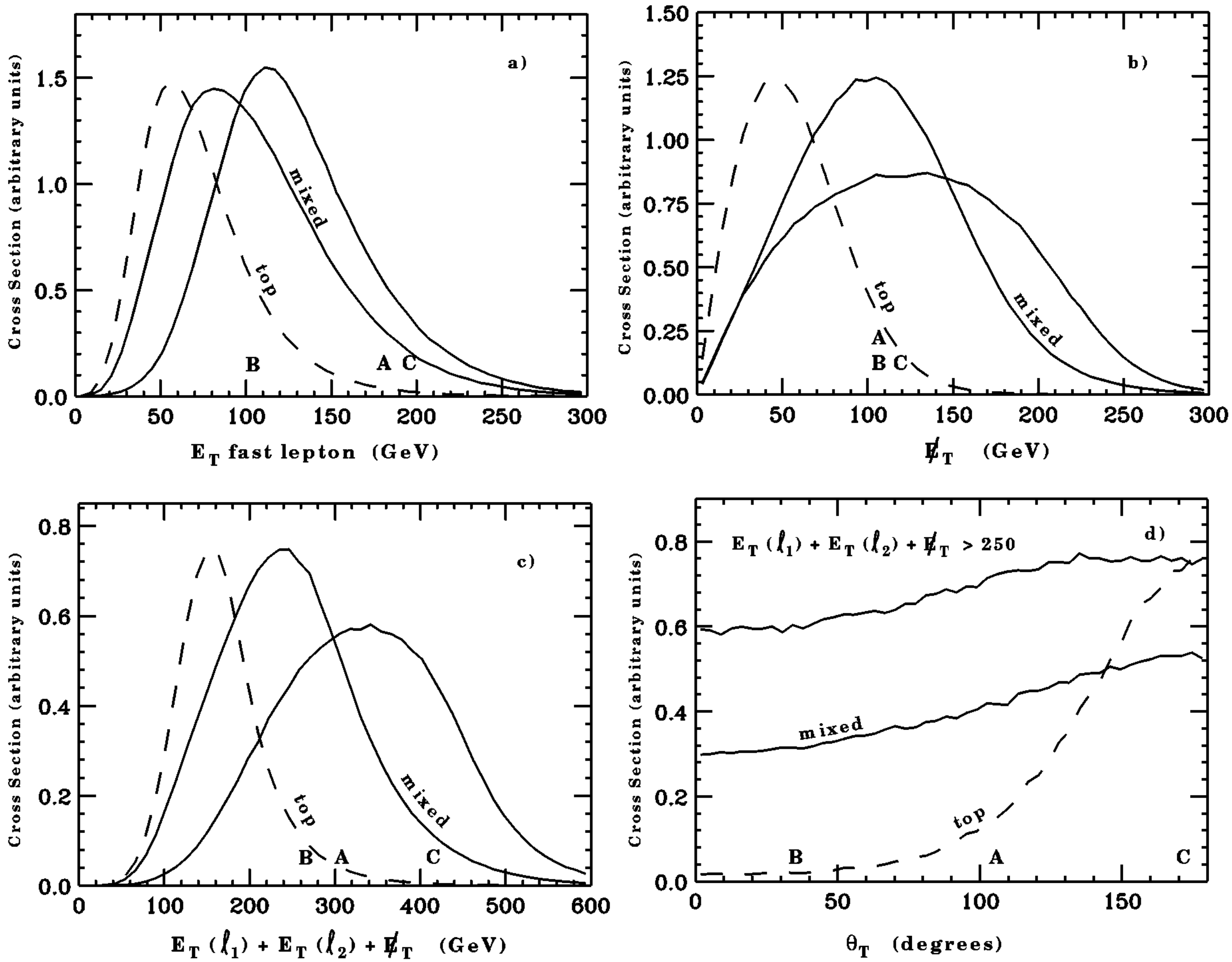
Plotted above are distributions of integrated weights for the ν weighting method applied by D0 and CDF.

Event B is on the tail of the expected distribution. ≥1 such deviation is expected in ~5% of experiments.

Included at right is a rough distribution of the Dalitz-Goldstein integrated weight for the CDF events.

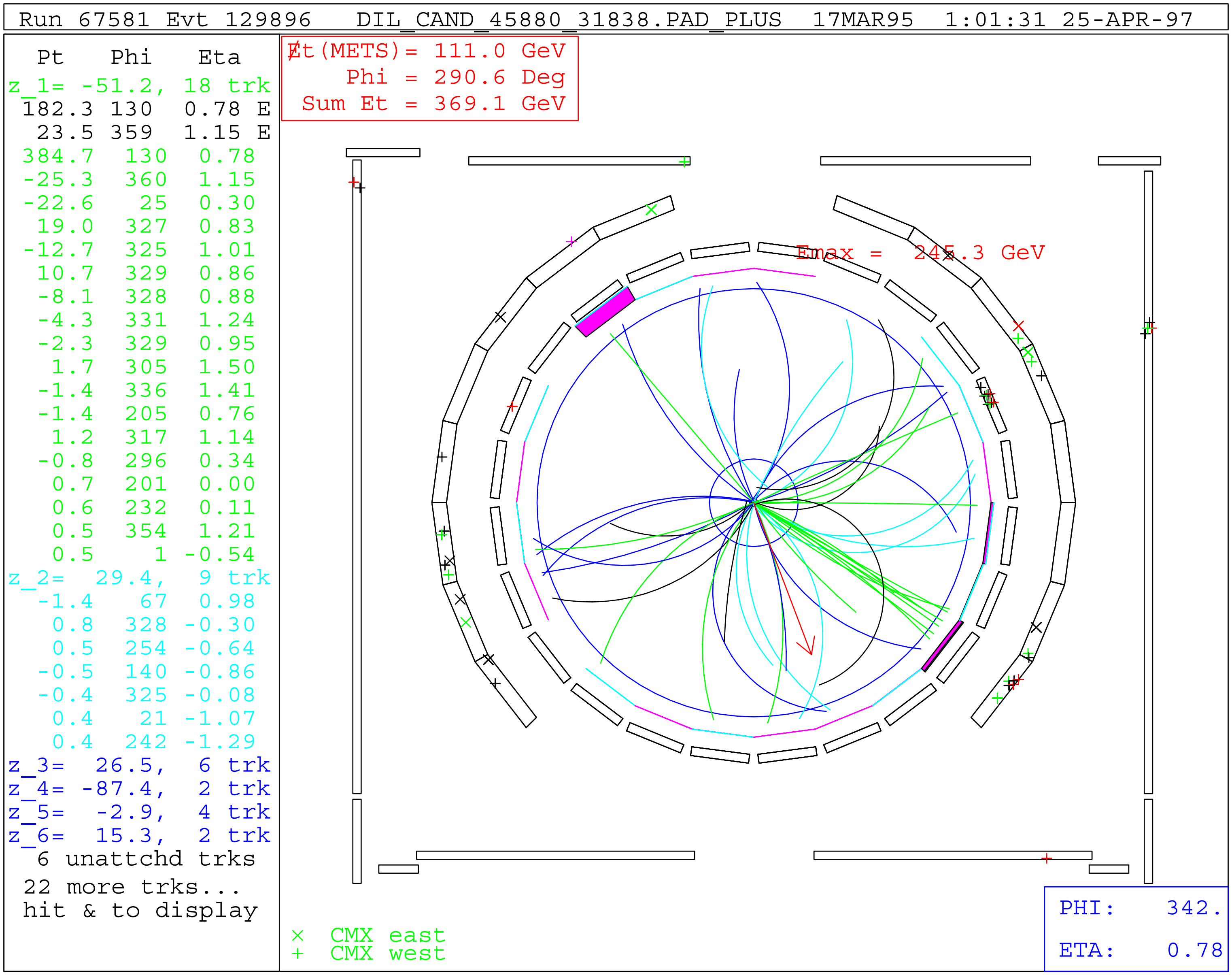


Unusual events in the top dilepton channel (cont'd)



Events A and B (CDF) and C (D0) were discussed by Barnett and Hall (PRL **77**, 3506). In (c) they plot $E_S \equiv$ scalar leptonic E_T. Among events with $E_S > 250$ GeV, events A and especially B have unusually small e-μ azimuthal opening angle θ_T, as exhibited in (d). Event C has a $p_T \sim 200$ GeV muon that is not well measured; we discuss it no further here.

Unusual top dilepton event "A"

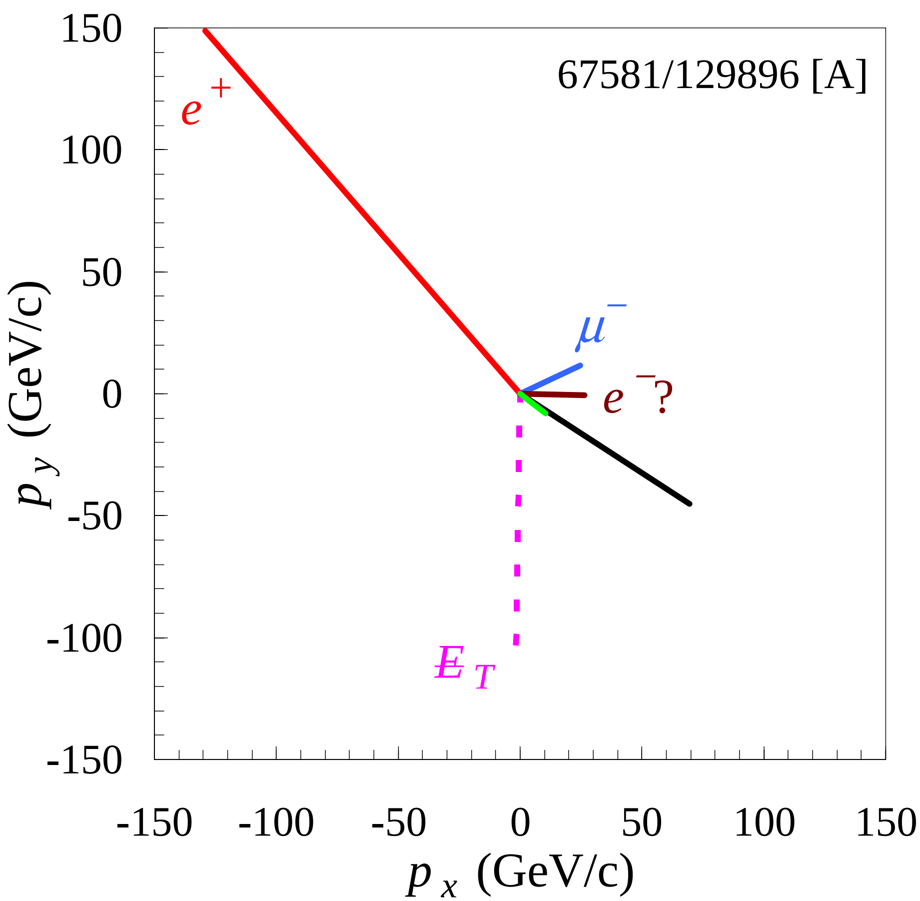


This is a trilepton candidate; the "jet" at 359° is associated with an isolated track and passes tight electron cuts (*E/p* ~ 1.1) except for proximity to an azimuthal module boundary.

Unusual top dilepton event "A" (cont'd)

Barnett and Hall discussed event A's unusual kinematics ($p_T(E) \sim 197$ GeV, $\theta_T \sim 106°$).
M. Hohlmann (U. Chicago thesis, 1997) computed $N_{expected}$ of such events from $t\bar{t}$:

(**a**) ⟨conventional $t\bar{t}$ dilepton events⟩	~ 6	$= 2.4 \pm 0.9 \times 10^{-6}$ events
(**b**) $P(t\bar{t} \to WW \to$ isolated electron, $p_T > 180$ GeV)	$\sim 10^{-2}$	
(**c**) $P(t\bar{t} \to b$ or $c \to$ isolated electron, $p_T > 20$ GeV)	$\sim 4 \times 10^{-4}$	
(**d**) ID efficiency for third charged lepton	$\sim 10^{-1}$	



Here we extend Hohlmann's calculation:

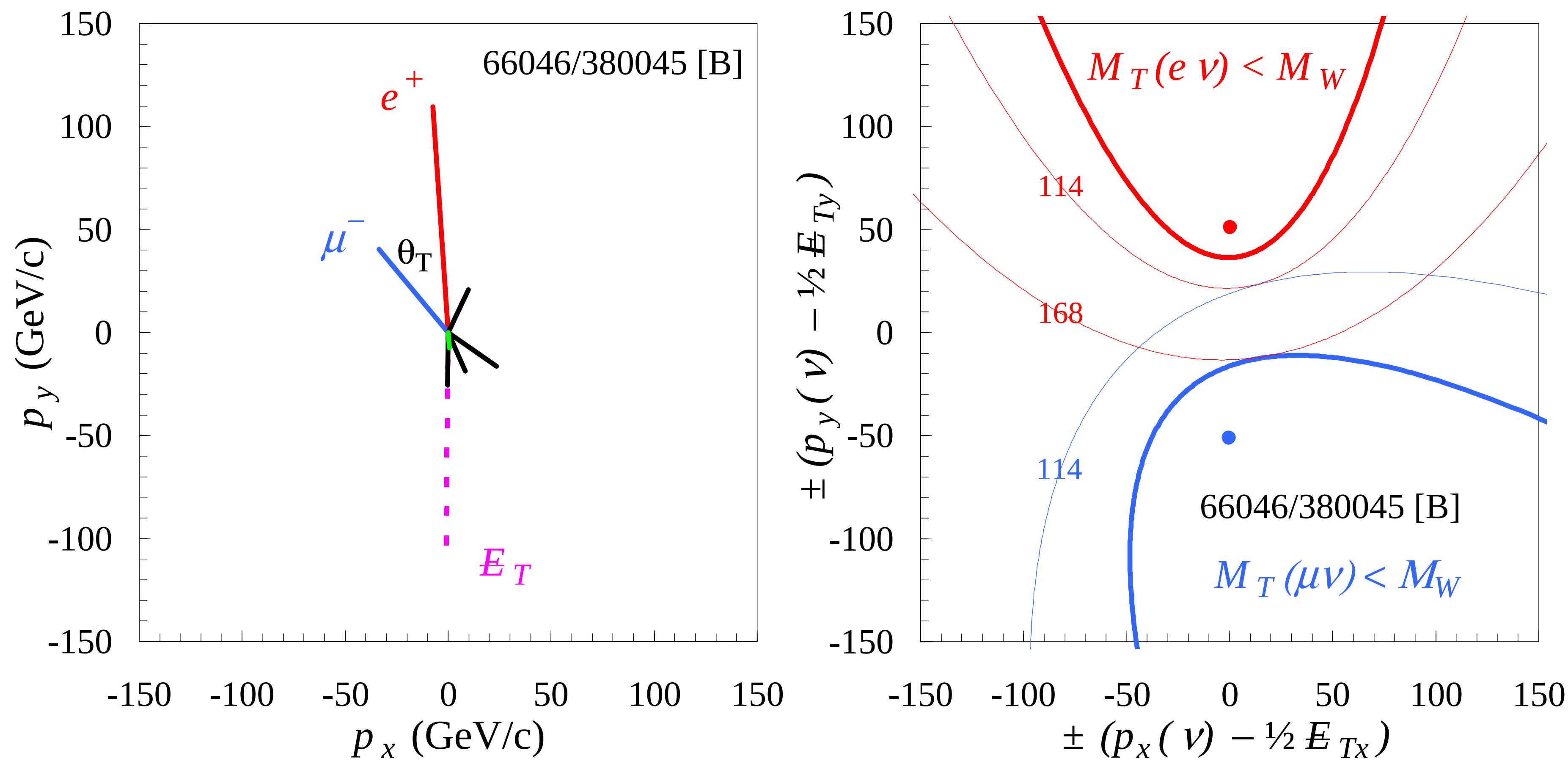
multiply (**b**) ×4 ($\mu, \tau, \not{E}_T$ in addition to e)
multiply (**c**) ×2 (μ in addition to e)

In addition we note that this event has two aspects, (**b**) and ((**c**)×(**d**)), each with small probability. Let the product of these two probabilities be u. Integrating over possible other pairs of probabilities with a product $< u$, one finds that the probability of obtaining at least as rare a pair of aspects is not u, but rather $u(1-\ln u)$.

Therefore our extended estimate for the expected number of such events from $t\bar{t}$ is:

$u = (4\times10^{-2}) \times (2\times4\times10^{-4}\times10^{-1}) \sim 3\times10^{-6}$
$u(1-\ln u) \sim 4\times10^{-5}$
$N_{expected} \sim 6 \times (4\times10^{-5}) \sim 3\times10^{-4}$ events .

Unusual top dilepton event "B"



At right the parabolæ are lines of constant transverse mass $M_T(l\nu)$. If $\mathbf{p}(\nu_e)+\mathbf{p}(\nu_\mu) = \not{E}_T$, and the e and μ both arise from W decay, the bold parabolæ must overlap.

Event B does not satisfy this requirement unless $\not{E}_T$ is overmeasured by ~50 GeV.

If uncertainties in the e and μ momenta are neglected, and if the $\not{E}_T$ lineshape were gaussian, this would be a ~3σ (~10^{-3}) fluctuation in $\not{E}_T$ using the standard CDF $\sigma(\not{E}_T)$. Balancing these oversimplifications is the fact that event B's scalar E_T is mostly leptonic, enhancing the $\not{E}_T$ accuracy. Then, for fluctuations of this type, $N_{expected} \sim 6 \times (\sim 10^{-3}) \sim 7\times 10^{-3}$ events .

SM background sources for unusual top dilepton events

CDF's top-to-$e\mu$ analysis considers SM backgrounds from:

$Z \to \tau\tau$	irrelevant here: $M(e+\mu+\not{E}_T) > 250$ GeV for both events (A) and (B)
QCD $b\bar{b}$	irrelevant here: ~0.02 standard events with low lepton p_T
WW + jets	~0.2 standard events:
	(event A) third lepton unexplained
	(event B) high $M_T(e\nu)$ unexplained (parabola plot); ≥4 jets unexpected
Fake leptons	~0.2 standard events:
	(A) third lepton unexplained
	(B) if two fake leptons: $\not{E}_T > 100$ GeV unexplained
	(B) if W + fake electron: $M_T(\mu\nu) > 130$ GeV unexplained
	(B) if W + fake muon: $M_T(e\nu) > 200$ GeV unexplained

A special trilepton background may also be considered for event (A) only:

WZ + jet	rarer than WW:
	$M(ee) > 130$ GeV unexplained; $M_T(\mu\nu) > 90$ GeV unexplained

Rough estimates of principal SM background levels

Event A: $N_{\text{expected}} \sim \left(\sim 0.2\ WW,WZ + \text{jet events}\right) \times \left(2.5\ \text{pb}/(9.5+2.5)\ \text{pb} \sim WZ/(WW+WZ)\right) \times$
$\times \left(3/10 \sim \text{BR}(Z \to ee,\mu\mu)/\text{BR}(W \to e\nu,\mu\nu)\right) \times \left(0.3 \sim 3^{\text{rd}}\ \text{lepton ID efficiency}\right) \times$
$\times \left(P(M(ee) > 130\ \text{GeV}) \sim 0.04\ \text{(from CDF Drell-Yan data)}\right) \sim 1.5\times10^{-4}$ events .

Event B: $N_{\text{expected}} \sim \left(\sim 0.2\ \text{fake lepton events}\right) \times \left(0.1 \sim \text{double fake} / (W + \text{single fake})\right) \times$
$\times \left(0.065 \sim P(\not{E}_T > 100\ \text{GeV} \mid \not{E}_T > 25\ \text{GeV})\ \text{(from D0 data)}\right) \sim 1.3\times10^{-3}$ events .

Probability of a similar two-event fluctuation?

Rough estimates of expected no. of CDF events in Run 1 at least as unusual as...

	Event A	Event B
$\bar{t}t$ origin	3×10^{-4}	7×10^{-3}
background origin	1.5×10^{-4}	1.3×10^{-3}
SM origin (sum of above)	5×10^{-4}	9×10^{-3}

The product of the SM probabilities for these two events is $u \sim 4 \times 10^{-6}$. The probability P of seeing two events whose probabilities have a product less than u is

$$u(1-\ln u) = P \sim 6 \times 10^{-5}.$$

This is only a rough estimate of P. Nevertheless, for reference, that portion of a normal curve of error which lies $> 3.8\sigma$ to one side of its peak accounts for $\sim 6 \times 10^{-5}$ of that curve's half-area.

Beyond-the-SM explanation?

Barnett and Hall: squark pair production with cascade

squark (~310 GeV) $\rightarrow$ quark + gaugino (~260 GeV)
gaugino $\rightarrow$ (neutrino or lepton) + slepton (~220 GeV)
slepton $\rightarrow$ lepton + neutralino (LSP)

Slepton decays yield hard leptons and substantial missing energy, while additional softer leptons can be produced in the gaugino cascade.

Other non SM mechanisms are possible.

Conclusions

The top quark mass measured by CDF and D0 is

$$m(t) = 174.3 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})\ \text{GeV/c}^2.$$

In its top dilepton sample CDF has observed two unusual μe events (one with a likely third electron, one unlikely to arise from two W's, both with high leptonic scalar E_T).

A back-of-the-envelope estimate for the probability P of observing two events with as low a product of individual probabilities is $P \sim 6 \times 10^{-5}$.

Can one accurately assess the degree to which an event with particular characteristics is rare? In principle, not if the event has already been detected and those characteristics have already been noted. This issue can be addressed in Run II. With 20× more data, CDF and D0 expect either to find additional events with similar properties, or to rule out the hypothesis that these two events have a common origin.

In lepton+jets $\bar{t}t$ data, with many kinematic distributions studied, no candidate for significant deviation from expectation has emerged. In particular, $m(\bar{t}t)$ and $y(\bar{t}t)$ spectra show no hint of new physics.

With 20× more data, many top quark measurements, now severely limited by statistics but not by systematics, will become considerably more interesting.