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Top Quark Physics at the Tevatron

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- A brief history of top physics
- Top production and decay properties
- New Run II results
- Concluding remarks

A Brief Pre-history of Top - 1

The first hint of a third generation of quarks can be argued to have been the demonstration by Kobayashi and Maskawa (1973) that three generations of quarks are needed to allow CP violation via a complex phase in the flavour matrix.

With the discovery of the Υ (1977) the hint becomes ground for technical proposals, and several experiments start searching for T hadrons.

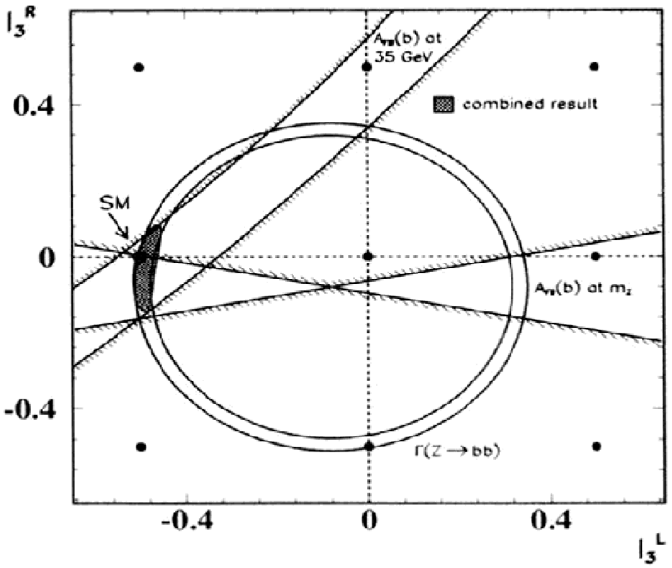
On the theoretical side, the renormalizability of the SM demands a cancellation of triangle anomalies, i.e. $-\Sigma_L I_3 (I_3 + Y/2)^2 = 0 \rightarrow \Sigma_L Q = -1 + 3(\frac{2}{3} - \frac{1}{3}) = 0$ and thus the existence of a partner for the newborn $Q = -1/3$ b quark.

Moreover, an isosinglet b quark generates copious FCNC decays such as $b \rightarrow s l^+ l^-$, which are not seen.

A Brief Pre-history of Top - 2

Additional evidence comes from several measurements at e^+e^- machines:

- PLUTO, DASP measure Γ_{ee} of $\Upsilon(1s)$ and determine that the b-quark must have $Q = -1/3$ (1978);
- PETRA measures $A_{FB} = -.228 \pm 0.06$ in $e^+e^- \to b\bar{b}$ reactions, when $A_{FB} = -0.25$ is expected if $I^b_{3,L} = -1/2$, $A_{FB} = 0$ if $I^b_{3,L} = 0$ (1983);
- ARGUS later argue that M_t must be largish since X_d is large in $B^0\bar{B}^0$ mixing (1987);
- LEP precision measurements of electroweak parameters, notably $\Gamma(Z \to b\bar{b})$, establish $I^b_{3,L} = -1/2$ (1992).



A Brief Pre-history of Top - 3

Searches start at electron colliders around the world, when a jump in $R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ and/or changes in event shape are sought. Mass limits are set at increasing values, up to $M_t > M_Z/2$ (ALEPH,1990).

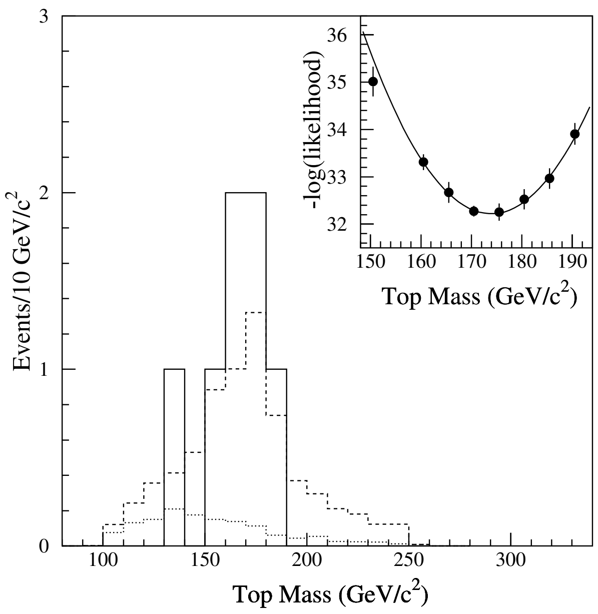
Hadron colliders soon join the group and rapidly take over:

- UA1 at the Sp$\bar{p}$S ($\sqrt{s} = 630\ GeV$) seeks direct evidence of $p\bar{p} \rightarrow W \rightarrow t\bar{b}$, and at one point obtains 12 $l + jj$ events on a background of 3.5, claiming discovery and quoting $M_t = 40 \pm 10\ GeV$ (1984). The new particle however refuses to show up in added statistics, and the result becomes $M_t > 41\ GeV$ at 95% C.L. (1988).
- UA2 improves a bit the limit ($M_t > 69\ GeV$, 1990), but by then eyes are already pointed at the Tevatron...

Top Discovery at Last

With its first 4 pb^{-1} of data CDF observes a very clear dilepton event, but only places a 95% CL limit at $M_t > 77\ GeV$ (1990), soon improved to $M_t > 91\ GeV$ (1992).

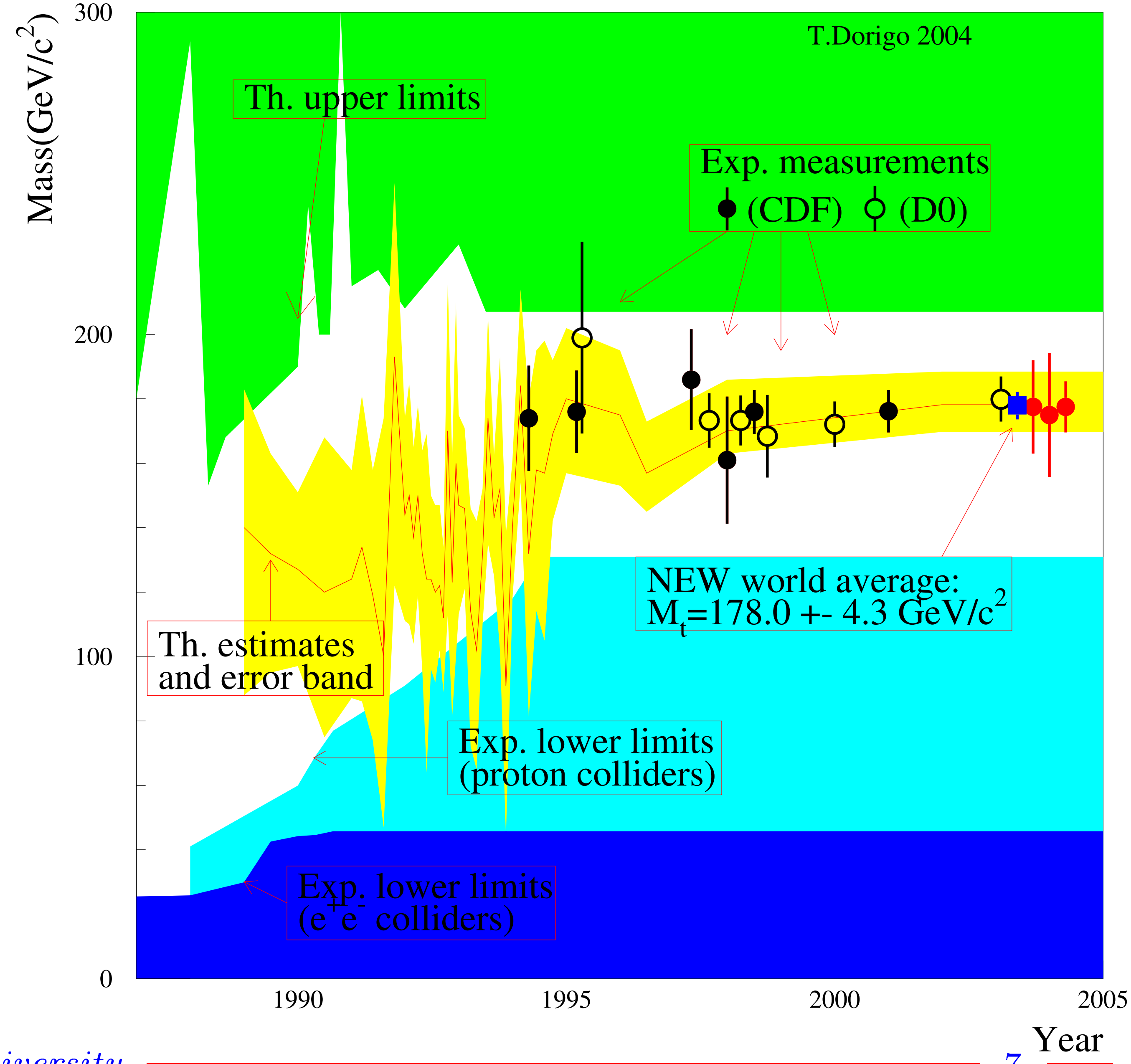
The breakthrough comes with the increased luminosity of Run I in 1992, when CDF is equipped with a new silicon detector capable of spotting b-quark jets. 7 events appear insufficient to claim discovery in 1994 (2.8σ), but the mass measurement is right-on ($M_t = 174 \pm 16\ GeV$).



Finally, in 1995 conclusive evidence is brought by both CDF and D0.
The quark sector of the SM is now complete.

A SM Success

This figure illustrates the convergence of direct and indirect determinations of M_t: a notable success of the Standard Model, brought together by the close interplay between experimental measurements and theoretical computations.



Top ID in the SM

- Mass:
  $178.1^{+10.4}_{-8.3}\ GeV$ (PDG 2002), $178.0 \pm 4.3\ GeV$ (NEW Run 1 average)
- Spin $= 1/2$
- $\Gamma \sim 1.5\ GeV$, or $\tau \sim 10^{-24} s$
- Couplings:
  strong (color triplet), e.m. ($Q = +2/3$), weak ($I^t_{3,L} = +1/2$)
- $|V_{tb}| = .99$ (th.), $0.97^{+0.16}_{-0.12}$ (CDF); branching ratios:
  - $t \to W^+b$: BR ~ 1 (th.), $0.94^{+0.26+0.17}_{-0.21-0.12}$ (CDF);
  - $t \to W^+s$: BR $\sim 10^{-3}$ (th.);
  - $t \to W^+d$: BR $\sim 5 \times 10^{-5}$ (th.);
    $t \to l\nu X$: BR $= 0.094 \pm 0.024$ (CDF);
  - $t \to \gamma c, \gamma u$: BR $\sim 10^{-8}$ (th.), < 0.032 (CDF);
  - $t \to Zc, Zu$: BR $\sim 10^{-12}$ (th.), < 0.137 (CDF).

Top mass: a Key EW Parameter

The top quark mass is LARGE. It is close to the scale of electroweak symmetry breaking. Its Yukawa coupling is “natural”: $y_t = \sqrt{2}\frac{M_t}{v} \sim 1$.

- ⋆ Is t actively involved in the breaking of EW symmetry?
- ⋆ In the MSSM, a large M_t was *predicted* (1982), since otherwise radiative corrections to M_h would prevent SU(2)xU(1) breaking.

In any case, M_t is a very important parameter for the tests of EW theory:

- ⋆ the large value of y_t makes it advantageous to probe the $t\bar{t}h$ vertex;
- ⋆ radiative corrections $\delta\rho$ depend quadratically on M_t;
- ⋆ a precise measurement of M_t yields vital information on M_h:
  - $\Delta M_W \sim 0.7 \times 10^{-2} \Delta M_t$ yield the same contribution to ΔM_h;
  - M_t & M_W at Tevatron Run II $\rightarrow \Delta M_h/M_h \sim 35\%$.

Top Width: the Chance to Study a Free Quark

The large mass of the top quark implies that the decay time is very short: $\Gamma_t \sim M_t^3 \sim 1.5\ GeV$. That is one order of magnitude larger than the hadronization scale $\Lambda_{QCD} \sim 0.2\ GeV$.

From that simple fact there follow important consequences:

- ⋆ the top quark is created and decays as a free quark;
- ⋆ top hadrons do not exist: since $M_{B^{**}} - M_B = 450\ MeV$ is independent on the heavy quark mass, the same splitting occurs between T^{**-} and T^-. T hadrons merge and act coherently, and what is left is a broad excitation curve.

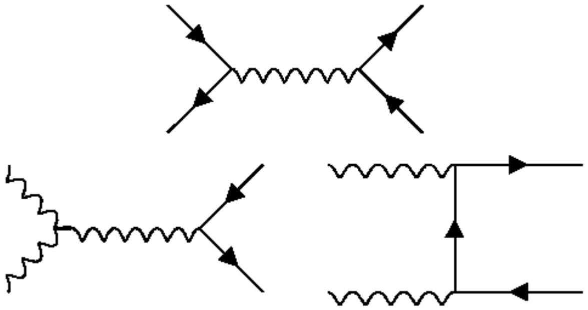
Γ_t, Continued

On the experimental side, several possibilities for testing production and decay properties of top quarks are granted by a large Γ_t:

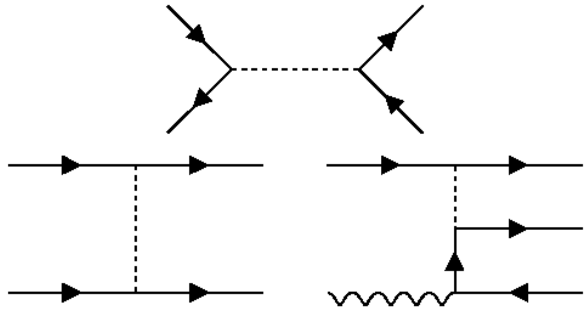
- decay products tell us about top polarization, because the depolarization time $\tau_d \sim M_t/\Lambda^2_{QCD}$ is much longer;
- we can study W helicity and verify:
  - ⋆ absence of $h_{W^+} = +1$ state, suppressed by chiral factor $(M_b/M_W)^2$;
  - ⋆ predicted fraction of longitudinal W, $\mathcal{F}_0 = \frac{M_t^2/2M_W^2}{1+M_t^2/2M_W^2} = 0.701 \pm 0.016$;
  - ⋆ constrain non-standard couplings, V+A contribution.

Top Production at the Tevatron

All direct measurements of top quark production and decay (save a few exotic production and decay limits) come from the Tevatron.
At $\sqrt{s} = 1.96\ TeV$, the dominant production process is direct production by strong interactions:



Pair production by $q\bar{q}$ annihilation dominates at the Tevatron (90%); in total,
$\sigma_{t\bar{t}} = 6.77 \pm 0.42\ pb$ (NLLO, $M_t = 175\ GeV$),
$\sigma_{t\bar{t}} = 5.6^{+1.6}_{-1.2}\ pb$ (CDF II).

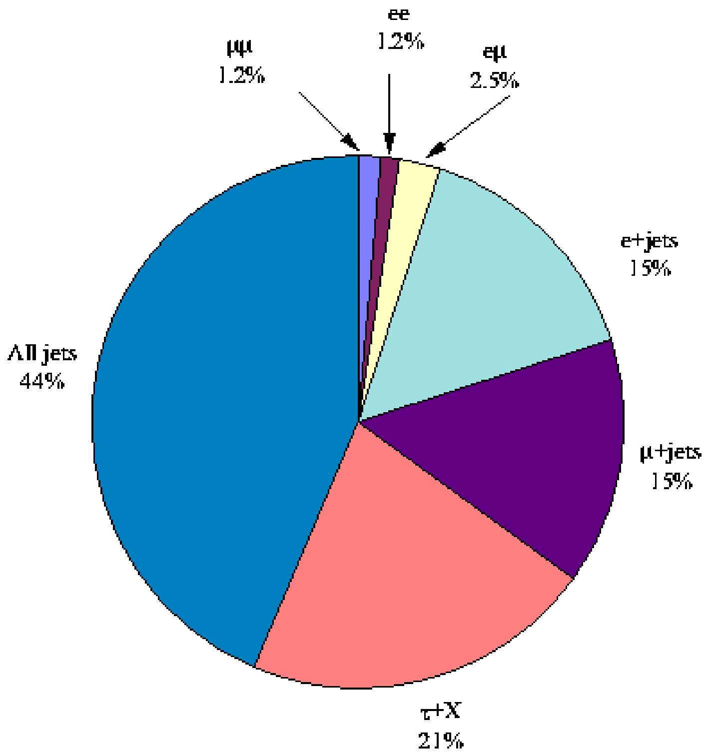


Single top is produced via a virtual W (31%) or through Wg fusion. The total is
$\sigma_{tX} = 2.9 \pm 0.3\ pb$ (NLO, $M_t = 175\ GeV$),
$\sigma_{tX} < 13.7\ pb\ (95\% CL)$ (CDF II).

Top Decay

Since $V_{tb} \sim 1$ and $M_t > M_W + M_b$, the decay $t \to W^+ b$ dominates.
$t\bar{t}$ final states are thus classified according to the decay of the W bosons:

- both $W^+ \to q\bar{q}'$ and $W^- \to q''\bar{q}''' \to$ all-hadronic final state (6 jets, 44%);
- one of the W decays to $e\nu_e$ or $\mu\nu_\mu \to$ single-lepton final state ($l\nu + 4$ jets, 30%);
- both W bosons decay to $e\nu_e$ or $\mu\nu_\mu \to$ dilepton final state ($l^+l^-\nu\nu + 2$ jets, 5%).
- $W \to \tau\nu$ decays are another story.



Production and Decay Properties

With an integrated luminosity of about 200 pb^{-1}/experiment, CDF and D0 have started to supersede their Run I results on the following measurements:

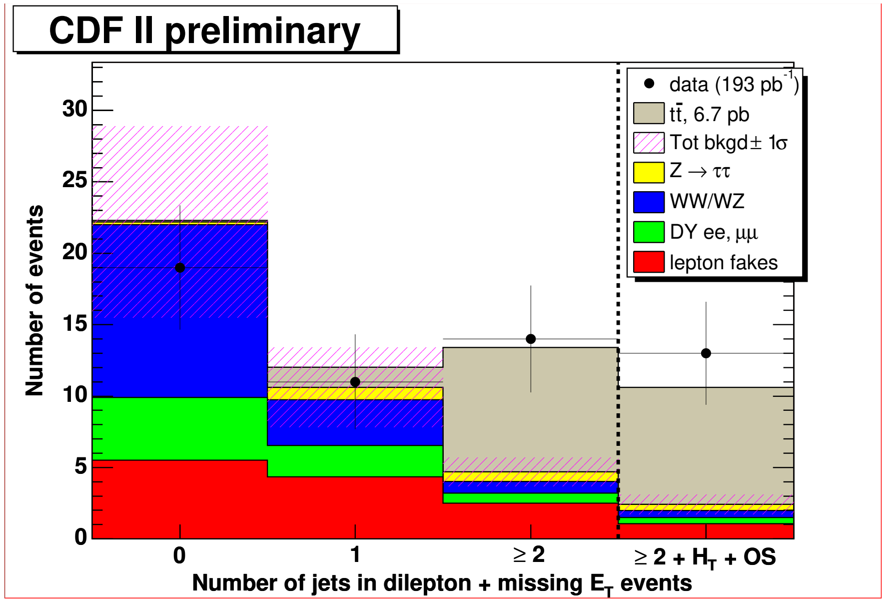
- ⋆ pair production cross section, $\sigma_{t\bar{t}}$;
- ⋆ top quark mass, M_t;
- ⋆ single top production search, σ_{tX};

In the meantime, new technologies are being developed to squeeze more information from the data:

- isolated track: a looser ID algorithm for W leptons (CDF II);
- DLM: improved M_t measurement (D0 Run I, CDF Run II);
- $Z \to b\bar{b}$: b-jet energy scale from the Z signal.

Measurements of $\sigma_{t\bar{t}}$ at $\sqrt{s} = 1.96\ TeV$
1 - Dileptons

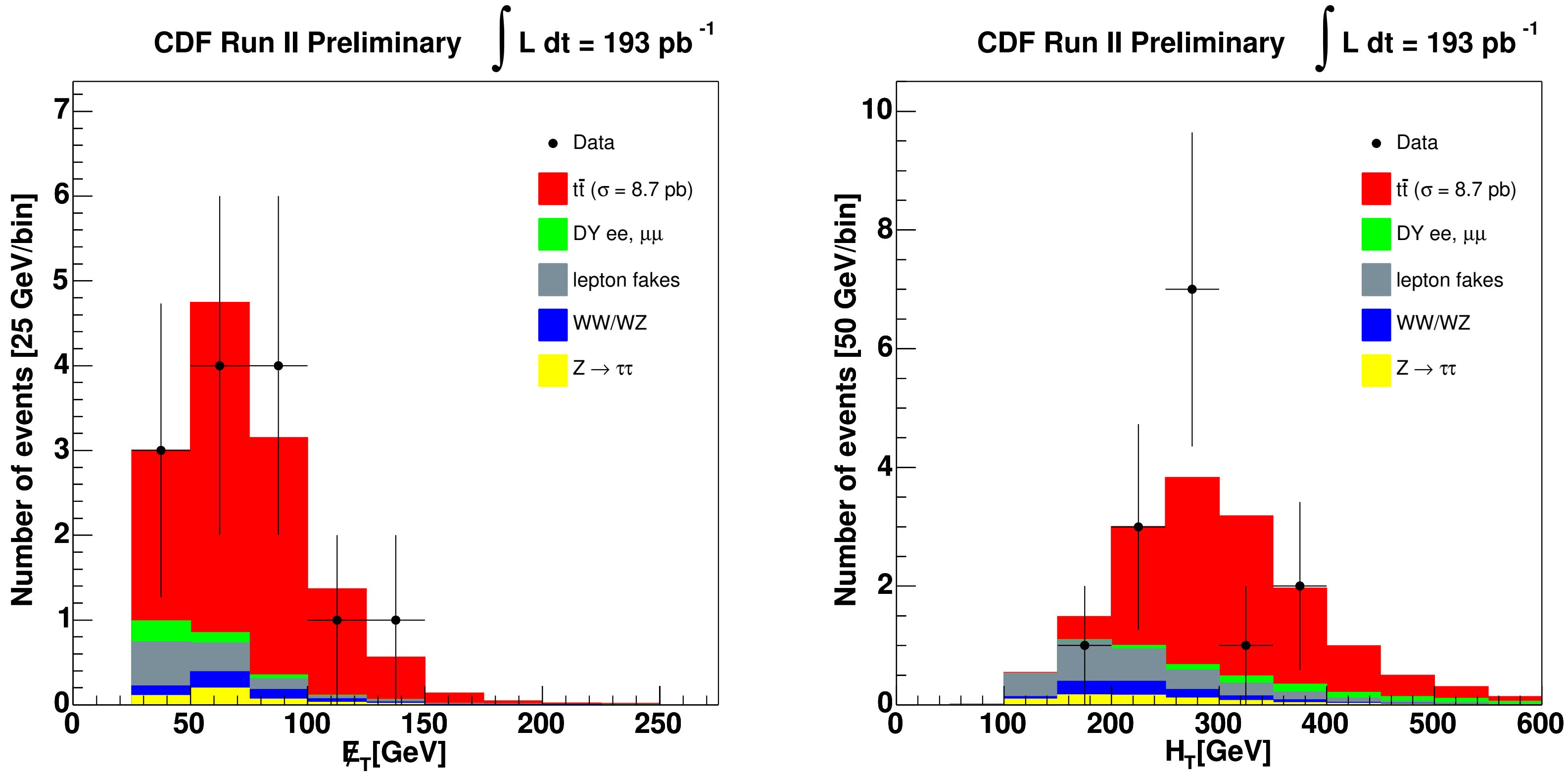
CDF has measured $\sigma_{t\bar{t}}$ by counting events with two high-P_T leptons plus jets and missing E_T. Backgrounds are small and the measurement error is dominated by statistics and the knowledge of signal efficiency.



Source	N jets 0j	1j	$\geq$ 2j	H_T, OS
WW/WZ	12.1 ± 4.9	3.2 ± 1.3	0.81 ± 0.33	0.49 ± 0.21
Drell-Yan	4.4 ± 2.0	2.2 ± 1.1	0.7 ± 0.4	0.43 ± 0.44
$Z \to \tau\tau$	0.19 ± 0.06	0.86 ± 0.26	0.69 ± 0.21	0.42 ± 0.13
Fakes	5.53 ± 1.14	4.35 ± 0.90	2.47 ± 0.52	1.07 ± 0.35
Total Background	22.2 ± 6.7	10.6 ± 2.8	4.7 ± 1.0	2.4 ± 0.7
$t\bar{t}$ (σ = 6.7 pb)	0.1 ± 0.0	1.4 ± 0.2	8.7 ± 1.2	8.2 ± 1.1
Total SM expectation	22.3 ± 6.7	12.0 ± 2.8	13.3 ± 1.7	10.6 ± 1.4
Run II data	19	11	14	13

The application of a cut on the sum of transverse energy of all identified objects ($H_T > 200\ GeV$) optimizes the expected sensitivity.

The kinematics of top candidates matches very well the expectations. Left: missing E_T; right: H_T (before the cut).



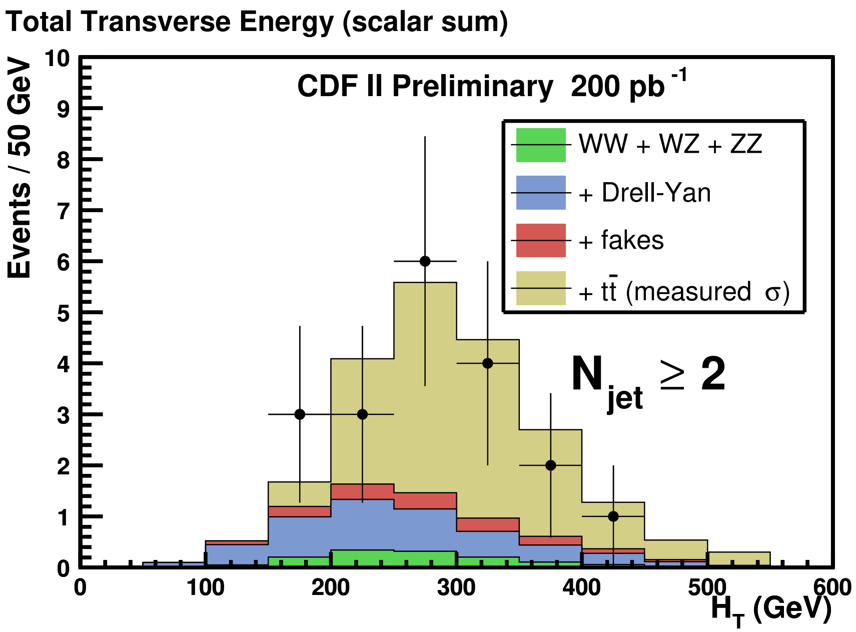
The cross section is measured at $\sigma_{t\bar{t}} = 8.7^{+3.9}_{-2.6}$ **(stat)** ± 1.5 **(syst) pb**.

An improved technique by CDF to identify dilepton decays of $t\bar{t}$ pairs relies on the search for events containing *one* high-P_T lepton and one *isolated track* of $P_T > 20$ GeV not pointing along the missing E_T.

The acceptance is increased, also due to contributing $\mu\tau$ and $e\tau$ topologies (22%); backgrounds are kept low by optimized cuts.

An *ad-hoc correction* to the $\not{E}_T$ is devised to deal with instrumental contributions, reducing the Drell-Yan backgrounds.

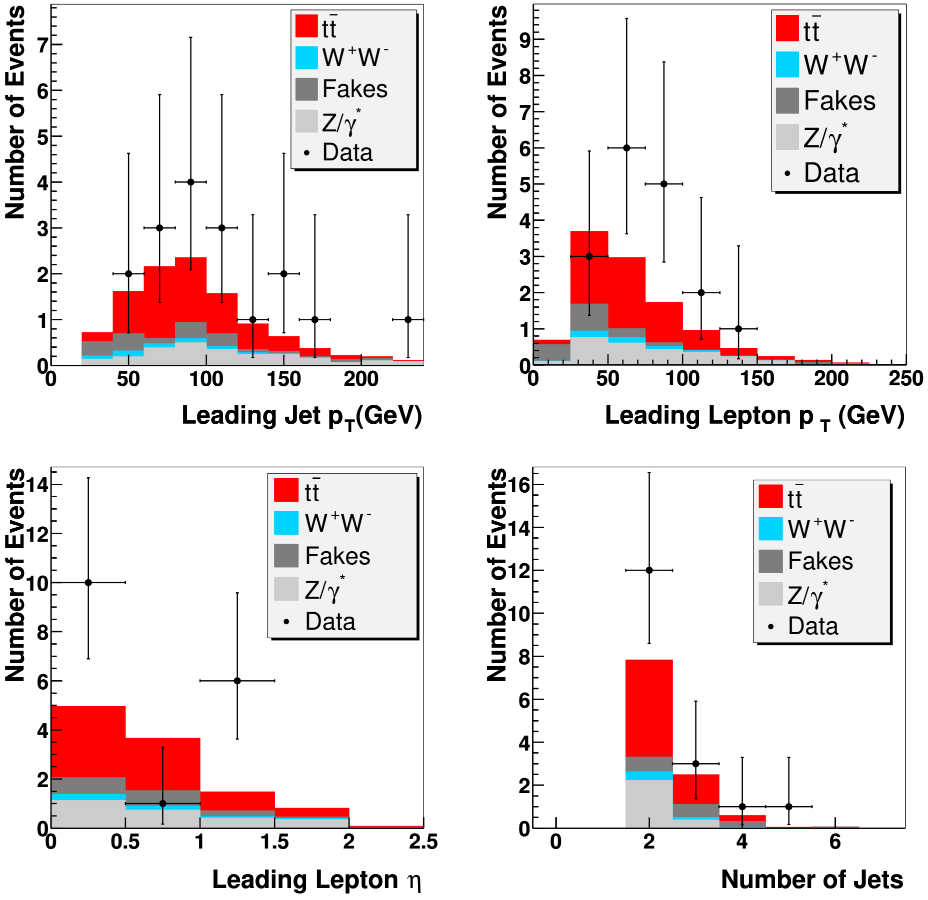
19 events with ≥ 2 jets are observed, with an expected background of 7.1 ± 1.0.



The result is $\sigma_{t\bar{t}} = 6.9^{+2.7}_{-2.4} \pm 1.2 \pm 0.4$ **pb**.

D0 also measured $\sigma_{t\bar{t}}$ using ee, $\mu\mu$, and $e\mu$ $t\bar{t}$ candidates with $\not{E}_T > 25$ GeV and two or more jets with $E_t > 20$ GeV from its Run II datasets.

Category	ee	$\mu\mu$	$e\mu$	$\ell\ell$
Z/γ^*	0.15 ± 0.10	2.04 ± 0.49	0.47 ± 0.17	2.66 ± 0.53
WW	0.14 ± 0.08	0.10 ± 0.04	0.29 ± 0.06	0.53 ± 0.11
Fakes	0.91 ± 0.30	0.46 ± 0.20	0.19 ± 0.06	1.56 ± 0.36
Total background	1.20 ± 0.33	2.61 ± 0.53	0.95 ± 0.19	4.76 ± 0.65
Expected signal	1.39 ± 0.19	0.83 ± 0.15	3.77 ± 0.44	5.99 ± 0.50
SM expectation	2.59 ± 0.38	3.44 ± 0.55	4.73 ± 0.49	10.76 ± 0.83
Selected events	5	4	8	17

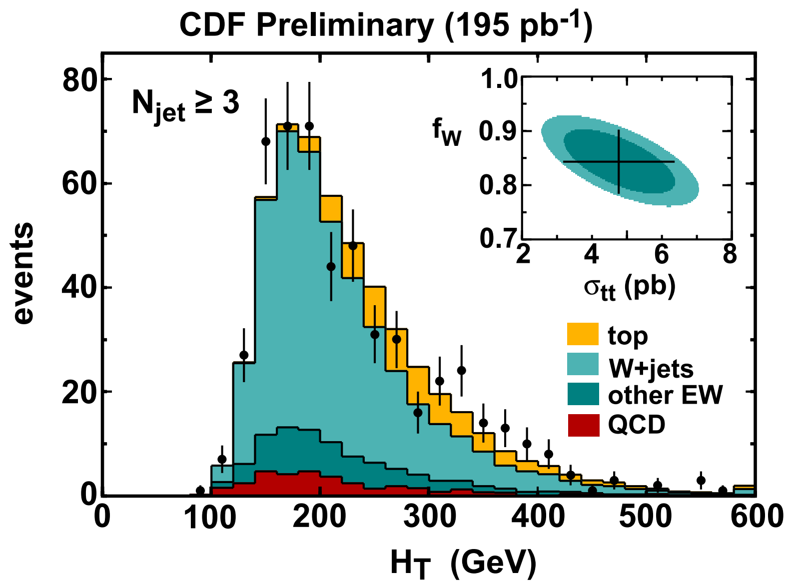


Backgrounds are lowered with cuts on H_t and a tighter $\not{E}_T$ selection and dilepton mass window cut in the ee and $\mu\mu$ channels.

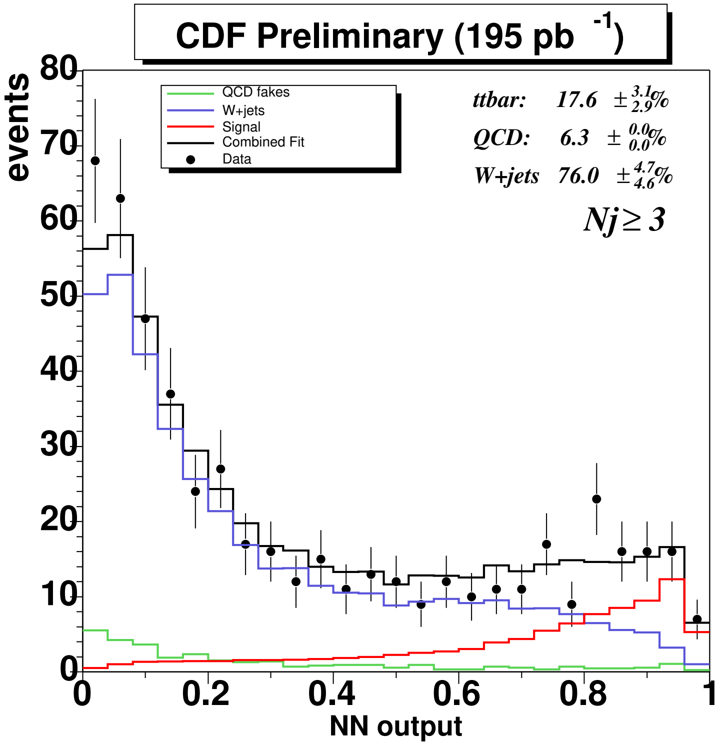
The combined dilepton channel result from D0 is $\sigma_{t\bar{t}} = 14.3^{+5.1}_{-4.3}(stat)^{+2.6}_{-1.9}(syst) \pm 0.9(lum)$ **pb**.

2 - the Single Lepton Channel

CDF has *5* new distinct results for $\sigma_{t\bar{t}}$ from $l+$ jets events. Two analyses use all $l+\geq 3$ jet events, two use SECVTX tagged events, one uses SLT (soft-lepton-tagged) events.

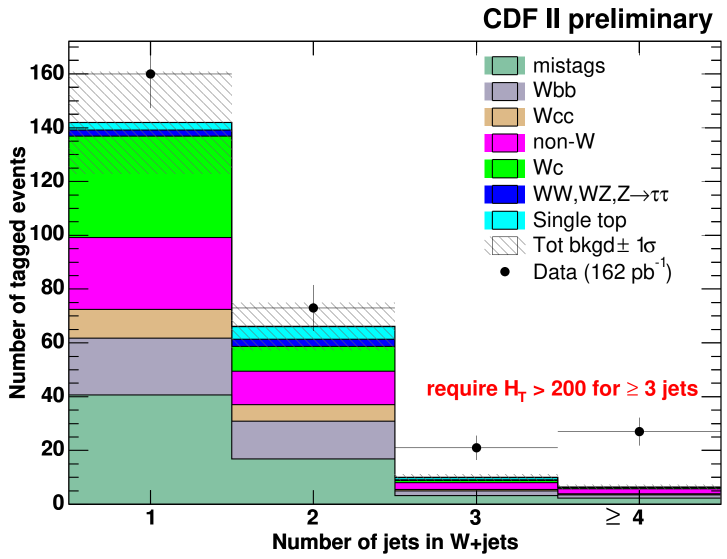


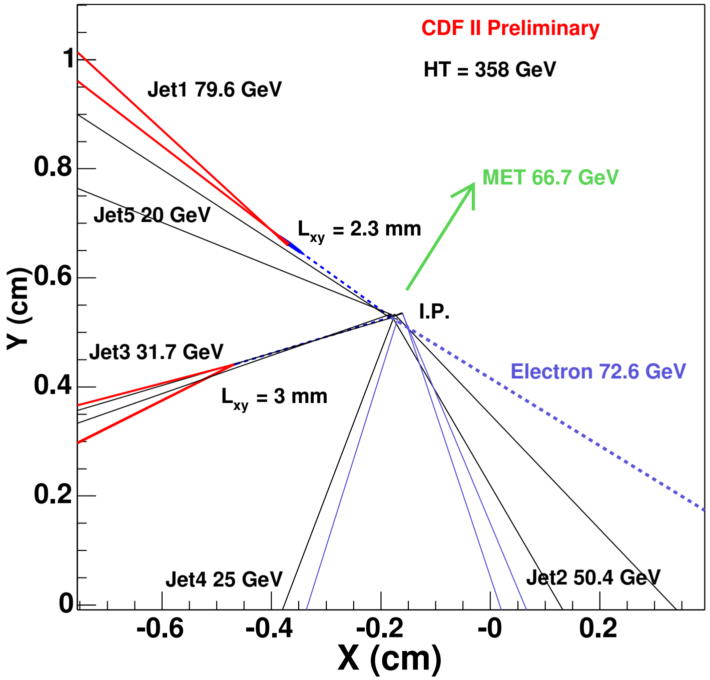
$\sigma_{t\bar{t}} = 4.7 \pm 1.6 \pm 1.8$ **pb**



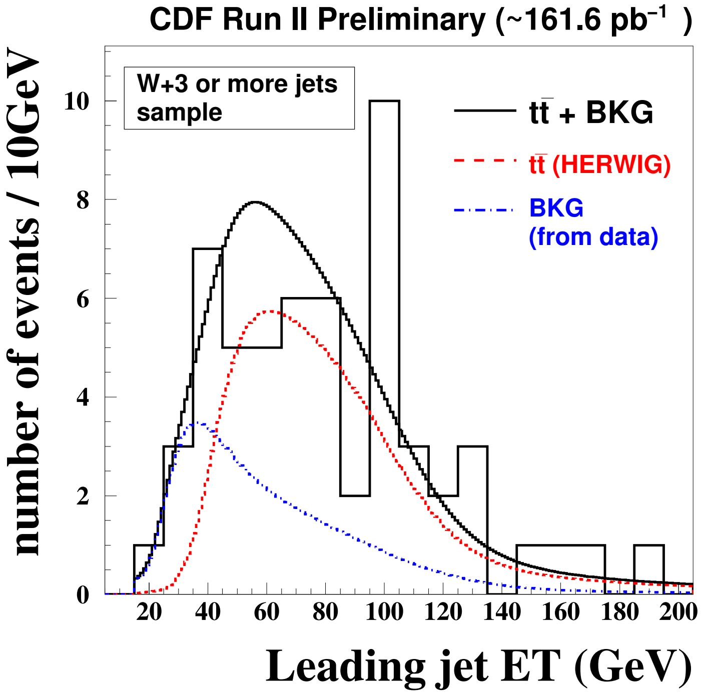
$\sigma_{t\bar{t}} = 6.7 \pm 1.1 \pm 1.5$ **pb**

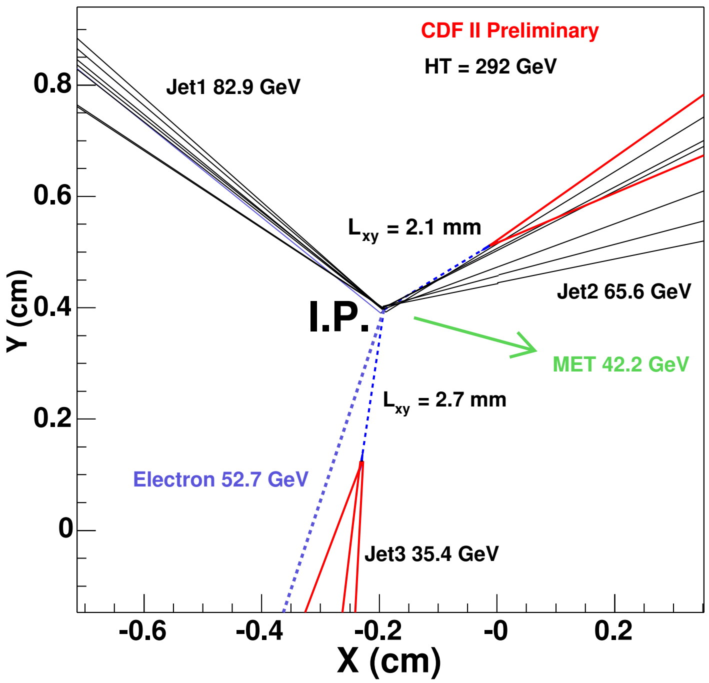
In the SECVTX tagged sample the S/N is larger. The most accurate measurement is still the old-fashioned counting experiment!





The excess in the three and four-jet bins (48 observed events, 13.8 ± 2.0 expected) amounts to $\sigma_{t\bar{t}} = 5.6^{+1.2+1.0}_{-1.0-0.7}$ **pb**.

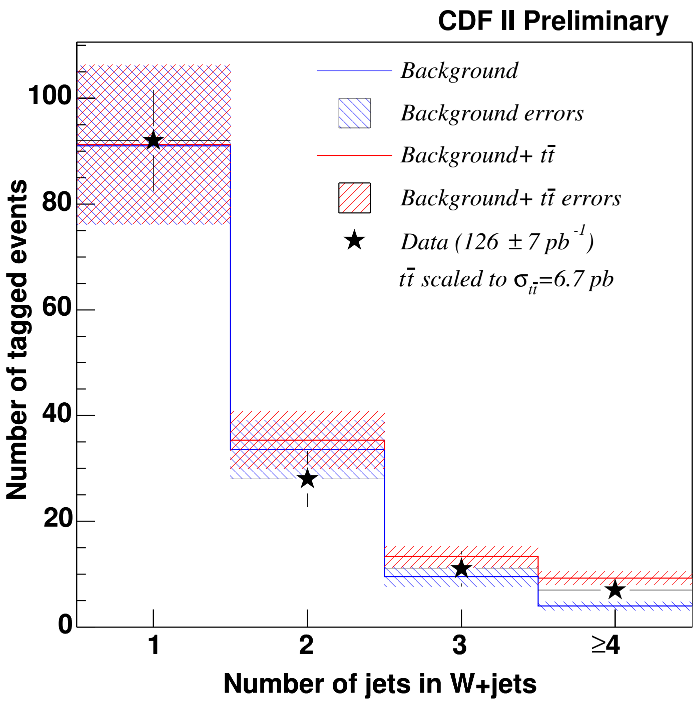




By fitting the most discriminating single variable in SECVTX tagged events to the sum of signal and concurrent backgrounds, CDF obtains yet another measurement of the production cross section:

$$\sigma_{t\bar{t}} = 6.0^{+1.5}_{-1.8} \pm 0.8 \ \mathbf{pb}.$$

The CDF SLT algorithm is only available for muons so far. Tagged jets are selected using a global χ^2 of soft muon candidate properties.



Background	W + 1 jet	W + 2 jets	W + 3 jets	W $\geq$ 4 jets
Events before tagging	11780	1867	295	84
Fake, $Wb\bar{b}$, $Wc\bar{c}$	68.7 ± 13.7	24.4 ± 4.9	6.0 ± 1.2	3.05 ± 0.6
Wc	5.3 ± 1.0	2.2 ± 0.4	0.4 ± 0.1	0.06 ± 0.02
WW, WZ, ZZ, Z$\to \tau^+\tau^-$	0.82 ± 0.1	0.88 ± 0.05	0.21 ± 0.01	0.035 ± 0.005
non-W	10.1 ± 4.8	4.4 ± 2.3	2.6 ± 1.5	0.8 ± 0.5
Drell-Yan	5.8 ± 3.2	1.1 ± 0.6	0.22 ± 0.14	0.03 ± 0.03
Single-Top	0.30 ± 0.02	0.56 ± 0.03	0.13 ± 0.01	0.026 ± 0.002
Total Background	91.1 ± 15.0	33.6 ± 5.5	9.5 ± 1.9	3.99 ± 0.8
Corrected Background			12.65±2.5	
$t\bar{t}$ expectation	0.23 ± 0.05	1.8 ± 0.2	3.8 ± 0.5	5.3± 1.0
Total Background plus $t\bar{t}$	91.4 ± 15.0	35.4 ± 5.5	21.72±2.93	
Tagged Events	92	28	11	7

From the small excess in the ≥ 3 jet bins the cross section is measured at $\sigma_{t\bar{t}} = 4.1^{+4.0}_{-2.8} \pm 1.9$ pb.

D0 has produced three new measurements of $\sigma_{t\bar{t}}$ from l+jet events. The two topological analyses are based on $l+4$ jet events ($E_t^{jet} > 15\ GeV$, $\not{E}_T > 20\ GeV$) and explicitly reject soft muon tagged events.

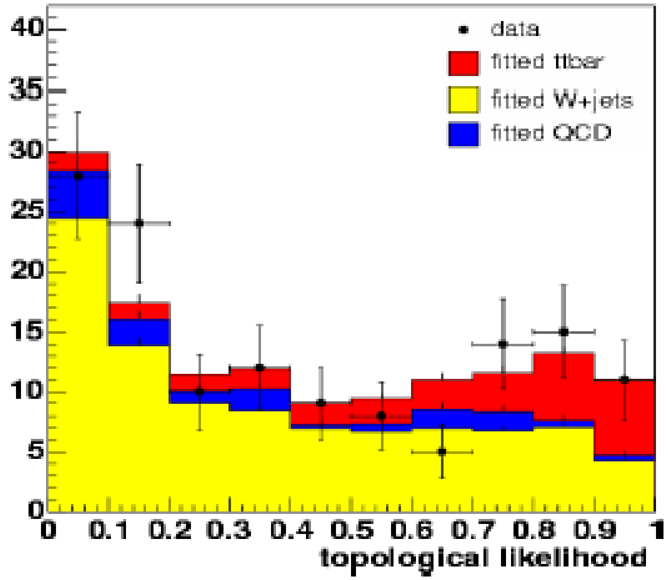
The electron and muon channel results from fits to a global topological likelihood are

$\sigma_{t\bar{t}} = 8.8^{+4.1+1.6}_{-3.7-2.1} \pm 0.6$ pb (e),

$\sigma_{t\bar{t}} = 6.0^{+3.4+1.6}_{-3.0-1.6} \pm 0.4$ pb (μ).

When combined they yield

$\sigma_{t\bar{t}} = 7.2^{+2.6+1.6}_{-2.4-1.7}$ pb.



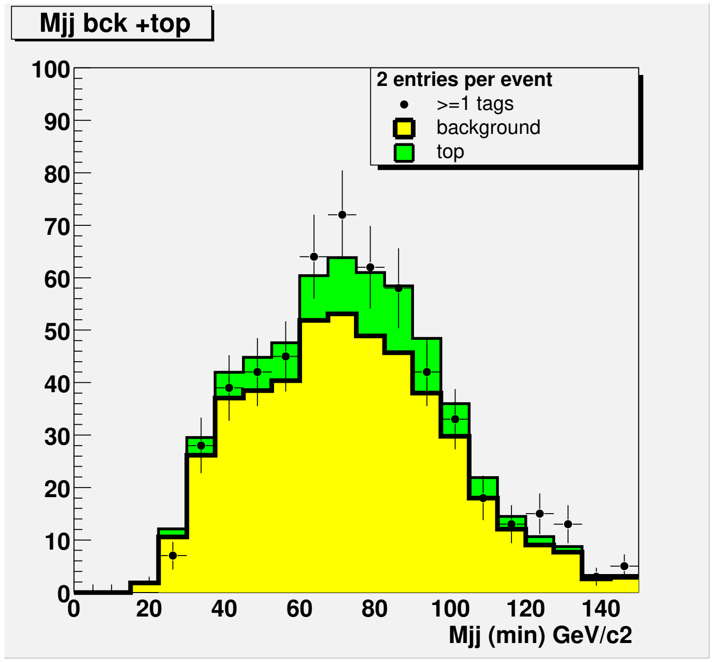
A third analysis identifies b-jets with a soft muon tagger. Soft muon candidates have $P_t > 4\ GeV$ and $\Delta R_{\mu j} < 0.5$. After a cut on $\Sigma_{jet} E_t > 110\ GeV$ and $\mathcal{A} > 0.04$, 17(9) e+jets (μ+ jets) events are selected.

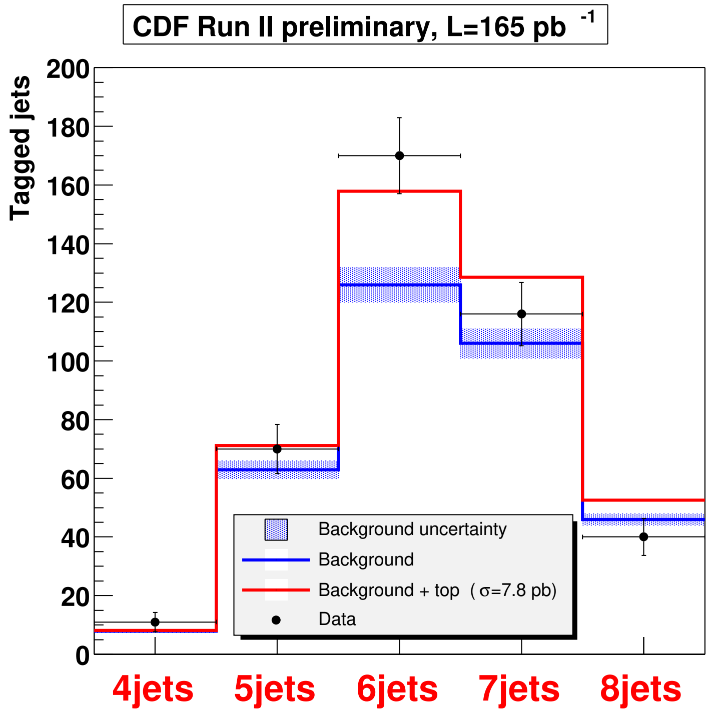
These correspond to $\sigma_{t\bar{t}} = 11.4^{+4.1+2.0}_{-3.5-1.8}$ pb.

3 - The All-jets Channel

Both CDF and D0 have measured $\sigma_{t\bar{t}}$ from multijet samples, relying on tight kinematical criteria and B tagging to increase the S/N ratio.

After a tight kinematic selection, CDF finds 284 events with $N_{jet} \geq 6$ and ≥ 1 b-tag, for a total of 326 tagged jets observed and 264.7 ± 17.2 predicted.

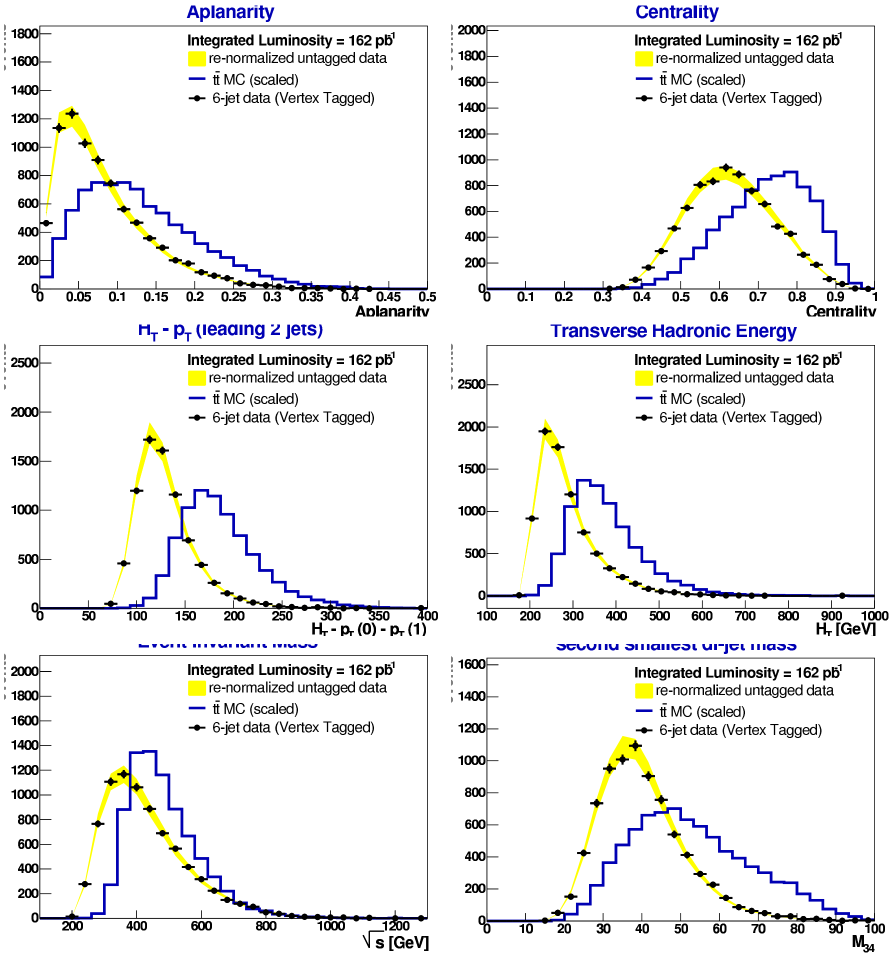


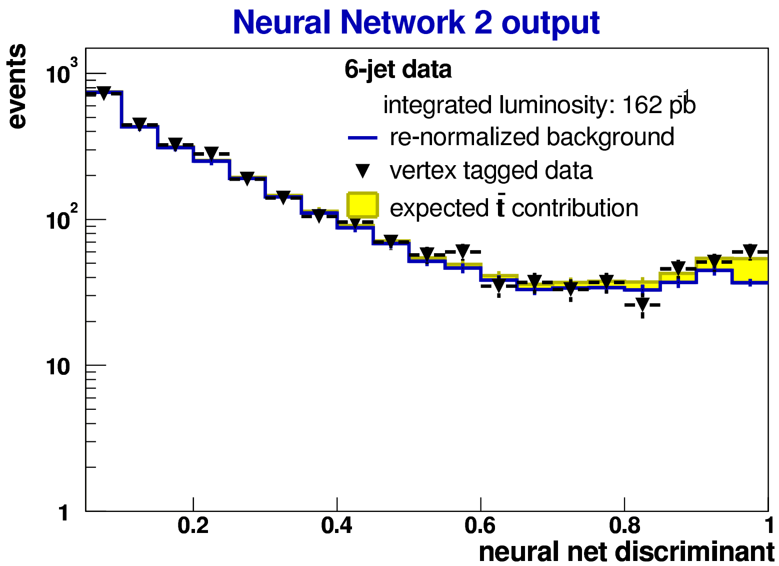


The excess corresponds to

$\sigma_{t\bar{t}} = 7.8 \pm 2.5^{+4.7}_{-2.3}$ pb.

D0 uses the soft muon tagger to enrich the sample of $b-$jets, and a Neural Network to separate QCD from $t\bar{t}$ based on kinematical information.





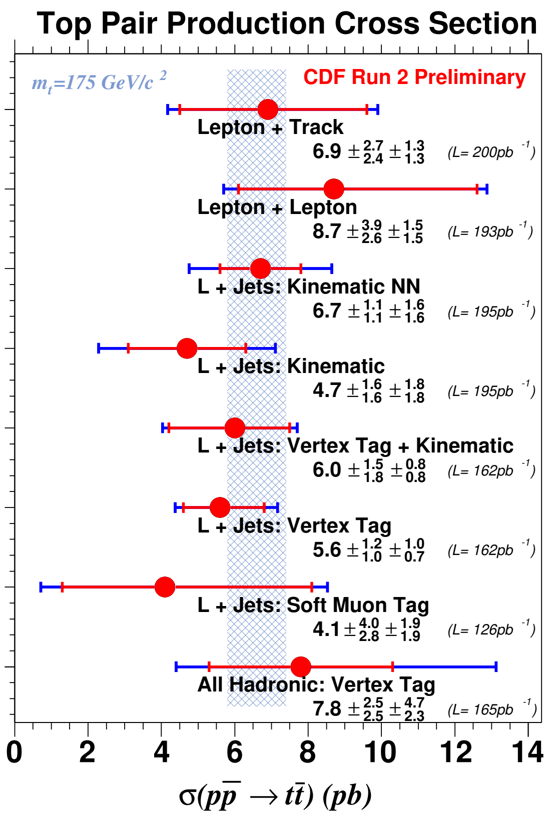
220 candidates are observed in the signal region, with $186 \pm 5 \pm 12$ expected from QCD sources.

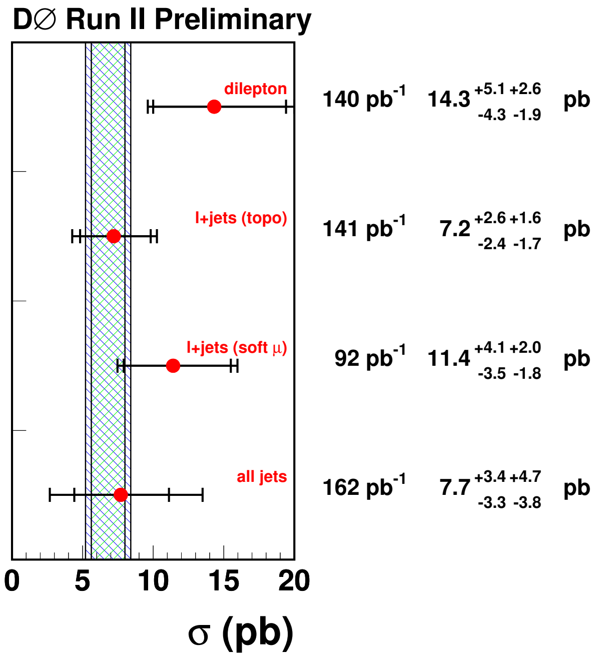
The measured cross section is

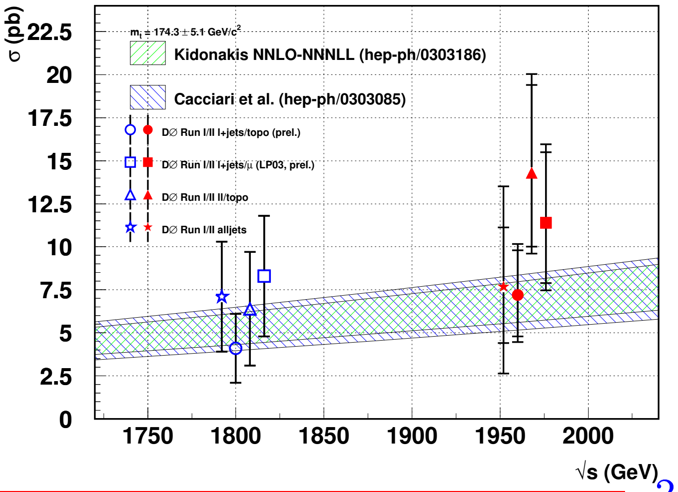
$\sigma_{t\bar{t}} = 7.7 \pm 3.5^{+3.7}_{-1.9} \pm 0.5$ pb.

Top Cross Section Summaries

A host of new results have been produced by CDF and D0 on the $t\bar{t}$ cross section. They all agree within uncertainties (many are correlated!), and match well NNLO calculations.







Top Mass Measurements: 1 - New D0 Run I Result

Recently (2002) D0 publicized an improved measurement of M_{top} from a re-analysis of a very clean sample of 22 $l + 4$ jet events collected in Run I, and based on the use of a dynamical likelihood method.

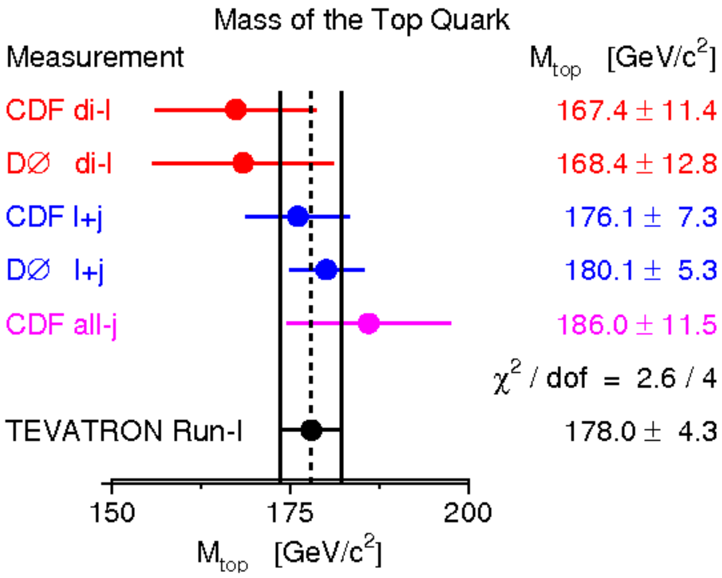
In this new approach, a $P(M_{top})$ is defined per each event, by comparing all the kinematic information with a LO matrix element through a convolution with transfer functions that relate objects at parton level with reconstructed quantities. The likelihood function also accounts for the probability that the event is background.
Pseudoexperiments foresee a reduction in the statistical error by a factor of two.

D0 thus finds $M_{top} = 179.9 \pm 3.6 \pm 6.0$ GeV, indeed a much improved result from the previous one ($M_{top} = 173.3 \pm 5.6 \pm 5.5$ GeV).

New World Average from Tevatron Run I

By considering the final Run I measurements in each decay channel by CDF and D0, and inserting the systematic errors in a correlation matrix, a new Run I world average has recently been computed as

$$M_{top} = 178.0 \pm 4.3 \text{ GeV}.$$



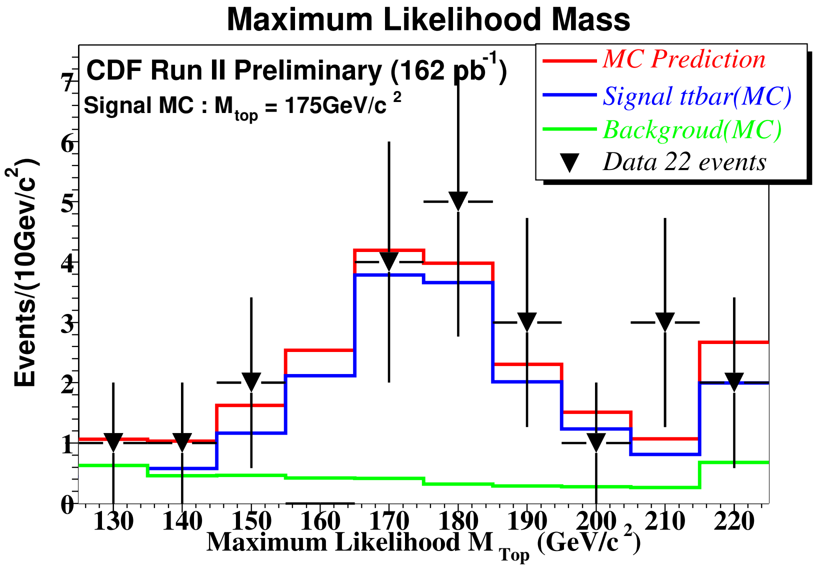
The statistical error is 2.7 GeV; the systematic error is 3.3 GeV, receiving the largest contribution from jet energy scale uncertainty (2.6 GeV).

The top quark mass is now known with a 2.4% precision.

M_{top}: Run II Results from CDF

In the summer 2003 CDF produced the first Run II measurements of the top mass from dilepton $t\bar{t}$ candidates ($M_{top} = 175^{+17.4}_{-16.9} \pm 8.4$ GeV) and $l+$ jets candidates ($M_{top} = 177.5^{+12.7}_{-9.4} \pm 7.1$ GeV), based on luminosities of 126 and 108 pb^{-1}, respectively.

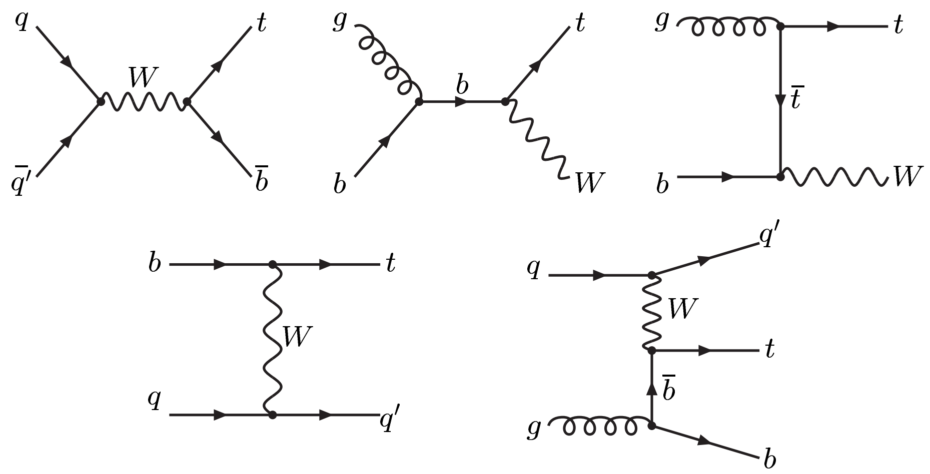
A new result based on 162 pb^{-1} of l+jet events, using the excellent DLM method pioneered by D0 is now public.
The improved result is still affected by a wanting uncertainty from the jet energy scale, but is getting close to the precision of the best Run I results:



$$M_{top} = 177.8^{+4.5}_{-5.0} \pm 6.2 \text{ GeV}.$$

SM Production of Single Top

Top quarks can also be produced at a $p\bar{p}$ collider by weak interaction: $\sigma_{tX} = 0.88(s) + 1.98(t) = 2.8\ pb$. The dominant processes are $t-$channel production by $W-g$ fusion and $W^* \rightarrow t\bar{b}$.



Single top production is interesting in its own right:

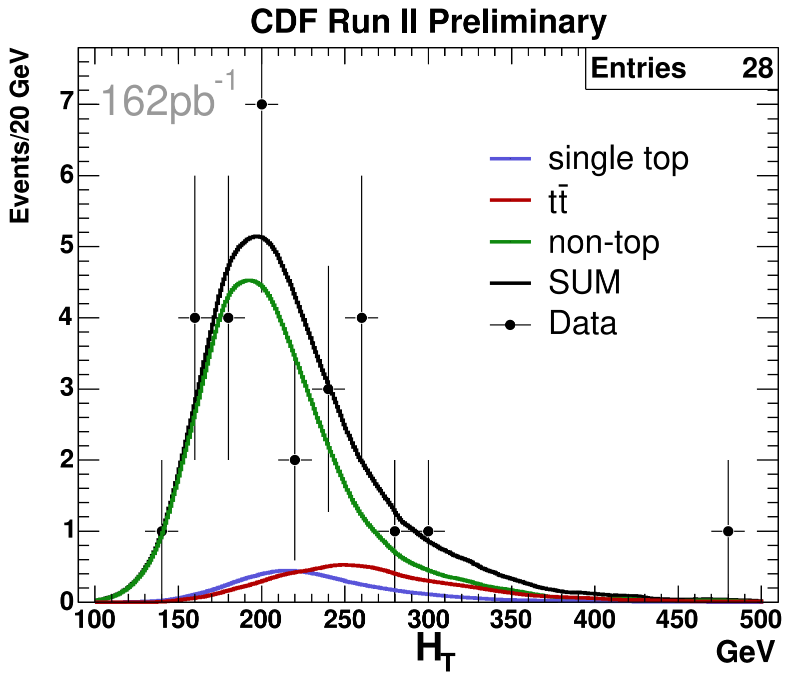
- ⋆ a precise measurement of the cross section would provide a direct determination of $|V_{tb}|$.
- ⋆ single top ($p\bar{p} \rightarrow t\bar{b}X \rightarrow l^+\nu b\bar{b}X$) is a significant background to SM Higgs searches ($p\bar{p} \rightarrow W^+HX \rightarrow l^+\nu b\bar{b}X$)
- ⋆ it is a challenging measurement! Fewer jets, less distinctive topology than $t\bar{t}$.

Single Top Searches

CDF recently improved its limit on both $s-$ and $t-$channel single top production using Run II data.

From W events with two jets ($E_t > 15$ GeV, $|\eta| < 2.8$), one of which SECVTX $b-$tagged, 28 events with $140 < M_{l\nu j_1} < 210\ GeV$ are selected.

The variable $H_t = \Sigma_j E_t + P_t^l + \not{E}_T$ is very similar in both signal processes and discriminates them from the main backgrounds.

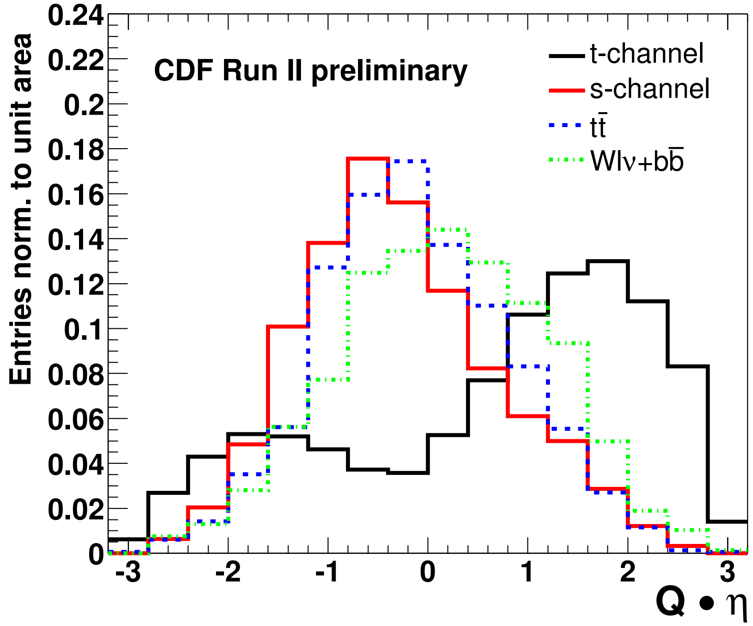


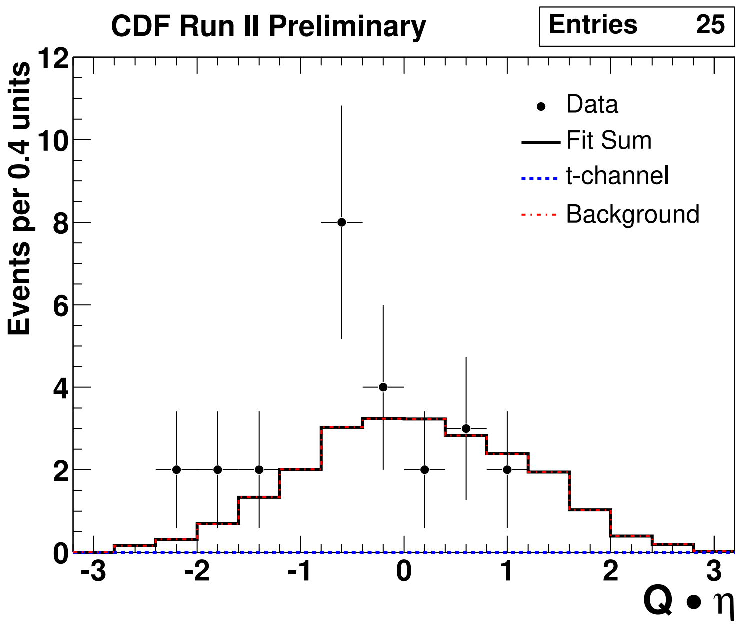
A likelihood fit to H_t allows to extract the limit on $s-$ and $t-$channel together as $\sigma_{tX} < 13.7$ pb (95% C.L.).

For a limit on $t-$ channel production alone, a further cut is applied on the leading jet: $E_t^1 > 30$ GeV, reducing the sample to 25 candidates.

In $t-$channel single top production, the charge of the W decay lepton has a peculiar effect on the rapidity distribution of the non $b-$tagged jet. This can be exploited with a fit to the $Q_l \times \eta_j$ distribution.

The fit prefers no signal, and the resulting limit at 95% C.L. is $\sigma_{tbj} < 8.5$ pb.

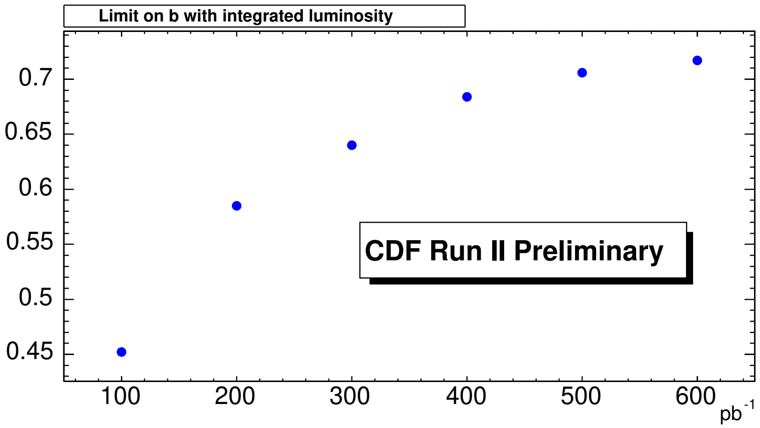




Branching Fraction Ratios

Using the measured values of $\sigma_{t\bar{t}}$ it is possible to extract limits on the branching fraction of unconventional top decays.

By measuring independently the number of $l+$ jets $t\bar{t}$ candidates with one and two SECVTX $b-$tags, a measurement of $R = B(Wb)/B(Wq)$, which is expected to be very close to 1 in the SM, can be derived. CDF finds $R = 0.54^{+0.49}_{-0.39}$ on a sample of 108 pb^{-1} of data.



Another way to look for anomalies in top decay is to take the ratio $R_\sigma = \sigma_{ll}/\sigma_{lj}$ between the cross section in the dilepton and single lepton channel.

From 125 pb^{-1} of Run II data CDF finds $R_\sigma = 1.45^{+0.83}_{-0.55}$, or $R_\sigma > 0.46$ (95% CL).

Concluding Remarks

⋆ The top quark is a very interesting particle:

- only quark whose mass can be measured directly;
- only quark that can be studied free of QCD effects;
- the large effect on radiative corrections makes it worth measuring M_t with the utmost precision;

⋆ CDF and D0 have started to extract new competitive measurements on top properties from their new datasets.

⋆ Many refinements are off the drawing board - the plan to measure M_{top} to within 1% is still on!