The Top Quark

a look back (and forward)
10 years after top first appeared in Fermilab data

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– the search

– the discovery (as I remember it!)

– what we know now

– Run II, LHC, LC

Increased accessible top mass ⇒ new analysis techniques

Note: I will not mention who did what.

- This was truly a collaborative effort.
- Success due to an extremely talented group of junior faculty, postdocs, and graduate students.
- I will forget some people.
- I don't know who was doing what in D0.

1974

With the discovery of the J/ψ :

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

GIM ✓ **(FCNC)**

1975-77

- **Acceptance of τ lepton in Mark I data (decay kinematics $\Rightarrow \nu_\tau$)**
- **Discovery at Fermilab of the $Y \Rightarrow b$ quark**

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

  - *b: non-SM? isosinglet? SM isodoublet?*

1984 DESY measurement of $e^+e^- \to b\bar{b}$ FB asymmetry: (22.5±6.5)%

c.f. 25.2% for SM isodoublet; 0% for isosinglet

- **If the SM were correct, there must be an isodoublet partner, the top quark.**
- **Mass = ?** **[*b/c/s* = 4.5/1.5/0.5 $\Rightarrow$ M_t = 15 GeV?]**

Searches in e^+e^- Collisions

PETRA could reach ~20 GeV (late '70s)

- search for narrow toponium resonance
- look for an increase in R = (# of hadron events)/(# of $\mu^+\mu^-$ events)
- global event characteristics: look for spherical component
- negative results $\Rightarrow$ $M_{top} > 23$ GeV

TRISTAN built to study top quark (early '80s)

- similar search techniques
- $M_{top} > 30$ GeV

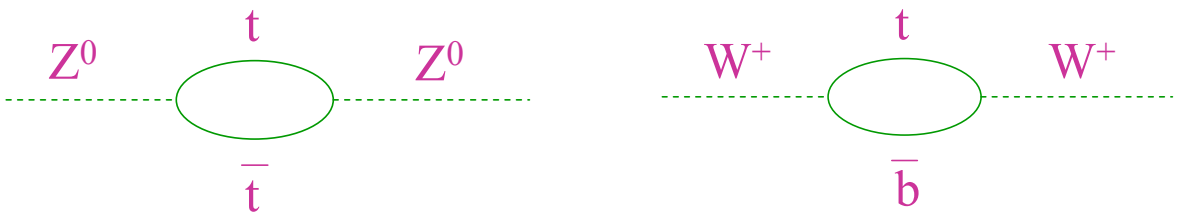
SLC/LEP

- look for $Z \rightarrow t\bar{t}$
- $M_{top} > 45$ GeV

That was the kinematic limit for direct search in e^+e^- collisions.

Predictions from Z^0 Decay

In the Standard Model, various EWK measurables depend on the mass of the top quark.



EWK radiative corrections $\propto M_t^2$

Precision measurements of Z^0 decay $\Rightarrow$ predictions of M_{top} (SM consistency)

Throughout the period 1990 – top discovery:

direct search lower limit > prediction lower limit

prediction upper limit < 200 – 225 GeV

Early Searches in Hadron Collisions

CERN $S\bar{p}pS$ ($\sqrt{s}$ = 540 GeV) built to observe *W, Z*

- single ring $\Rightarrow \bar{p}$ production & cooling

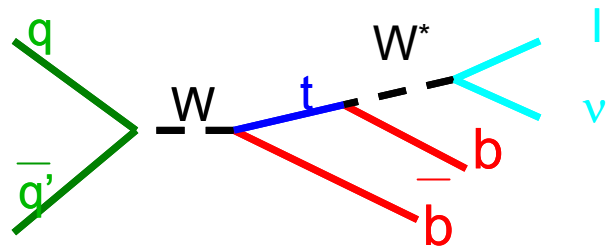
+: access to much higher mass

–: backgrounds are severe and/or event rates are very low

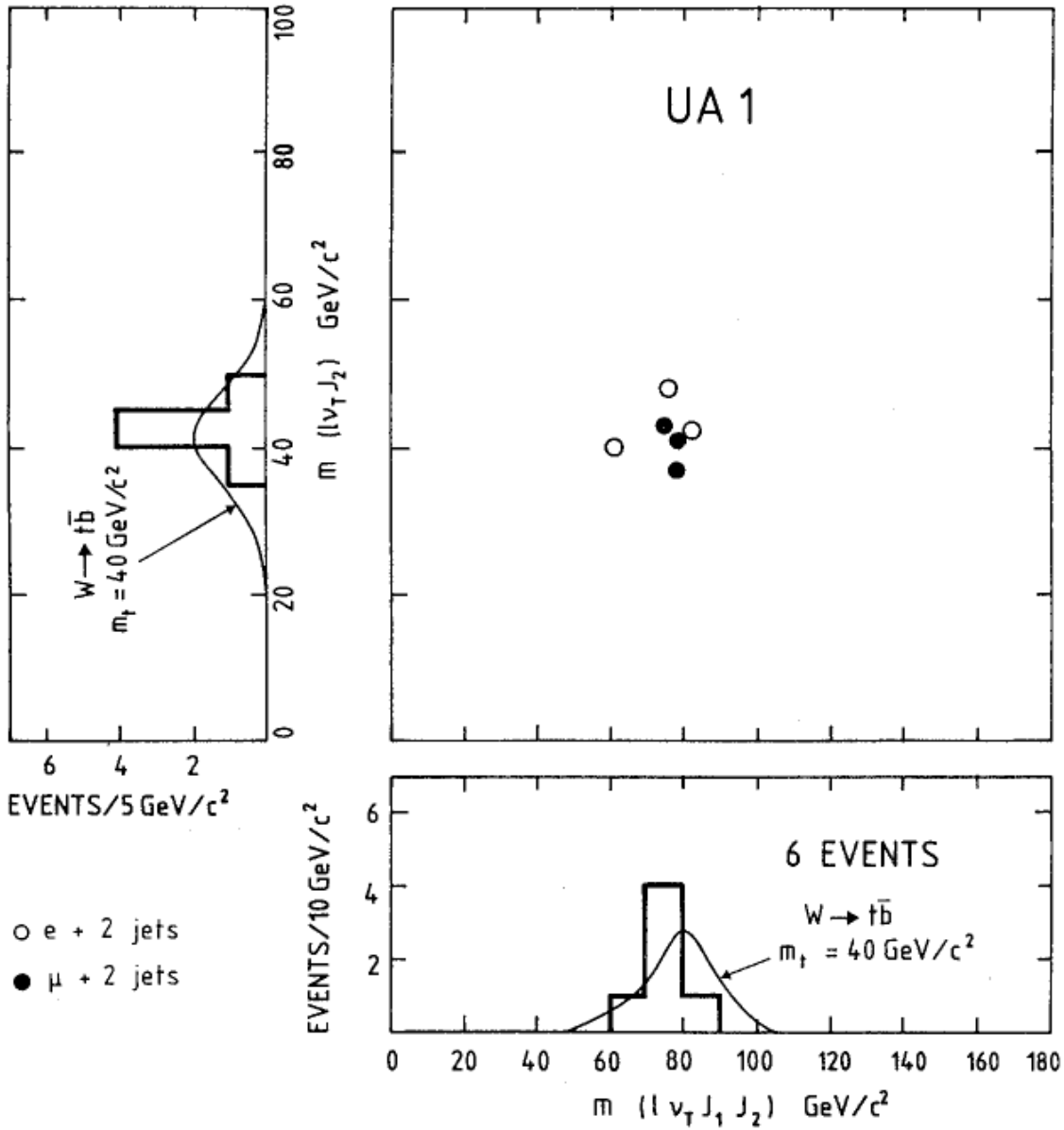
–: reconstruction difficult: jets

1984: UA1

$W \rightarrow t\bar{b} \rightarrow l\nu b\bar{b}$

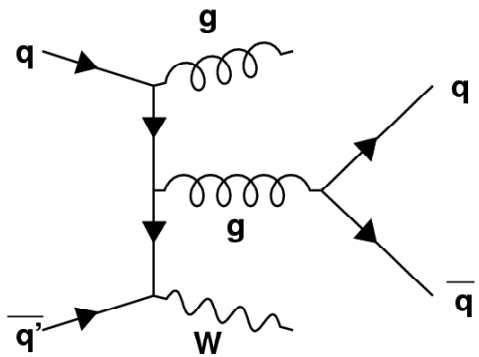


- isolated high P_T lepton
- 2 or 3 hadron jets
- Observe 5 events (e + >=2 jets); 4 events (μ + >=2 jets)
- Expected background: 0.2 events
  - fake leptons dominate
  - $b\bar{b}$ & $c\bar{c}$ production negligible
- Conclude: results consistent with M_{top} = 40 ±10 GeV.
  Stop just short of claiming discovery.


UA 1
m (lν_T J_2) GeV/c²
W → tb̄
m_t = 40 GeV/c²
EVENTS/5 GeV/c²
○ e + 2 jets
● μ + 2 jets
EVENTS/10 GeV/c²
6 EVENTS
W → tb̄
m_t = 40 GeV/c²
m (l ν_T J_1 J_2) GeV/c²

1988 UA1

- x6 data sample (600 nb^{-1})
- much better understanding of backgrounds
  - fake leptons
  - W + jets
  - DY, J/ψ, Y
  - $b\bar{b}$, $c\bar{c}$



channel	observed	expected background
μ + ≥ 2 jets	10 events	11.5 ± 1.5 events
e + ≥ 1 jets	26 events	23.4 ± 2.8 events

(+ 23 expected if M_{top} = 40 GeV)

Conclude: $M_{top} > 44$ GeV

1988-89 Fermilab in the Hunt

At CERN, UA2 remains after detector upgrades.

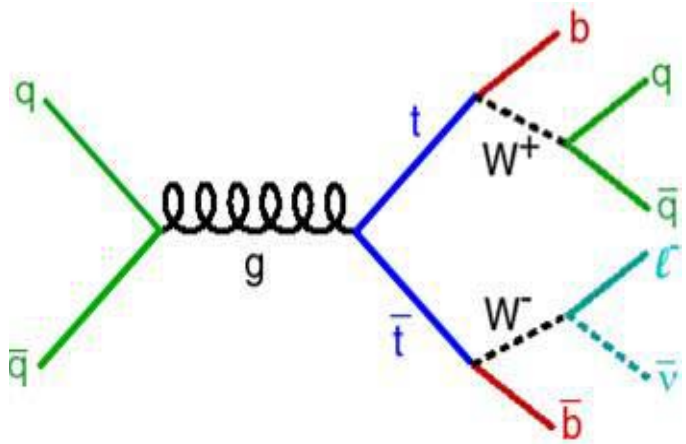
Fermilab: $\sqrt{s} = 1.8$ **TeV vs. 0.63 @ CERN**

$\Rightarrow$ **much larger mass reach (75 GeV @ UA2)**

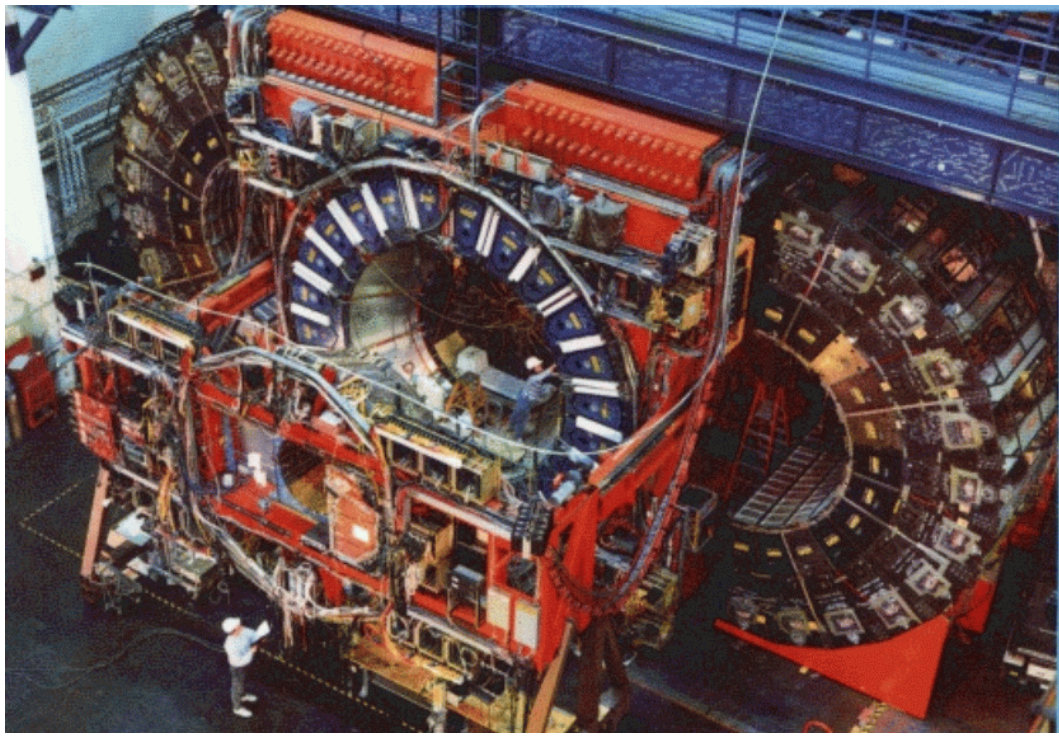
Competition! BBC, Nova: "The Race for the Top"

Pair production dominates at Fermilab: $t\bar{t} \rightarrow WbW\bar{b}$

%	$e\nu$	$\mu\nu$	$\tau\nu$	$q\bar{q}$
$e\nu$	1.2	2.5	2.5	14.8
$\mu\nu$		1.2	2.5	14.8
$\tau\nu$			1.2	14.8
$q\bar{q}$				44.4

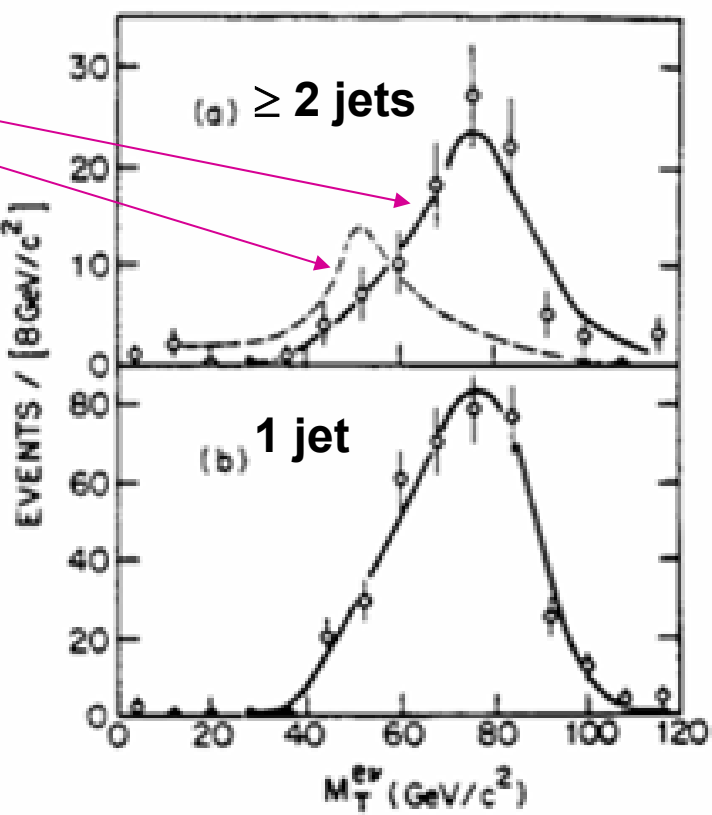


12 countries, 62 institutions
767 physicists



CDF

- $e\nu + \geq 2$ jets
  - dominant background: W + jet production
  - discriminant: $e\nu$ transverse mass
    - background: W on shell
    - signal (40-80 GeV top): W off shell



  - $M_{top} > 77$ GeV

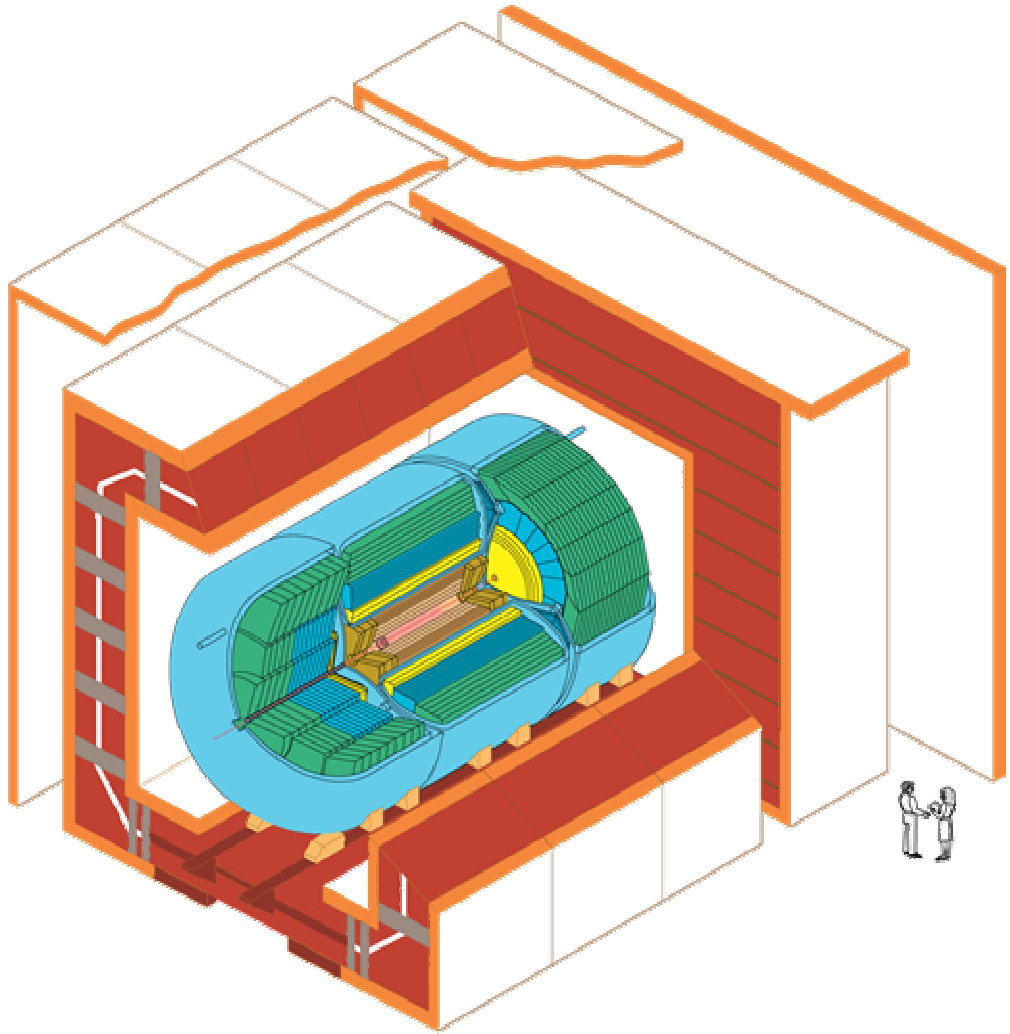
[UA2 used a similar technique: > 69 GeV]

- $e\mu$
  - **expected event rate much smaller since 2 x BR($W \to e\nu$)**
  - **Background is very small**
    - **no W + jets**
    - **no Drell-Yan**
    - **dominant background is $Z \to \tau\tau \to e\mu$X (expect 1 event)**
  - **observe 1 event**
  - **M_{top} > 72 GeV (expect 7 events from 70 GeV top quark)**

Strategy Change when $M_{top} > M_W + M_b$

- top decays to on-shell W $\Rightarrow$ no $M_T(l\nu)$ discriminant
- major difference:
  - background (~5 x N_{signal}): W + jets (largely light quarks & gluons)
  - signal (~10/yr for 175 GeV): W + jets (2 jets are *b*-jets)
- Last CDF top publication on '88-89 data
  - dilepton: include *ee*, $\mu\mu$ (missing E_T requirement, *Z* mass cut)
  - single lepton: require low P_T μ (semi-leptonic *b* decay)
- $M_{top} > 91$ GeV

19 countries
83 institutions, 664 physicists



DØ Detector

D0 Joins the Hunt

Run I: 1992-95

- **Tevatron:** higher luminosity
- **D0:** excellent calorimetry, large solid angle μ coverage
- **CDF:** silicon vertex detector added to magnetic spectrometer

Run Ia:

D0 – optimized analysis strategy for 100 GeV mass

• $e\mu + \not\!\!E_T + \geq 1\,jet$:		1 event	(background - 1.1 events)
• $ee + \not\!\!E_T + \geq 1\,jet$:		1	(0.5)
• $e + \not\!\!E_T + \geq 4\,jets$	with aplanarity cut:	1	(2.7)
• $\mu + \not\!\!E_T + \geq 4\,jets$	with aplanarity cut:	0	(1.6)

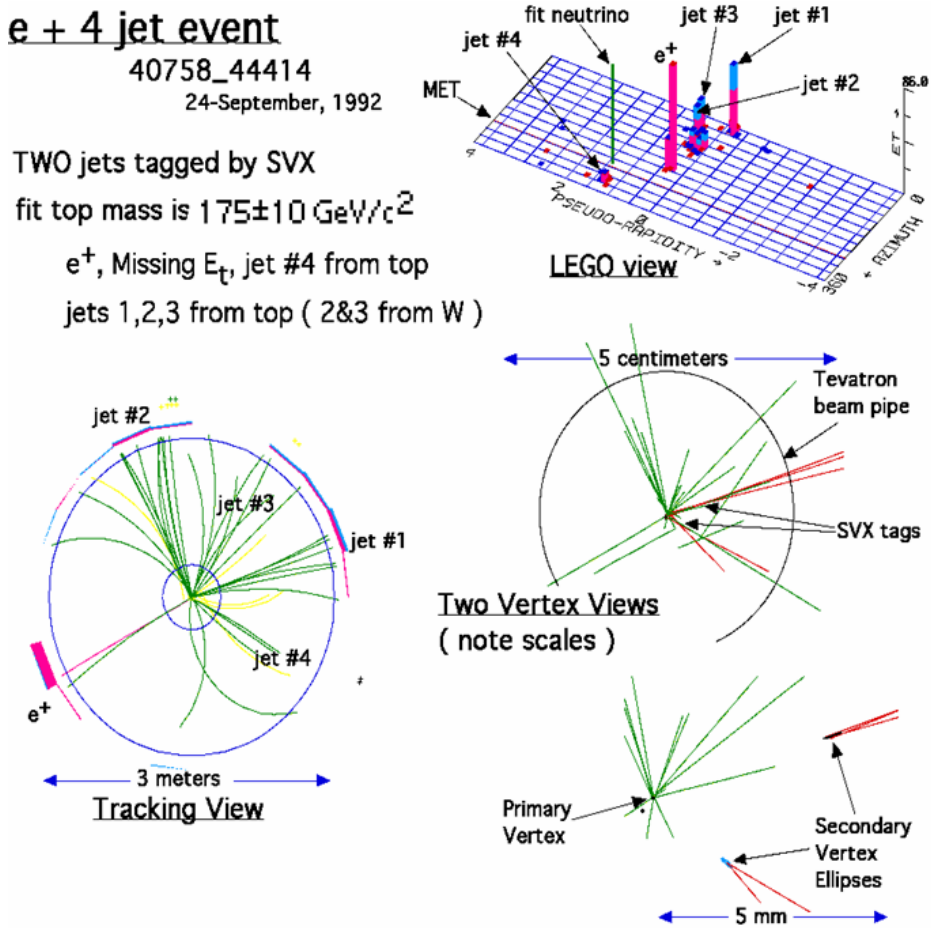
$M_{top} > 131$ GeV @ 95% CL

CDF – very different activity

New: SVX (40 μm impact parameter resolution)

⇒ **identify *b*-jets by secondary vertex**

powerful discriminant against background



Strategy:

- **dilepton: + 2 jets (Q value OK)**
- **single lepton: *b* tagging**
  - **soft *e* or *μ* (semi-leptonic *b* decay)**
  - **secondary vertex**

August, 1993 Collaboration Meeting

- **Each group (dilepton, sec. vertex, soft lept.): status report**

  Small, not statistically significant excess.

	estimated background	observed
dilepton	0.6 events	2 events
1 lepton, vertex *b*-tag	2.3	6
1 lepton, lepton *b*-tag	3.1	7

3 events in common

- **In total, however, the numbers were becoming significant.**

  background fluctuation probability: 1/400 (2.8σ)

Aside: big collaborations – monolith or competitive?

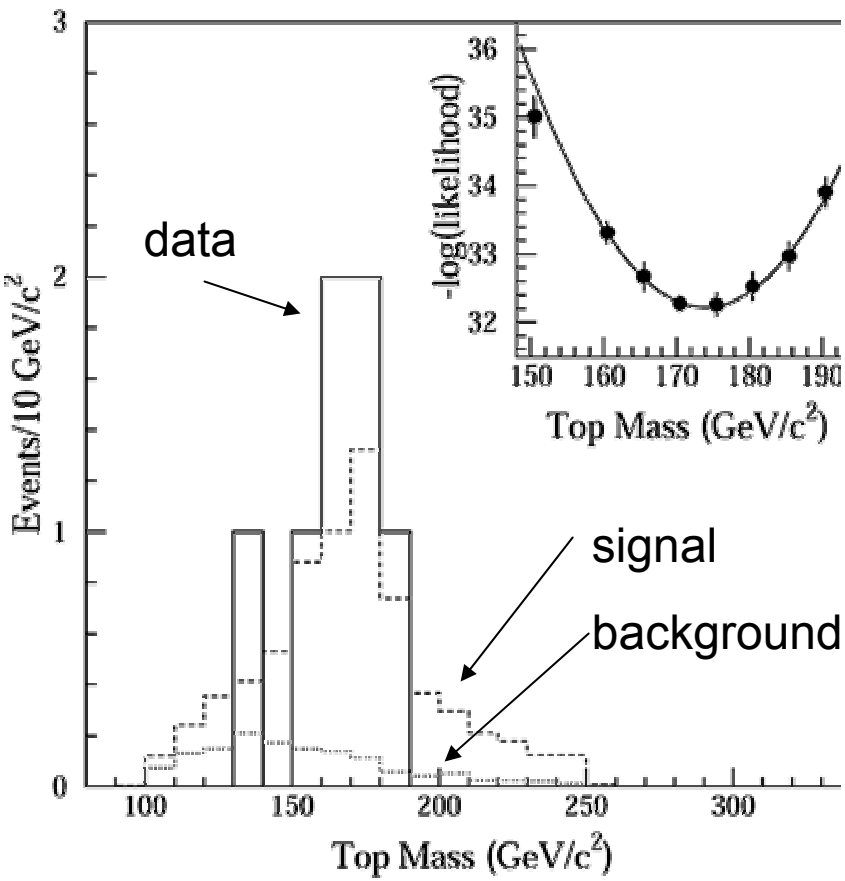
- **Many were skeptical, demanding additional studies, cross checks**
- **an additional 8 months before result submitted and made public**

– :

- best single lepton + *b*-tag control sample: $Z + \geq 3$ jets
  - expect 0.6 events, see 2 events
  - worrisome even if not statistically significant (higher stat. tests OK)
- # of $l\nu$ + 4-jet events (pre-tag) smaller than expected from signal plus background (1.5-2 σ)

+ :

- various kinematic distributions supported $t\bar{t}$
- mass distribution favored signal + background (2.3 σ)



Final question: What does CDF conclude?

Title of PRL & 60-page PRD:

"Search for the Top Quark"

"Evidence for the Top Quark"

"Observation of the Top Quark"

How to decide?

- **counting experiment: 2.8 σ**
- **few checks with some discrepancy – none major**
- **other checks consistent with a signal**
- **mass distribution – looks (too) good**

Counting was the *a priori* technique ⇒ "Evidence"

$$\sigma_{t\bar{t}} = 13.9^{+6.1}_{-4.8}\ \text{pb}$$

$$M_t = 174 \pm 10^{+13}_{-12}\ \text{GeV}$$

D0: more data & re-optimized for heavy top (single & di-lepton)

- **Observed 7 events; expected 4-6 from background**
- **⇒ no independent evidence**

Note:

There were a number of other analyses in CDF at the time:

- **difference in expected jet E_T spectra for signal & background**
- **separate two components – SM background & SM $t\bar{t}$**

CDF chose not to use these in the first publications.

- **invariant mass peak vs. tail in a P_T distribution**
- **something new: premature to assume it to be a top quark with SM couplings**

Now that the top quark is established with its SM properties ~verified, these techniques are used by both D0 and CDF.

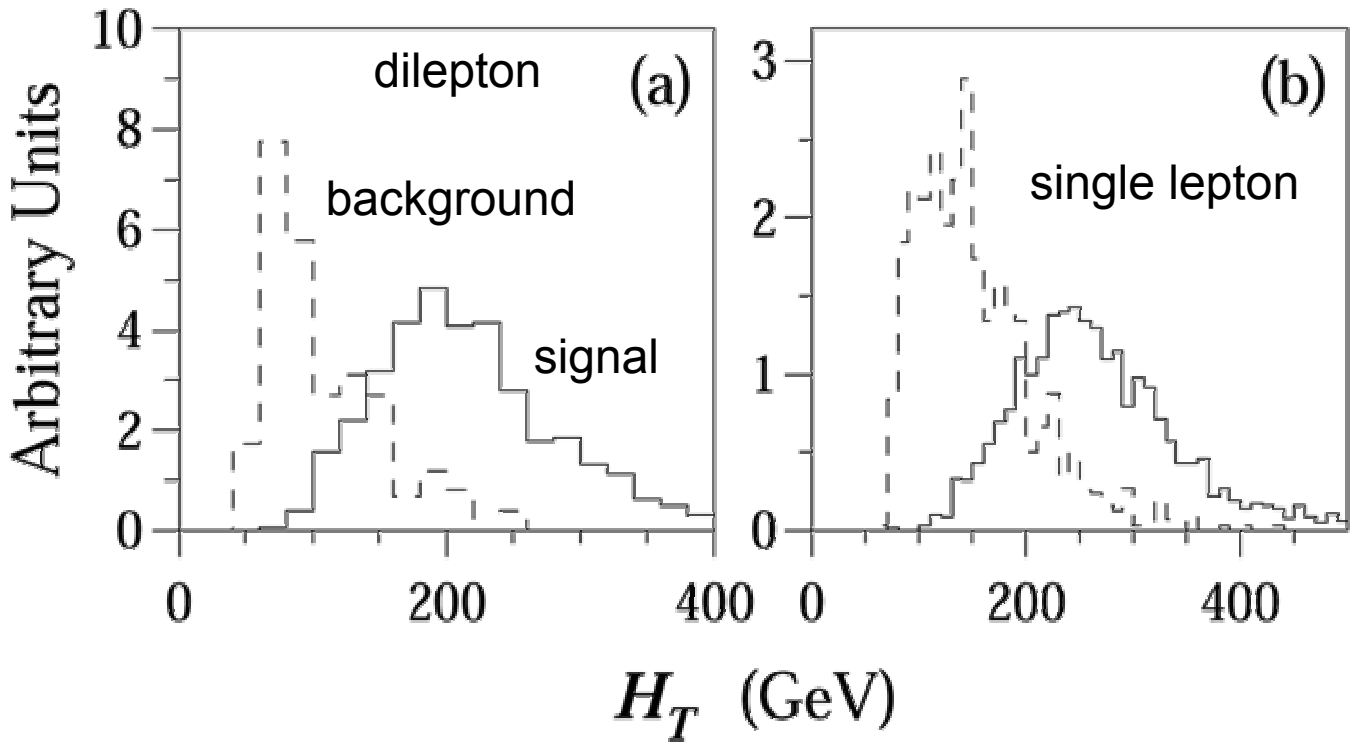
Discovery Papers

By early 1995 (Run Ia+b), analyzed x3.5 data sample.

D0: further optimized for high mass top quark

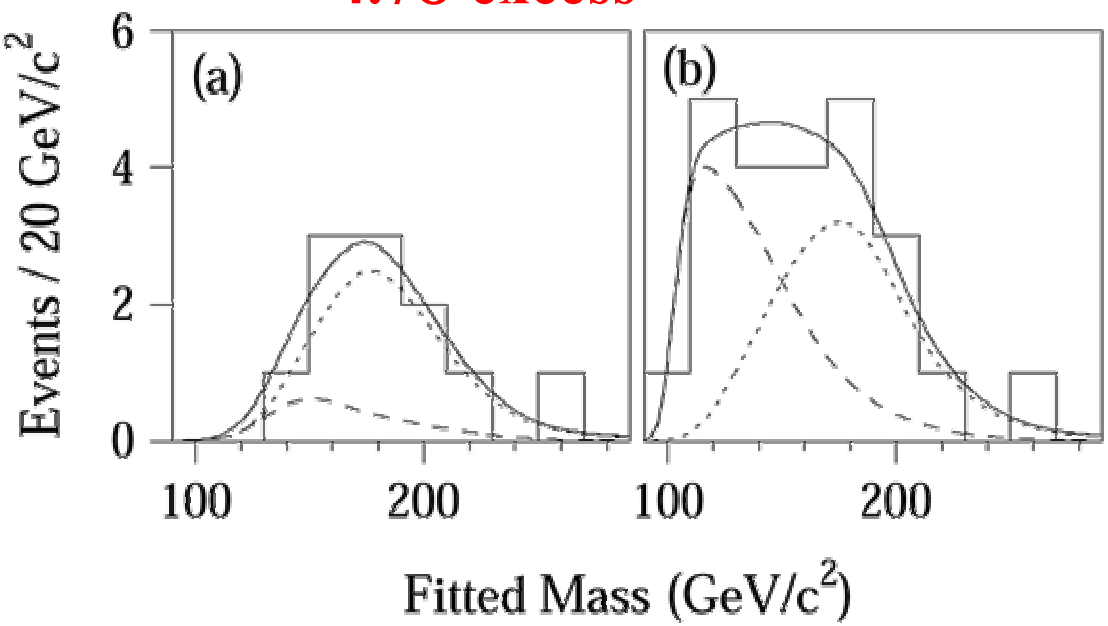
- **Require large H_T (ΣE_T of objects) to suppress background.**

  improves S/B by ~ x2.5



	estimated background	observed
dilepton	0.65 events	3 events
1 lepton, untagged	1.9	8
1 lepton, tagged	1.2	6
TOTAL	3.8	17

4.7σ excess



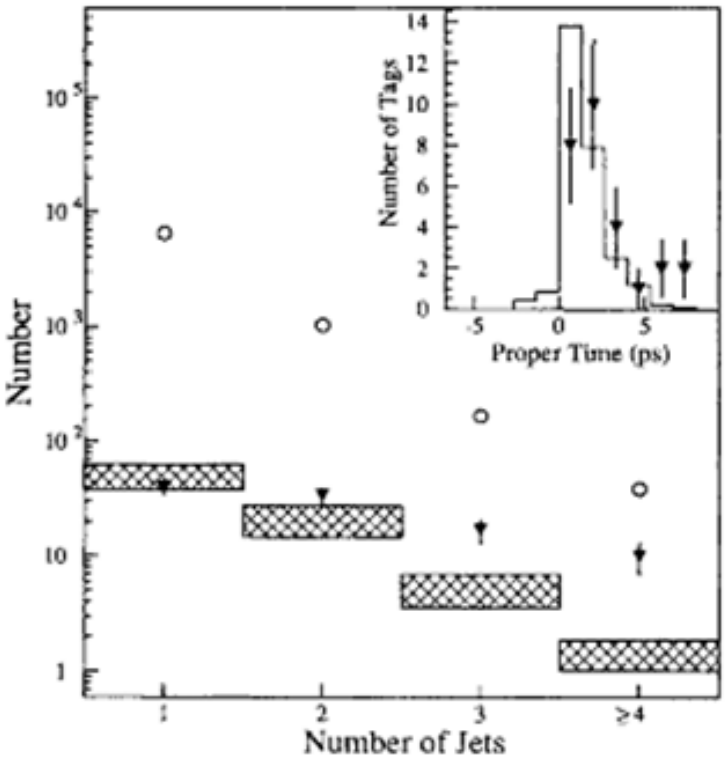
$M_{top} = 199 \pm 30$ GeV

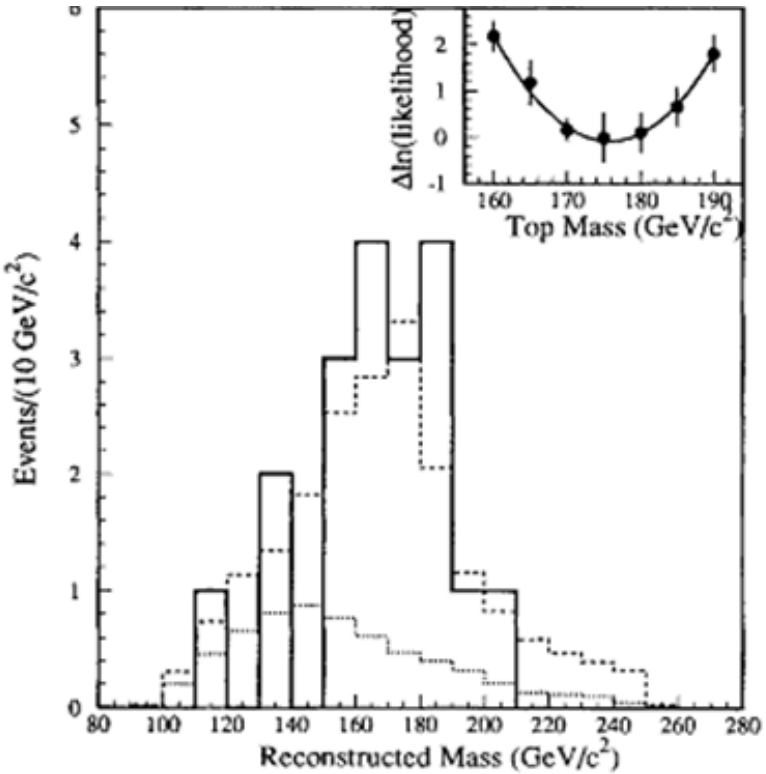
CDF:

- new improved SVX ⇒ x2 *b*-tag efficiency
- > 50% probability to tag at least 1 jet in a $t\bar{t}$ event
- previous "–" now OK with larger statistics

	estimated background	observed
dilepton	1.3 events	6 events
1 lepton, vertex b-tag	6.7	27
1 lepton, lepton *b*-tag	15.4	23

4.8σ excess





$$M_{top} = 176 \pm 8 \pm 10 \text{ GeV}$$

CDF & D0 papers submitted simultaneously.

What do we know about the top quark?

Ans: a lot, but not yet very precisely!

largely statistics

also systematics

- **jet energy scale**
- **ISR, FSR**

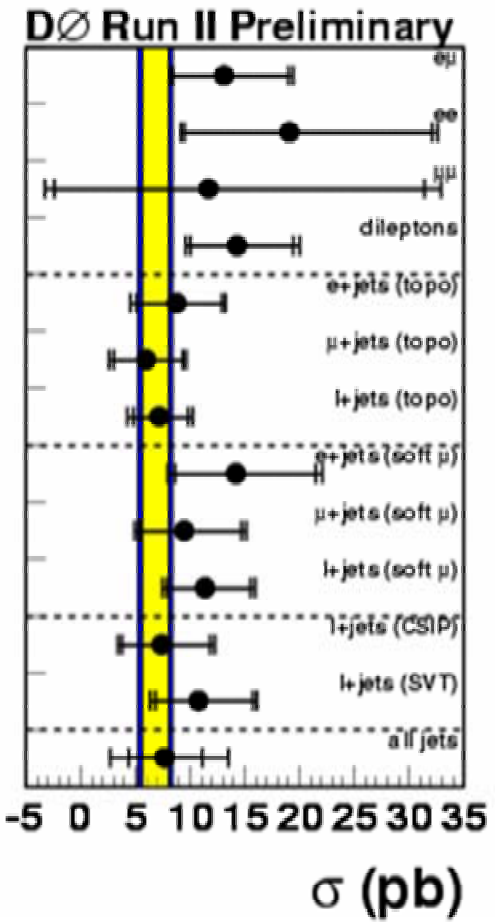
…

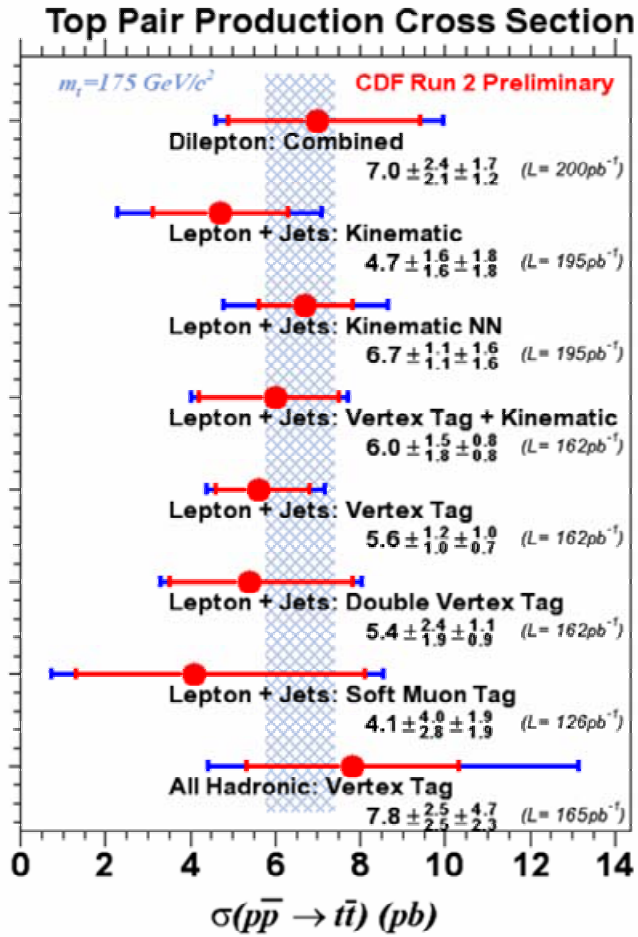
All SM decay modes have been seen at ~ the expected rate.

- ***e*/μ + τ (hadronic) + jets (*b*-tagged)**
- **6 jets**
  - **topological cuts**
  - ***b*-tag**
  - **D0: neural net**
  - **CDF: excess tags in 6-jet bin**

Production Cross Section

- **first property measured: # of events, background, effic., luminosity**
- **Sensitive to the strong interaction coupling of the top quark**
- **Techniques: counting, kinematic fitting, neural network**





Mass

- **lifetime < hadronization time ⇒ decays as a quark**
- **important: consistency check of SM**
- **not an easy problem**
  - **single lepton: $l\nu + 4$ jets**
    - **assigning the jets to the q, $\bar{q}$, b, $\bar{b}$**
    - **quadratic ambiguity in P_z^{ν}**

      ⇒ 24 combinations – no b-tag

      12 combinations – 1 b-tag

      4 combinations - 2 b-tags (low statistics)
    - **jet energy scale, ISR, FSR**
  - **Dilepton: $ll\nu\nu + 2$ jets**
    - **2 ν's ⇒ not enough constraints ($|M|^2$ weighting; add constraint [min $P_z(t\bar{t})$])**
  - **all hadronic: $q\bar{q}'q\bar{q}'b\bar{b}$**
    - **large backgrounds**
    - **large combinatorics**

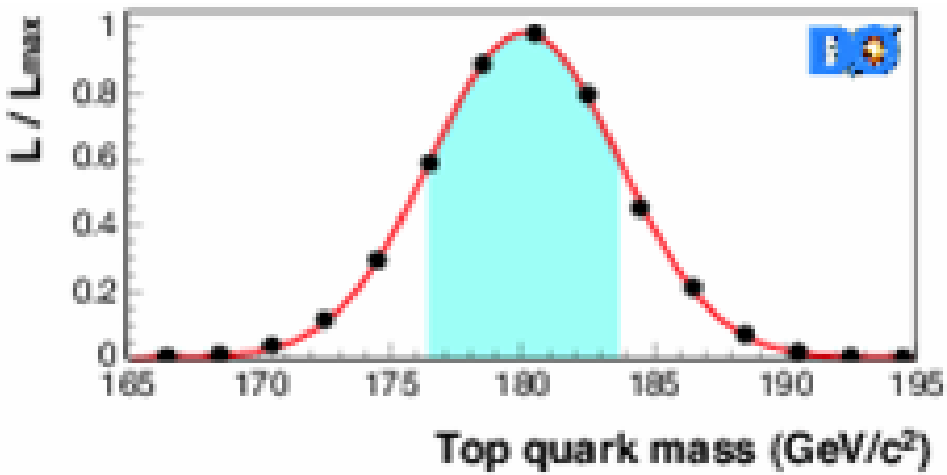
New results in the single lepton channel

- Weighting solutions by the $|M|^2$ and PDF's
  - K. Kondo (1988, 91, 93)
  - R.H. Dalitz and G.R. Goldstein (1992, 93, 99)
- additional input to select correct solution $\Rightarrow$ reduce uncertainty

D0 reanalysis of run I data: Dalitz-Goldstein method

A signal, background discriminant selected 22 events.

$M_{top} = 180.1 \pm 3.6 \pm 3.9$ GeV

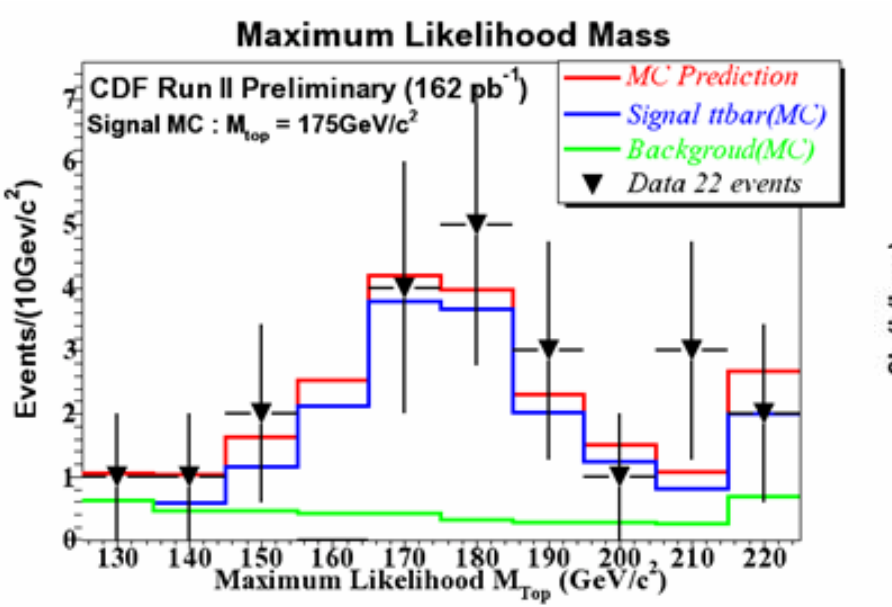


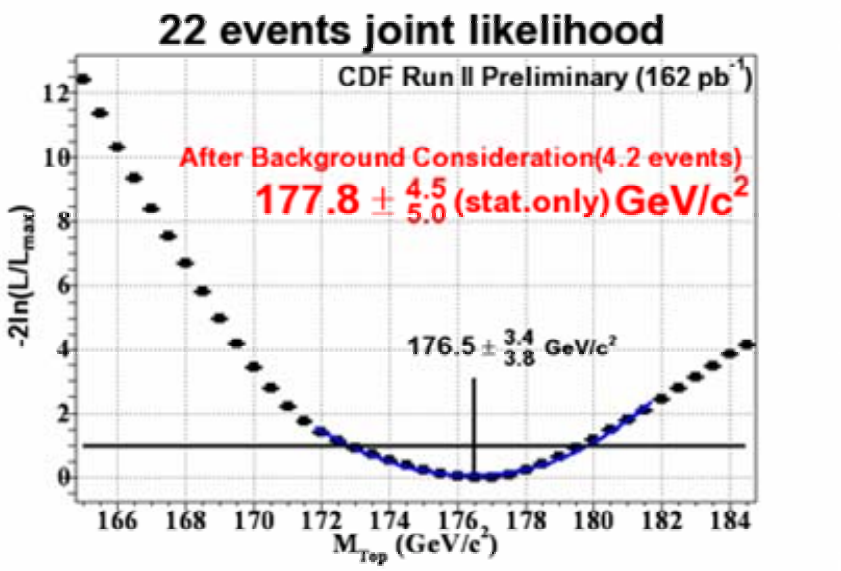
Uncertainty reduced by 1/3 relative to previous method.

Shift of mass up by ~ 7 GeV (< 2σ)

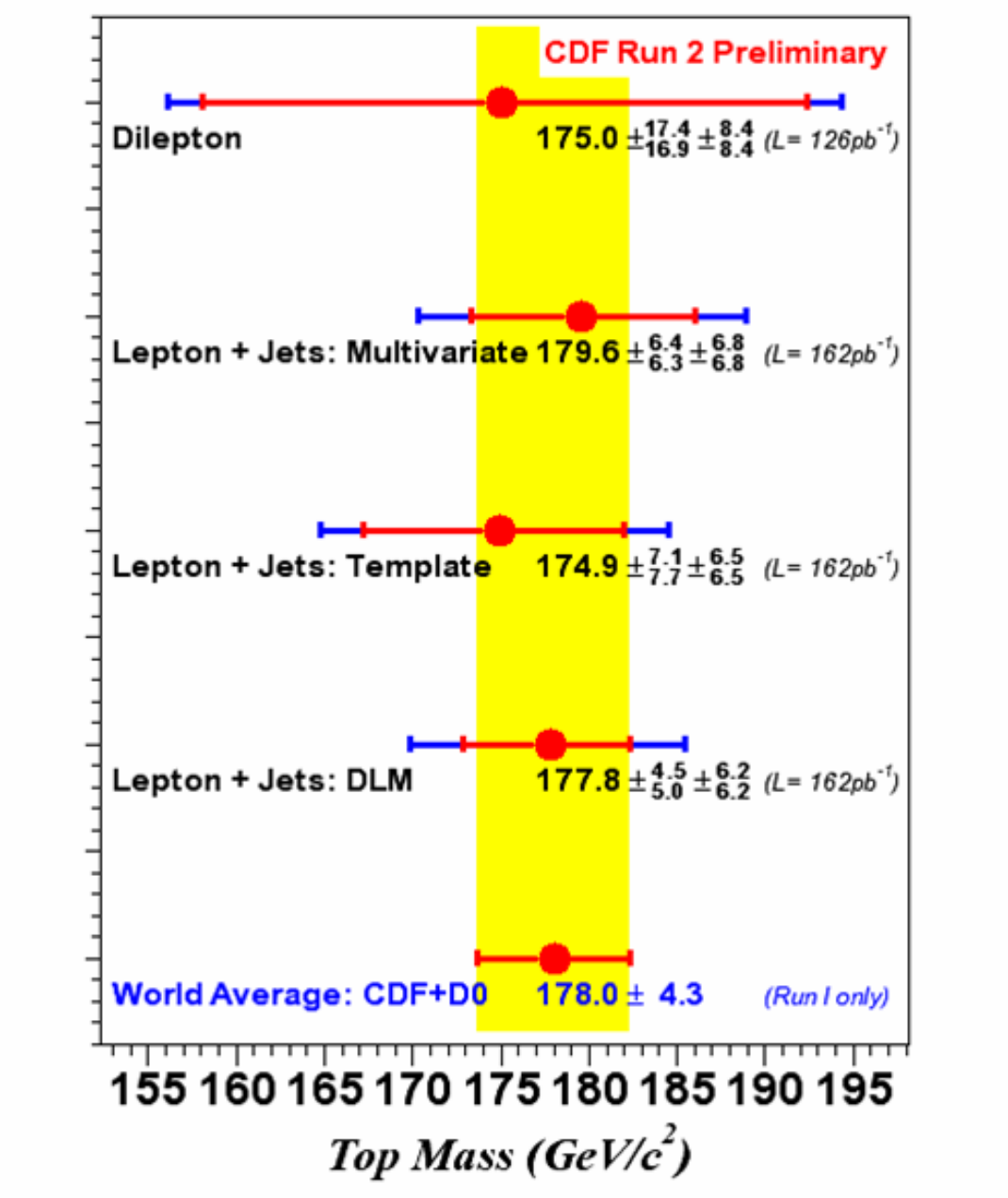
CDF run II data: Dynamical Likelihood Method (Kondo)

22 events with a *b*-tagged jet



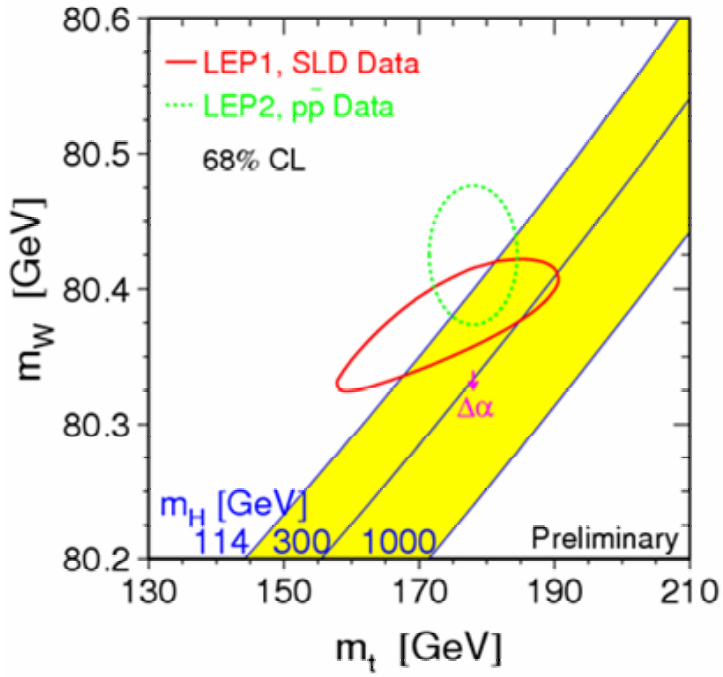


$$M_{\text{top}} = 177.8^{+4.5}_{-5.0} \pm 6.2 \text{ GeV}$$ **(Jet energy scale still under study.)**


CDF Run 2 Preliminary
Dilepton
175.0 ±17.4/16.9 ±8.4/8.4 (L= 126pb-1)
Lepton + Jets: Multivariate
179.6 ±6.4/6.3 ±6.8/6.8 (L= 162pb-1)
Lepton + Jets: Template
174.9 ±7.1/7.7 ±6.5/6.5 (L= 162pb-1)
Lepton + Jets: DLM
177.8 ±4.5/5.0 ±6.2/6.2 (L= 162pb-1)
World Average: CDF+D0
178.0 ± 4.3
(Run I only)
155 160 165 170 175 180 185 190 195
Top Mass (GeV/c2)

Now: $M_{top} \Rightarrow$ **Higgs mass**

Later: M_{top}, M_W, M_H **provide SM test**



High mass $\Rightarrow$ potentially important role tor top quark

Yukawa coupling to Higgs: $\lambda_f \bar{\psi} \psi H$

$$\lambda_f = m_f (2\sqrt{2} G_F)^{1/2}$$

$$M_{\text{top}} = 178\ \text{GeV} \Rightarrow \lambda_t = 1.02 \text{ (strong)}$$

New physics in EWK symmetry breaking sector could be reflected in top quark properties.

Decay Channels

SM: BR($t \to Wb$) ≅ 100%

Measure BR($t \to Wb$) / BR($t \to Wx$) and BR($t \to Wb$) / BR($t \to Xb$)

R = BR($t \to Wb$) / BR($t \to Wx$): (CDF run II data)

- **count # of $l\nu$ + ≥4-jet events with 0, 1, 2 b-tags**
- **neural net separation of signal and background**

$R = 1.06^{+0.27}_{-0.24} \pm 0.16$ (Cousins-Feldman limit: R ~ > 0.6 @ 95% CL)

BR($t \to Xb$) where $X \to$ hadrons or τ's, not e or μ (CDF run II)

- **Count # of single-lepton and dilepton events**

BR($t \to Xb$) < 0.46 @ 95% CL

W Helicity in Top Decay

A low mass *t* would decay into a left-handed *W*.

Massive top: *W* in SM - left handed or longitudinal polarization.

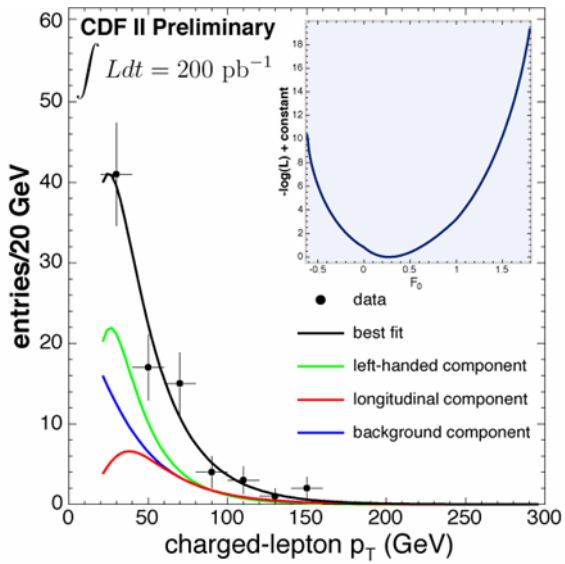
- ***l*** **angular distribution in** ***W*** **rest frame**

  $\Rightarrow$ ***l*** P_T **distribution in the lab frame**

$$F_0 = \frac{1}{1 + 2\left(\frac{M_W}{M_{top}}\right)^2} = 0.70$$

CDF run II: single and di-lepton

$$F_0 = 0.27^{+0.35}_{-0.21}$$

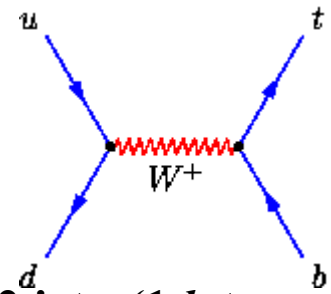


D0 run I: $|M|^2$ weighting $F_0 = 0.56 \pm 0.31$

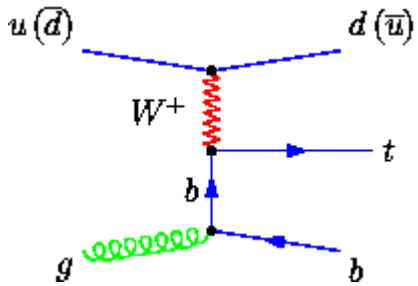
Top Production

Single Top (V_{tb} or τ_t) CDF run II

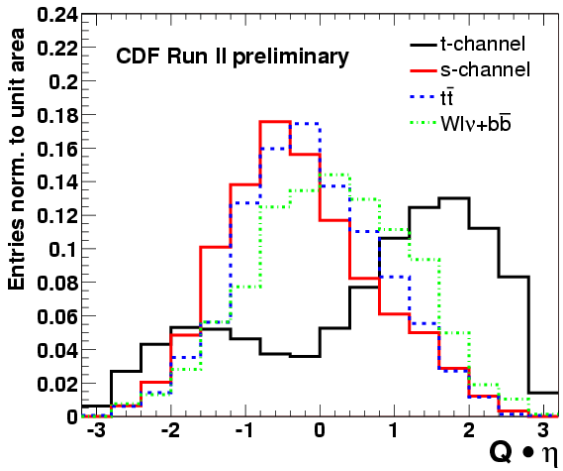
s-channel

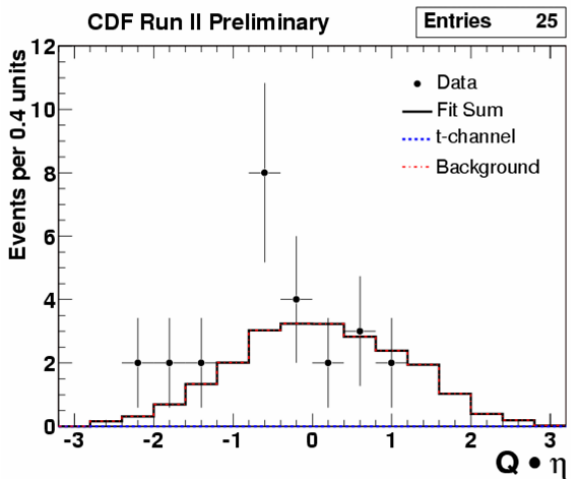


t-channel



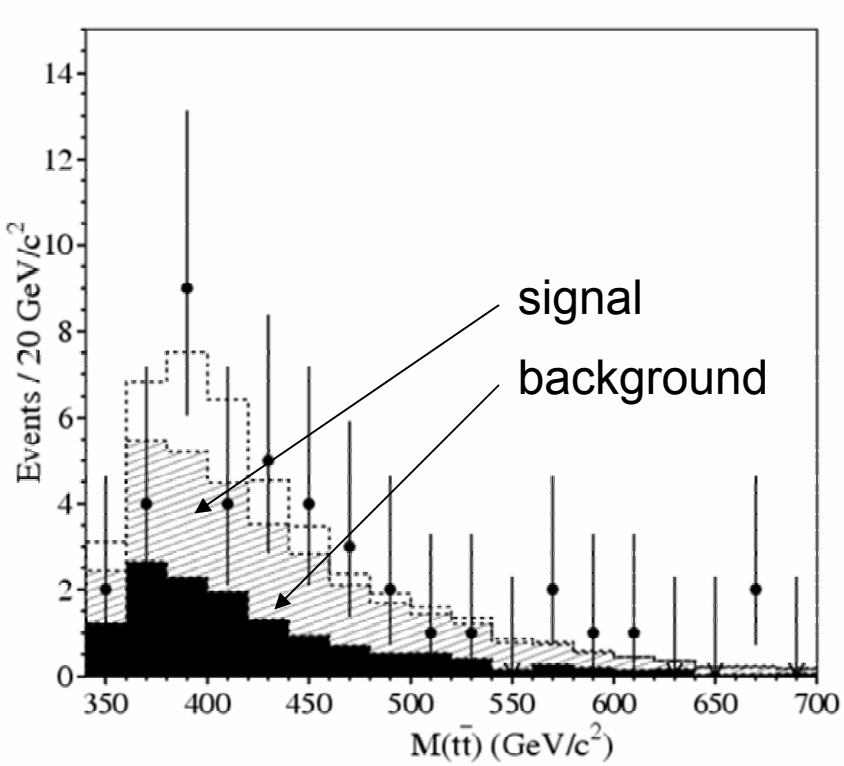
- $l\nu$ + 2 jets (1 *b*-tagged)
- backgrounds large (fewer jets)
- Require 140 < M(*l*+*ν*+*b-jet*) < *210* GeV
- t-channel search: correlation between *l* charge, non-*b*-jet rapidity

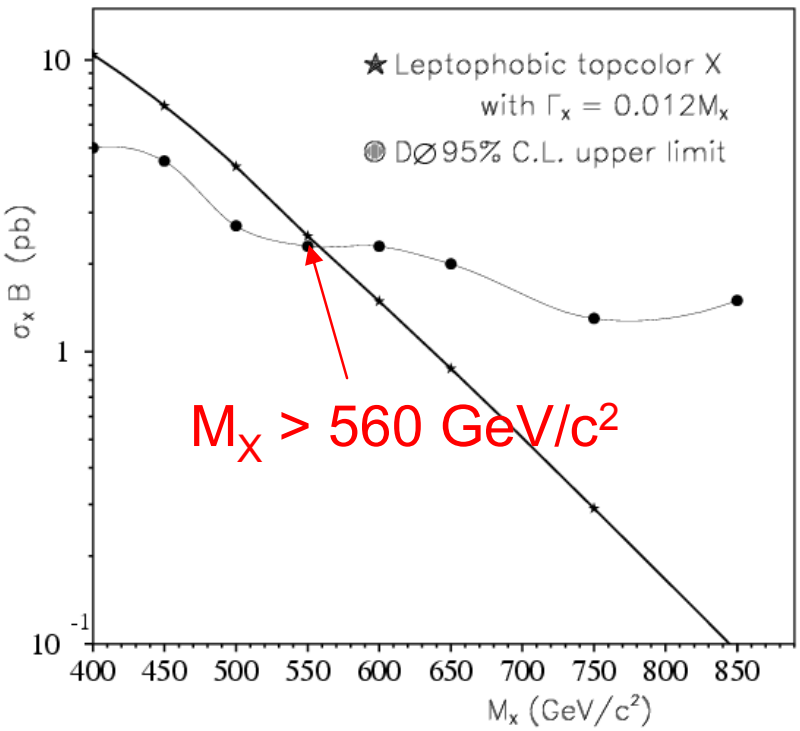




σ_t < 8.5 pb @ 95% CL (theory: 2 pb) Will need a few fb^{-1}.

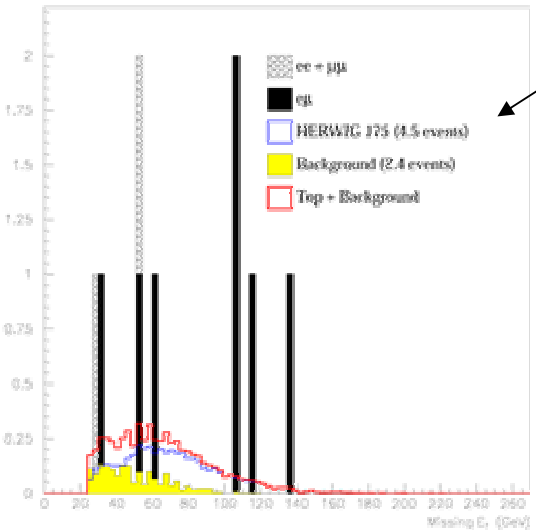
$t\bar{t}$ from resonance decay (ex. topcolor) D0 run I





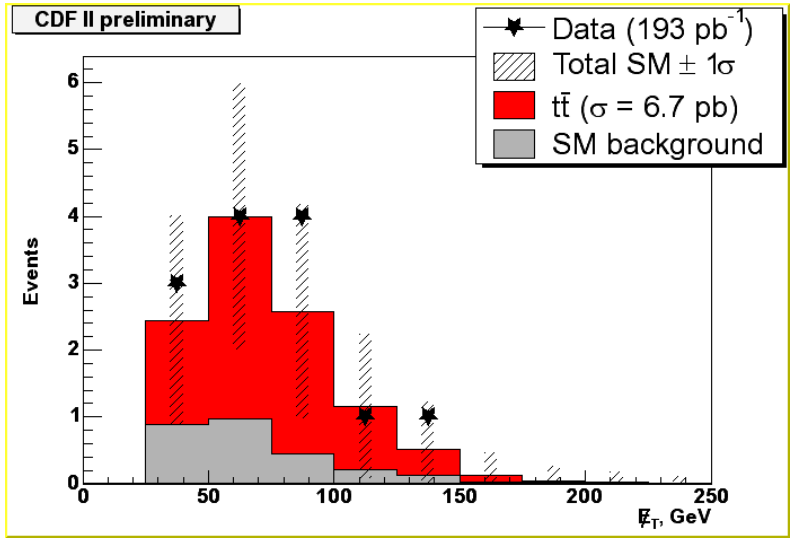
None of the Above

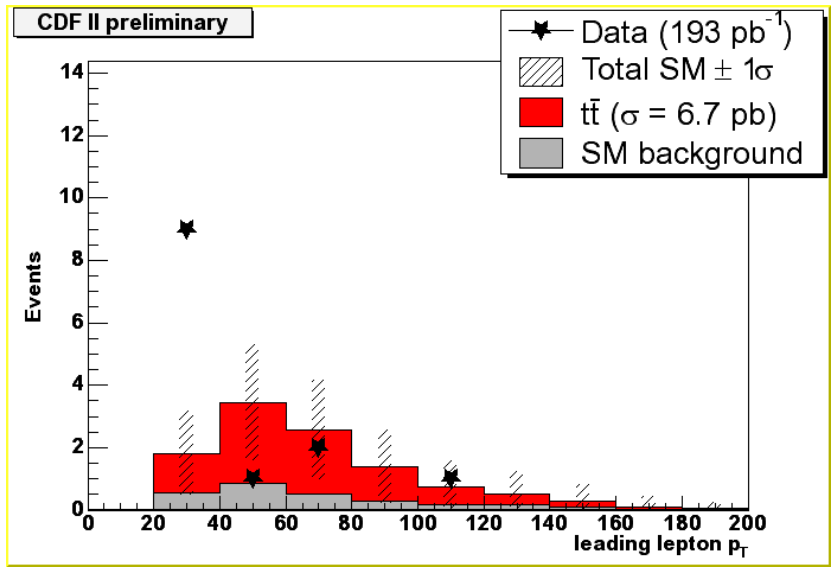
Some of the run I CDF dilepton events didn't look so top-like.



0 100 200 GeV

$\not\!\!E_T$





No large mass scale anomaly so far.

What's Next?

Run II **4-7 fb^{-1}**

How are we doing?

Most important sample will be double *b*-tagged.

Current CDF rate is close to pre-run-II prediction.

$\Rightarrow$ ~1000 CDF & D0 combined in 5 fb^{-1}

Measurement	Precision
Top Mass	2-3 GeV/c^2
$\delta\sigma(ttbar)$	9%
$\delta\sigma(ll)/\sigma(l+j)$	12%
$\delta B(t\rightarrow Wb)$	2.8%
$\delta B(W_{longitudinal})$	5.5%
δV_{tb}	13%
$B(t\rightarrow c\gamma)$	$<2.8 \times 10^{-3}$
$B(t\rightarrow Zc)$	$<1.3 \times 10^{-2}$

LHC

- **8×10^6 $t\bar{t}$ pairs, 2×10^6 EWK single top in 10 fb^{-1}**
  - **mass**
  - **lifetime**
  - **couplings**
  - **spin correlations**
  - **FCNC decay**
  - **top Yukawa coupling via $t\bar{t}H$ production**
  - **…**

LC

- **threshold scan $\Rightarrow \delta M_{top} \sim 0.2$ GeV**
- **polarized beams $\Rightarrow$ axial & vector $t\bar{t}Z$ couplings to ~10%**

Conclusions

- **The 15 year quest for the top quark ended successfully a decade ago.**
- **An important byproduct: development of powerful high mass analysis techniques.**
- **The study of top properties now underway will greatly improve with more data.**
- **Large top mass may $\Rightarrow$ important role in new physics**