Discovery of the TOP-Quark

– Introduction
– Production Mechanisms
– Decay Modes
– Indirect Evidence
– Direct Observation at Fermilab
– Properties (Mass, Width, Production cross section, Decay Modes)
– Implications for the Higgs-Mass
– Further Studies (Fermilab, LHC)

Literature:

W. Hollik, Th. Mueller, Phys. Bl. 53 (1997) 127
C. Campagnari, M. Franklin, Rev. Mod. Phys., Vol. 69 (1997) 137
P.C. Bhat, H.B. Proper, S.S. Snyder, Fermilab-Pub-98/236
D. Chakraborty, J. Konigsberg, D. Rainwater, hep-ph/0303092 (2003)
Review of Particle Properties, P.R.D., V. 66 (2002) 010001-98 and -430

Introduction

Top-Quark (t)

– Directly found 1995/96, but eagerly awaited since long to complete the SM

– t-Quark is astonishingly heavy ($m(t) \approx 40 \times m(b)$)
Connected to new physics beyond SM ?

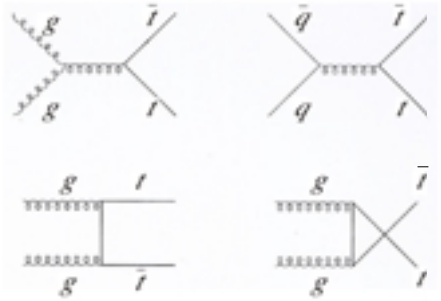
– t-Quark has a very short life time ($\Gamma \approx 1$ GeV $\triangleq$ $10^{-24}s$ (SM))
↳ life time shorter than hadronization time ($\approx 10^{-23}s$)
↳ t-Quark forms no hadrons

– t-mass can be measured very accurately
(in contrast to masses of other quarks (hadronization effects are disturbing))

– $m(t)$ important for Higgs-mass estimate
Strong coupling to Higgs-field because of high mass

Production Mechanisms (1)

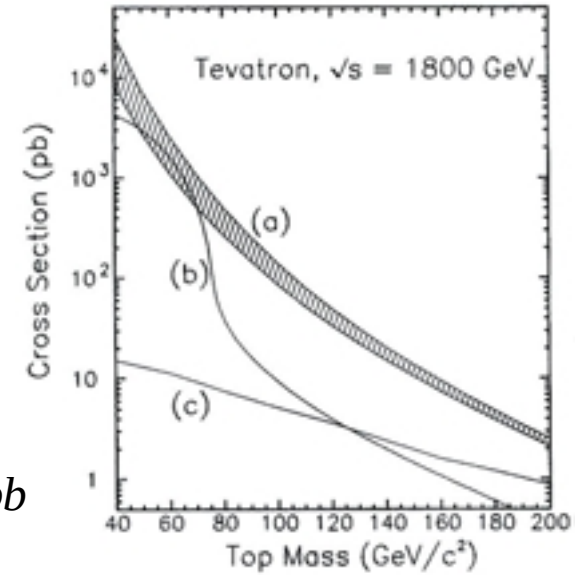
SM: (a) Pair production $p\bar{p} \rightarrow t\bar{t} + X$



Dominant for $\sqrt{s}$ = 1.8 TeV and $m(t)$ = 175 GeV

$Z, \gamma \rightarrow t\bar{t}$ also possible, but small cross section

Top-production cross sections in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. (a) $p\bar{p} \rightarrow t\bar{t}$ from Laenen, Smith, and van Neerveen (1994) (the band represents the estimated theoretical uncertainty), (b) sum of $t\bar{b}$ and $\bar{t}b$ from W decay (Drell-Yan), (c) sum of $t\bar{b}$ and $\bar{t}b$ from W-gluon fusion. See text for details.



$\sigma(\bar{p}p \rightarrow t\bar{t} + X)$ ($\sqrt{s}$ = 1.8 TeV; $m(t)$ = 175 GeV) $\approx 10pb$

($\approx 10^{-10}$ x $\sigma_{inelast.}$)

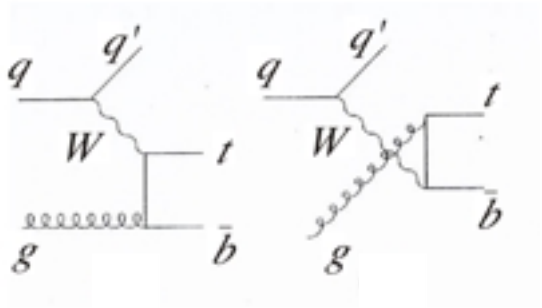
(b) Drell-Yan Production (Single t-production) $\bar{p}p \rightarrow W^+ + X$

$\hookrightarrow t\bar{b}$

Small cross section for $\sqrt{s}$ = 1.8 TeV $\approx 0.9pb$

Production Mechanisms (2)

(c) W-Gluon-Fusion (Single t-production) $p\bar{p} \rightarrow t\bar{b} + X$



Small cross section for $\sqrt{s}$ = 1.8 TeV $\approx 2.4pb$

$\sigma_{pp} \rightarrow t\bar{t} + X$ ($\sqrt{s}$ = 14 TeV ; LHC) $\approx 700pb$

Decay Modes

SM: $t \to W + b$ Dominant

$\left.\begin{array}{l} \to W + c \\ \to W + d \end{array}\right\}$ CKM unterdrückt

Very small rates:

$t \to q\gamma$ (FCNC)

$t \to qZ$ (")

⋮

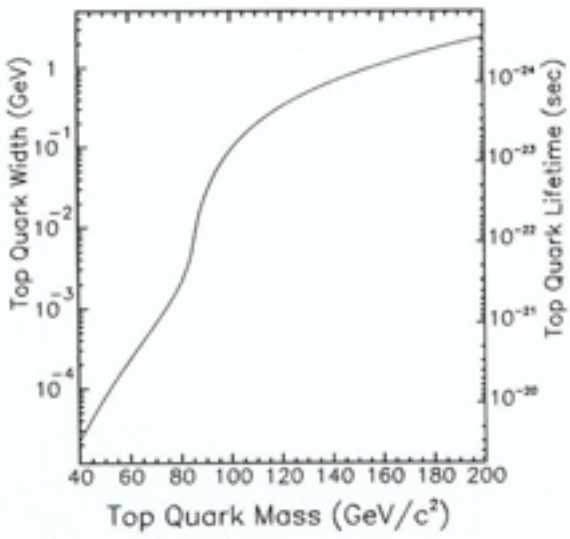
Decay modes in $p\bar{p} \to t\bar{t} + X$

Decay modes for a $t\bar{t}$ pair and their lowest-order branching ratios, assuming standard model decays.

Decay mode	Branching ratio
$t\bar{t} \to q\bar{q}q\bar{q}b\bar{b}$	36/81
$t\bar{t} \to q\bar{q}e\nu b\bar{b}$	12/81
$t\bar{t} \to q\bar{q}\mu\nu b\bar{b}$	12/81
$t\bar{t} \to q\bar{q}\tau\nu b\bar{b}$	12/81
$t\bar{t} \to e\nu\mu\nu b\bar{b}$	2/81
$t\bar{t} \to e\nu\tau\nu b\bar{b}$	2/81
$t\bar{t} \to \mu\nu\tau\nu b\bar{b}$	2/81
$t\bar{t} \to e\nu e\nu b\bar{b}$	1/81
$t\bar{t} \to \mu\nu\mu\nu b\bar{b}$	1/81
$t\bar{t} \to \tau\nu\tau\nu b\bar{b}$	1/81

Non SM: See later

Lifetime of Top-Quark



Indirect Evidence

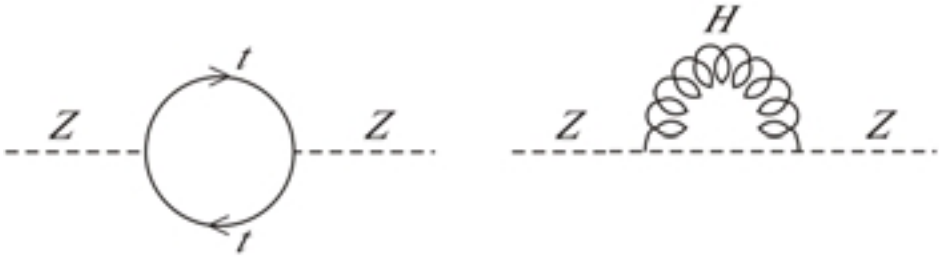
Request for 6th quark in SM:

– Weak Isospin of *b*-quark was measured to be $(I_3)_W = -1/2 \Rightarrow$ Top = Weak Isospin Dublett Partner

– SM only renormalizable, if triangle diagrams cancel for each generation
Only possible, if *t*-Quark ($Q = +2/3$) exists

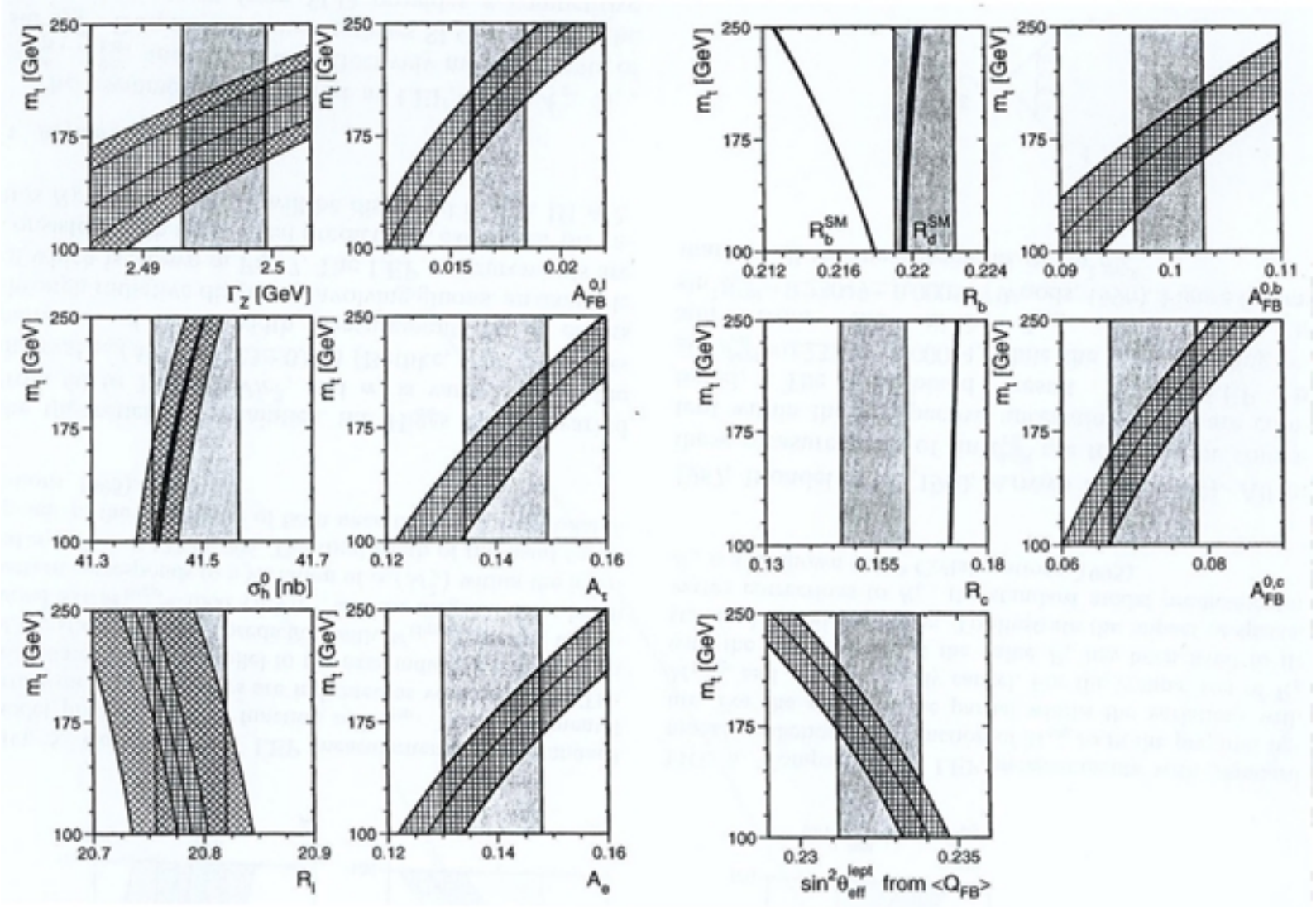
Top-Quark and Higgs play essential roles in radiative corrections of electro-weak processes
→ Mass Constraint for *t*-Quark (and Higgs)

Example: *Z*-Mass



Sensitive Quantities (Line shape and asymmetries at the *Z*-peak)

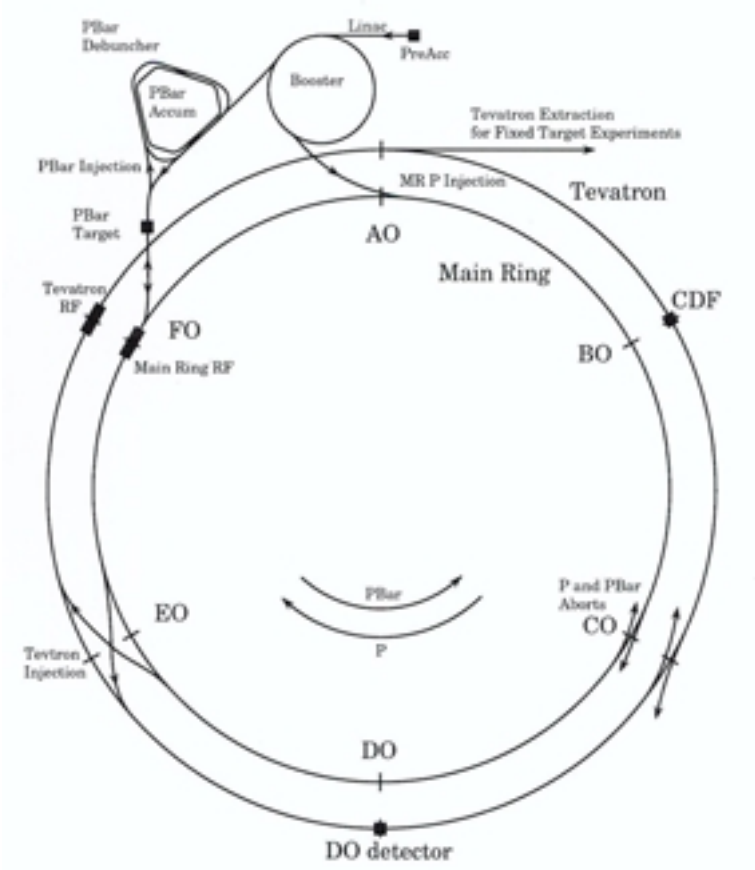
(1) Total Width of Z : Γ_Z
(2) Hadronic Cross section (m_Z) : $\sigma^0_{Hadr.}$
(3) Ratio of hadronic/leptonic widths : R_ℓ
(4) Forward/Backward Asymmetry in $Z \rightarrow \ell\ell$-decays : $A^{0,\ell}_{FB}$
⋮



$$\Rightarrow m_{\mathrm{t}} = \left(181.3\ {}^{+6.1\ \ +15.7\ (m_{\mathrm{H}} = \ \ 70\,\mathrm{GeV})}_{-6.2\ \ -17.3\ (m_{\mathrm{H}} = 1000\,\mathrm{GeV})}\right)\ \ \mathrm{GeV}/c^2$$

Direct Observation of the Top-Quark at Fermilab (1)

Run 1: (1992-96) $\bar{p}p$ (E_{CM} = 1.8 TeV); $L_{Peak} = 2 \times 10^{31}\ cm^{-2}s^{-1}$; $\int Ldt = 162(pb)^{-1}$

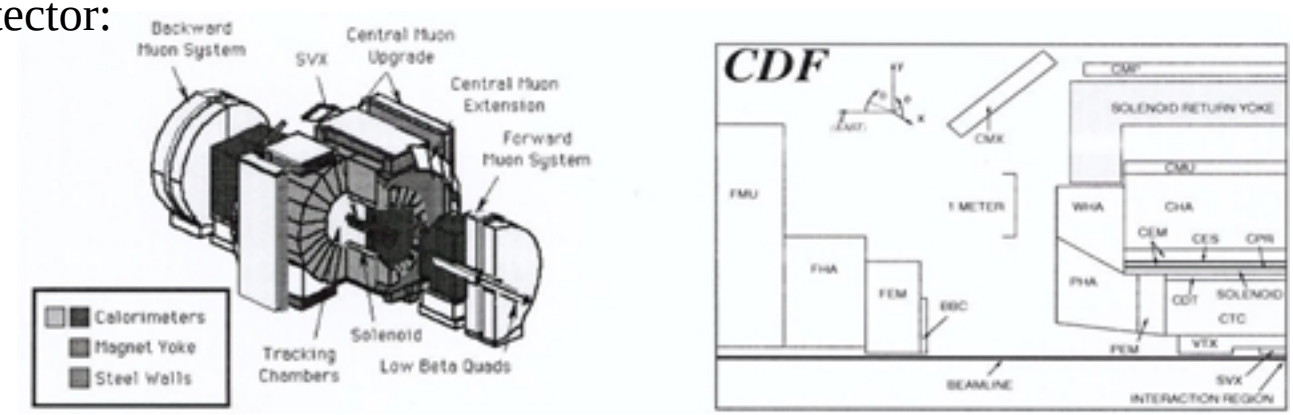


Run 2: (2001→) Main Ring → Main Injector ($L \rightarrow 8 \times 10^{31}\ cm^{-2}s^{-1}$); Recycler ($L \rightarrow 2 \times 10^{32}$);
1.8 TeV → 2.0 TeV

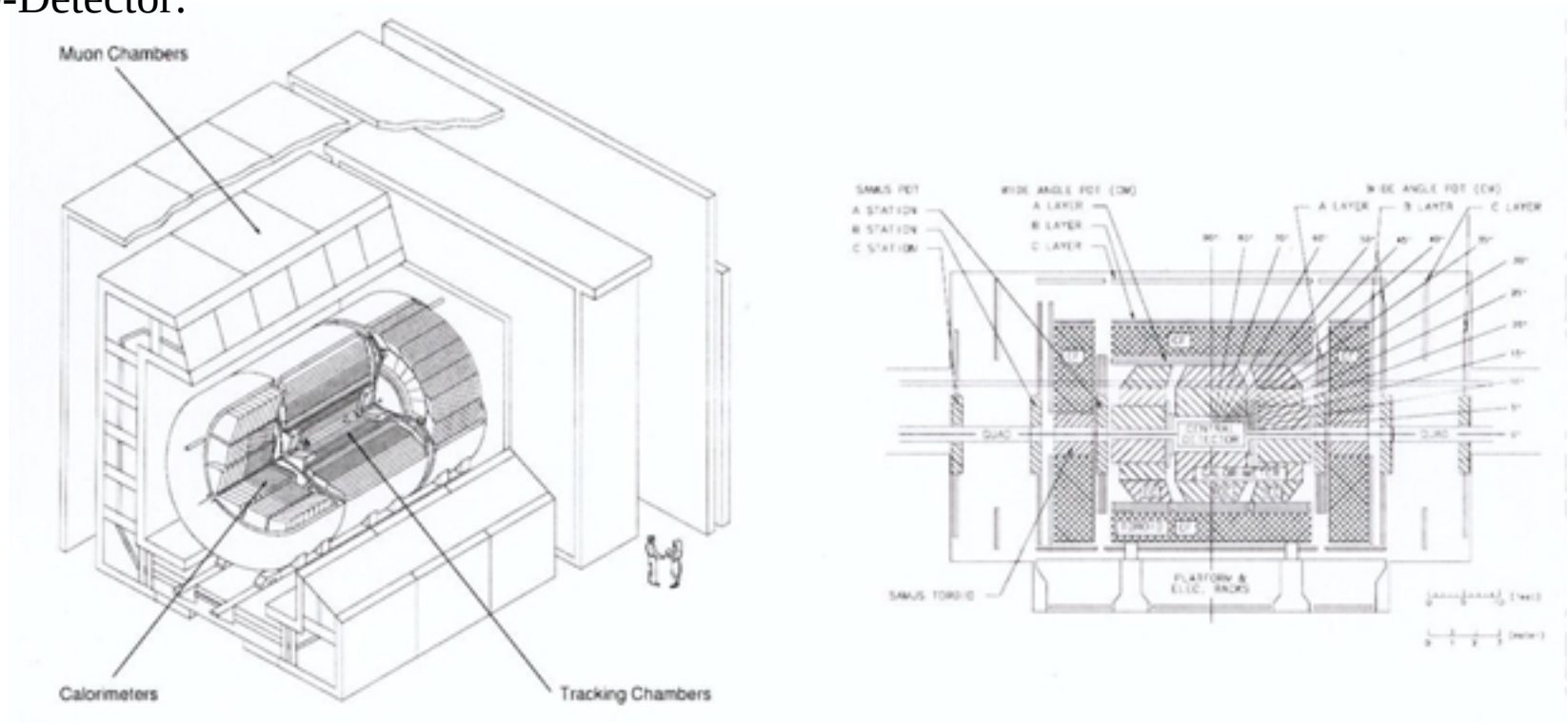
Detector Upgrades: DO: Central magnetic field; Si-Vertex-Det.; Scint. Fiber Tracker
CDF: Expanded Vertex Detector

Direct Observation of the Top-Quark at Fermilab (2)

CDF-Detector:



DO-Detector:



Direct Observation of the Top-Quark at Fermilab (3)

t-Signals in various decay channels

Up to now (Run1) only *t*-pair production has been seen; No single *t*-signals yet

$$p\bar{p} \to t\bar{t} + X; \quad t \to W^+ + b; \quad \bar{t} = W^- + \bar{b}$$

$$\hookrightarrow \ell^+, \bar{\nu} \qquad \hookrightarrow \ell^-, \nu$$

$$q, \bar{q} \qquad q, \bar{q}$$

Dilepton Channel:

$b, \bar{b}, 2\ell, 2\bar{\ell}$ ≙ *b*-Jet; $\bar{b}$-Jet; Charged Lepton; Anticharged Lepton (*e*, μ, τ) ; Missing ν; Missing $\bar{\nu}$

Background (For $\ell = e, \mu$):

- Drell-Yan ($W \to t\bar{b}$)
- $Z \to \tau\,\tau$
- QCD $b\bar{b}$
- WW ($W \to \ell + \nu$)
- Radiative *Z*, $W\bar{b}$, *WZ*, *ZZ*
- \+
- Fake Leptons
- Mismeasured μ-tracks

Direct Observation of the Top-Quark at Fermilab (4)

Cuts:

	Standard Dilepton (ee, $e\mu$, $\mu\mu$)	τ-Dilepton ($e\tau$, $\mu\tau$)	ℓ + jets/b-tag	All jets
Lepton p_T(GeV/c)	> 20	$p_T^\tau > 15$ $p_T^{e,\mu} > 20$	> 20	—
Lepton $\|\eta\|$	< 1.0	$\|\eta^\tau\| < 1.2$ $\|\eta^{e,\mu}\| < 1.0$	< 1.0	—
$\not\!\!E_T$ (GeV)	> 25	—	> 20	—
$S_{\not\!\!E_T}$ (GeV$^{1/2}$)	—	> 3	—	—
Jet E_T (GeV)	> 10	> 10	> 15	> 15
Jet $\|\eta\|$	< 2.0	< 2.0	< 2.0	< 2.0
Number of jets	≥ 2	≥ 2	≥ 3	≥ 5
H_T (GeV)	—	—	—	> 300
$H_T^{\rm all}$(GeV)	—	> 180	—	—

Direct Observation of the Top-Quark at Fermilab (5)

Most important cuts: Large $(P_T)_{Lepton}$ $\rightarrow$ Eliminates QCD-background ($\approx 10^{10}$ x $\sigma_{t\bar{t}}$), mostly along the beam direction

b-Tagging $\rightarrow$ Eliminates *q*(= *u*, *d*, *s*) – and gluon-jets

Soft Lepton Tagging (SLT)
22% of all b‘s decay emitting an electron or muon.
The leptons are close to a jet and have $P_\perp < 20$ GeV/c

Displaced Vertices Tagging (DVT)
b‘s travel several mm‘s (ps) before they decay $\rightarrow$ 2. Vertex

Also important: Kinematical Fitting of events / Neural Network Techniques

Modeling of events/background: PHYTHIA / HERWIG

$t\bar{t}$-efficiency: (0.74 ± 0.08) %

Observed events ($\int$ Ldt = 109 ± 7 pb^{-1}): 9 Dilepton events (e, μ); Estimated Background: 2.4 ± 0.5

Direct Observation of the Top-Quark at Fermilab (6)

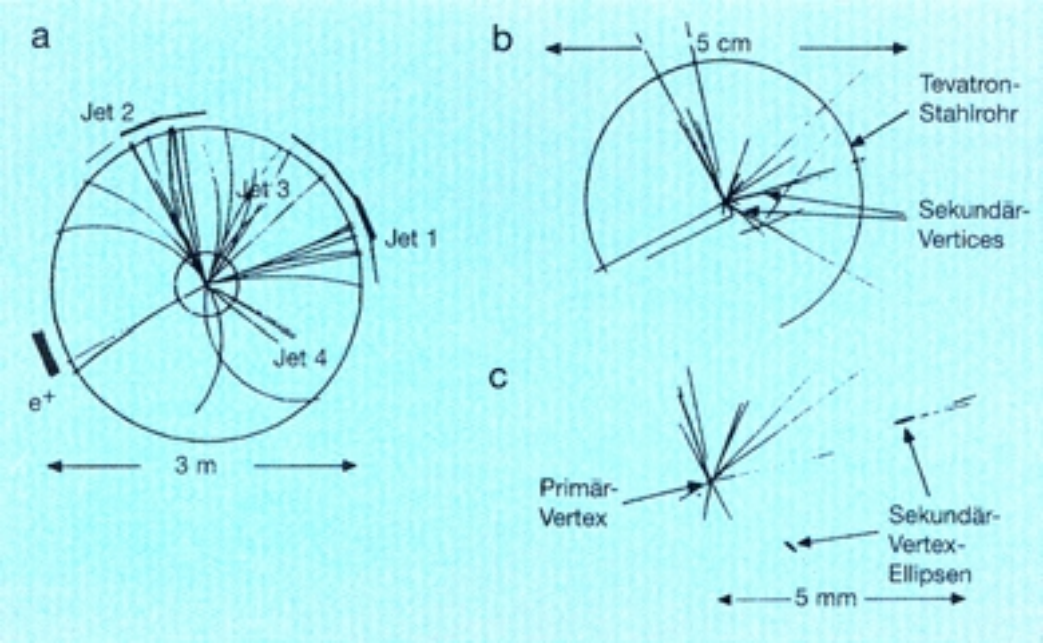
Lepton + Jets-Channel:

b-Jet, $\bar{b}$-Jet, Charged Lepton, Missing ν, q-Jet, $\bar{q}$-Jet

Cuts as above + topologial conditions (sphericity/aplanarity)

Observed events	Est. Background
34 (DVT)	9.2 ± 1.5
40 (SLT)	22.6 ± 2.8

Typical event:



Direct Observation of the Top-Quark at Fermilab (7)

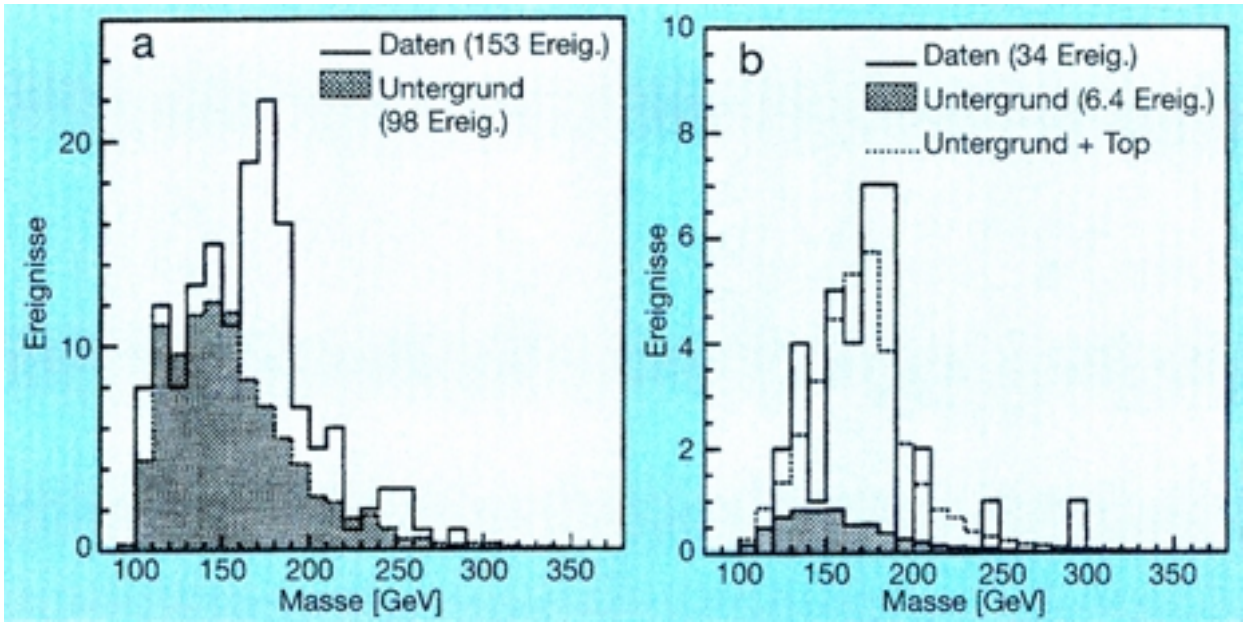
All Jet-Channels

b-Jet; $\bar{b}$-Jet; $2q$-Jets; $2\bar{q}$-Jets

Cuts as above + highly sophisticated topologies

Observed events	Est. Background
187 (DVT)	142 ± 12
157 (SLT)	120 ± 18

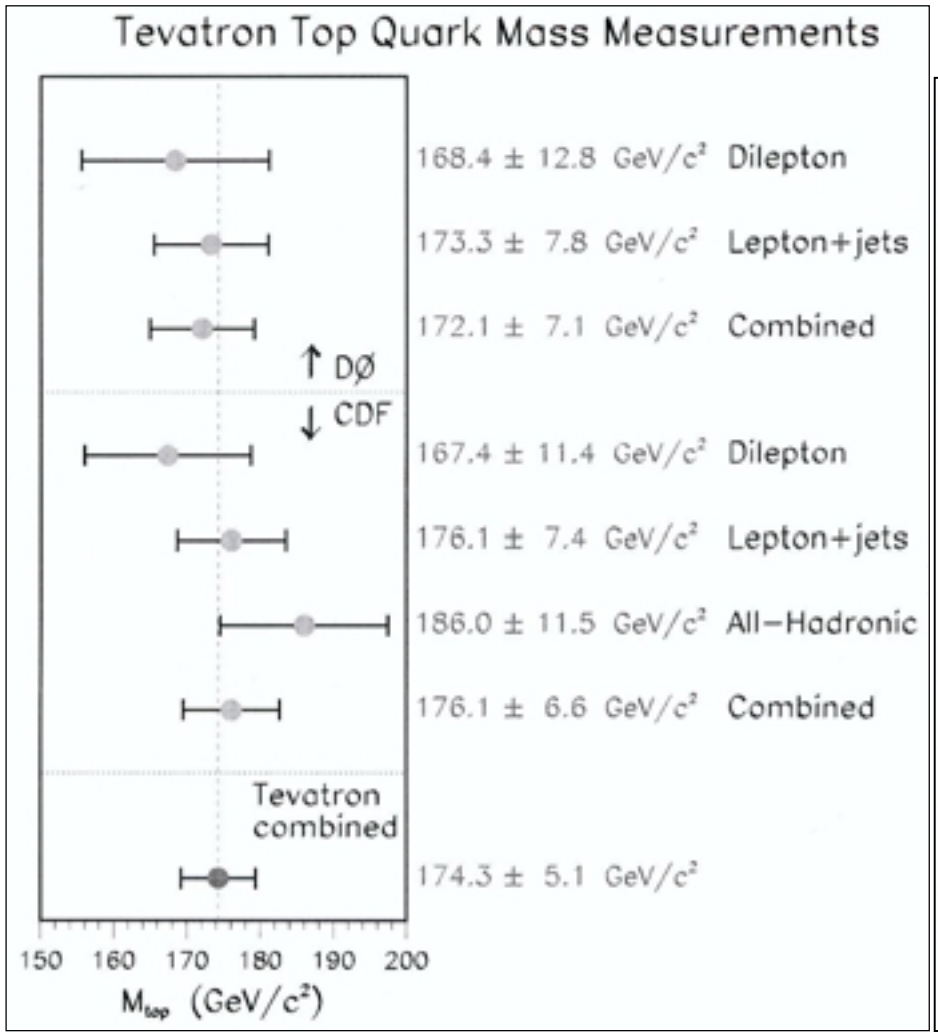
Resulting Spectra (CDF)



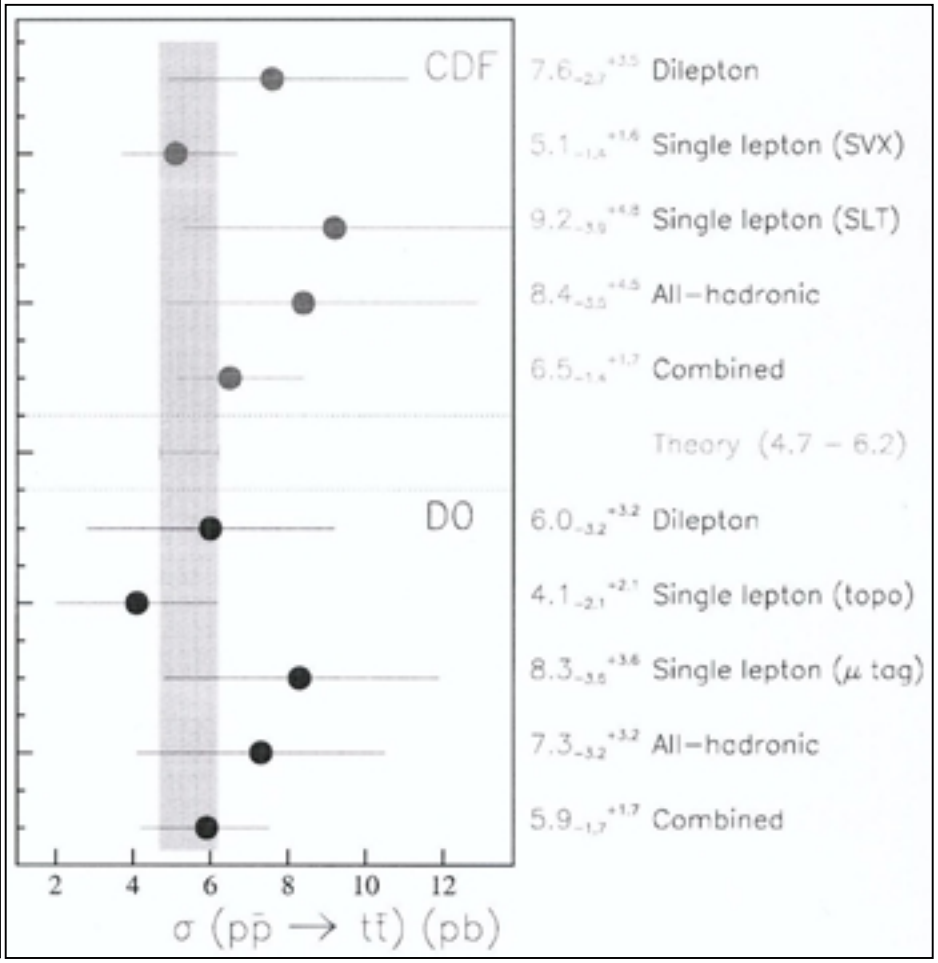
No b-Tag b-Tag

Mass, Production cross section of the Top-Quark

Mass : m_t



Production Cross Section : $\sigma_{t\bar{t}}$

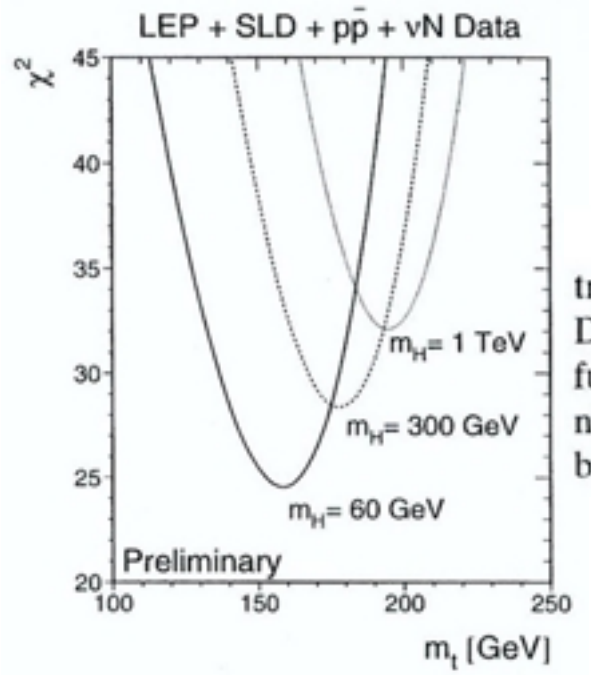


Common Fit to data with m_t and $\sigma_{t\bar{t}}$ as free parameters

SM predictions well fulfilled. Also width in agreement with SM

Implications for the Higgs-Mass (m_{H^o})

SM: Dependence of many observables on m_{H^o} is mostly logarithmic, therefore no accurate constraints are possible.
m_t is very essential in these considerations



The χ^2 curves for the standard model fit to the electroweak precision measurements from LEP, SLD, CDF, and D0 (W mass only) and neutrino-scattering experiments as a function of M_{top} for three different Higgs-mass values spanning the interval 60 GeV/$c^2 \leqslant M_{Higgs} \leqslant$ 1000 GeV/c^2. The number of degrees of freedom is 14 (LEP Collaborations, 1995).

Best Fit values (PDG):

$$m_{H^o} = 88\ ^{+53}_{-35}\ \text{GeV/c}^2$$

or

$$m_{H^o} < 196\ \text{GeV/c}^2\ (95\%\ \text{CL})$$

Exp. (LEP2): $m_{H^o} > 117$ GeV/c^2 (from $e^+e^- \rightarrow H^oZ^o$)

Further Studies (Fermilab (Run 2) / LHC)

1) $\sigma(m_t) \rightarrow$ 3-4 GeV/c^2

2) Test of SM

SM: $B(t \rightarrow bW) > 0.998$

Also allowed, but very rare and beyond future sensitivities:

$t \rightarrow Ws, Wd, WbZ$

$t \rightarrow X^0 q$ ($X^0 = g, \gamma, Z, H$; $q = c, u$) (FCNC)

3) Top related effects beyond SM (Extended Higgs-Sector/SUSY/New Strong Dynamics (Technicolor, ...)/...)

t-production: $t\bar{t}$-resonances (visible in $t\bar{t}$-pair production cross section)

New Heavy Vector Boson ($W^{\pm}$) or Charged Scalar ($\phi^{\pm}$), ... (Enhanced single Top production)

t-decays: $t \rightarrow bH^{\pm}$ (Extended Higgs Sector)

$\hookrightarrow (\tau\nu_\tau)$

$t \rightarrow X^0 q$ ($X^0 = g, \gamma, Z$; $q = c$) (FCNC) Greatly enhanced compared to SM

$t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0$ (t-squark + neutralino) (SUSY)

$\hookrightarrow c \tilde{\chi}_1^0$

$\vdots$