The Top Quark: present and future

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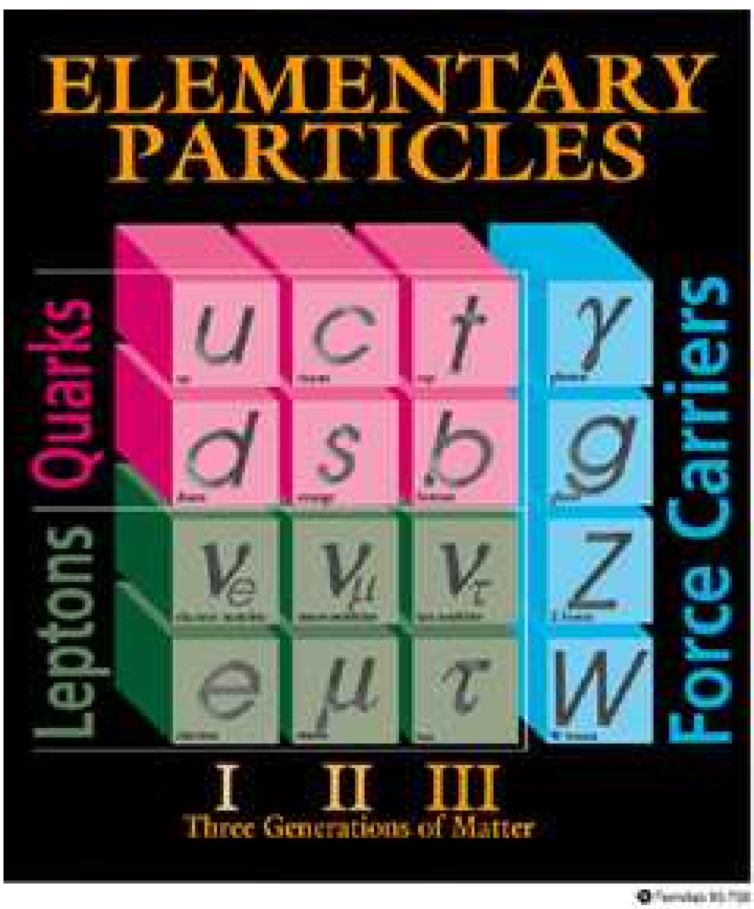
Outline

Outline (contd.)

4. Top quark properties
   - 4.1. Mass
   - 4.2. Spin
   - 4.3. Charge
   - 4.4. Gauge couplings
   - 4.5. Lifetime and V_{tb}
   - 4.6. Yukawa coupling
5. Summary and Outlook

1. Introduction

The discovery of the top quark in 1995 at the Tevatron $p\bar{p}$ collider at Fermilab by the DØ and CDF collaborations gave direct support to the three-generation structure of the Standard Model and opened up the new field of top-quark physics.
We recently celebrated the 10th anniversary of this monumental milestone.



1.1. Theoretical Perspective

In the SM, the top quark is defined as the $SU(2)_L$ (weak isospin) partner of the bottom quark.

- $S = \frac{1}{2}$
- $Q = \frac{2}{3}$
- Transforms as a color triplet under the SU(3) gauge group of strong interactions.

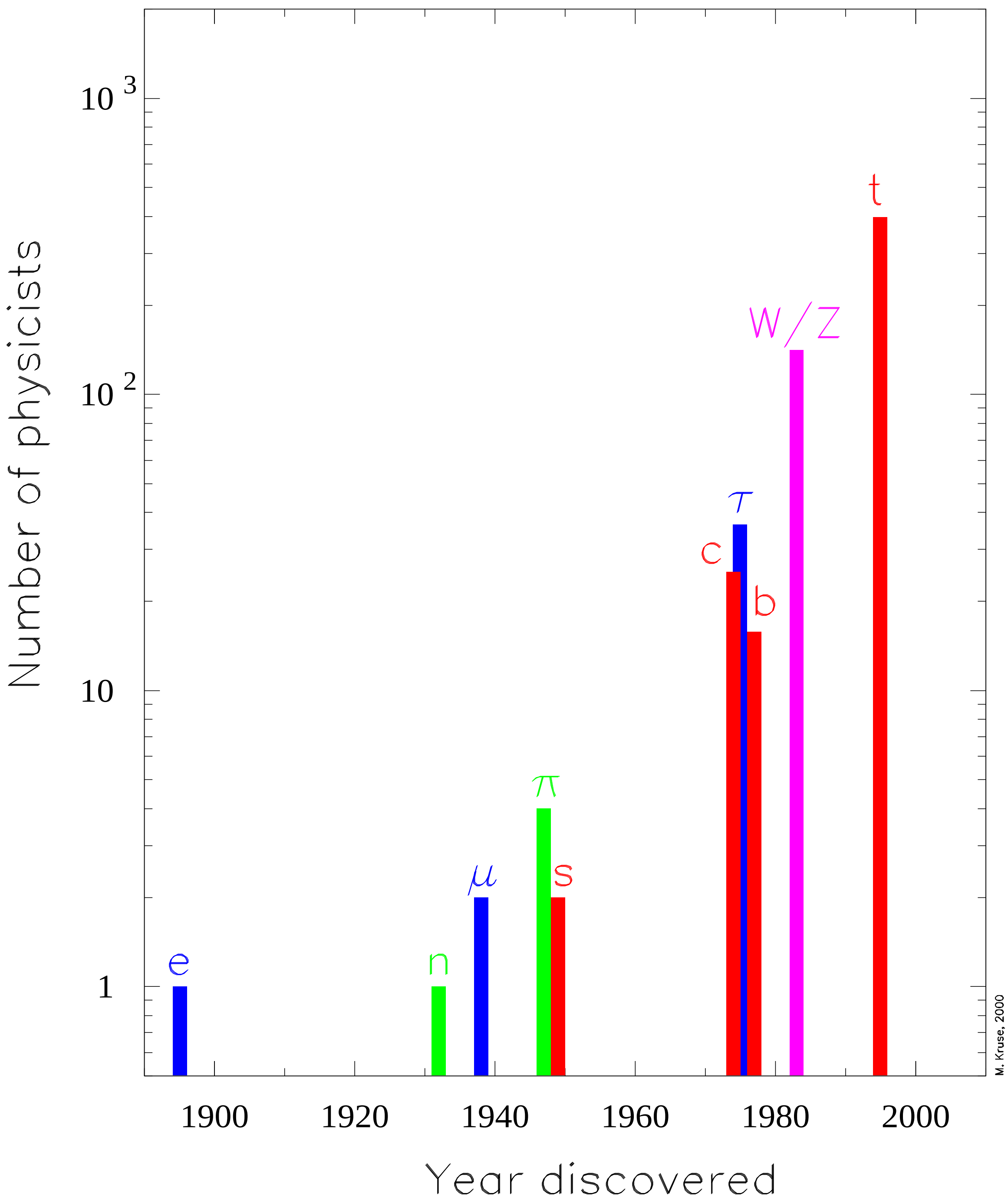
None of these quantum numbers has been directly measured, but a large amount of indirect evidence support these assignments. These include precision measurements of $\Gamma(Z \to b\bar{b})$, A_{FB}, B^0-$\bar{B}^0$ mixing, and FCNC decays of B mesons.

- Measurement of $\sigma(p\bar{p} \to t\bar{t})$ at the Tevatron is consistent with theoretical calculations for a color-triplet quark.
- Run 2 of the Tevatron (2001-2008) will firmly establish the identity of the top quark.
- The LHC (2007-) and the ILC (2015? -) will be needed for precise determination of top quark properties and to look for subtle hints of new physics.

Status of the Standard Model

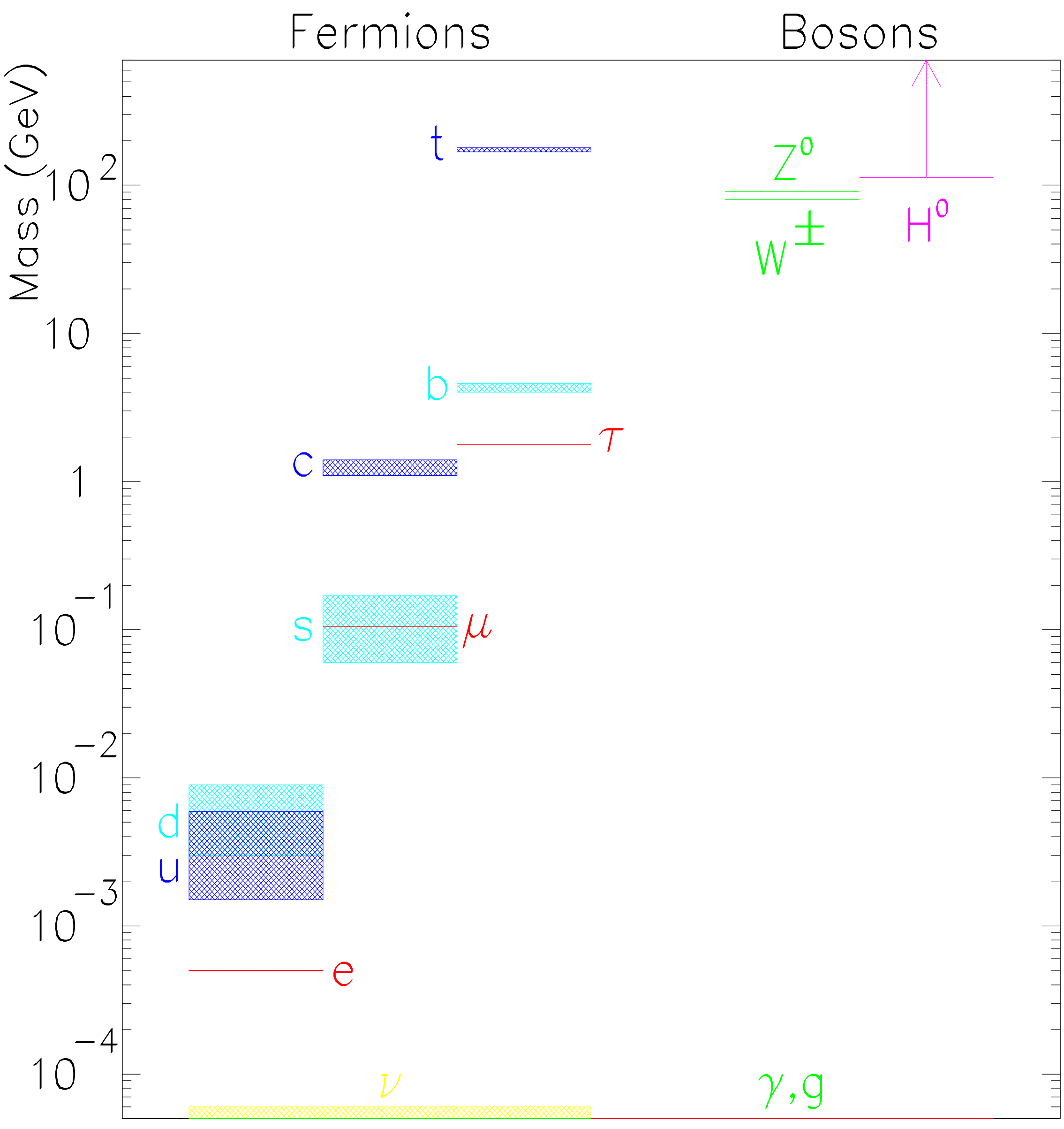
- There are many reasons to believe that there is physics beyond the SM. Indeed, recent dramatic cosmological observations make it an inescapable conclusion.
- Mechanisms behind the breaking of electroweak and flavor symmetries are not well understood/tested.
- Yet, we have no direct experimental evidence so far of any phenomenon beyond the SM produced in a terrestrial laboratory.
- The last fundamental constituents of the SM to be found, the top quark and the W/Z vector bosons, firmly establish it as a valid effective theory for the energy regime explored at man-made particle accelerators to date.
- Only the Higgs boson remains unobserved, but measurements of m_t & M_W constrain M_H.
- Finding the last pieces of the SM has not been getting any easier . . .

Discovery of elementary particles



What is special about the top quark?

Its large mass sets the top quark apart.



$1\,\text{GeV} \approx 1.6 \times 10^{-24}\,\text{g} \approx m_{\text{proton}}$

Some interesting consequences of large m_t

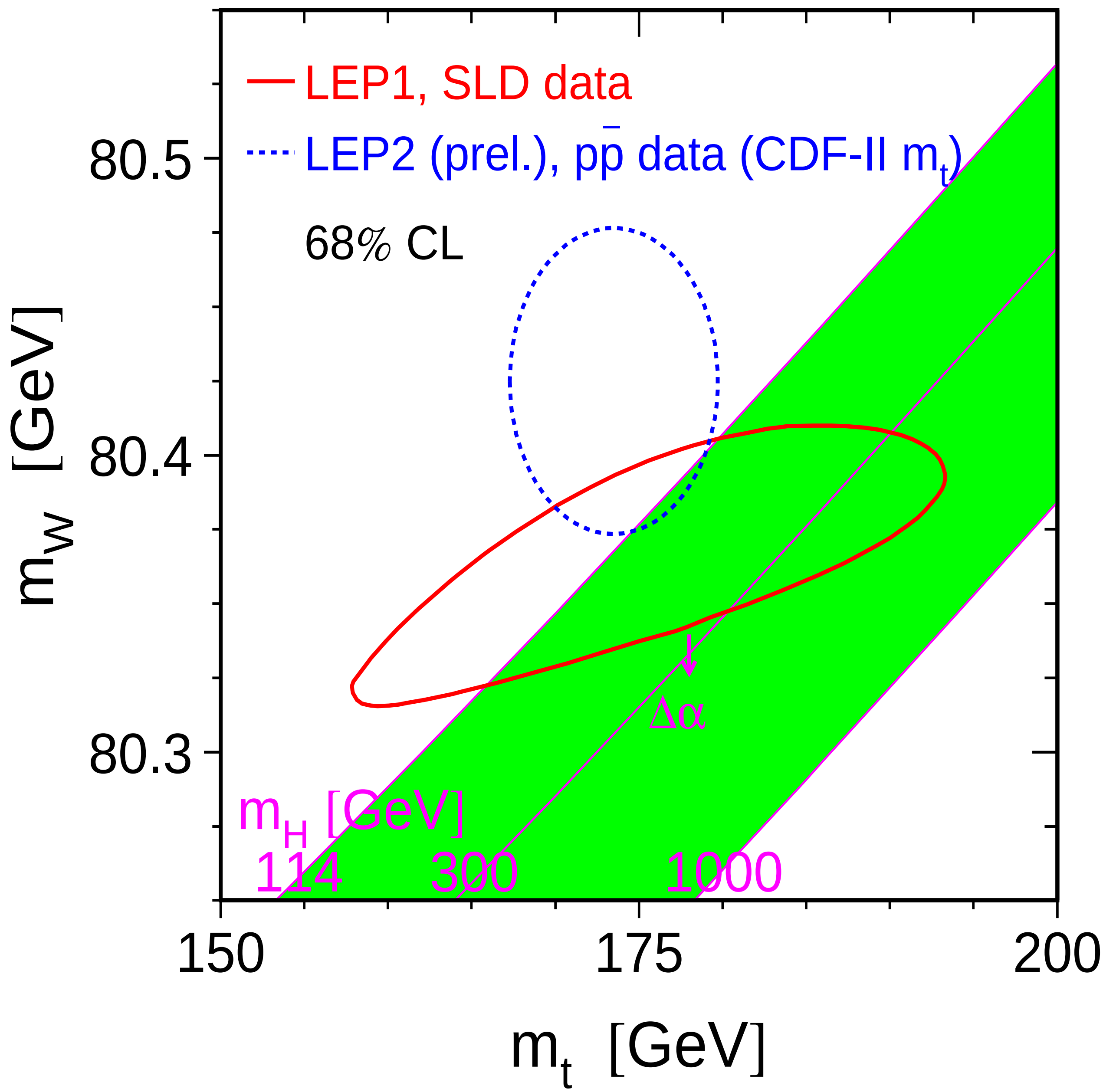
- Top quark and Higgs boson contribute to the radiative (loop) corrections to M_W. Thus, precise measurements of M_W and m_t together constrain M_{H^0}.

- The only fermion heavier than the gauge bosons ($W^\pm$, Z^0) $\Rightarrow$extremely short lifetime ($\sim 4\times 10^{-25}$ s). The top quark decays before hadronization ($\tau_{\text{had}} \approx 28 \times 10^{-25}$ s). This gives us an opportunity to study the properties of a bare quark, free from long-range effects of the strong interaction, e.g. confinement.

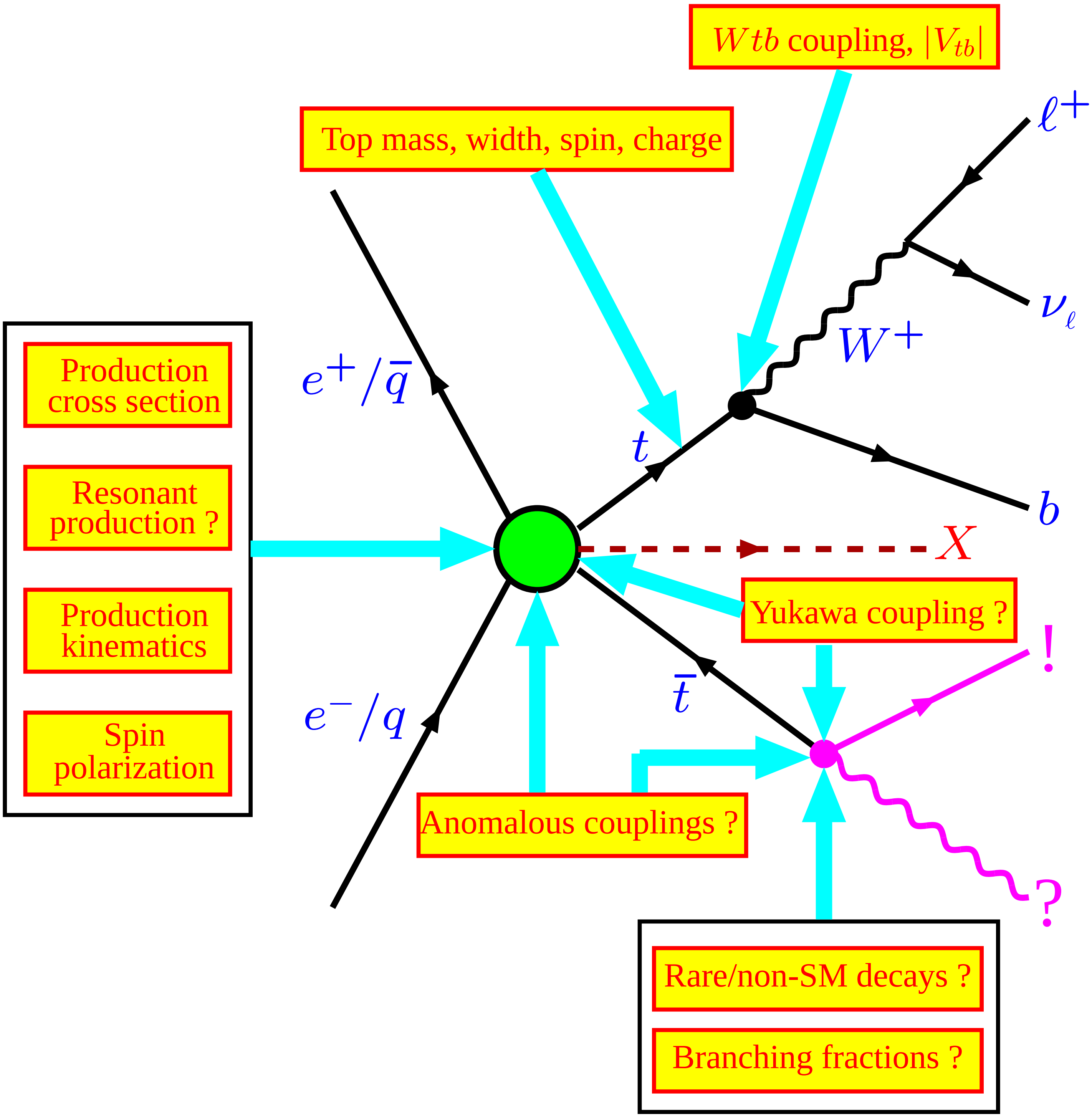
- An excellent place to look for on-shell production of particles beyond the SM that are known to be heavier than other fermions ($\tilde{t}$, $H^\pm$).

- Most likely to shed light on the mechanism of generation of fermion masses. Interesting to the study of any mass-dependent coupling. Top Yukawa coupling is curiously close to 1.

Constraint on M_H from m_t and M_W



Top Physics Potential

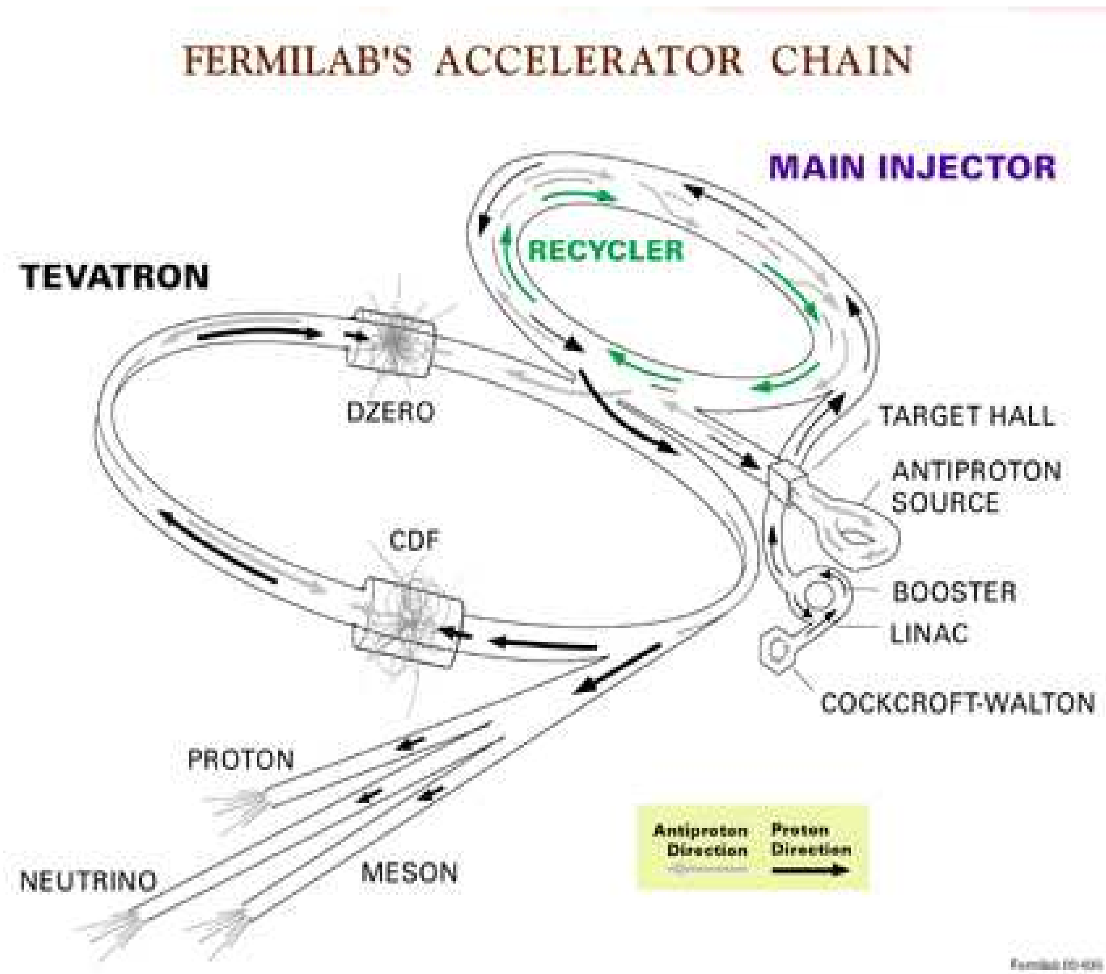


1.2. The Experimental Arena

Producing top quarks

- Tevatron, the proton-antiproton ($p\bar{p}$) collider at Fermilab (Batavia, Illinois), is so far the only facility in the world where top quarks have been produced.
  - Discovery by CDF & DØ experiments in March, 1995 (Run 1, $\sqrt{s} = 1.8$ TeV), based on ~ 150 signal events detected.
  - Ongoing Run 2 ($\sqrt{s} = 1.96$ TeV) is expected to deliver a $\mathcal{O}(100)$-fold increase in signal yield by 2008.
- LHC, a stronger pp collider ($\sqrt{s} = 14$ TeV) under construction at CERN (Geneva, Switzerland) will start operation in 2007 and produce $\mathcal{O}(10^8)$ signal events each year.
- ILC, an e^+e^- collider capable of producing top quarks is being designed ($\sqrt{s}$ up to 1 TeV), hopefully to be commissioned by 2015.

The Accelerator (Tevatron at Fermilab)



- CM energy: $\sqrt{s} = 1.96$ TeV.
- Instantaneous luminosity: $\mathcal{L} \approx 10^{32}$ cm^{-2}s^{-1} $= 10^{-4}$ pb^{-1}s^{-1}.
- Total luminosity recorded by each experiment (DØ CDF): $\int \mathcal{L}dt \approx 500 \pm 30$ pb^{-1}. (1992-present)
- Expected $t\bar{t}$ production cross section: $\sigma(p\bar{p} \to t\bar{t}) \approx 7$ pb.

Beam Luminosity

Instantaneous Luminosity

$$\mathcal{L} = \frac{N_p N_{\bar{p}} B f_0}{4\pi\sigma^2} \qquad (1)$$

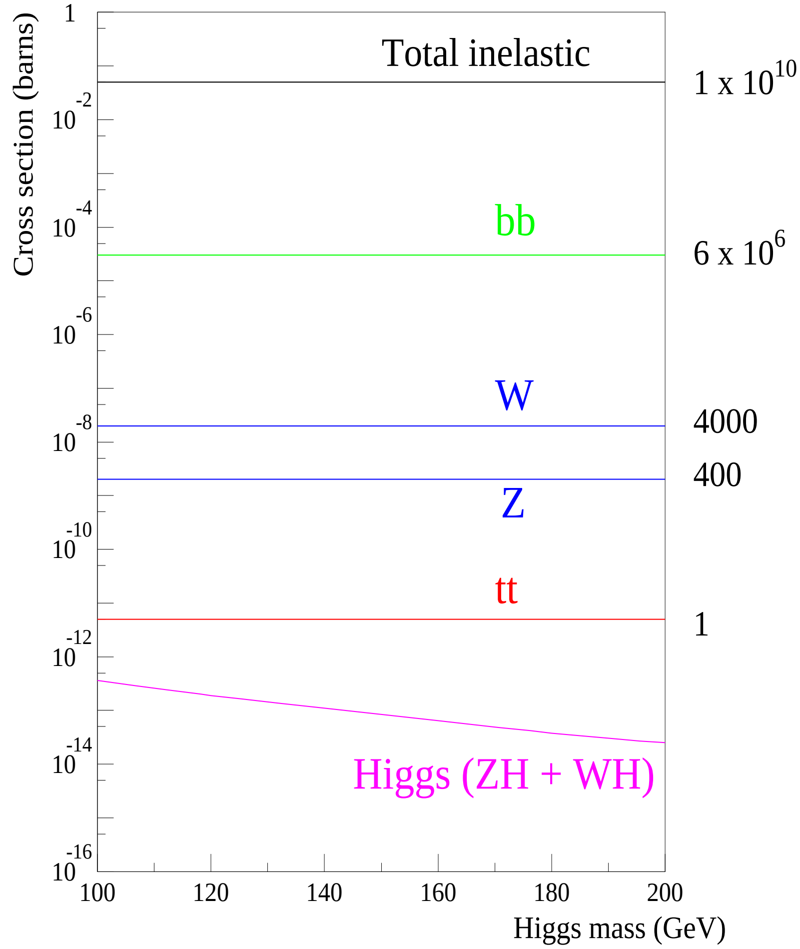
Parameter	Run 1	Run 2
N_p (protons/bunch)	2×10^{11}	2×10^{11}
$N_{\bar{p}}$ (antiprotons/bunch)	6×10^{10}	6×10^{10}
N_p (protons/bunch)	2×10^{11}	2×10^{11}
B (# bunches in ring)	6	36
f_0 (protons/bunch)	50 KHz	50 KHz
	(3.5 μs bunch spacing)	(396 ns bunch spacing)
σ^2 (beam “area”)	3×10^{-5} cm^2	2×10^{-5} cm^2
$\langle\mathcal{L}\rangle$	1.6×10^{31} cm^{-2}s^{-1}	2×10^{32} cm^{-2}s^{-1}

$$N_{p\bar{p}\to t\bar{t}} = \sigma(p\bar{p} \to t\bar{t}) \int \mathcal{L}dt \qquad (2)$$

Parameter	Run 1	Run 2
$\int \mathcal{L}dt$	0.11 fb^{-1}	2 fb^{-1}
$\sigma(p\bar{p} \to t\bar{t})$	5 pb	7 pb
$N_{p\bar{p}\to t\bar{t}}$	600	14000

A note on units: 1 barn (b) = 10^{-24} cm^2, 1 fb = 10^{-15} b

Cross sections at Tevatron ($\sqrt{s} = 1.8$ TeV)



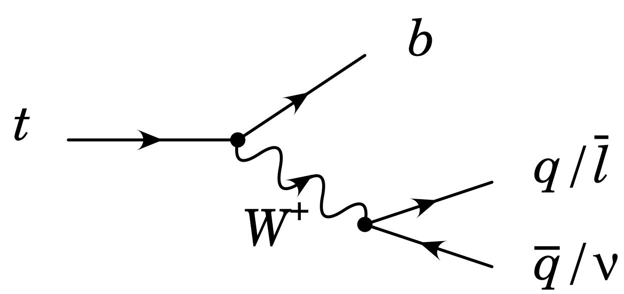
- Small cross sections require high luminosity, and the ability to quickly decide which of the $\sim 10^7$ events/s are interesting.
- Altogether over 10^{14} total collisions in Run 1, roughly one in every 10^{10} producing a $t\bar{t}$ event.
- When running at maximum luminosity, about 5 $t\bar{t}$ events are produced every hour in Run 2.
- But these events must be detected and fi ltered from billions of others arising from less interesting processes.

Top production at Tev2, LHC, and ILC

Collider	Tevatron	LHC	ILC
type	$p\bar{p}$	pp	e^+e^-
E_{CM} (TeV)	1.96	14.0	$\sim$1.0
$\langle\mathcal{L}\rangle$ (cm^{-2}s^{-1})	$\mathcal{O}(10^{32})$	$\mathcal{O}(10^{34})$	$\mathcal{O}(10^{34})$
$\int\mathcal{L}dt$ (fb^{-1})	~ 2	$\sim$300	$\sim$1000
σ_{total} (pb)	$\sim 10^{11}$	$\sim 10^{11}$	$\mathcal{O}(10)$
$\sigma(b\bar{b})$ (pb)	$\sim 3\cdot 10^{7}$	$\sim 3\cdot 10^{8}$	$\mathcal{O}(1)$
$\sigma(WX)$ (pb)	$\sim 4\cdot 10^{4}$	$\sim 2\cdot 10^{5}$	$\mathcal{O}(1)$
$\sigma(t\bar{t})(a)$ (pb)	$6.70^{+0.71}_{-0.88}$	825^{+58}_{-43}	~ 0.8
σ(single t) (pb)	2.91 ± 0.02	315^{+8}_{-2}	~ 0

Detecting top quarks

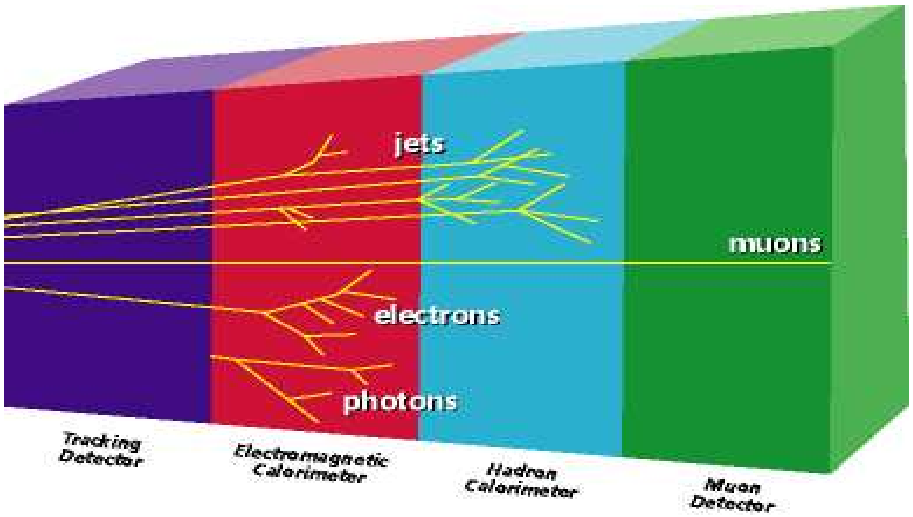
- Extremely short lifetime ⇒detection of top quark involves identification of its decay products and reconstruction of the event.
- In the SM, a top quark decays almost exclusively to a W boson and a bottom quark. So, $B(t \to W^+ b) \approx 1$.
- Therefore, the final state of a top quark event is primarily classified by the decay mode of the corresponding W boson:
$B(W \to \ell\nu_\ell) \approx \frac{1}{9}, \quad (\ell = e/\mu/\tau)$.
$B(W \to u\bar{d}) \approx B(W \to c\bar{s}) \approx \frac{1}{3}$.



- The charged leptons (e, μ, τ) can be separately identified, although τ's can be difficult.
- Neutrinos don't interact in the detector ⇒only inferred from the principle of momentum conservation. No flavor-tagging is possible.

- Quarks hadronize into a “jet” of particles.
  - The light ones (u, d, s) cannot be separated from each other and from gluons.
  - Jets from b and c quarks are often tagged by an isolated decay vertex or an associated e/μ from semileptonic decay.
- Large mass of top quark ⇒small boost ⇒good angular separation between light FS partons.
- The spectrum of top quark decay products spans across the full range of SM particles.
- So, we need versatile, hermetic detectors that
  - can register and identify different kinds of particles, and measure their momenta as accurately and precisely as possible,
  - covers as much of the full 4π solid angle around the interaction point as possible.
- At the Tevatron and the LHC, collisions happen at a much higher rate than can be permanently recorded. Roughly one in a billion collisions contain top quarks. Need the best possible online trigger+filter system to ensure maximum efficiency.

The particle detectors



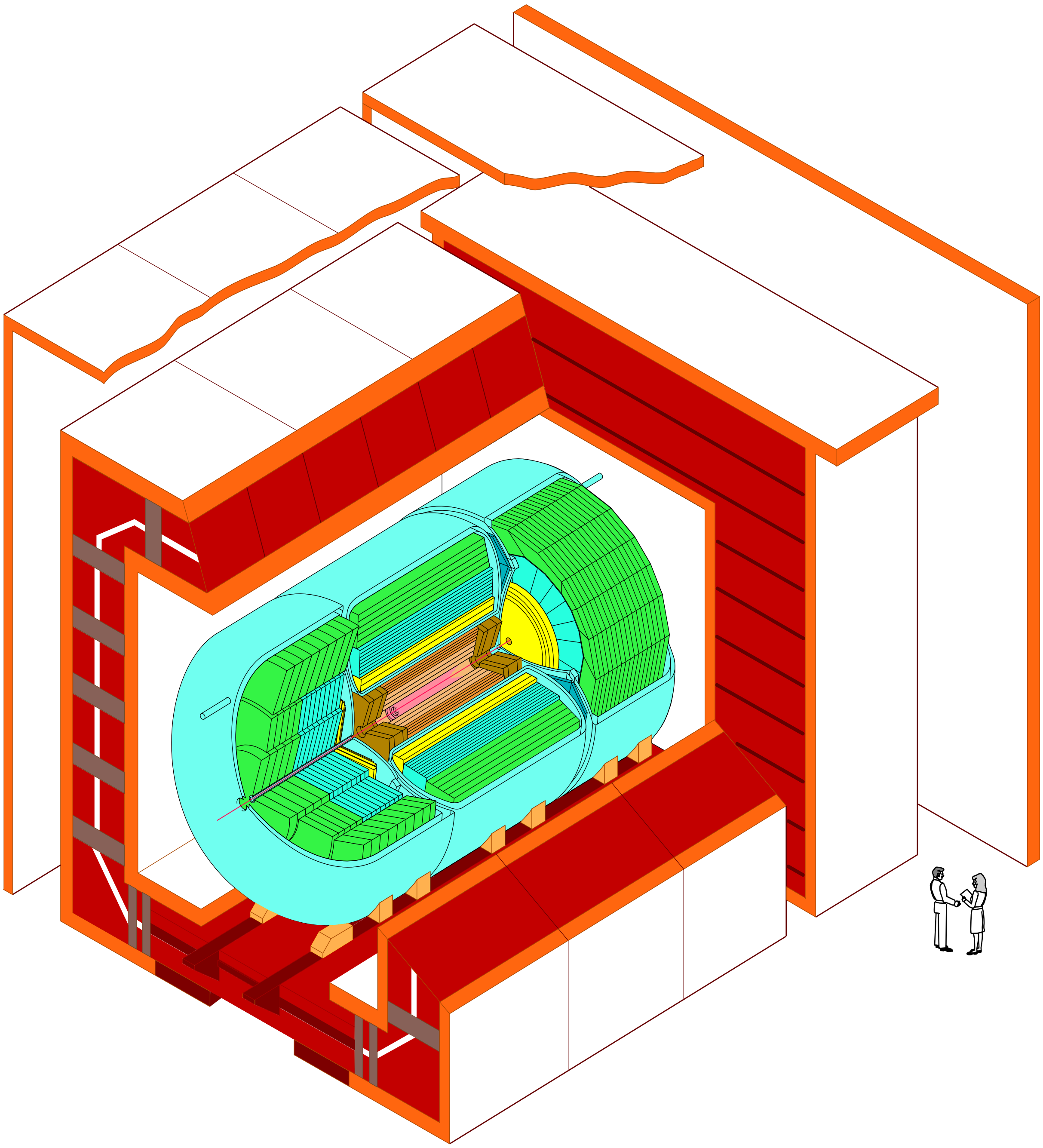
- Accurate tracking of charged particles is necessary for locating the collision vertex (and any secondary decay vertex) and for charged lepton identification. A magnetized tracking volume allows momentum spectrometry.

- Electrons and photons deposit their energy through electromagnetic interactions in the dense media of a calorimeter. The energy is contained in a short and very narrow volume.

- Quarks and gluons form "jets" of hadrons that also deposit all their energy in the calorimeter, but primarily through strong (nuclear) interactions. The resultant "showers" of energy penetrate deeper and spread wider.

- Muons penetrate through the calorimeter, and leave information about their momenta in magnetized tracking devices located outside of it.
- Neutrinos leave no trace in any detector component, and their presence can only be inferred from the principle of conservation of momentum. Only the component of neutrino momenta perpendicular to the beamline ($\not\!\!E_T$) can be measured at hadron colliders.
- Tau leptons decay before reaching any detector element: either leptonically (to e or μ) or hadronically to a small number of charged and neutral particles, and one or more neutrinos. Hadronic decays of τ's lead to calorimetric energy profiles narrower than those initiated by quarks and gluons.
- A jet initiated by a b (c) quark is often (sometimes) characterized by a secondary decay vertex well separated from the primary production vertex of the B (C) hadron. Such decays also contain e's and μ's more often than lighter jets (u, d, s, g).

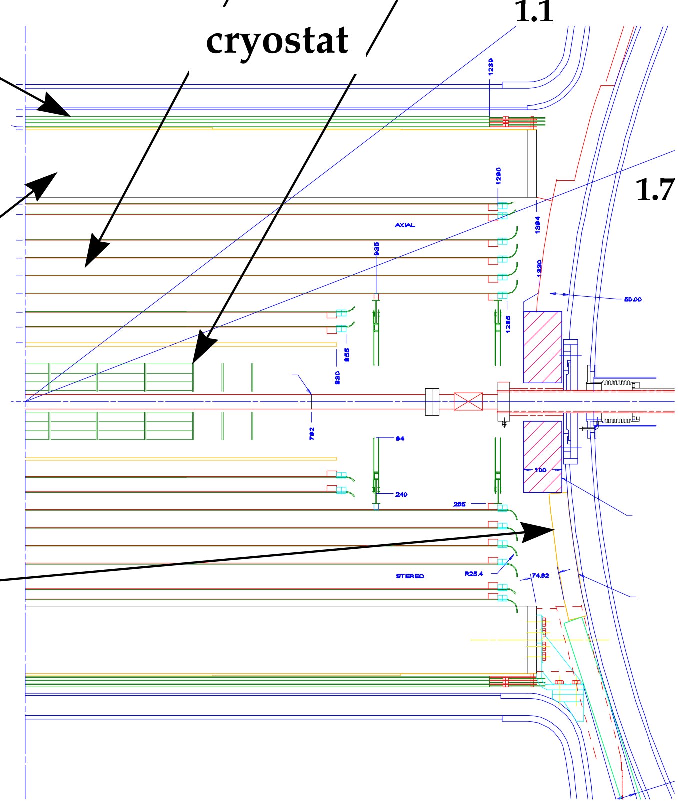
The DØdetector



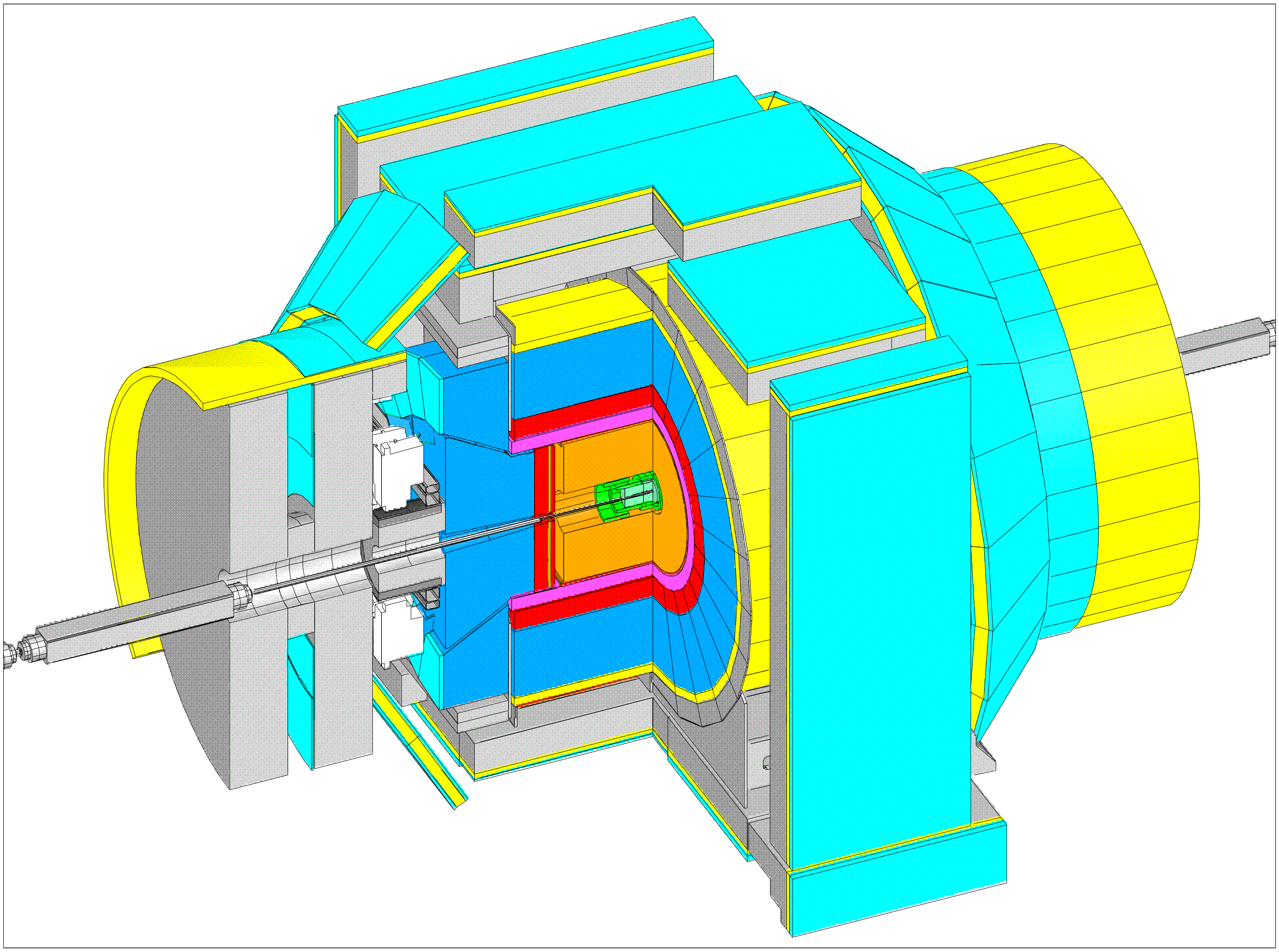
DØ Detector

The D0 Upgrade - Tracking

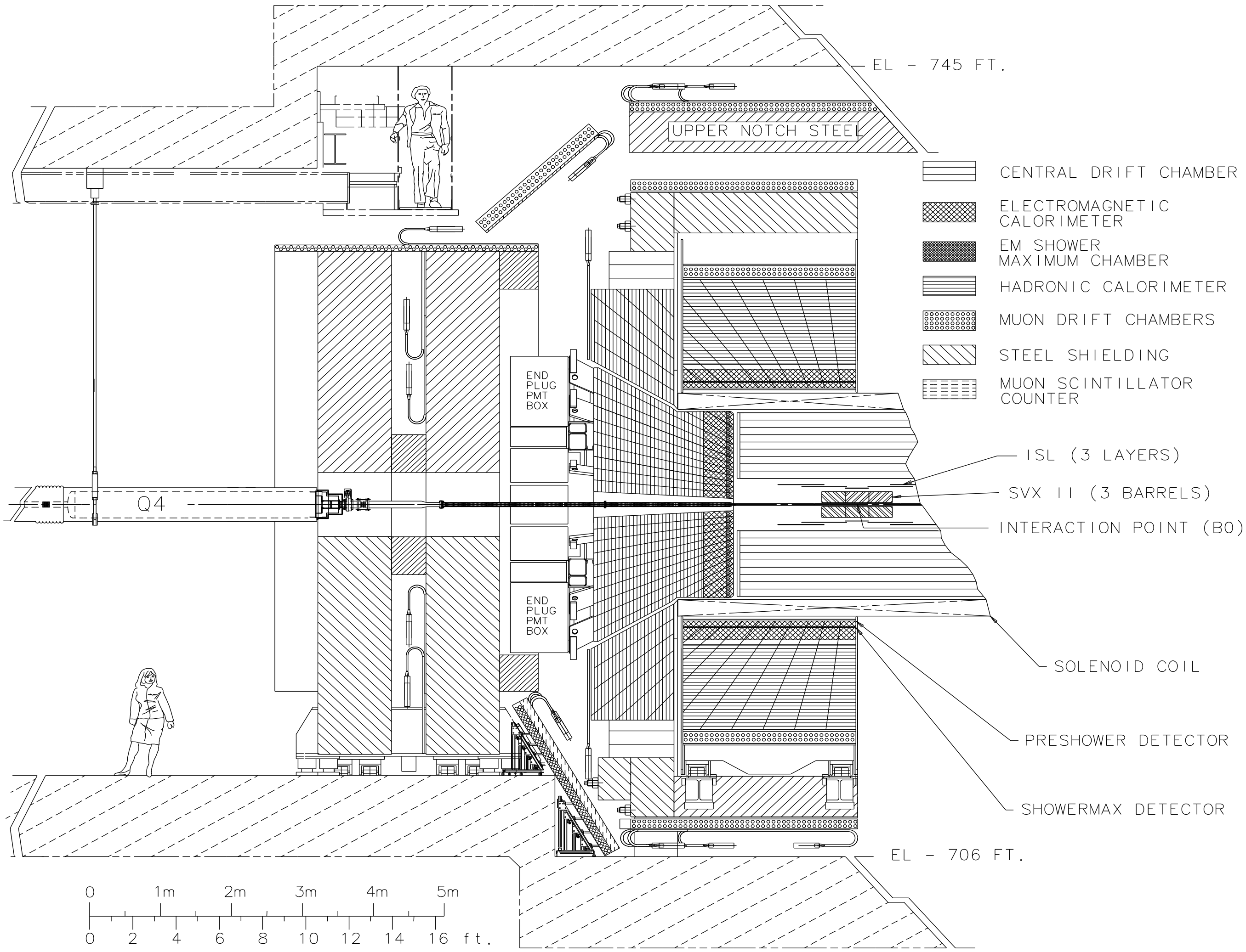
- **Silicon Tracker**
  - Four layer barrels (double/single sided)
  - Interspersed double sided disks
  - 840,00 channels
- **Fiber Tracker**
  - Eight layers sci-fi ribbon doublets (z-u-v, or z)
  - 74,000 830um fibers w/ VLPC readout
- **Central Preshower**
  - Scintillator strips, WLS fiber readout
  - 6,000 channels
- **Solenoid**
  - 2T superconducting
- **Forward Preshower**
  - Scintillator strips, stereo, WLS readout
  - 16,000 channels



The CDF detector



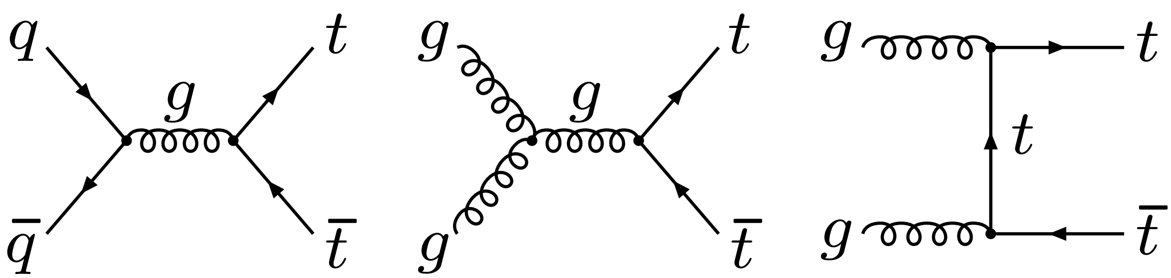
The CDF detector: elevation



2. Production of Top Quarks

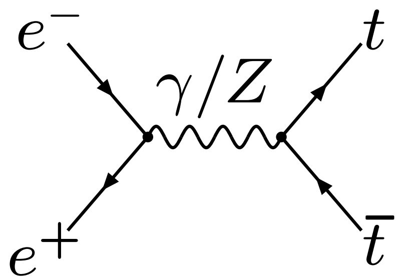
2.1. Top-antitop pair production

- At hadron colliders, top quarks are produced most often in pairs via strong interactions.



- Such events have been used in measuring the rate of production ($\sigma(p\bar{p} \rightarrow t\bar{t})$) and the mass of the top quark (m_t) at the Tevatron.
- Strong interaction $\Rightarrow$
  - More signal, but also extremely large background. Triggering is a major challenge.
  - Signal smudged by initial-state radiation, spectator interaction, multiple collisions.
  - Energy and polarization of colliding partons cannot be precisely controlled or determined.

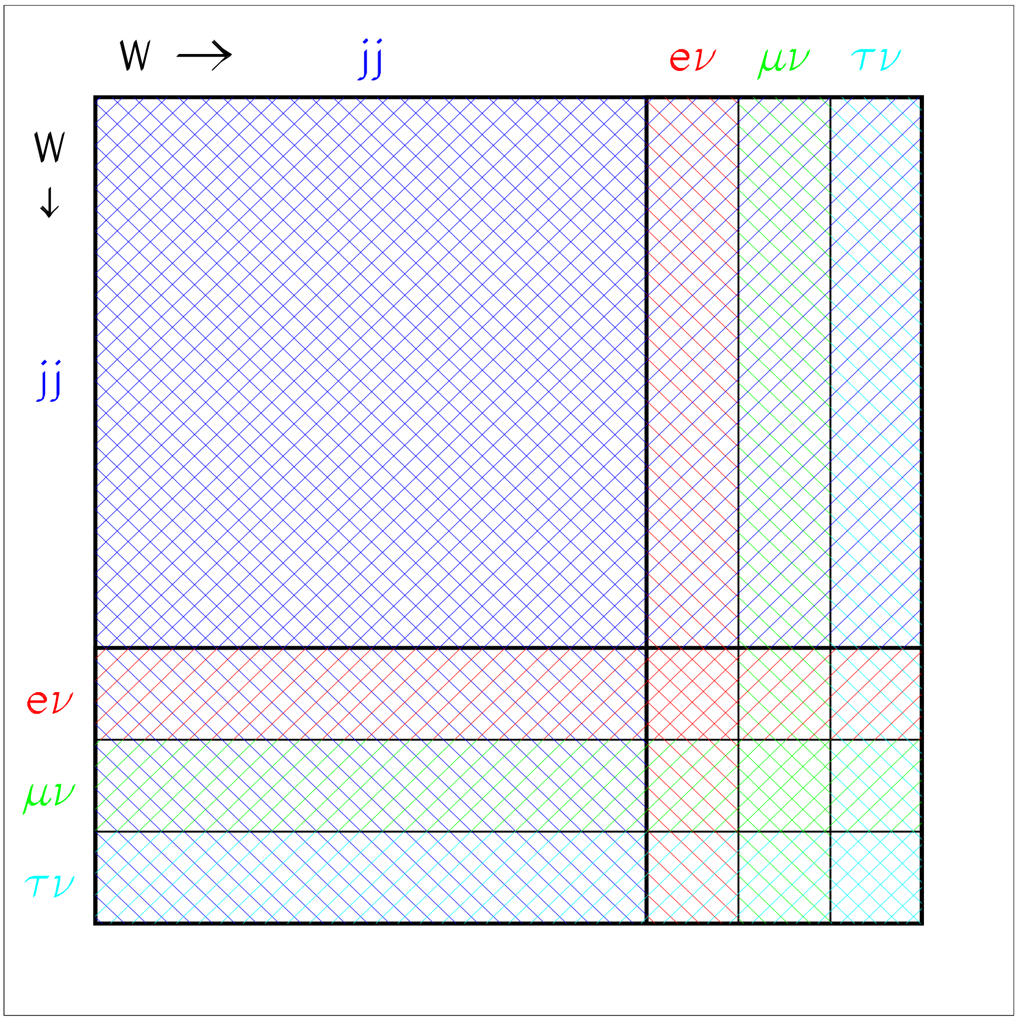
- At a lepton collider, top quarks are produced in pairs via electroweak interactions

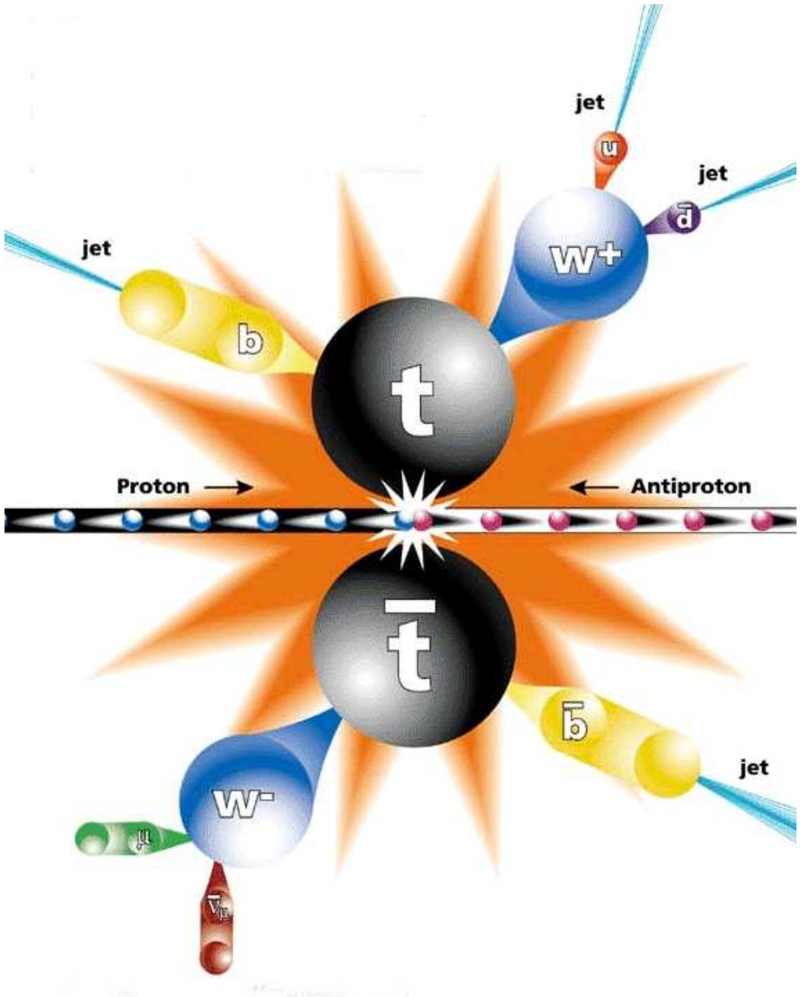


- Although the cross section for this process is much smaller, it has many desirable features. Electroweak interaction $\Rightarrow$
  - Fewer events, but background-free. No triggering necessary, all events are recorded.
  - No initial-state radiation, spectator interaction, multiple collisions. One clean event can be better than a dozen dirty ones.
  - Energy and polarization of colliding partons can be precisely controlled: extremely useful for precision measurements of mass, width, coupling parameters.
  - Events can be fully reconstructed.
  - Unique sensitivity to some new physics scenarios through production cross section, kinematics, and decays.

The final state signature of $t\bar{t}$ events

- Each $t\bar{t}$ pair decays into two W bosons and two b quarks.
- The final state of a $t\bar{t}$ system is primarily classified by the decay modes of the two W bosons:

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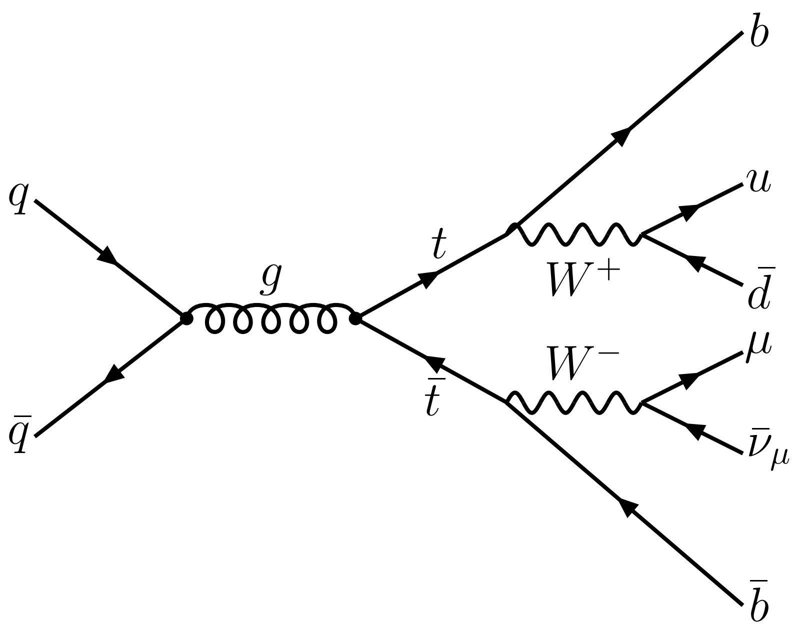
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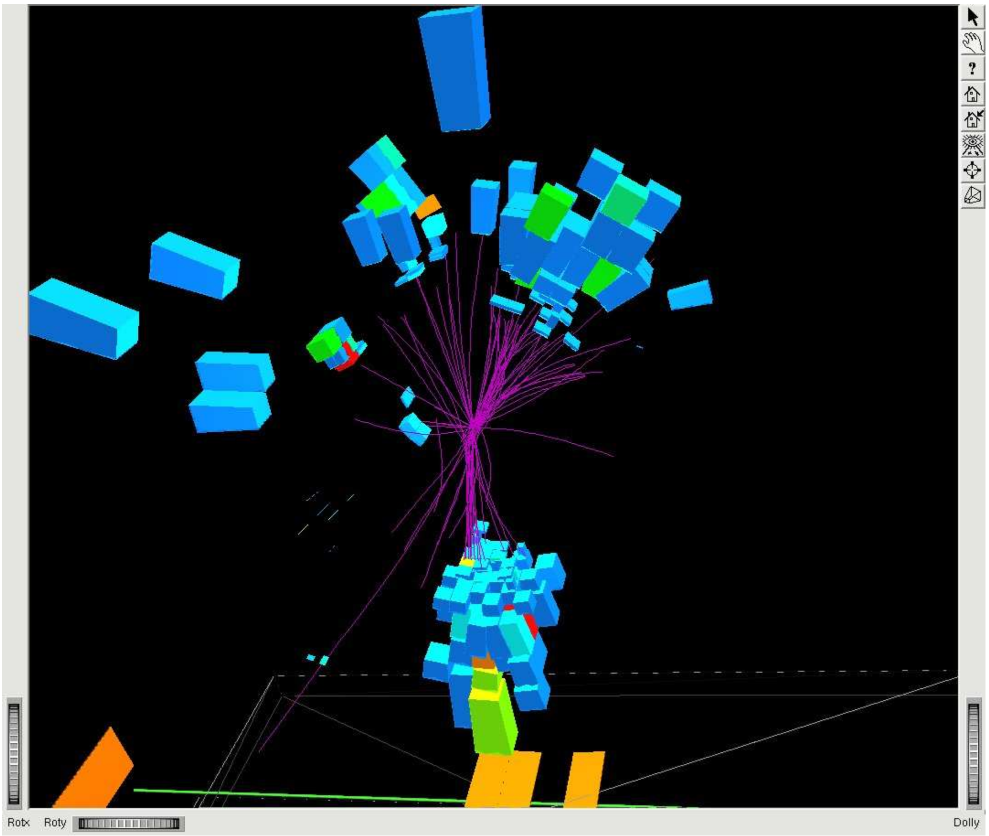
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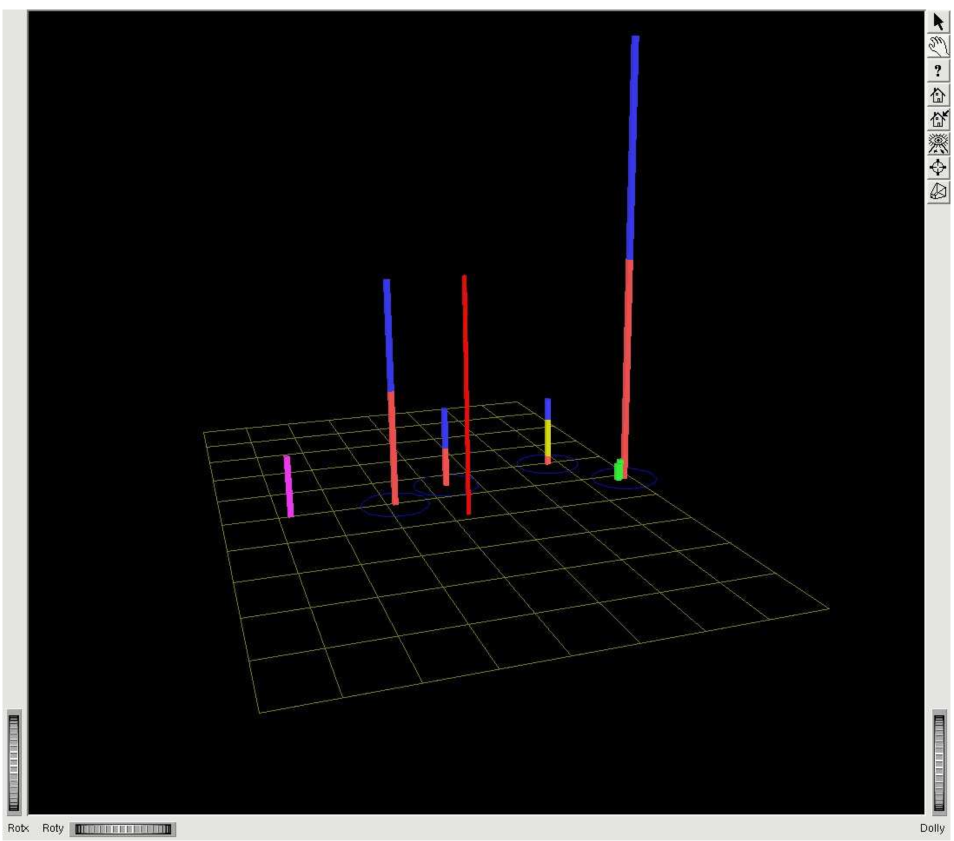
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Decay channels for $t\bar{t}$ events

Three broadly defined channels:

1. Dilepton channels: Both Ws decay leptonically (to e or μ).

   Signal:
   Two isolated high-p_T leptons, large missing transverse momentum (from 2 neutrinos) and two high-p_T (or high E_T) jets (from 2 b quarks).

   Background:
   - Physics: $ZX \to \tau^+\tau^- X \to l^+l^- + \not{E}_T + jets, WWX \to l^+l^- + \not{E}_T + jets.$
   - Instrumental: Jets initiated by quarks or gluons in QCD multijet events misidentified as electrons, muons from decays of heavy quarks being misidentified as being isolated, measurement fluctuations resulting in large $\not{E}_T$.

2. Single lepton channels: One W decays leptonically (to e or μ) while the other decays hadronically (to 2 jets).

Signal:
One isolated high-p_T lepton, large missing transverse momentum (from 1 neutrino) and four high-E_T jets (2 from W and 2 from bs).

Background:

- Physics: $WX \rightarrow l + \not{E}_T + jets.$
- Instrumental: Jets initiated by quarks or gluons in QCD multijet events misidentified as electrons, muons from decays of heavy quarks being misidentified as being isolated, measurement fluctuations resulting in large $\not{E}_T$.

3. All-hadronic channels: Both Ws decay hadronically (each to 2 jets).

   Signal:
   Six high-E_T jets (4 from Ws and 2 from bs).

   Background:
   - Physics: QCD multijet events containing b or c quarks.
   - Instrumental: Negligible.

Events with jets tagged as b candidates are given special consideration. This is particularly important at hadron colliders, since such jets are rare in background. In the more contaminated channels, b-tagging may be a part of basic selection.

Measurement of $\sigma(p\bar{p} \to t\bar{t})$

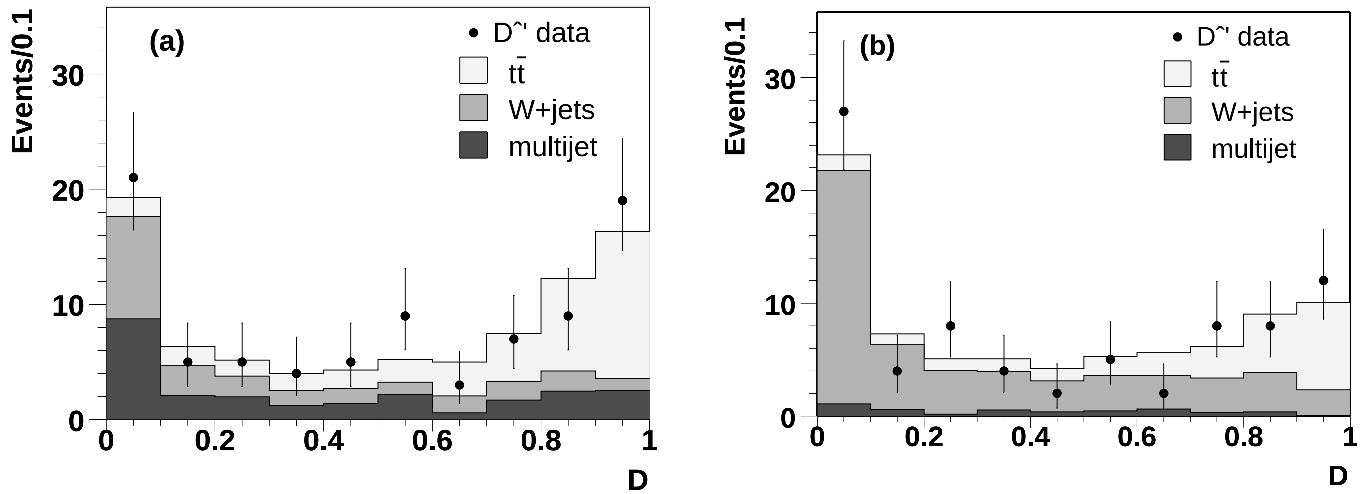
General procedure

- Devise selection criteria to maximize signal significance. Typically, one looks for events containing high-p_T partons well separated from each other. Jets, e, μ, τ, ν, with p_T above 15-20 GeV are required. The exact threshold depends on detector resolution, # of objects, background etc. Sophisticated pattern-recognition algorithms (e.g. artificial neural networks) are used often.

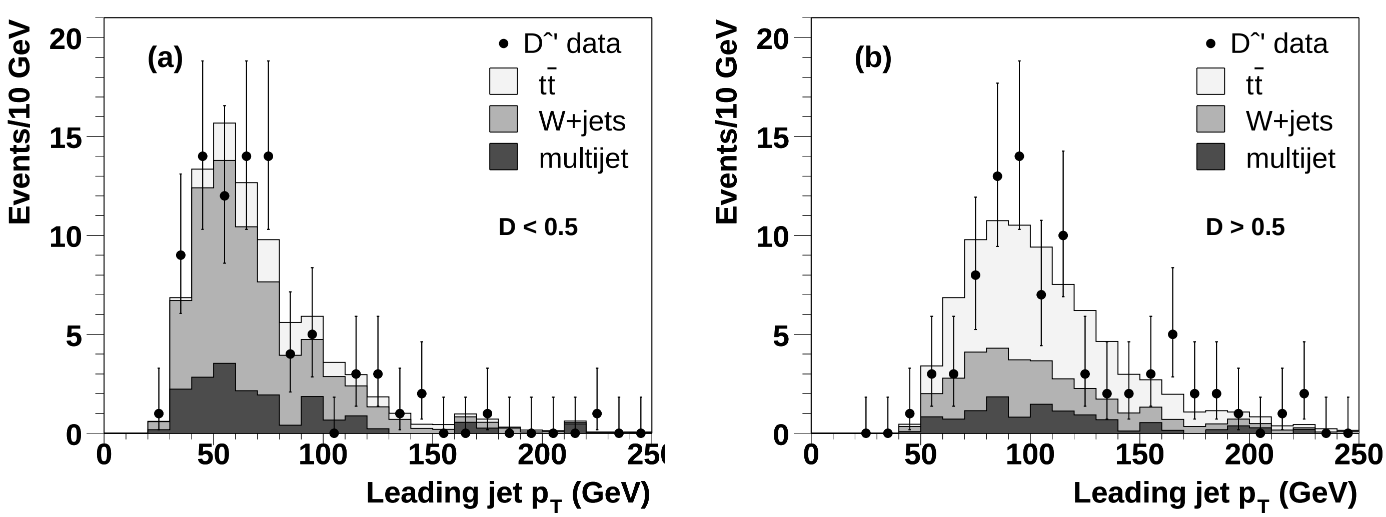
- Estimate background using data (extrapolating from background-dominated regions of phase space) and/or Monte Carlo simulations.

- Any significant excess in data over estimated background is interpreted as Signal. Signal cross section is calculated by dividing the excess by total luminosity:

$$\sigma = \frac{N_{\text{obs}} - \langle N_B \rangle}{\int \mathcal{L} dt} \tag{3}$$



Neural network output for (a) e+jets, and (b) μ+jets candidates (DØ Run 2 topological analysis, 230 pb^{-1}).

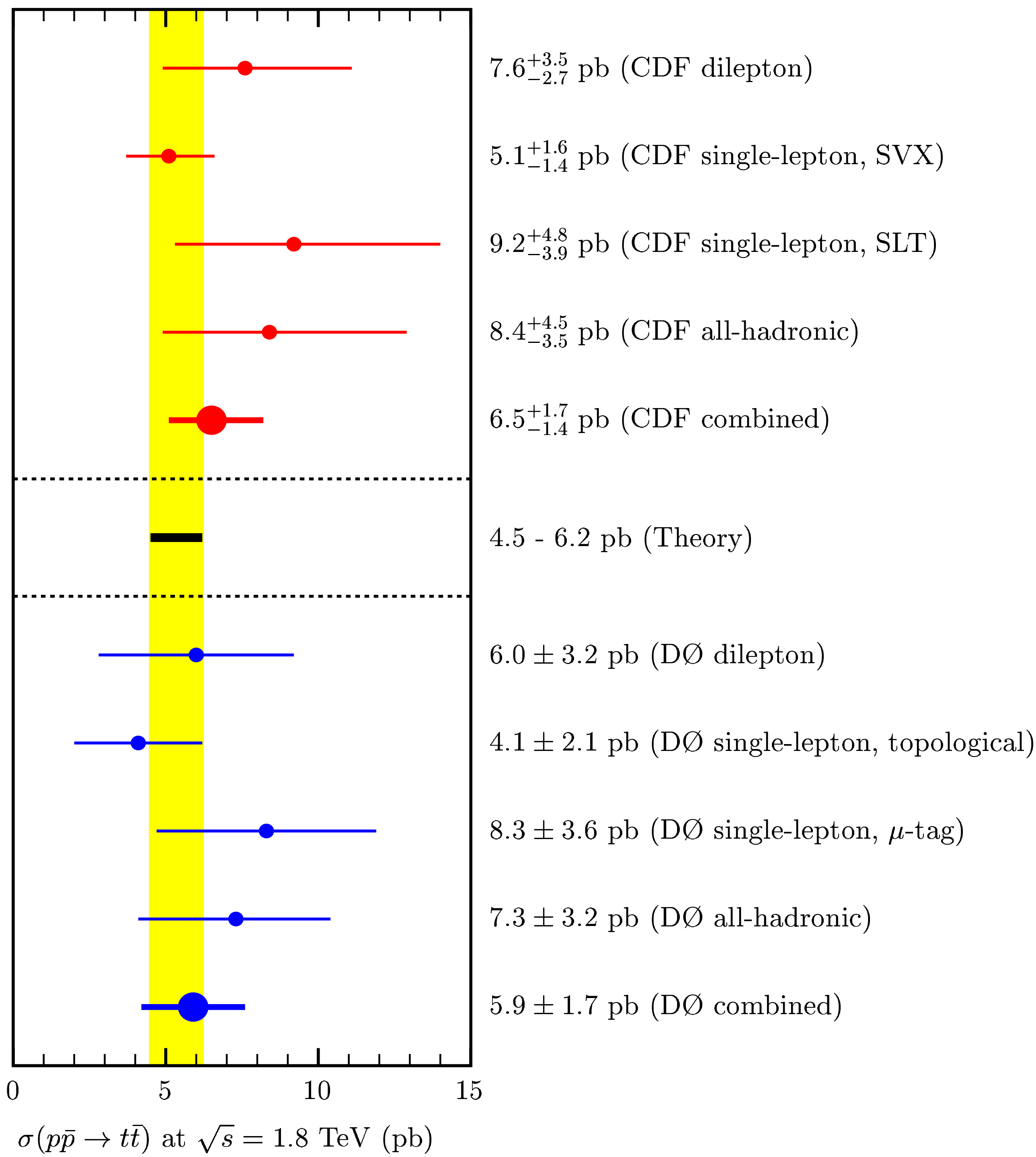


Leading jet p_T distribution for (a) $D_{NN} < 0.5$, and (b) $D_{NN} > 0.5$ in the same sample.

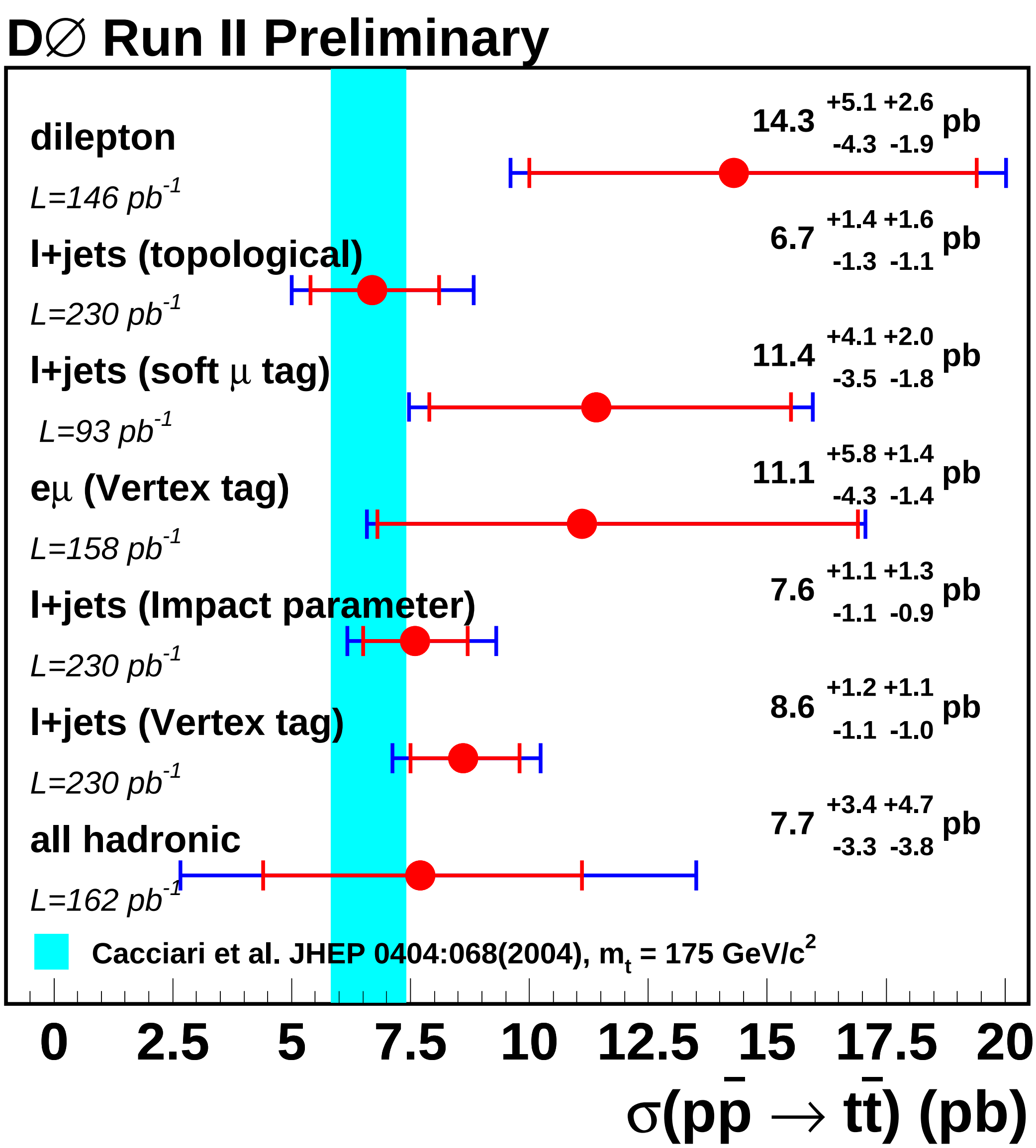
$\sigma(p\bar{p} \to t\bar{t})$ from Tevatron Run 1

	DØ		CDF	
Channel	N_{obs}	$\langle N_B \rangle$	N_{obs}	$\langle N_B \rangle$
Dilepton	5	1.4 ± 0.4	9	2.4 ± 0.5
Single lepton (SVX b-tag)	-	-	34	9.2 ± 1.5
Single lepton (Lepton b-tag)	11	2.4 ± 0.5	40	22.6 ± 2.8
Single lepton (Topological)	19	8.7 ± 1.7	-	-
All-hadronic	41	24.8 ± 2.4	187	142 ± 12
$e\tau$, $\mu\tau$	-	-	4	~ 2
$e\nu$	4	1.2 ± 0.4	-	-

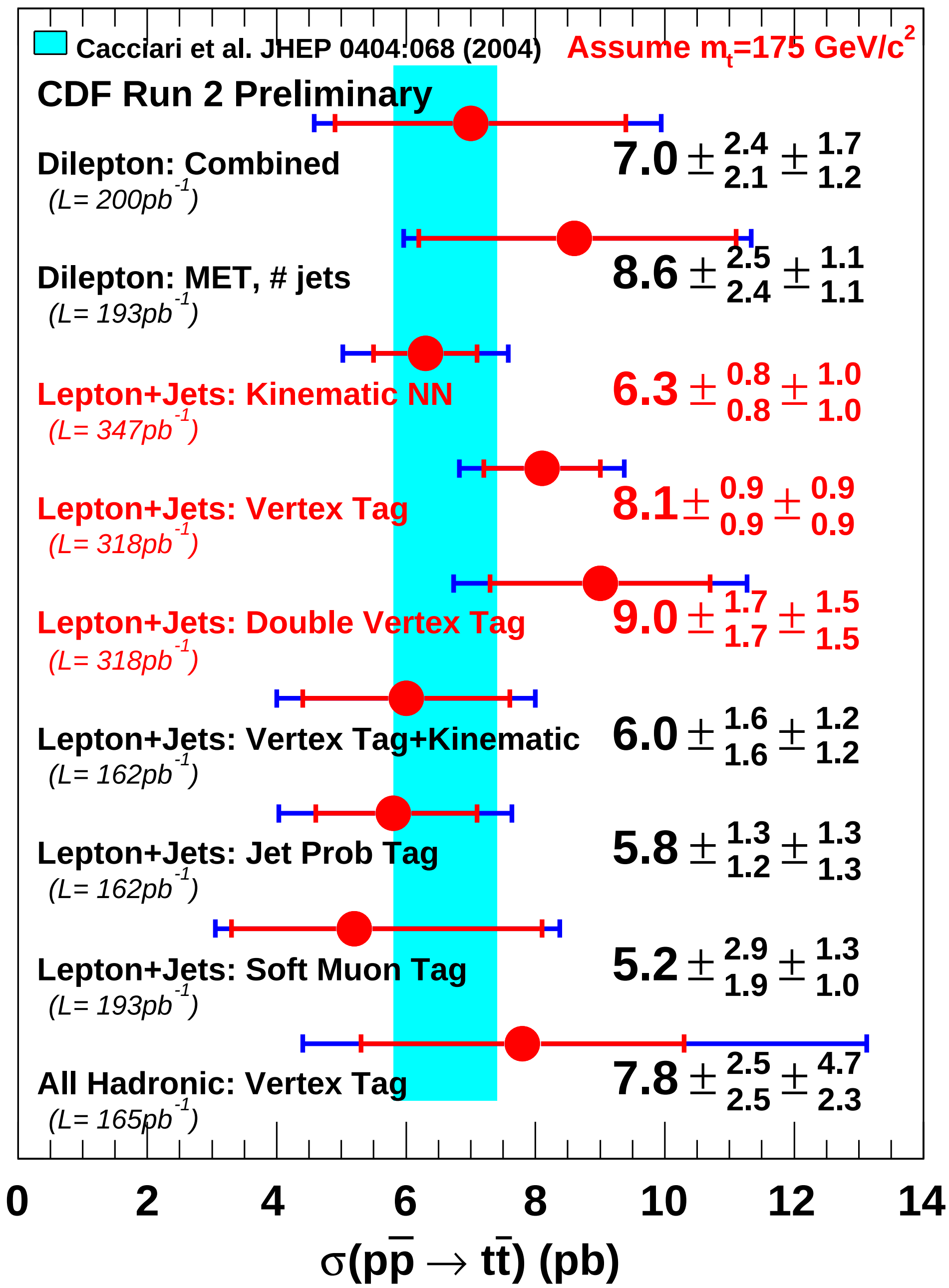
$\sigma(p\bar{p} \to t\bar{t})$ from Tevatron Run 1



$\sigma(p\bar{p} \to t\bar{t})$ from DØRun 2

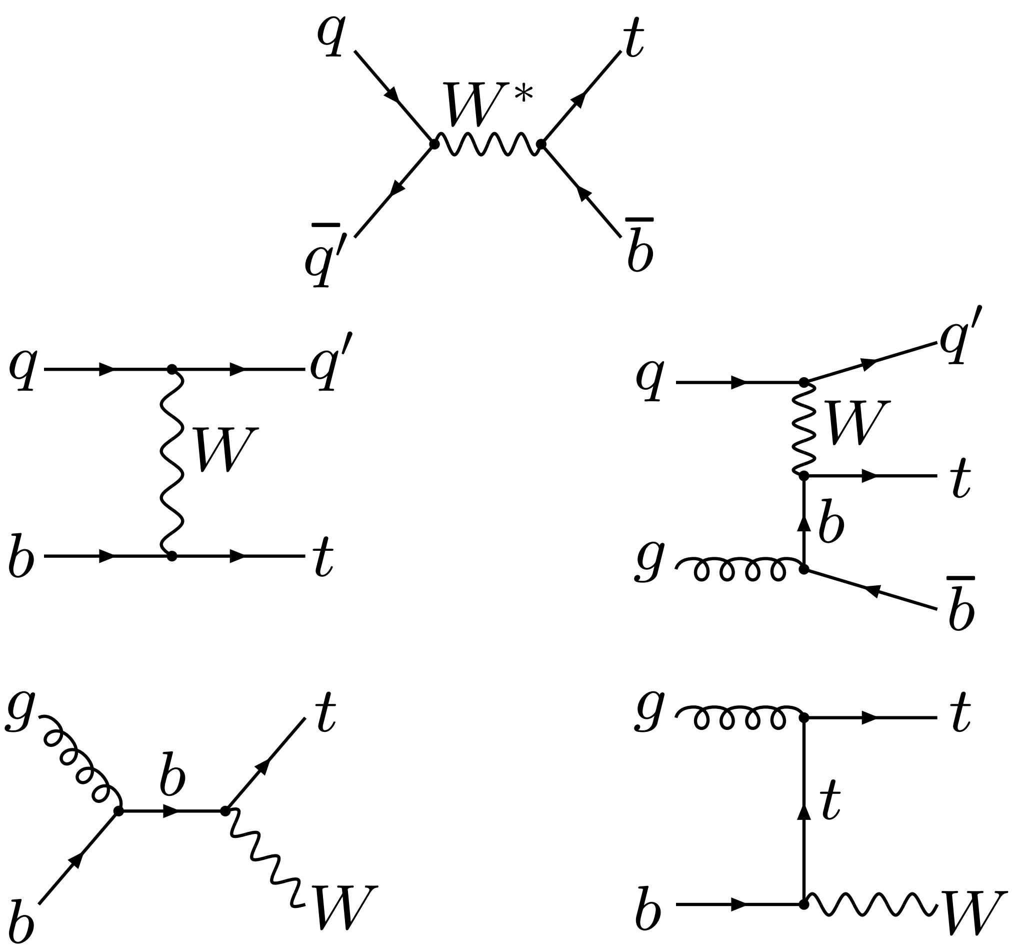


$\sigma(p\bar{p} \to t\bar{t})$ from CDF Run 2



2.2. Single Top Production

- At hadron colliders, top quarks can be produced singly via weak interactions.



Such events occur less than half as frequently as $t\bar{t}$ and the signal is more difficult to extricate from background.

- Rate and kinematics are direct probe of Wtb vertex in general and $|V_{tb}|$ in particular
  - All cross sections are proportional to $|V_{tb}|^2$).
  - $V - A$ structure of $SU(2)_L$ weak interaction ⇒polarized production of top.
- Important background to WH production followed by $H \longrightarrow b\bar{b}$.
- Theoretical predictions:

Process	Tevatron Run 2	LHC (t)	LHC ($\bar{t}$)
$\sigma^{NLO}_{s-\text{chan}}$ (pb)	0.447 ± 0.002	6.55 ± 0.03	4.07 ± 0.02
$\sigma^{NLO}_{t-\text{chan}}$ (pb)	0.959 ± 0.002	152.6 ± 0.6	90.0 ± 0.5
$\sigma^{LL}_{\text{assoc.}}$ (pb)	0.093 ± 0.024	31^{+8}_{-2}	31^{+8}_{-2}

- Latest limits from DØ:
  - $\sigma(tb)_{s-\text{channel}} < 6.4$ pb at 95% CL
  - $\sigma(tqb)_{t-\text{channel}} < 5.0$ pb at 95% CL

2.3. Sensitivity to New Physics

- Heavy scalar or vector bosons, both charged and neutral, fundamental and composite, appear in all extensions of the SM. ⇒new ways for both pair- and single-top production.
  - Neutral bosons (Z', ϕ^0, η_T) alter $\sigma(t\bar{t}X)$.
  - Charged bosons (W', $\phi^\pm$, $\pi_t^\pm$) alter $\sigma(tX)$.
- Since these models seek to explain why the top quark is so heavy, implications are usually stronger for top than for other fermions.
- Precision measurement of the cross sections and comparison with SM predictions allows us to constrain or discover such processes.
- We have found no significant deviation from the SM so far, but large uncertainties in both theoretical calculations and experimental measurements lead to rather weak constraints on parameters of new physics models.
- Some of these processes can hide behind the large background at hadron colliders (Tevatron, LHC), but will be easily detected at a lepton collider (ILC).

3. Decays of Top Quarks: 3.1. SM decays

- The SM predicts $B(t \to Wb) > 0.998$.
- The rest goes to off-diagonal CKM modes, $t \to Wq$, where $q = s, d$. We'll talk about these later.
- Flavor-changing neutral current (FCNC) decays, $t \to X^0 q$, where $X^0 = g, \gamma, Z, H$, are highly suppressed by the GIM mechanism. Branching fractions are $\mathcal{O}(10^{-13})$ - not accessible in the foreseeable future.
- Current direct limits on FCNC decays of top from Tevatron (CDF, Run 1):
  - $B(t \to c\gamma) + B(t \to u\gamma) < 0.032$,
  - $B(t \to cZ) + B(t \to uZ) < 0.33$,
- Limits expected from LHC: $\sim 2 \times 10^{-4}$ for both.
- Few extensions of the SM predict FCNC t decays at such high levels. Still, we need to stay alert…

W helicity in top decays

- SM, $t \rightarrow Wb$ decays are described purely by the universal $V - A$ charged current interaction.
- The W is “real” in a top decay $\Rightarrow$distinctive helicities. Decay to a positive-helicity W boson is suppressed by a chiral factor m_b^2/M_W^2. So, the W helicity is essentially a superposition of only the zero- ane negative-helicity states.
- At tree level in the SM, ignoring m_b, the fraction of longitudinal (zero-helicity) W bosons in the top rest frame is:

$$\mathcal{F}_0 = \frac{m_t^2/M_W^2}{1 + m_t^2/M_W^2} = 0.701 \pm 0.016 \tag{4}$$

- Finite m_b and NLO effects $\Rightarrow\sim$2% change.
- The large top mass exposes the longitudinal mode of the W $\Rightarrow$precise measurement of $\mathcal{F}_0$ serves as a stringent test of the SM.
- Indirect limit from $b \rightarrow s\gamma$ data (CLEO) constraints $\mathcal{F}_+$ to a few %.

- Angular distributions of decay products are sensitive functions of the $\mathcal{F}$'s.
- Both DØ and CDF have measured the $\mathcal{F}$'s in dilepton and single-lepton channels using several strategies ($\int_{Run2} \mathcal{L}dt = 162$ pb^{-1}, $\mathcal{F}_+ = 0$ assumed for measurements of $\mathcal{F}_l$):

Expt(Run)	Method	Result
CDF(1)	$p_T(\ell)$	$\mathcal{F}_0 = 0.91 \pm 0.37 \pm 0.13$, $\mathcal{F}_+ < 0.28$ (98% CL)
CDF(1)	$M^2(\ell b)$	$\mathcal{F}_+ < 0.24$ (95% CL)
DØ(1)	ME	$\mathcal{F}_0 = 0.56 \pm 0.31$
CDF(2)	$p_T(\ell)$	$\mathcal{F}_0 = 0.27^{+0.31}_{-0.21}$, $\mathcal{F}_0 < 0.88$ (95% CL)
CDF(2)	$M^2(\ell b)$	$\mathcal{F}_0 = 0.89 \pm 0.32 \pm 0.17$, $\mathcal{F}_0 > 0.25$ (95% CL)
DØ(2)	$\cos\theta^*$	$\mathcal{F}_+ < 0.24$ (90% CL)

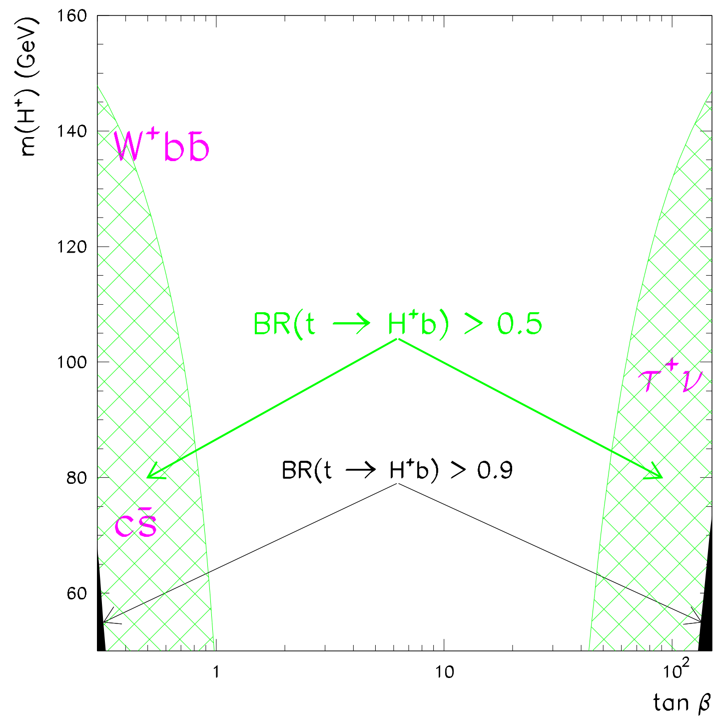
- The statistical uncertainty will be reduced by an order of magnitude by the end of Run 2, and to negligible levels at the LHC and the ILC.

3.2. Top Quark Decays Beyond the SM

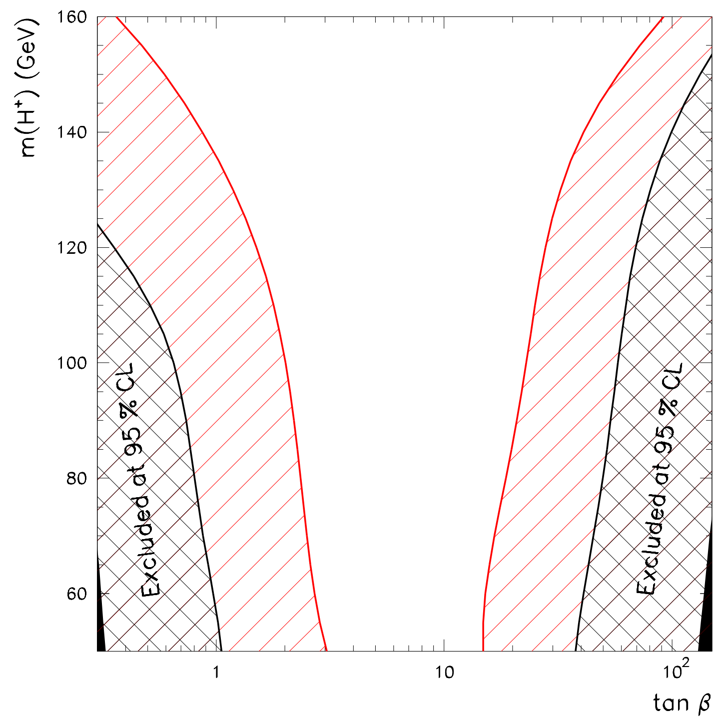
- In virtually every extension to the SM, alternative possibilities arise to compete with the SM modes:
  - Extended Higgs sector $\Rightarrow t \rightarrow H^+ b$
  - SUSY $\Rightarrow t \rightarrow \tilde{t}\tilde{\chi}_1^0$,
  - TC2 $\Rightarrow t \rightarrow \pi_t^+ b$
- In all cases, the coupling depends on fermion mass, or flavor, or both $\Rightarrow$look in data for deviations in the production rates and branching fractions from those predicted by the SM.
- Both appearance of new modes or enhancement over SM-predicted values, and disappearance of SM modes (to make way for new ones that may be hidden in excessive background) have been searched for by DØ and CDF for some of the more popular scenarios.
- Often, there are too many free parameters, and one is forced to make "reasonable" assumptions about some of them in order to pin down the rest ...

Search for $t \to H^+ b$

- The Standard Model postulates one complex scalar (Higgs) doublet. After 3 of its 4 degrees of freedom are expended in giving mass to the $W^\pm$ and Z^0 bosons, one manifests itself as a physical particle: H^0.
- The simplest extension to the SM $\Rightarrow$ a two-Higgs-doublet models (2HDM), resulting in five physical Higgs bosons: H^0, h^0, A^0, $H^\pm$.
- The electroweak sector in a 2HDM has 2 additional parameters: $\tan\beta$, m_{H+} (or m_A), where $\tan\beta \equiv$ ratio of V.E.V.'s of the two doublets.
- If $m_{H+} < m_t - m_b$, and $\tan\beta$ is not too close to $\sqrt{\frac{m_t}{m_b}}$, then $t \to H^+ b$ can compete with $t \to W^+ b$.
- Such a $H^\pm$ is not expected to noticeably alter the top production cross sections at any collider, but decays will be affected since Higgs coupling is proportional to mass.

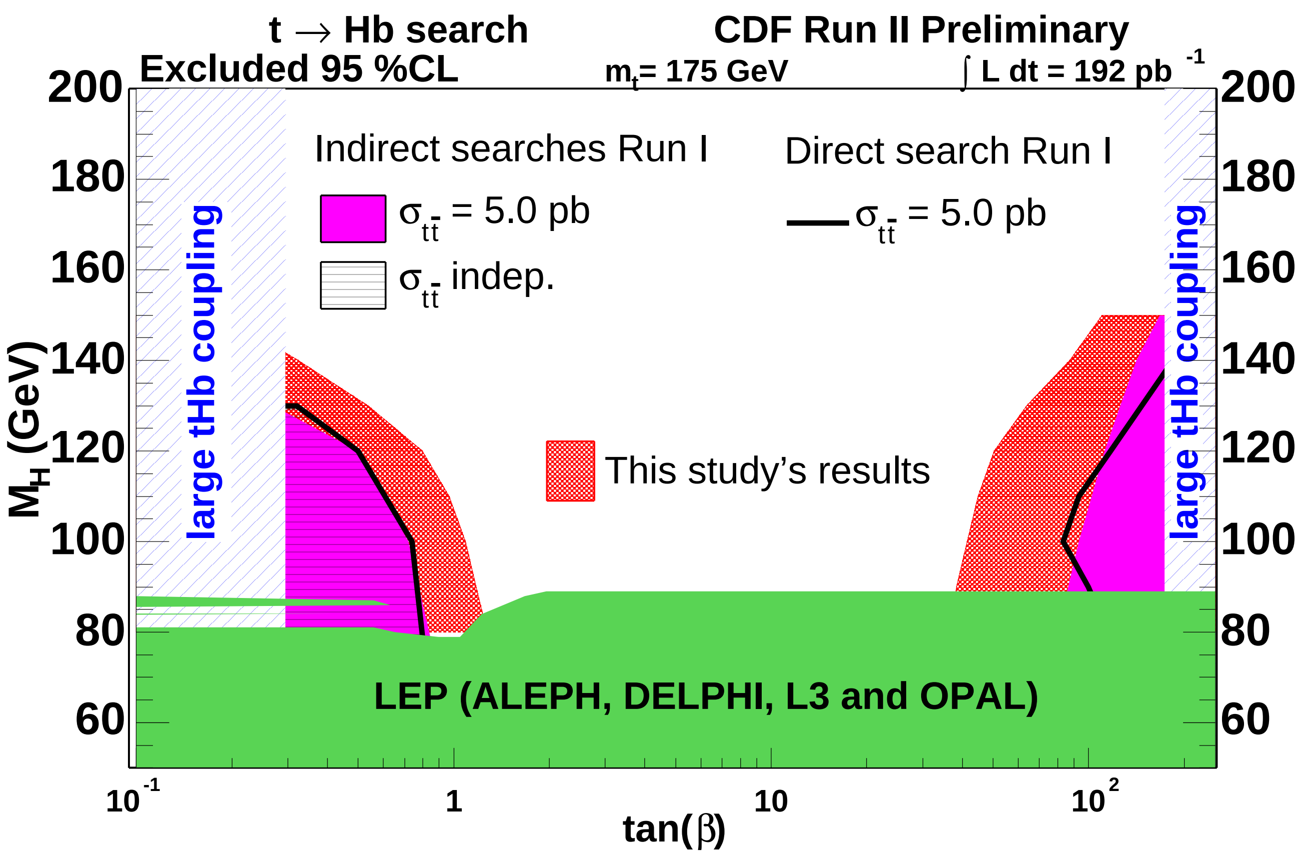


Disappearance search results from DØ Run1:



The Run 1 (Run 2 expected) limit corresponds roughly to $B(t \to H^+b) < 0.45(0.11)$ at 95% CL, except where $Wb\bar{b}$ dominates.

Run 1 and preliminary Run 2 results from CDF:



- No sign of a light charged Higgs as yet, but ...
- Some assumptions that went into in these analyses need coser scrutiny.

Supersymmetric Decays of the Top Quark

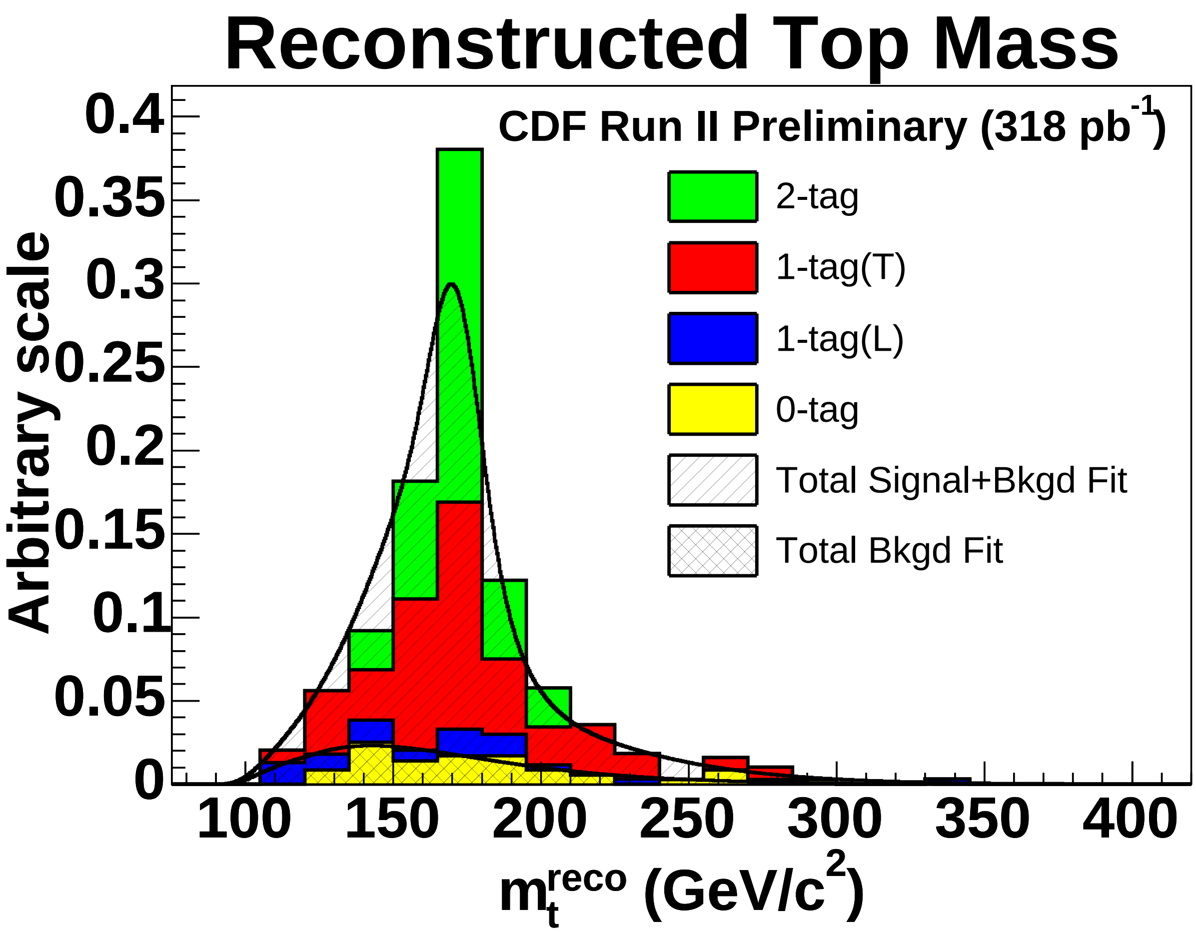
- The lightest stop, $\tilde{t}_1$ is thought likely to be the lightest squark, possibly lighter than top.
- This opens the possibility of $t \longrightarrow \tilde{t}\tilde{\chi}_1^0$, which can end in either $bq_1\bar{q}_2\tilde{\chi}_1^0\tilde{\chi}_1^0$, or $c\tilde{\chi}_1^0\tilde{\chi}_1^0$, depending on the superparticle masses and couplings.
- Since the branching fraction cannot be too large, it is best to look for events where precisely one of the top decays in the new way.
- The final state objects are the same, but angular and moomentum spectra are different.
- Unfortunately, often the new signatures face worse background than SM.
- Early results show nothing unusual, but they're pretty weak. Our main goal at this time is to understand the issues and set up the procedure. Stringent results will have to await high-volume (LHC) and/or ultra-clean (ILC) data.

4. Top quark properties: 4.1. Mass

General procedure

- Event selection and background estimation is similar to those for $\sigma(t\bar{t})$ measurement, but any associated bias on m_t must be carefully accounted for.
- Examine strongly m_t-dependent variables (reconstructed m_t, if available, is a natural choice).
- Using simulated signal templates for different values of m_t, determine which one best fits the excess of data over background.
- Combinatorial ambiguities, often compounded by extra jets from initial- and final state radiation, or occassional loss of a jet pose serious difficulties.
- Weighing each candidate and each interpretation of it differently, depending on how well it fits signal and background hypotheses, affords the most precise measurement, but it is a more involved procedure.

m_t from single-lepton events at CDF

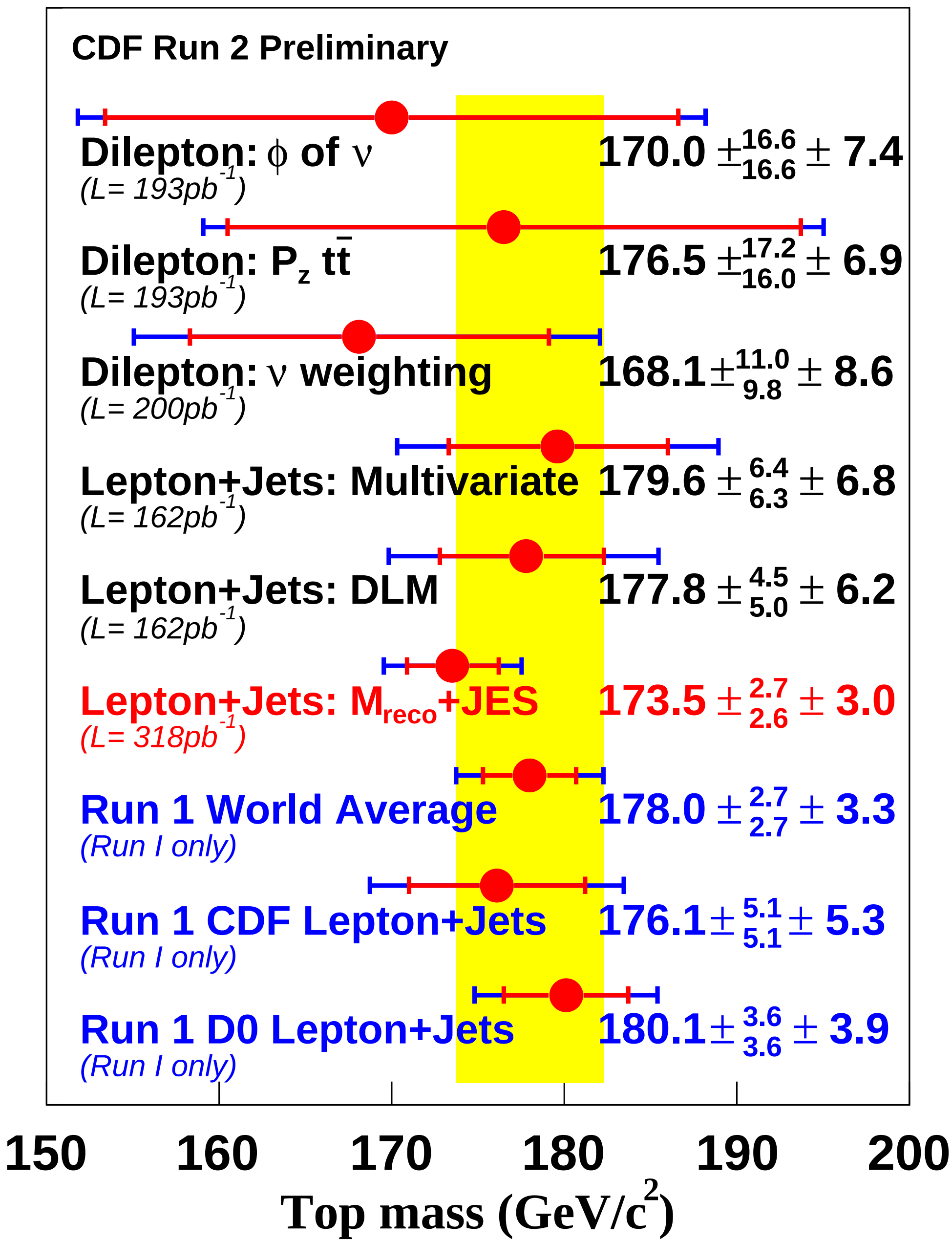


Template method with in-situ JES determination gives (preliminary result based on 138 candidate events from $\int \mathcal{L}\lceil\sqcup = \ni\infty\forall$ pb^{-1})

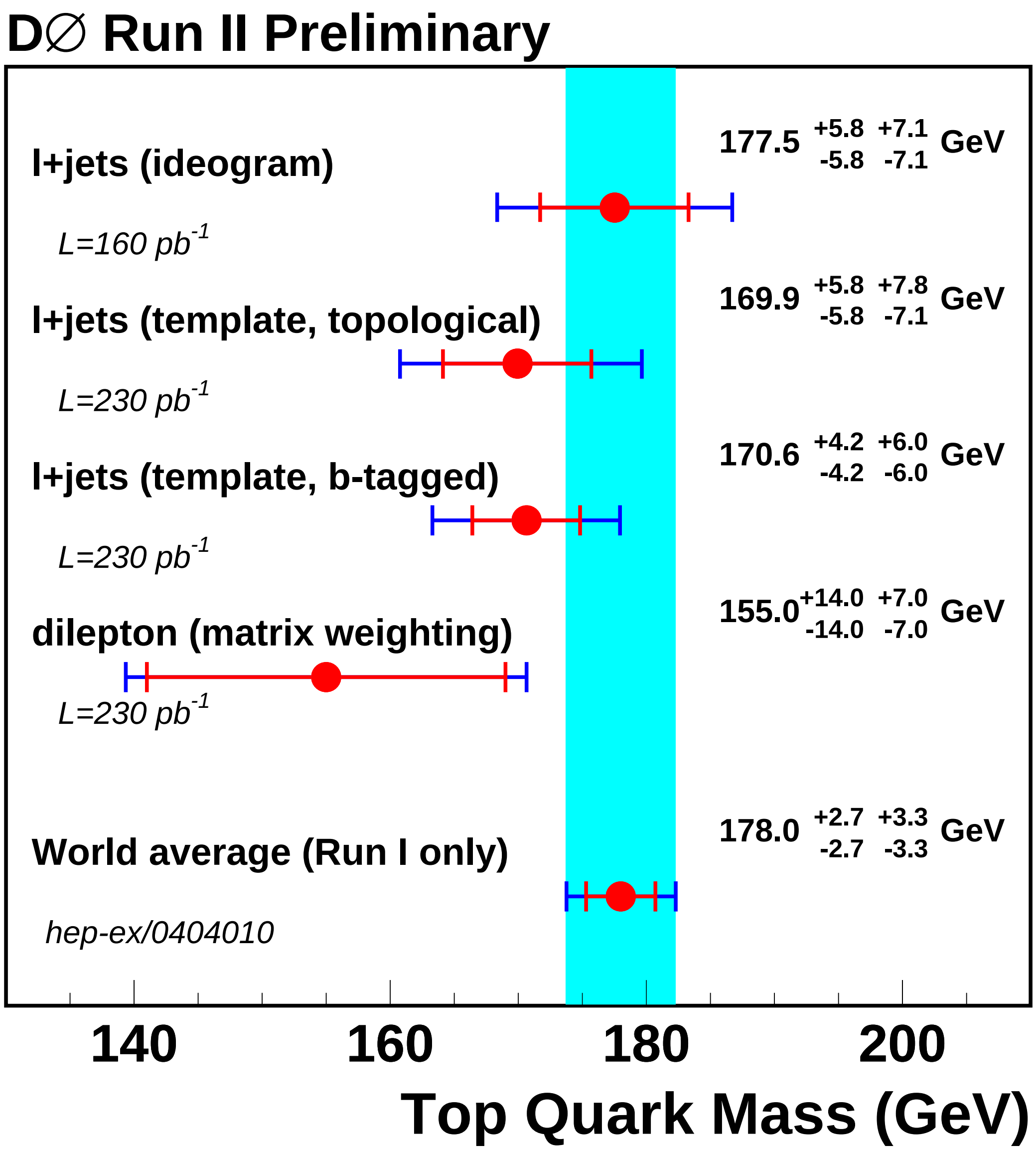
$$m_t = 173.5^{+2.7}_{-2.6}\ \text{(stat)} \pm 2.5\ \text{(JES)} \pm 1.7\ \text{(syst)}$$

A total uncertainty of 4.1 GeV: better than Run 1 world average.

Latest results from CDF



Latest results from DØ



Present and future of top mass measurement

- Measuring m_t, together with M_W, is vitally important in order to constrain M_H.
- Top mass has now been determined to 2.3%.
- It is still limited by statistics. Some of the systematics will improve with statistics.
- Matrix-element method will further reduce the statistical uncertainty.
- Combining different channels and results from DØ and CDF will help too.
- By the end of Run 2, we hope to bring the total uncertainty to below 3 GeV.
- More precise but rarer final states ($b \longrightarrow \psi \longrightarrow \ell^+\ell^-$) will be accessible to the LHC experiments. These combined with end-point fits - another luxury afforded by huge statistics - could allow for $\sim$1 GeV precision in m_t from experiment.
- Theoretical uncertainties, owing to incompleteness of radiative corrections, are $\sim$1.5 GeV. These are very difficult to reduce.

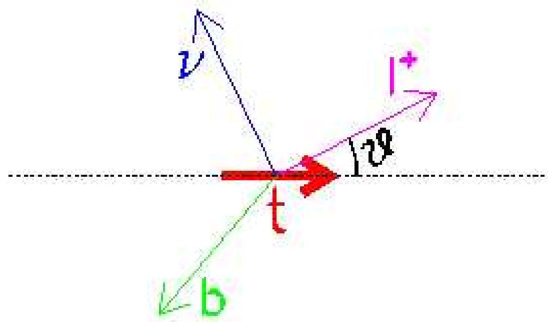
- At the ILC, threshold scans, full event reconstruction, and cleaner events, precise theoretical calculation of many sensitive variables etc. should allow for measurement of m_t within $\mathcal{O}(100)$ MeV.

Expected precision of m_t, M_W measurements:

Collider	Tevatron	LHC	ILC
type	$p\bar{p}$	pp	e^+e^-
δm_t (GeV)	3	1	0.1
δM_W (MeV)	26	9	1

4.2. Spin

- Decay before hadronization ⇒spin at production reflected on angular distribution of decay products.
  - No other quark decays quickly enough.
- At Tevatron and LHC, the colliding particles are unpolarized, so the spin of each top considered separately is random, but the spins of the top and the antitop in a given event are correlated.
- At the ILC, with polarized beams, the spin of each top quark, as well as the correlation, can be studied.
- The charged lepton and down-type quarks are most sensitive, but it is difficult to uniquely identify the latter ⇒only the dilepton and single-lepton channels are useful.
- A good test for Wtb coupling. A significant departure from the SM prediction could point to new physics.



Differential decay rate of top quark:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_i)} = \frac{1+\alpha_i \cos\theta_i}{2} \qquad (5)$$

particle (i)	α_i for m_t = 175 GeV
e^+ or d	1
ν or u	-0.31
W^+	0.41
b	-0.41

- For $t\bar{t} \longrightarrow l^+l^-X$ events at the Tevatron, one studies the double-differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}. \qquad (6)$$

- All spin-correlation information is in κ.

- Within large statistical uncertainties, current measurements (from Run 1) are consistent with the SM predictions. The method has been established, vastly improved results are expected soon.

4.3. Charge

- Some theorists contend that the observed "top" could be an exotic quark with $Q = -\frac{4}{3}$.
- The only way to check this at hadron colliders is to compare the observed rate and kinematics of $t\bar{t}\gamma$ events with SM predictions.
- Either way, the rate is too low for a definitive test at the Tevatron.
- At the LHC, the issue can be resolved with 4-6 months of data ($\sim$10 fb^{-1}).
- At the ILC, $\sigma(t\bar{t})$ is extremely sensitive to Q_t. The debate can be settled with less than 1 hour of data.

4.4. Gauge couplings

- It is important to measure the top quark's coupling to the SM gauge bosons: g, $W^{\pm}$, Z, and γ, lest anomalous couplings, which may or may not involve new particles, go undetected. Search for CP violation in the top sector is normally addressed in this language.
- Couplings to g and $W^{\pm}$ are fairly well tested already at the Tevatron, and will continue to be refined through studies of pair- and single-top production, kinematics, spin correlations, W helicity, etc.
- Couplings to Z and γ are harder to study at hadron colliders, but will be possible with sufficient statistics at the LHC.
- The ILC will offer high-precision tests of all of top quark's gauge couplings, especially the electroweak.

4.5. Lifetime and V_{tb}

- The CKM matrix element V_{tb} is intimately related to the top quark lifetime. At LO,

$$\Gamma\,(t \to Wb) \;=\; \frac{G_F}{8\pi\sqrt{2}}\, m_t^3\, |V_{tb}|^2 \left(1 - 3\,\frac{M_W^4}{m_t^4} + 2\,\frac{M_W^6}{m_t^6}\right) \;=\; 1.56\,\text{GeV} \tag{7}$$

where $\Gamma = \frac{\hbar}{\tau}$ is the width of the top quark, and τ its lifetime. The NLO result for the width is 1.42 GeV.

- Indirect measurements assuming 3 generations of quarks lead to $0.9990 < |V_{tb}| < 0.9993$.

- Direct tests without the 3-generation assumption has been carried out at the Tevatron, by measuring

$$R \equiv \frac{B(t \to bW)}{B(t \to qW)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} \tag{8}$$

  - $R = 0.94^{+0.31}_{-0.24}$ (CDF, Run 1),
  - $R = 0.70^{+0.29}_{-0.26}$ (DØ, Run 2).

- We expect R to be measured within 5% at the Tevatron, and within 3% at the LHC, which translates, assuming SM gauge couplings, to 12% and 5%, respectively, on $|V_{tb}|$.
- At the ILC, direct measurement of $\Gamma(t)$ from threshold scans should have a precision of $\mathcal{O}(1\%)$.

4.6. Yukawa couplings

- Yukawa couplings relate the matter content of the SM to the source of mass generation, the Higgs sector.
- When the Higgs field acquires a vacuum expectation value v, the top quark is endowed with a mass $m_t = \frac{Y_t v}{\sqrt{2}}$. Since $v = 246$ GeV and $m_t \approx 174$ GeV, $Y_t = 1$, a theoretically interesting value, leading to speculation that new physics studies of the top quark may open a door to new physics.
- The ttH coupling can be accessed through
  - $gg \to H$ (through a top-quark loop),
  - $gg \to tH$,
  - $gg \to ttH$.
- Unfortunately, the first suffers from overwhelming background, and the cross sections are too low for the other two at the Tevatron.
- Even at LHC, strong cancellations will limit the reach to light Higgs only (which, how-

ever, is strongly favored by the current measurements of m_t and M_W).

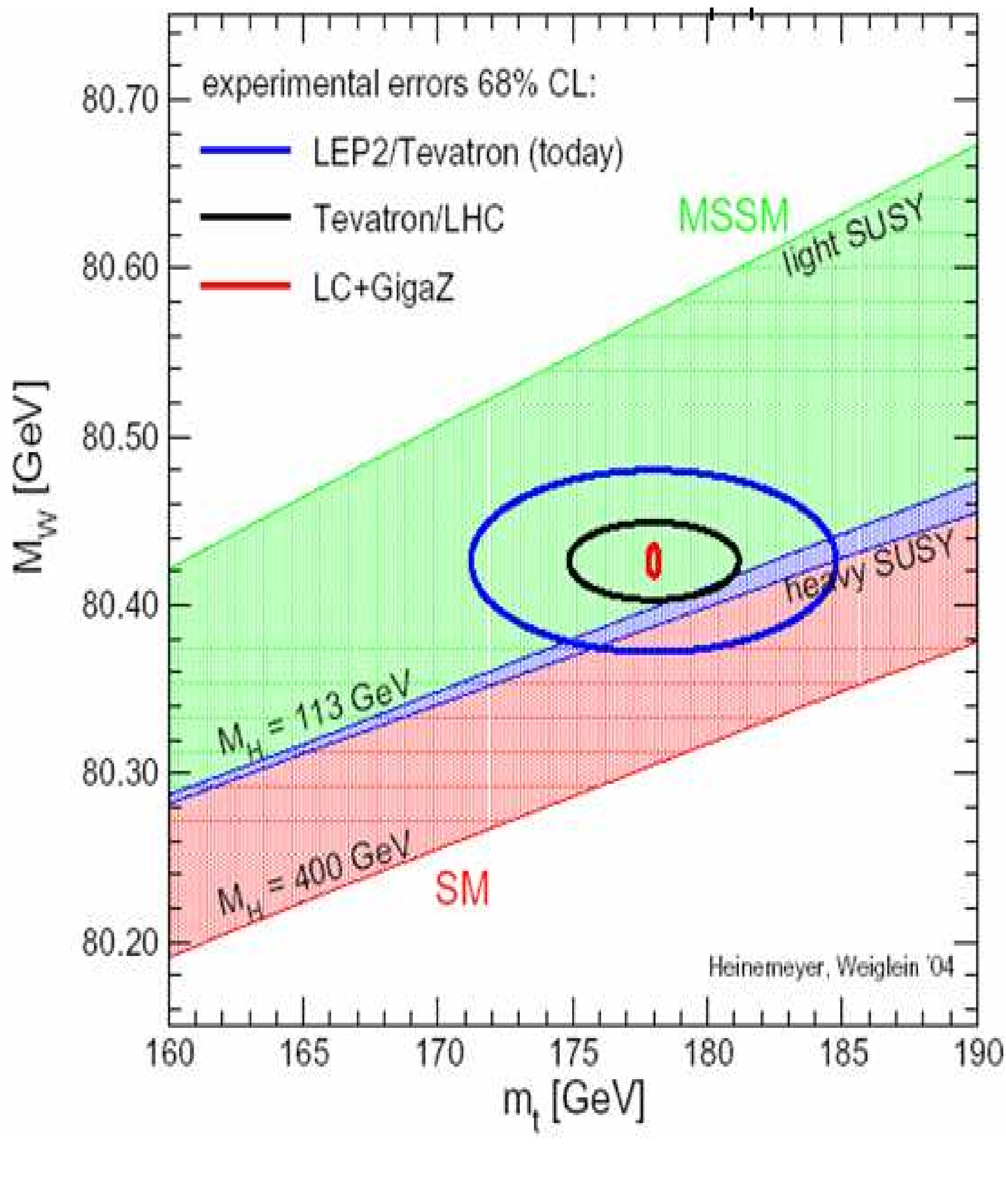
- Measurements of Higgs branching fractions based on large samples may prove more fruitful.
- Strong constraints can be put on models where $Y_t \gg 1$.
- Unless M_H is too large, precision measurements at the ILC of Higgs production and decay properties will yield the best results on Y_t.

Summary and Outlook

- Using $\sim$ 500 pb^{-1} of data collected at the Fermilab Tevatron, both DØ and CDF have studied several aspects of top physics including measurements of its pair-production cross section and mass, several tests of the SM Wtb coupling, and some searches for physics beyond the SM.
- The mass of top quark has been determined within 2.3%, the most precise of all quarks.
- Within large statistical uncertainties, single top production, top-antitop spin correlation, and W helicity measurements agree well with the SM predictions.
- A search for charged Higgs bosons reveals no signal, and rules out a large part of previously unexplored parameter space.
- Results from searches for flavor-changing neutral currents in decays of the top quark are consistent with the SM.
- $M_{Z' \to t\bar{t}} < 610$ GeV excluded at 95 % CL.

We look forward with great expectations to the completion of Run 2 of the Tevatron, the LHC (2007-), and eventually the ILC (2015?-). Together, these enterprises will help us gain a better understanding of the workings of Nature.

"In physics, one discovery often leads to others. Top opens a new world – the domain of a very heavy fermion – in which the strange and wonderful may greet us."


experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
LC+GigaZ
MSSM
light SUSY
heavy SUSY
M_H = 113 GeV
M_H = 400 GeV
SM
Heinemeyer, Weiglein '04
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
190
m_t [GeV]