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## **Top Quark, W-boson and Light Higgs**

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# Top Quark, W-boson and Light Higgs

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In this presentation I will concentrate on top quark physics, the W-boson mass and the possibility of discovering a light Higgs boson via associated production at the Fermilab Tevatron.

## 1. INTRODUCTION

The top quark, the W-boson and the Higgs boson form an interesting triptych of elementary particles. In the Standard Model knowing the mass of two of these particles, usually the top quark and W-boson, we can predict the mass of the third, the Higgs boson. Therefore in this proceedings I will primarily cover the following topics, top quark physics, W-boson mass and the light Higgs boson at the proton-antiproton collider at Fermilab, the Tevatron. Other hadron collider topics to be cover in this conference include B-physics [1], QCD [2], Electroweak Physics [4] and Supersymmetry [3].

## 2. TOP QUARK PHYSICS

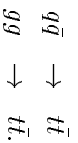
The most surprising thing about the top quark is that its mass is approximately 175 GeV, nearly twice as heavy as the W and Z bosons and more than 30 times the mass of its electro-weak partner the b-quark. The Yukawa coupling constant of the top quark

$$m_t \sqrt{2\sqrt{2}G_F} \sim 1$$

whereas for the electron the Yukawa coupling is  $3 \times 10^{-6}$ . Why is the top quark so heavy? Does it have a special roll in Electro-Weak symmetry breaking? Does it have Standard Model couplings? These are some of the question that need to be answered.

### 2.1. Pair Production

At a hadron collider the dominant mode of top quark production at hadron colliders is via quark-antiquark annihilation or gluon-gluon fusion




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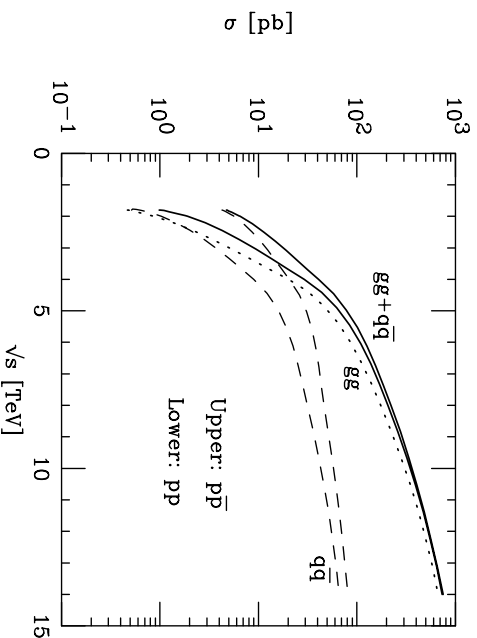


Figure 1. The lowest order QCD top quark pair production cross sections as a function of  $\sqrt{s}$  for a 175 GeV top quark mass.

Fig 1 is the lowest order cross sections for these subprocesses verses  $\sqrt{s}$  for  $m_t = 175 \text{ GeV}$  for both proton-antiproton and proton-proton accelerators. For the Tevatron the dominant production mechanism, 80 to 90 % of the total cross section, is quark-antiquark annihilation whereas at the LHC gluon-gluon fusion is 80 to 90 % of the total. At the Tevatron the top quark pairs are produced with a typical speed in the zero momentum frame of 0.6c whereas at the LHC this speed is 0.8c.

Recently a number of authors [5] - [7] have calculated the cross section for top quark pair production not only at next to leading order but they have summed the large logarithms to all orders in perturbation theory. For the Tevatron these results are displayed in Fig 2. Even though these authors all agree on the top cross-section at the Tevatron they disagree in principal on how these calculations should be performed.

Fig 3 is the cross section verses the mass of the top

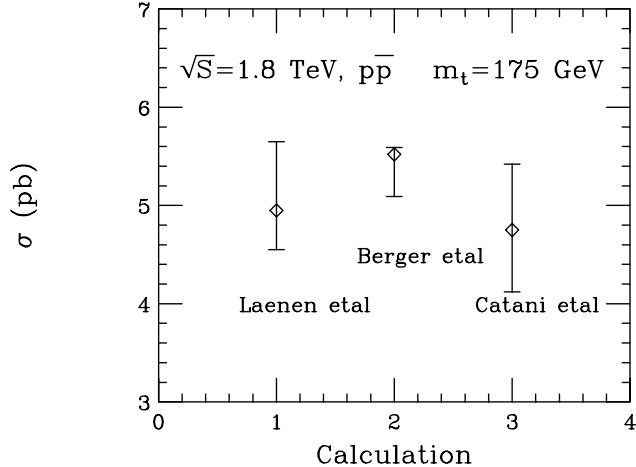


Figure 2. Resummed Next to Leading Order top quark cross sections from Laenen et al [5], Berger et al [6] and Catani et al [7].

quark for the calculation by Catani et al [7]. The functional dependence of the other calculations is essentially the same with the cross section dropping by a factor of 2 for every 20 GeV increase in the top quark mass. Also shown on this figure are the results from CDF and D0.

In raising the energy of the Tevatron from 1.8 to 2.0 TeV the top cross section increases by 38 % with the gluon-gluon fusion component increasing from 10 to 20 % of the total.

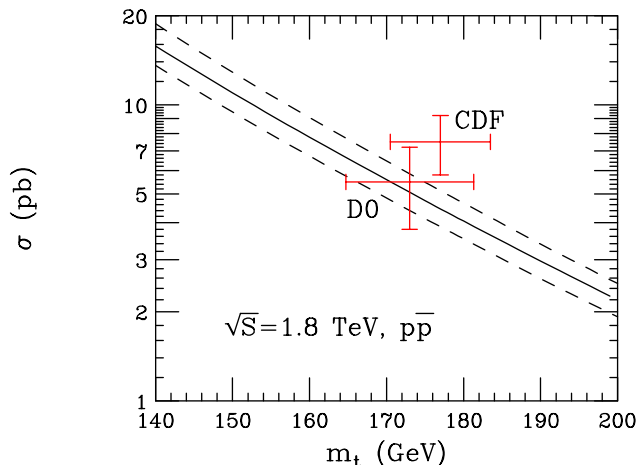


Figure 3. The dependence of the top quark cross section as a function of the top quark mass for the Catani et al calculation [7]. The latest experimental results are also shown.

## 2.2. Top Quark Decay

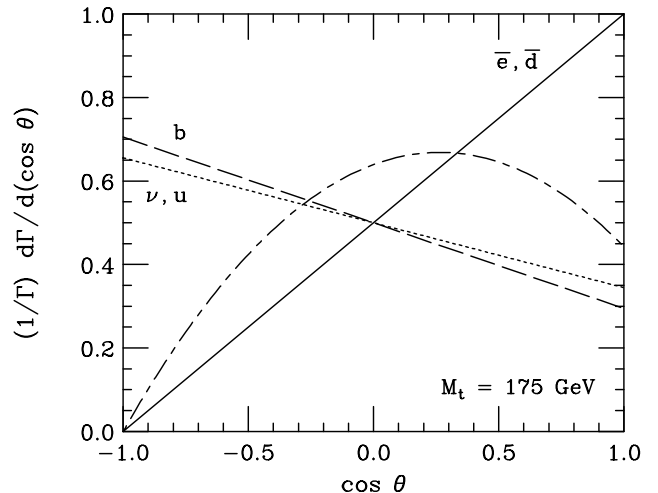


Figure 4. Angular correlations in the decay of a 175 GeV spin-up top quark. The labeled lines are the angle between the spin axis and the particle in the rest frame of the top quark. The unlabeled dot-dash line is the angle between the b quark and the positron (or d-type quark) in the rest frame of the W-boson.

In the Standard Model the top quark decays primarily into b-quark and a W boson,

$$\begin{aligned}
 t \rightarrow b W^+ &\rightarrow b l^+ \nu \\
 &\rightarrow b \bar{d} u.
 \end{aligned}$$

For a 175 GeV the width of this decay mode is 1.5 GeV, see Bigi et al [8]. Thus the top quark decays before it hadronizes and any spin information introduced in the production mechanism is passed on to the decay products. Fig 4 gives the correlations of the decay products with the spin direction for a polarized top quark [9]. Also shown on this figure is the correlation of the charged lepton (or d-type quark) with the b-quark direction in the W-boson rest frame showing the  $m_t^2 : 2m_W^2$  ratio of longitudinal to transverse W-bosons in top quark decay. Fig 5 shows the correlations between the W-boson decay direction relative to the spin-direction and the charge lepton (or d-type quark) direction relative to the minus b-quark direction in the W-boson rest frame. That is, if the  $W^+$  is emitted in the spin direction it is longitudinal and in the minus spin direction it is transverse.

## 2.3. Spin Correlations in Pair Production

Fig 6 is the relevant three vectors for the spin correlation studies of the top quark pairs produced by

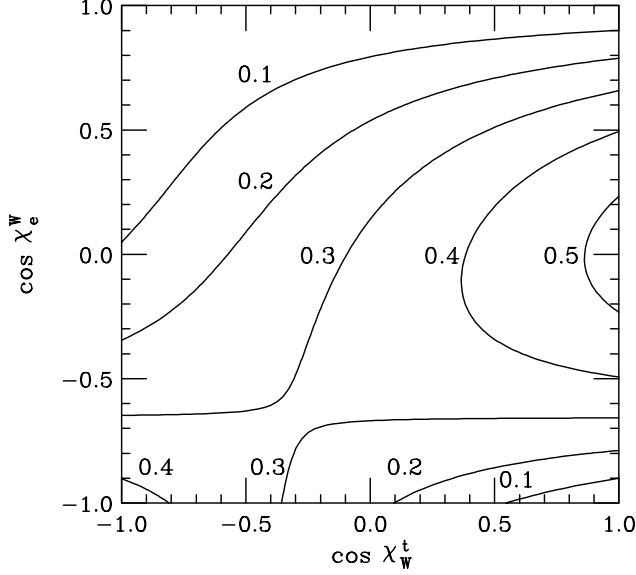


Figure 5. Decay distribution contours.  $\chi_W^t$  is the angle between the top-quark spin and direction of motion if the W-boson in the top quark rest frame.  $\pi - \chi_e^W$  is the angle between the direction of motion of the b-quark and the positron in the W-boson rest frame.

quark-antiquark annihilation<sup>[10]</sup>. If the angle  $\psi$  is chosen such that

$$\tan \psi = \frac{\beta^2 \cos \theta^* \sin \theta^*}{(1 - \beta^2 \sin^2 \theta^*)}$$

then the top quarks are produced in only the Up-Down and Down-Up configurations *i.e.* the Up-Up and Down-Down components identically vanish<sup>[11], [12]</sup>. This spin basis is known as the Off-Diagonal basis.

For the Up-Down spin configuration, the preferred emission directions for the charged leptons (or d-type quarks) of the top and anti-top quark are given by the directions of  $(t + ms)/2$  and  $(\bar{t} + m\bar{s})/2$  respectively. Whereas for the Down-Up configuration the preferred directions are  $(t - ms)/2$  and  $(\bar{t} - m\bar{s})/2$  respectively. These vectors make an angle  $\omega$  with respect to the beam direction with

$$\sin \omega = \beta \sin \theta^*.$$

Near threshold  $\psi$ ,  $\omega \approx 0$  whereas for ultrarelativistic tops  $\psi$ ,  $\omega \approx \theta^*$  as expected.

#### 2.4. New Physics in Production

Hill and Parke [13] have studied the effects of new physics on top quark production in a general operator formalism as well as in topcolor models. In these models the distortions in top quark production and shape are due to new physics in the  $q\bar{q}$  subprocess. The effects of a coloron which couples weakly to the light genera-

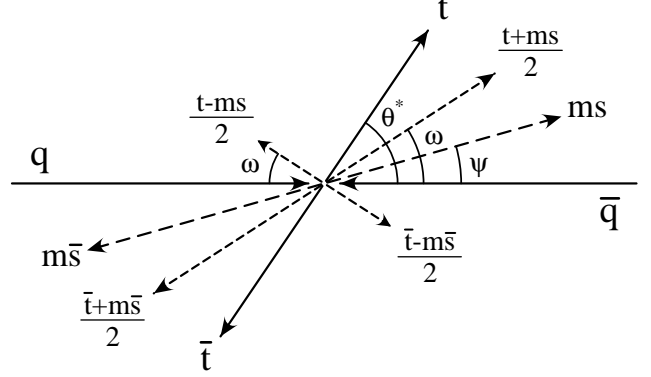


Figure 6. Spin and Momentum vectors for  $q\bar{q} \rightarrow t\bar{t}$  in the zero momentum frame.

tions but strongly to the heavy generation is given in Fig 8.

Similarly Eichten and Lane [14] have studied the effects of multi-scale technicolor on top production through the production of a techni-eta resonance, see Fig 9. Here the coupling of the techni-eta is to  $gg$ , therefore only this subprocess is different than the standard model. At the Fermilab Tevatron top production is dominated by  $q\bar{q}$  annihilation while at the LHC it is the  $gg$  fusion subprocess that dominates. Therefore these models predict very different consequences for top production at the LHC.

#### 2.5. Experimental Results

Both CDF and D0 have observed the top quark pair events in the dilepton channel, the lepton plus jet channel and the all jets channel. To get the latest information on the measurement of the mass and production cross sections see the CDF web page at [www.cdf.fnal.gov](http://www.cdf.fnal.gov) and the D0 web page at [www-d0.fnal.gov](http://www-d0.fnal.gov).

At the time of this conference the CDF<sup>[15]</sup> results are

$$\begin{aligned} m_t &= 176.8 \pm 4.4 \pm 4.8 \text{ GeV} \\ \sigma_{t\bar{t}} &= 7.5_{-1.6}^{+1.9} \pm 1.67 \text{ pb} \end{aligned}$$

and for D0<sup>[16]</sup>

$$\begin{aligned} m_t &= 173.3 \pm 5.6 \pm 6.2 \text{ GeV} \\ \sigma_{t\bar{t}} &= 5.53 \pm 1.67 \text{ pb} \end{aligned}$$

For a comparison with theory see Fig 3. What is surprising about these results is that with approximately 100 top quark events in total the top mass is already known quite accurately. Unfortunately all top quark experimental results so far are consistent with the Standard Model.

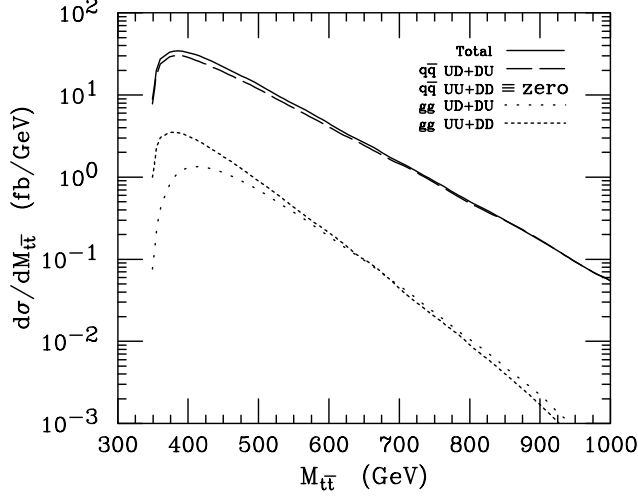


Figure 7. Invariant mass distribution of the  $t\bar{t}$  pair decomposed into the spin components Up-Down, Down-Up, Up-Up and Down-Down using the Off-Diagonal spin basis.

## 2.6. Single Top Quark Production

Recently reliable results for the next to leading order calculations for single top quark production at hadron colliders via a virtual W-boson [17] or via W-gluon fusion [18] have been presented. A comparison of the rates for these processes can be found in Fig 10 for events with the topology positron, missing transverse energy plus jets. The rates for both of these single top processes are proportional to the CKM matrix element  $V_{tb}$  squared therefore these processes can be used to measure this important Standard Model parameter. For  $2 \text{ fb}^{-1}$  ( $30 \text{ fb}^{-1}$ ) of data at the Tevatron the expected uncertainty on  $V_{tb}$  is 12% (3%).

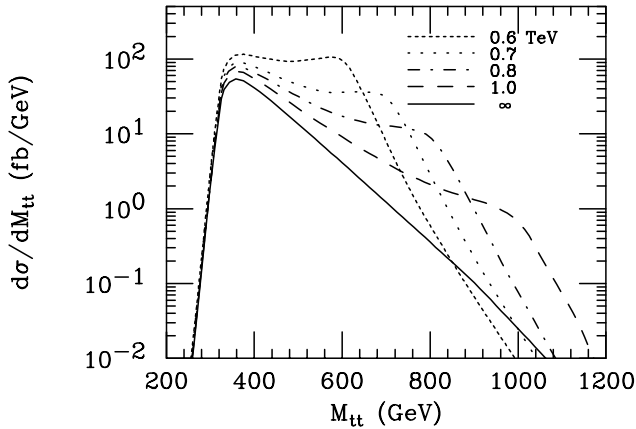


Figure 8. The invariant mass of the  $t\bar{t}$  pair for the technicolor octet model.

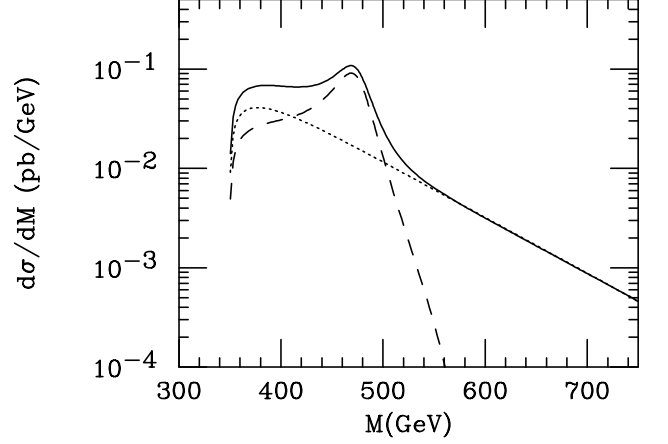


Figure 9. The invariant mass of the  $t\bar{t}$  pair for the two scale technicolor model.

Single top quark production is a great source of polarized top quarks with the polarization being in the direction of the d-type quark in the event *i.e.* the anti-proton direction for  $W^*$  production and the spectator jet for production via W-gluon fusion. The production of single top quarks through a virtual W-boson is sensitive to form factors in the  $Wtb$  vertex at a  $Q^2 = m_t^2$ . Hints of new physics could be discovered in this process.

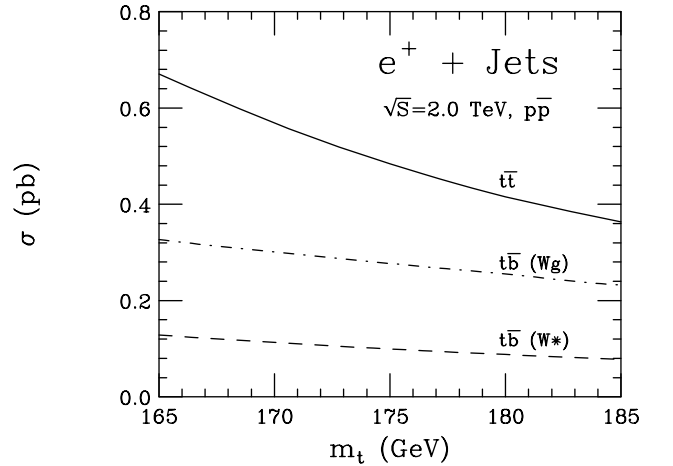


Figure 10. The cross sections versus mass of the top quark for top pair production [7], single top via W-gluon fusion [18] and single top via a virtual W-boson [17] in the channel positron, missing energy plus jets for the 2 TeV Tevatron.

### 3. W-BOSON AND LIGHT HIGGS PHYSICS

In the Standard Model the mass of the top quark, W-boson and Higgs boson are all related to one another. So precision measurements of the top quark mass and W-boson mass will give us information on the Higgs boson mass.

#### 3.1. W-boson Mass

The latest result on the W-boson mass from CDF [19] is

$$m_W = 80.38 \pm 0.12 \text{ GeV}$$

and from D0 [20] is

$$m_W = 80.44 \pm 0.11 \text{ GeV}.$$

Fig 11 is a summary of the current results from all experiments on the W-boson mass.

In the Standard Model, because of radiative corrections, knowing the W-boson mass and the top quark mass gives a determination of the Higgs boson mass. Fig 12 shows the current experimental results on this indirect measurement of the Higgs boson mass. Unfortunately at the current level of accuracy on the W and top mass measurements little can be said about the Higgs boson mass except that light values seem to be preferred. If this holds up with increased precision on these measurements it is great news as it means the Higgs boson is easily accessible or there is new physics near at hand. Either outcome would be great for particle physics.

Improvements in the W-boson mass can be expected from LEP2 possible reaching an uncertainty of 34 MeV. With a few  $\text{fb}^{-1}$ s of data the Tevatron should reach an uncertainty of 40 MeV on the W-boson mass and almost 2 GeV on the top quark mass. If TeV33 gets 30 to 100  $\text{fb}^{-1}$  of data the uncertainty on the W-boson mass will probably reach 20 MeV and top quark mass of 1 GeV. This would greatly enhance the determination of the Higgs boson mass from Fig 12.

#### 3.2. Light Higgs Boson

The mass of the W-boson and mass of the top quark suggest that the Higgs boson is light. SUSY models predict that the lightest Higgs be less than 150 GeV (125 GeV in the minimal model, MSSM). LEP2 will explore up to a mass of 95 GeV by the year 2000. At the Tevatron a light Higgs [21] can be explored up to a mass of 130 GeV [22] - [24] with sufficient integrated luminosity, 30 - 100  $\text{fb}^{-1}$ , using the subprocess

$$q \bar{q}' \rightarrow W + H$$

with the W decaying leptonically and the Higgs decaying to  $b\bar{b}$ . The physics backgrounds for this process are

$$q \bar{q}' \rightarrow W + b + \bar{b} \text{ (QCD)}$$

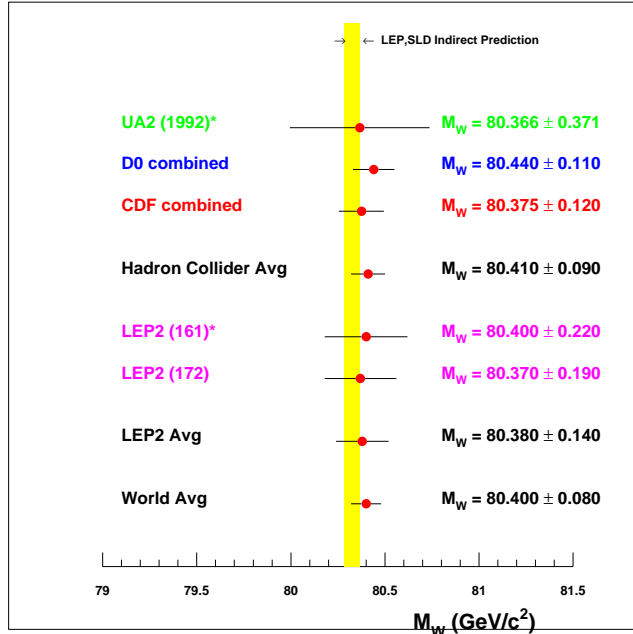


Figure 11. Summary of W-boson mass measurements.

$$\begin{aligned} &\rightarrow t + \bar{b} \\ &\rightarrow W + Z. \end{aligned}$$

This physics requires double b-tagging with high efficiency and low fake rates. Also one needs good resolution on the  $b\bar{b}$  mass, above the Z-boson peak, then with very large data sets the Higgs boson will be observable if its mass is below 130 GeV. The process  $q\bar{q} \rightarrow Z + H$  will also be useful [23]. Hopefully the Tevatron can obtain these large data sets before the LHC has obtained significant data sets.

### 4. CONCLUSION

Hadron Colliders provide a rich, diverse “feast of physics”. The top quark, W-boson and Higgs boson form a very rich triptych but there is also QCD, B-physics, Electroweak, SUSY etc. While the Fermilab Tevatron still holds the energy frontier it should be exploited to the fullest possible extent with luminosity upgrades to both accelerator and detectors.

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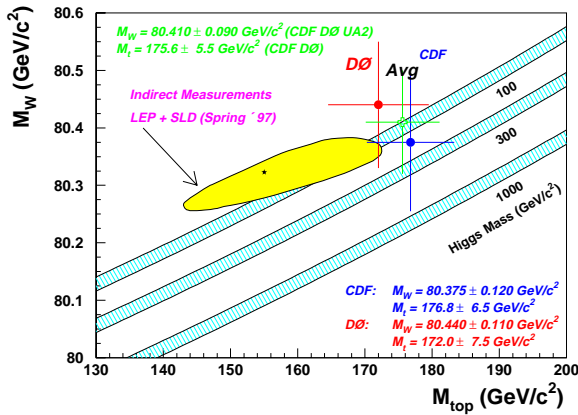


Figure 12. The relationship between the mass of the top quark, W-boson and Higgs boson in the Standard Model plus the latest experimental information.

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