# Testing the Standard Model at the Fermilab TEVATRON

*Push it to the Edge!!*

- Motivation
- Means
- Opportunity
- Anticipated Results
- Discussion
- What is to be done?

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## *Motivations*

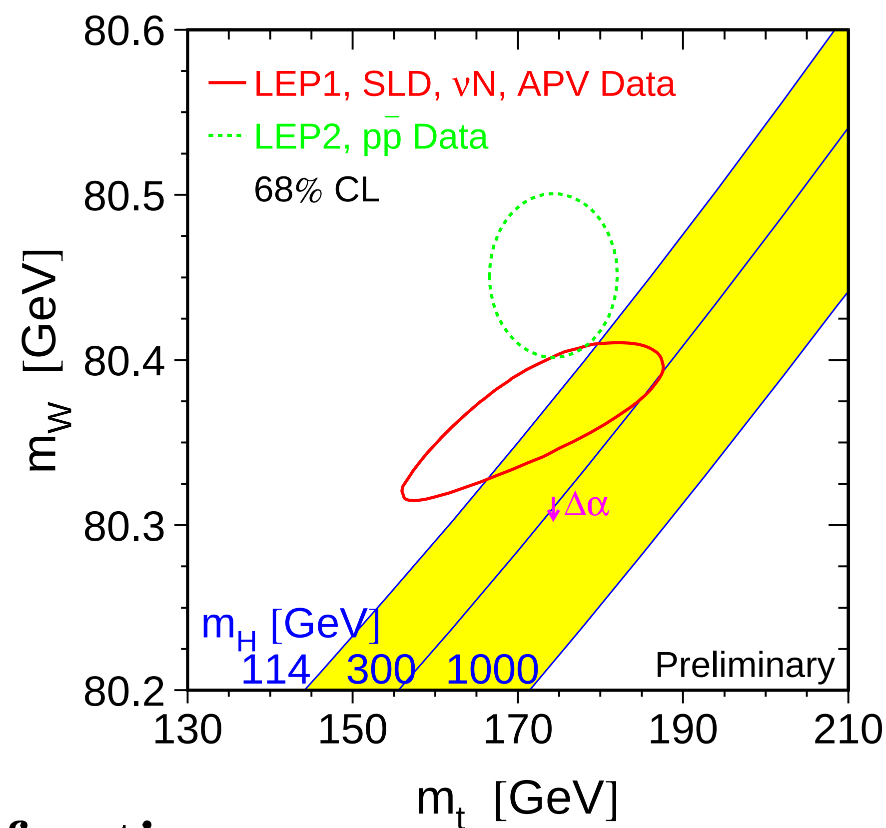
*Recall:*

during the 1990's, interplay of

- *indirect* indication for $M_t$ from precision EWK meas't
- *direct* search for $t\bar{t}$

converged remarkably well...

*(so we know how to play this game)*




**Now we are in the business of confronting**

*indirect indications for $m_h$*

**with**

*direct searches for the Higgs boson.*

This time the whole game will be played out at FERMILAB.

How will it turn out, and how can we make it as interesting as possible?

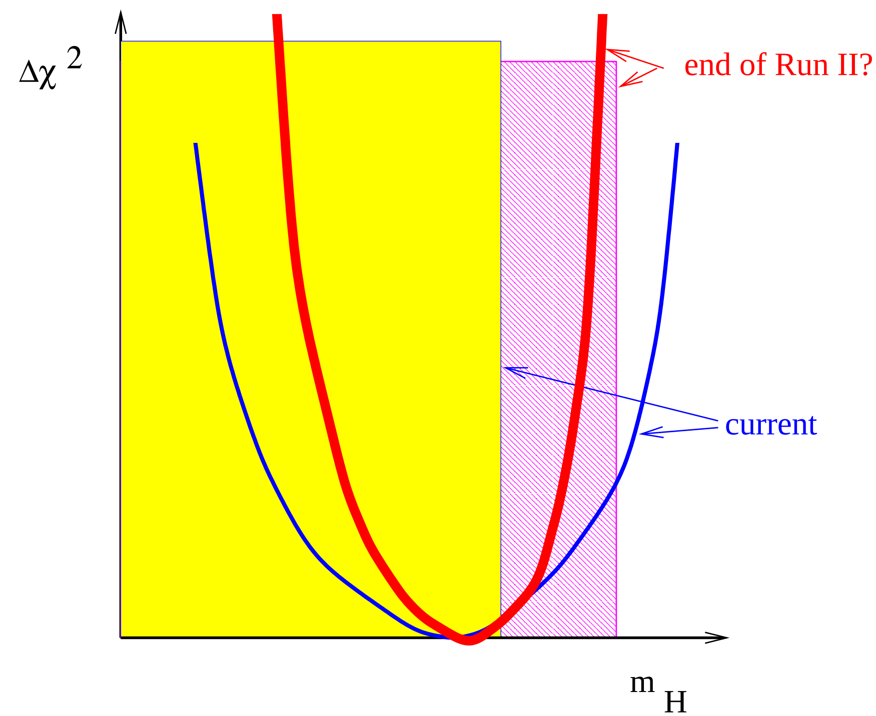
***Before*** the LHC turns on, (and certainly before any *LC* gets into operation)

## The goal should be to test the SM **definitively**

( – not just 'a shot at' the Higgs before LHC).

The 'pincers' for squeezing the SM are

- direct searches for the SM Higgs
- fits to precision EWK observables
  1. $m_t$ to 1 GeV
  2. $m_W$ to 15 MeV
  3. $A_{\rm FB} \Longrightarrow \sin^2\theta_W$ to $< 0.0002$.

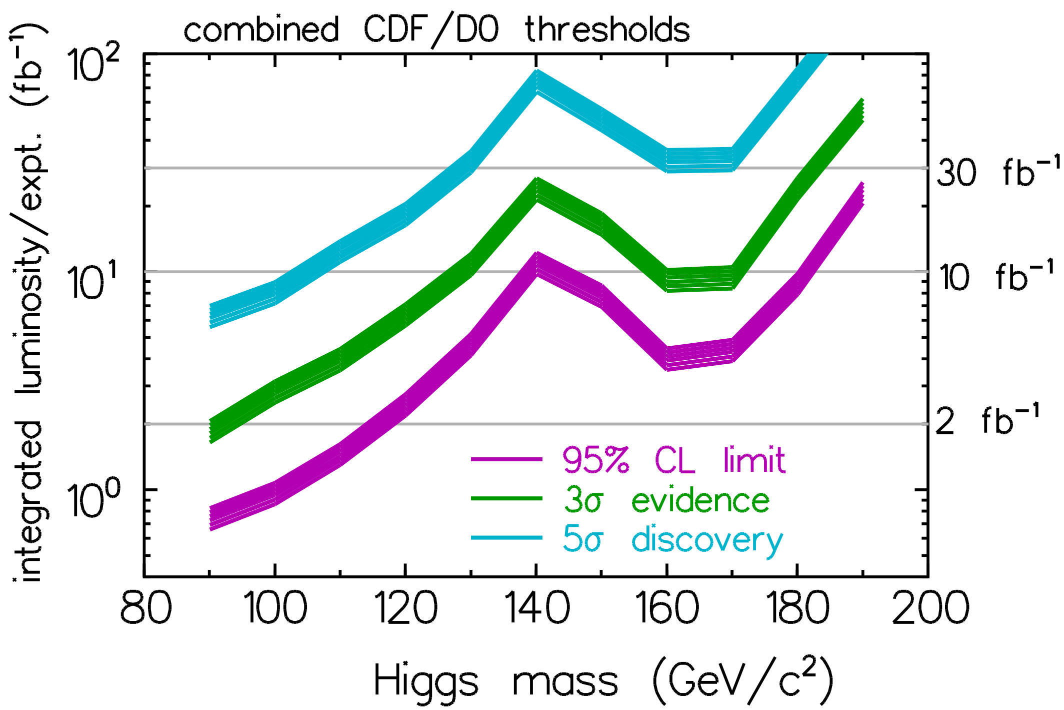



**What happens if we do not find a Higgs boson?**

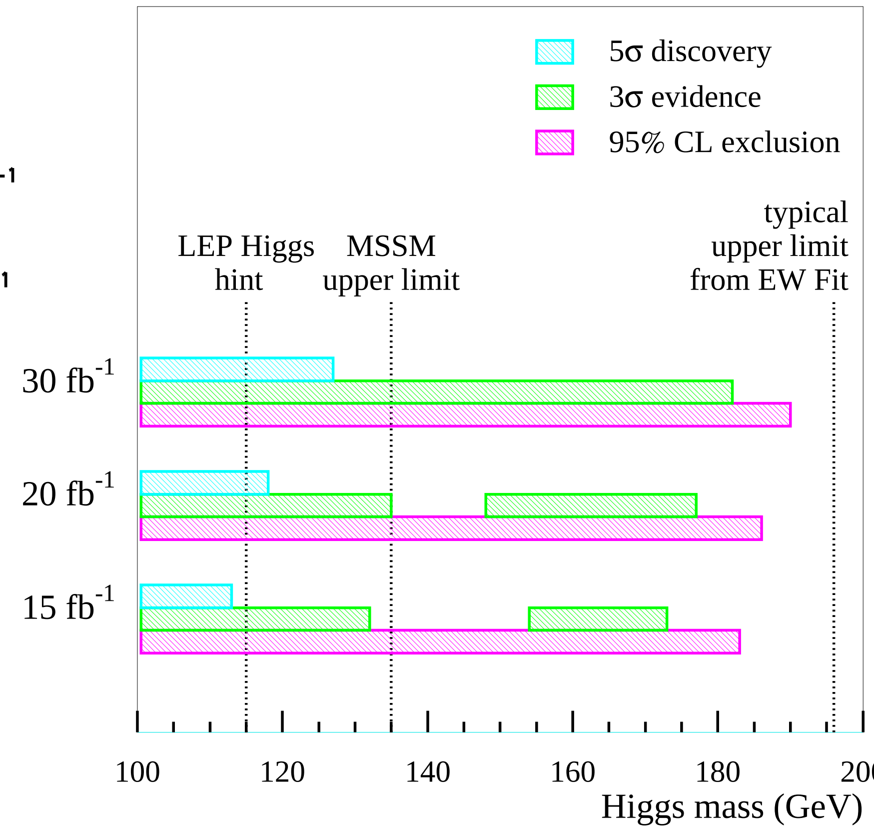
With sufficient luminosity and hard work, the Tevatron experiments really *push the SM to the edge of self-inconsistency*.

# *Means, part I*

The SM search is difficult, but not hopeless. (cf J.Womersley's talk).
Much has been learned from searches at Run I. (M.Kruse, this session).




(FNAL Higgs/SUSY WS, hep-ph/0010338)




One can (and does) argue about discovery potential... However,
if there's no SM-like Higgs, FERMILAB will exclude $m_h < 180$ GeV w/ 10 fb$^{-1}$.

# *Means, part II*

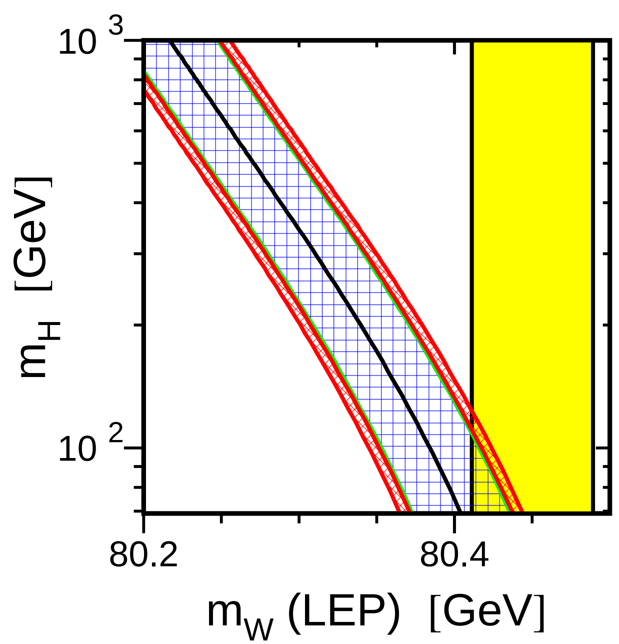
Focus on *Precision Electroweak Observables*, such as

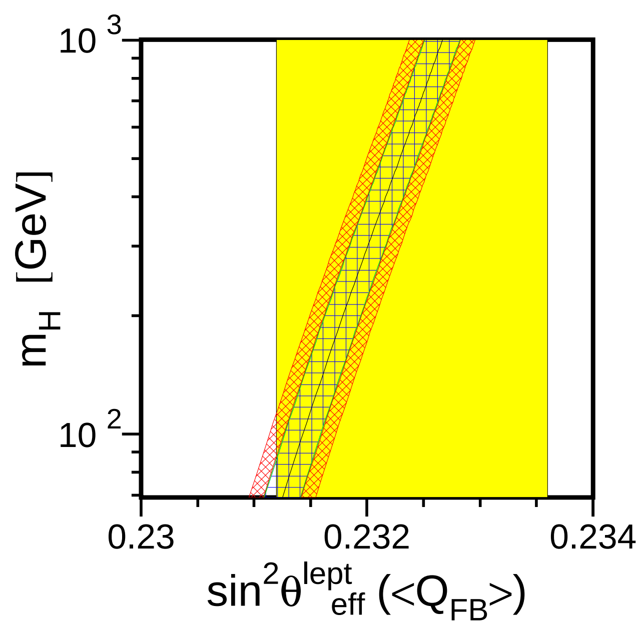
$M_W$, the $W$ mass & $\sin^2\theta_W$, extracted from FB, LR, pol'n asymmetries

Radiative corrections will depend parametrically on $m_h$, $m_t$, $\alpha_{\rm EM}$, $\alpha_{\rm S}$, etc.

We have empirical knowledge of $m_t$, $\alpha_{\rm EM}$, $\alpha_{\rm S}$, to a given accuracy (which we need to improve), but $m_h$ is unknown.

*Concept:* compare $M_W^{\rm theo}$ and $\sin^2\theta_W^{\rm theo}$ to $M_W^{\rm meas}$ and $\sin^2\theta_W^{\rm meas}$ to infer $m_h$.

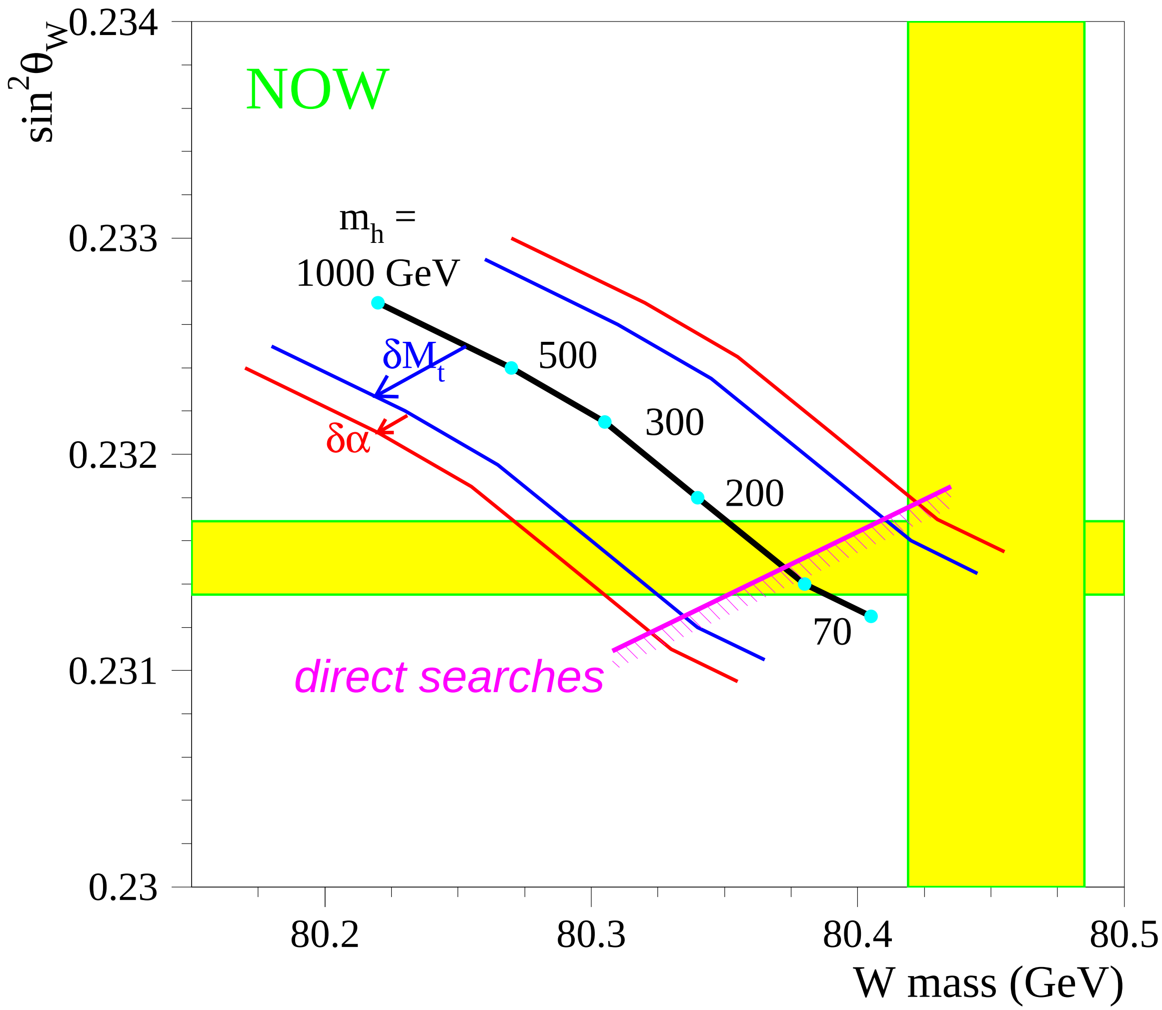



Blue band shows $\delta M_t = 5.1$ GeV, red band shows $\Delta\alpha^{(5)}_{\rm had} = 0.00036$.

LEPEWWG

hep-ex/0112021




Here the information from $M_W$ & $\sin^2\theta_W$ is depicted together.

The preference for a 'light' Higgs ($m_h < 200$ GeV) is clear.

*The Mission:* reduce the errors on $M_t$, $M_W$ and $\sin^2\theta_W$.

## *Opportunity*

In Run I, the TEVATRON ran at $\sqrt{s_{p\bar{p}}} = 1.8$ TeV and delivered $\sim 110$ pb$^{-1}$.

- discovery of the top quark, $\boxed{\delta M_t \sim 5 \text{ GeV}}$
- precise measur't $\boxed{\delta M_W \sim 68 \text{ MeV}}$
- $W$ charge asymmetry constrains PDF's
- $\boxed{A_{\mathrm{FB}}}$ in $\gamma^*, Z \to \ell^+\ell^-$

*Since then,* major upgrades of the accelerator & both detectors (DØ + CDF)

- Main Injector replaced the Main Ring
- Recycler for $\bar{p}$'s
- electron cooling
- many systemic improvements
- advanced Si inner tracking & new outer tracking
- new readout electronics and DAQ
- extended muon coverage & new endplug calorimetry (CDF)
- superconducting magnet (DØ)

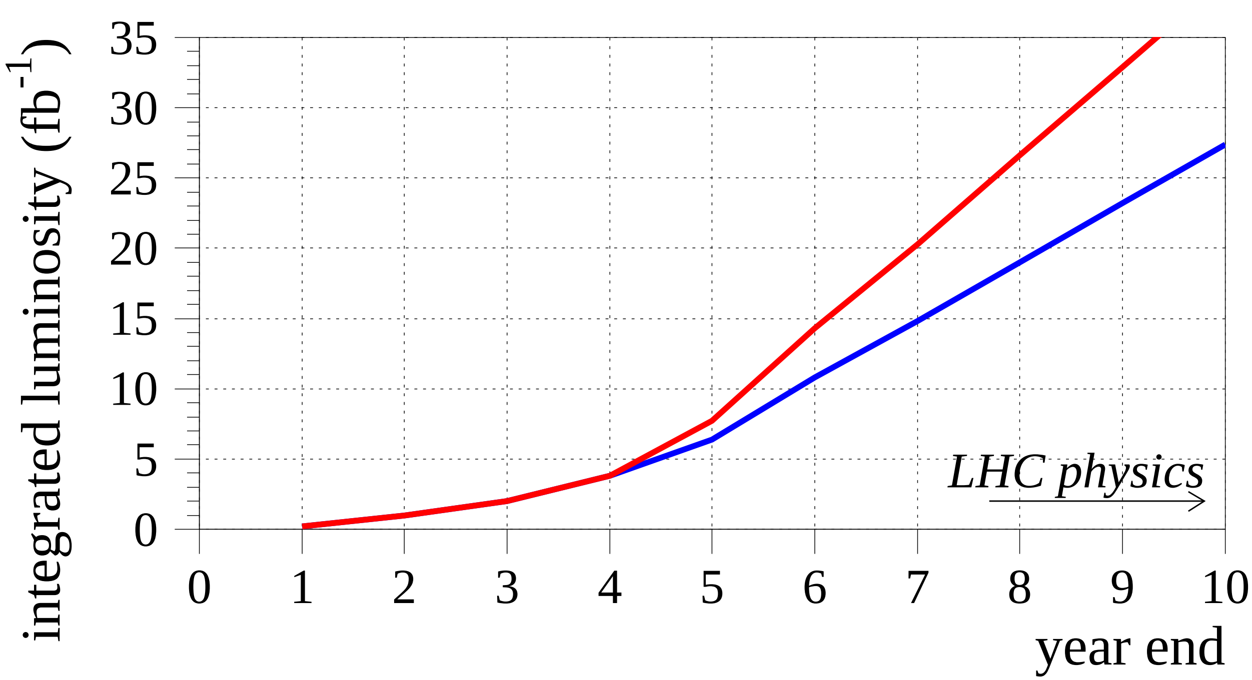
have been carried out.

Answer? *What is Run II.*

**Run 2a**: original goal, 2 $\text{fb}^{-1}$ by 2004 ($20\times$ Run I).

**Run 2b**: inspired by Snowmass 96 ("Tev33")
aiming for 15 $\text{fb}^{-1}$ by 2007.

There are now discussions of a luminosity upgrade in an attempt to accumulate $\sim 30\ \text{fb}^{-1}$ by 2008–9. <u>This is speculative.</u>



# Future top mass Measurements

**Run 2a**: relatively crude estimates based on Run 1 $\Longrightarrow \delta M_t \sim 2$–$3$ GeV

**Run 2b**: Concentrate on leptonic and double-leptonic events.
Event samples will be large enough to demand a *double b-tag*.
For 15 fb$^{-1}$, per experiment, 3200 $\ell\nu$ + jets and 1200 $2\ell + 2\nu$ events.

**The main issue is the energy scale.**

If we were limited by Run 1 methods, then we could not reduce this uncertainty below a couple GeV.

However, both experiments will collect special calibration samples

$$p\bar{p} \to Z \to b\bar{b}$$

which will help set the energy scale to within $\sim 0.5$ GeV.

In addition, the decays $W \to q\bar{q}'$ within the top events themselves provide an independent calibration point.

*The next most important systematic is* **Monte Carlo Modeling**.

At issue is the radiation of extra gluons – everywhere (initial state, final state quarks).

The Run 1 approach was not well honed – there is plenty of room for tuning the simulations.

The modeling of the jet activity in top events can be constrained by comparing double-tagged events to the simulation.

This uncertainty decreases slightly with luminosity.

We estimate $\sim 1$ GeV.

Ordinary systematics scale with the luminosity.

## $\ell\nu$+jets event sample w/ double $b$-tag

| *integrated luminosity* | 0.1 | 2 | 15 | 30 $fb^{-1}$ |
|---|---|---|---|---|
| number of events | 40 | 420 | 3170 | 6340 |
| **statistical** | **5.6** | **1.7** | **0.63** | **0.44** |
| jet scale $W \to$jets | 4.2 | 1.8 | 0.64 | 0.45 |
| jet scale $Z \to b\bar{b}$ | - | 0.53 | 0.19 | 0.14 |
| MC model ($g$-rad'n) | 1.9 | 1.1 | 0.97 | 0.96 |
| event pile-up | 1.6 | 0.49 | 0.18 | 0.13 |
| $W \to$jets background | 2.5 | 0 | 0 | 0 |
| $b$-tag | 0.4 | - | - | - |
| **total systematic** | **5.5** | **2.1** | **1.2** | **1.1** |
| **total** | **7.8** | **2.7** | **1.3** | **1.2** |

An extrapolation from DØ results.

Yields scaled from Run 1 taking into account higher cross section and double-tagging with $\epsilon_b = 0.65$

Jet scale information to be combined.

(all numbers in GeV)

## $2\ell + 2\nu$ event sample

| *integrated luminosity* | 0.1 | 2 | 15 | 30 $fb^{-1}$ |
|---|---|---|---|---|
| number of events | 6 | 160 | 1200 | 2400 |
| **statistical** | **12.3** | **2.4** | **0.87** | **0.62** |
| jet scale | 2.0 | 0.88 | 0.32 | 0.23 |
| MC model | 2.3 | 1.0 | 0.96 | 0.96 |
| event pile-up | 1.4 | 0.27 | 0.10 | 0.07 |
| background | 0.9 | 0.17 | 0.06 | 0.05 |
| method | 0.9 | 0.17 | 0.06 | 0.05 |
| **total systematic** | **3.6** | **1.4** | **1.0** | **1.0** |
| **total** | **12.8** | **2.8** | **1.3** | **1.2** |

Yields scaled from the Run 1 DØ analysis taking into account higher cross section.

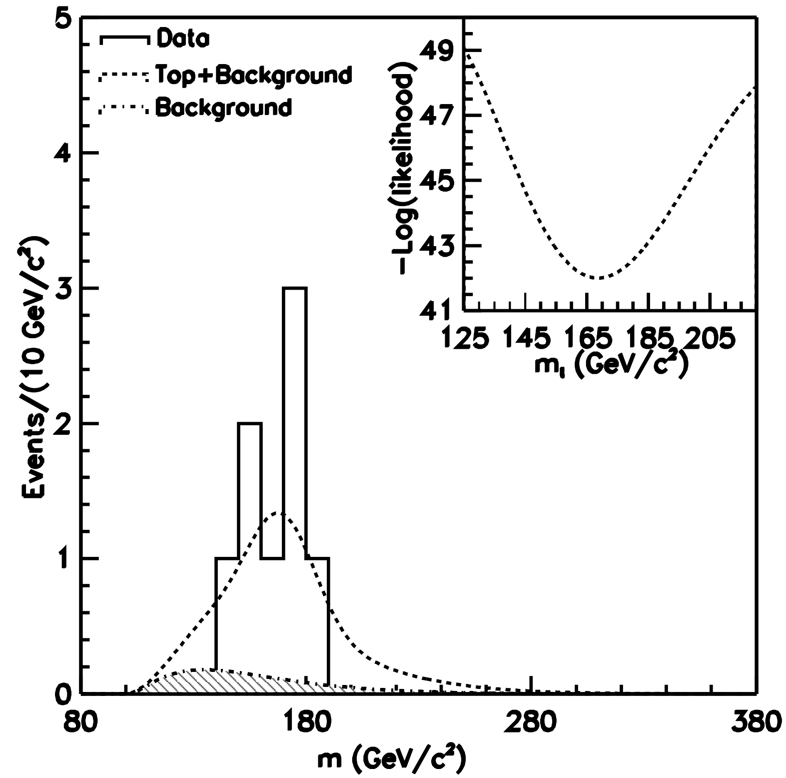
No $b$-tagging.

(all numbers in GeV)

One channel, one experiment $\longrightarrow$ 1.2 GeV.
Combine both channels and two experiments.

After 15 $\text{fb}^{-1}$,
the error is dominated by
the systematic uncertainty in
MC modeling (gluon radiation).

This uncertainty will be
correlated among channels
and experiments.




Projection: $\delta M_t \sim 1$ GeV

# Future $W$ mass Measurements

**Run 2a**: fit the $M_T$ spectrum as in Run 1.

The Working Group on Precision Measurements reported hep-ex/0011009

- statistical error will be $\sim 13$ MeV
- most systematics are driven by $N_Z$
  (detector calibration & recoil model)
- PDF's greatly aided by $W$-asymmetry
- new QED calculations
- conservatively projected $\delta M_W \sim 30$ MeV

**Run 2b+** will employ a variety of methods:
$M_T$, $p_T^\ell$, and the 'ratio method'

- For $M_T$ & $p_T^\ell$, fit MC templates to the data.
- In the ratio method, real $Z$ data is rescaled (and re-smeared) to fit the $W$ data. Developed by DØ, most experimental and some theoretical uncertainties reduced, at the cost of statistical sensitivity.
- In all cases the statistical error falls far below the systematic error.
- The main systematics in the $M_T$, $p_T^\ell$ and the ratio methods differ, so they can be used to check for consistency at the level of 10 MeV or so.

*next page,*

Transverse Mass

An extrapolation from DØ Run 1 $W \to e\nu$

## Transverse Mass Fit

| *uncertainty* | 0.82 | 2 | 15 | 30 $\text{fb}^{-1}$ |
|---|---|---|---|---|
| **statistical** | **96** | **19** | **7** | **5** |
| **prod'n & decay model** | **30** | **14** | **13** | **13** |
| $p_T^W$ (1) | 10 | 5 | 5 | 5 |
| PDF's (1) | 22 | 5 | 5 | 5 |
| radiative decays (1) | 15 | 10 | 10 | 10 |
| $W$ width | 10 | 6 | 5 | 5 |
| **detector model** | **57** | **13** | **8** | **8** |
| cal. linearity | 20 | 7 | 3 | 2 |
| cal. uniformity | 10 | 2 | 1 | 1 |
| energy resolution | 25 | 5 | 2 | 2 |
| recoil resolution | 24 | 4 | 2 | 1 |
| recoil response | 20 | 4 | 1 | 1 |
| **backgrounds** | **11** | **2** | **1** | **1** |
| hadrons | 10 | 2 | 1 | 1 |
| $Z \to e^+e^-$ | 5 | 1 | 0 | 0 |
| **total systematic** | **66** | **19** | **16** | **15** |
| **total** | **116** | **27** | **17** | **16** |

DØ extrapolation

(1) estimated by FNAL QCD/WZ study group

DØ fit $p_T^\ell$ and gained a few percent.

CDF combined $\mu^\pm$ and $e^\pm$, and gained 30%.

## Ratio Method

An (optimistic) extrapolation from DØ results.

| *uncertainty* | 0.82 | 2 | 15 | 30 $fb^{-1}$ |
|---|---|---|---|---|
| **statistical** | **211** | **44** | **16** | **11** |
| **total systematic** | **50** | **10** | **4** | **3** |
| **total** | **217** | **44** | **16** | **12** |

Note the statistical error is larger & the systematic error is smaller than the $M_T$ error. This competes with the $M_T$ method only at the highest luminosities.

One method, one channel, one experiment → 15 MeV.
Systematics differ partially between methods, and between channels.

Projection: 15 MeV, perhaps 10 MeV.

# $\sin^2\theta_W$ from $A_{\rm FB}$

Same as the forward-backward asymmetry measured at LEP, in principle

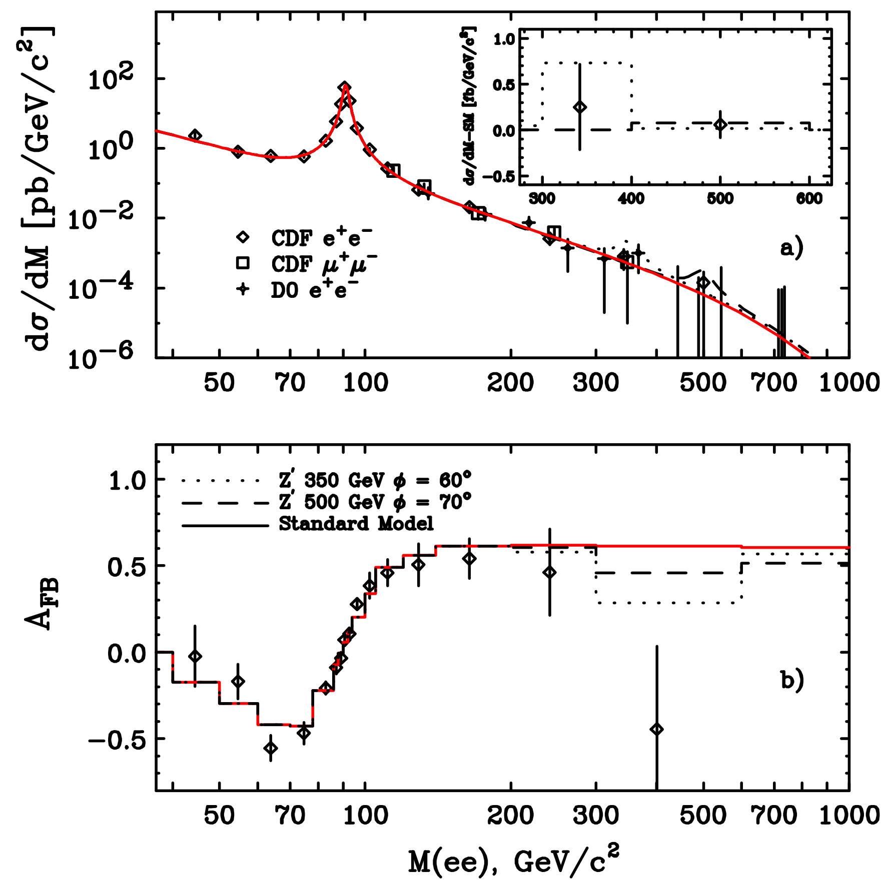
$$u\bar{u} + d\bar{d} \to Z \to \ell^+\ell^- .$$

$A_{\rm FB}$ measured at the $Z$ pole $\Longrightarrow$ a measurement of $\sin^2\theta_W$.

CDF Run 1 electron result:

$A_{\rm FB} = 0.070 \pm 0.015_{\rm stat} \pm 0.004_{\rm syst}$

for $75 < M_{ee} < 105$ GeV.



Taking the statistical error to scale as $1/\sqrt{\mathcal{L}}$,

$$\delta A_{\mathrm{FBstat}} = 0.0016 \text{ for } 10 \text{ fb}^{-1}, \textit{ or}, \ 0.0009 \text{ for } 30 \text{ fb}^{-1} \ .$$

The most important systematic uncertainty comes from the PDF's, which are greatly constrained by the measurement of the $W$ charge asymmetry. It is expected that this uncertainty (and all others) will be much smaller than the statistical error. There is a theoretical uncertainty coming from the limited coverage in rapidity and from the $p_T$ distribution. The distributions of both $y_Z$ and $p_T^Z$ will be measured and this uncertainty will be reduced.

The electron and muon channels have essentially the same sensitivity. Combining two channels from two experiments,

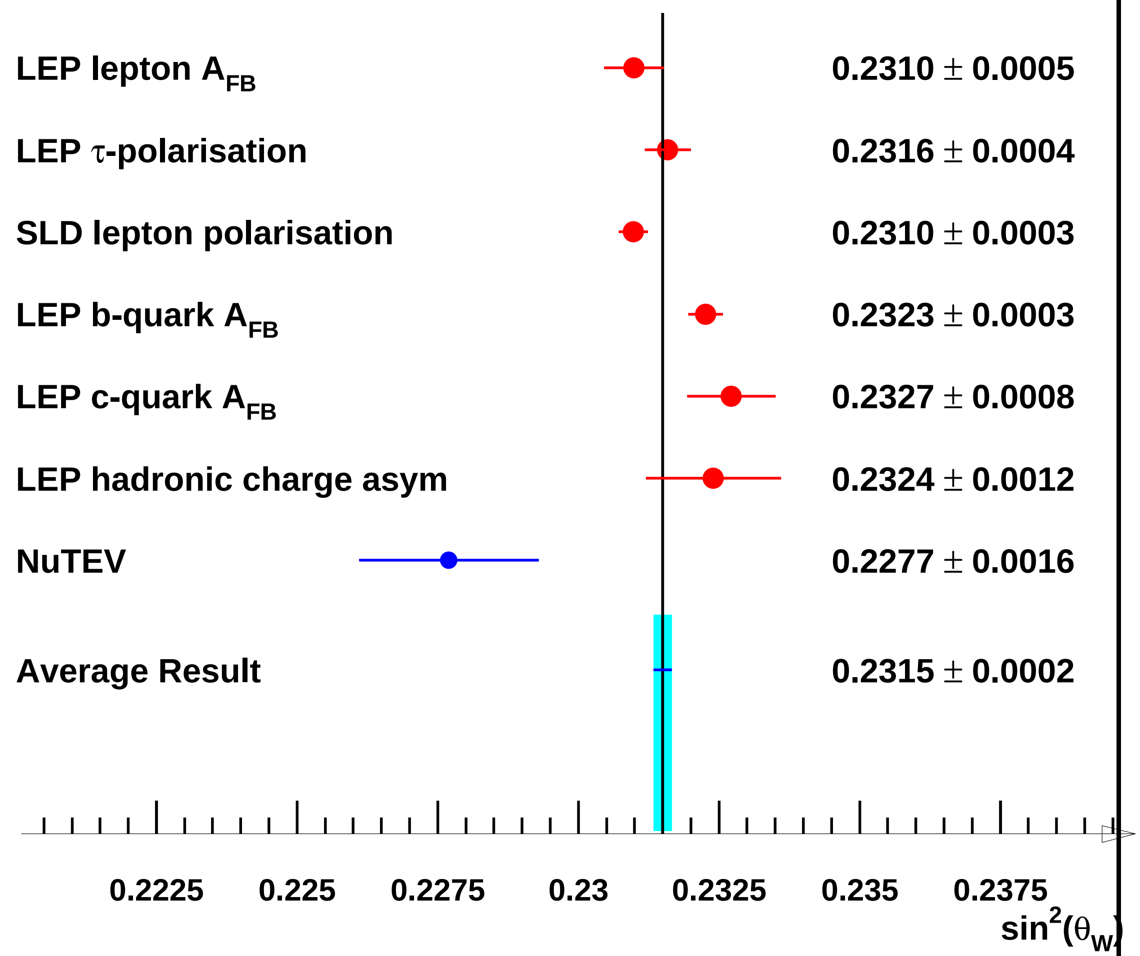
- $\delta \sin^2\theta_W \approx 0.00028$ for 10 fb$^{-1}$, and
- $\delta \sin^2\theta_W \approx 0.00016$ for 30 fb$^{-1}$ .

(The current *world average* is $\delta \sin^2\theta_W = 0.00017$.)

This measurement will also help us understand the discrepancy between

$$A_\ell(\mathrm{SLD}) = 0.23098 \pm 0.00026$$
$$A_{\mathrm{FB}}^{0,b} = 0.23240 \pm 0.00031,$$

a difference of $0.00142 \pm 0.00040$.



## $\alpha_{\rm QED}(Q^2)$

The TEVATRON cannot provide this number, of course!
At issue is the contribution of light quarks/hadrons, $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$.
There are a variety of calculations which employ

$$R^{\rm had}(s) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

from low-energy data.

The BES Collaboration have recently greatly improved the data (7% for $\sqrt{s} = 2$–$5$ GeV) leading to a significantly reduced uncertainty on $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$.

The LEPEWWG uses a 'data-driven' value from Burkhardt & Pietrzyk,

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = (276.1 \pm 3.1) \times 10^{-4}$$

and also considers a more 'theory-guided' value from Martin *et al.*,

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = (273.8 \pm 2.0) \times 10^{-4}.$$

There are plans to measure $R^{\rm had}(s)$ at CLEO-c.

- near the $B\bar{B}$ threshold (now)
- 100 MeV steps for $\sqrt{s} = 3$–$3.8$ GeV.
- 20 MeV steps up to $\sqrt{s} = 5$ GeV
- It might be possible to go down to $\sqrt{s} \sim 2$ GeV.
- systematics limited at $\sim 2\%$ by theoretical uncertainties on the Bhabha cross section
- time scale O(6 years)

On this basis, one can anticipate a large reduction in the uncertainty.

We take $$\delta(\Delta\alpha^{(5)}_{\rm had}(M_Z^2)) = 1.0 \times 10^{-4}.$$

## *Anticipated Results*

We have made the following projections:

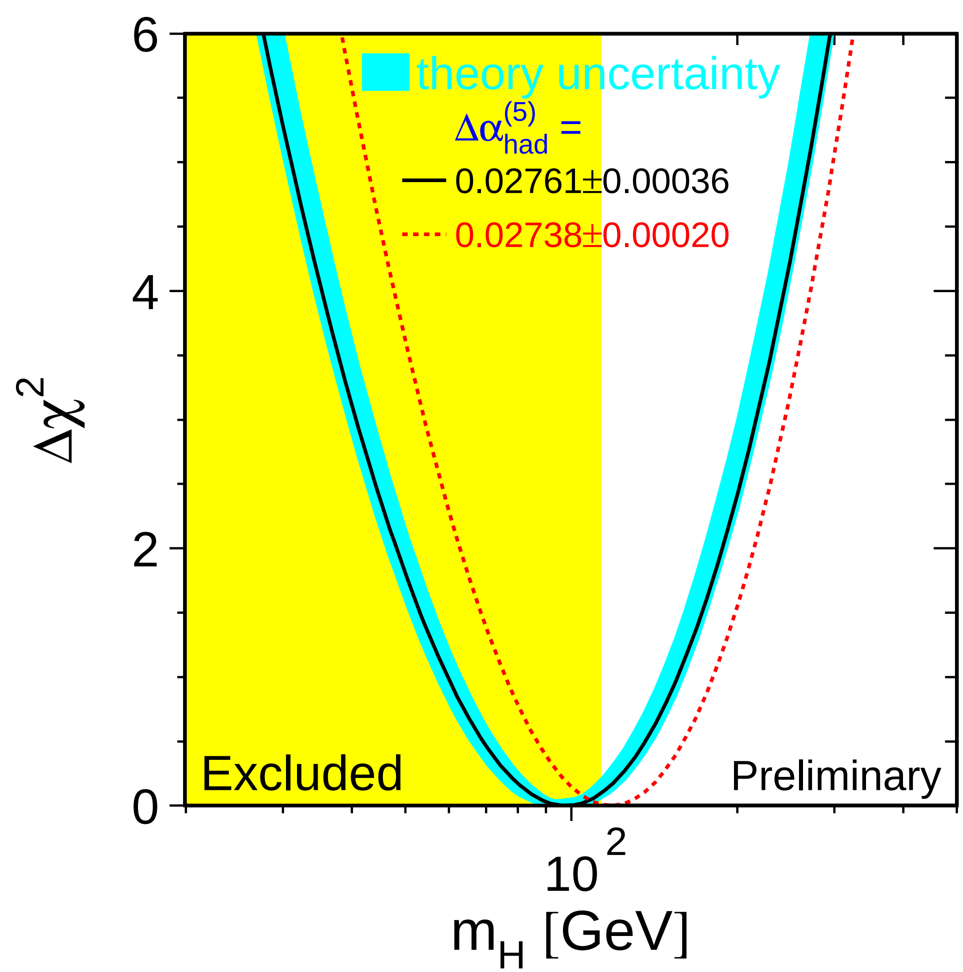
| *integrated luminosity* | 2 | 15 | 30 $\text{fb}^{-1}$ |
|---|---|---|---|
| $\delta M_t$ (GeV) | 2 | 1.5 | 1 |
| $\delta M_W$ (MeV) | 30 | 20 | 15 |
| $\delta \sin^2\theta_W$ | 0.0008 | 0.00028 | 0.00016 |

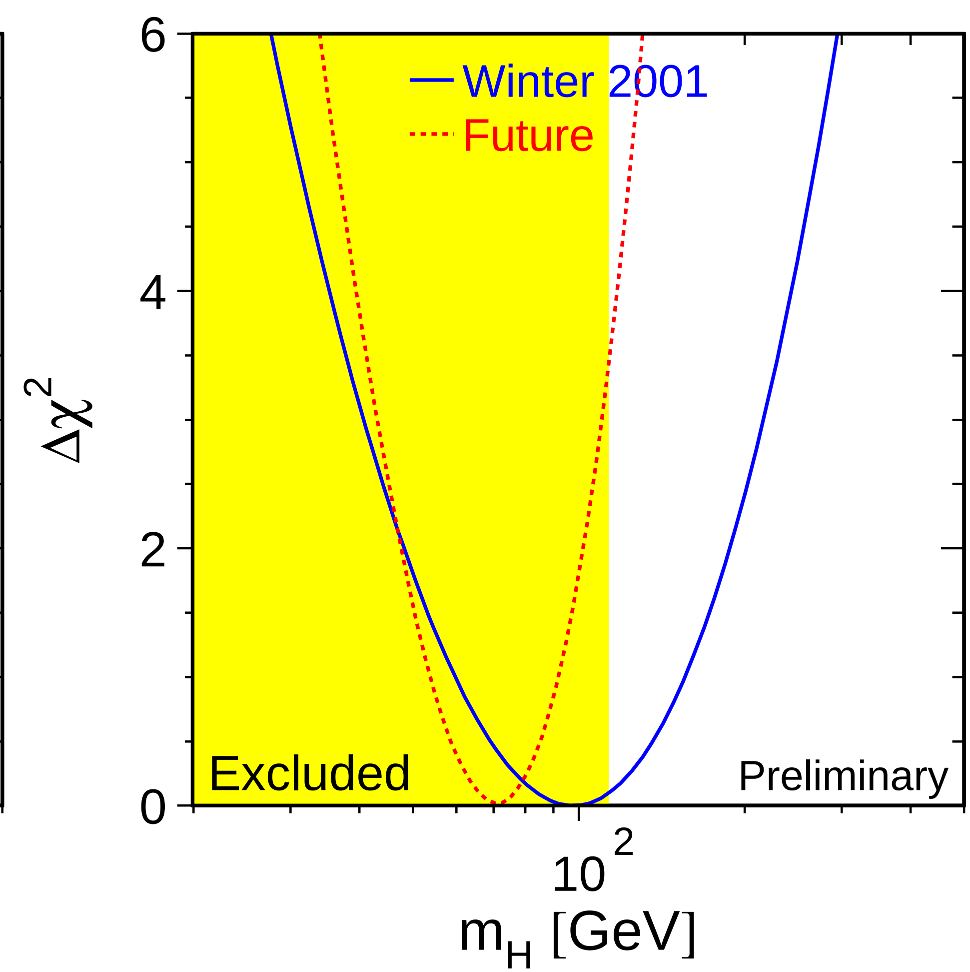
and $\delta(\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)) = 1.0 \times 10^{-4}$.

As a preliminary exercise, take the current central values for $M_W$, $M_t$, etc. and shrink the errors to

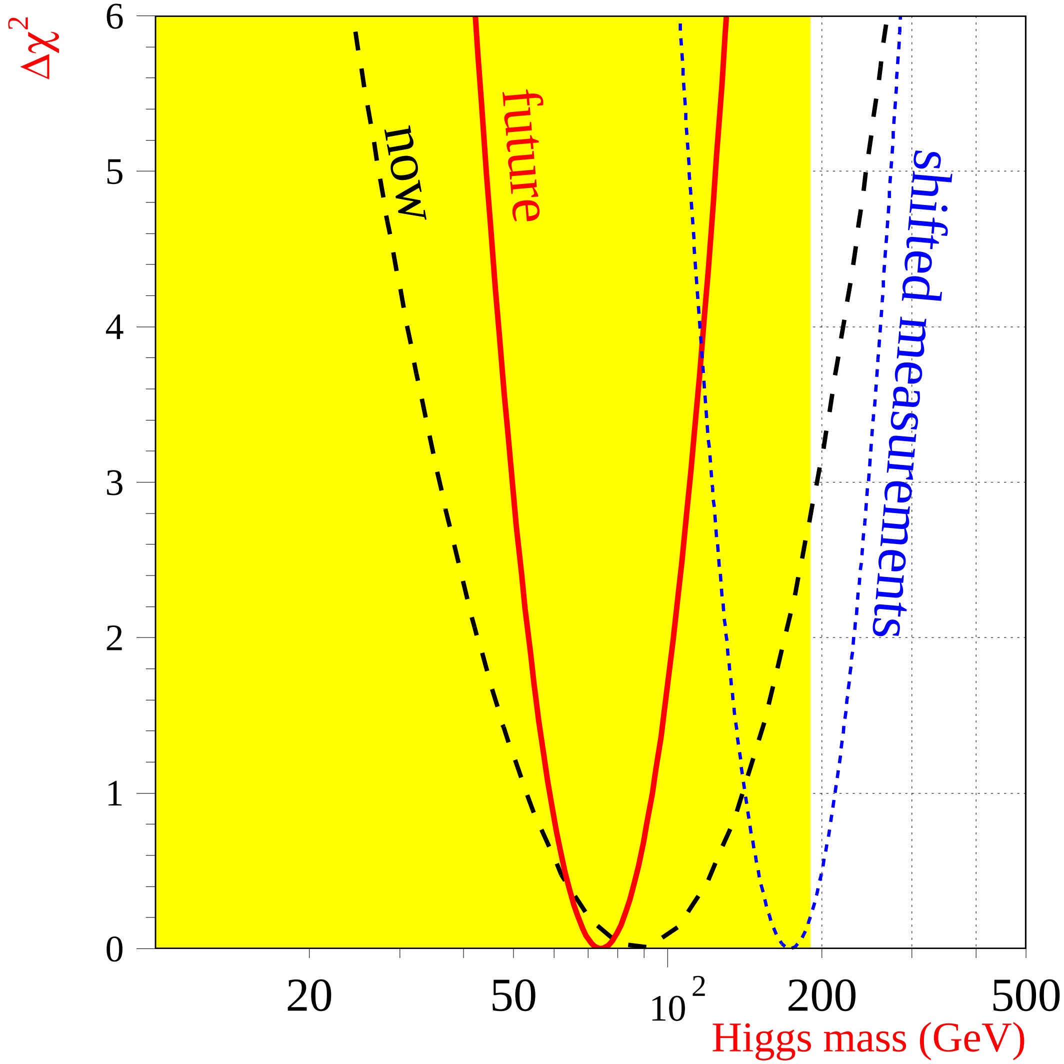
- $\delta M_t = 1$ GeV,
- $\delta M_W = 20$ MeV,
- $\delta \sin^2\theta_W = 0.00012$, and
- $\delta(\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)) = 1.0 \times 10^{-4}$.

Compare the Official LEPEWWG plot with how it might look in the future:



## *Discussion*



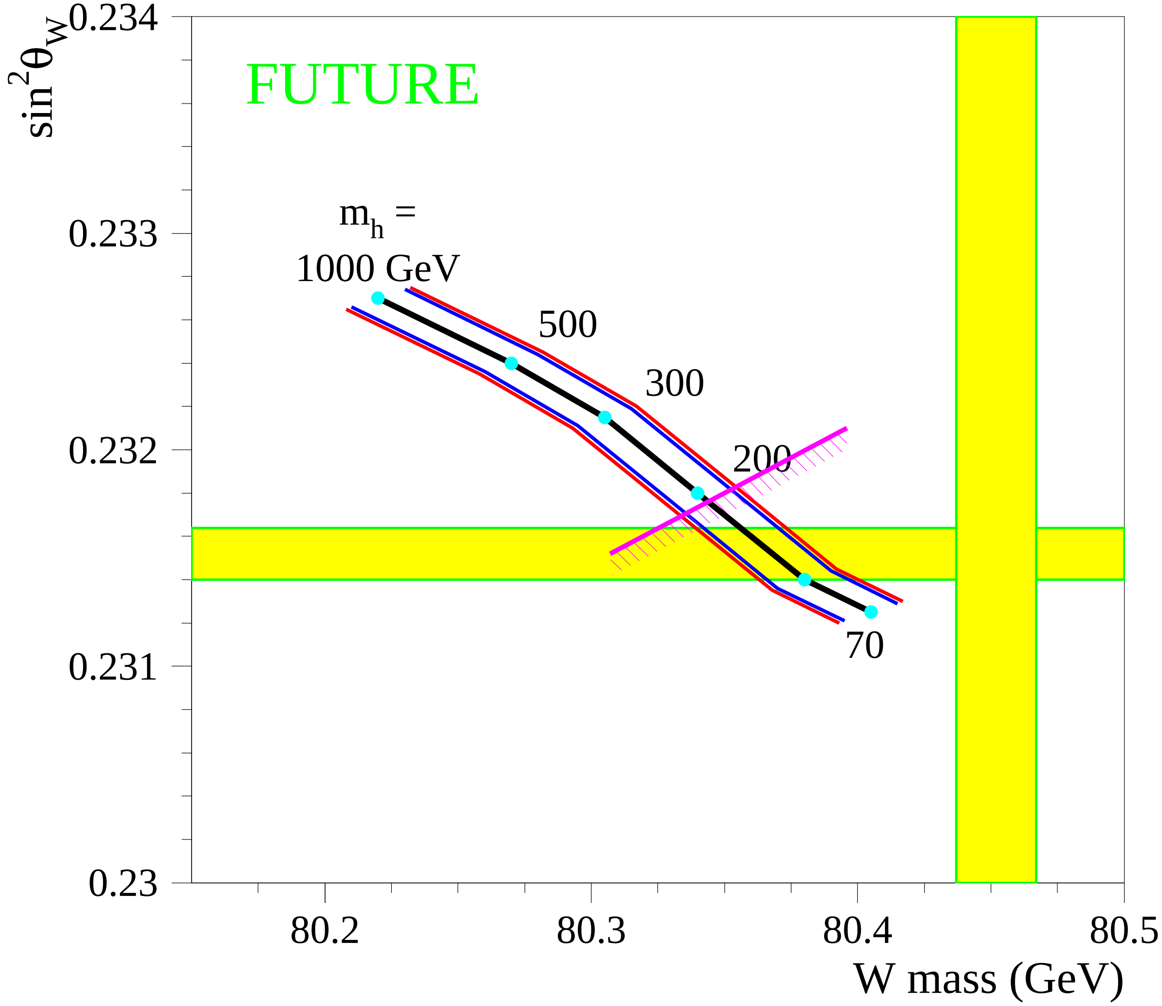

*black:* Summer 2001

*red:* future TeV precision, keep current central values

*blue:* future TeV precision, pessimistically shift $M_t$, $M_W$, $\sin^2\theta_W$ & $\alpha^{(5)}_{\mathrm{had}}$ by $1\sigma$ in the 'wrong' direction.

(prob $< 0.1\%$)

Going back to the $M_W$, $\sin^2\theta_W$ plane:




Clearly the SM would be in trouble if the measurements turned out like this and there were no signs of a Higgs boson!

## *What is to be done?*

First of all,
take the data, search for the Higgs boson
and make the measurements!!

Clearly this will take years.

In the mean time, we are working on the experimental underpinnings of this study.

We also need to account for the probability of fluctuations in the central values when evaluating the likelihood of falsifying the Standard Model.

*Main Message:*

The TEVATRON will squeeze the SM very hard before LHC turns on.