Testing the Standard Model at the Fermilab TeVatron

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P1-WG1

- What is Run II.
- W mass measurement
- top mass measurement
- Forward-backward asymmetry
- $(\alpha_{\mathrm{QED}}(M_Z^2))$
- Putting it all together

What is Run II.

In Run I (1992-95), the TEVATRON ran at $\sqrt{s}_{pp} = 1.8$ TeV and delivered $\sim 110\ \mathrm{pb}^{-1}$.

- discovery of the top quark, $\delta M_{\mathrm{t}} \sim 5$ GeV
- precise measurement $\delta M_{\mathrm{W}} \sim 68$ MeV
- W charge asymmetry constrains PDF's
- A_{FB} in $Z \to \ell^+\ell^-$

Major upgrades of the accelerator

- Main Injector replaced by the Main Ring
- Recycler for $\bar{p}$'s
- many systemic improvements

and both detectors (DØ and CDF)

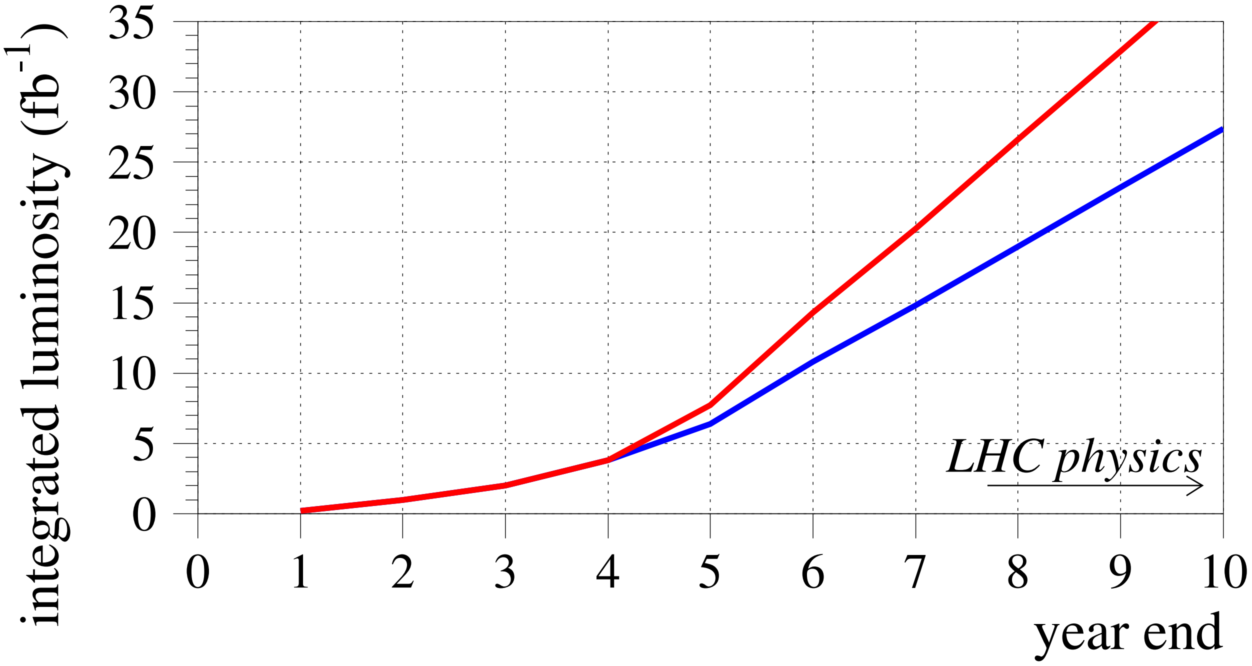
- advanced Si inner tracking & new outer tracking
- new readout electronics and DAQ
- extended muon coverage &
  new endplug calorimetry (CDF)
- S.C. magnet (DØ)

have been carried out.

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

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

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



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 ~ 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 $\delta M_{\mathrm{W}} \sim 30$ MeV

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

- For M_T & p_T^ℓ, 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^ℓ 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 $W \to e\nu$ (U.Heintz)

uncertainty	0.82	2	15	30 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
e^- removal	15	7	7	7
selection bias	5	1	0	0
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**

Notes:

- (1) as estimated by FNAL QCD/WZ study group
- W width directly measured
- calorimeter data assumes Z data only (no J/ψ, π^0)
- energy resolution limited by Γ_Z at 30 fb^{-1}
- e^- angle peculiar to DØ Run 1 (omitted from table)
- e^- removal assumes only factor 2 better
- *caveat:* Detector assumed to function as expected.

DØ also performed a fit to p_T^ℓ and gained a few percent in the total error.

CDF fit to muons also, and gained 20–40% over the electron and muon channels alone.

Ratio Method

An (optimistic) extrapolation from DØ results (U.Heintz).

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.

Future top mass Measurements

Run 2a: relatively crude estimates based on Run 1. projection: $\delta M_{\mathrm{t}} \sim 2$–$3$ 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.
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 ~ 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 extremely crude (compare two untuned MC programs).

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 ~ 1 GeV.

Ordinary systematics scale with the luminosity.

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

An extrapolation from DØ results (M.Narain).

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

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**

(Jet scale information to be combined.)

$2\ell + 2\nu$ event sample

Yields scaled from Run 1 DØ analysis taking into account higher cross section and with no b-tagging.

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**

Again, one channel, one experiment $\rightarrow$ 1.2 GeV. Combine both methods and two experiments.

Projection: $\delta M_t \sim 1$ GeV

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

This is the same as the forward-backward asymmetry measured at LEP, in principle

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

When A_{FB} is measured near the Z pole, a measurement of $\sin^2\theta_W$ can be extracted.

CDF published an analysis based on the electron sample from Run 1 (110 pb^{-1}):

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

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

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

- $\delta A_{\mathrm{FBstat}} = 0.0016$ for 10 fb^{-1} (a DØ study estimated 0.0014), and
- $\delta A_{\mathrm{FBstat}} = 0.0009$ for 30 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 importance of the discrepancy between

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

a difference of 0.00142 ± 0.00040.

$\alpha_{\rm QED}(M_Z^2)$

The TEVATRON cannot provide this number, of course!
It is a crucial input parameter to tests of the SM.
At issue is the contribution of light quarks/hadrons, $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$, to the running of $\alpha_{\rm QED}$.
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 $R^{\mathrm{had}}(s)$ at CLEO-c.
(ref: L.Gibbons)

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

Putting it Together.

We have made the following projections:

integrated luminosity	2	15	30 fb^{-1}
δM_{W} (MeV)	30	20	15
δM_{t} (GeV)	2	1.5	1
$\delta \sin^2 \theta_W$	0.0008	0.00028	0.00016

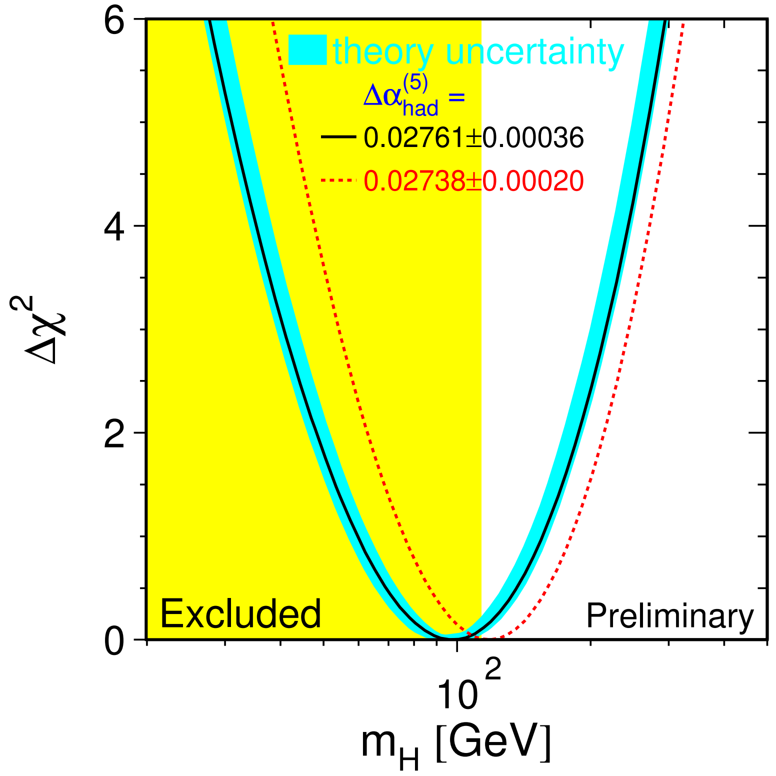
and $\delta(\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)) = 1.0 \times 10^{-4}$.

As a preliminary exercise, take the current central values for M_{W}, M_{t}, etc. and shrink the errors to

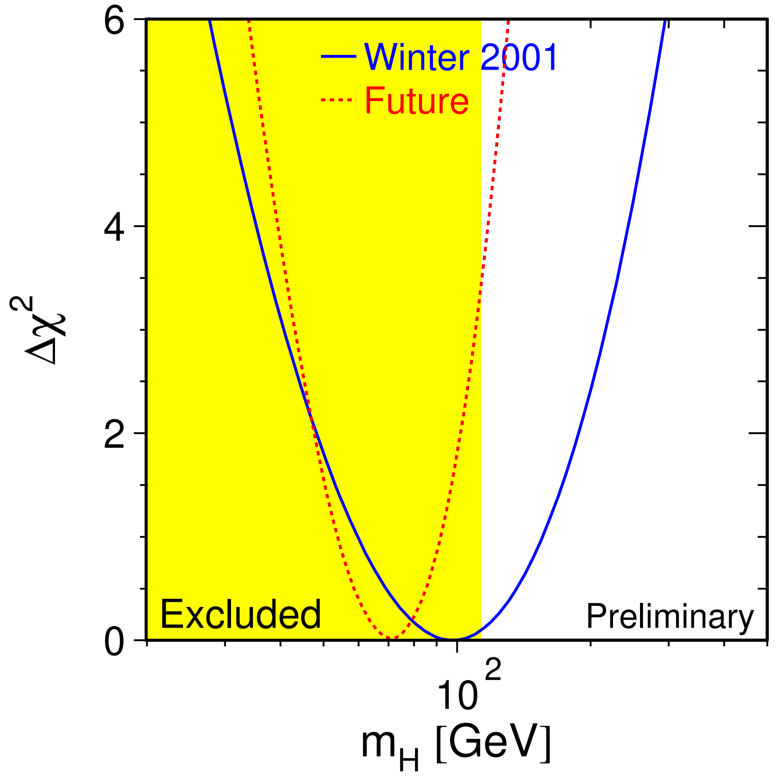
- $\delta M_{\mathrm{W}} = 20$ MeV,
- $\delta M_{\mathrm{t}} = 1$ GeV and
- $\delta(\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)) = 1.0 \times 10^{-4}$.

(We do not use the A_{FB} information as we do not have a good grasp on the systematics yet.)

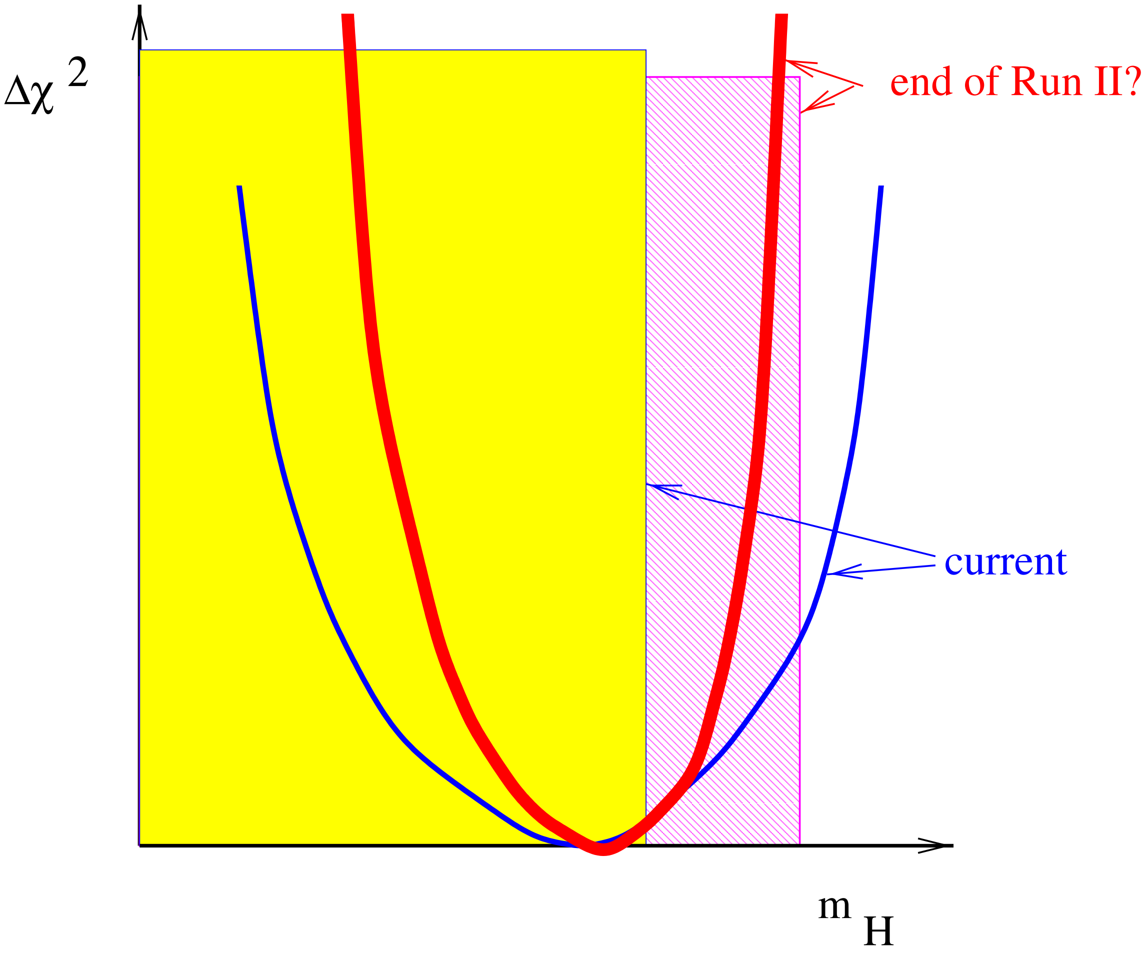
Official LEPEWWG plot:



From Martin Grünewald:



If there is no observation of a Higgs boson
(exclusion at 95% CL up to $\sim$ 190 GeV)
then the SM would be severely challenged.



- position of minimum *will* shift
- error estimates assume no problems with detector
- $\mathcal{L} \to 30\ \mathrm{fb}^{-1}$ is not an official FERMILAB goal – yet.