What Have We Learned from LEP and the Tevatron Run 1?

- Introductory Remarks
- Electroweak !
- The Third Generation
- A dusting of QCD
- Where New Physics is Not – *or is it?*
- Concluding Remarks

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Current and Upcoming Discoveries

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Introductory Remarks

Obviously, I cannot go into great depth everywhere!

Instead, i will try to give some highlights:

- What has lasting value?
- Where are there hints of something exciting?

So this will reflect my tastes, biases and limitations –

I apologize for leaving important things out!

I will interject some remarks on experimental physics, which has gone a tremendous development since the late 1980's!

Perhaps I will pose a question on the side to show where one might still put some thought, or think about further analyses.

Tally ho!

Electroweak!

Before LEP and Run 1, the SM looked like a good model (not a theory).

No one expected it to be accurate – NP (New Physics) would surely show up directly, or at least indirectly when tying together various precision EW measurements.

Before LEP and Run 1, M_W and M_Z were know only to about 2 GeV, and $\nu - N$ scattering was providing the picture of fermion couplings (g_V and g_A).

Let's start where UA1 & UA2, and TRISTAN left off...

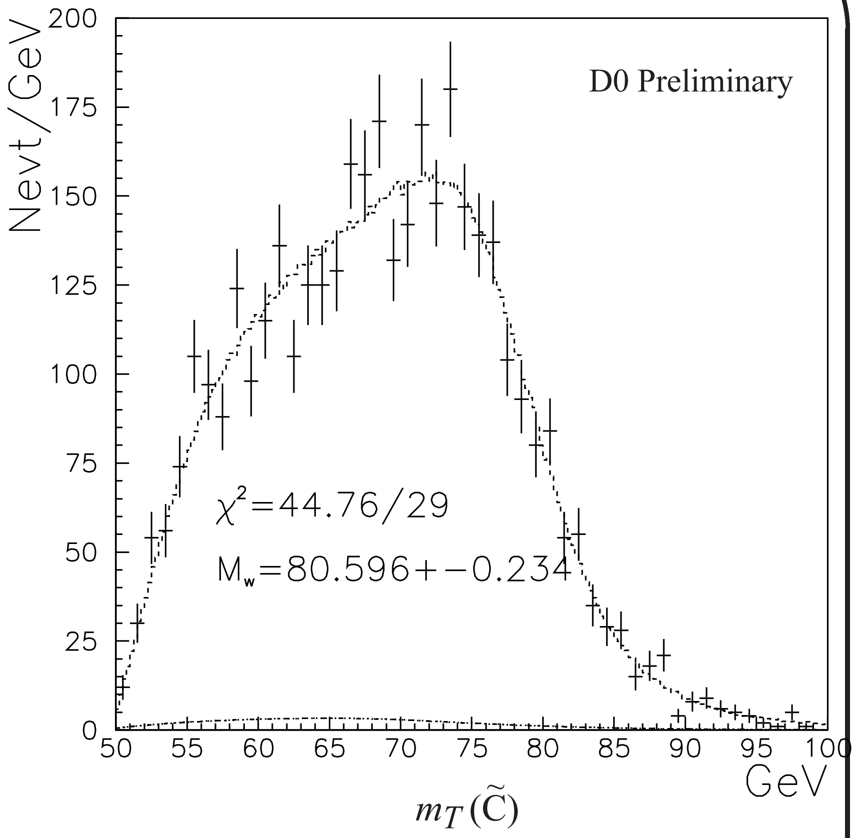
M_W from Run 1

$p\bar{p} \to WX,\ W \to e\nu, \mu\nu$

control *many* tough details precisely

- underlying ev, n-interact'n
- "reconstruction" of p_T^ν
- p_T^W dist'n esp. nonpert part (Z)
- E & p scales (Z) & resol'n
- QED radiation & corrections

This is 'direct reconstruction.'



$\boxed{M_W = 80.451 \pm 0.039 \text{ GeV}}$

focus: energy scale problems

E/p simply does not work for CDF data! So, normalize to M_Z.

Ultimate development: stretch and squeeze the Z distributions so that they can directly be used as templates for the W ('ratio method')

M_Z from LEP

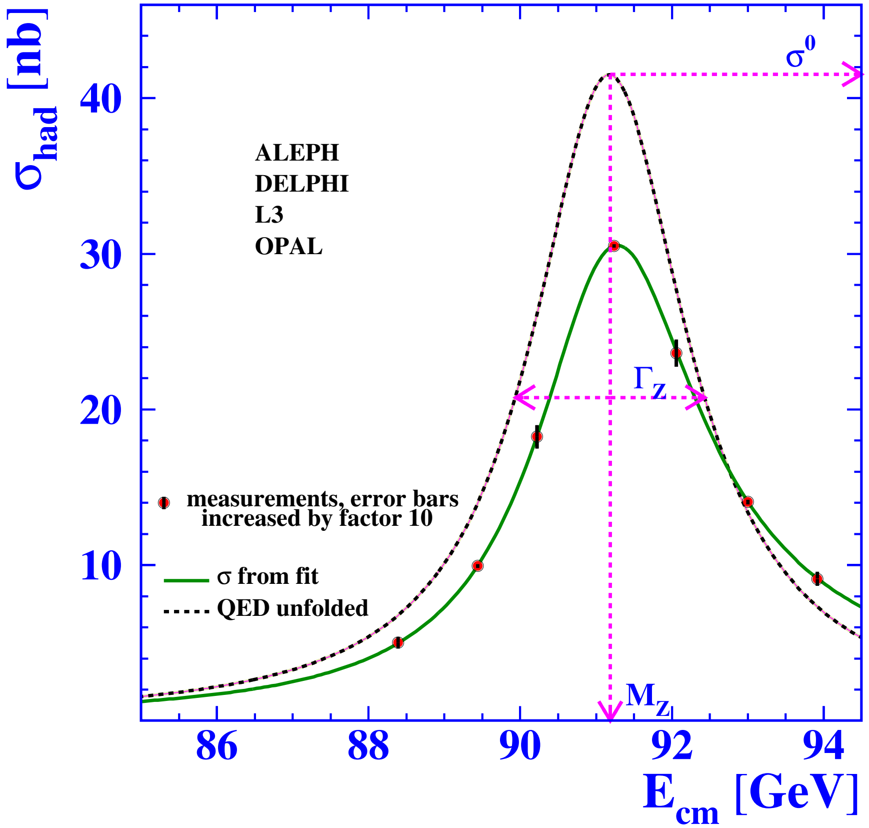
$e^+e^- \to Z \to visible$

a completely different story – measure the energy dependence of σ based on a very inclusive selection of events.

challenges:

- setting the beam energy scale (by method of resonant depolarization)
- good theoretical description of the lineshape (rad.corr. are large!)

This is the 'line shape' method.



$$M_Z = 90.1876 \pm 0.0021 \text{ GeV}$$

M_W also obtained at LEP, of course.

focus: number of light, left-handed neutrino flavors

inferred from the total Z and partial widths.

$\boxed{N_\nu = 2.9841 \pm 0.0083 \text{ – not quite 3}}$

The recent NuTeV result casts this in an interesting light:

$\boxed{N_\nu = 2.964 \pm 0.012 \text{ – even smaller}}$

Combined value:

$$\boxed{N_\nu = 2.978 \pm 0.0068}$$

which is 3.3σ below $N_\nu = 3$.

Could this be interpreted a sign of mixing with ‘other’ neutrinos?

$\boxed{M_W \text{ and } M_Z \text{ are NOT INDEPENDENT!}}$

– not in the SM and not in many extensions.

$$M_W = M_Z \cos\theta_W \tag{1}$$

where the mixing angle θ_W also determines the behavior of the Z

Several asymmetries can be defined which depend parametrically on $1 - (M_W/M_Z)^2$ – best known as $\sin^2\theta_W$.

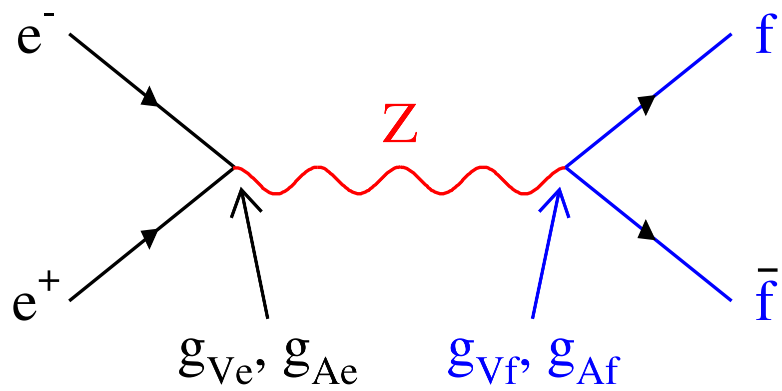
The most naive test of the SM:
extract $\sin^2\theta_W$ from the measured asymmetries and compare to Eq. 1.

What are these asymmetries? – Let me talk about just a couple.

. $\boxed{A_{LR} \text{ from SLC}}$ $\boxed{A_\ell^{0,b} \text{ from LEP}}$

$\sin^2\theta_W$ is about vector and axial coupling constants:

$$\sin^2\theta_W = \frac{1}{4}\,(1 - \frac{g_V}{g_A}).$$



Asymmetries depend on particular combination of g_V and g_A:

$$\mathcal{A}_f = \frac{2\,g_{Vf}\,g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

For example,

$$A_{LR} = \frac{1}{\mathcal{P}_e}\,\mathcal{A}_e \qquad \text{and} \qquad A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

where $\mathcal{P}_e$ is the e^- beam polarization.

A_{LR} from SLD

- polarized beams are unique to SLC
- switch $\mathcal{P}(e^-)$ between -0.75 and +0.75 while $\mathcal{P}(e^+) = 0$
- count events in an inclusive manner – simple!
- The great challenge was obtaining high polarization, and in knowing its actual value. ($\delta\mathcal{P}_e = 0.6\%$)
- clean, simple, powerful. . . *the world's best single measurement*

$$\boxed{\sin^2\theta_W = 0.23098 \pm 0.00026}$$

- beautiful for its clarity and robustness

$A_{FB}^{0,b}$ from LEP

- $\mathcal{A}_e$ extracted from $A_{FB}^{0,b}$
- beams are unpolarized – all the business is in the final state
- tag b-flavor in a variety of ways: high-p_T leptons, kaon tagging, vertex charge, jet charge, etc.
- required very careful tuning and control of b-physics in Monte Carlo.
- hard, yet. . . *the world's second best measurement*

$$\boxed{\sin^2\theta_W = 0.23226 \pm 0.00031}$$

- an impressive *tour de force*

Compilation of $\sin^2\theta_W$ measurements at Z-pole:

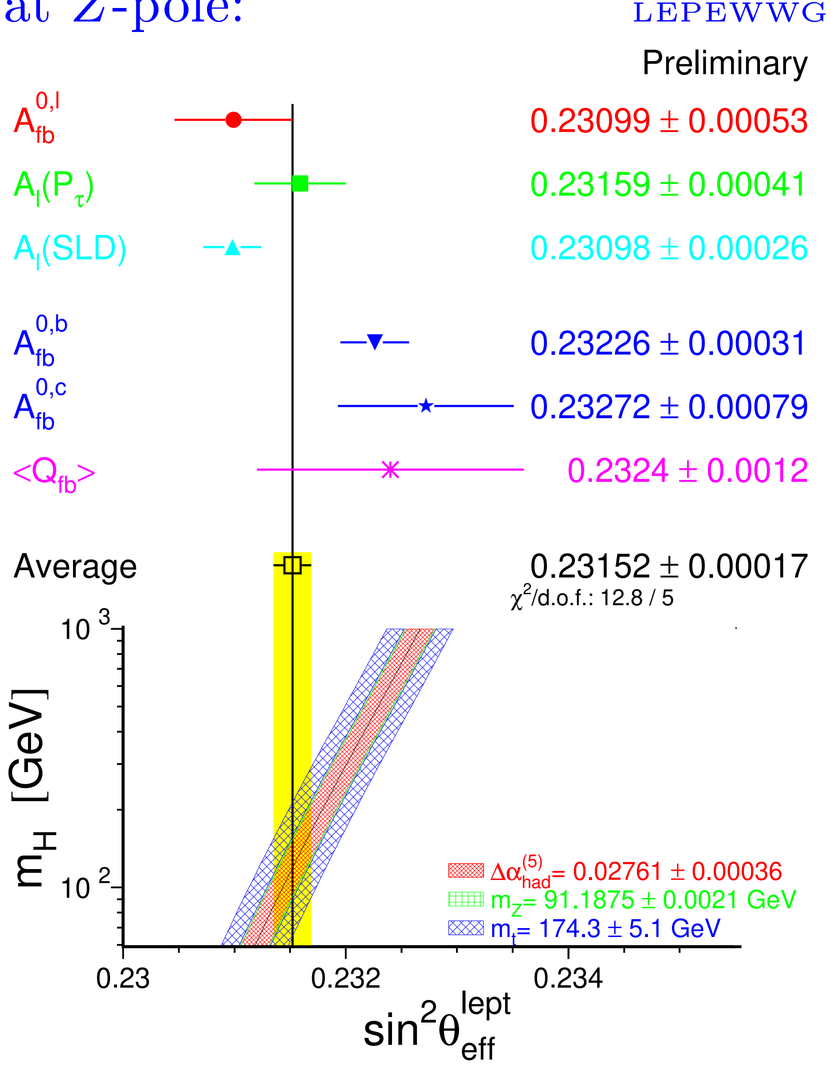
Combined relative precision: 0.07%!

Compare the two most precise values. *they disagree at the 3σ level!*

The third best measurement, from τ polarization, sits halfway in between.

The χ^2/d.o.f is miserable.

There is a problem here!



Prospects for more measurements: A_{FB} at the TEVATRON (U.Heintz)

Theoretical insights: "beautiful mirrors" (C.Wagner)

Global Fits to Precision EWK Observables

Coming back to comparing EW mixing as regards boson masses on the one hand, and fermion couplings on the other:

This is best done using so-called 'global fits' of the SM to any and all precision electroweak measurements. It is interesting at the level of radiative corrections. (Up until circa 1994, there had been no experimental evidence supporting weak corrections!)

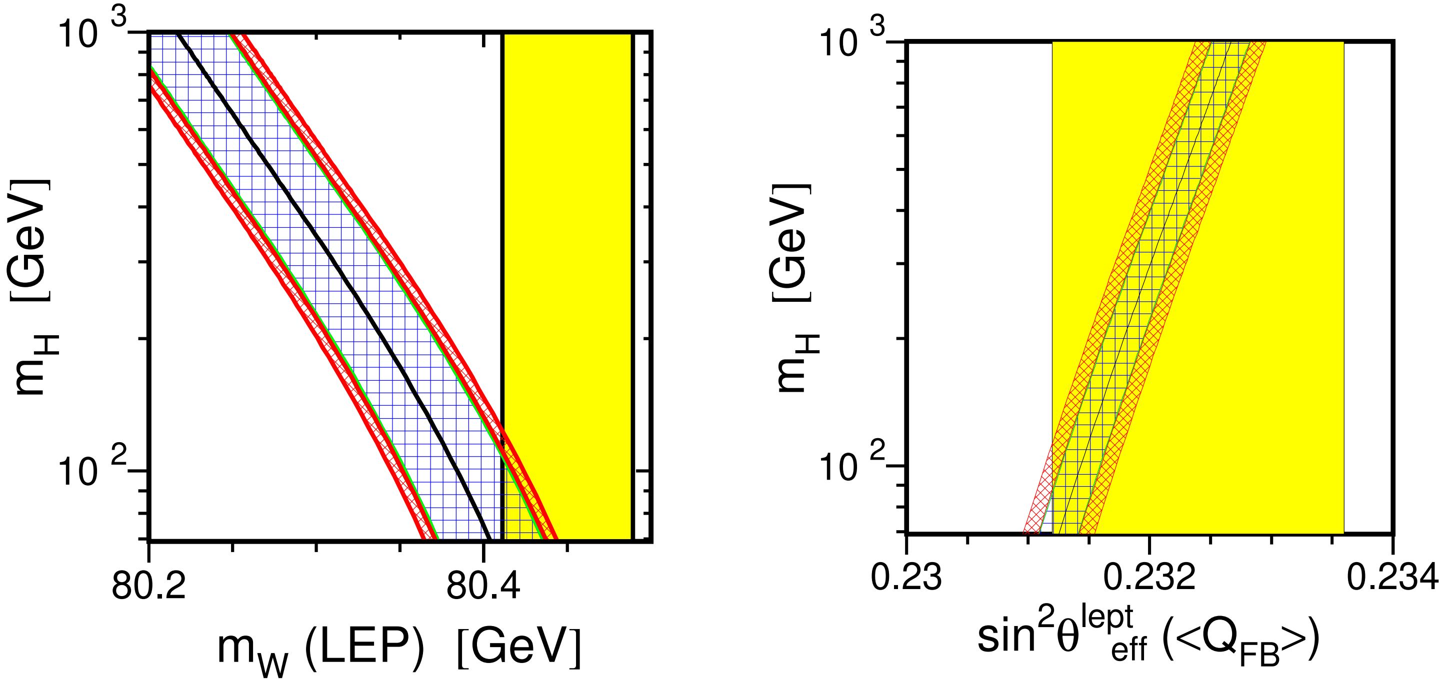
The predictions for each observable involve radiative corrections through which several parameters enter: m_h, m_t, $\alpha_{\rm EM}$, $\alpha_{\rm S}$, etc.

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.

This presents an opportunity to infer m_h through its participation in *virtual effects*! (a replay of the top quark story. . .)

Basic Concept:

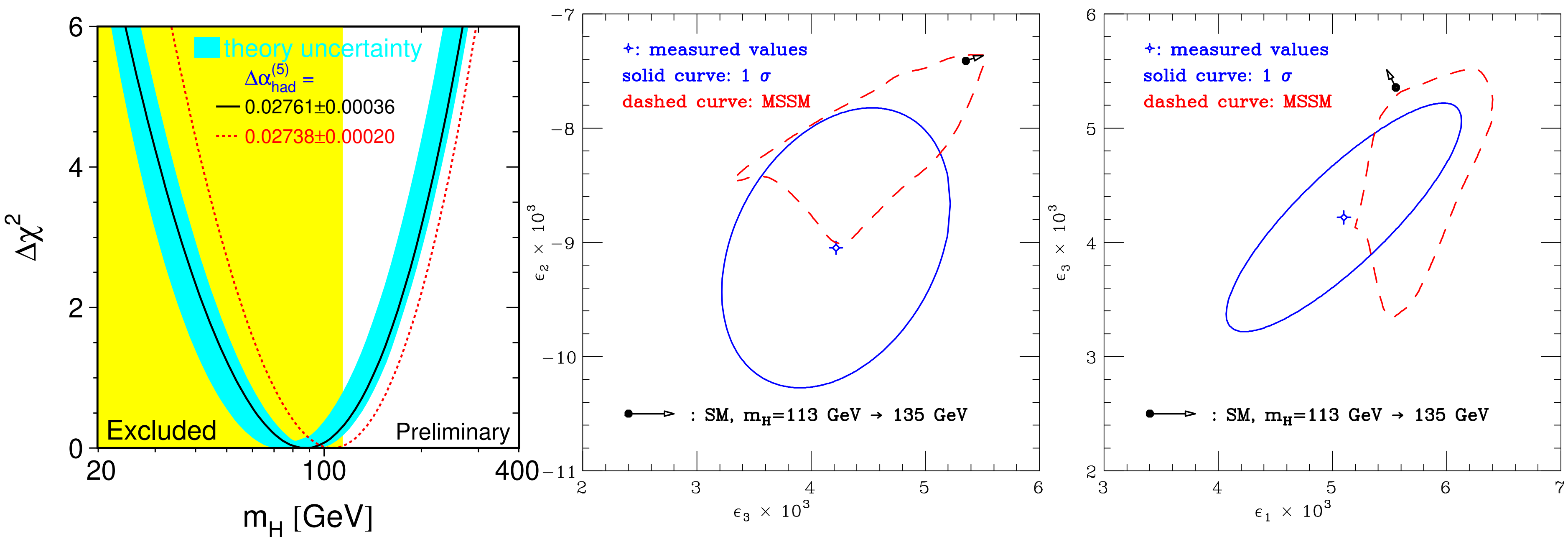
compare $M_W^{\rm theo}$ and $\sin^2\theta_W^{\rm theo}$ to $M_W^{\rm meas}$ and $\sin^2\theta_W^{\rm meas}$ to infer m_h.



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

LEPEWWG `hep-ex/0112021`

Conclusion of the Fitting Exercises



This shows that precision EWK measurements agree with the SM, provided the as yet undiscovered higgs boson is not too heavy.

(See M.Carena's talk for a larger discussion.) mb

Also, the allowed virtual effects from NP are very constrained. Not many speculations can match that easily, save SUSY.

Electroweak!

The Standard Model is **correct** – *as far as it goes. . .*

We are convinced of EWSB but we (officially) have not found the Higgs boson which triggers it. In fact, one can imagine a case in which the upper limit from global EW fits and the lower limit from direct searches cross, thereby eviscerating the SM...

We know the precise couplings of all (light) matter fermions, up to a sign.

We know the number of light, left-handed neutrino flavors.
but the NuTeV result is interesting. . .

We know $\sin^2\theta_W$ measured a dozen different ways.
It mostly hangs together – *but not totally*.
problem! problem! problem! Who will take this on?

We know SUSY is a viable extension of the SM.

Many versions of dynamical SB are not viable, though there are a few that are (technically). But they are not popular.

Is there a potential problem here?

Nearly everyone is hungry to uncover the MSSM particle spectrum and have a go at the underlying parameters.

(Is this the blind leading the blind, *i.e.*, a bias???)

Higgs boson is responsible not only for EWSB, but also for chiral symmetry breaking, *i.e.*, for giving masses to the fermions.

Let's turn now to the heaviest generation: τ, b and t...

The Third Generation

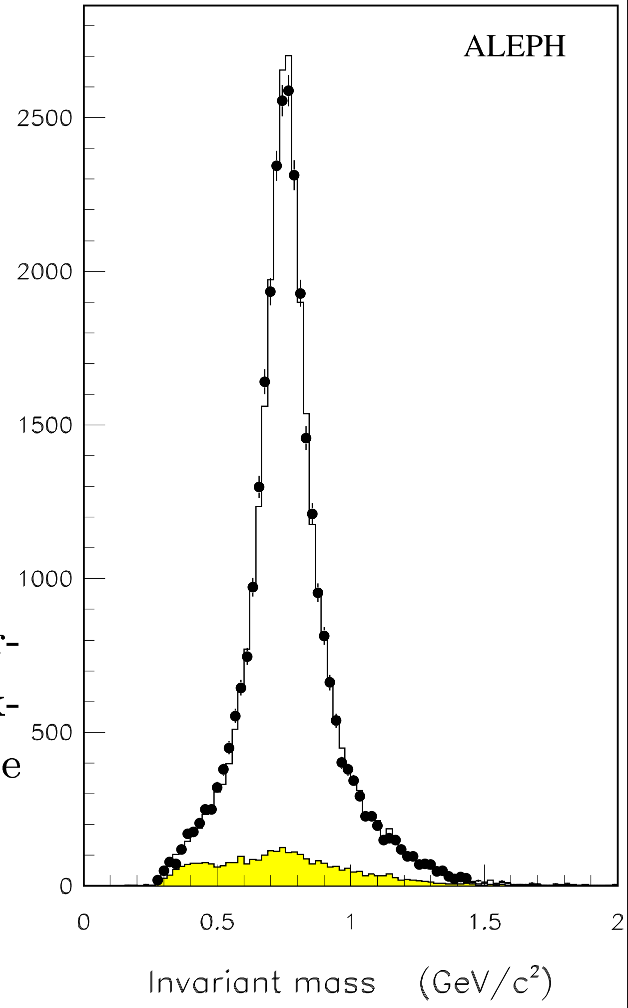
τ leptons we have gone from resolving anomalies to exploring very rare decays, CPV, getting limits on M_{ν_τ}, to proving information with helps in the extraction of the hadronic contribution to alpha!

b hadrons We are now well acquainted with the B hadrons. Several new ones were discovered, most lately: the B_c. Both LEP and TEVATRON made very precise measurements of lifetimes and BR's (CLEO played a big role here too, of course.) Don't forget: mixing and the first forays in CP violation

The t quark finally discovered at the Tevatron, it is VERY HEAVY. (SUSY: Is it perhaps responsible for EWSB?) no large deviations in BR's, cross section, and no large $t\bar{t}$ resonances. But there is a problem – see below. We need larger event samples...

τ leptons

Notice: Sometimes, in going from one generation of experiments to the next, anomalies get resolved. τ decays provide an example:



Before LEP (& CLEO) there was a problem with τ BR's:

Compare topological BR's (n-prong)
with sums of exclusive BR's
and find a deficit in the latter ($\sim 2.5\sigma$ level).

Implication: There are new, unexpected τ decays.

LEP resolved this handily – τ decays are very well understood and have been used to test CVC, PCAC and to extract the ρ lineshape ($\tau\nu$ is like e^+e^-) which helped reduce uncertainties in the running of α_{EM}.

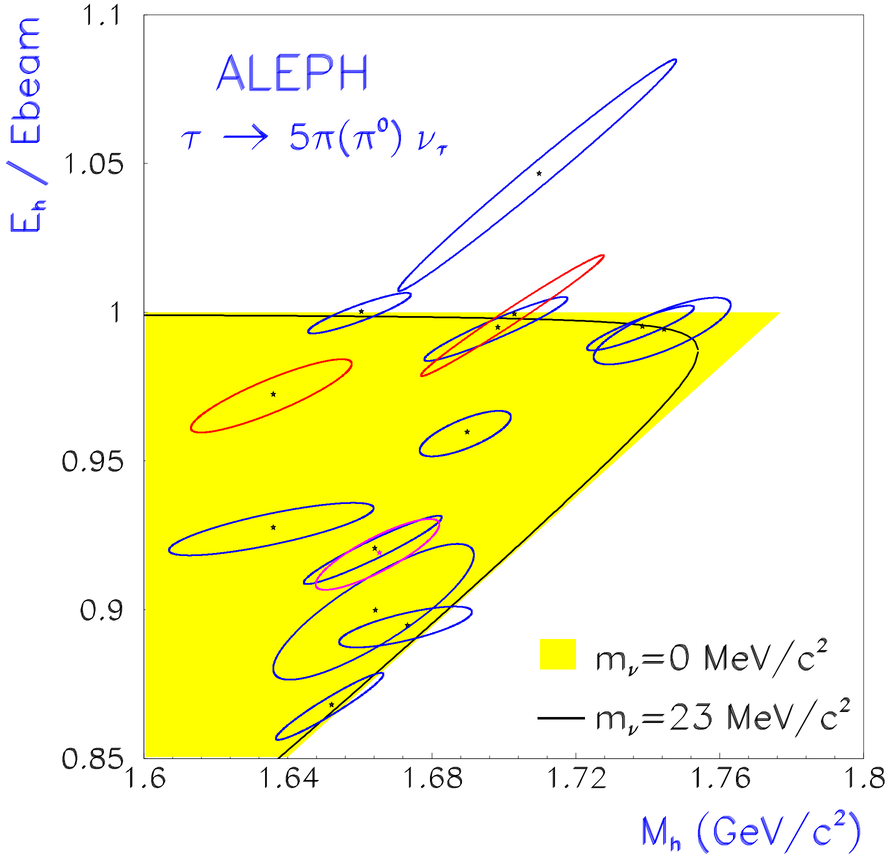
LEP accumulated huge numbers of τ's allowing study of rare, high-multiplicity decays.

Observe the endpoint and infer an upper limit on M_{ν_τ}!

Example from ALEPH Collab. $\tau \to 5\pi(\pi^0)\nu_\tau$

Exploit energy *and mass* information to increase sensitivity.

$$\boxed{M_{\nu_\tau} < 18.2 \text{ MeV at } 95\% \text{ CL}}$$

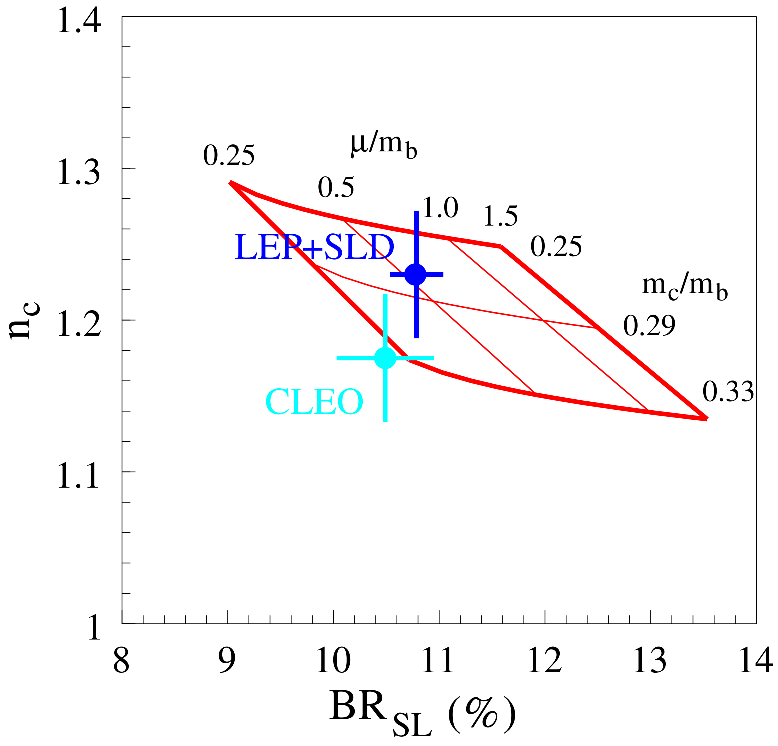


This may look silly in light of what we now know about mass splittings, but perhaps the method could be carried further in future lepton and photon colliders. . .

b-hadrons

The (former) $\mathcal{B}(b \to \ell X)$ Puzzle:

Prediction from Γ_ℓ and τ_B was always higher than measurement, despite many refinements in the latter.



Possibility of NP in $b \to sg$.

Much better techniques developed for measuring $\mathcal{B}(b \to \ell X)$.

Eventually more or less resolved by a careful counting of charm produced in B decays.

Caveat: agreement requires QCD corrections to be evaluated at a low scale!

Need higher orders.

What about Lifetimes? They should be easy!

Theory has fairly solid predictions for lifetimes ratios. OPE + HQET + modeling

Measurements require some care, but are generally quite robust and reliable.

ratios of b-hadron lifetimes:

B^+/B_d^0	$1+\sim 0.05$	1.063 ± 0.020
B_s^0/B_d^0	$1+\mathcal{O}(0.01)$	0.946 ± 0.039
baryon$/B_d^0$	0.90–0.95	0.780 ± 0.035

Theory gets b-baryon lifetime wrong!

Problem: It could be serious, basic defects in the whole theoretical picture, or lesser problems with the quark models used to determine baryon parameters. Spectator partons may be more important than anticipated; lattice says corrects are larger. There also may be a violation of quark-hadron duality.

Nonetheless, we forge ahead for the holy grail: CP violations in the B-system…

B-mixing

a QM phenomenon, very similar to K^0 flavor oscillations.

CP violation is possible if the two mass eigenstates have different masses and different widths. $\Delta m \neq 0$ and $\Delta\Gamma \neq 0$

Δm is manifested in flavor oscillations as a function of time.

Experimentally, the basic task to is measure the initial and final flavors of the meson (B_d^0 or B_s^0), and to measure its decay distance and energy.

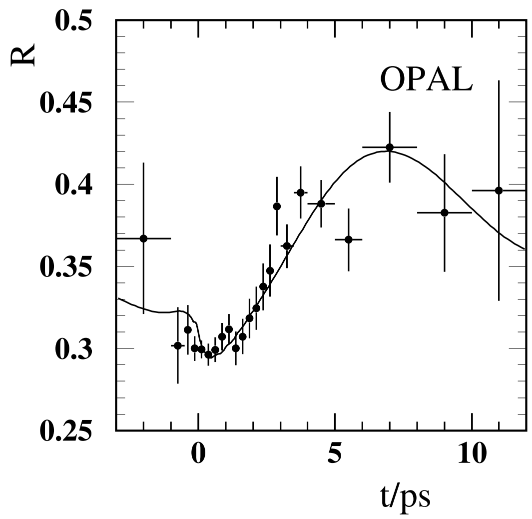
Many tagging methods have been invented – they are mostly well known and it is not possible to go through them here.

The results are impressive:

$$\boxed{\Delta m_d = 0.487 \pm 0.014\ \mathrm{ps}^{-1}}$$

Can't tell yet whether $\Delta\Gamma_d \neq 0$.

Can't extract V_{td} b/c theoretical uncertainties too large.



B_s mixing is more difficult. First, the oscillations are much faster, which challenges the detector capabilities. Second, the B_s mesons are rarer and less easy to pick out, so backgrounds are a bigger problem.

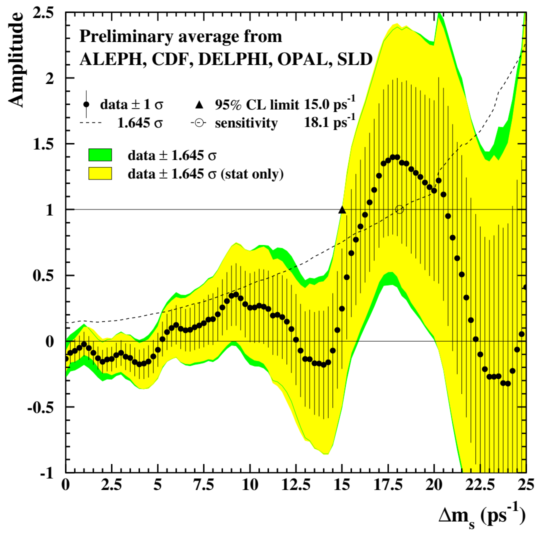
However, it is expected that $\Delta\Gamma_s$ is not so small, so that if Δm_s and $\Delta\Gamma_s$ are measured, one might hope to observe CP violations.

Furthermore, the ratio $\Delta m_s/\Delta m_s$ constrains the ratio of CKM elements V_{ts}/V_{td} with relatively little theoretical uncertainty.

B_s oscillations have not yet been observed, despite a large effort (& friendly competition) at LEP, CDF and SLD.

A clever means of combining data has been devised: float the amplitude of the oscillatory term as a function of Δm_s: amplitudes for independent measurements are readily combined.

$\boxed{\Delta m_s > 15.0\ \mathrm{ps}^{-1} \text{ at } 95\%\ \mathrm{CL}}$



The Top Quark

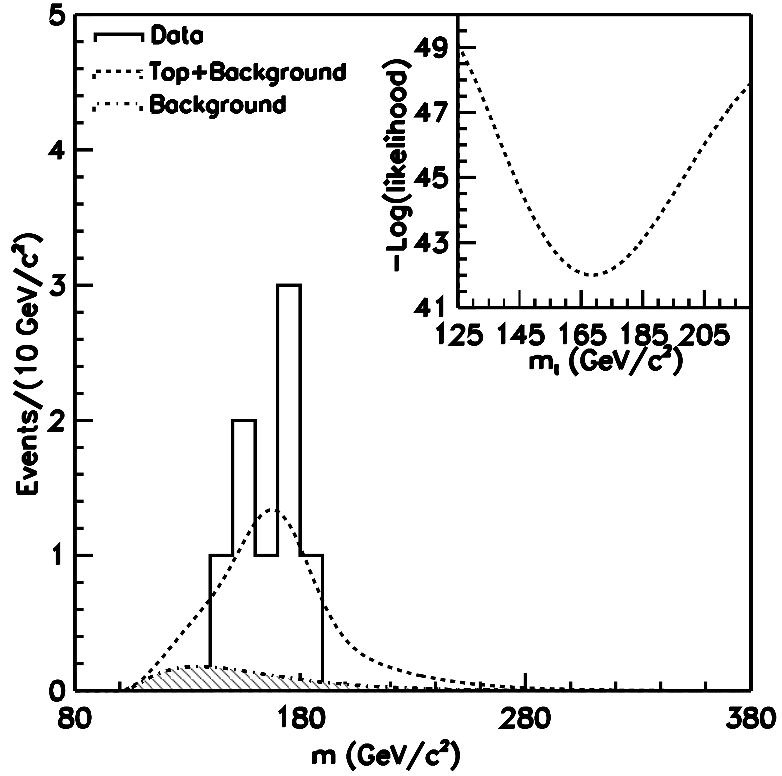
This is the only fundamental particle discovered during the entire period of LEP and RUN 1!

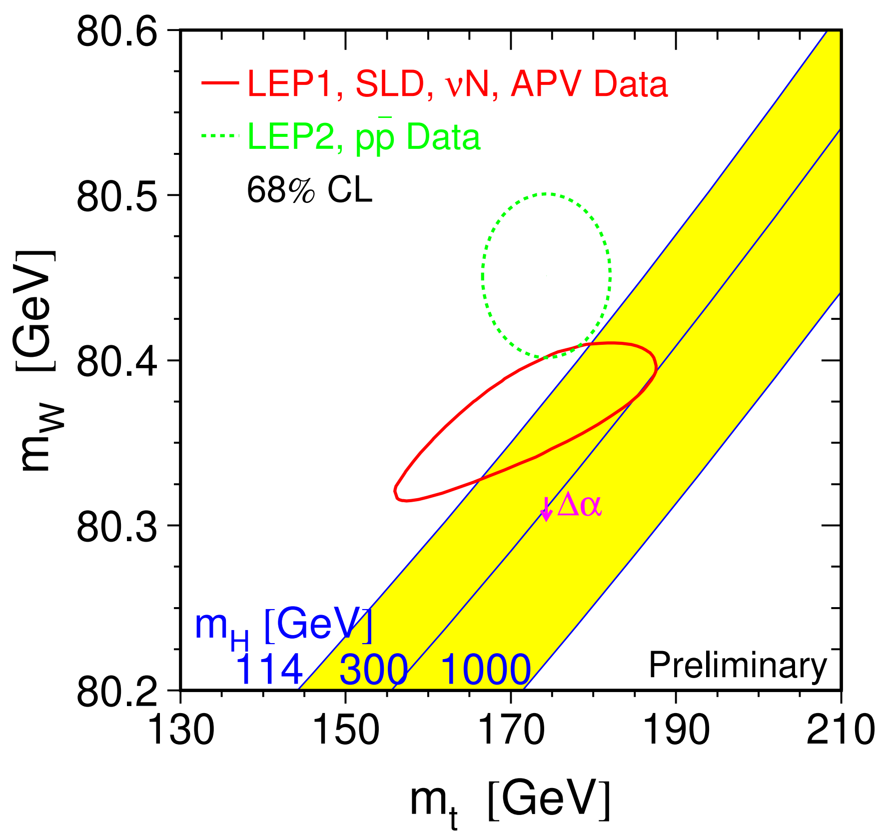
It is *much* heavier than was expected: $\boxed{M_t = 174.3 \pm 3.2 \pm 4.0 \text{ GeV}}$ which is comparable to the electroweak scale itself.

The indirect top mass inferred from global electroweak fits drifted upward over the years, as the lower limit set by the TEVATRON experiments rose.

The direct measurement quickly followed its discovery in 1995.
Three event topologies are involved, depending on how the W decays: $\ell\nu\ell\nu b\bar{b}$, $\ell\nu b\bar{b}JJ$ and $b\bar{b}4J$.

The events were culled from the W+jets sample and b-tagging was applied. Only a small number of events were selected, but enough to make measurements of the mass:





Important point: the indirect value for the top mass agrees well with this direct measurement.

We have also learned that

- BR's must be similar to the SM $\Longrightarrow$ no new large channels
- cross section is similar to the SM $\Longrightarrow$ no new large sources of $t\bar{t}$
- no large $t\bar{t}$ resonances
- no large FCNC
- the polarization of the W is like the SM (probes EWSB)
- In the CDF sample, the kinematics and properties of some of the events *DO NOT* correspond well to SM predictions. (more, later)

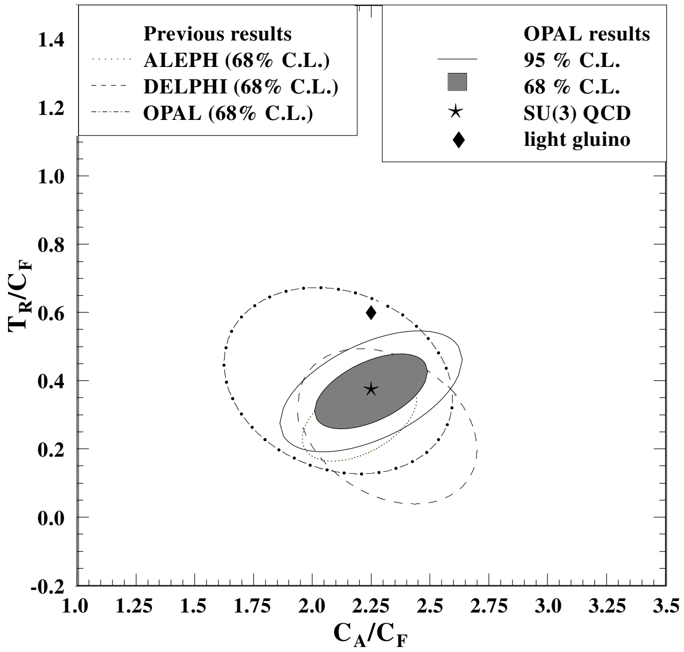
The grain is coarse at this point. $\Longrightarrow$ stay tuned for Run II.

A Dusting of QCD

Group Structure

QCD is a non-Abelian gauge theory built on $SU(3)_c$ and an internal 'color' charge. We know there are three colors from numerous sources. But how do we know $SU(3)_c$ is the right group?

Answer comes from the analysis of angular correlations of four-jet events at LEP 1. The group is realized in terms of 'color factors' which determine the angular distributions. Careful fitting allows these constants to be extracted.



$SU(3)_c$ is clear winner.

NB: light gluinos excluded.

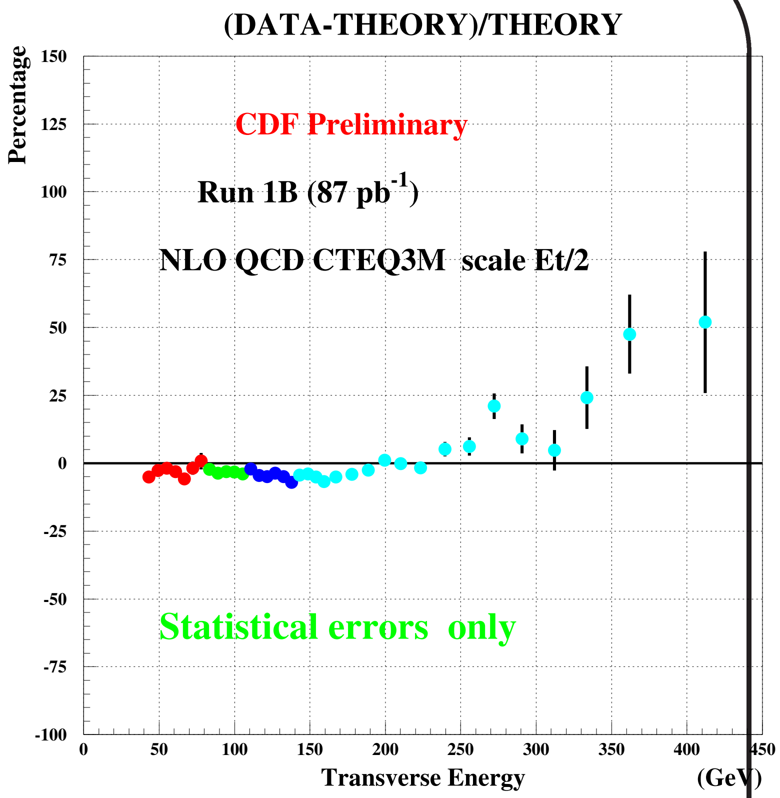
So this bolsters the image of QCD as a gauge theory like EW. Probably perturbation theory should work fine, right?

CDF High-E_T Excess

A bread&butter QCD measurement: inclusive E_T distribution of jets.

After a long and careful analysis, **CDF saw an excess at high-E_T** wrt QCD predictions.

The DØ data agree with the CDF data, and also with QCD predictions.



It seems possible that the gluon content of the proton was too low in the original predictions. Has this really been resolved?

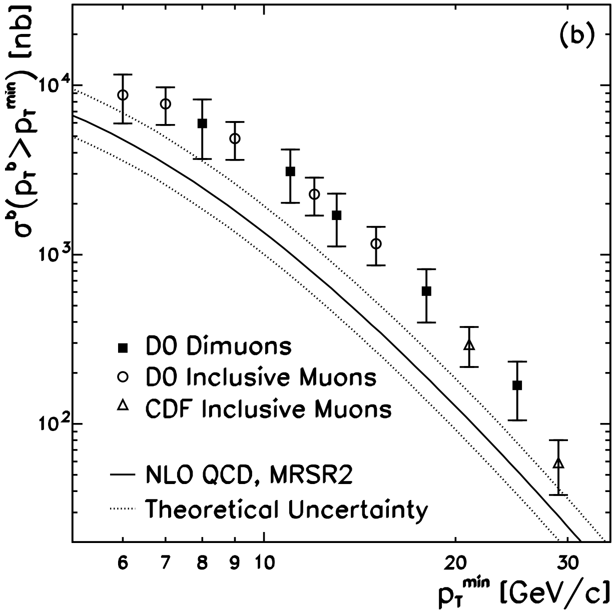
Inclusive B Production at the TEVATRON

1. direct: b's produced as primary, high-p_T particles
2. flavor excitation: b quarks inside the proton
3. fragmentation: b's produced in jet fragmentation

Several means to measure $d\sigma(B)/dp_T$

- inclusive leptons
- inclusive J/ψ
- exclusive $B \to D$

All disagree violently with theory, falling a factor 2–3 higher than predicted!



This is a major problem which does not have a simple solution.

– QCD corrections are large & peculiar new mechanisms proposed

– there could be NP, such as light $\tilde{b}$ (C.Wagner)

A Dusting of QCD

There are many more important topics in QCD that I must skip, including

- the many measurements of α_S
- quark-gluon jet differences
- probes of quark-hadron duality
- structure functions from DY and W-asymmetry
- diffractive physics at the TEVATRON
- two-photon physics at LEP

Where the New Physics is (not) at

part I: null results

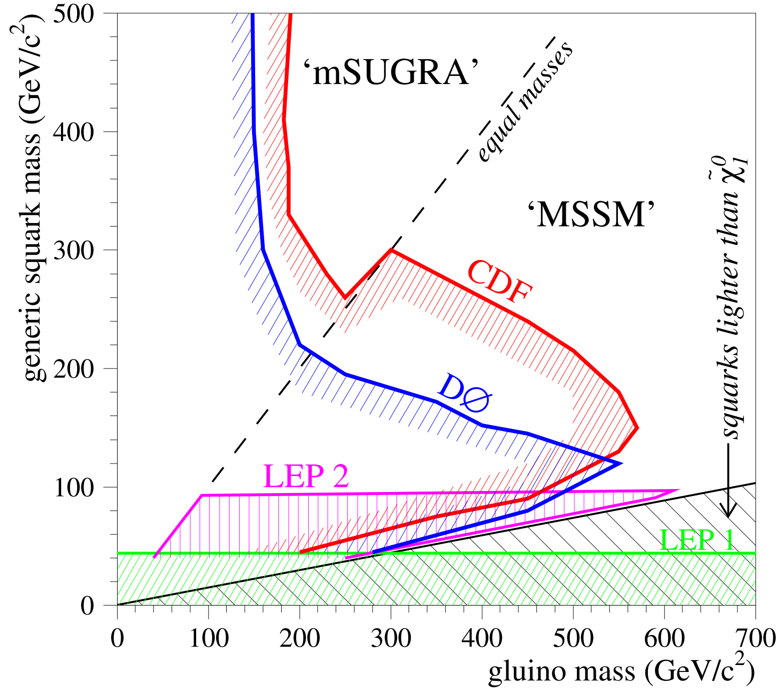
The street under the lampost is bare.

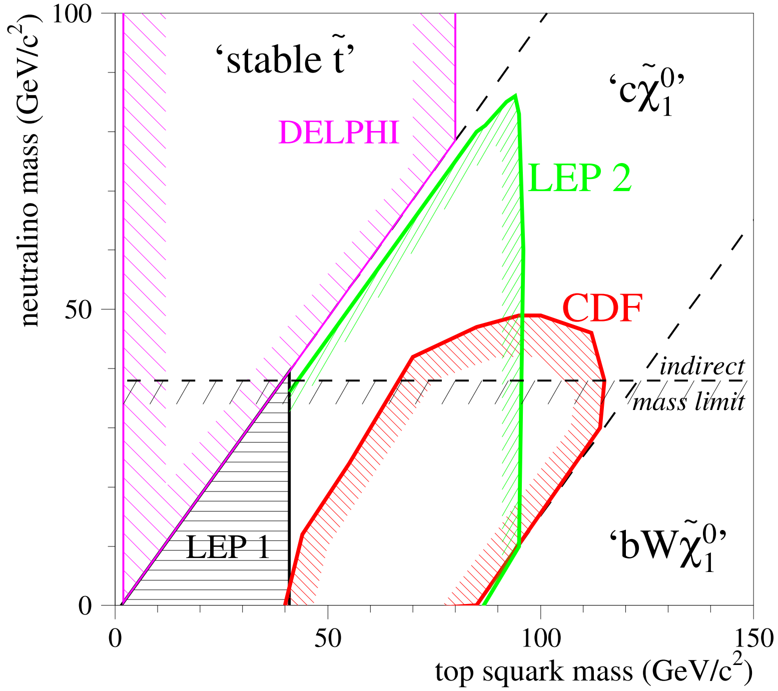
No signs of anything in dedicated searches for supersymmetry
(grav-med, gauge-med, anom-med, RPV, etc. etc.)
or of new bosons, LQ, compositeness, etc.

blanket statements – *unless SUSY is bizarre...*

- All sparticles with color are heavier than ~ 270 GeV.
- All other charged sparticles are heavier than ~ 90 GeV.
- The sneutrinos are probably heavier than ~ 50 GeV.
- Granting gaugino mass unification, the lightest neutralino *(best dark matter candidate of the decade?)*, is at least 37 GeV.
  (limit is much higher in many scenarios.)

A random example or two:





part II: tantalizing hints and limit exceptions

The Higgs at LEP

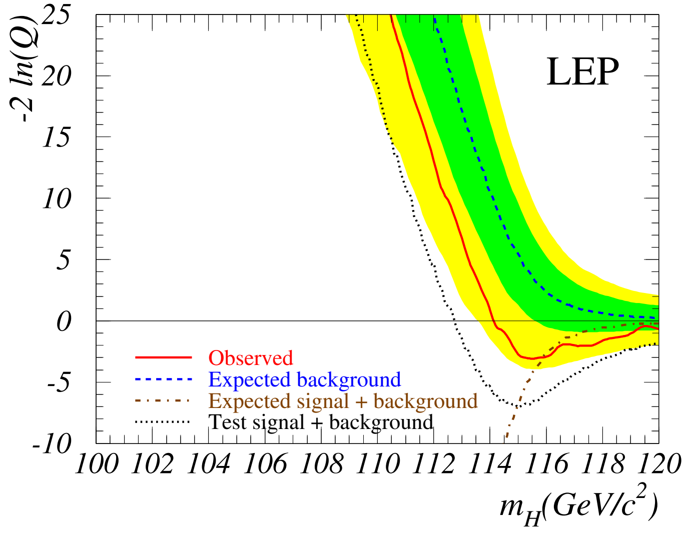
Some signal-like events appeared near $m_h = 114$ GeV, but the significance was quite low.

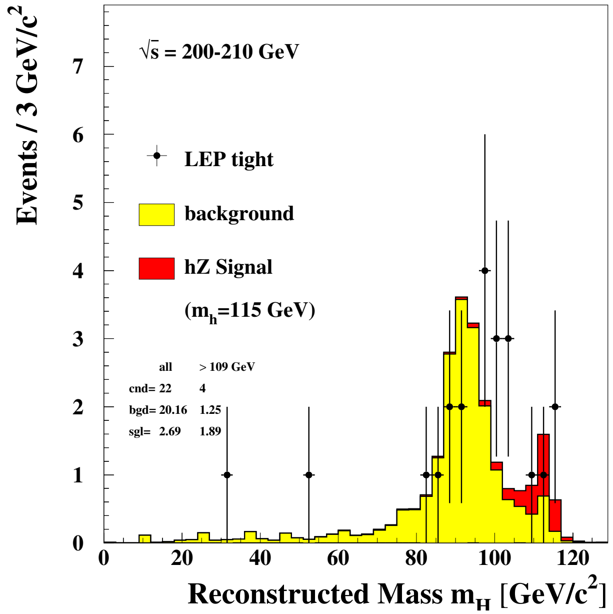
More data were taken, and the significance increased precisely as if signal really were present.

The LEP program was terminated.

Upon reanalysis, the overall significance has eroded, and most of the effect comes from ALEPH.

$$\boxed{m_h > 113 \text{ GeV at } 95\% \text{ CL}}$$





The CDF $ee\gamma\gamma$ Affair

$$p\bar{p} \to e^+e^-\gamma\gamma\not{E}_T$$

A single event, difficult to explain in the SM, spurred many theoretical speculations and even some definite predictions tied to the kinematics of this single event.

Searches directed at these models have excluded them.

CDF carried out exhaustive analyses *not keyed to any specific theory*, including a set of $\ell + \gamma + \not{E}_T$ categories.

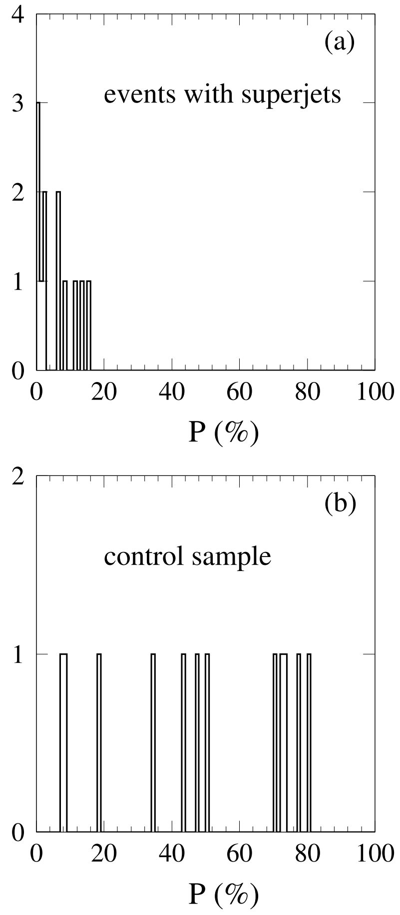
In one of these categories, there is a 2.7σ excess over SM predictions.

Process	$e\gamma\not{E}_T X$	$\mu\gamma\not{E}_T X$	$\ell\gamma\not{E}_T X$
Predicted μ_{SM}	3.4 ± 0.3	4.2 ± 0.5	7.6 ± 0.7
Observed N_0	5	11	16
$P(N \geq N_0 \vert \mu_{SM})$	0.26	0.0054	0.0072

Superjets

Consider the W+2,3 jets sample, from which the top was discovered.

There are three methods of tagging b-jets, and they have all been carefully calibrated using *data*.



The b-tag rates individually agree with SM pred's.

However, there is an anomalous rate of jets with a secondary vertex tag *plus an energetic lepton.*

. *predicted:* 4.4 ± 0.6 *observed:* 13 .

Additionally, the kinematic properties of these events do not match the simulation (KS prob $\sim 1-4\times 10^{-6}$). For a closely-related control sample, however, the match is very good (KS prob $= 0.5$).

More data is need to see if this is an incredible statistical fluctuation...

Concluding Remarks

A lot of very rich physics has been done at LEP and the TEVATRON RUN 1!

A recurring theme – testing the indirect with the direct.

Experimental techniques have evolved to meet the challenges of the time – this will surely continue.

Many of the most fruitful areas are characterized by a give-and-take between measurement and theory.
NB: There remain important experimental results not understood by theory.

Let's see what comes next!