Electroweak Physics

Lecture II:

Status of Electroweak Physics

Acknowledgement:

Slides from M. Gruenewald, P. Renton, F. Teubert

Review

- Introduction to electromagnetic and weak interactions
- Motivation for Electroweak Unification
- Introduced nomenclature for electroweak studies
- Described electron-positron collisions and implications of the data

Helicity Conservation

Extreme Relativistic Limit (ERL): $E >> mc^2$ $\qquad$ $E = pc$ $\qquad$ $\gamma >> 1$

Massless limit $\qquad$ **Helicity = chirality**

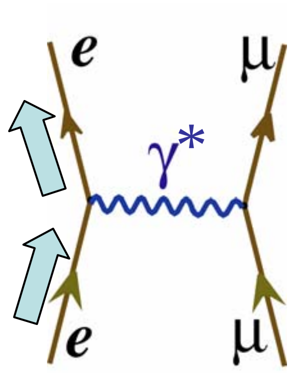
$$P_L \equiv \frac{(1-\gamma^5)}{2} \qquad P_R \equiv \frac{(1+\gamma^5)}{2} \qquad P_i P_j = \delta_{ij} P_j \qquad \sum_i P_i = I \qquad P_{L,R} u \equiv u_{L,R}$$

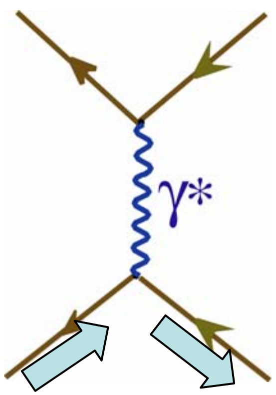
$$J_\mu^{EM} = q\bar{u}\gamma_\mu u = q(\bar{u}_L + \bar{u}_R)\gamma_\mu (u_L + u_R)$$

But $\bar{u}_L \gamma_\mu u_R = \bar{u}_R \gamma_\mu u_L = 0$

$$J_\mu^{EM} = q\bar{u}_R \gamma_\mu u_R + q\bar{u}_L \gamma_\mu u_L$$

What are the implications?

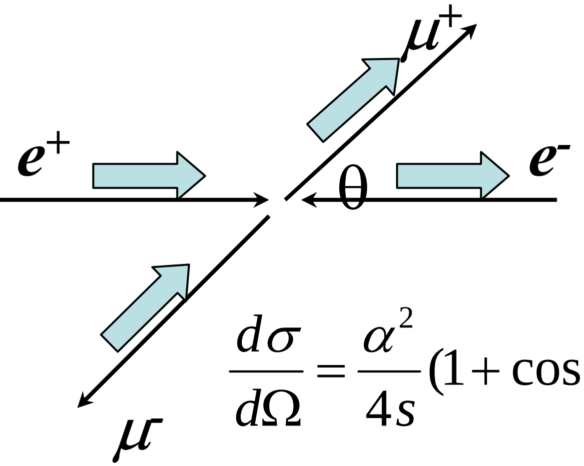




For particle-antiparticle collisions

$e^-_L + e^+_R$ *or* $e^-_R + e^+_L$

Angular Distribution



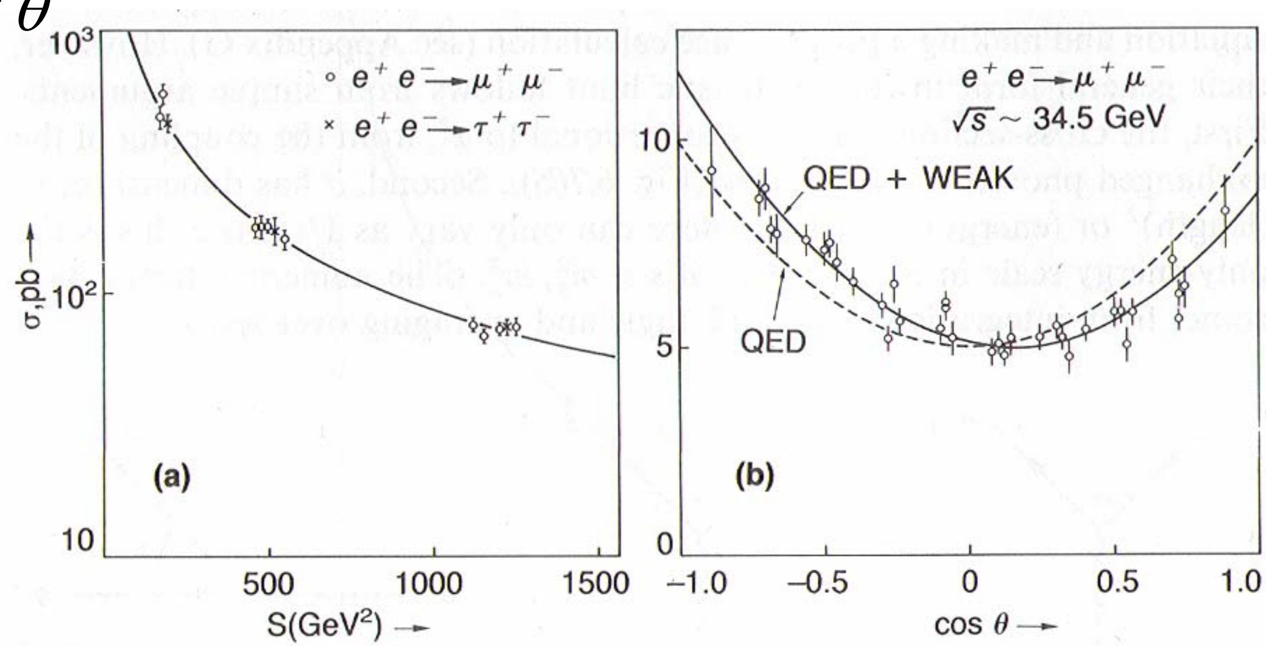
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

Start with spin 1 (forward or backward) along axis of collision: what is the probability of getting +1 or -1 along θ?

$$d^j_{\lambda\lambda'}(\theta) \equiv \langle j\lambda' | e^{-i\theta J_y} | j\lambda \rangle$$

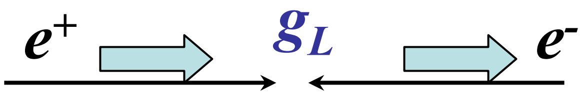
$$d^1_{11}(\theta) = d^1_{-1-1}(\theta) = \frac{1}{2}(1+\cos\theta) \qquad d^1_{1-1}(\theta) = d^1_{-11}(\theta) = \frac{1}{2}(1-\cos\theta)$$

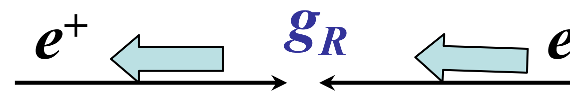
$$\sum (d^j_{\lambda\lambda'}(\theta))^2 = 1+\cos^2\theta$$



Z Decays

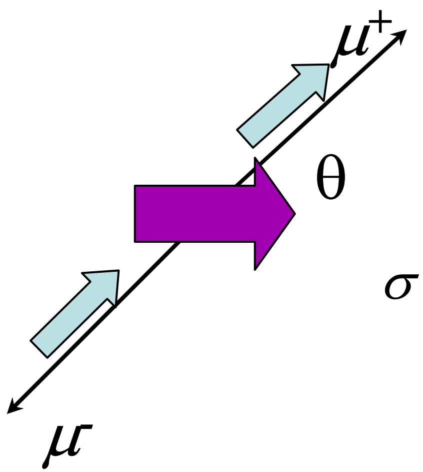
$$e^+e^- \rightarrow Z^0 \rightarrow l^+l^-, q\bar{q} \qquad J_\mu^Z \sim g_R \bar{u}_R(e)\gamma_\mu u_R(e) + g_L \bar{u}_L \gamma_\mu u_L$$





Even if electrons and positrons are unpolarized, the Z's are produced polarized

$$P_Z = \frac{N_+ - N_-}{N_+ + N_-} = \frac{g_R^2 - g_L^2}{g_R^2 + g_L^2}$$



A_{++}: probability of J = +1 Z boson producing a J = +1 final state

$$A_{++} = \frac{g_R^e g_R^\mu}{2}(1+\cos\theta)$$

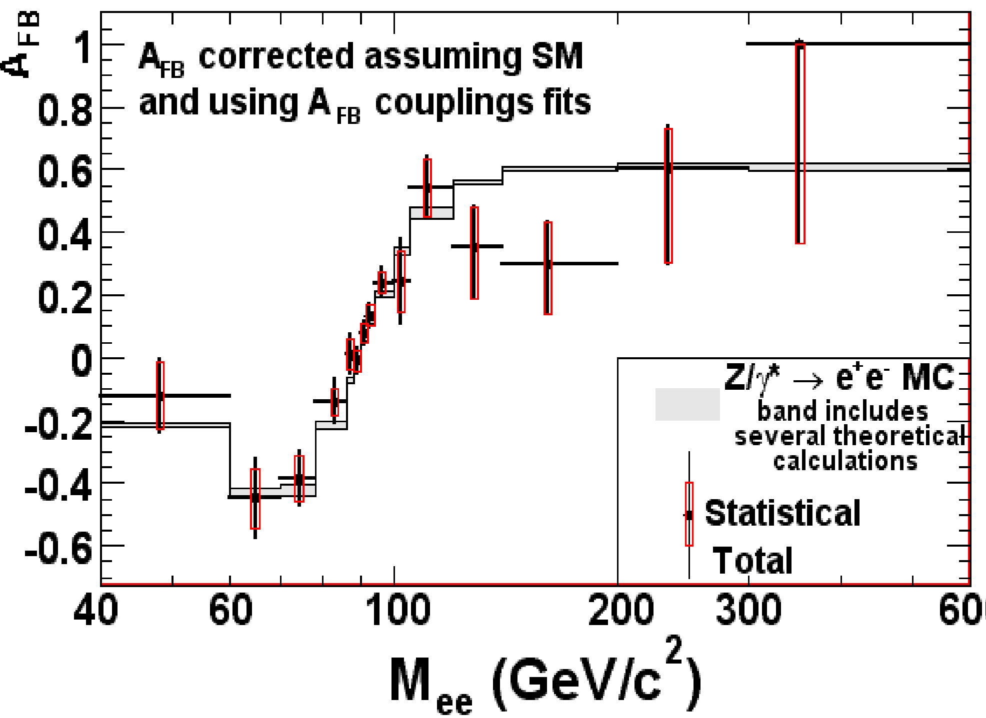
$$\sigma \propto \sum A_{ij}^2 = \left[(g_R^e)^2 + (g_L^e)^2\right]\left[(g_R^\mu)^2 + (g_L^\mu)^2\right](1+\cos^2\theta) + \left[(g_R^e)^2 - (g_L^e)^2\right]\left[(g_R^\mu)^2 - (g_L^\mu)^2\right]2\cos\theta$$

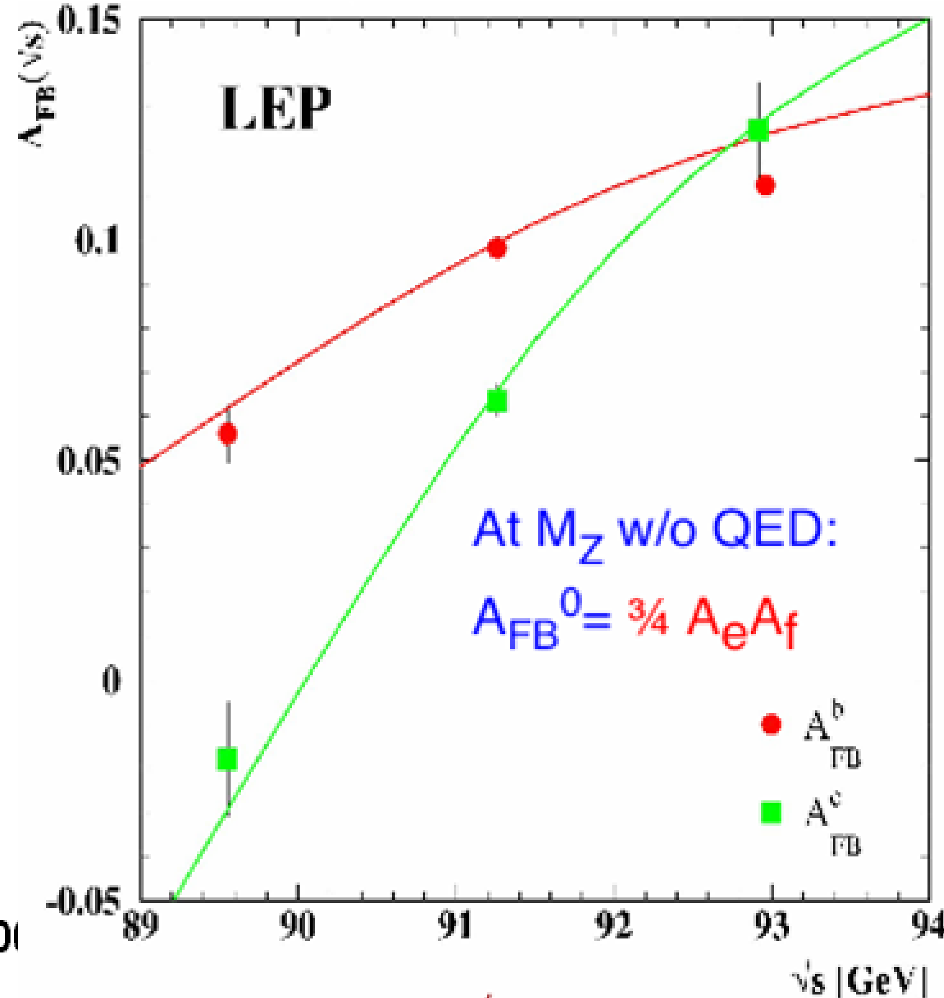
$$\sigma \propto (1+\cos^2\theta) + 2P_eP_\mu\cos\theta \qquad P_e = \frac{(g_R^e)^2 - (g_L^e)^2}{(g_R^e)^2 + (g_L^e)^2} \qquad P_\mu = \frac{(g_R^\mu)^2 - (g_L^\mu)^2}{(g_R^\mu)^2 + (g_L^\mu)^2}$$

Forward Backward Asymmetry

$$P_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2} \approx 2 \frac{g_{Vf}}{g_{Af}} \approx 1 - 4 \sin^2 \theta_W$$

$$A_{FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)} = \frac{3}{4} P_e P_f$$





$$A_f = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2} \Leftrightarrow \sin^2\theta_{eff}$$

Left-Right Asymmetry

AFB is the product of 2 small numbers.

Can they be disentagled?

Polarize the electron beam and measure Z production

$$P_b = \frac{N_+ - N_-}{N_+ + N_-}$$

Fraction of beam polarized along or against the momentum

$$A_{LR} = \frac{N_{Z-} - N_{Z+}}{N_{Z-} + N_{Z+}} = \frac{(1-P_b)g_L^2 - (1+P_b)g_R^2}{(1-P_b)g_L^2 + (1+P_b)g_R^2} = P_b P_e$$

All final states can be used!

This was the motivation for the SLAC Linear Collider:

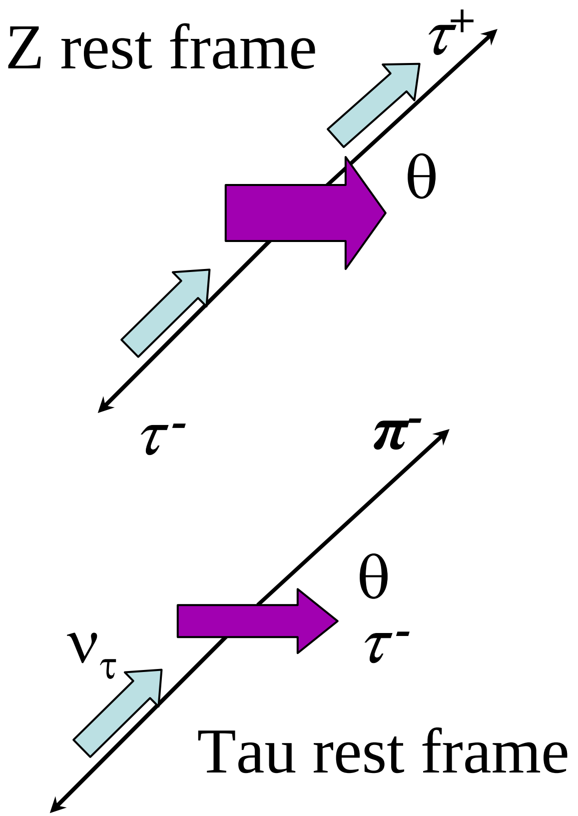
Could compete with a factor of 10 to 100 less luminosity

Tau Polarization

Instead of polarizing the initial state,

Analyze the final state: need a polarization filter

For tau leptons, use the weak decay!



$$\Gamma_\tau = \frac{G_F^2 m_\tau^5}{192\pi}$$

Lifetime ~ few ps

Travels a few mm

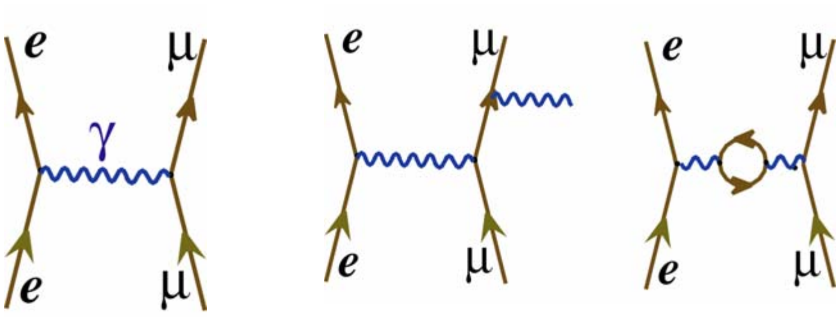
V-A interaction reveals tau polarization

Pion lab energy distribution is related trivially to the rest frame angular distribution

Perturbation Theory

From Feynman rules: *Construct all possible diagrams*

Consistent with standard conservation laws



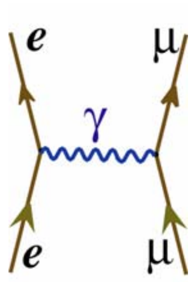
Amplitude is sum of all possible states: Feynman's path integral formulation of QM

Problem: Total amplitude diverges

- *Feynman rules with electric charge*
- *Calculate $\sigma_1(e)$ for a test process*
- *Measure $\sigma_1(e)$ and extract e*
- *Calculate $\sigma_2(e)$ for another process*

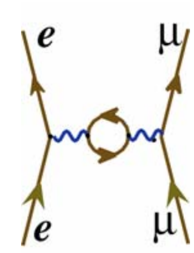
Charge Renormalization

Start with



$$M_1 \sim \frac{e^2}{q^2}$$

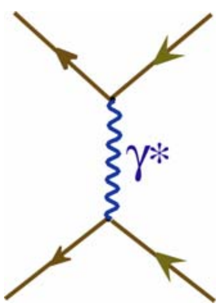
Add

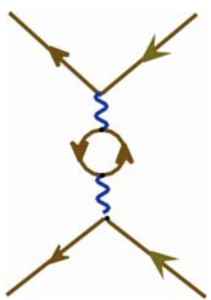


Introduce parameter $\Sigma_{\gamma\gamma}(q^2)$ **(It is infinite)**

$$M_1 \sim i\frac{e^2}{q^2} + i\frac{e^2}{q^2}\frac{i\Sigma_{\gamma\gamma}(q^2)}{q^2}$$

$$e^2 \Rightarrow e^2(1-\Pi_{\gamma\gamma}(q^2))$$





Introduce parameter $\Sigma_{\gamma\gamma}(p^2)$ **(Also infinite)**

$$M_2 \sim \frac{e^2}{p^2}(1-\Pi_{\gamma\gamma}(p^2))$$

$$M_2 \sim \frac{e^2}{p^2}(1-[\Pi_{\gamma\gamma}(p^2)-\Pi_{\gamma\gamma}(q^2)])$$

Finite!

Running Couplings

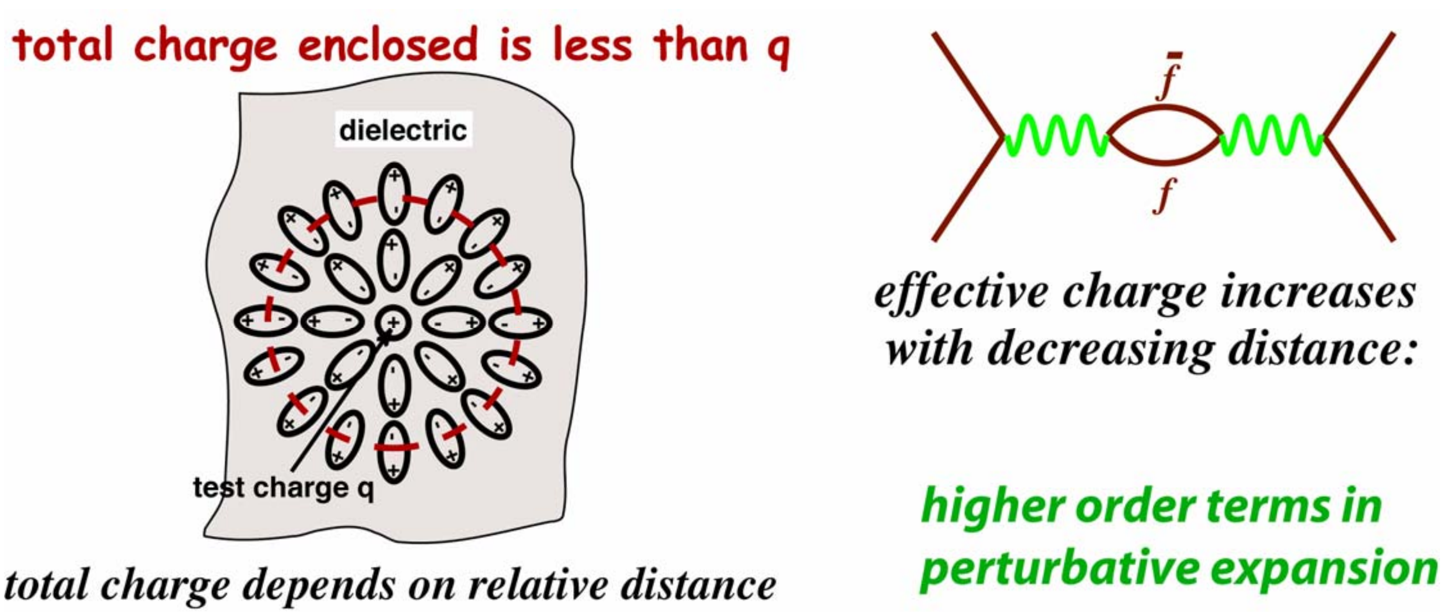
Fine structure constant: 1/137 at low energy, 1/128 at Z pole

Not all Quantum Field Theories behave this way:

The ones that do are renormalizable theories

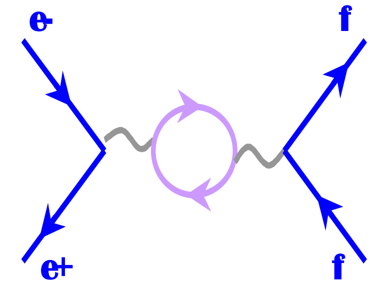
Electroweak theory: t'Hooft and Veltman

QCD: Gross, Politzer and Wilzcek



Calculation of Running

The shift $\Delta\alpha$ can be determined analytically for lepton loops and by a dispersion integral over the e+e- annihilation cross section for light quarks (u,d,s,c,b)



$$\Delta\alpha_{lepton} = \sum_{l=e,\mu,\tau} \frac{\alpha}{3\pi}\left(\log\frac{m_Z^2}{m_l^2} - \frac{5}{3}\right) + \ldots$$

$\alpha(m^2_Z) = \alpha / (1-\Delta\alpha)$

Optical theorem

$$\Delta\alpha_{hadron} = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} \frac{m_Z^2\, ds'}{s'\left[s' - m_Z^2\right]} \frac{\sigma(e^+e^- \to \gamma^* \to q\bar{q})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

Electroweak Input Parameters

For electroweak interactions, there are three parameters needed:

1. Scale of electromagnetism (electric charge)
2. Scale of the weak interaction (Vector boson mass)
3. Weak mixing angle

Parameters are chosen from experimental measurements:

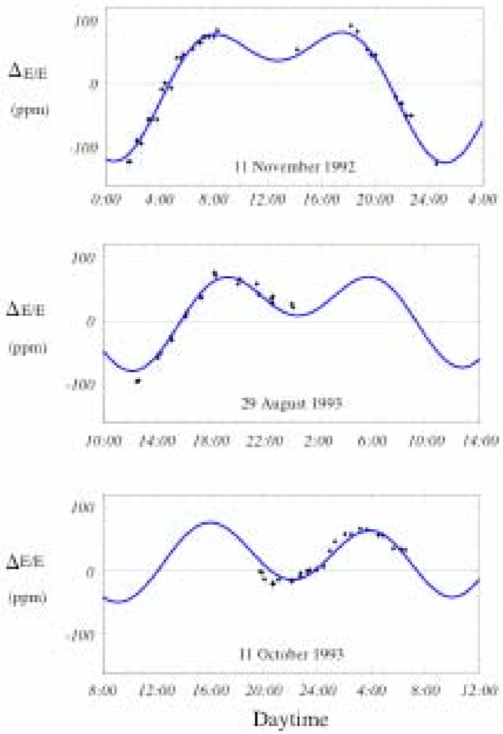
1. Low energy Thomson Scattering
2. The muon lifetime
3. The mass of the Z boson

Z mass know to 23 parts per million!

LEP at CERN

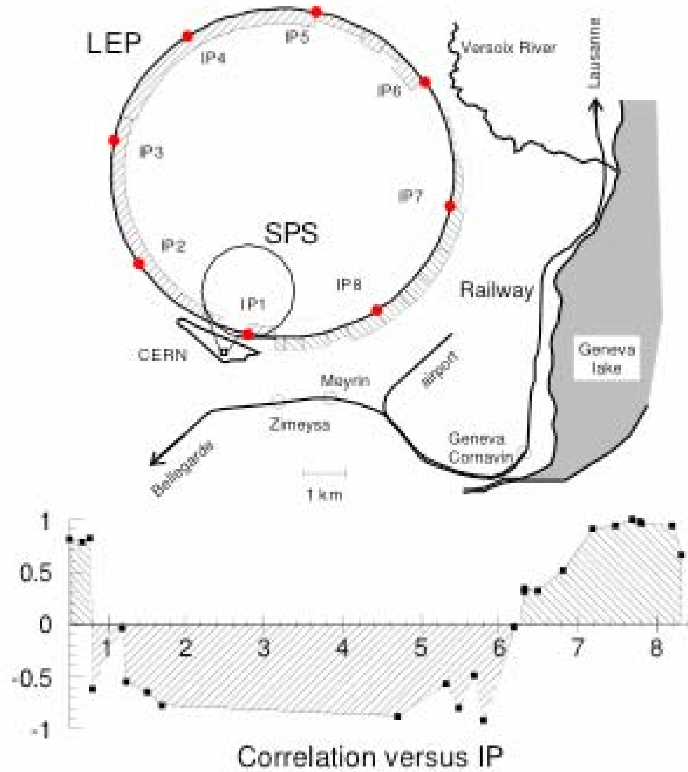
Main energy systematics

Tides and other ground motion:



Use tidal model and beam position monitors to correct for orbit changes

Trains

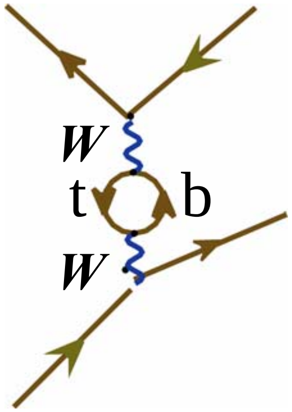


Use NMR probes and *thermal* model to extrapolate energy during fills

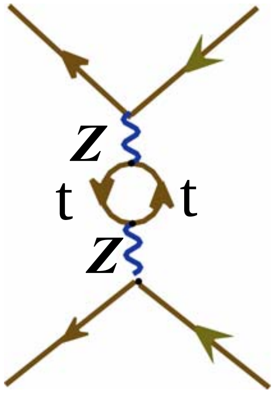
Indirect Evidence for the Top

Measure any asymmetry on the Z pole: function of weak mixing angle

The answer differs from what you would get at tree level



Muon decay



Z production

$$\Pi_{WW} - \Pi_{ZZ} \propto m_t^2 - m_b^2$$

Electroweak Precision Data

Very high Q^2 physics at LEP, SLC, and the Tevatron:

More than 1000 measurements with (correlated) uncertainties

Combined to 17 precision electroweak observables

Z boson physics (LEP-1,SLD):

5 Z lineshape and leptonic forward-backward asymmetries

2 Polarised leptonic asymmetries P_τ, $A_{LR(FB)}$

1 Inclusive hadronic charge asymmetry

6 Heavy quark flavour results (Z decays to b and c quarks)

W boson & top quark physics – ongoing at Tevatron's Run-II:

2 W boson mass and width (LEP-2, Tevatron)

1 Top quark mass (Tevatron)

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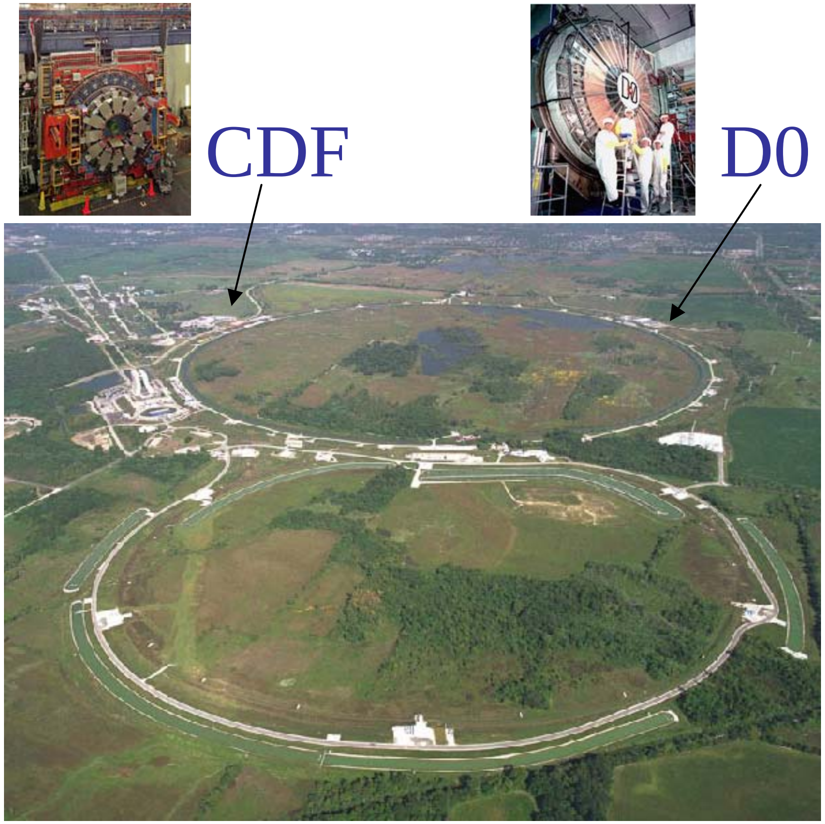
17

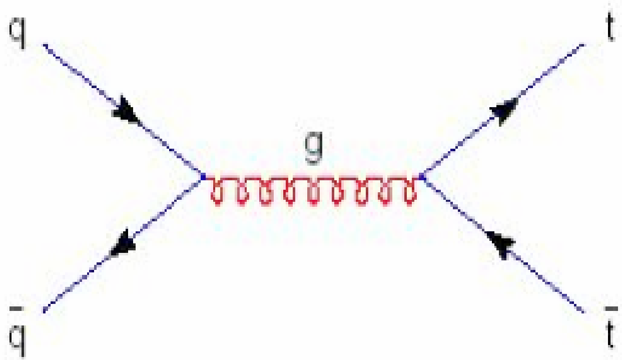
Fermilab



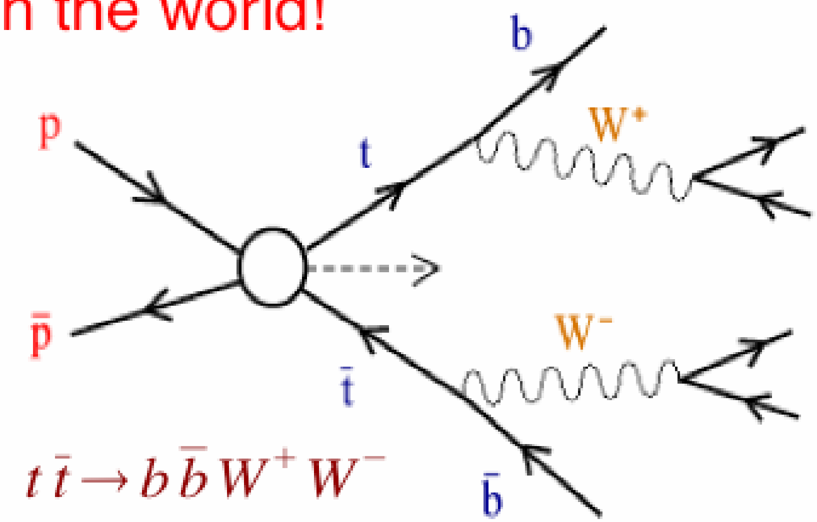
Top Physics

Tevatron: only source of top quarks in the world!

Primarily top-pair production

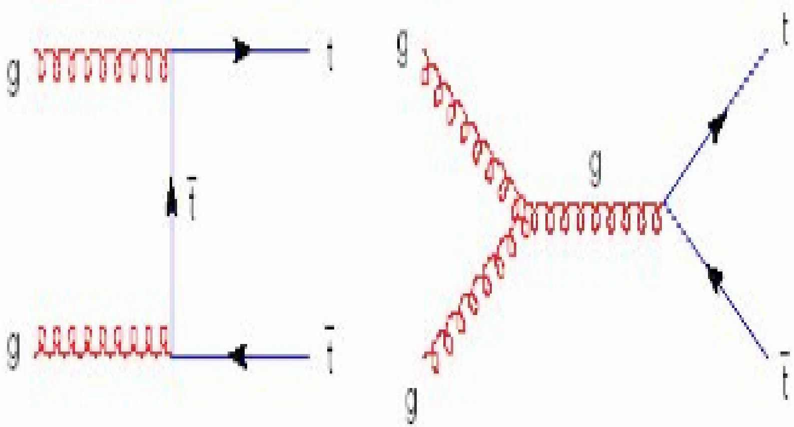


$q\bar{q}$ annihilation (85%)

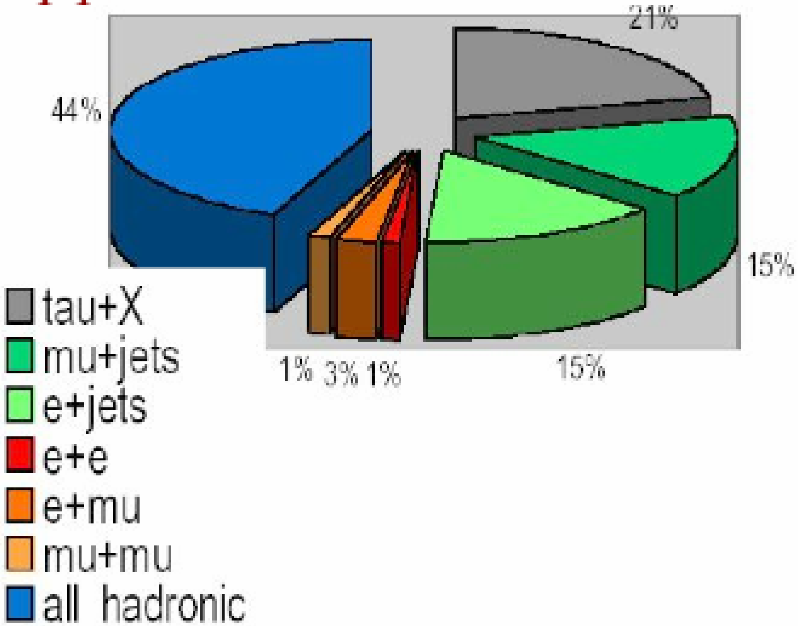


$$p\bar{p}\rightarrow t\bar{t}X,\ \ t\bar{t}\rightarrow b\bar{b}W^{+}W^{-}$$

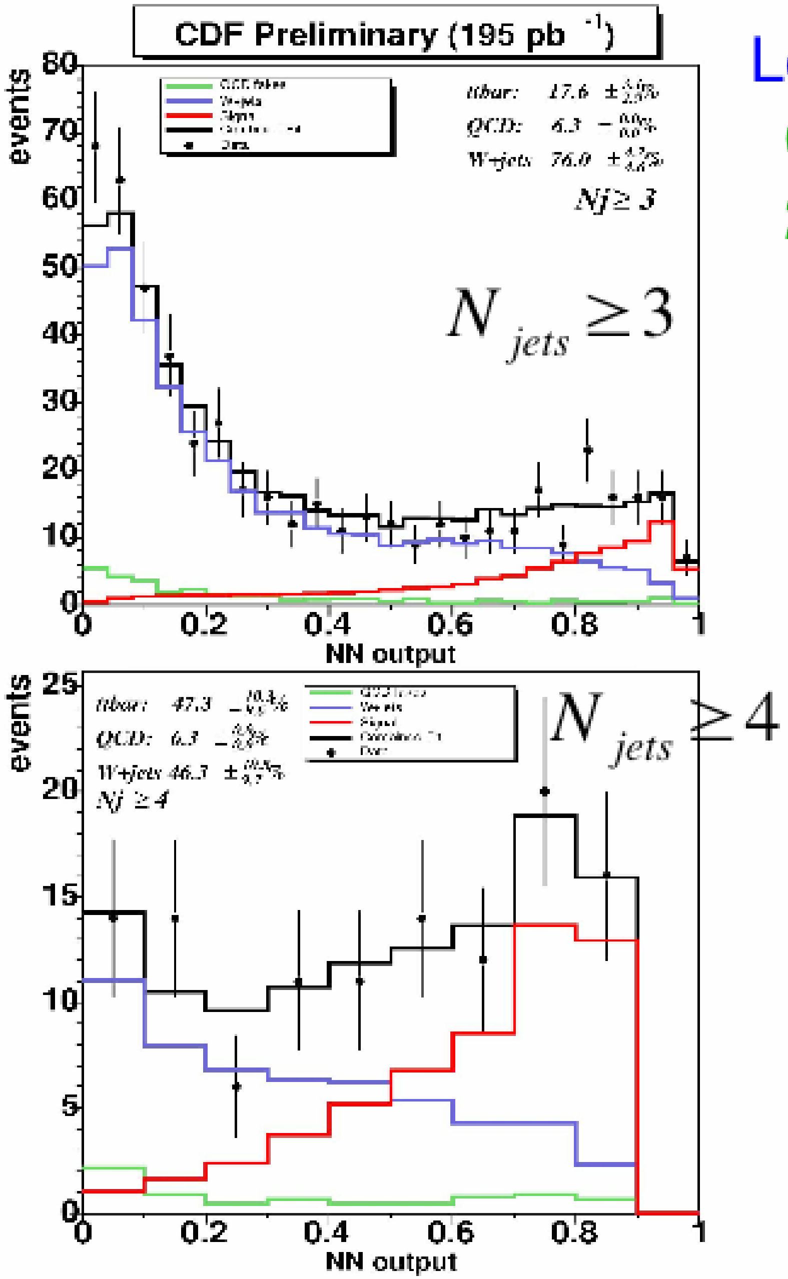
$$W^{-}\rightarrow q\bar{q},l^{-}\bar{\nu}$$



gluon fusion (15%)

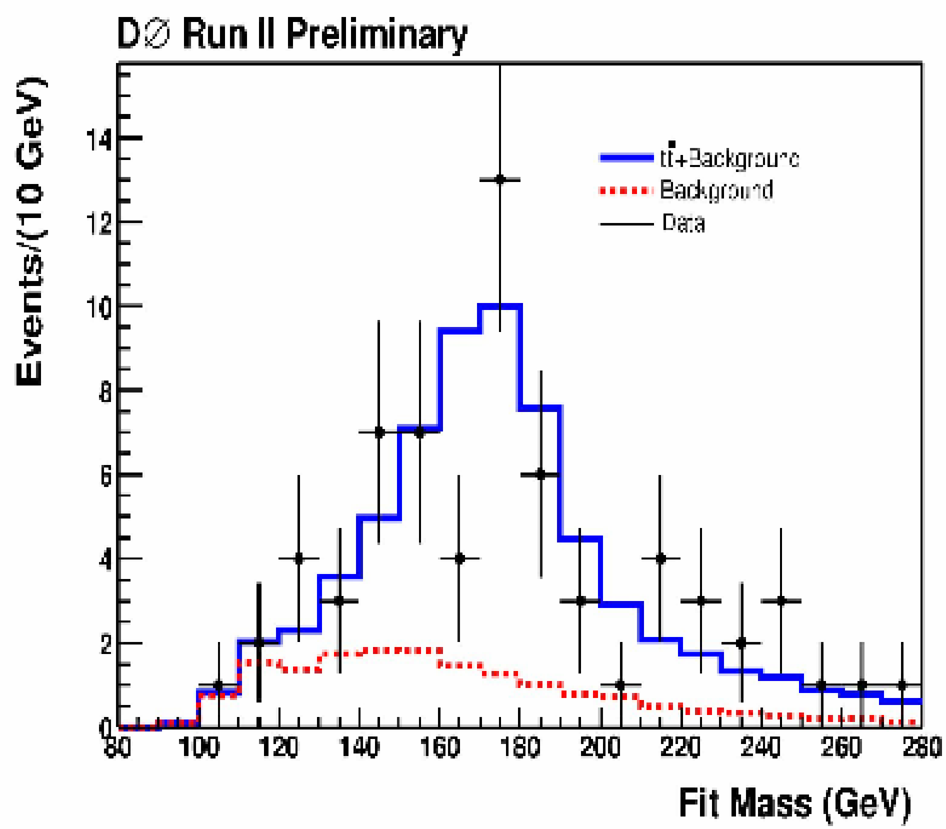


Top Production

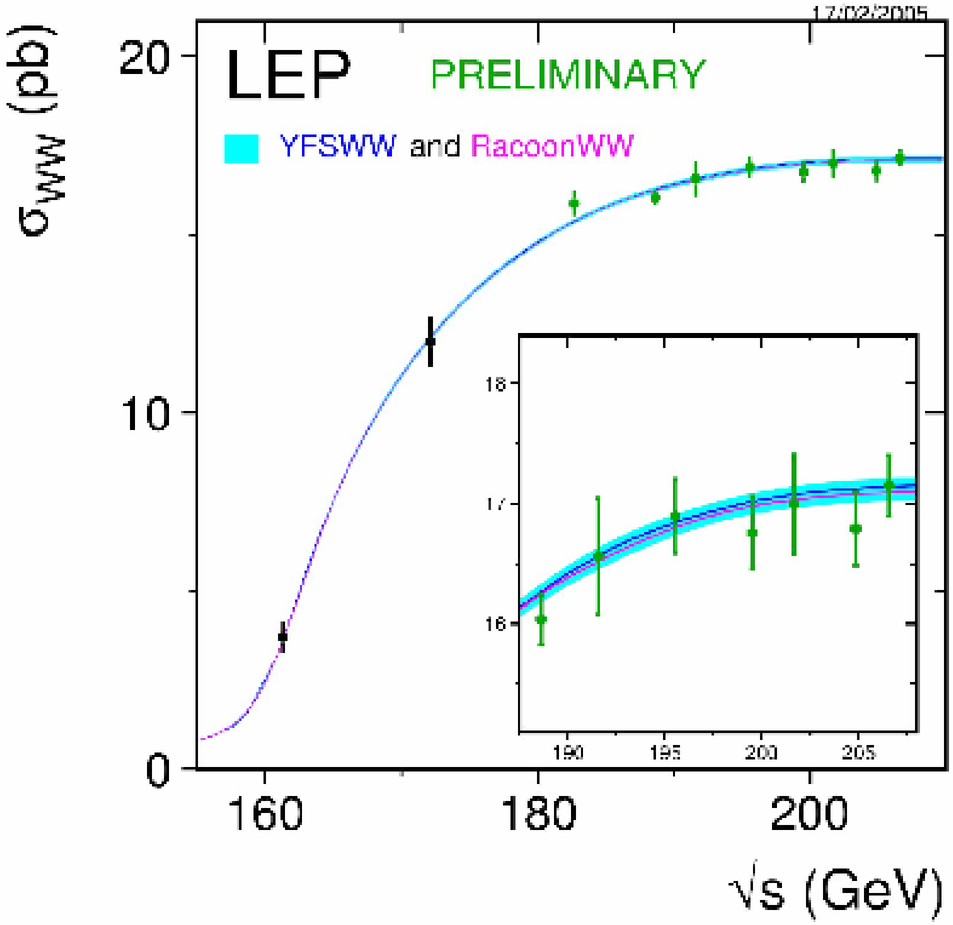


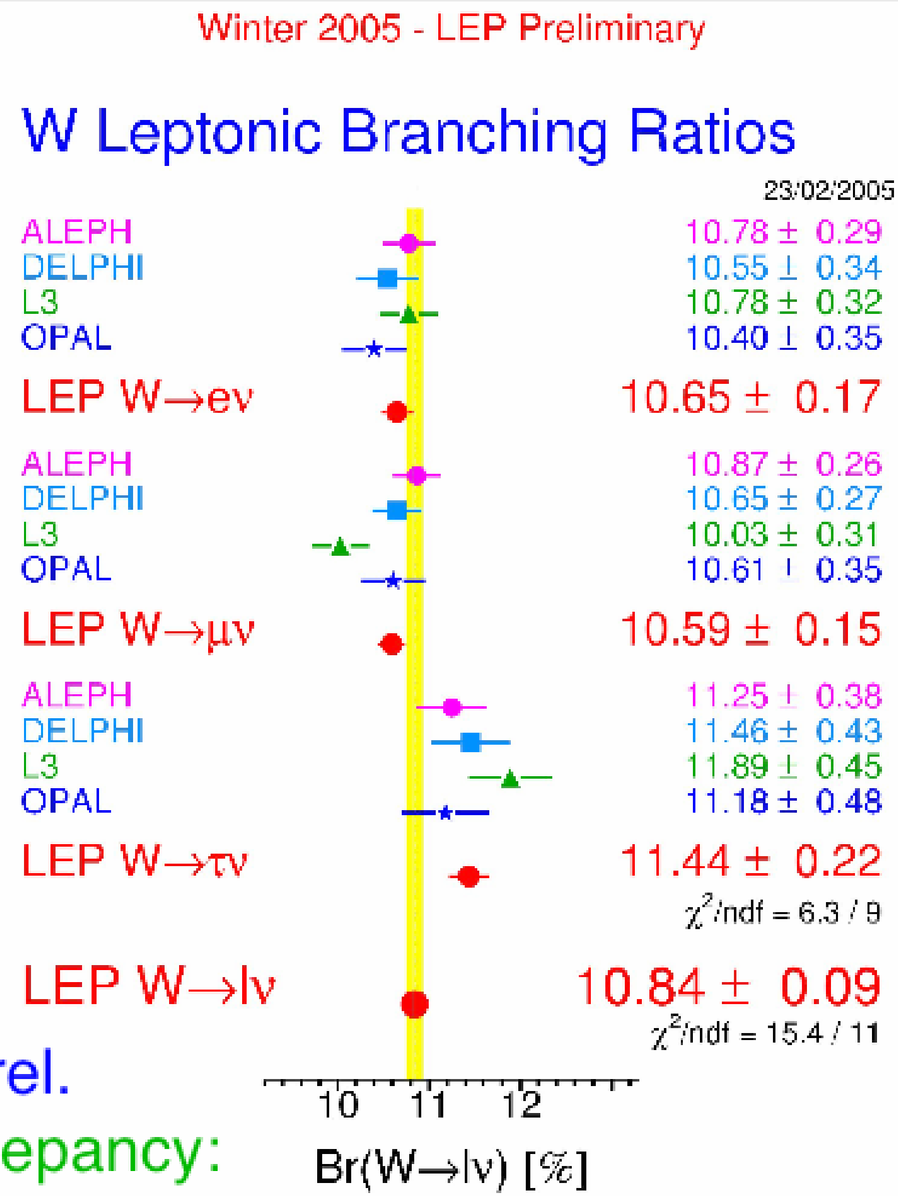
Lepton+jets most promising channel:

- Charged lepton, 2 b-quark jets
- 2 other jets, only 1 neutrino
- Invariant mass M(top) = M(Wb)



W-Pairs at LEP





ALEPH, DELPHI, L3 final, OPAL prel.

Subsequent maximisation of discrepancy:

W-tau branching fraction ~2.9σ above W-e/μ average

Standard Model Analysis

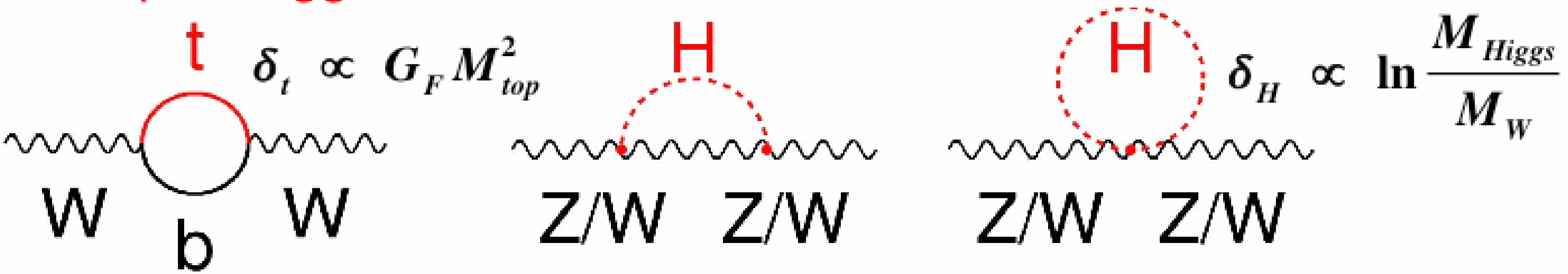
SM: Each observable calculated as a function of:

$\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_{top}, M_{Higgs} (and G_F)

- $\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02761±0.00036]
- $\alpha_s(M_Z)$: given by Γ_{had} and related observables
- M_Z: constrained by LEP-1 lineshape

Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

M_{top}, M_{Higgs} enter through electroweak corrections (~ 1%)!



$$\delta_t \propto G_F M_{top}^2$$

$$\delta_H \propto \ln \frac{M_{Higgs}}{M_W}$$

Calculations by programs TOPAZ0 and ZFITTER

Heavy Particle Masses W and Top

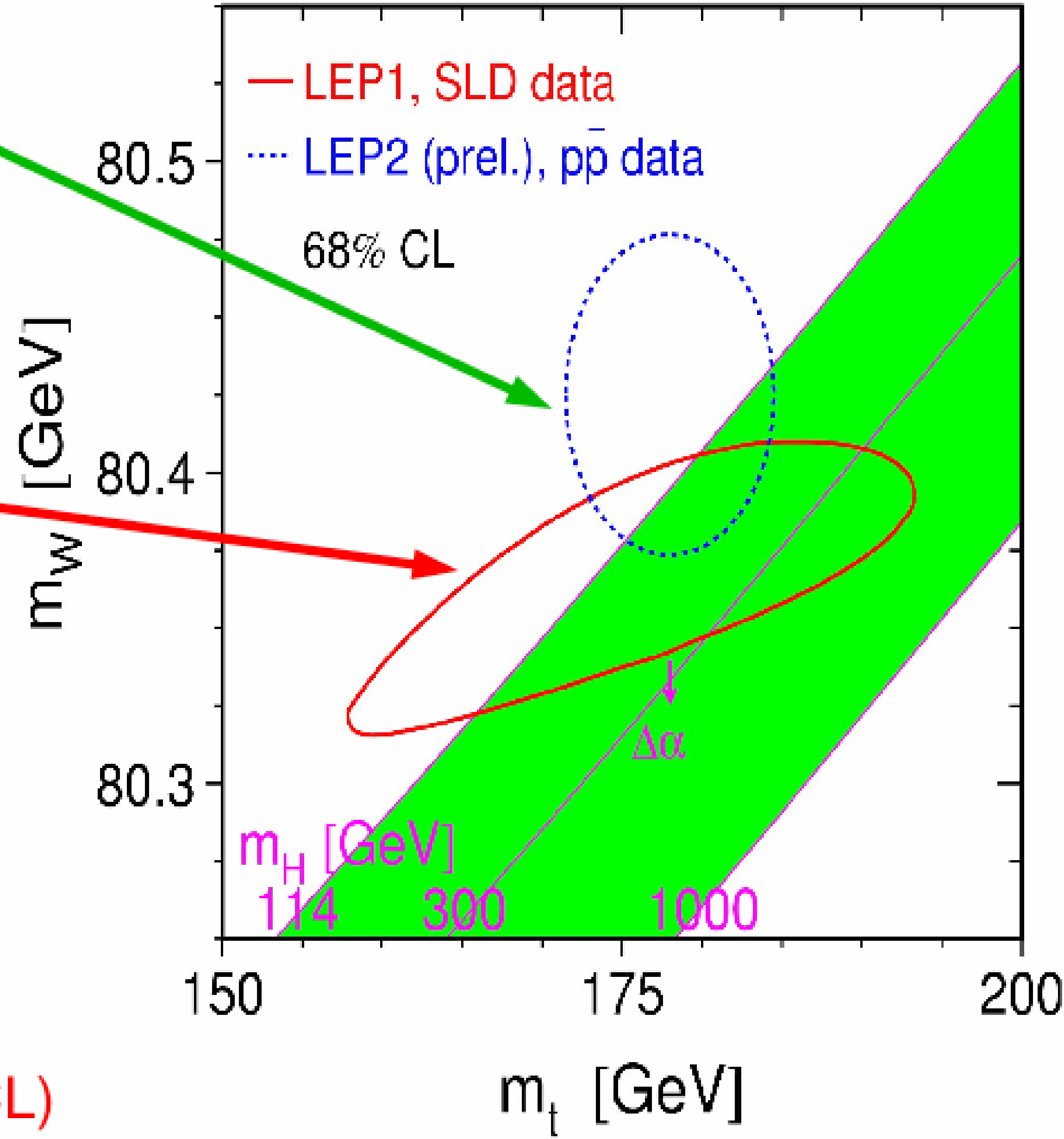
Direct measurements:
  Tevatron and LEP2

Z-Pole measurements:
  Constrain electroweak radiative corrections
  Allow to predict M_W and M_{top} within SM

Good agreement:
  Successful SM test

Both data sets prefer a light Higgs boson

$M_{Higgs} < 280$ GeV (95%CL)



Standard Model Analysis

$M_{Higgs} = 126^{+73}_{-48}$ GeV

Incl. theory uncertainty:

$M_{Higgs} < 280$ GeV (95%CL)

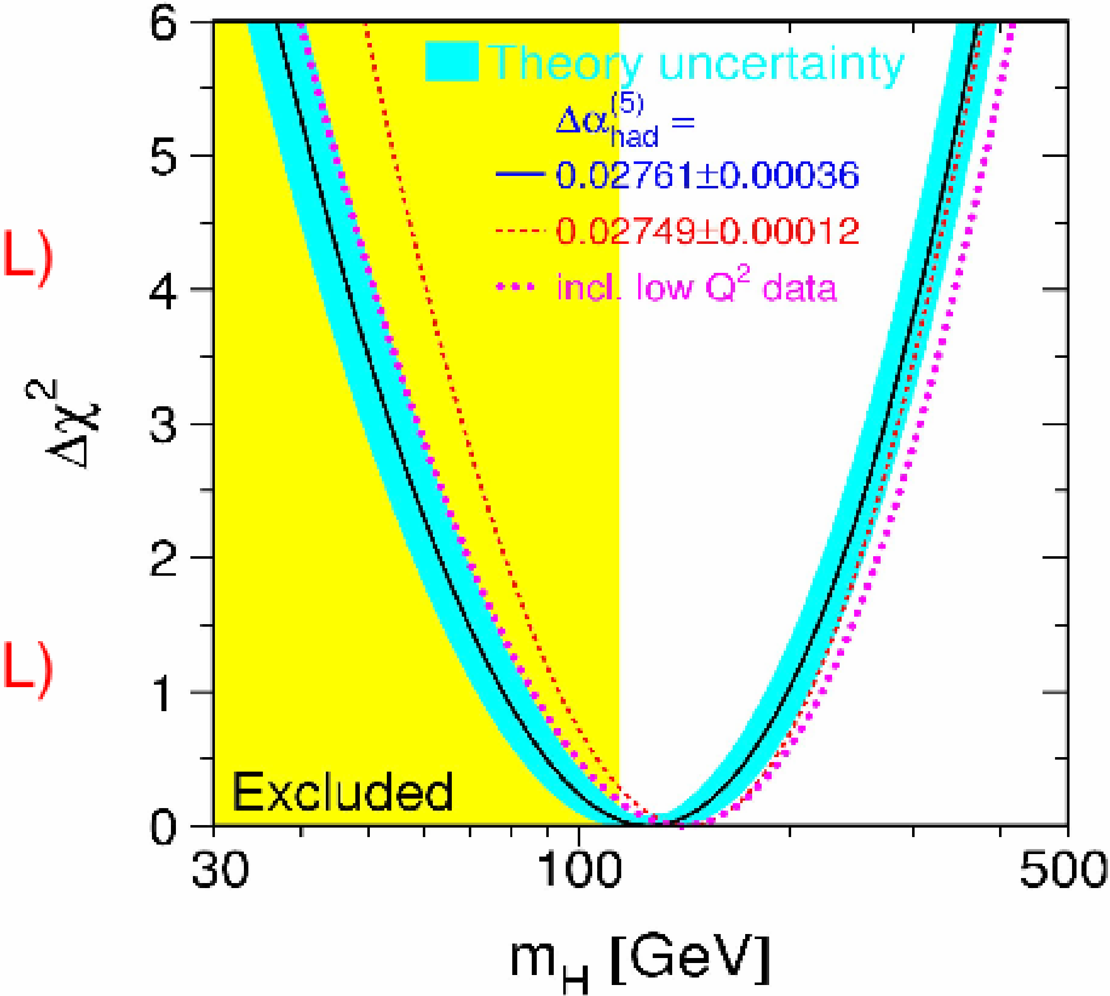
does not include:

Direct search limit (LEP-2):

$M_{Higgs} > 114$ GeV (95%CL)

Renormalise probability for $M_H > 114$ GeV to 100%:

$M_{Higgs} < 300$ GeV (95%CL)

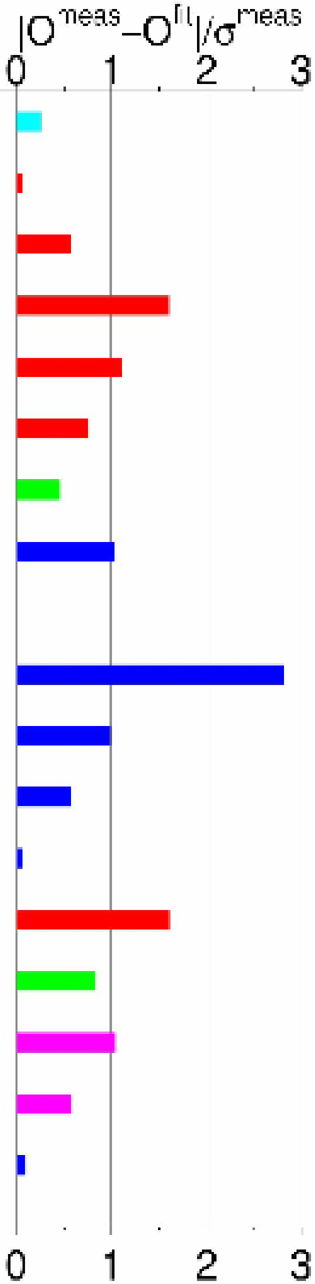


Theory uncertainty:

Dominated by two-loop calculations for $\sin^2\Theta_{eff}$

Standard Model Analysis

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02770
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.390
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.4



Fit to 17 high-Q^2 observables plus $\Delta\alpha_{had}$:

χ^2/ndof = 18.3/13 (14.7%)

Largest χ^2 contribution:

A_l(SLD) vs. $A_{fb}b$(LEP)

Decided in favour of leptons by M_W

Afb(b) has largest pull: 2.8

Predict observables measured in reactions with low-Q^2:

$$Q^2 \ll M_W^2$$

Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

$\sin^2\Theta_{eff} = (1-g_{Vl}/g_{Al})/4$

$= 0.23153 \pm 0.00016$

$\chi^2/ndof = 11.8/5$ [3.8%]

Subsequent observation:

0.23113±0.00021 leptons

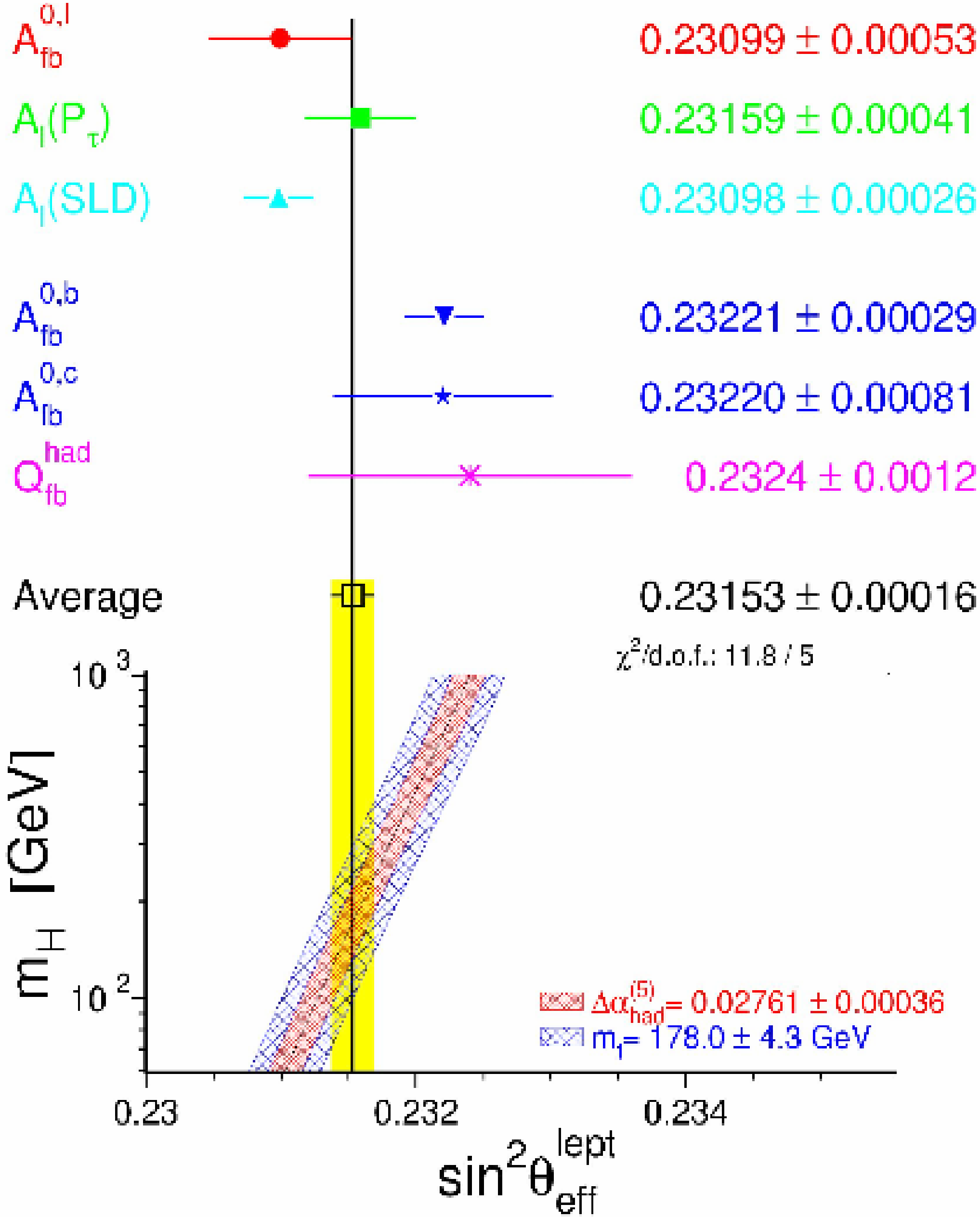
0.23222±0.00027 hadrons

3.2 σ difference

But is really:

A_l(SLD) vs. A_{fb}b(LEP)

3.2 σ difference



Summary

- The electroweak theory has been tested to extraordinary precision
- Typical scale is 0.1%
- No significant deviations, but some tantalizing hints
- The Higgs boson is expected to be light
- Should we pack up and go home? Some answers in Lecture III