Precision Tests of the Electroweak Interactions

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Outline

PART I

- Status of the SM
- Test of the EW interactions at LEP/SLC

PART II

- Test of the EW interactions at Tevatron
- SM Analysis and NuTev
- Conclusions and Future Prospects

PART I

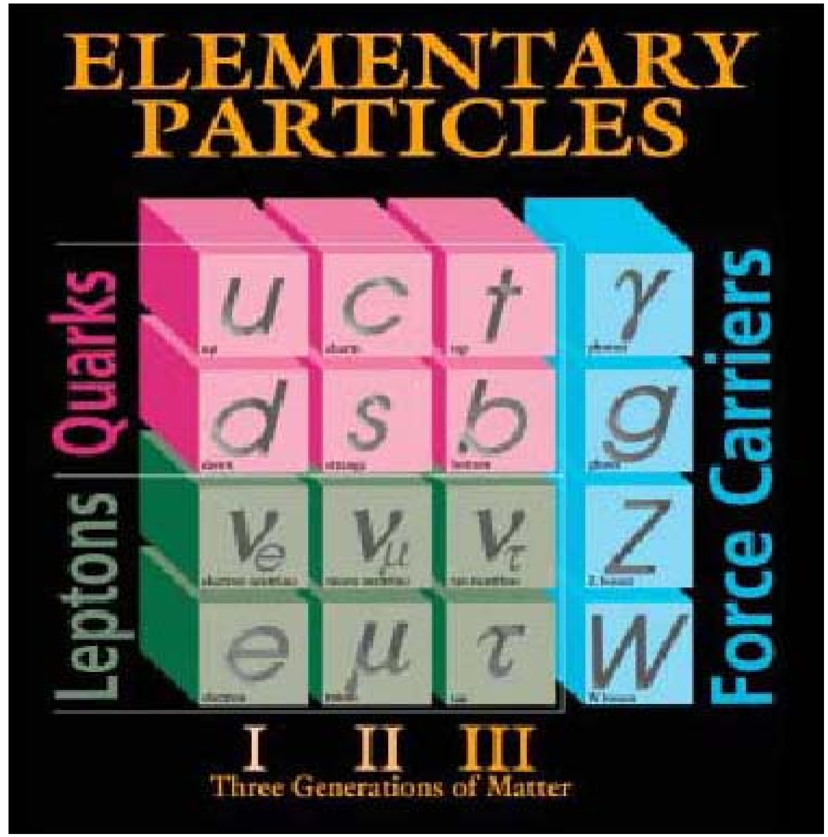
What have we learned the last 50 years
or
Status of the Standard Model

The physical world is

composed of
Quarks and Leptons

interacting via
force carriers
(Gauge Bosons)

Last entries: top-quark 1995
tau-neutrino 2000



- 1968 – Standard Model by Glashow, Salam and Weinberg

  unification of electromagnetic and weak interactions,
  existence of the weak neutral current predicted.

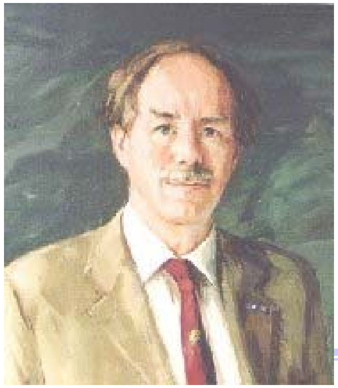
- 1973 – Neutral Currents discovered (Gargamelle experiment)

  to avoid flavour changing neutral currents GIM mechanizm
  requires existence of fourth quark (charm)

- 1974 – Charm quark discovered (Richter/Ting)

  Do the Z and W bozons realy exist with mass around 90 GeV?
  Construction of SPS at CERN.

- 1983 - Discovery of W and Z bosons at CERN
  (C. Rubia, UA1 and UA2 experiments)



SM is renormalizable (t'Hooft and Veltman 1971)

The SM Lagrangian of EW interactions

$$
\begin{aligned}
\mathcal{L}_{SM} = \;& \\
&-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu \\
&-\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- \\
&-M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)\right] + \frac{2M^4}{g^2}\alpha_h \\
&-igc_w \left[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)\right] \\
&-igs_w \left[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)\right] \\
&-\frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 \left(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu\right) + g^2 s_w^2 \left(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu\right) \\
&+g^2 s_w c_w \left[A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu\right] - g\alpha \left[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right] \\
&-\frac{1}{8} g^2 \alpha_h \left[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right] - gMW^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c_w^2} Z^0_\mu Z^0_\mu H \\
&-\frac{1}{2} ig \left[W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)\right] + \frac{1}{2} g \left[W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)\right] \\
&+\frac{1}{2} g \frac{1}{c_w} Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \frac{1 - 2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- \\
&-\phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu \left[H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 \\
&+2(2s_w^2 - 1)^2 \phi^+\phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) \\
&+\frac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda \\
&-\bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] \\
&+\frac{ig}{4c_w} Z^0_\mu \left[(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\frac{4}{3} s_w^2 - 1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \frac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)\right] \\
&+\frac{ig}{2\sqrt{2}} W^+_\mu \left[(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)\right] + \frac{ig}{2\sqrt{2}} W^-_\mu \left[(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \gamma^5) u^\lambda_j)\right] \\
&+\frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} \left[-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)\right] - \frac{g}{2} \frac{m_e^\lambda}{M} \left[H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)\right] \\
&+\frac{ig}{2M\sqrt{2}} \phi^+ \left[-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j)\right] + \frac{ig}{2M\sqrt{2}} \phi^- \left[m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j\right] \\
&-\frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- \\
&+\bar{X}^0 \left(\partial^2 - \frac{M^2}{c_w^2}\right) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) \\
&+igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H \\
&+\frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1 - 2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] \\
&+\frac{1}{2} igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}
$$

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+\frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2}|\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu)|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

where $\Psi_f(x)$ is the Dirac spinor of fermion $f = e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$, $\Psi_L(x) = (a^i_L(x), b^i_L(x)), i = 1, 2, 3$ denotes the $SU(2)_L$ doublet of left-handed fermions with a^i_L with $I^3_i = 1/2$ (neutrinos) and b^i_L with $I^3_i = -1/2$ (charged leptons), I^3_i denotes the 3.component of the weak isospin, Q_f the electric charge, $s_w = \sin\theta_w$, $c_w = \cos\theta_w$ with θ_w denoting the weak mixing angle, g is the $SU(2)_L$ gauge coupling constant, g' is the $U(1)_Y$ gauge coupling constant, $e = \sqrt{4\pi\alpha}$ with α being the fine structure constant, $\eta(x)$ denotes the Higgs field, $A_\mu(x)$ the electromagnetic field, $W^\pm_\mu(x), Z_\mu(x)$ are the 3 weak gauge fields. m_f, M_W, M_Z, M_η denote the fermion, W boson, Z boson and Higgs boson masses, respectively,

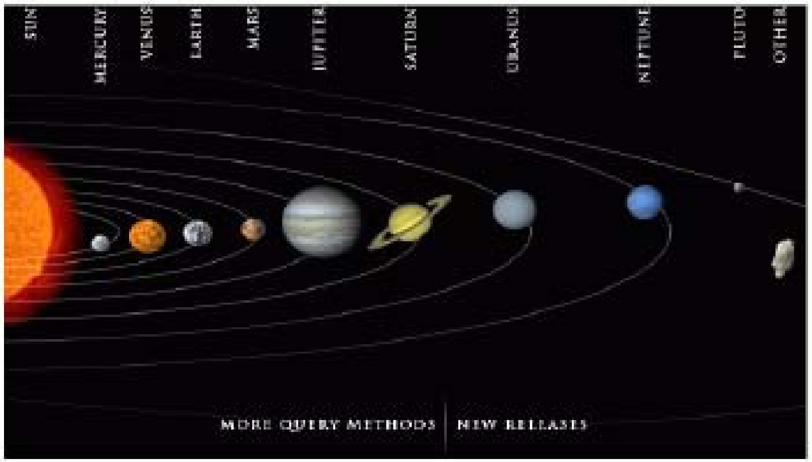
The fermion masses in $\mathcal{L}_{GSW}$ result from their Yukawa interaction with the Higgs field ($\tilde{\Phi} = i\sigma^2\Phi^* = (\Phi^{0*}, -\Phi^-)$)

$$\mathcal{L}_{Yukawa} = \sum_{ij} c_{ij}\bar{\Psi}^i_L b^j_R \Phi + \sum_{ij} \tilde{c}_{ij}\bar{\Psi}^i_L a^j_R \tilde{\Phi} + h.c.$$

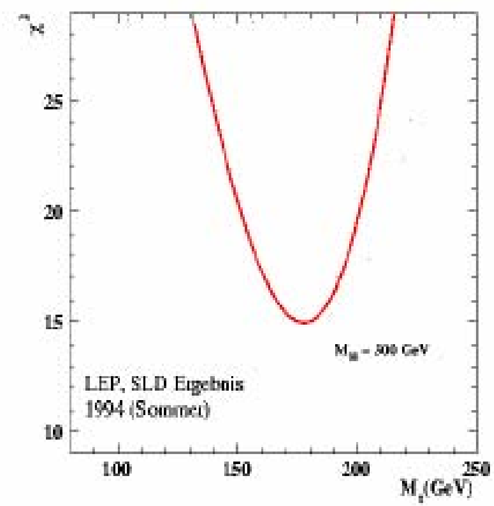
with $b^i_R, b^i = e, \tau, \mu$ are SU(2) singlets of right-handed leptons. With $\Phi = (0, v + \eta)/\sqrt{2}$ and after diagonalization of the mass matrix the fermion mass terms arise with $m_f = v/\sqrt{2}c^H_i, c_{ij} = \delta_{ij}c^H_i$.

Precision in Physics

example: astronomy



example: Particle physics

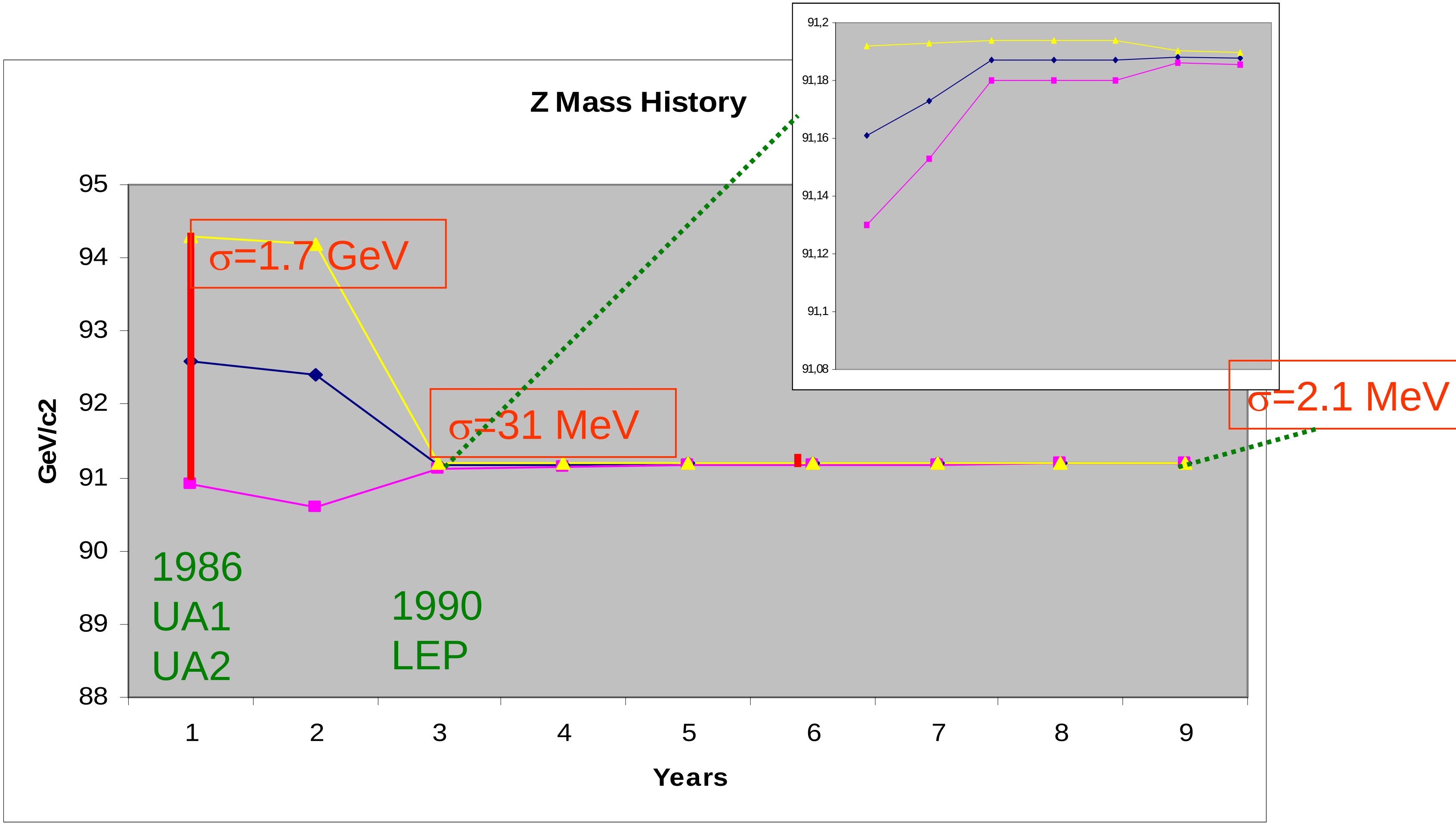


observed: small deviations from the expected trajectories of the planets
predicted: an additional planet can explain the observation
discovery: PLUTO was found

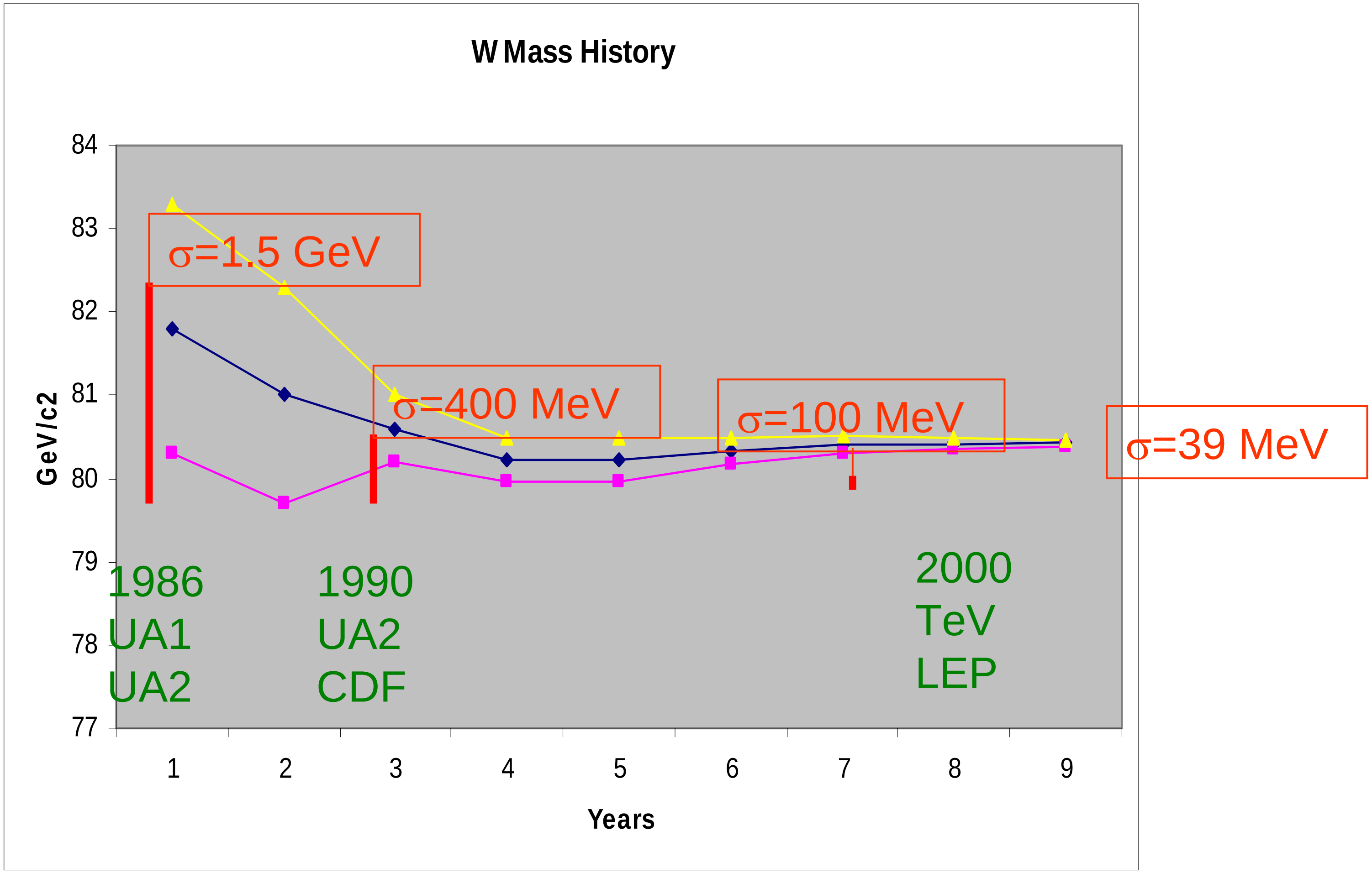
indirect prediction for mass of the top quark

discovery: 1995, Tevatron (USA) at the predicted mass

23 Years of W and Z Physics



23 Years of W and Z Physics



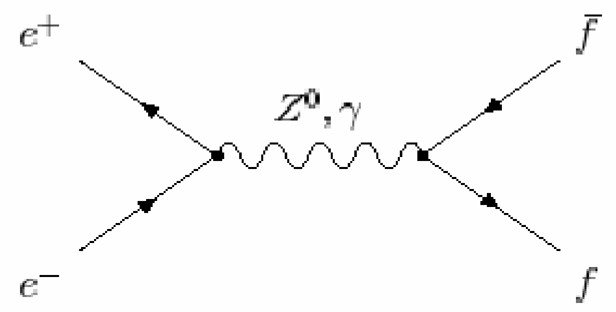
Strategy of the precision tests

Standard Model describes electroweak interactions of quarks , leptons and Higgs boson by exchange of

W

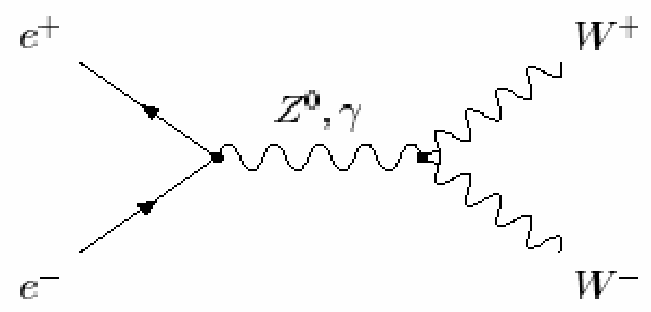
γ	$m_\gamma = 0$		
$W^\pm$	$M_W = 81$	GeV	
Z^0	$M_Z = 92$	GeV	

1st step: build LEP1 (SLC) collider at $\sqrt{s} \approx 90\,GeV$



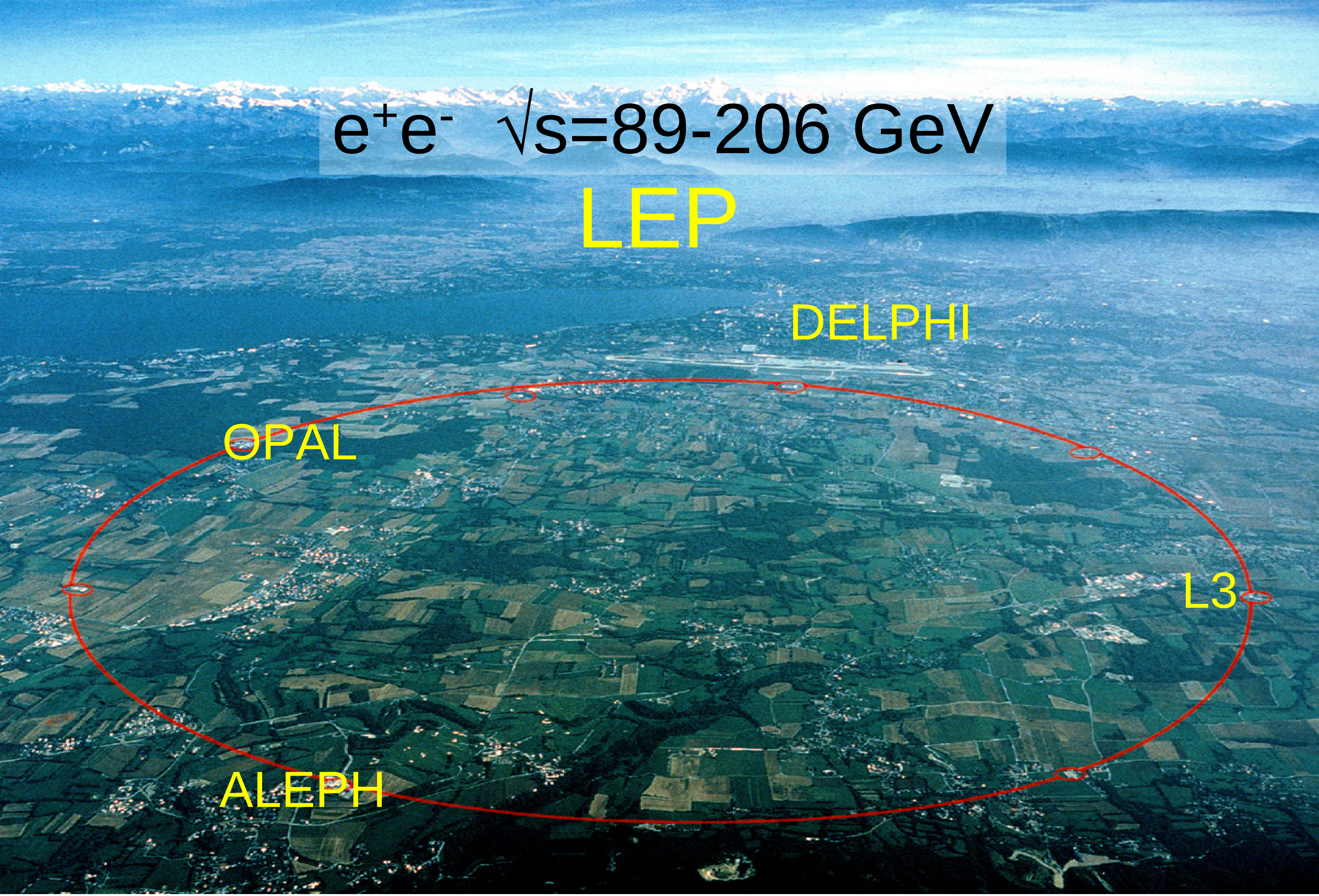
(with possible electron beam polarization at SLAC)

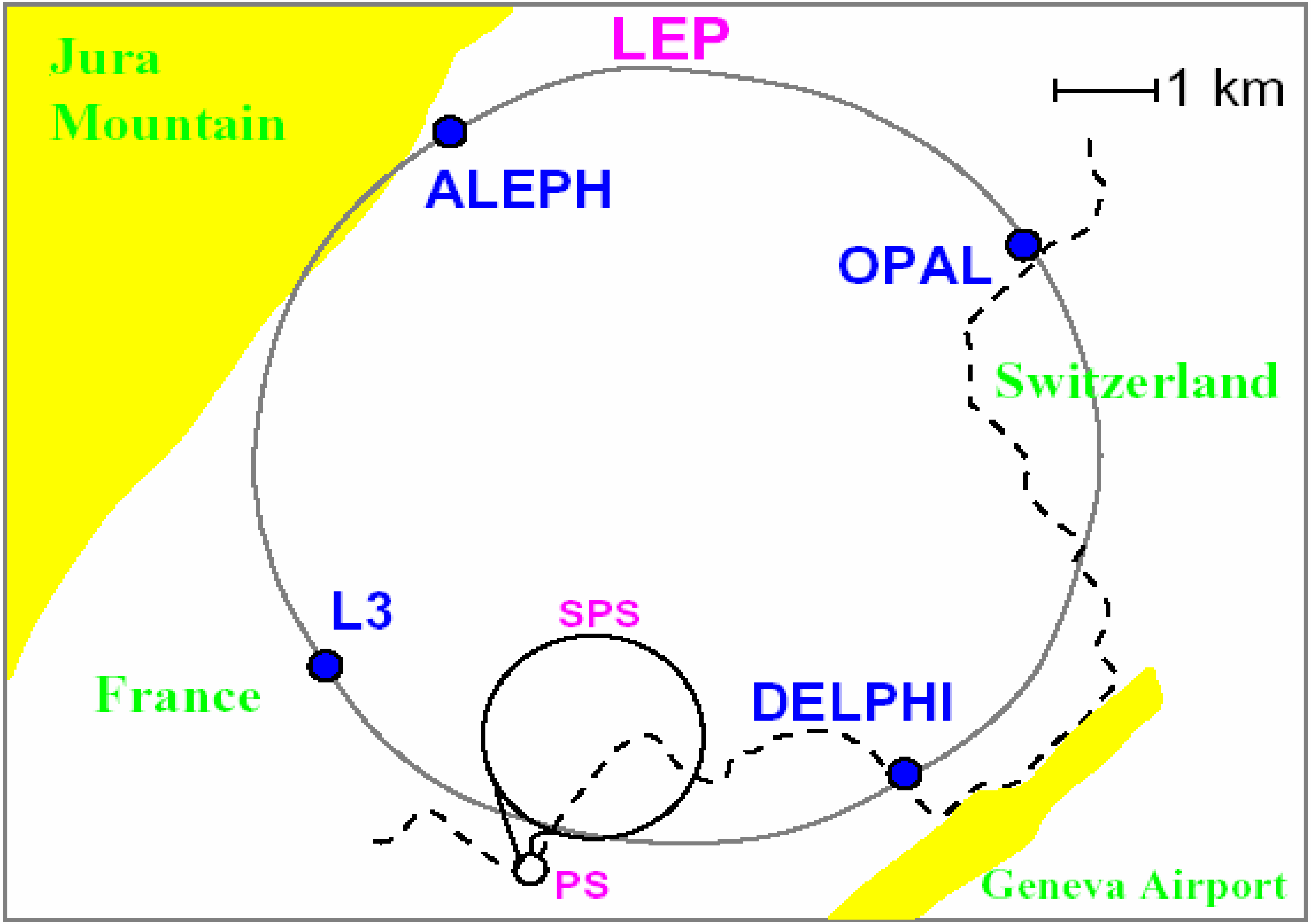
2nd step: increase the energy to $\sqrt{s} > 160\ \ GeV$ (LEP only)



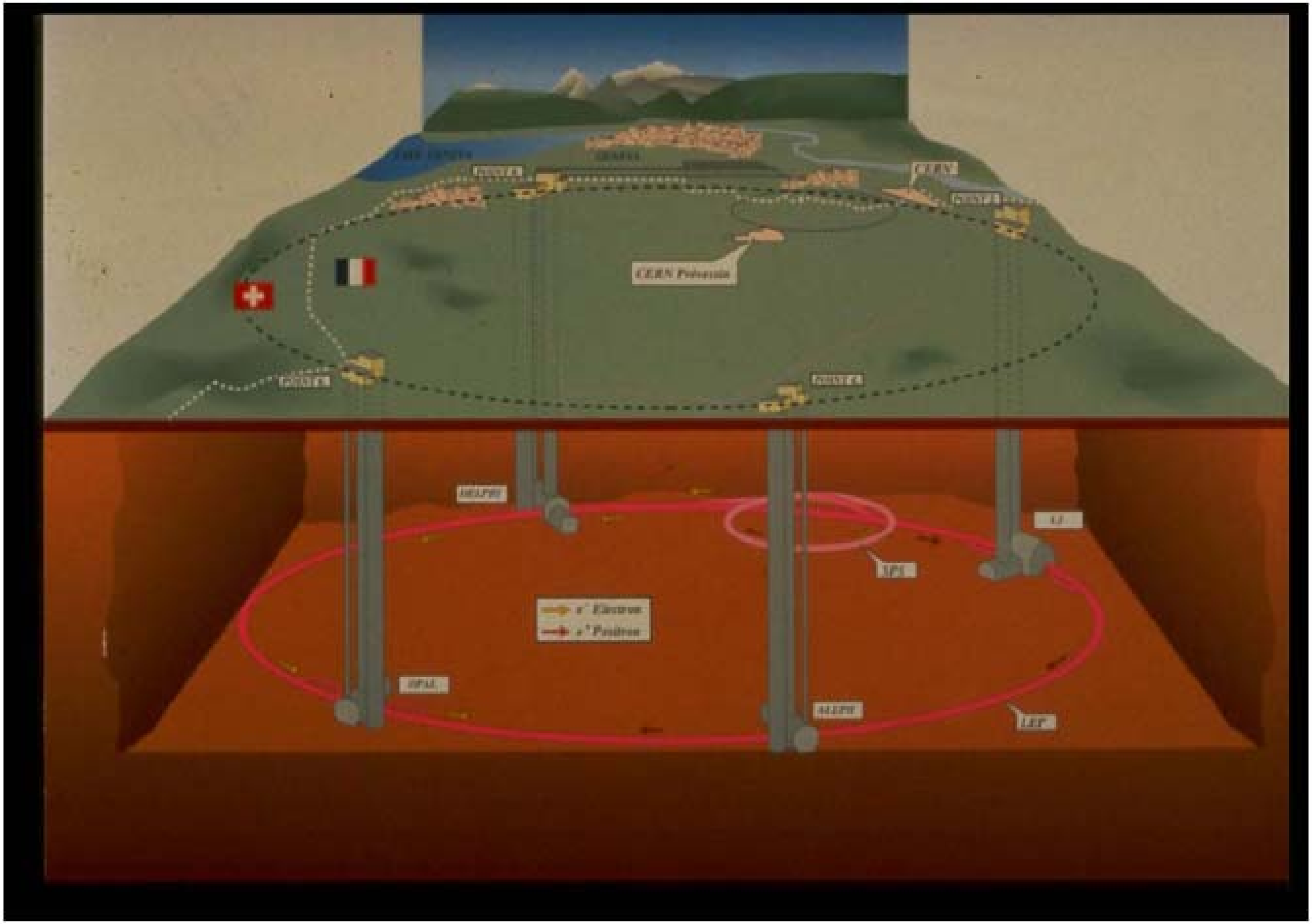
and

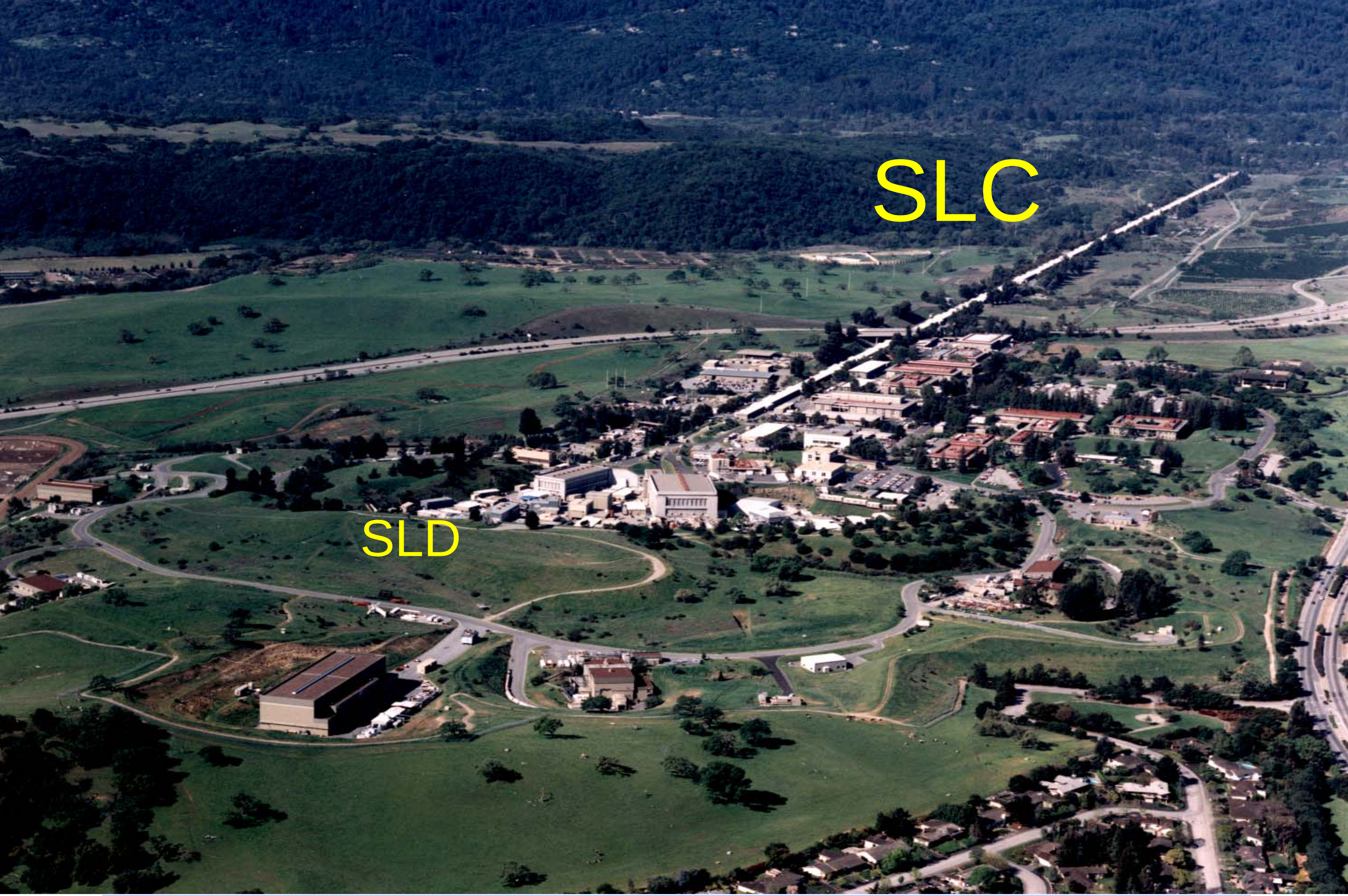
- Study W and Z production
- Check model internal consistency
- Look for Higgs boson(s) and supersymmetric particles


e^+e^- $\sqrt{s}$=89-206 GeV
LEP
DELPHI
OPAL
L3
ALEPH


LEP
1 km
Jura
Mountain
ALEPH
OPAL
Switzerland
L3
SPS
France
DELPHI
PS
Geneva Airport

The LEP collider at CERN




SLC
SLD

Parameters of the Standard Model

Parameters of the Standard Model.

In the context of the SM, any EW process can be computed at **tree level** from α, m_W , m_Z.

When **higher orders** are included, any observable can be predicted as

$$O(\alpha, m_W, m_Z, \alpha_s, m_{Higgs}, m_{top})$$

and the rest of m_f which are known with adequate precision

On-Shell renormalization scheme

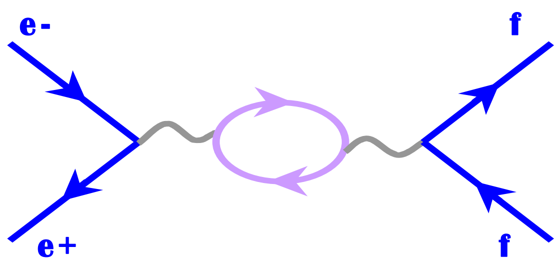
Contrary to what happens with "exact gauge symmetry" theories, like QED or QCD, the effect of **heavy particles do not decouple**, and there is sensitivity to m_{top} and to less extend to m_{Higgs}, or to any kind of "**heavy new physics**".

The usual procedure has been to take G_μ, the Fermi Constant measured in muon decay, to predict m_W and use this more precise value to predict any other observable.

Therefore, the input parameters are chosen to be:

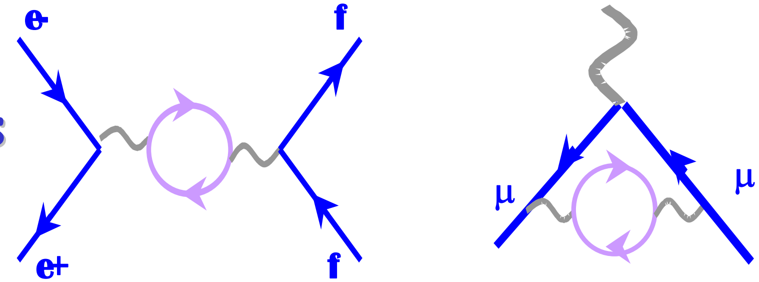
$$\alpha^{-1}(0) = 137.03599877(40)$$
$$\alpha_s(m_Z) = 0.118(2)$$
$$G_\mu(m_\mu) = 1.16637(1)\times 10^{-5}\ \mathrm{GeV}^{-2}$$
$$m_Z = 91.1875(21)\ \mathrm{GeV}$$

But… the relevant scale is $q^2 \approx m^2_Z$ …



The running of $\alpha(Q^2)$.

Since vacuum polarization effects screen the electric charge, the coupling increases when evaluated at a high scale of the γ momentum transfer…



$\alpha(m^2_Z) = \alpha / (1-\Delta\alpha)$ $a_\mu \sim \alpha(Q^2) / 2\pi$

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):

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

Optical Theorem

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

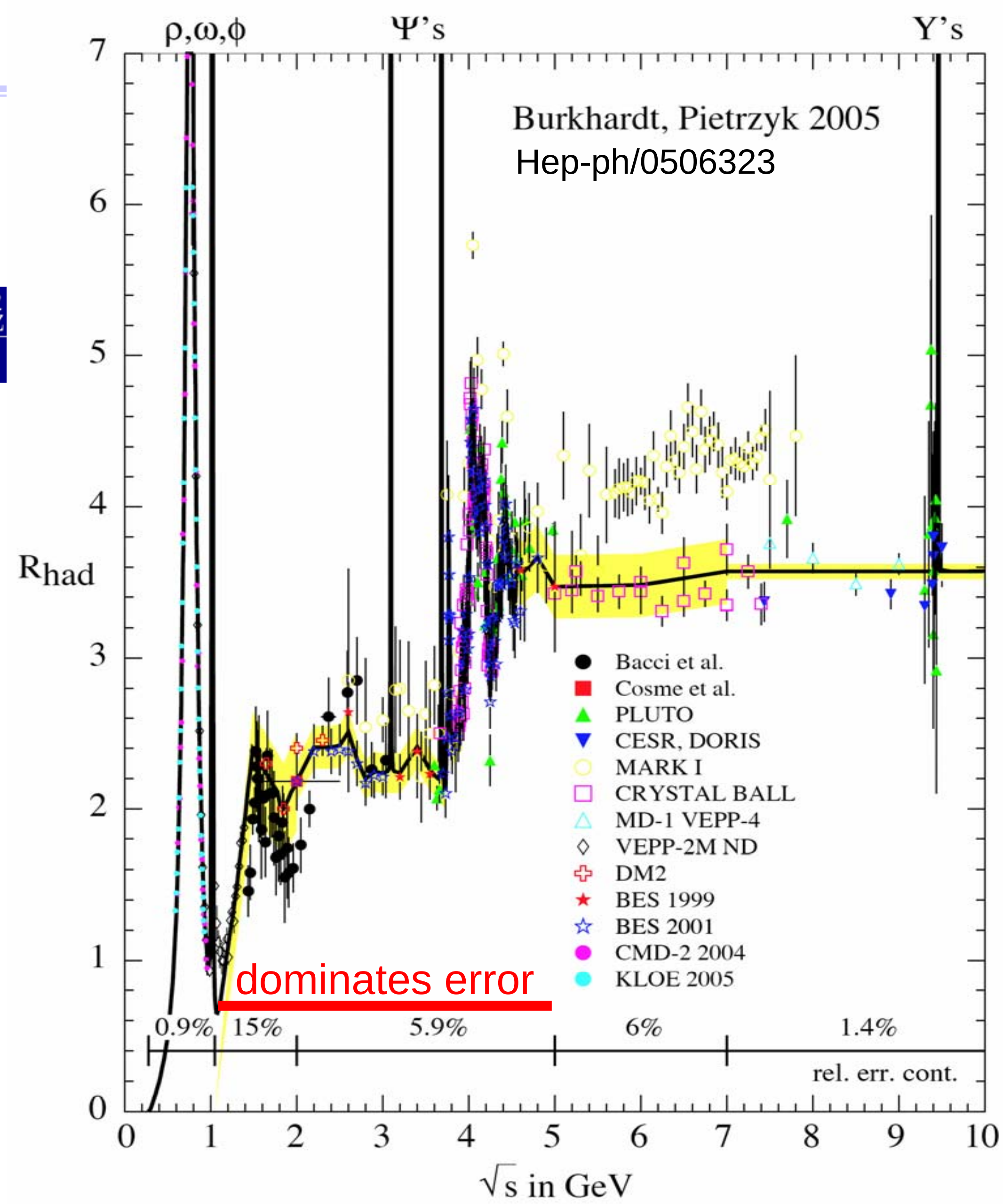
$$\frac{1}{\alpha_{\mathrm{QED}}(M_Z^2)} = \frac{1 - \Delta\alpha_{\mathrm{lep}}(M_Z^2) - \Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) - \Delta\alpha_{\mathrm{top}}(M_Z^2}{\alpha_{\mathrm{QED}}(0)}$$

$$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) = -\frac{\alpha_{\mathrm{QED}}(0)\ s}{3\pi}\mathcal{P}\left(\int_{s'=4m_\pi^2}^{\infty} \frac{R_{\mathrm{had}}(s')}{s'(s'-M_Z^2)}ds'\right)$$

$$\alpha^{-1}_{\mathrm{QED}}(0) = 137.035\,999\,11\ (46)$$

$$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) = 0.02758\ (35)$$

$$\alpha^{-1}_{\mathrm{QED}}(M_Z^2) = 128.940\ (48)$$

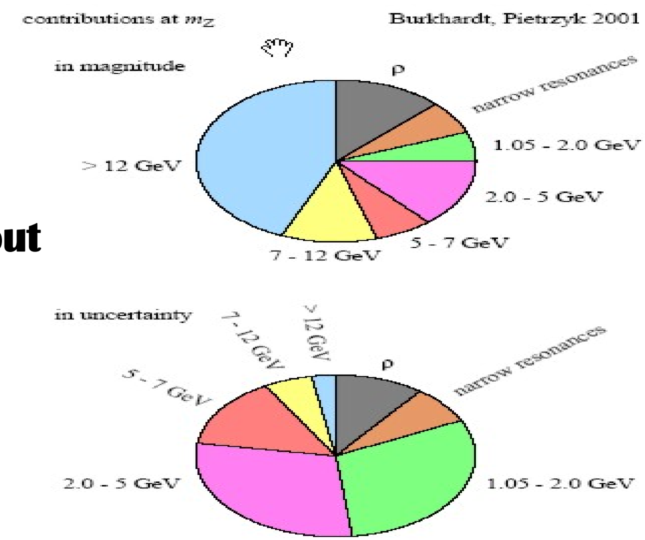


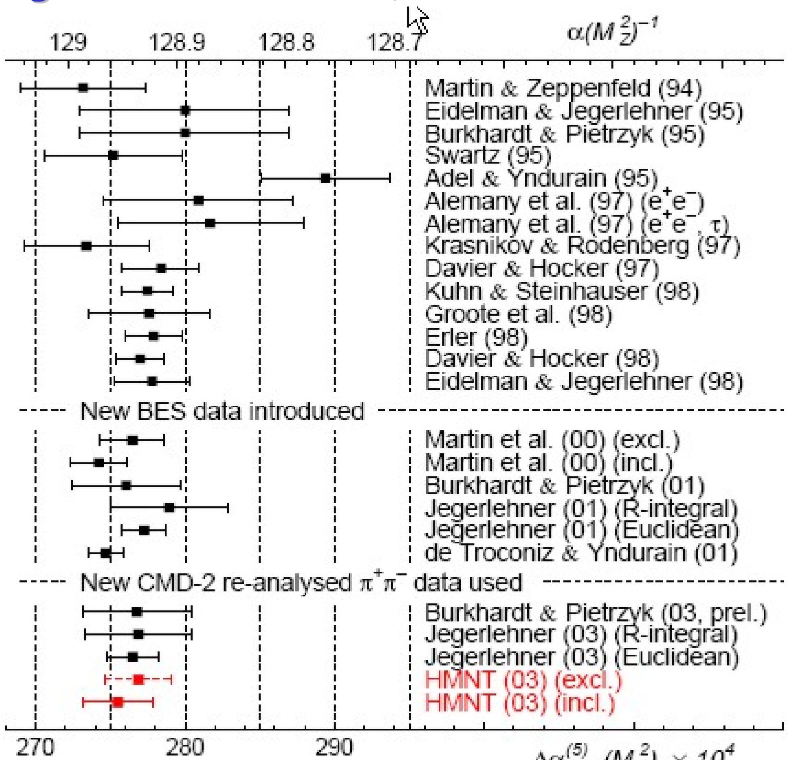
$\alpha(M_z^2)$

Using the latest experimental data from BESII:

$\Delta\alpha^5_{hadron} = 0.02761 \pm 0.00036$ (Burkhardt and Pietrzyk 2001) **using CMD-2 and KLOE latest data, seem to cancel out**

$\Delta\alpha^5_{hadron} = 0.02755 \pm 0.00023$ (Hagiwara et al. 2003) **using CMD-2 latest data**





hep-ph/0312250

These data has also confirm the validity of extending the use of perturbative QCD in the calculation of $\Delta\alpha^5_{hadron}$.
The most precise of these theory-driven calculations gives,

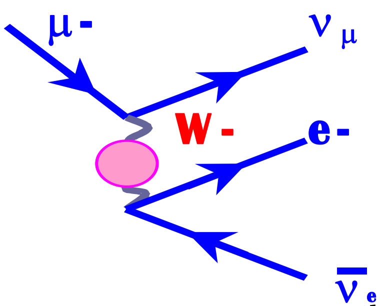
$\Delta\alpha^5_{hadron} = 0.02747 \pm 0.00012$ (Troconiz and Yndurain 2001)

EW Radiative Corrections

Quantum loops generate corrections in three sectors:

$$\sin^2\theta_W \equiv 1 - m^2_W / m^2_Z$$

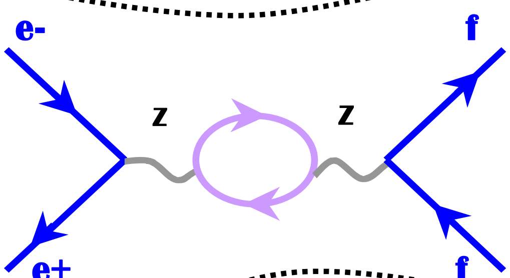
DEFINITION



$$m_W^2 \sin^2(\theta_W) = \frac{\pi\alpha}{\sqrt{2}G_\mu} (1+\Delta r)$$

$$\Delta r \approx \Delta\alpha + \Delta r_W (m_{Top}, m_{Higgs})$$

$$\approx 0.06 - 0.014$$



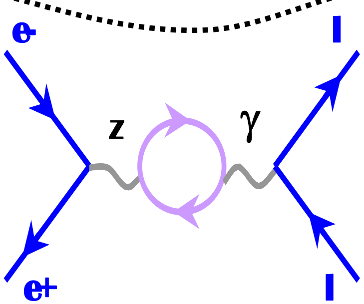
$$\rho = \rho_0 / (1-\Delta\rho)$$

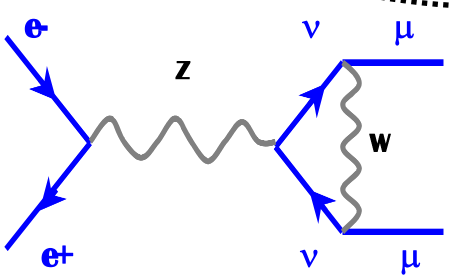
$$\Delta\rho \approx \Delta\rho (m_{Top}, m_{Higgs})$$

$$a = \sqrt{\rho}\, I_3$$

$$\approx 0.005$$

$\sin^2\theta_{eff}$





$$v = \sqrt{\rho}\, I_3 (1 - 4|Q| \kappa \sin^2\theta_W)$$

$$\kappa \approx 1 + \Delta\kappa_{QED} + \Delta\kappa_W (m_{Top}, m_{Higgs})$$

$$\approx 1 + 0.038 + 0.002$$

EW Radiative Shift

- Four free parameters in gauge-Higgs sector
  - Conventionally chosen to be
    - α=1/137.0359895(61)
    - G_F =1.16637(1) x 10^{-5} GeV $^{-2}$
    - M_Z=91.1875 ± 0.0021 GeV
    - M_H
  - Express everything else in terms of these parameters

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{\pi\alpha}{2\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2} \qquad \Rightarrow \text{Predicts } M_W$$

Inadequacy of Tree Level Calculations

- Mixing angle is predicted quantity
  - On-shell definition $\cos^2\theta_W = M_W^2/M_Z^2$
  - Predict M_W

$$\boxed{M_W^2 = \pi\sqrt{2}\,\frac{\alpha}{G_F}\left(1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2}}\right)^{-1}}$$

$$\boxed{s_W{}^2 c_W{}^2 = \frac{\pi\alpha}{G_F M_Z^2}}$$

  - Plug in numbers:
    - M_W predicted =80.939 GeV
    - M_W(exp) =80.404 $\pm$ 0.030 GeV
  - Need to calculate beyond tree level

Modification of tree level relations

$$\boxed{G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W}\frac{1}{(1-\Delta r)}}$$

- Δr is a physical quantity which incorporates 1-loop corrections

- Contributions to Δr from top quark and Higgs loops

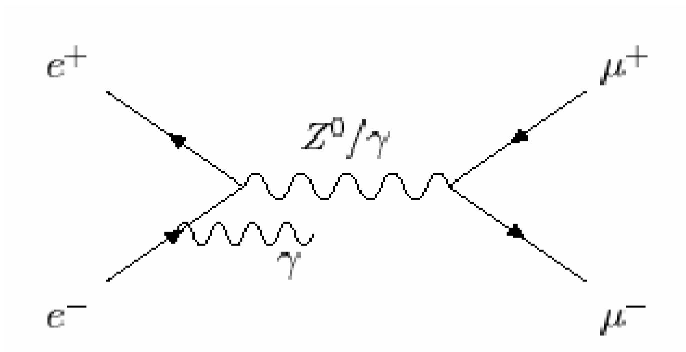
$$\Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)$$

$$\Delta r^h = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2} - \frac{5}{6}\right)$$

Extreme sensitivity of precision measurements to m_t

QED and EW corrections

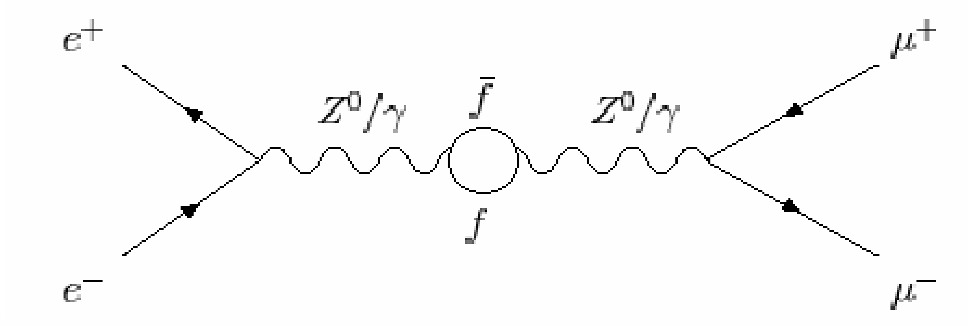
QED:



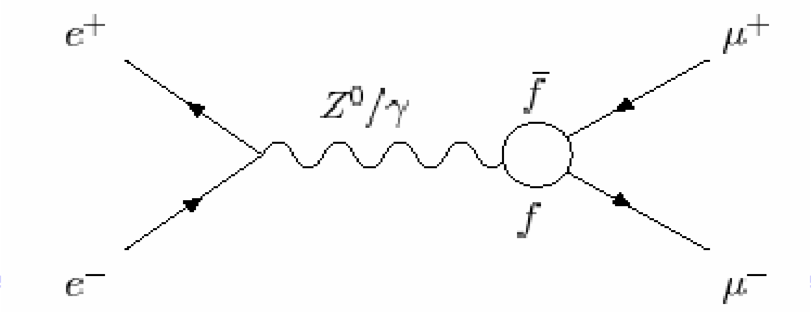
+ ....

EW:

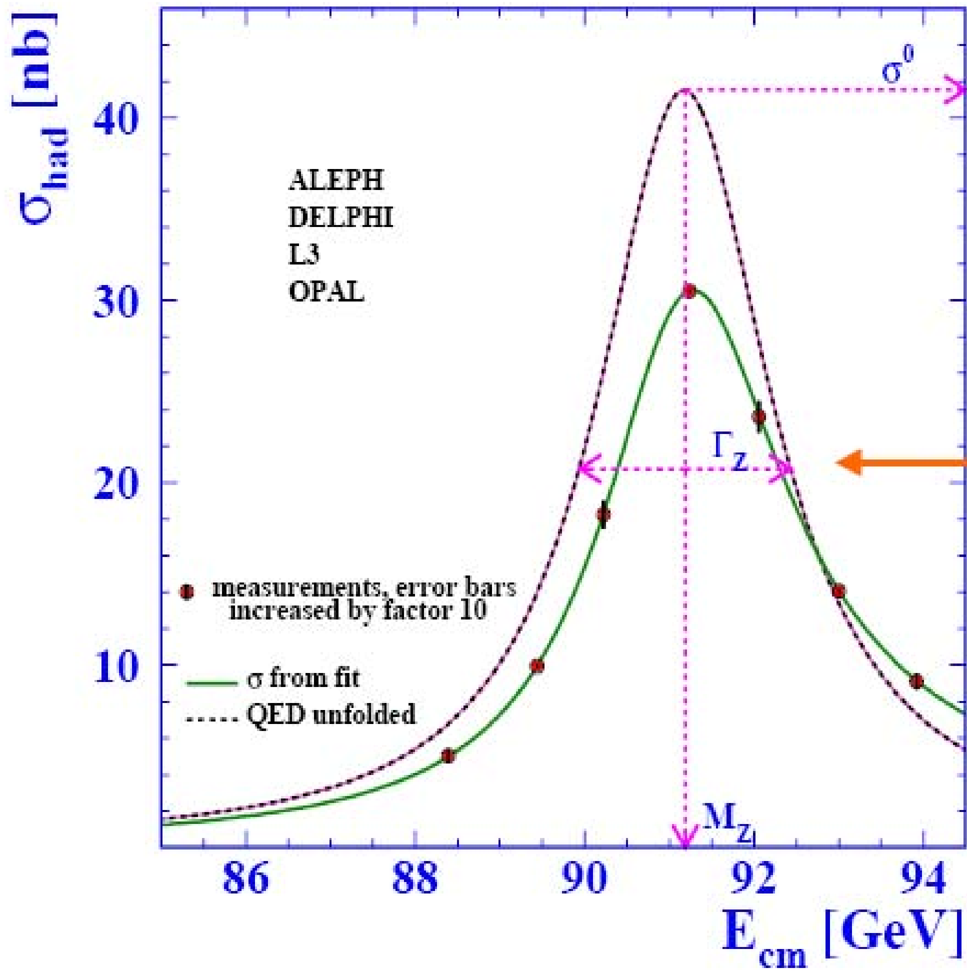
Vacuum polarization



Vertex correction



Precision at the Z



The 4 exps. collected 15.5 million Z decays to quarks plus 1.7 million decays to charged leptons, integrated L $\cong$ 200 pb^{-1} per exp.

The final hadronic cross section, measured and QED deconvoluted.

Radiative corrections large but v. well known.

Tests of the EW interactions at LEP/SLC

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

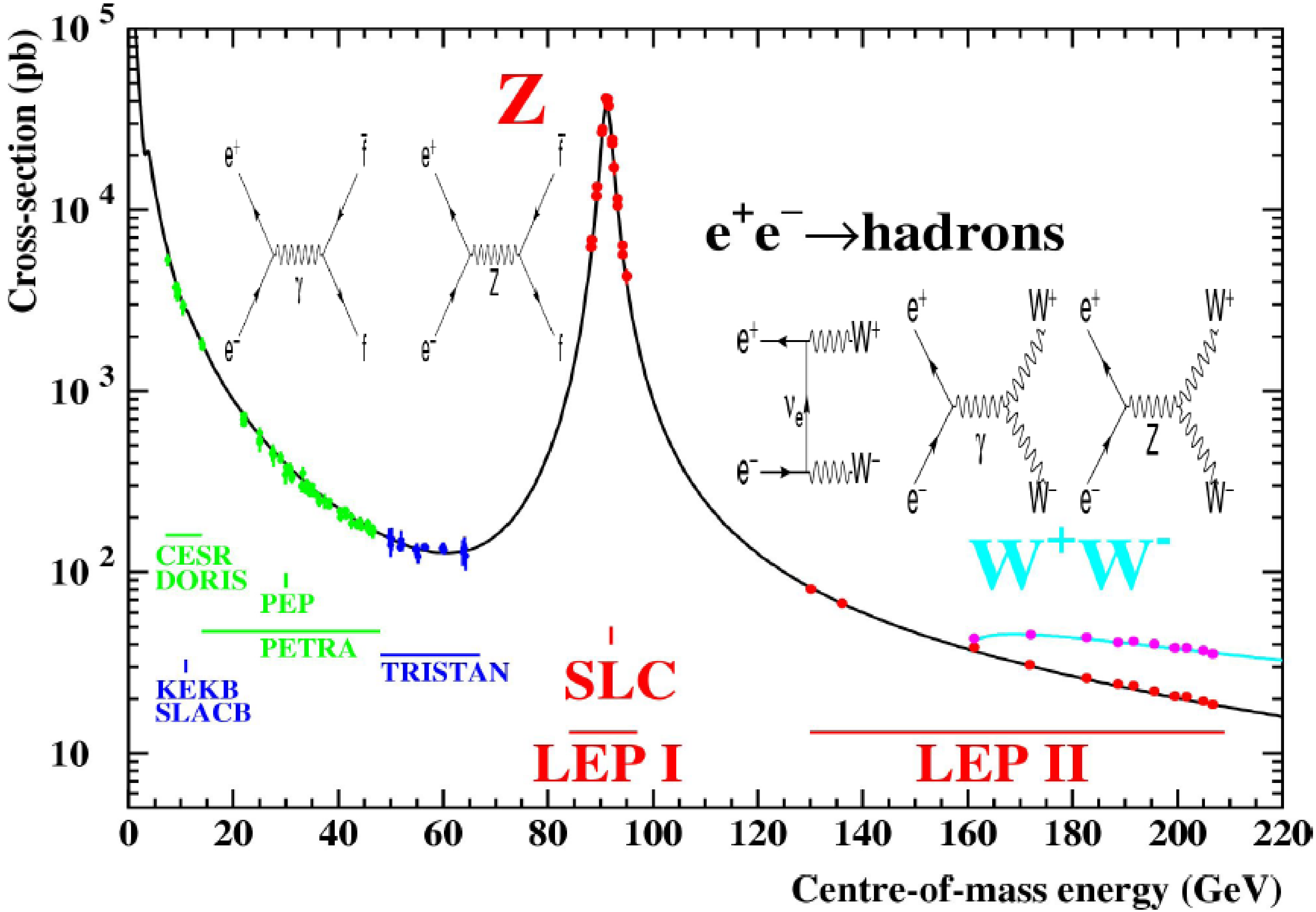
Z-pole physics (LEP-1,SLD):

- 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)

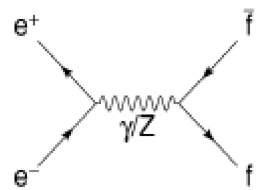
e^+e Interactions

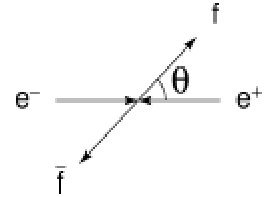


Z Physics

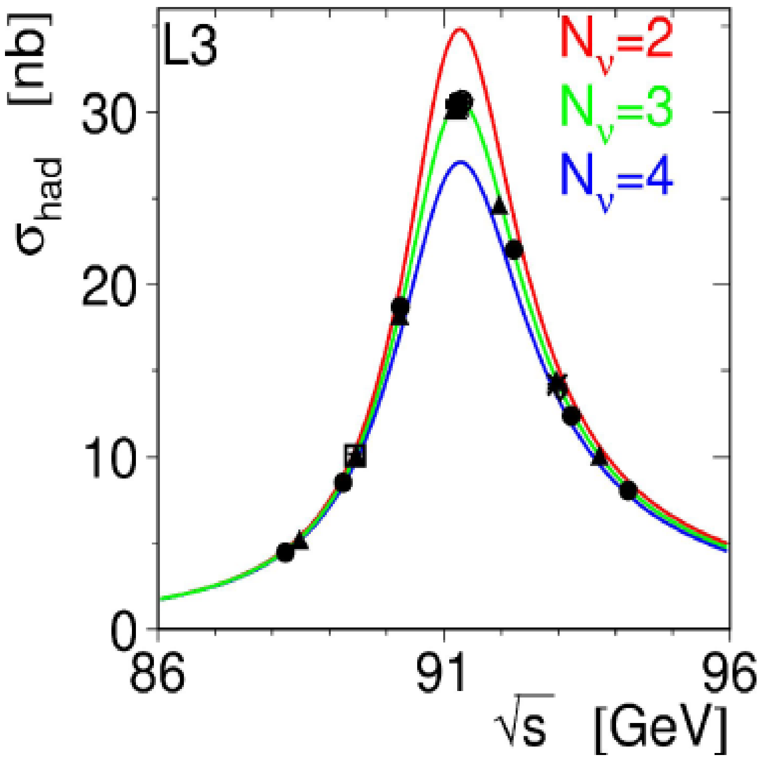
Cross sections:

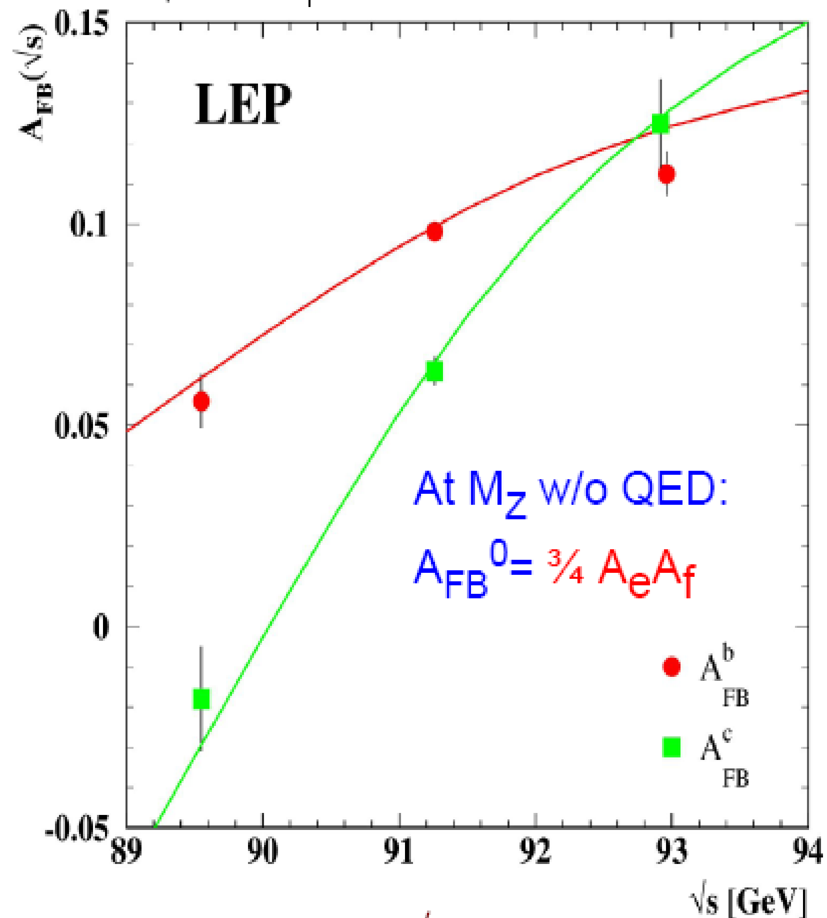
$$M_Z = 91.1875 \pm 0.0021 \quad GeV$$
$$\Gamma_Z = 2.4952 \pm 0.0023 \quad GeV$$
$$N_\nu = 2.9840 \pm 0.0082$$





$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$





$$\Gamma(Z \to f\bar{f}) \propto g_{Vf}^2 + g_{Af}^2$$

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

The full set

of nearly uncorrelated pseudo-observables from EWWG.

- Total Z width: $\Gamma_Z = 2.4952 \pm 0.0023$ GeV,
- Z peak cross section: $\sigma^0_{had} \equiv \frac{12\pi}{m_Z^2} \cdot \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$,
- Ratios $R_f^0 \equiv \Gamma_{had}/\Gamma_{ff}$ for f = e,μ,τ; also $R_q^0 \equiv \Gamma_{qq}/\Gamma_{had}$ for q = b,c,s,
- Forward backward asymmetries for f = e,μ,τ; b,c,s. At Z pole:

$$A_{FB}^{0,f} \equiv \frac{3}{4} A_e A_f \qquad A_f \equiv \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2},$$

- τ polarisation: $P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e\cos\theta}$.

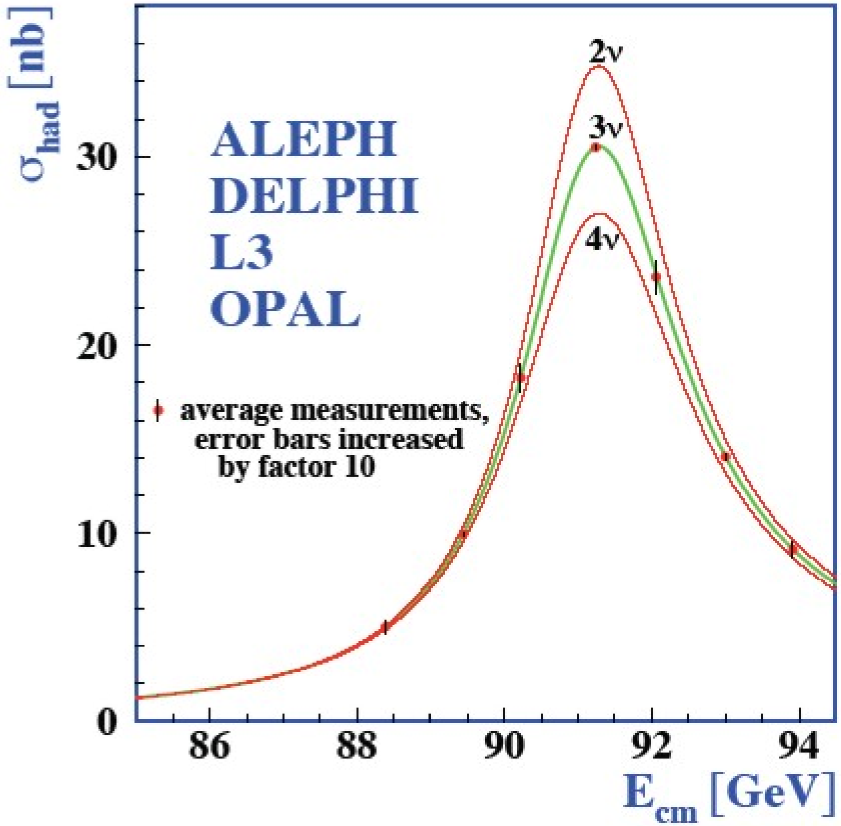
Z lineshape at LEP

Final results from LEP:

$m_Z = 91.1875 \pm 0.0021$ GeV
$\Gamma_Z = 2.4952 \pm 0.0023$ GeV
$\sigma^0_h = 41.540 \pm 0.037$ nb
$R_l = 20.767 \pm 0.025$

$$\Gamma_l = \frac{G_\mu m_Z^3}{6\pi\sqrt{2}}((g_V^l)^2 + (g_A^l)^2)(1 + \Delta_{QED})$$

$\Delta\rho = 0.0054 \pm 0.0010$ (5.4 σ)



The invisible width defined as $\Gamma_{inv} \equiv \Gamma_Z - \Gamma_h - (3+\Delta\tau)\,\Gamma_l = 499.0 \pm 1.5$ MeV allows to quote a limit on invisible non SM Z decays as:

$\Delta\Gamma_{inv} < 2.1$ MeV @ 95% c.l.

Number of light neutrino species: $N\nu \equiv \Gamma_{inv} / \Gamma_l \; * \; (\Gamma_l / \Gamma_\nu)_{SM}$

$N\nu = 2.9840 \pm 0.0082$ (-1.9σ) 0.0054 (theor.) $\oplus$ 0.0063 (exp.)

The final result

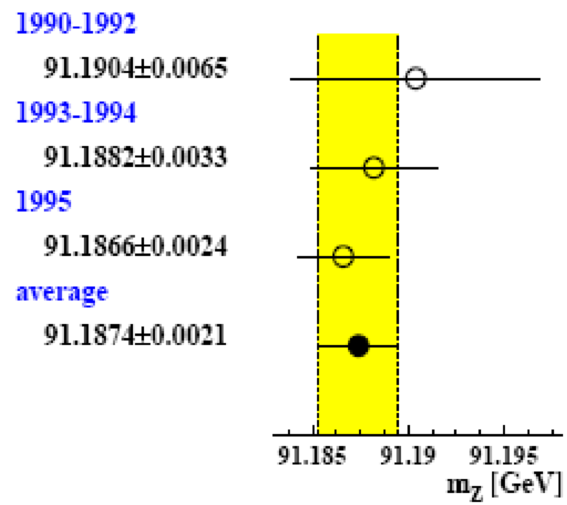
$2 \cdot 10^{-5}$ accuracy for one of the most fundamental constants:

$$m_Z = 91.1874 \pm \mathbf{0.0021}\ \text{GeV}$$

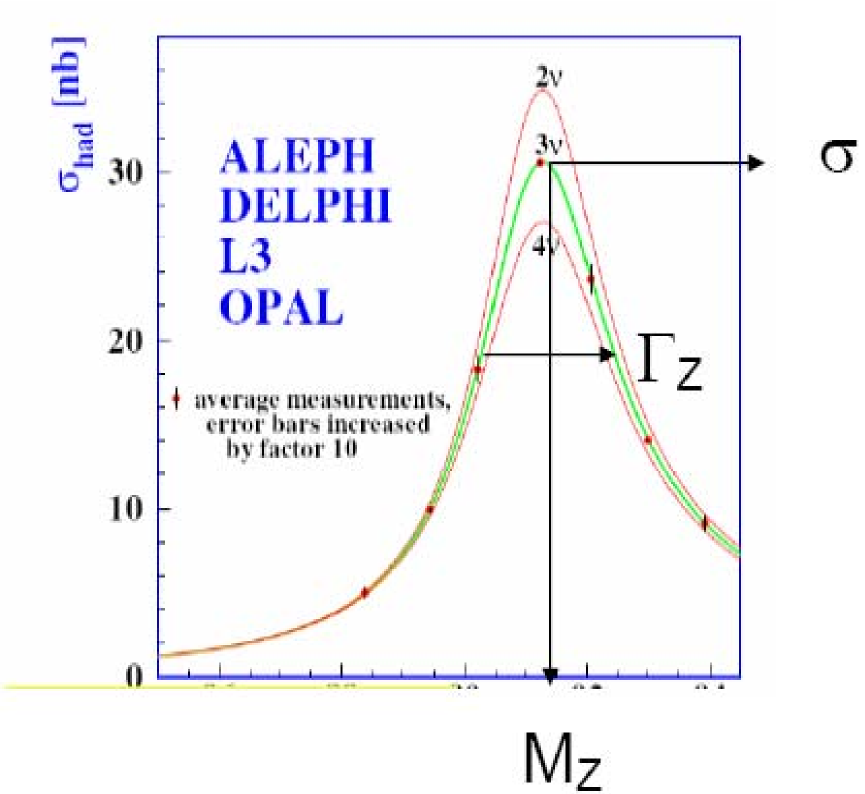
This cannot be exceeded with any one of the future machines, not even with a GigaZ Linear Collider!

Essential:

- Beam energy measurement using the technique of **resonant depolarisation** plus careful control of all machine parameters, still **dominant error of ±1.7 MeV,**
- Close cooperation with theory.



Z cross section

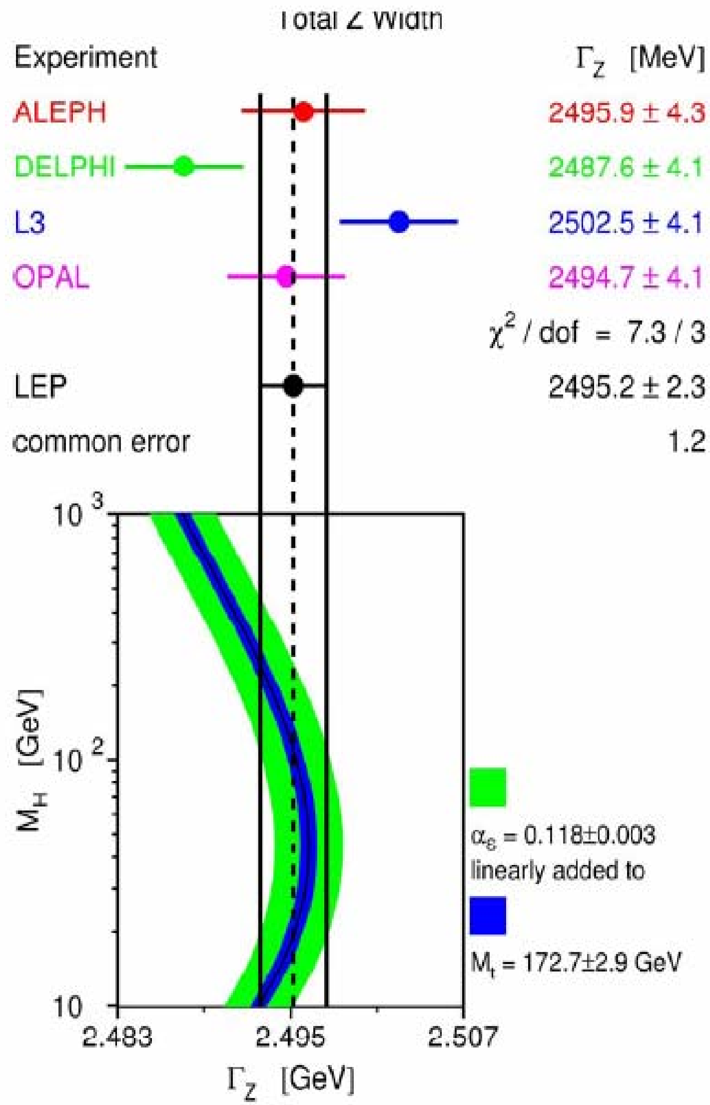


Requires precise calibration of energy of machine

Number of light neutrinos: N_υ=2.9840±0.0082

Total Z Width from LEP

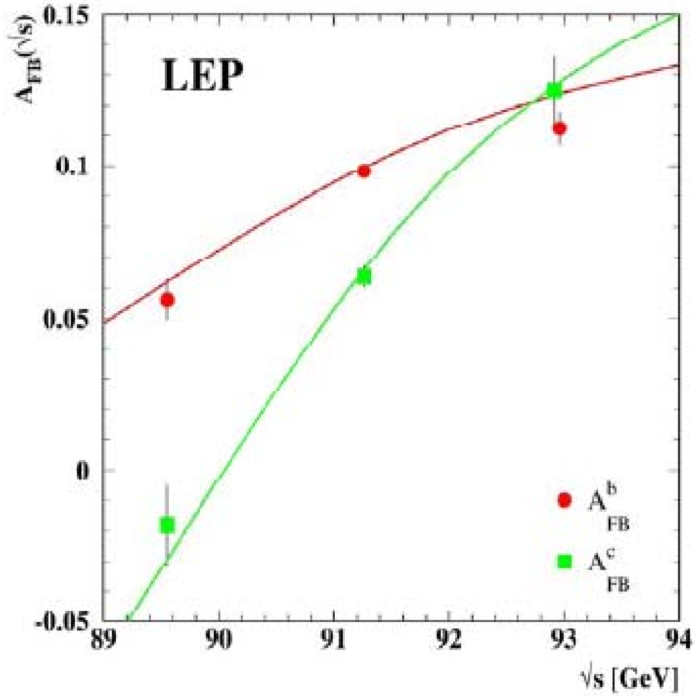
- Largest uncertainty is from α_s



Forward-Backward Asymmetry

$$A_{FB} = \frac{\int_0^1 dz \frac{d\sigma}{dz} - \int_{-1}^0 dz \frac{d\sigma}{dz}}{\int_{-1}^1 dz \frac{d\sigma}{dz}}$$

$$\boxed{A_{FB,Z-peak}(f\bar{f}) = \frac{3}{4}\frac{(L_e^2 - R_e^2)(L_f^2 - R_f^2)}{(L_e^2 + R_e^2)(L_f^2 + R_f^2)}}$$



Very sensitive to fermion couplings

$$A_{FB,Z-peak}(f\bar{f}) \approx (1 - 4\sin^2\theta_W)(\ldots)$$

Asymmetries are very small

The measurements of **Asymmetries at the Z pole are** determinations of the ratio:

$$A_f \equiv \frac{2\left(\frac{g_V^f}{g_A^f}\right)}{1+\left(\frac{g_V^f}{g_A^f}\right)^2}$$

$\sin^2\theta_{eff} = 1/4\ (1 - g^l_V/g^l_A)$

$= \kappa \sin^2\theta_W$

Average of

LEP: A^l_{FB} , A^τ_{POL}

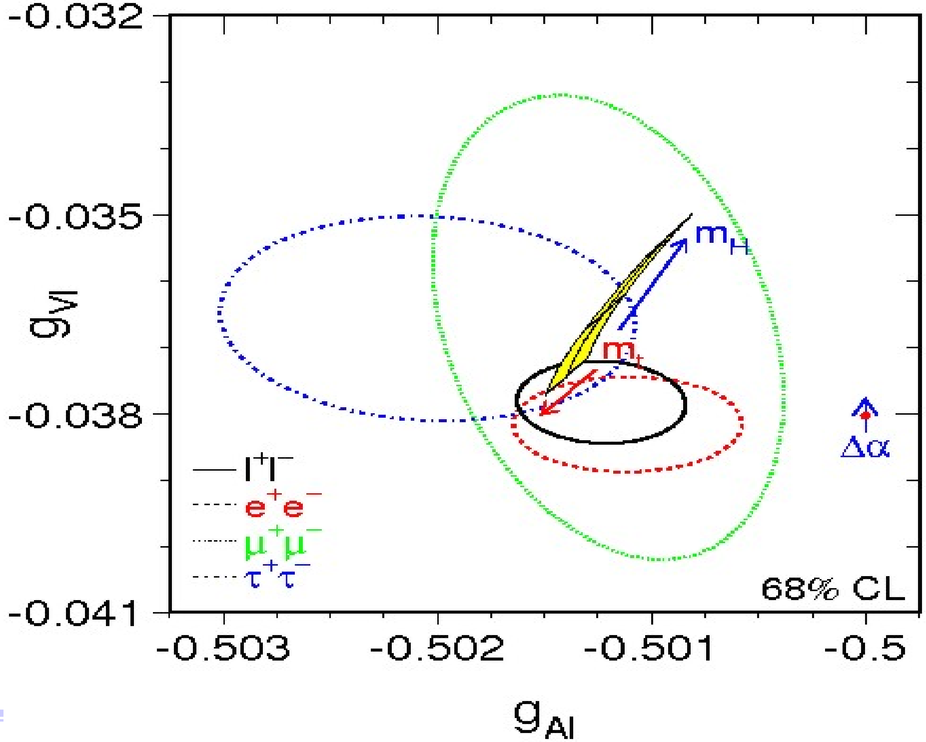
SLC: A_{LR} (χ^2/dof = 1.6/2)

$A_l = 0.1501 \pm 0.0016$

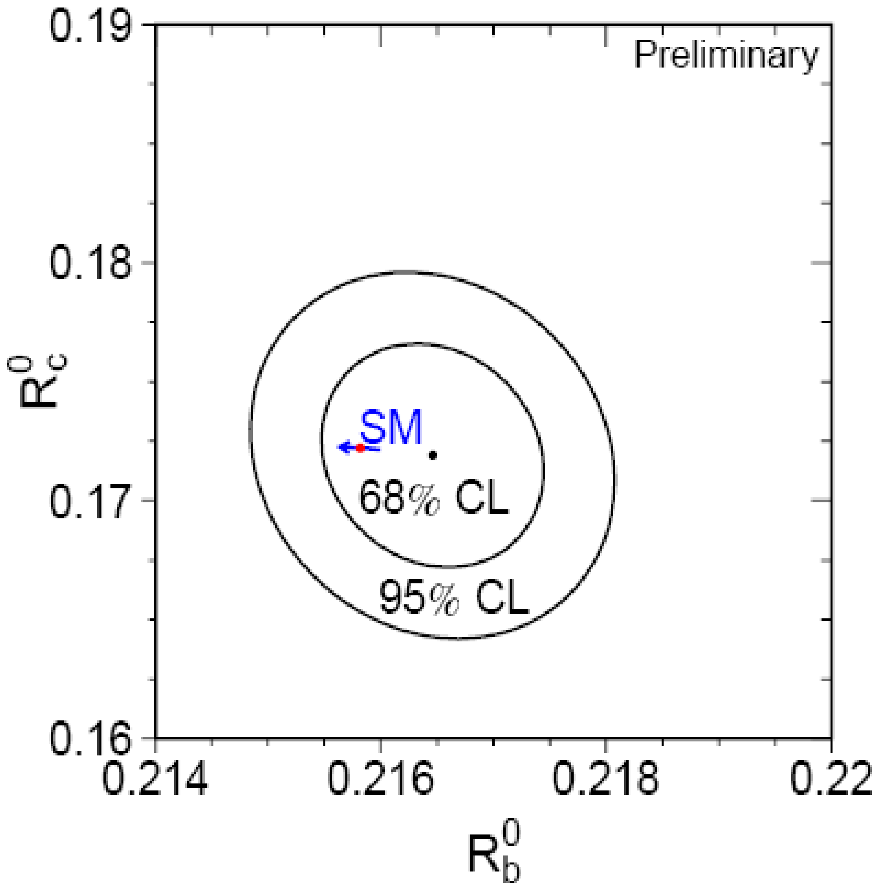
$\sin^2\theta_{eff} = 0.23113 \pm 0.00021$

and using the leptonic width,

$$\Gamma_l = \frac{G_\mu m_Z^3}{6\pi\sqrt{2}}((g_V^l)^2 + (g_A^l)^2)(1+\Delta_{QED})$$



$Z \to$ quarks



Now R_b agrees with SM!

$$R_b^0 \equiv \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} \qquad R_c^0 \equiv \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$$

R_b contains higher order ew. contributions ~ m_t^2, nearly independent of QCD, QED or other ew. corr.

Measurement of R_b requires extremely high quality of b tagging.
$\rightarrow$ High resolution silicon microvertex detectors + multi-tag methods + control of hemisphere correlations …

Heavy Flavour Results at the Z-Pole

Finally: really final HF results available

$R_b = \Gamma_b/\Gamma_{had}$	0.21629 ± 0.00066
$R_c = \Gamma_c/\Gamma_{had}$	0.1721 ± 0.0030
$A_{fb}(b) = \frac{3}{4} A_e A_b$	0.0992 ± 0.0016 *
$A_{fb}(c) = \frac{3}{4} A_e A_c$	0.0707 ± 0.0035
A_b	0.923 ± 0.020
A_c	0.670 ± 0.027

+ small correlations

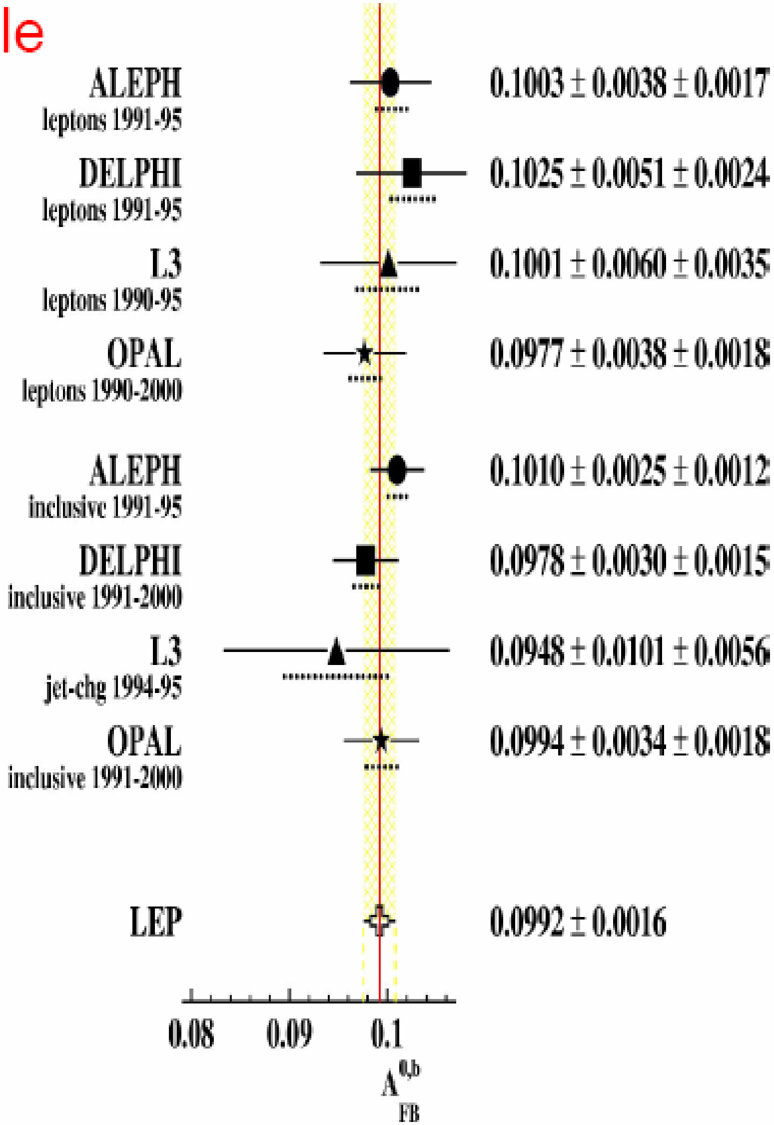
Heavy-flavour combination:

χ^2/ndof = 53/(105-14) low!

Central values very consistent

Several systematic tests

dominated by MC statistics



Comparison of all Z-Pole Asymmetries

Effective electroweak mixing angle:

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

$= 0.23153 \pm 0.00016$

$\chi^2/ndof = 11.8/5$ [3.7%]

Subsequent observation:

0.23113±0.00021 leptons

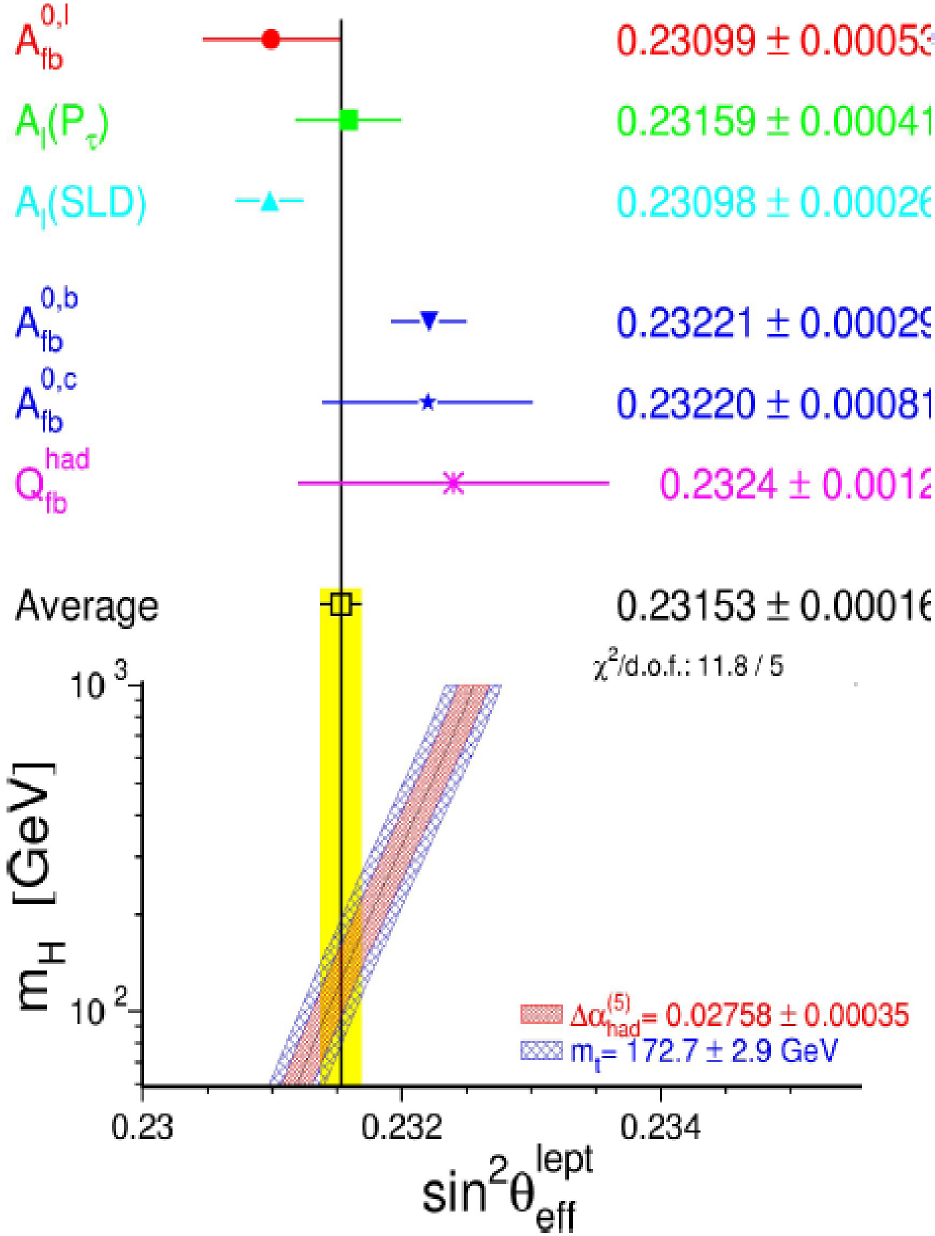
0.23222±0.00027 hadrons

3.2 σ difference

But is really:

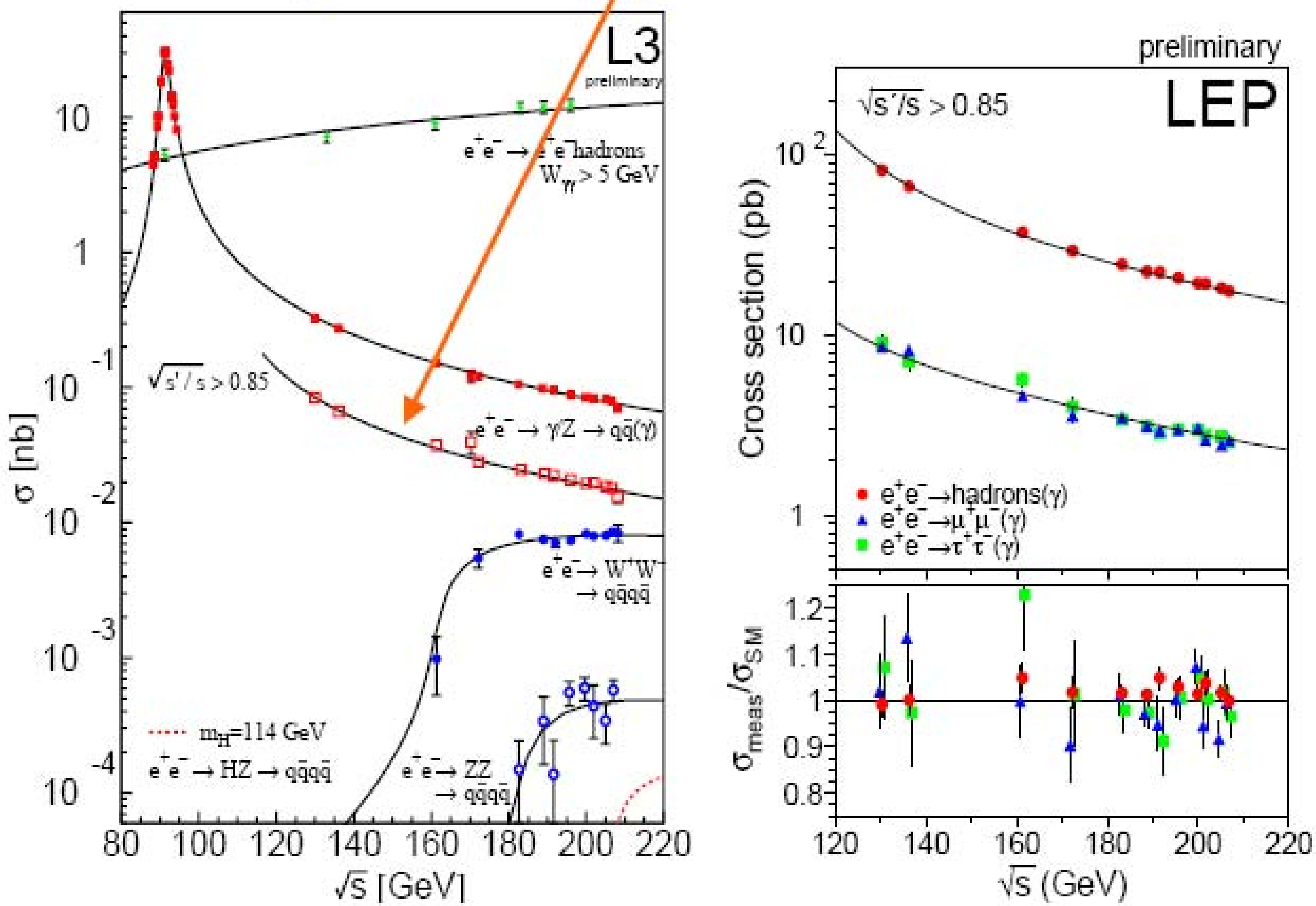
A_l(SLD) vs. A_{fb}b(LEP)

3.2 σ difference



2 fermion production above Z

Compared to other processes cross-section still high.



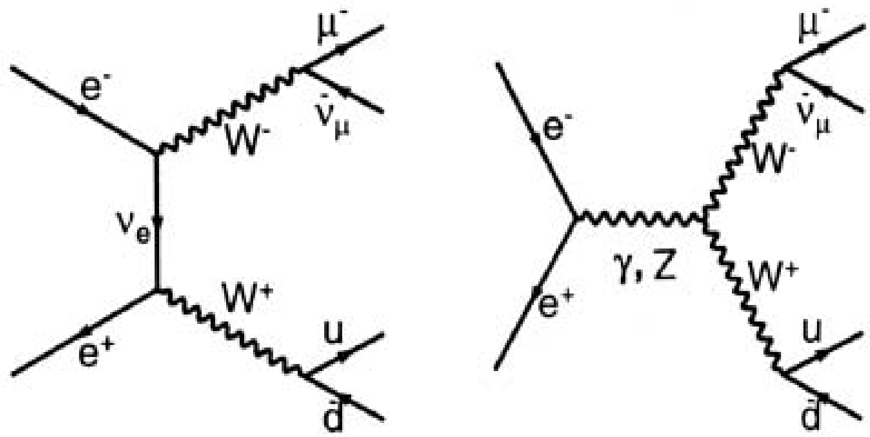
Cut on $\sqrt{s'/s}$ selects interesting events.

Combined for hadrons, μμ, ττ, bb, cc by EWWG.

Agreement with SM, but hadronic cross-section 1.8 σ high.

W^+W^- Production

Focus of SM tests at LEP2: Measurement of m_W, investigation of structure of triple boson couplings.

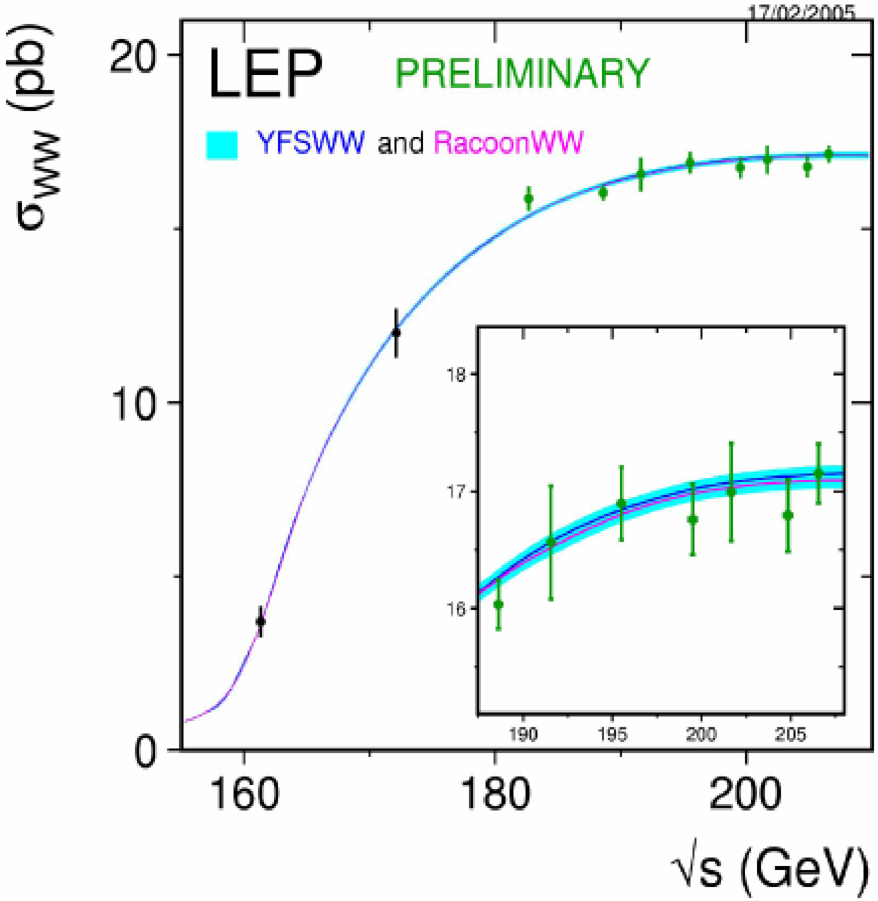


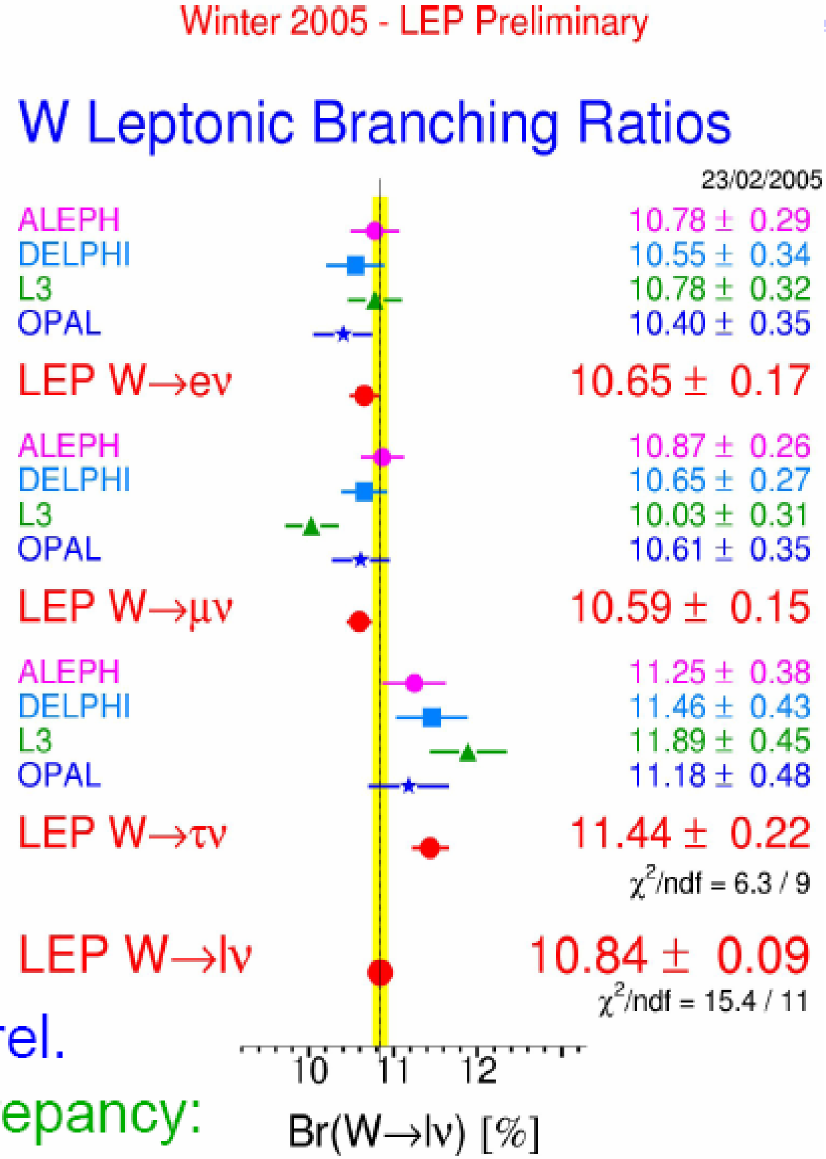
CC03 diagrams

Each LEP experiment has collected about 10000 W^+W^- events.
Five decay classes: Fully hadronic (45.6%), 3 semileptonic (each 14.6%), fully leptonic (10.6)%.

Powerful tools to separate four fermion events originating from W production from background, e.g. neural networks.
Typical efficiency for WW selection 85% at v. high purity.

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

W mass

Before crossing W-pair threshold precise m_W value from Z data using SM relations. **Updated indirect value using measured m_t** :

$$\mathbf{m_W = 80.373 \pm 0.023\ GeV\ .}$$

Small error sets scale for direct mass measurements.

In SM m_W depends on m_t, m_H and $\Delta\alpha$ (complete 2-loop, Freitas et al.):

$$m_W = 80.3767 + 0.5235\left(\left(\frac{m_t}{174.3}\right)^2 - 1\right) - 0.05613\ln\left(\frac{m_H}{100}\right) - 1.081\left(\frac{\Delta\alpha}{0.05924} - 1\right) + - ...$$

Significant deviation of direct meas. from indirect value would indicate new physics and existence of new fundamental particles.

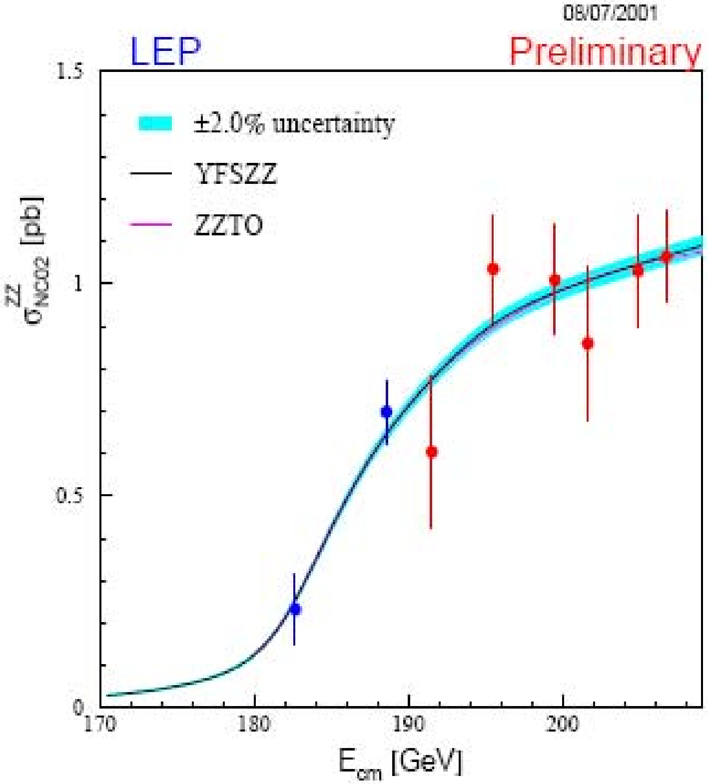
At LEP2 two independent methods:

- Meas. of the total cross-section near threshold at E_{CM} = 161 GeV:

  $m_W = 80.40 \pm 0.21$ GeV. (Estimated error for GigaZ: Δm_W = 0.006 GeV)

ZZ production

- New test of SM. Search for existence of anomalous neutral gauge boson couplings (ZZZ, ZZγ).



Combined results (NC02, only t- and u-channel exchange).

All experiments analyse $ZZ \rightarrow qqqq$ (4 jets), $qq\nu\nu$ (2jets + missing energy), qql^+l^- (2jets + 2 isolated leptons),
4 lepton final states;
statistic v. limited.

Contributions to QCD

Clean environment, hadronic cm. energy well defined, well collimated jets, enough statistics to investigate even rare topologies.

Typical early topics:
- Tests of QCD, measurements of α_s, understanding of fragmentation,

Later: Global studies (up to which level can the accurate data be described).

Ew precision quantities depend on α_s:

$$R_{lept} = \frac{\Gamma(Z \to hadrons)}{\Gamma(Z \to leptons)} = 19.934 \cdot \left(1 + 1.045\frac{\alpha_s}{\pi} + 0.94\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3\right)$$

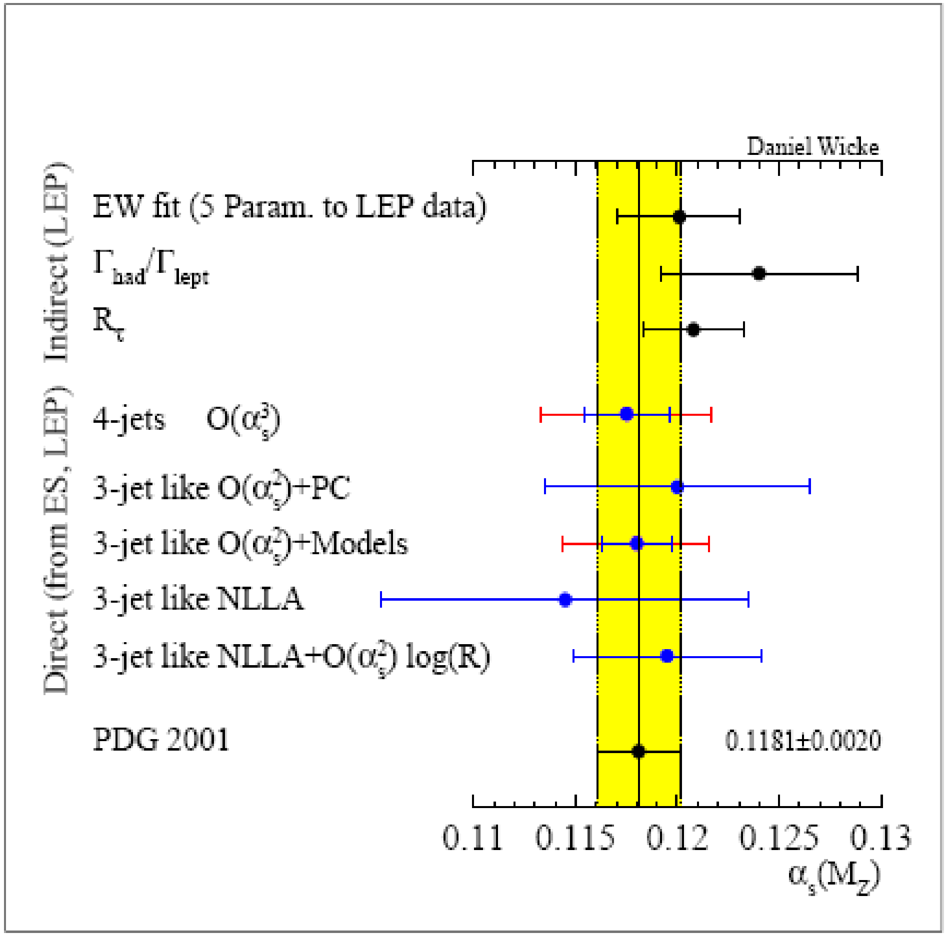
With final $R_{lept} = 20.767 \pm 0.025$:

$$\alpha_s(m_Z) = 0.124 \pm 0.004(\exp.) \pm 0.002(m_H, m_t)^{+0.003}_{-0.001}(QCD)$$

Best measurement?

- Relies on electroweak sector of MSM,
- Convergence, at m_Z α_s^3-term $\cong$ 63% of α_s^2-term.

All LEP α_s measurements



Studies of

- gauge structure of QCD,
- running b-quark mass,
- colour coherence,
- hadronisation models,
- power corrections as alternatives to hadronisation models,
- differences between quark and gluon jets,

are all consistent with QCD predictions.

For this fig.: Theoretical uncertainties for all α_s from event shapes evaluated from change in renormalisation scale μ by factor 2.

Before LEP

What was known or expected in summer 1989 before start of LEP (G. Altarelli; LP, Stanford and R. Barbieri; EPS, Madrid):

$m_Z = 91.12 \pm 0.16$ GeV $\quad m_W = 80.0 \pm 0.36$ GeV

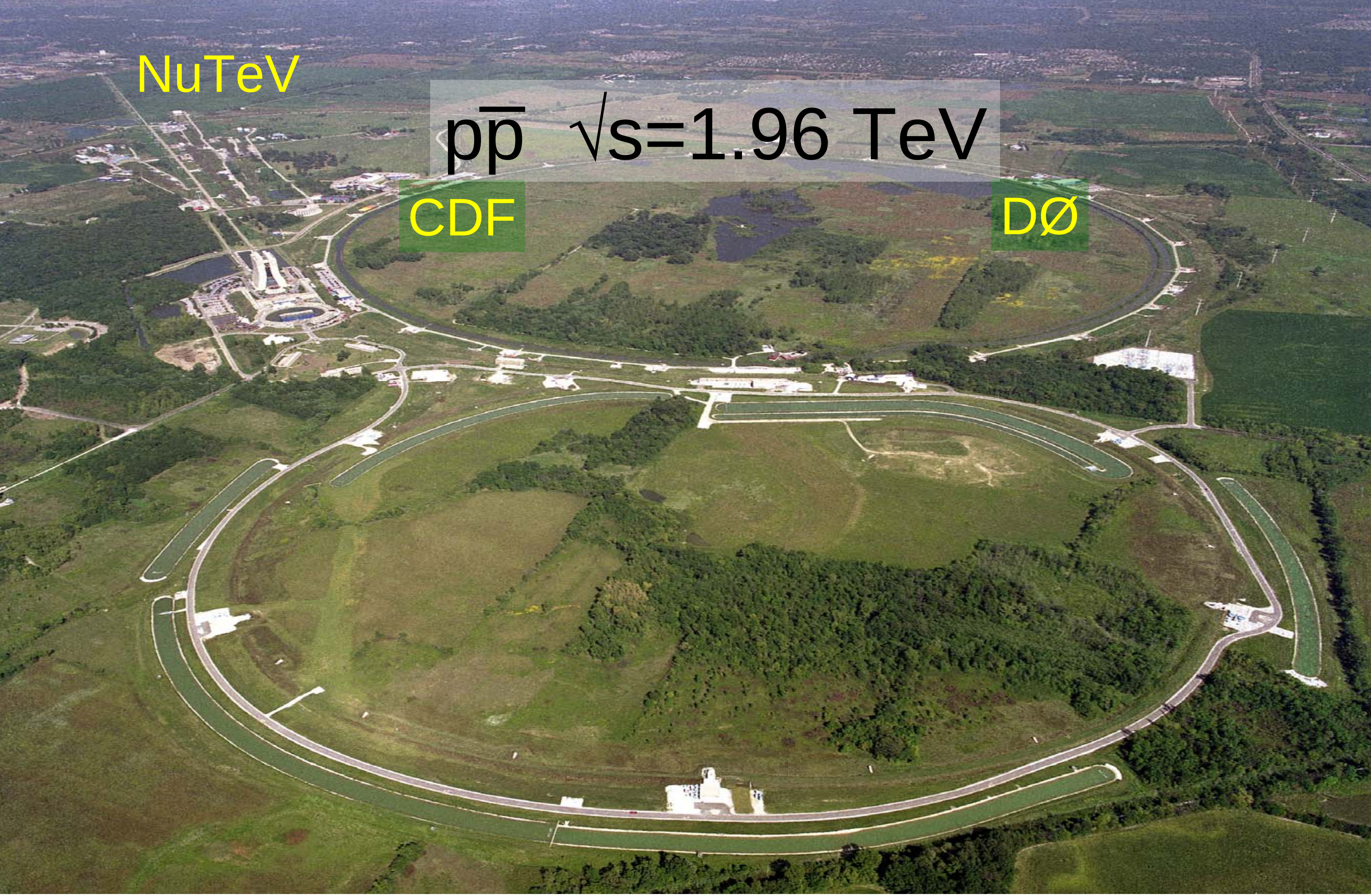
$\sin^2\theta_W = 0.227 \pm 0.006 \quad N_\nu = 3.0 \pm 0.9$

Quantity	Expected error	Achieved
m_Z	50 to 20 MeV	**2.1 MeV**
m_W	100 MeV	**39 MeV**
N_ν	0.3	**0.008**
$A^{0,\mu}_{FB}$	0.0035	**0.0013**
$A^{0,b}_{FB}$	0.0050	**0.0017**
$\mathcal{A}_\tau$	0.0110	**0.0043**

In the end, all measurements are much more precise. SM continues to be in good shape.

PART II

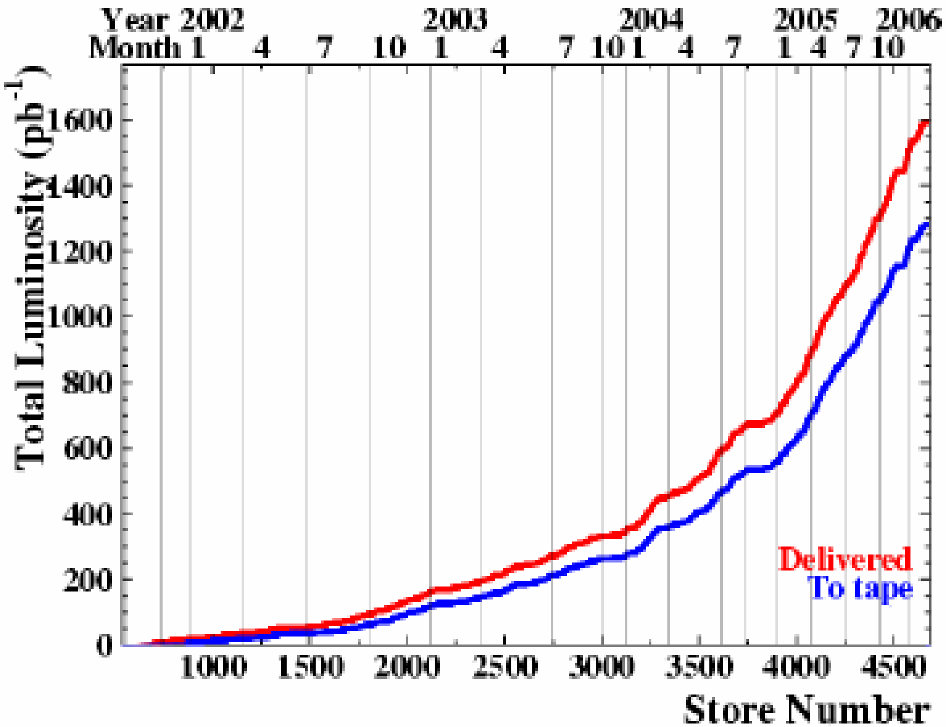
Tests of the EW interactions at Tevatron


NuTeV
$p\bar{p}$ $\sqrt{s}$=1.96 TeV
CDF
DØ

Tevatron

Tevatron running $p\bar{p}$ at $\sqrt{s}$=2 TeV

Scheduled to shut down 2009-2010



Z's at the Tevatron

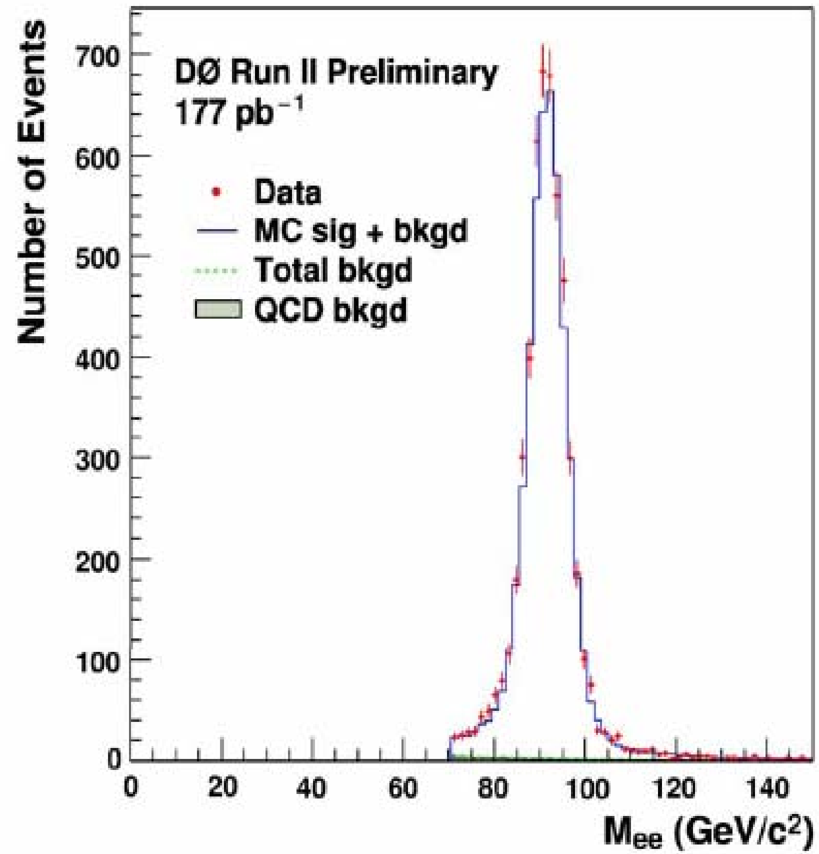
Z-production $q\bar{q} \rightarrow Z \rightarrow e^+e^-$

Amplitude has pole at M_Z

$$\frac{1}{(p_e + p_{\bar{e}})^2}$$

Invariant mass distribution of e^+e^-

$$m_{ee}^2 = (p_e + p_{\bar{e}})^2 \approx M_Z^2$$



W's at the Tevatron

Consider $W \rightarrow e\nu$

Invariant mass of the leptonic system

$$m_{e\nu}^2 = \left(E_e + E_\nu\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2 - \left(p_{ez} + p_{\nu z}\right)^2$$

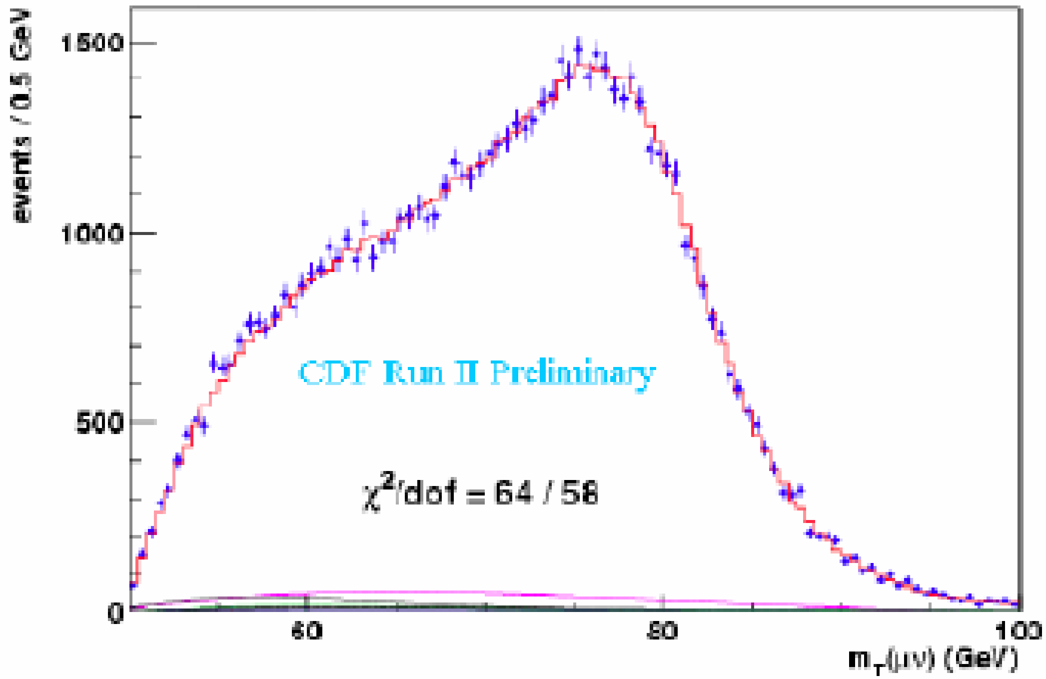
Missing transverse energy of neutrino inferred from observed momenta

Can't reconstruct invariant mass

Define transverse mass observable

$$\begin{aligned} m_T^2 &= \left(E_{eT} + E_{\nu T}\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\nu T}\right)^2 \\ &= 2\vec{p}_{eT}\vec{p}_{\nu T} = 2E_{eT}E_{\nu T}(1 - \cos\phi) \end{aligned}$$

W Mass Measurement



Location of peak gives M_W

Shape of distribution sensitive to Γ_W

Statistics enough to best LEP 2

W boson properties

- **Decay width**

$$\Gamma(W \to e\nu) = \frac{G_F M_W^3}{6\sqrt{2}\pi}(1+\delta) \approx 226 MeV$$

$\delta \approx -.35\%$ Small

$$\Gamma(W^+ \to u_i \bar{d}_j) = \frac{F G_F M_W^3}{6\sqrt{2}\pi}\left|V_{ij}\right|^2 \approx 706\left|V_{ij}\right|^2 MeV$$

$F = N_c\left(1 + \frac{\alpha_s(M_W)}{\pi}\right)$ quarks

=1 leptons

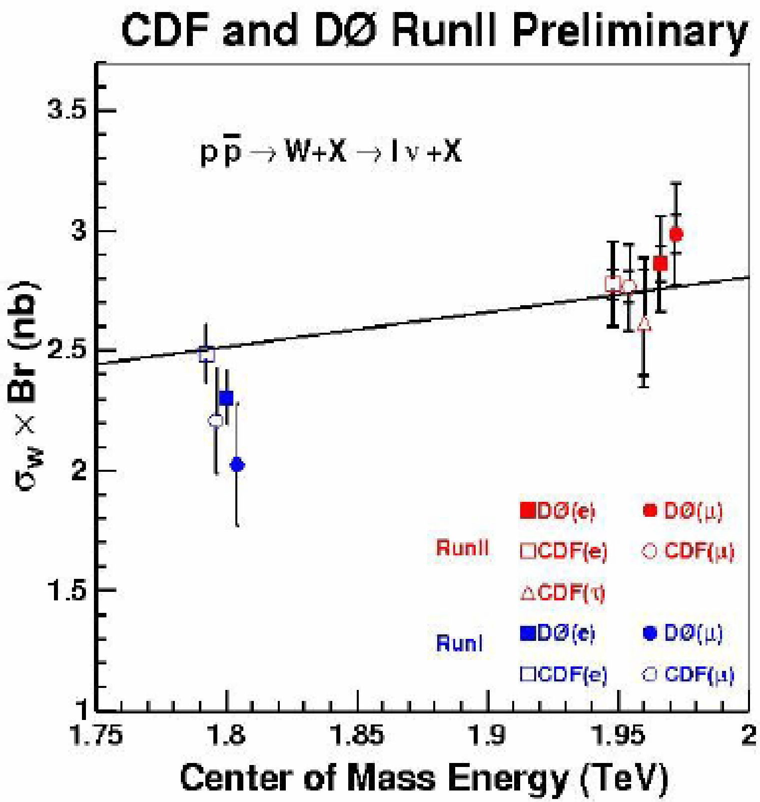
$$\boxed{\Gamma_W(theory) = (3+2F)\,\Gamma(W \to e\nu) =\approx 2.0936 \pm 0.0022\ GeV}$$

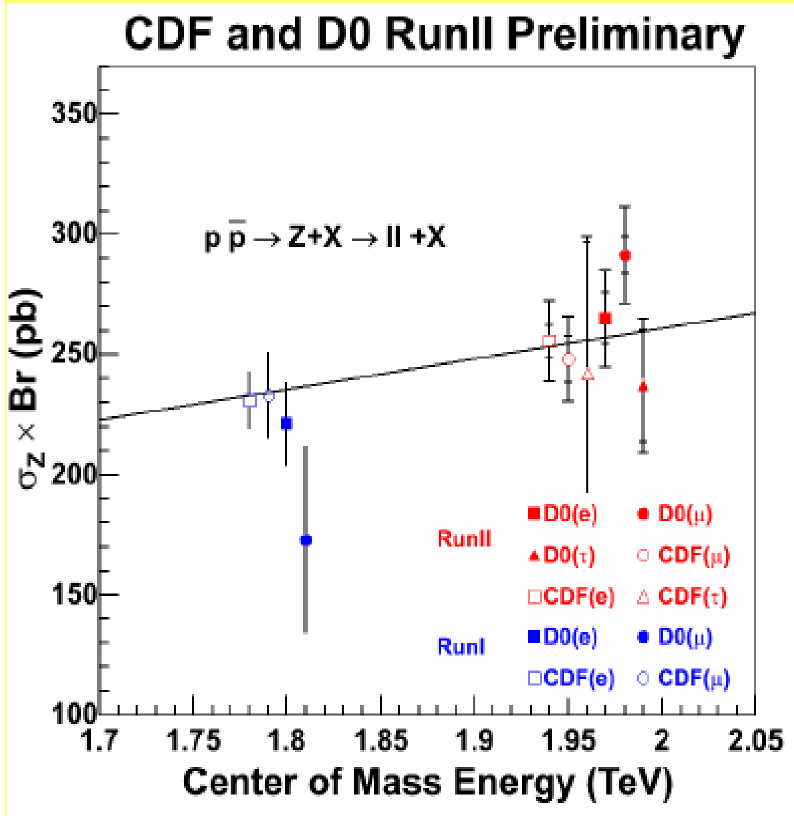
Largest contribution to error is error on α_s and M_W

W/Z Physics at the Tevatron

Leptonic decay modes of W and Z (including tau leptons!):

4,000-14,000 Z's per e/μ   40,000-120,000 W per e/μ





Largest uncertainties:

- Luminosity (~6%)
- Lepton id efficiencies and PDFs (1-1.5% each)

W Boson - Mass and Width

Tevatron (CDF, D∅): $p\bar{p} \to WX$, $W \to e\nu, \mu\nu$

Transverse mass

$$m_T^2 = 2E_T^e E_T^\nu \cos\phi(e,\nu)$$

Final Run-I combination

Awaiting Run-II results!

Uncertainties dominated by:

Statistics

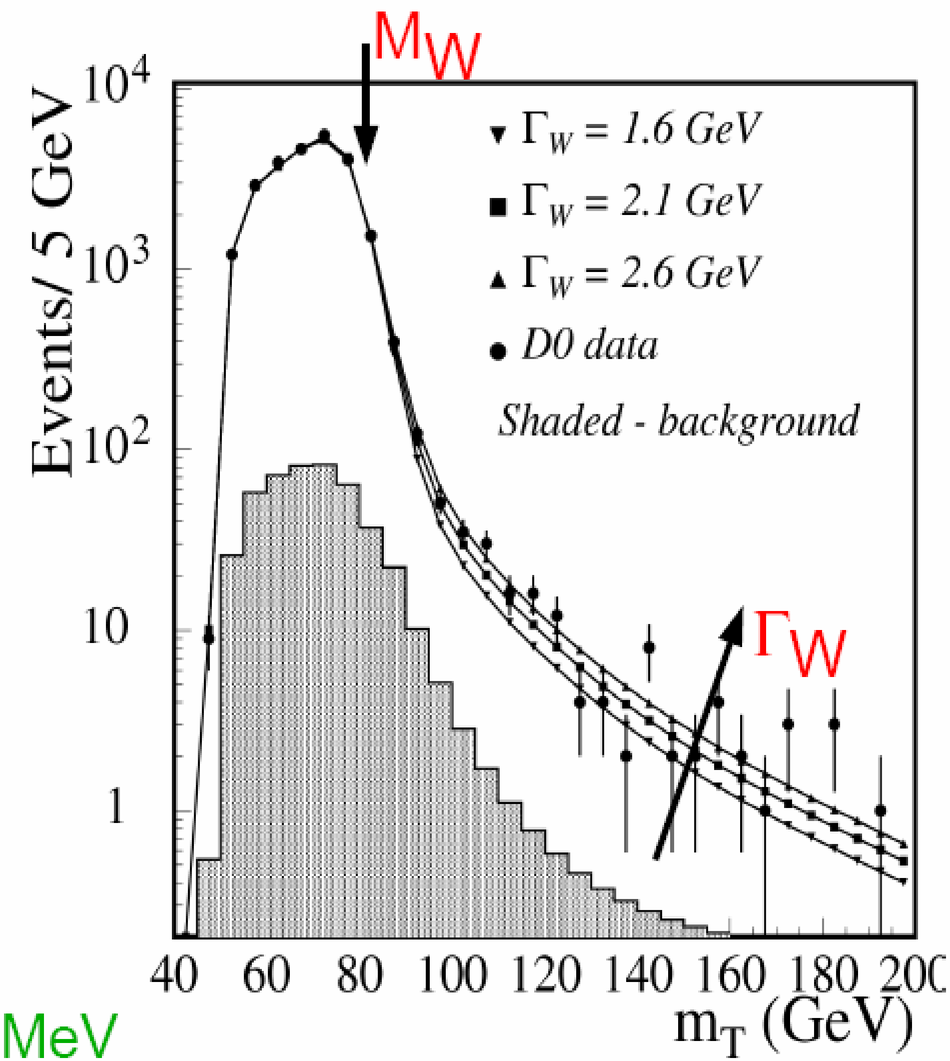
Lepton energy scale -

will reduce with more data

Then: Signal model

PDFs, gluon radiation

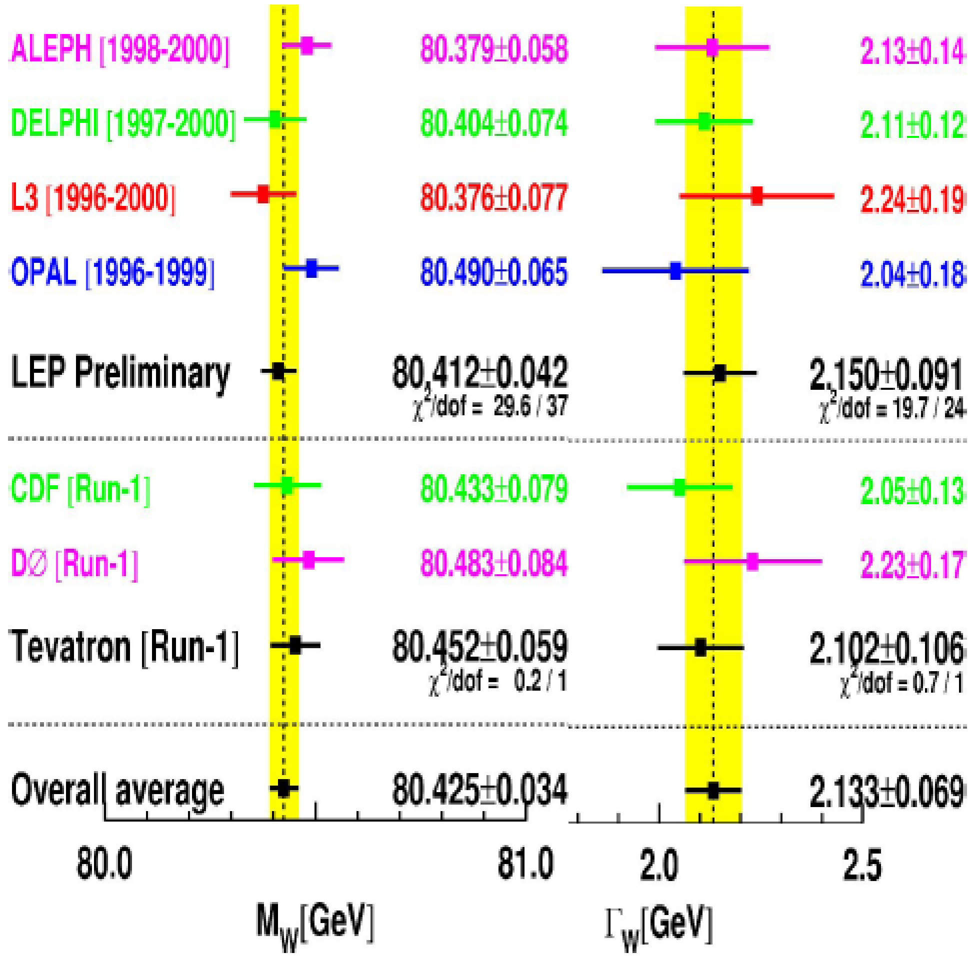
QED corrections in $W \to l\nu$

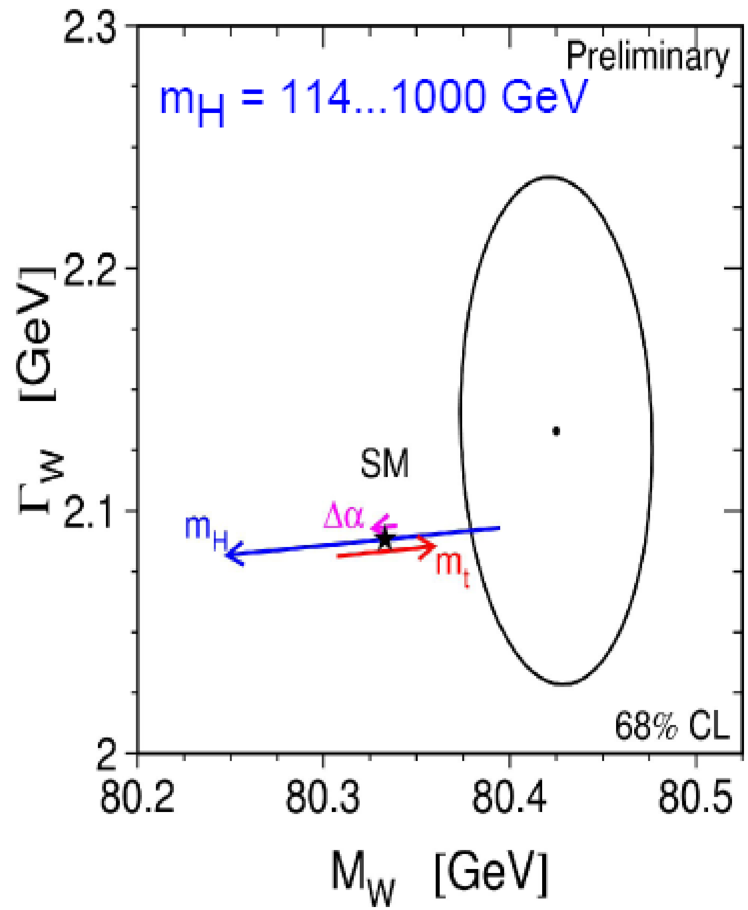


Run-II expectation: δM_W < 25 MeV

W Boson - Mass and Width

Very good agreement between all six experiments:





Correlation M_W-Γ_W: -0.07

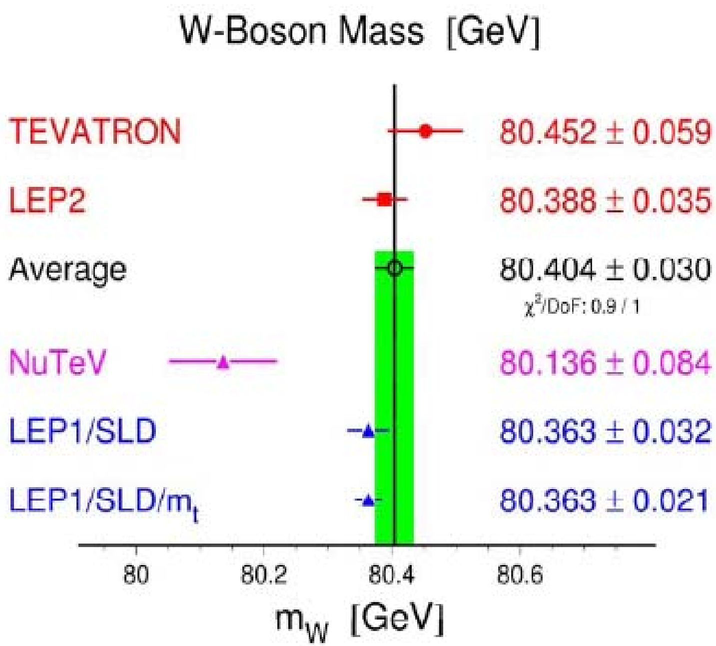
SM comparison:

Small Higgs-boson mass

World Average for W mass

Direct measurements (Tevatron/LEP2) and indirect measurements (LEP1/SLD) in excellent agreement

Indirect measurements *assume* a Higgs mass

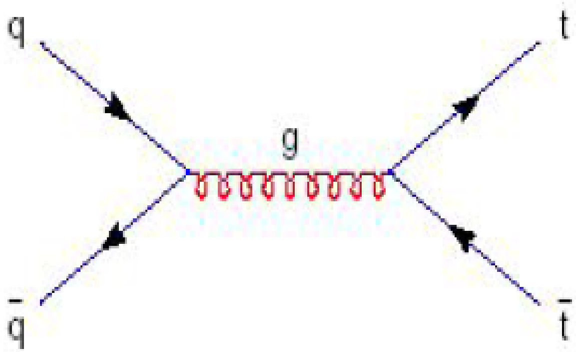


LEPEWWG home page, 2006

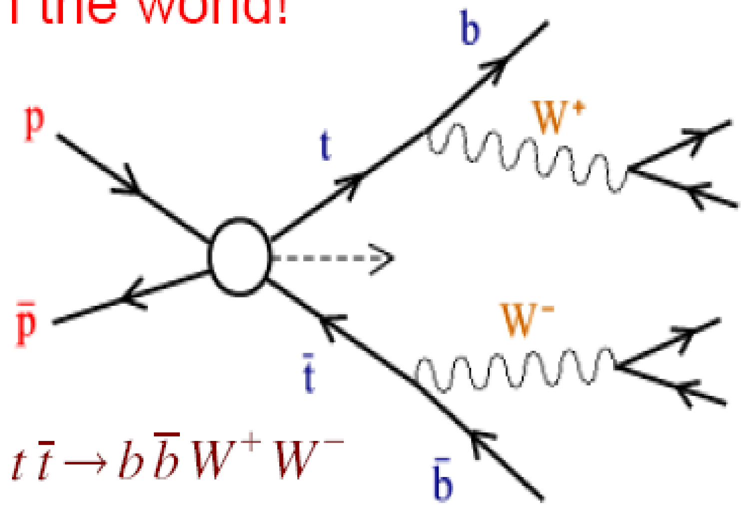
Top Physics

Tevatron: only source of top quarks in the world!

Primarily top-pair production

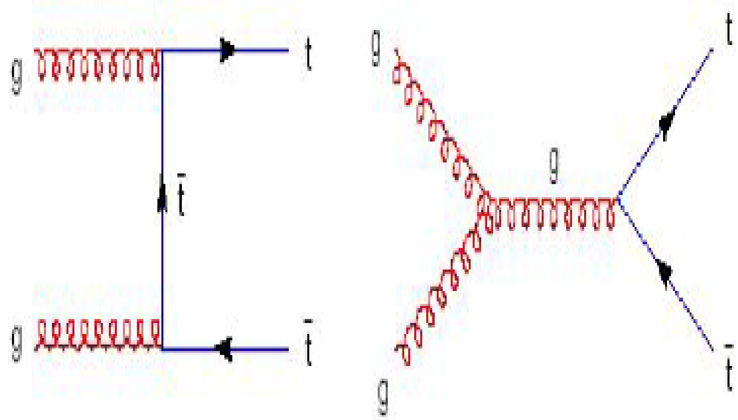


$q\bar{q}$ annihilation (85%)

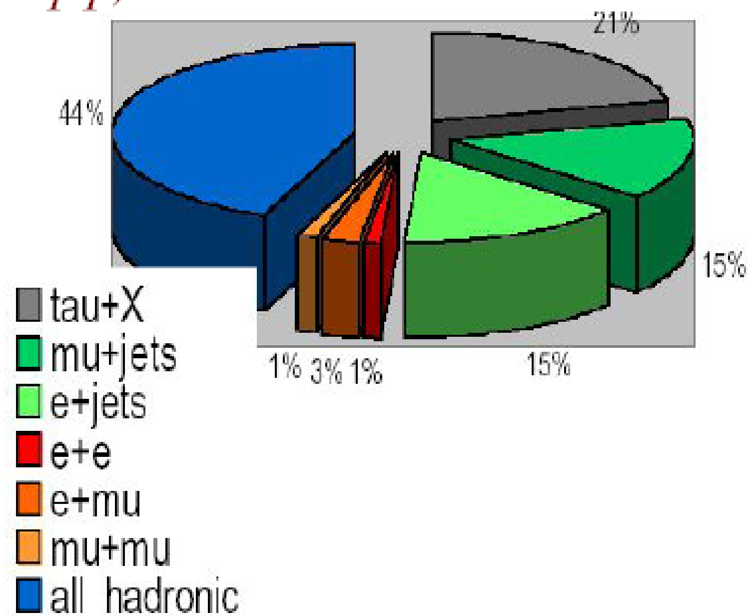


$$p\,\bar{p} \to t\,\bar{t}\,X,\quad t\,\bar{t} \to b\,\bar{b}\,W^+\,W^-$$

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

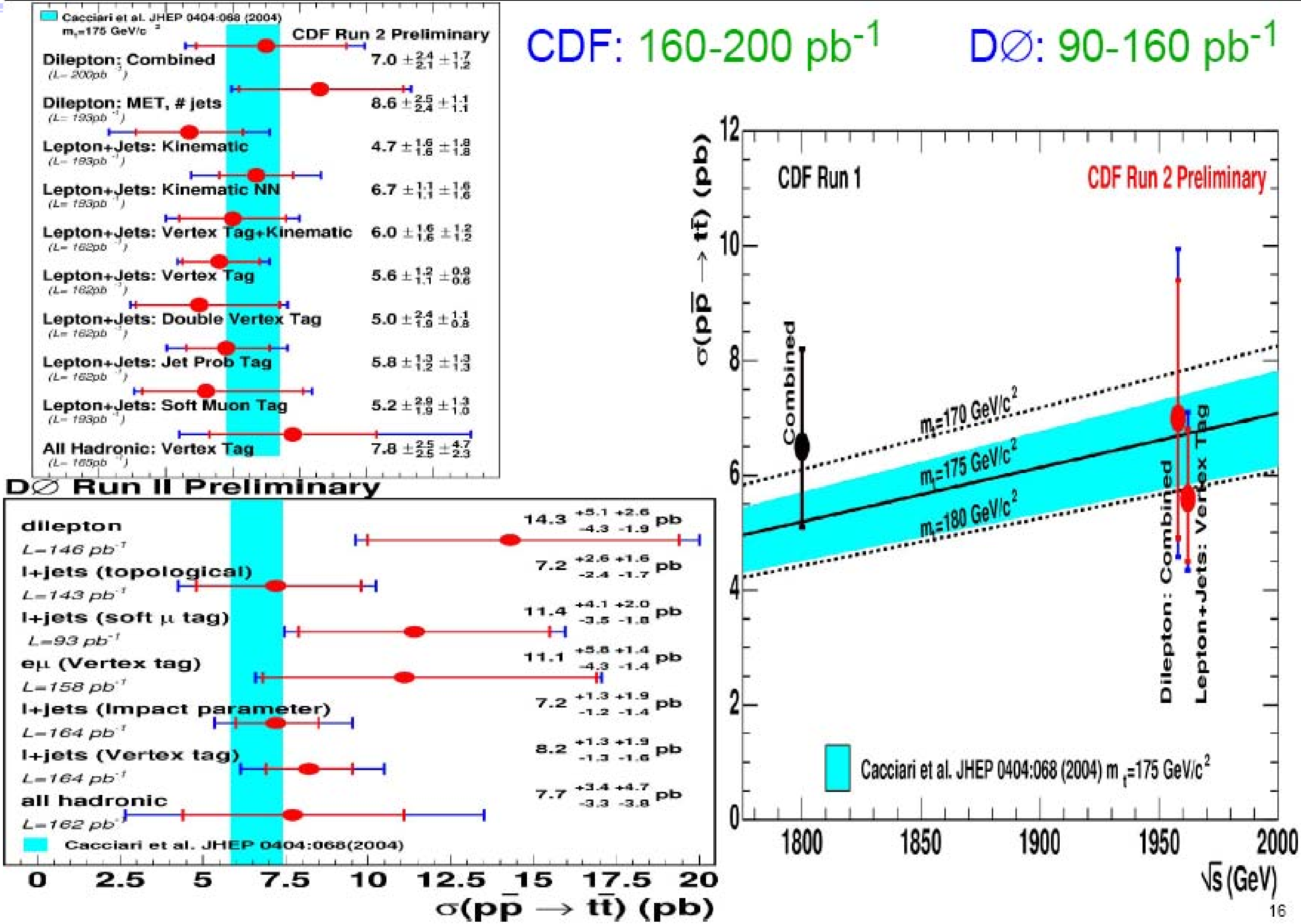


gluon fusion (15%)

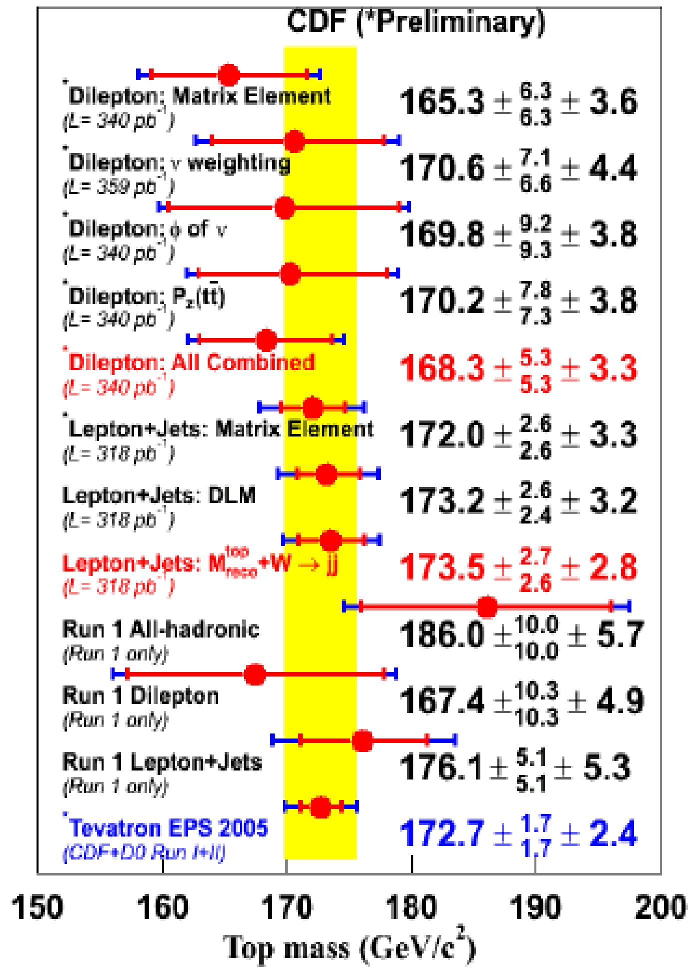


Top-Pair Cross Section

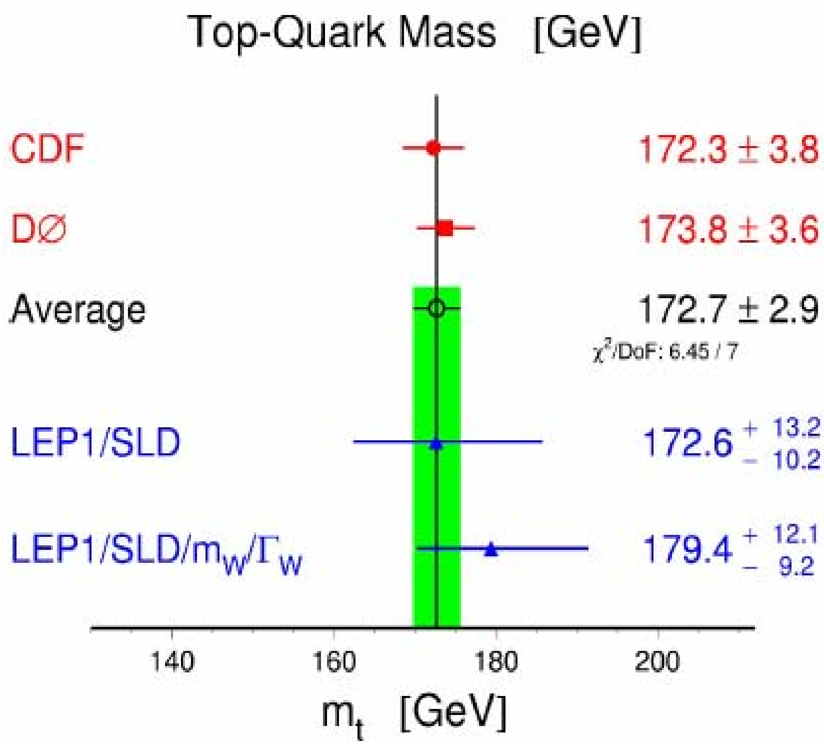
CDF: 160-200 pb^{-1} DØ: 90-160 pb^{-1}

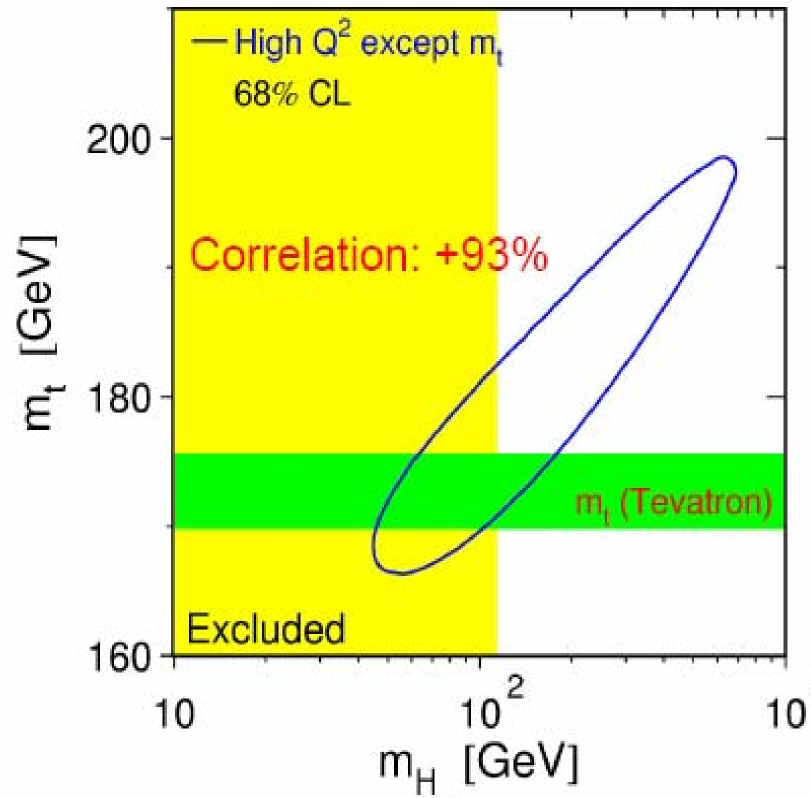


Top Quark Mass Measured in Many Channels



Heavy Particle Masses: Top Quark



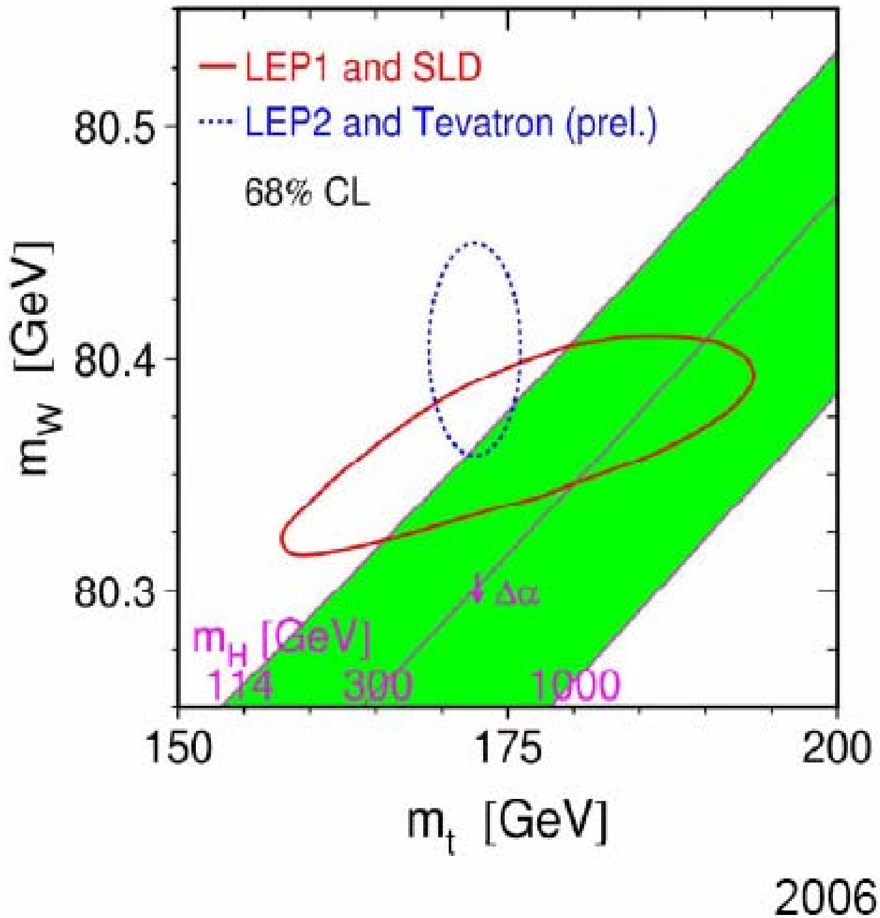


Predicted M_{top} in very good agreement with measurement

Measured M_{top} more than 3 times as precise as prediction

Top Quark mass pins down Higgs Mass

- Data prefer a light Higgs



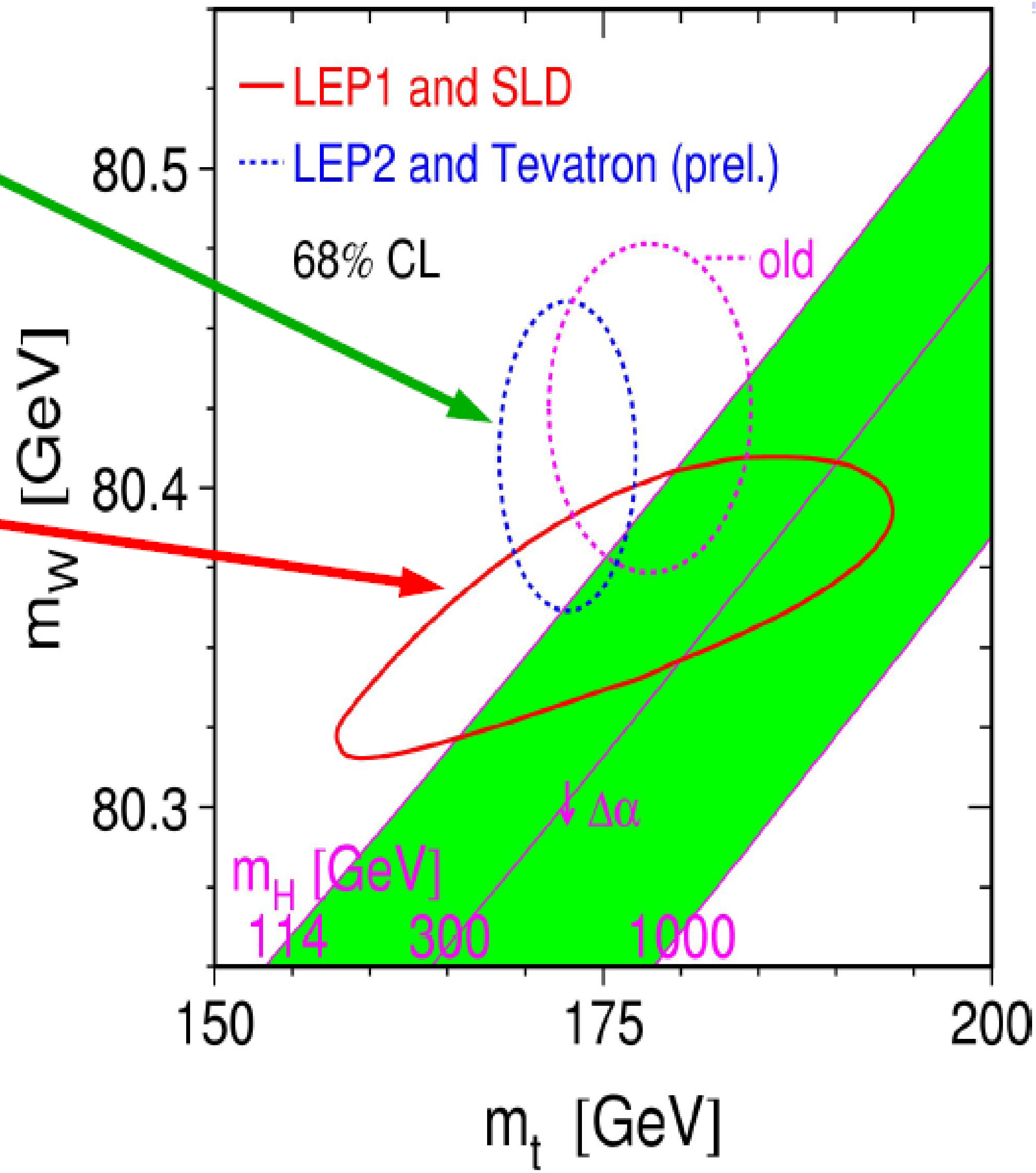
Heavy Particle Masses W and Top

Direct measurements:
  LEP2 and Tevatron

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

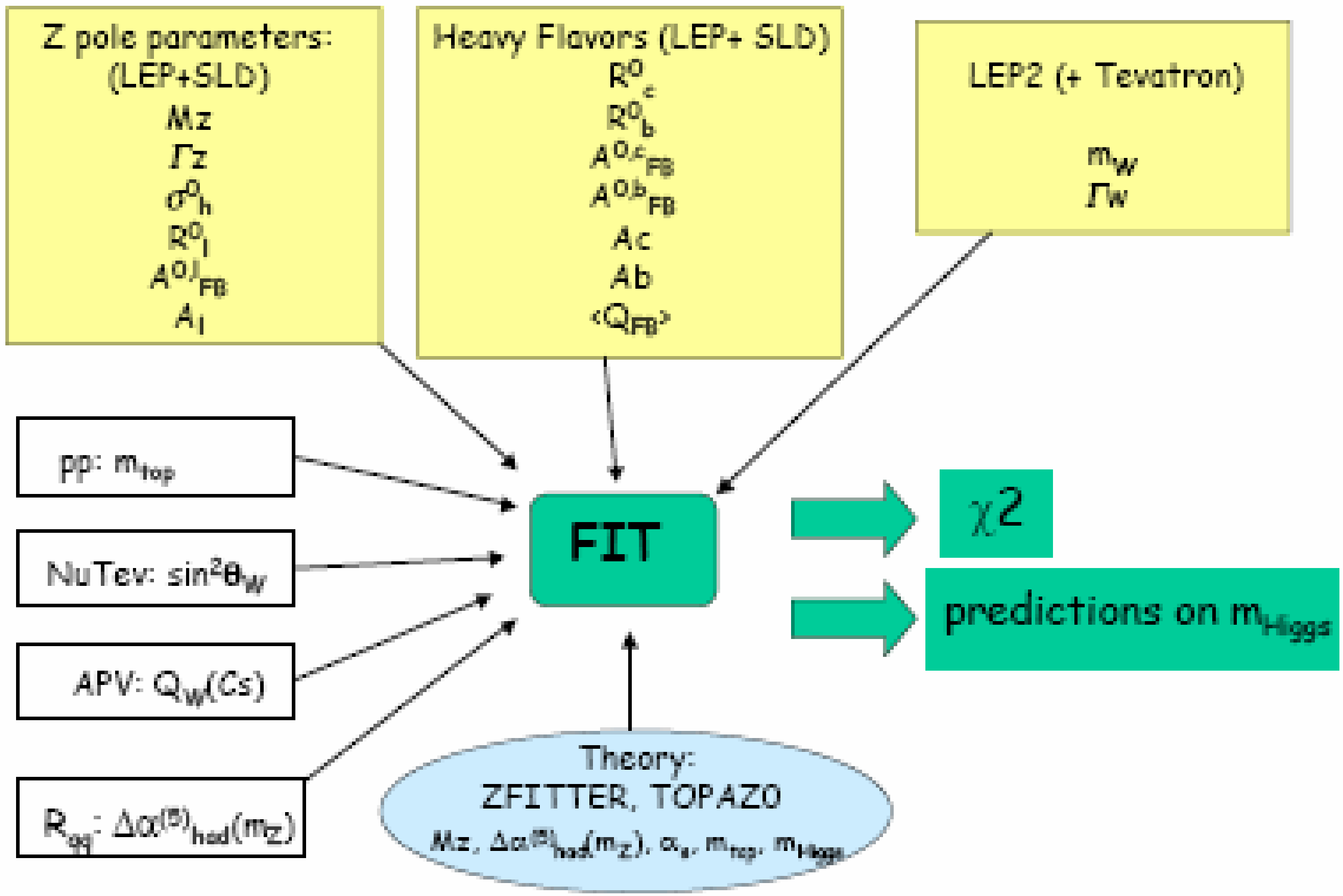
Good agreement:
  Successful SM test

Both data sets prefer a light Higgs boson



SM Analysis and NuTev

Global electroweak fit



Global electroweak fit

NEW inputs:

- Γ_W direct meas. for the first time
- $A^{0,b}_{FB}$ $A^{0,c}_{FB}$ from LEP
- $\sin^2\theta_W$ from NuTev final result (see talk by K.McFarland) hep-ph/0111059, Phys.Rev.Lett. 88 (2002)
- $Q_W(Cs)$ from APV hep-ph/0111019

χ^2/NDF=28.8/15 Prob.=1.7%

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]

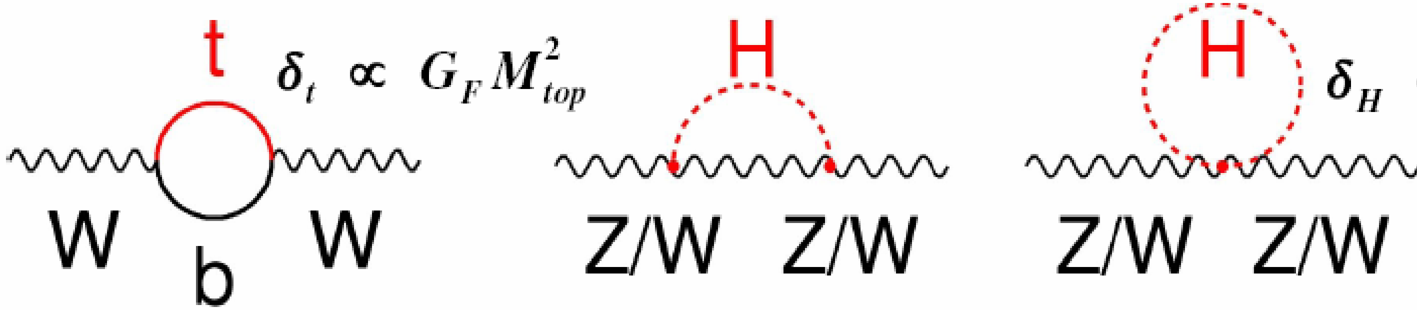
$\alpha_s(M_Z)$: given by Γ_{had} and related observables

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

Standard Model Analysis

Fit results:

$\Delta\alpha_{had}$	=	0.02767 ± 0.00034
$\alpha_s(M_Z)$	=	0.1186 ± 0.0027
M_Z	=	91.1874 ± 0.0021 GeV
M_{top}	=	173.3 ± 2.7 GeV
$\log_{10}M_H$	=	1.96 ± 0.18

$M_{Higgs} = 91^{+45}_{-32}$ GeV

$\Delta\alpha_{had}$ marginally improved

$\alpha_s(M_Z)$ one of the best

M_Z ~ unchanged

M_{top} error improved by few %

Correlations:

0.01			
-0.01	-0.02		
-0.02	0.05	-0.03	
-0.51	0.11	0.07	**0.52**

Strong correlations with:

fitted $\Delta\alpha_{had}$ - reduced to -0.20 with pQCD $\Delta\alpha_{had}$

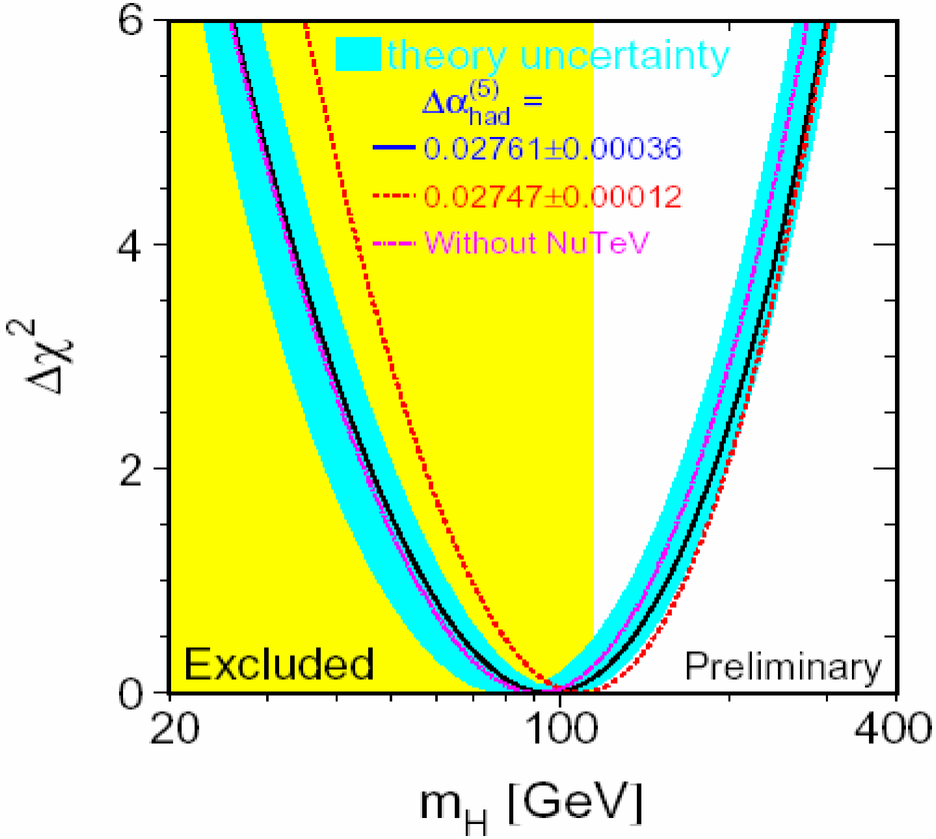
fitted M_{top} - 20 % shift in M_{Higgs} for 3 GeV shift in meas. M_{top}

M_{top} measurement crucial!

Higgs limit

Fit to all data:

- dark-blue: ZFITTER 6.36
- one-sided 95 % CL limit at
  $\Delta\chi^2 = 2.69$ (1.64 σ)
- light-blue band: syst. theory error
- dashed magenta: without NuTeV
  small effect: limit ~15 GeV lower
- dashed red: theory-driven $\alpha(m_Z)$
  curve shifted, smaller error, limit almost unchanged



$m_{\mathrm{H}} = 96^{+60}_{-38}\,\mathrm{GeV}$

$m_{\mathrm{H}} < 219\,\mathrm{GeV}$ @ 95 %CL (1-sided)

Standard Model Analysis

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

Incl. theory uncertainty:

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

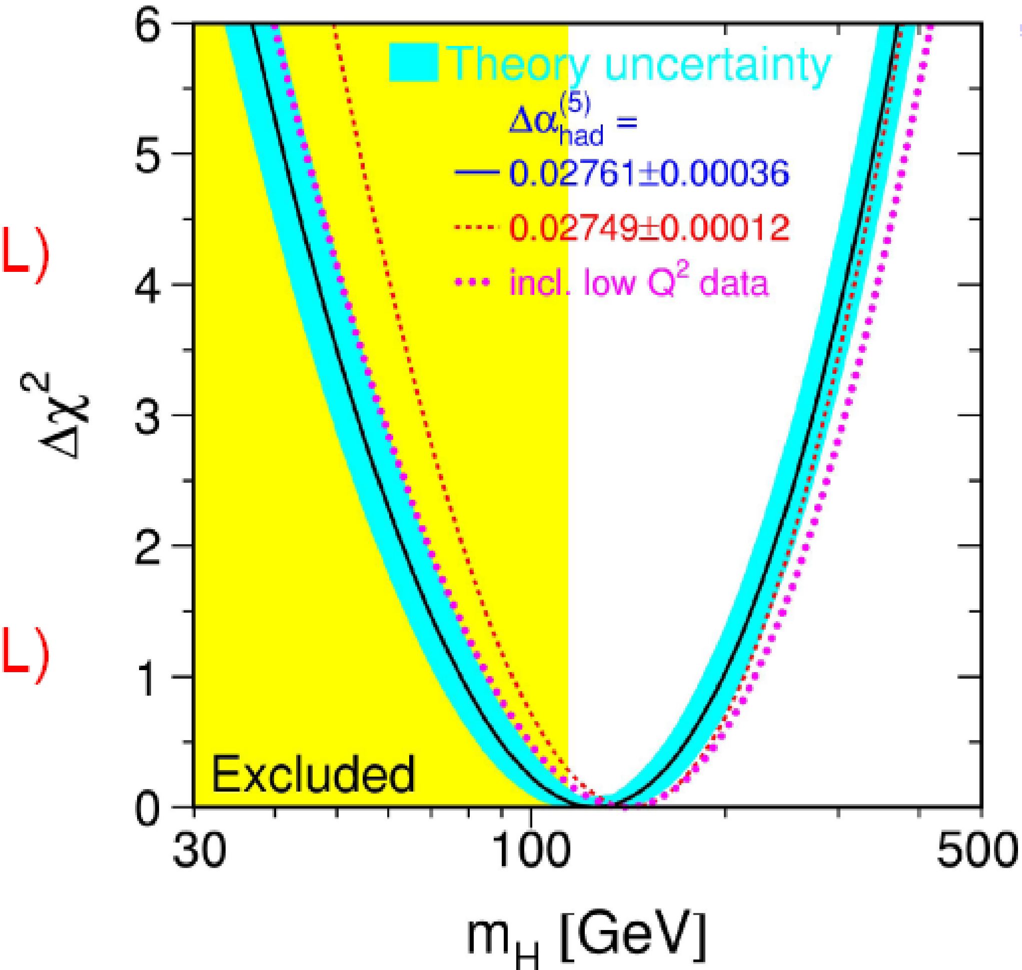
does not include:

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)

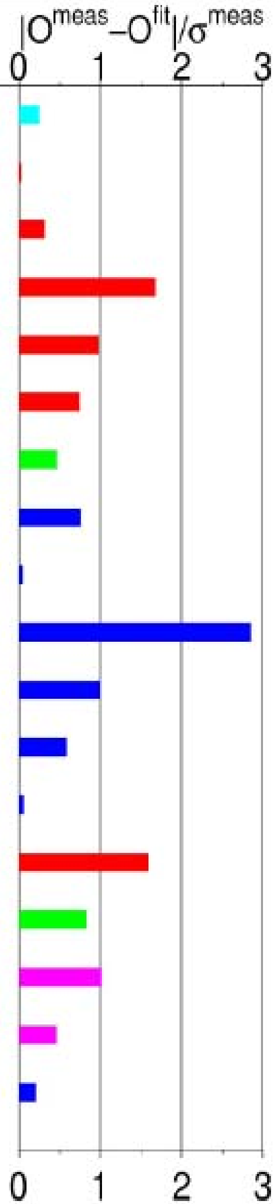


Theory uncertainty:

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

Standard Model Analysis

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3



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

χ^2/ndof = 18.6/13 (13.6%)

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:

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

20

Predictions for Low-Q^2 Measurements

Electron-nucleus atomic parity violation (APV) in atomic transitions:

Parity-violating t-channel contribution due to γ/Z interference

Weak charge Q_W of the nucleus (Z protons, N neutrons)

$$Q_W(Z,N) = -2\,[\,(2Z+N)C_{1u} + (Z+2N)C_{1d}\,]$$

with $C_{1q} = 2g_{Ae}g_{Vq}$ at $Q^2 \rightarrow 0$ (q=u,d)

$Q_W(Cs) = -72.74 \pm 0.46$ SM fit: -72.91 ± 0.03 ✔

Møller scattering (e^-e^-) with polarised e^- beam (E-158 experiment):

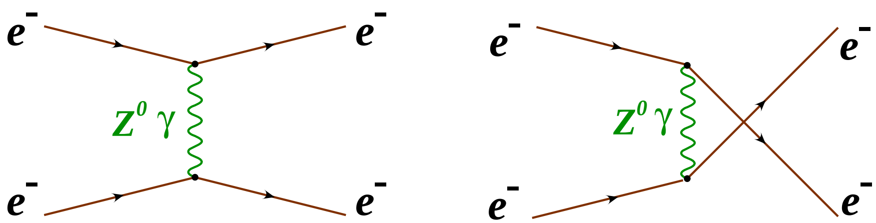
Parity-violating t-channel contribution due to γ/Z interference

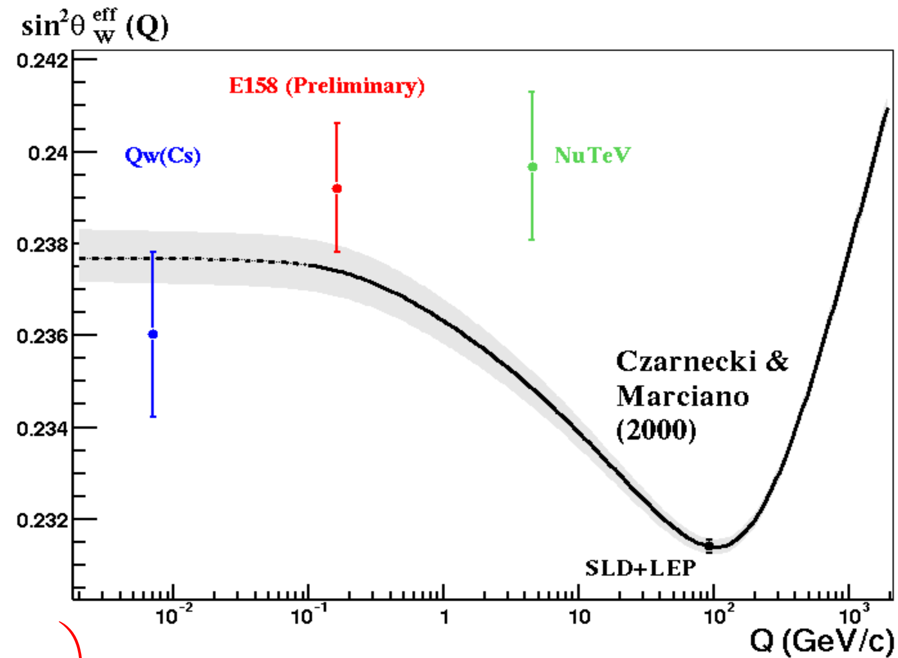
$A_{PV} = (\sigma_R-\sigma_L)/(\sigma_R+\sigma_L) \propto Q_W(e^-) = -4g_{Ae}g_{Ve}$ at $Q^2 \sim 0.03\ GeV^2$

$\sin^2\Theta_{eff}(Q=M_Z) = 0.2333 \pm 0.0015$ SM fit: 0.2314 ± 0.0001 ✔

$\sin^2\theta_{eff}$ at low Q^2 (E-158)

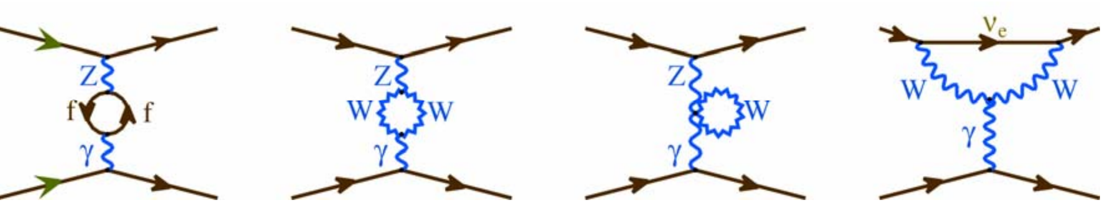
Møller scattering :





Scatter polarized (up to 80%) 50 GeV electrons off unpolarized atomic electrons, and measure the asymmetry

$$A_{ee} = mE \frac{\rho G_F}{\sqrt{2}\pi\alpha} \frac{16\sin^2\theta}{(3+\cos^2\theta)^2} \left(\frac{1}{4} - \kappa(Q^2)\sin^2\theta_W \right) + \ldots$$



$\sin^2\theta_{eff}(Q^2=0.026\ \mathrm{GeV}^2)$ =
0.2403±0.0010 (stat)±0.0009 (syst)
(Run I + II + III, preliminary)

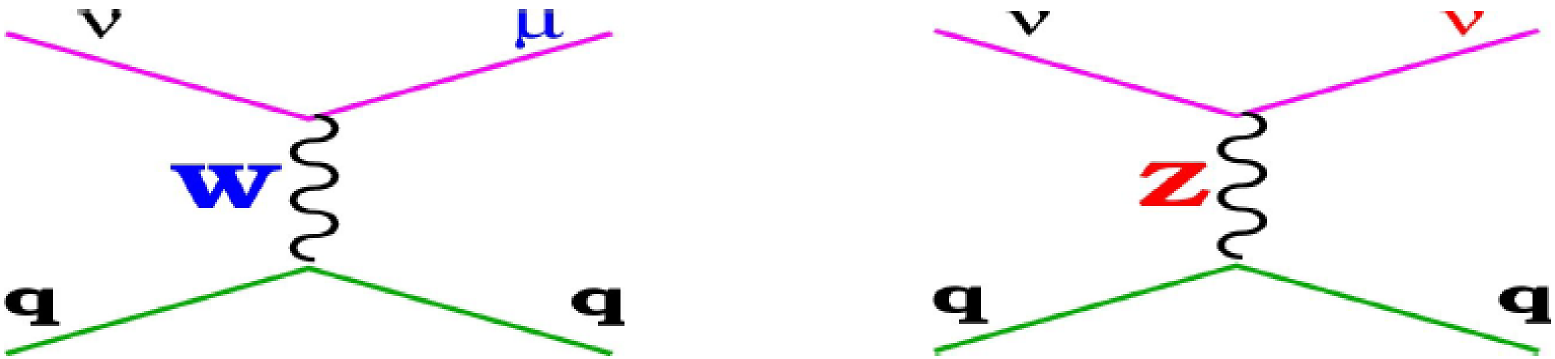
$$\frac{\kappa(Q^2=0.026)}{\kappa(m_Z)} = 1.038 \pm 0.006$$

However, $\kappa(Q^2)$ completely dominated by $\Delta\alpha(Q^2)$, hence mostly sensitive to new physics at born level (eg. Z', LFV, Contact Interactions, …)

NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC) neutral current (NC)



Paschos-Wolfenstein relation (iso-scalar target):

$$R_{-} = \frac{\sigma_{NC}(\nu)-\sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu)-\sigma_{CC}(\bar{\nu})} = 4g_{L\nu}^{2}\sum_{q_\nu}\left[g_{Lq}^{2}-g_{Rq}^{2}\right] = \rho_\nu\rho_{ud}\left[\frac{1}{2}-\sin^2\theta_W^{(on-shell)}\right]$$

+ electroweak radiative corrections

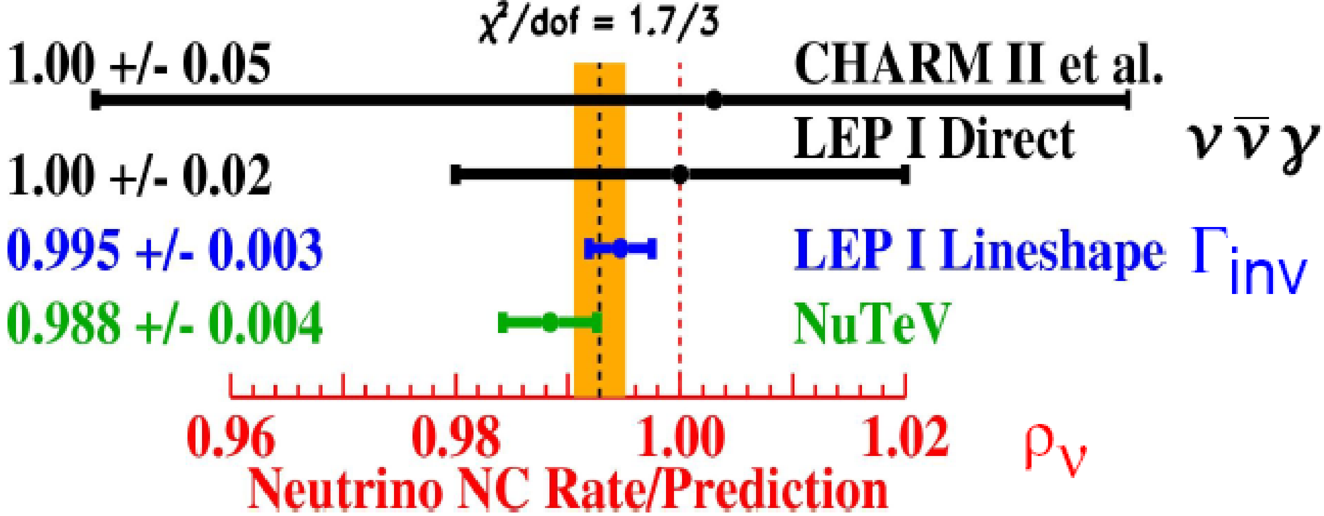
Effective couplings: g_L, g_R at $<Q^2> \sim 20\ GeV^2$

Historically result quoted in terms of: $\sin^2\Theta_W = 1-(M_W/M_Z)^2$

Factor two more precise than previous νN world average

NuTeV's Result

Strength of ν coupling ρ_ν (assuming $\sin^2\Theta_W$ ok):



Various explanations:

New physics:

Z', contact interactions, lepto-quarks, new fermions, neutrino oscillations, . . .

But likely rather old physics:

Theory uncertainty (QED, LO PDFs)

Isospin violating PDFs, sea asymmetry

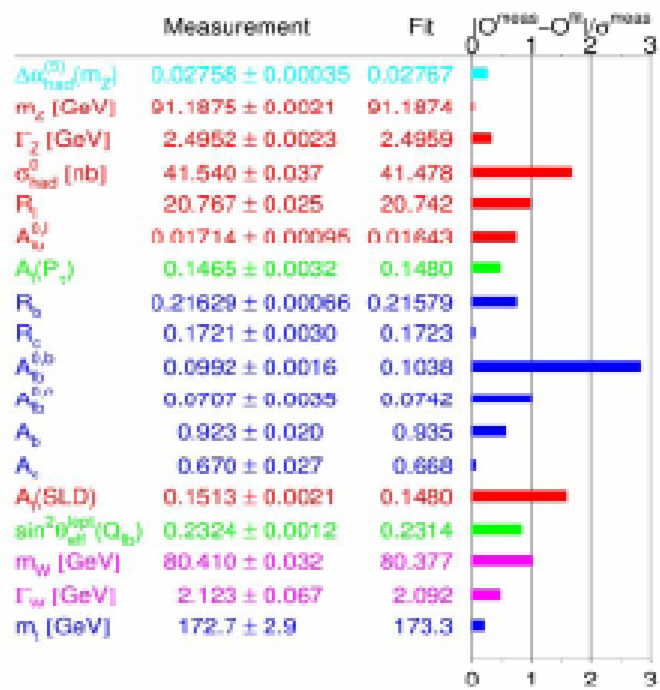
Conclusions and future prospects

Electroweak Theory is Precision Theory

2005

We have a model….
And it works to the 1% level

Gives us confidence to predict the future!



- The standard model of ElectroWeak interactions describes all precision measurements, O(0.1%). The precision is such that one needs to add the EW radiative corrections sensitive to heavy particles:

$$m_{top} = 172.7 \pm 2.9 \text{ GeV}$$

$$m_{Higgs} = 126^{+73}_{-48} \text{ GeV}$$

$$m_{Higgs} < 280 \text{ GeV} \quad @95\% \text{ c.l.}$$

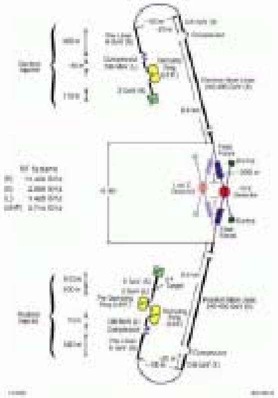
- Any improvement on this indirect determination of m_{Higgs} needs an improvement on the uncertainty on m_{Top}.

- The biggest discrepancy is on the interpretation of the ratio of NC and CC as measured by NuTeV as a determination of $\sin^2\theta_{eff}$. However this interpretation depends on theoretical uncertainties that must be reevaluated, before the 3σ discrepancy is taken at face value.
- The medium-term future is bright in our field. The EW precision measurements tells us that something has to happen at energy scales of O(1 TeV)… which happen to be the energy scale of LHC and $e^+ e^-$ linear colliders.

Science Timeline

Tevatron LHC LHC Upgrade ILC

2006 2007 2012

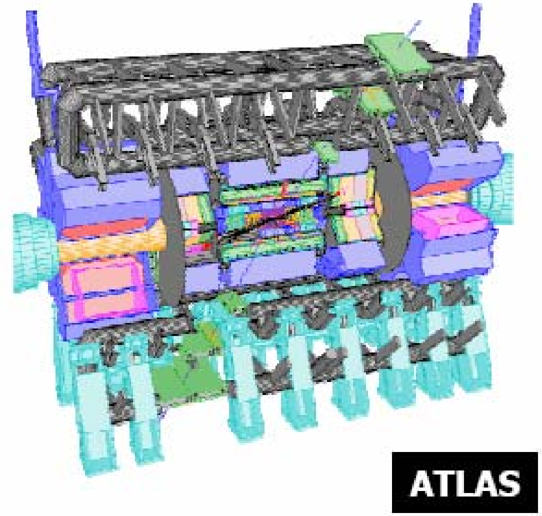


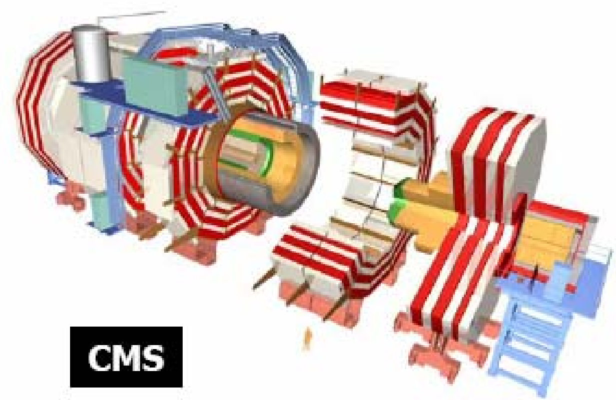
Large Hadron Collider (LHC)

- proton-proton collider at CERN (2007)
- 14 TeV energy
  - 7 mph slower than the speed of light
  - *cf.* 2TeV @ Fermilab

    (307 mph slower than the speed of light)
- Typical energy of quarks and gluons 1-2 TeV

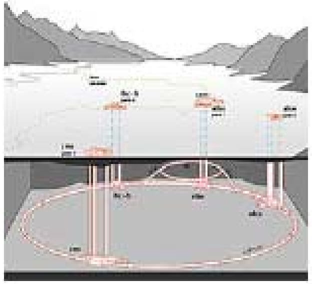
The Large Hadron Collider





LHC is Big….

- ATLAS is 100 meters underground, as deep as Big Ben is tall



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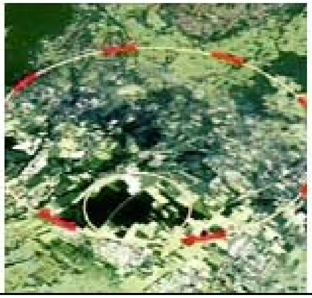
- The accelerator circumscribes 58 square kilometers, as large as the island of Manhattan



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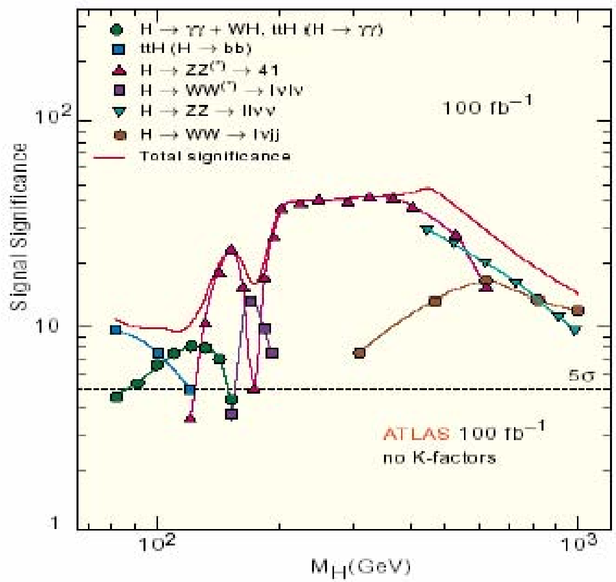
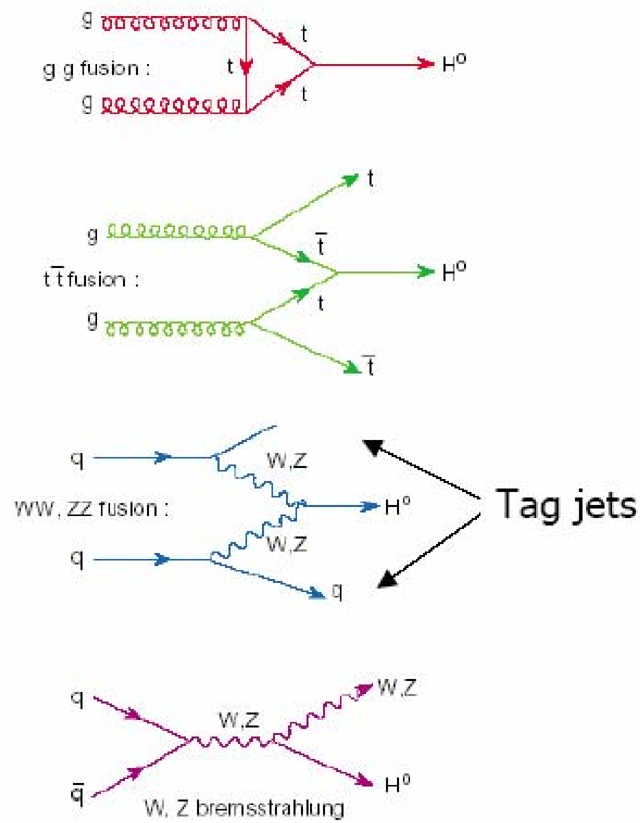
LHC Will Require Detectors of Unprecedented Scale

- CMS is 12,000 tons (2 x's ATLAS)
- ATLAS has 8 times the volume of CMS

Standard Model Higgs

- **Discovery for all possible masses**





Beyond discovery, we need to verify that the Higgs actually provides a) vector bosons and b) fermions with their masses

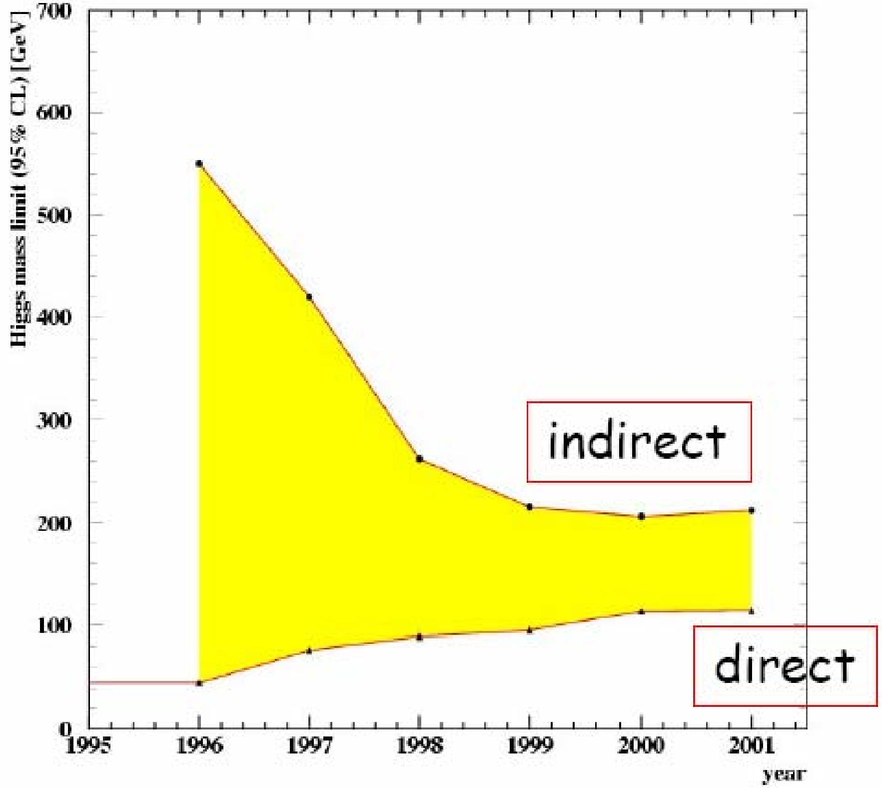
- **Measure various ratios of Higgs couplings and branching fractions by comparing rates in different processes**
  - **uncertainties ~ 25-30%**

- By 201x at the LHC, if all goes well
  - We will observe at least one and maybe several Higgs bosons
    - Test their properties at the 20% level
    - Not always able to differentiate SM from MSSM Higgs
      - But almost always expect to discover SUSY directly in other ways
  - Or we will observe some other signal of EWSB
    - Technicolor
    - Strong WW scattering
  - And we will know a lot more about physics at the TeV scale
    - SUSY?
    - Extra dimensions?

The next steps

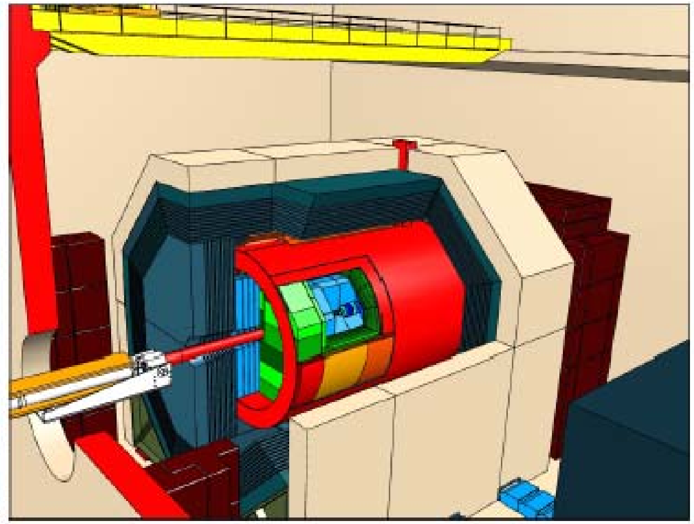
We know enough now to predict with great certainty that fundamental new understanding of how forces are related, and the way that mass is given to all particles, will be found with a Linear Collider operating at an energy of at least 500 GeV.

Experimental limits on the Higgs boson mass



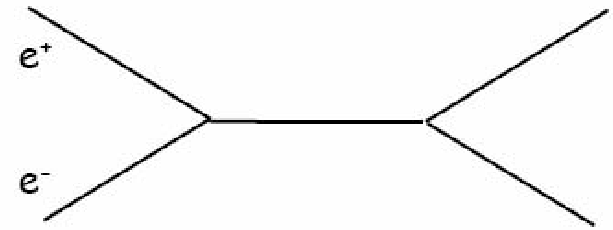
M_H between 114 and ~200 GeV

The Linear Collider



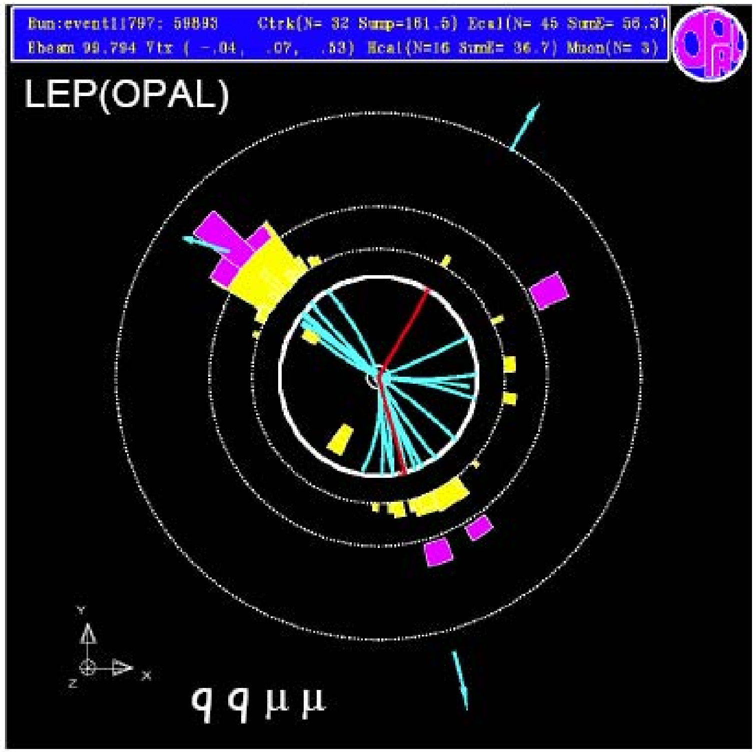
Highest priority new HEP facility
Costs $5-7B
Requires an international effort
Operation by 2015-2020?

The power of e^+e^- Colliders



Electron-Positron Linear Collider offers

- well defined initial state
  - collision energy $\sqrt{s}$ well defined
  - collision energy $\sqrt{s}$ tuneable
  - precise knowledge of quantum numbers
  - polarisation of e^- and e^+ possible
- Clean environment
  - collision of point-like particles
  - $\rightarrow$ low backgrounds
- precise knowledge of cross sections
- Additional options: e^-e^- , $e\gamma$, $\gamma\gamma$ collisions



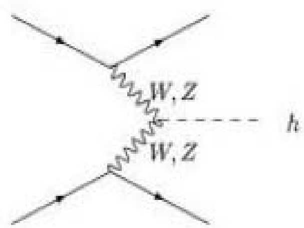
Machine for
Discoveries and Precision Measurements

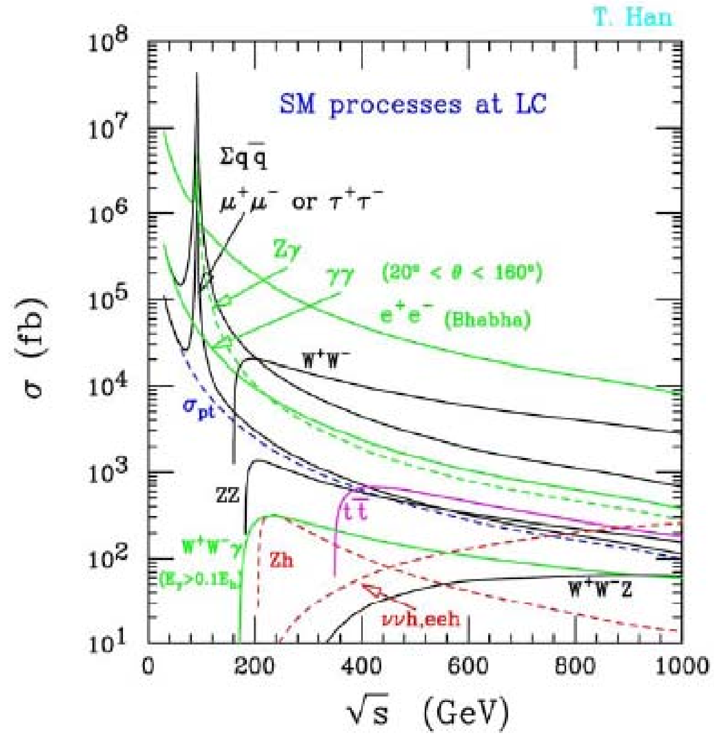
Generalities of e$^+$e$^-$ interactions

- 2→2 processes, $\sigma \approx 1/s$

$$\sigma(e^+e^- \to \gamma \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

- Vector boson fusion processes, $\sigma \approx 1/M_V^2 \log^2(s/M_V^2)$





T. Han, TASI05, hep-ph/0508097

Precision physics of Higgs-Bosons

Discovery and first measurements at the LHC (perhaps at Tevatron?)

The Higgs boson is a new form of matter
- a fundamental scalar
- a new force coupling to mass

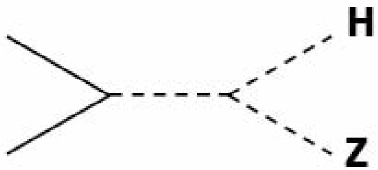
Therefore, need to establish Higgs mechanism as the mechanism responsible for
- giving mass to elementary particles
- breaking of the electroweak symmetry

Task of the Linear Collider:

Precision measurements to determine
mass(es)
quantum numbers (spin zero)
couplings (proportional to masses of bosons, quarks, leptons)
self-coupling ($\rightarrow$ reconstruction of Higgs potential)

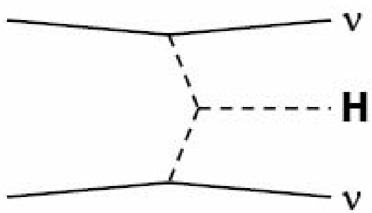
Higgs at a Linear Collider

- No longer about discovery; about precision
  - Plays the role that LEP did to the SPS for W/Z
- Exploit
  - Aggressive detector technology (charm tagging, calorimetry)
  - Polarization
- Higgs production at a LC:



For $\sqrt{s}$ = 500 GeV (few$\times$100fb^{-1} per year)

m_H = 120 GeV, $\sigma \sim$ 80fb
m_H = 240 GeV, $\sigma \sim$ 40fb
(cf. total $e^+e^- \rightarrow \bar{q}q$ cross section few pb)

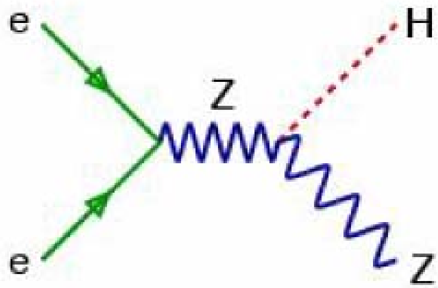


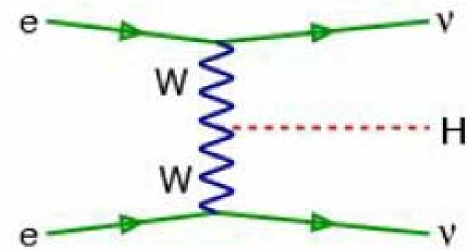
HZ process allows H reconstruction
in a model independent way (from Z)

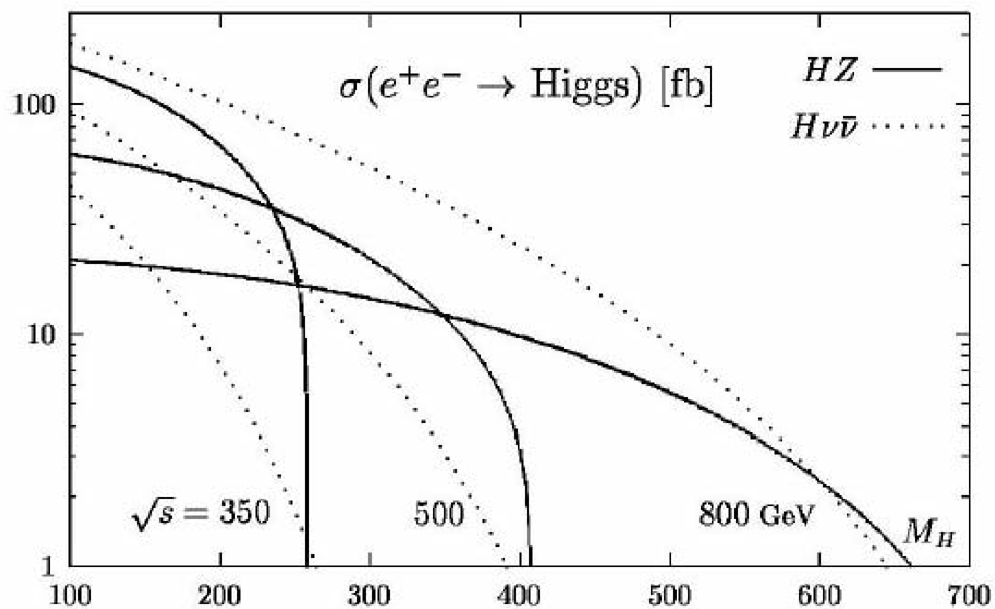
For an 800 GeV machine,
HZ is suppressed, H$\nu\nu$ dominant

Precision physics of Higgs bosons

Dominant production processes at LC:







Precision electroweak tests

high luminosity running at the Z-pole

Giga Z (10^9 Z/year) ≈ 1000 x “LEP” in 3 months

with e^- and e^+ polarisation

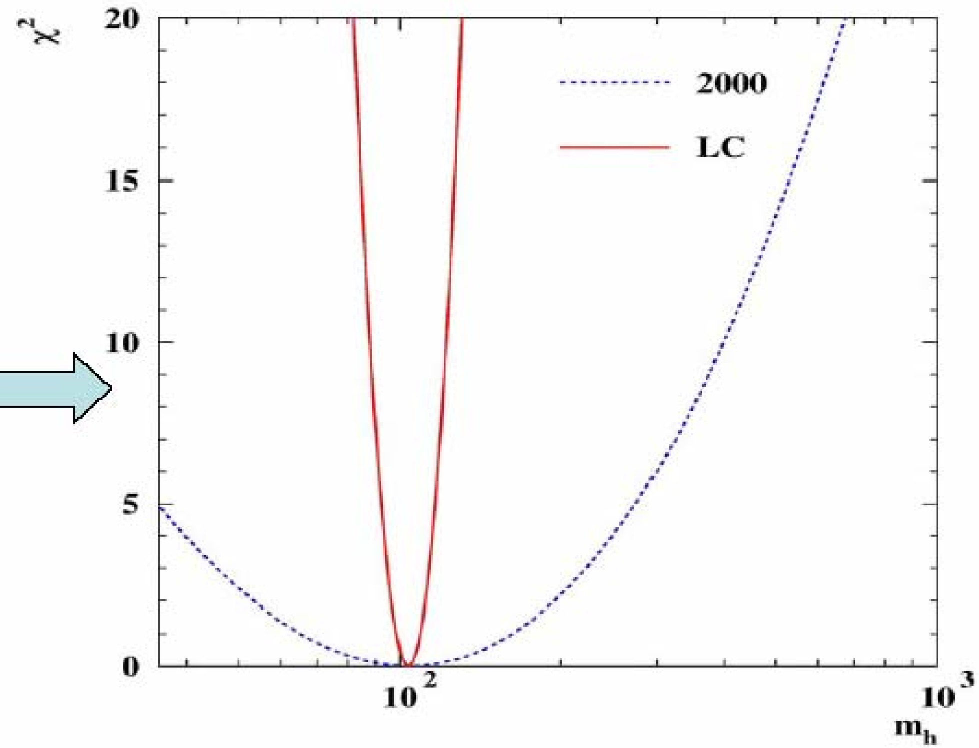
$\Delta \sin\Theta_W = 0.000013$

together with

$\Delta M_W = 7$ MeV
(threshold scan)

And

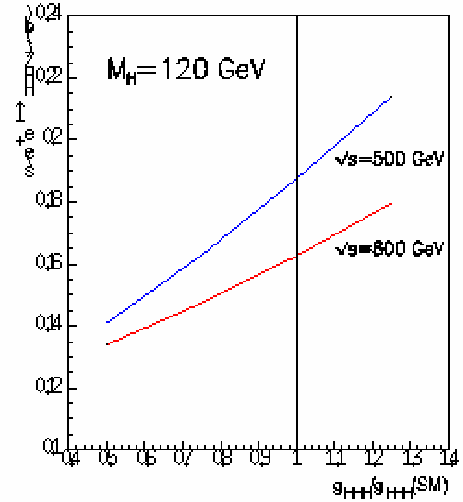
$\Delta M_{top} = 100$ MeV



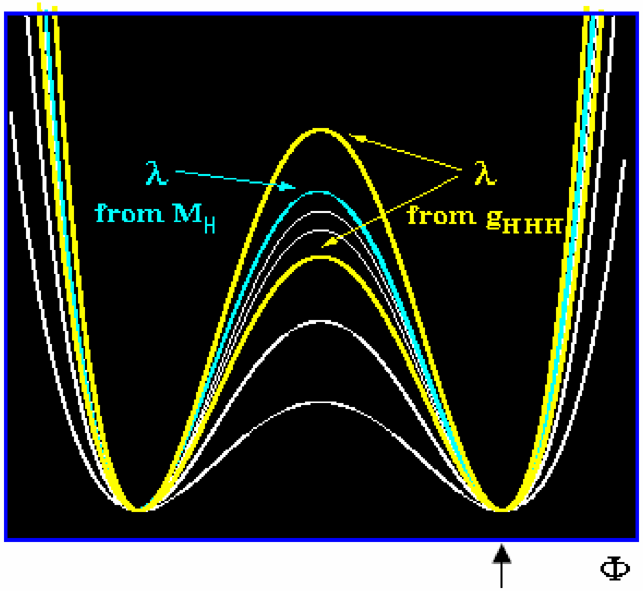
Higgs self-coupling

- Shape of the Higgs potential can be tested if the HHH coupling is determined
  - Extract from ZHH production (→ 6 jets)
  - Cross section tiny ~ 0.2 fb
    ⇒ requires O(1 ab^{-1})
  - g_{HHH} at the 20 - 30% level

$$e^+e^- \rightarrow HHZ$$



g/g(SM)



Precision physics of Higgs bosons

Conclusion

The precision measurements at the Linear Collider are crucial to establish the Higgs mechanism responsible for the origin of mass and for revealing the character of the Higgs boson

If the electroweak symmetry is broken in a more complicated way then foreseen in the Standard Model the LC measurements strongly constrain the alternative model