Electroweak measurements and interpretation
(mainly LEP, SLD and Tevatron)

- key aspects of the Electroweak theory
- important parameters to measure in the theory
- overview of the key experiments and analyses
- combining the measurements (Higgs boson constraints)
- interpretation of the results and outlook for the future

Jorgen D'Hondt
(Vrije Universiteit Brussel)

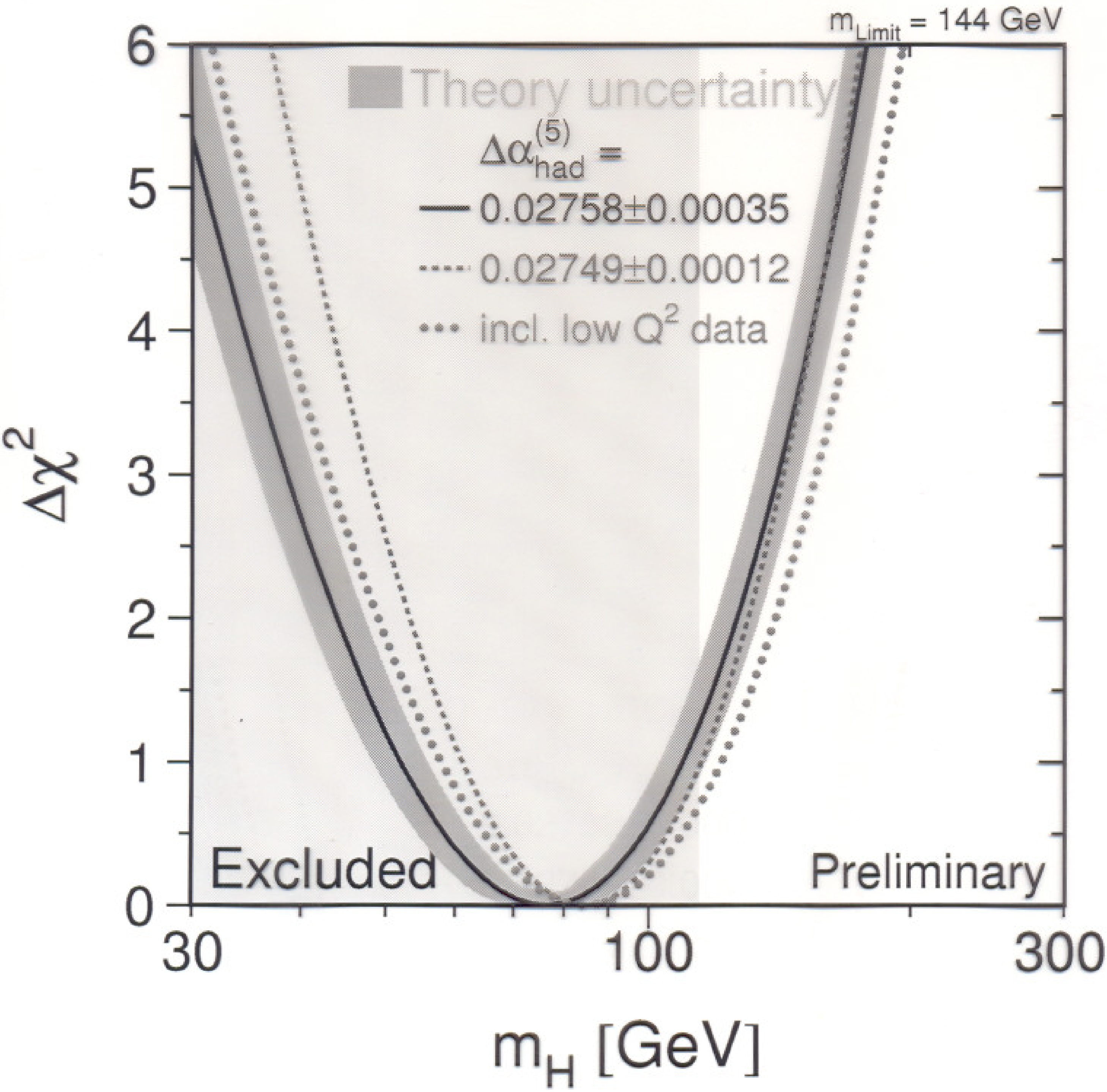
Belgian-Dutch-German Summer School – September, 2007

Who am I ?

- **DELPHI** (LEP) on WW physics (as PhD student)
  - measuring the W boson mass
  - phenomenological effects (soft-QCD)
  - tuning fragmentation parameters (hard versus soft QCD)
- **CMS** (LHC) on the building of the Tracker (as post-doc)
  - constructing and testing the silicon modules of the Tracker
- **CMS** (LHC) on top quark physics (as professor)
  - prepare analyses for top quark measurements at the LHC
  - jet reconstruction and calibration, b-tagging methods
  - currently the convenor of this effort in the CMS experiment
- for the future interest in experiments at the energy frontier (measurements and searches) and the link between cosmology/astro-particle physics and collision physics

AIM OF THESE LECTURES

WHAT GOES INTO THE HIGGS BLUEBAND PLOT OR TO LEARN SOMETHING ABOUT THE ELECTROWEAK FIT



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

MAIN REFERENCE

+ hep-ex/0509008

CERN-PH-EP/2006-042
LEPEWWG/2006-01
ALEPH 2006-001 PHYSICS 2006-001
DELPHI 2006-014 PHYS 948
L3 Note 2833
OPAL PR 419
hep-ex/0612034
14 December 2006

A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model

The LEP Collaborations[1] ALEPH, DELPHI, L3, OPAL, and the LEP Electroweak Working Group[2]

Prepared from Contributions of the LEP Experiments to the 2006 Summer Conferences.

[1]The LEP Collaborations each take responsibility for the preliminary results of their own experiment.

[2]WWW access at `http://www.cern.ch/LEPEWWG`

The members of the LEP Electroweak Working Group who contributed significantly to this note are:
J. Alcaraz, P. Azzurri, A. Bajo-Vaquero, E. Barberio, A. Blondel, D. Bourilkov, P. Checchia, R. Chierici, R. Clare, J. D'Hondt, B. de la Cruz, P. de Jong, G. Della Ricca, M. Dierckxsens, D. Duchesneau, G. Duckeck, M. Elsing, M.W. Grünewald, A. Gurtu, J.B. Hansen, R. Hawkings, St. Jezequel, R.W.L. Jones, T. Kawamoto, E. Lançon, W. Liebig, L. Malgeri, S. Mele, M.N. Minard, K. Mönig, C. Parkes, U. Parzefall, B. Pietrzyk, G. Quast, P. Renton, S. Riemann, K. Sachs, A. Straessner, D. Strom, R. Tenchini, F. Teubert, M.A. Thomson, S. Todorova-Nova, A. Valassi, A. Venturi, H. Voss, C.P. Ward, N.K. Watson, P.S. Wells, St. Wynhoff †.
† deceased.

1. The ElectroWeak Model

Very brief review

Family				T Weak-isospin	T_3 3° comp.	Q Charge
$\psi_i =$	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$1/2$	$+1/2$ $-1/2$	0 -1
	ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$	0	0	0
	e_R	μ_R	τ_R	0	0	-1
$\psi_i =$	$\begin{pmatrix}u\\ d\end{pmatrix}_L$	$\begin{pmatrix}c\\ s\end{pmatrix}_L$	$\begin{pmatrix}t\\ b\end{pmatrix}_L$	$1/2$	$+1/2$ $-1/2$	$+2/3$ $-1/3$
	u_R	c_R	t_R	0	0	$+2/3$
	d_R	s_R	b_R	0	0	$-1/3$

The weak isospin structure of the fermions with "L" left-handed and "R" right-handed.

→ as singlets.

→ transform as doublets under SU(2)

After spontaneous symmetry breaking:

$$\mathcal{L}_{\text{Fermions}} = \sum_i \bar{\psi}_i \left(i\partial\!\!\!/ - m_i - \frac{g\, m_i H}{2 M_W} \right) \psi_i$$

Charged current $\quad - \dfrac{g}{2\sqrt{2}} \displaystyle\sum_i \bar{\psi}_i \gamma^\mu (1-\gamma^5) \left(T^+ W_\mu^+ + T^- W_\mu^- \right) \psi_i$

QED $\quad - e \displaystyle\sum_i Q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu$

Neutral current $\quad - \dfrac{g}{2\cos\theta_W} \displaystyle\sum_i \bar{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu$

THIS MODEL LEADS TO RELATIONS BETWEEN SOME PARAMETERS (CFR. LECTURES ON EW THEORY)

$$G_F = \frac{\pi \alpha}{\sqrt{2}\, m_W^2 \sin^2\theta_W^{tree}} \quad \text{at tree level}$$

G_F : FERMI CONSTANT FROM MUON DECAY

α : ELECTROMAGNETIC FINE-STRUCTURE CONSTANT

m_W : W BOSON MASS

$\sin^2\theta_W^{tree}$: ELECTROWEAK MIXING ANGLE

RELATION BETWEEN CHARGE & NEUTRAL CURRENT:

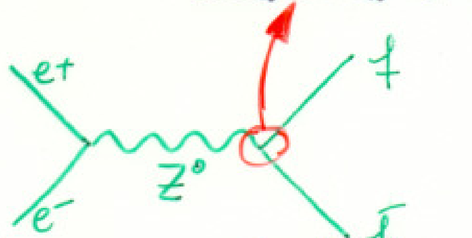
$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W^{tree}} \equiv 1 \quad \text{at tree level}$$

m_Z : Z BOSON MASS

THE INTERACTION OF THE Z BOSON WITH FERMIONS DEPENDS ON CHARGE Q AND T_3 :

$$\begin{cases} g_L^{tree} = \sqrt{\rho_0}\left(T_3^f - Q_f \sin^2\theta_W^{tree}\right) \\ g_R^{tree} = -\sqrt{\rho_0}\, Q_f \sin^2\theta_W^{tree} \end{cases}$$

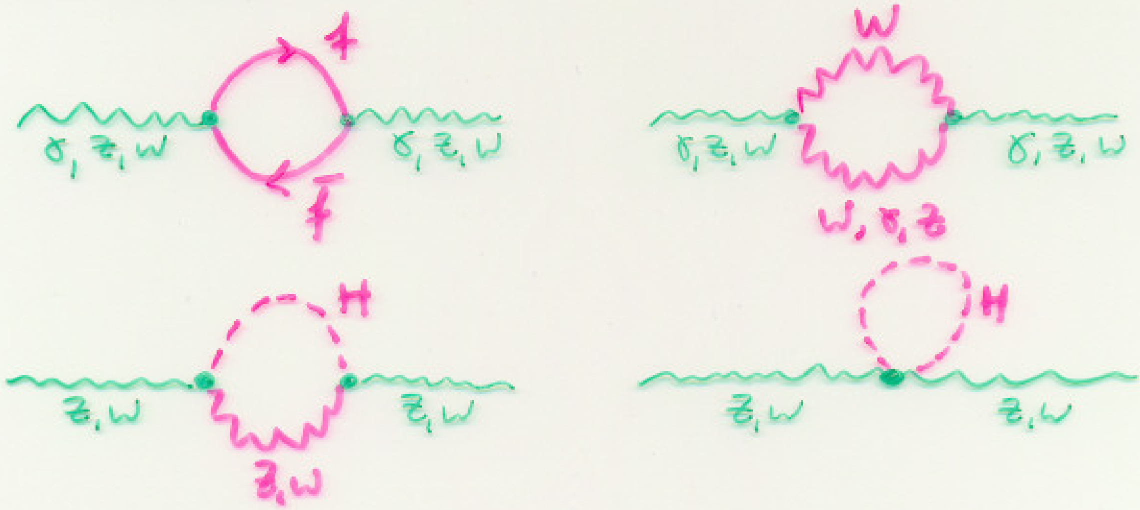
$$\frac{e}{\sin\theta_W \cos\theta_W}\, g^f$$



OR VECTOR vs. AXIAL-VECTOR

$$\begin{cases} g_V^{tree} \equiv g_L^{tree} + g_R^{tree} = \sqrt{\rho_0}\left(T_3^f - 2Q_f \sin^2\theta_W^{tree}\right) \\ g_A^{tree} \equiv g_L^{tree} - g_R^{tree} = \sqrt{\rho_0}\, T_3^f \end{cases}$$

THESE ARE TREE LEVEL QUANTITIES TO BE MODIFIED BY RADIATIVE CORRECTIONS TO PROPAGATORS AND VERTICES



THE VALUE OF $\sin^2\theta_W$ DEPENDS ON THE RENORMALIZATION PROCEDURE TO RENORMALIZE THESE CORRECTIONS $\rightsquigarrow$ "ON-SHELL" SCHEME

$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \equiv 1$$

TO ALL ORDERS IN PERTUBATION THEORY

AT TREE LEVEL THE EW THEORY DETERMINED BY THREE "INPUT" PARAMETERS

α, G_F, m_Z (with QCD also α_s)

WITH THE ABOVE LOOPS THE EW OBSERVABLES DEPEND ON

α, G_F, m_Z, m_{top}, m_{Higgs}

THE EW CORRECTIONS TO THE COUPLINGS ARE ABSORBED IN COMPLEX FORM FACTORS (AT THE Z-POLE)

$\Rightarrow$ effective couplings & $\sin^2\theta^f_{eff}$

ABSORBING EW CORRECTIONS TO COUPLINGS:

$$\begin{cases} g_{Vf} = \sqrt{\mathcal{R}_f}\left(T_3^f - 2\,Q_f\,\mathcal{K}_f\,\sin^2\theta_W\right) \\ g_{Af} = \sqrt{\mathcal{R}_f}\;T_3^f \end{cases}$$

$\mathcal{R}$ and $\mathcal{K}_f$ are complex form factors

$$\begin{cases} \mathcal{R}_f : \text{overal scale} \\ \mathcal{K}_f : \text{for the on-shell EW mixing angle} \end{cases}$$

IN TERMS OF THE REAL PARTS OF THESE FORM FACTORS THE EFFECTIVE EW MIXING ANGLE AND THE REAL EFFECTIVE COUPLINGS ARE DEFINED AS:

$$\begin{cases} \sin^2\theta_{eff}^f \equiv \kappa_f \sin^2\theta_W \\ g_{Vf} \equiv \sqrt{\rho_f}\left(T_3^f - 2\,Q_f\,\sin^2\theta_{eff}^f\right) \\ g_{Af} \equiv \sqrt{\rho_f}\;T_3^f \end{cases}$$

WITH

$$\rho_f \equiv \Re(\mathcal{R}_f) \qquad \kappa_f \equiv \Re(\mathcal{K}_f)$$

HENCE THE RATIO BECOMES

$$\frac{g_{Vf}}{g_{Af}} = \Re\left(\frac{g_{Vf}}{g_{Af}}\right) = 1 - 4\,|Q_f|\,\sin^2\theta_{eff}^f$$

THE CORRECTIONS ARE IN THE DEFINITION OF ρ_f AND κ_f:

$$\begin{cases} \rho_f = 1 + \Delta\rho_{se} + \Delta\rho_f \\ \kappa_f = 1 + \Delta\kappa_{se} + \Delta\kappa_f \end{cases}$$

→ flavour specific vertex corrections

→ universal corrections from the propagator self-energies

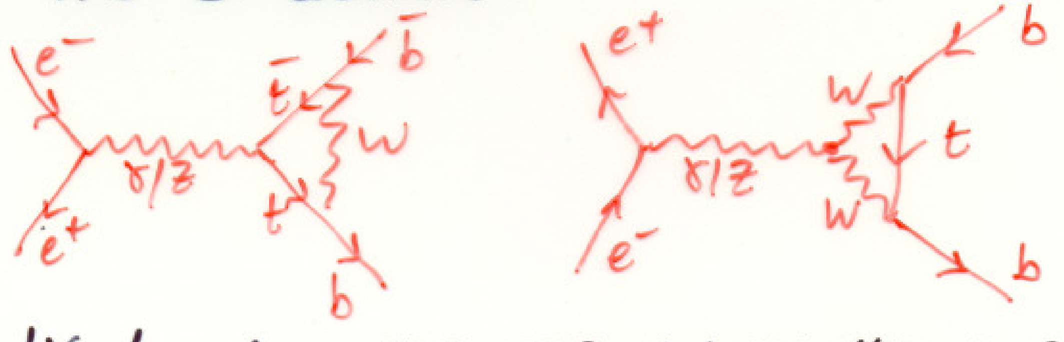
IN LEADING ORDER: for $m_H \gg m_W$

$$\Delta\rho_{se} = \frac{3 G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right]$$

$$\Delta\kappa_{se} = \frac{3 G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2}\,\frac{\cos^2\theta_W}{\sin^2\theta_W} - \frac{10}{9}\cdot\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right]$$

THE RADIATIVE CORRECTIONS HAVE A QUADRATIC DEPENDENCE ON m_t AND A WEAKER LOG DEPENDENCE ON m_H.

THE FLAVOUR DEPENDENCE IS VERY SMALL EXCEPT FOR THE b-QUARK.



AS $|V_{tb}| \approx 1$ THE TOP QUARK HAS A SIGNIFICANT CONTRIBUTION

$$\Delta\kappa_b = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} + \dots$$

$$\Delta\rho_b = -2\,\Delta\kappa_b + \dots$$

HENCE THE PARAMETER ρ IS MODIFIED BY LOOPS:

$$\rho = 1 + \Delta\rho$$

FROM THE PREVIOUS RELATIONS WE GET

$$\cos^2\theta_W \sin^2\theta_W = \frac{\pi\,\alpha(0)}{\sqrt{2}\, m_Z^2\, G_F} \cdot \frac{1}{1-\Delta r}$$ low mom. transfer

$$\cos^2\theta_{eff}^f \sin^2\theta_{eff}^f = \frac{\pi\,\alpha(0)}{\sqrt{2}\, m_Z^2\, G_F} \cdot \frac{1}{1-\Delta r^f}$$ at the Z-pole

WITH

$$\begin{cases} \Delta r = \Delta\alpha + \Delta r_W \\ \Delta r^f = \Delta\alpha + \Delta r_W^f \end{cases}$$

THE $\Delta\alpha$ TERM ARISES FROM THE RUNNING OF THE ELECTROMAGNETIC COUPLING DUE TO FERMION LOOPS IN THE PHOTON PROPAGATOR, USUALLY DIVIDED AS:

$$\Delta\alpha(s) = \underbrace{\Delta\alpha_{e\mu\tau}(s) + \Delta\alpha_{top}(s)}_{\text{precise calculations}} + \Delta\alpha_{had}^{(5)}(s)$$

FROM THE ANALYSIS OF LOW ENERGY e^+e^- DATA USING A DISPERSION RELATION

THE EFFECTS ARE ABSORBED AS

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)}$$

$$\alpha(0) = 1/137.036 \longrightarrow \alpha(m_Z) = 1/128.945$$

IN THE WEAK PART Δr_W THE VALUE OF $\Delta\rho$.
USUALLY G_F AND m_Z ARE BETTER MEASURED COMPARED TO m_W, HENCE ONE USUALLY CALCULATES m_W VIA G_F AND m_Z:

$$m_W^2 = \frac{m_Z^2}{2}\left(1 + 1 - 4\frac{\pi\alpha}{\sqrt{2}\, G_F\, m_Z^2}\cdot\frac{1}{1-\Delta r}\right) + \dots$$

$\Rightarrow$ THIS GIVES YOU A DEPENDENCY BETWEEN m_W, m_t, m_H ... AND PREVIOUS EQUATIONS BETWEEN $\sin^2\theta_W$, m_t, m_H, ...

ALL THE ABOVE IS IN LEADING ORDER TO ILLUSTRATE THE MAIN ELECTROWEAK RELATIONS. THE FULL CALCULATIONS AND SO-CALLED EW-FIT ARE PERFORMED TO HIGHER ORDER
(programs as TOPAZ0 and ZFITTER)

ALL TOGETHER:

- MEASURING COUPLINGS $\rightarrow$ SENSITIVE TO $\sin^2\theta_W$
- MEASURE m_W

$\Rightarrow$ THESE PARAMETERS ARE AT THE HEART OF THE ELECTROWEAK THEORY & SENSITIVE TO m_t & m_H VIA LOOP CORRECTIONS

THE ABOVE EQUATIONS PROVIDE THE BASIS FOR THE INTERPRETATIONS

... AT THE END OF LECTURE 2.

HENCE APART FROM OTHER FERMION MASSES AND MIXINGS, THE STANDARD MODEL HAS 3 FREE PARAMETERS : α, G_F, m_Z (+ m_H, m_t VIA LOOPS)

(i) • MEASURE eg. COUPLINGS PRECISELY $\Rightarrow \sin^2\theta_W$

(ii) • MEASURE THE "FREE" PARAMETERS PRECISELY (PREDICT eg. $\sin^2\theta_W$ & m_W)

↳ POSSIBLE SINCE THE PRECISE m_Z MEASUREMENT

• TEST CONSISTENCY BETWEEN eg. $\sin^2\theta_W$ BETWEEN (i) & (ii)

• CONSTRAIN UNMEASURED QUANTITY m_H

• FIND THE HIGGS BOSON ...

$\alpha = 1 / 137.03599911(46)$ (eg. magnetic moment $e^\pm$)

(defined at very low energy scales)

$\Downarrow$

run up to higher scales $\alpha = \alpha(M_Z)$

$G_F = 1.16637(1) \times 10^{-5}\ \text{GeV}^{-2}$ (muon life time)

$m_Z = 91.1876 \pm 0.0021\ \text{GeV}$ (lineshape)

$\Rightarrow$ $\boxed{\text{GET EXPERIMENTS WHICH CAN MEASURE OBSERVABLES SENSITIVE TO } \sin^2\theta_W \text{ \& } m_W \text{ WHICH IS ON HIS TURN SENSITIVE TO } m_H \text{ AND } m_t}$

$\Rightarrow$ LECTURE ① : $\sin^2\theta_W$ $\Rightarrow$ LEP I & SLC

LECTURE ② : m_W & m_t $\Rightarrow$ LEP II & Tevatron

(2). THE EXPERIMENTS FOR $\sin^2\theta_W$

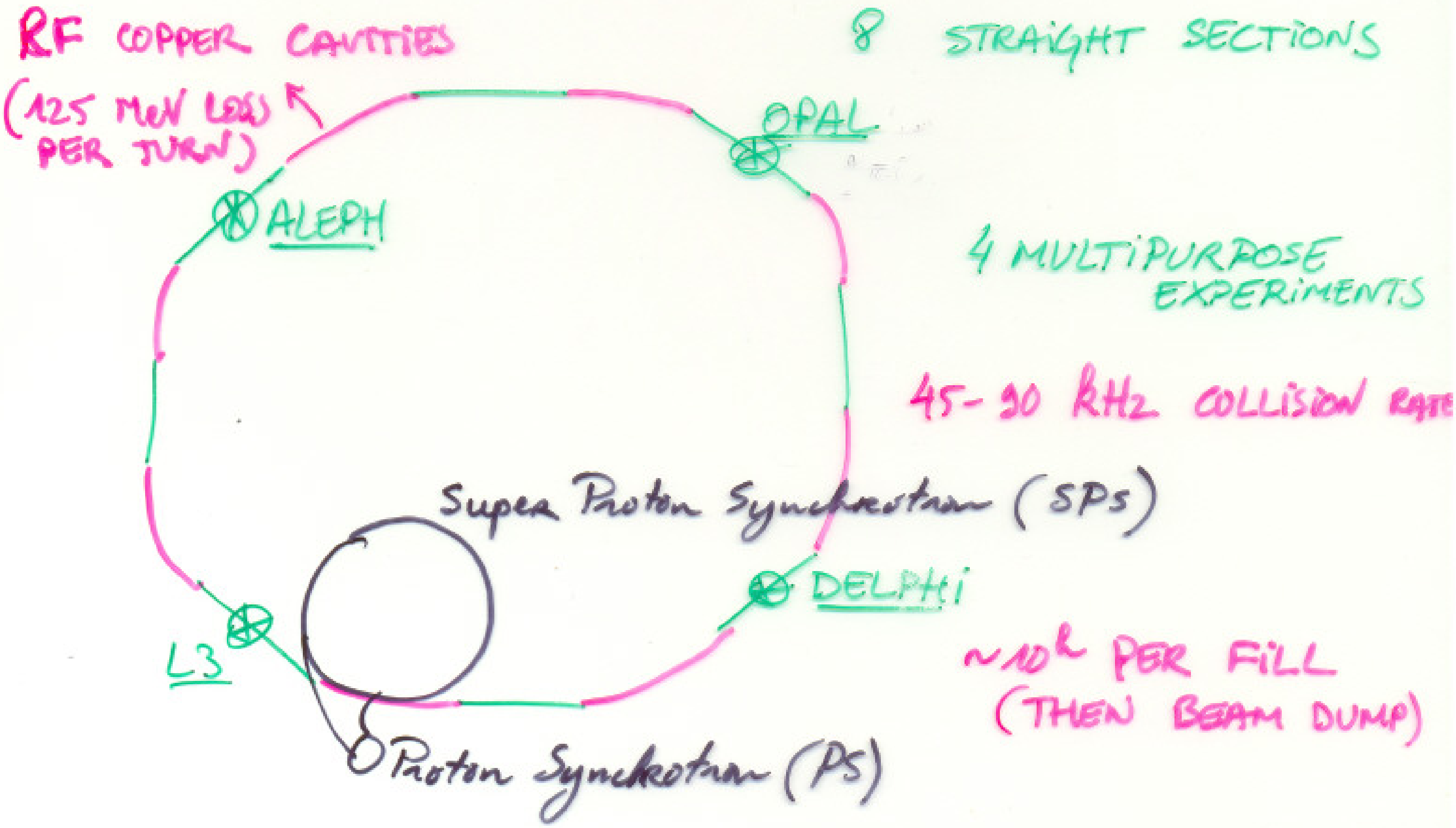
THE PROCESS UNDER STUDY IS $e^+e^- \to f\bar{f}$

TWO ACCELERATORS DESIGNED DURING THE 1980s TO ESTIMATE THE Z-POLE PARAMETERS WITH HIGH PRECISION: LEP & SLC

I. LEP: LARGE ELECTRON-POSITRON COLLIDER

(1989–2000)

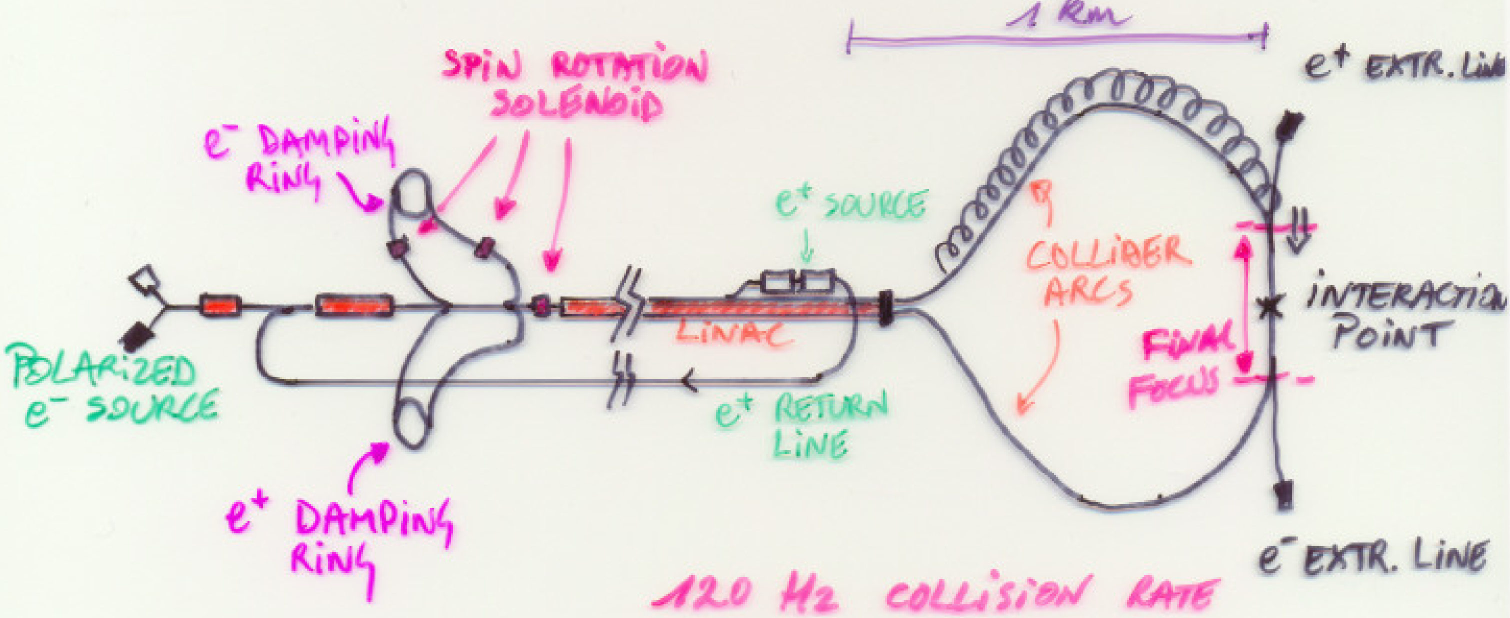
THE LARGEST PARTICLE ACCELERATOR IN THE WORLD WITH 27 km CIRCUMFERENCE.



AT PEAK LUMINOSITY ($2 \times 10^{31}\ cm^{-2}s^{-1}$) EACH EXPERIMENT COLLECTED ABOUT 1000 Z BOSONS EVERY HOUR.

II. STANFORD LINEAR COLLIDER @ SLAC

THE FIRST e^+e^- LINEAR COLLIDER OF 3.2 km LENGTH



DAMPING RINGS REDUCE THE SIZE & ENERGY SPREAD OF THE ELECTRON & POSITRON BUNCHES

- STARTS WITH 2 CLOSELY SPACED ELECTRON BUNCHES (1 LONGITUDINALLY POLARISED)
- STORED IN DAMPING RING AT 1.2 GeV
- BACK IN LINAC AT 30 GeV TO A TARGET FOR POSITRON CREATION (THEY GO BACK TO START AT 200 MeV AND GO TO DAMPING RING)
- SYNCHRONIZATION WITH SECOND 2-ELECTRON BUNCH START
- FINAL ENERGY OF 46.5 GeV (1 GeV LOST IN ARCS)
- ELECTRONS MANIPULATED TO GET LONGITUDINAL POLARISATION AT INTERACTION POINT

MAIN ADVANTAGE COMPARED TO LEP IS THE POLARIZATION (LOTS OF WORK TO KEEP POLARIZATION FROM SOURCE TO COLLISION)

CRUCIAL: MEASURE THE POLARIZATION
(PRECISION OF 0.5% ACHIEVED WHILE DESIGNED WAS 1%)
HEAD-ON COMPTON SCATTERING OF A POLARIZED HIGH-POWER LASER BEAM WITH THE ELECTRON BEAM

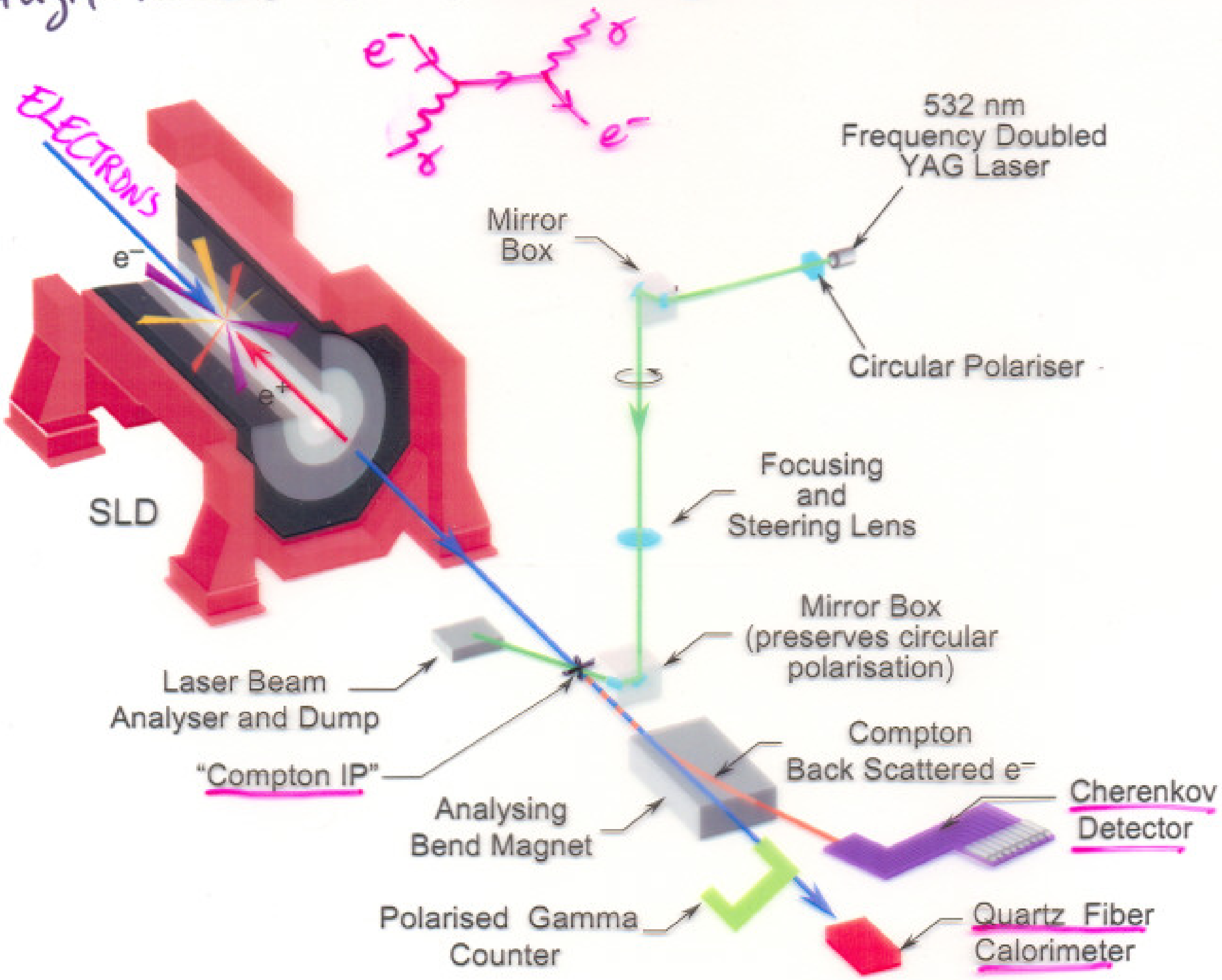


Figure 3.1: A conceptual diagram of the SLD Compton Polarimeter. The laser beam, consisting of 532 nm wavelength 8 ns pulses produced at 17 Hz and a peak power of typically 25 MW, were circularly polarised and transported into collision with the electron beam at a crossing angle of 10 mrad approximately 30 meters from the IP. Following the laser/electron-beam collision, the electrons and Compton-scattered photons, which are strongly boosted along the electron beam direction, continue downstream until analysing bend magnets deflect the Compton-scattered electrons into a transversely-segmented Cherenkov detector. The photons continue undeflected and are detected by a gamma counter (PGC) and a calorimeter (QFC) which are used to cross-check the polarimeter calibration.

HADRONIC CROSS SECTION VERSUS $\sqrt{s}$

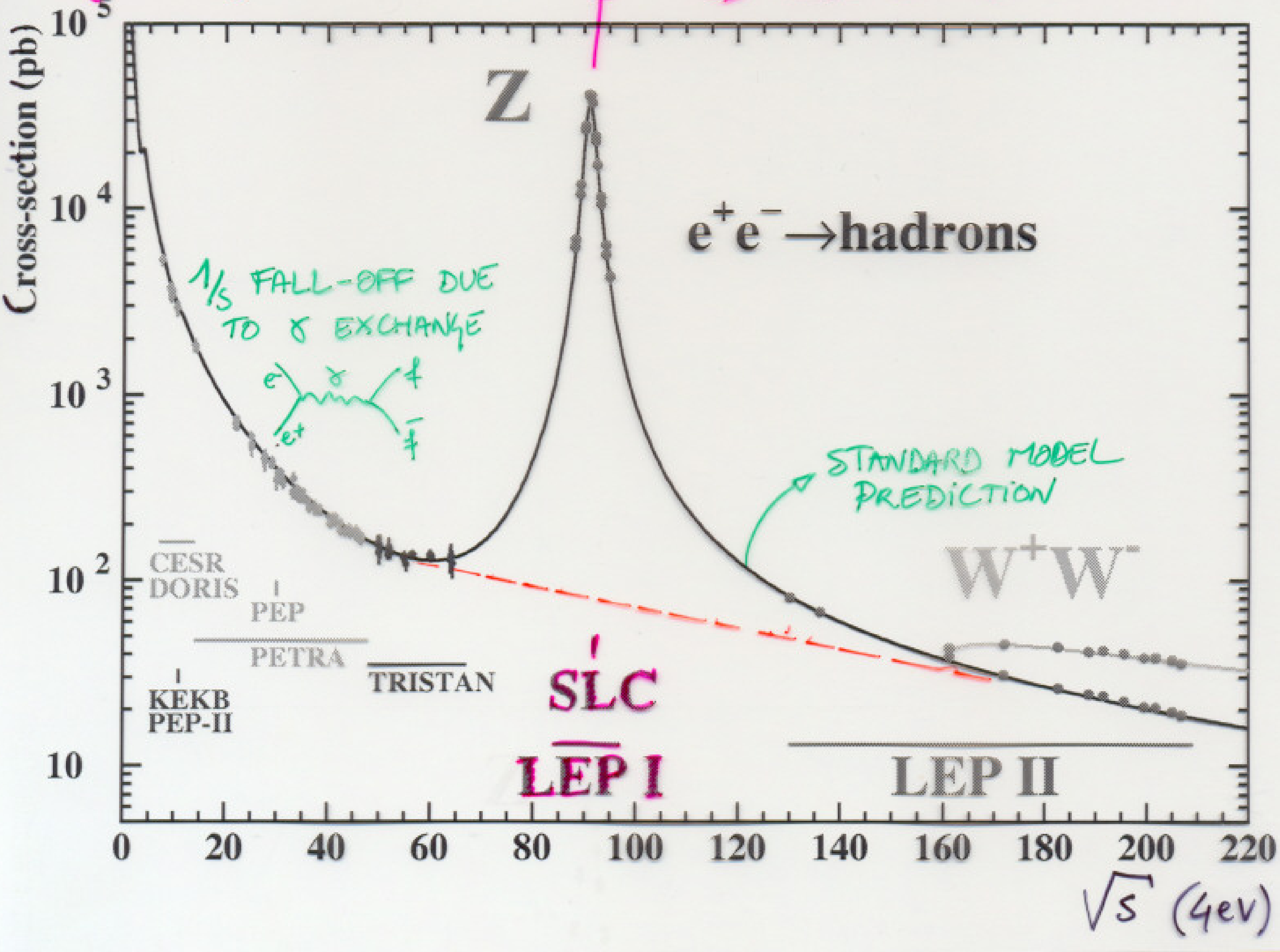
LEP : 1989 → 2000 $\sqrt{s} = m_Z \pm 3$ GeV → 17M Z^0

SLC : 1989 → 1998 → 0.6M Z^0
(with longitudinal polarization)

OPTIMAL ENERGY REGION TO STUDY THE $e^+e^- \to f\bar{f}$ PROCESSES

VERY HIGH CROSS SECTION
⇒ LOTS OF Z BOSONS

LOG-SCALE !



EXAMPLE OF THE ACHIEVEMENTS OF LEP & SLC

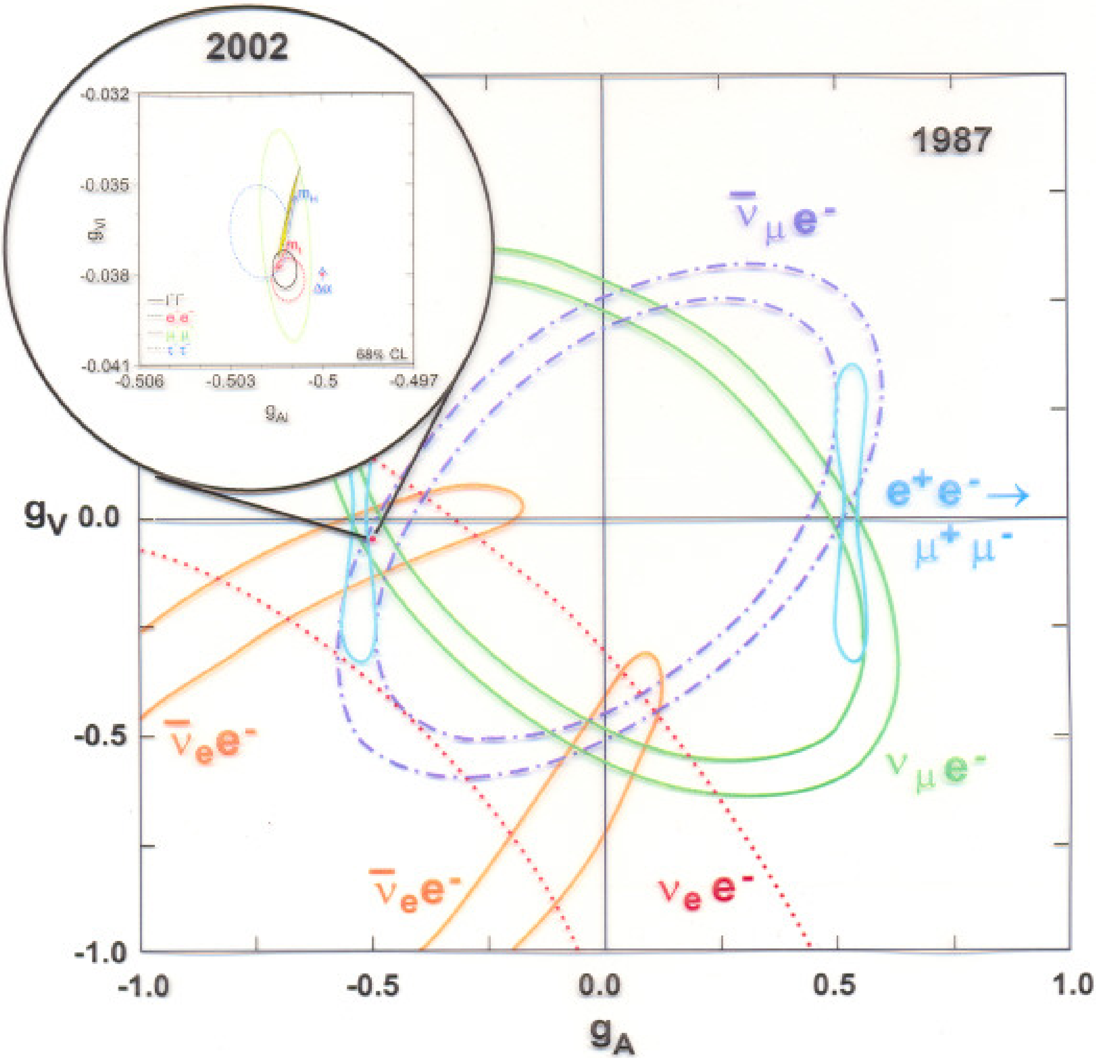


Figure 1.15: The neutrino scattering and e^+e^- annihilation data available in 1987 constrained the values of $g_{V\ell}$ and $g_{A\ell}$ to lie within broad bands, whose intersections helped establish the validity of the SM and were consistent with the hypothesis of lepton universality. The inset shows the results of the LEP/SLD measurements at a scale expanded by a factor of 65 (see Figure 7.3). The flavour-specific measurements demonstrate the universal nature of the lepton couplings unambiguously on a scale of approximately 0.001.

3. Basic Measurements

THE DETAILED DETECTORS AROUND THE COLLISION POINTS ARE ABLE TO MEASURE PRECISELY THE $e^+e^- \to \gamma/Z \to f\bar{f}$ PROCESS. ALSO THE FLAVOURS OF LEPTONS AND SOME QUARKS CAN BE DISTINGUISHED.

(NOT THE MAIN TOPIC OF THIS LECTURE)

- TOTAL CROSS-SECTIONS

$$\sigma = \frac{N_{sel} - N_{bck}}{\varepsilon_{sel} \cdot \mathcal{L}}$$

N_{bck} & ε_{sel} FROM SIMULATION

- CROSS-SECTION VERSUS $\sqrt{s}$

  NEEDED FOR Z BOSON MASS AND WIDTH

- RATIO OF CROSS-SECTIONS OF DIFFERENT DECAYS

  FOR PARTIAL WIDTHS & RELATIVE STRENGTH OF Z COUPLINGS

- ASYMMETRIES OF ANGULAR DISTRIBUTIONS

  MIXTURE OF VECTOR & AXIAL-VECTOR COUPLINGS

  → HERE THE POLARIZATION OF THE COLLIDING e^- AND e^+ CAN HELP

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

forward-backward asymmetry

(NEEDS 4π ACCEPTANCE, HENCE A_{FB} USUALLY FROM FITS ON ANGULAR DISTRIBATIONS)

⊗ $$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \cdot \frac{1}{\langle P_e \rangle}$$

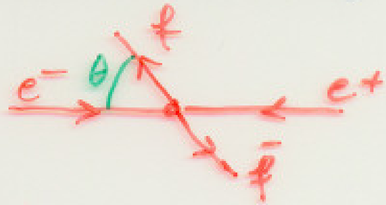
left-right asymmetry

DOES NOT NEED ACCEPTANCE

(N_L : #Z FOR LH e^- BUNCHES) ($\langle P_e \rangle$: MAGN. OF POLARISATION)

4. THE PROCESS $e^+e^- \to f\bar{f}$

DIFFERENTIAL CROSS-SECTION AROUND Z-POLE USING THE COMPLEX-VALUED EFFECTIVE COUPLING CONSTANTS



$$\frac{2s}{\pi} \frac{1}{N_c^f} \frac{d\sigma_{EW}}{d\cos\theta}(e^+e^- \to f\bar{f}) =$$

σ^γ

$$|\alpha(s)\, Q_f|^2 (1+\cos^2\theta)$$

γ-Z interference

$$- 8\, \Re\left\{ \alpha^*(s)\, Q_f\, \chi(s) \left[g_{Ve}\, g_{Vf} (1+\cos^2\theta) + 2\, g_{Ae} g_{Af} \cos\theta \right] \right\}$$

σ^Z

$$+ 16\, |\chi(s)|^2 \left[\left(|g_{Ve}|^2 + |g_{Ae}|^2 \right) \cdot \left(|g_{Vf}|^2 + |g_{Af}|^2 \right) \cdot (1+\cos^2\theta) + 8\, \Re\{ g_{Ve}\, g_{Ae}^* \}\, \Re\{ g_{Vf}\, g_{Af}^* \} \cos\theta \right]$$

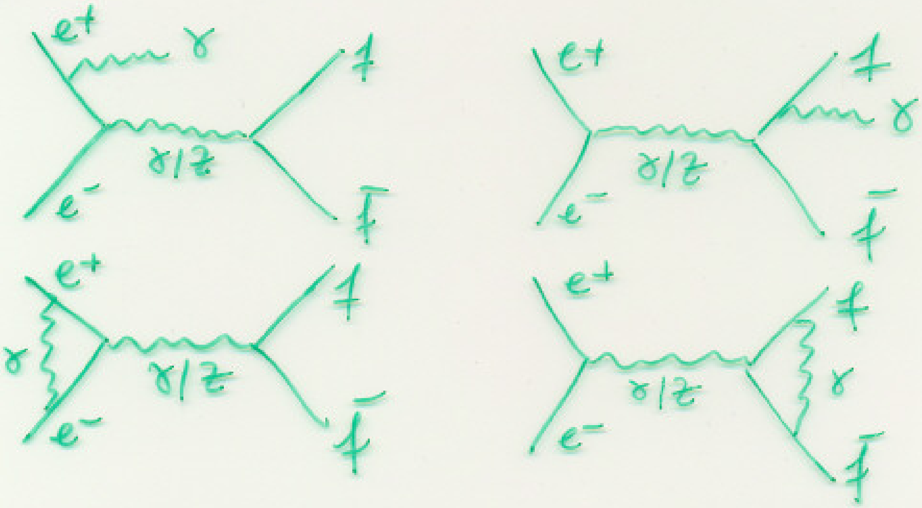
WITH $\chi(s) = \frac{G_F\, m_Z^2}{8\pi\sqrt{2}} \cdot \frac{s}{s - m_Z^2 + i s \frac{\Gamma_Z}{m_Z}}$ propagator term

N_c^f : one for leptons & three for quarks

RATHER MODEL-INDEPENDENT IF COUPLINGS ARE FREE
ONLY ASSUMPTION IS THAT THE Z PROCESSES VECTOR & AXIAL-VECTOR COUPLINGS TO FERMIONS, HAS SPIN 1 AND INTERFERES WITH THE PHOTON.

[FOR ELECTRONS $e^+e^- \to e^+e^-$ ALSO THE BHABHA TERM)

PHOTON RADIATION FROM INITIAL & FINAL STATES LIKE



AND THEIR INTERFERENCE ARE TREATED BY CONVOLUTING THE EW KERNEL CROSS-SECTION $\sigma_{ew}(s)$ WITH A QED RADIATOR

$$\sigma(s) = \int_{4m_f^2/s}^{1} dz \; H_{QED}^{tot}(z,s) \; \sigma_{ew}(zs)$$

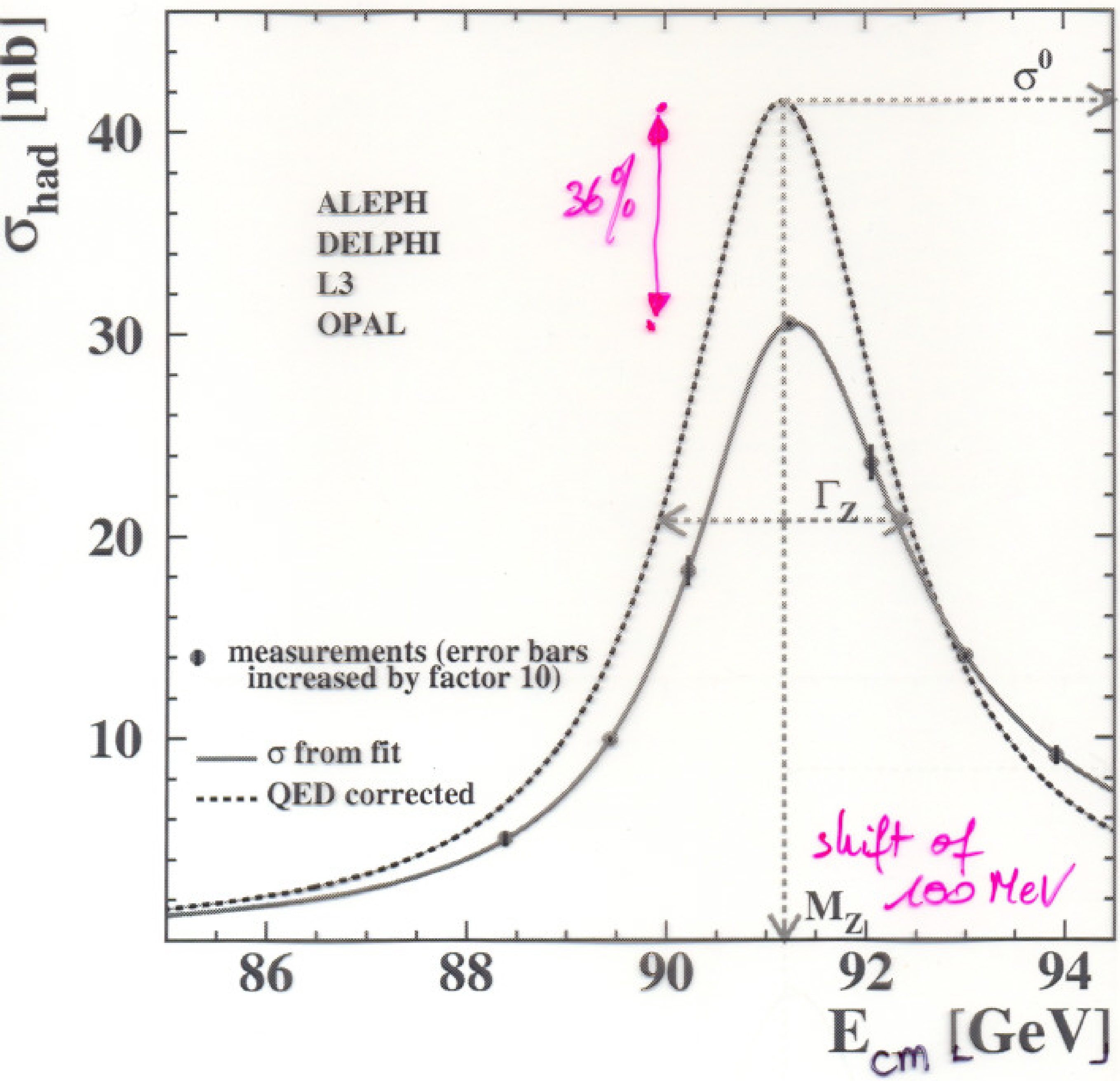
THE SAME PROCEDURE IS USED FOR THE FORWARD-BACKWARD ASYMMETRIES $\sigma_F - \sigma_B$ WITH H_{QED}^{FB}.
[calculated to 3° ORDER]

THESE CORRECTIONS ARE IMPORTANT AND ESSENTIALLY INDEPENDENT OF THE EW CORRECTIONS DISCUSSED PREVIOUSLY.

$\Rightarrow$ HENCE THE PARAMETERS IN EQUATION $d\sigma_{EW}/d\cos\theta$ CAN BE EXTRACTED FROM DATA IN A MODEL-INDEPENDENT WAY

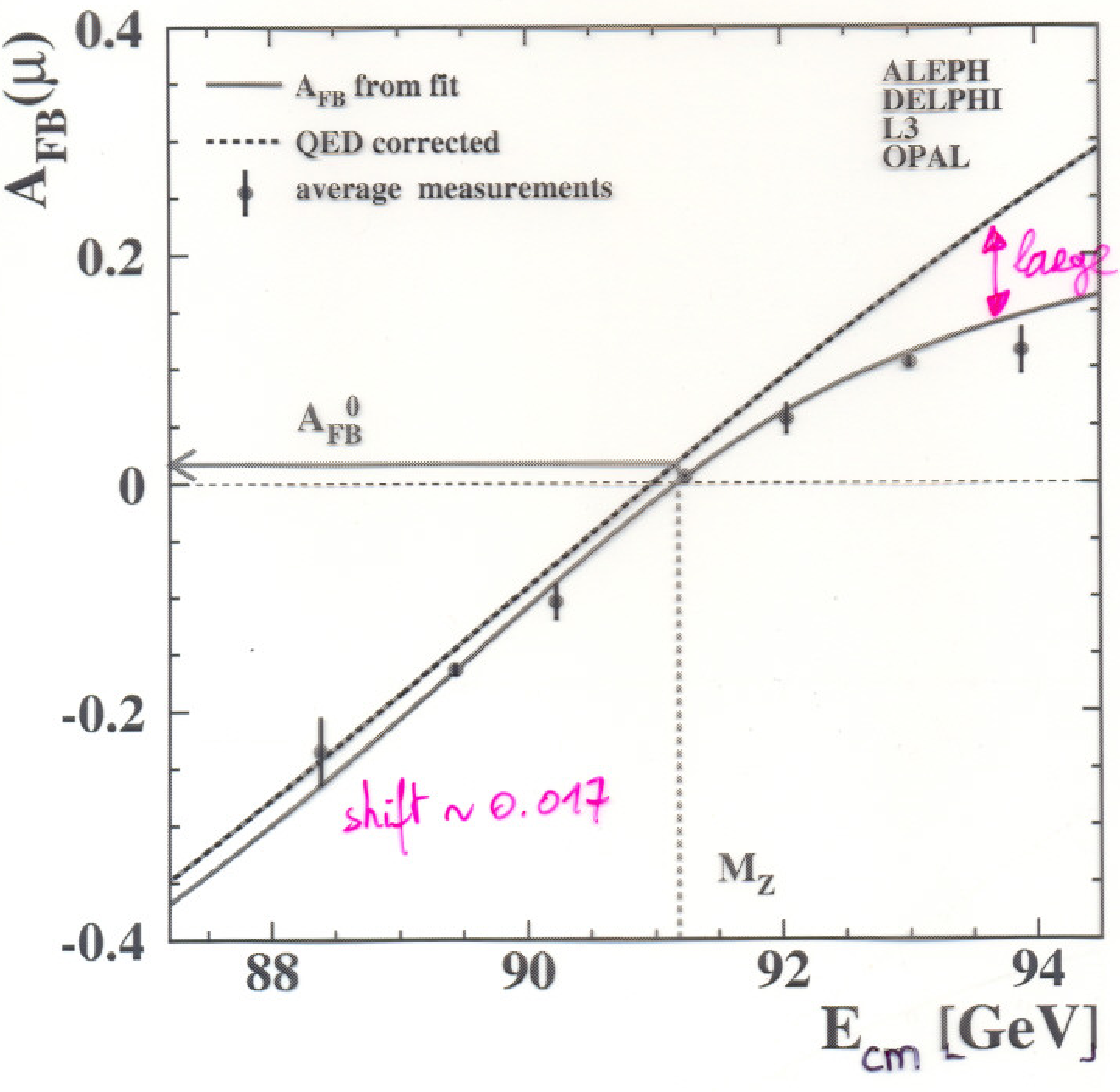
EFFECT OF QED RADIATIVE CORRECTIONS ON THE LINESHAPE OF THE Z

(hadronic cross section)



EFFECT OF QED RADIATIVE CORRECTIONS ON THE FORWARD-BACKWARD ASYMMETRIES.

$(e^+e^- \to \mu^+\mu^-)$



* CROSS SECTIONS & PARTIAL WIDTHS

THE CROSS SECTION FROM THE $\cos\theta$-SYMMETRIC Z PRODUCTION TERM CAN ALSO BE WRITTEN AS :

$$\sigma_{f\bar{f}}^{Z} = \sigma_{f\bar{f}}^{peak} \frac{s\,\Gamma_Z^2}{(s-m_Z^2)^2 + s^2 \frac{\Gamma_Z^2}{m_Z^2}}$$

removes QED corr.

WITH $\sigma_{f\bar{f}}^{peak} = \frac{1}{R_{QED}} \sigma_{f\bar{f}}^{0}$ $\qquad \sigma_{f\bar{f}}^{0} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$

WHERE YOU HAVE THE PARTIAL DECAY WIDTHS OF THE INITIAL (Γ_{ee}) AND FINAL ($\Gamma_{f\bar{f}}$) STATES. THE OVERALL HADRONIC WIDTH IS GIVEN AS

$$\Gamma_{had} = \sum_{q \neq t} \Gamma_{q\bar{q}}$$

HENCE THE TOTAL WIDTH CAN BE WRITTEN AS

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv.}$$

$$\Gamma_{inv} = N_\nu \, \Gamma_{\nu\bar{\nu}}$$

AS WE MEASURE CROSS-SECTIONS WHICH DEPEND ON SEVERAL PARTIAL WIDTHS, THESE MEASUREMENTS ARE CORRELATED. THE USE OF A SET OF 6 PARAMETERS (MOTIVATED EXPERIMENTALLY):

- m_Z
- Γ_Z
- $\sigma_{had}^0 = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$ hadronic pole cross-sec.
- $R_e^0 = \Gamma_{had}/\Gamma_{ee}$
- $R_\mu^0 = \Gamma_{had}/\Gamma_{\mu\mu}$
- $R_\tau^0 = \Gamma_{had}/\Gamma_{\tau\tau}$

if universality is assumed this becomes 1 parameter

TRADITIONALLY THE BRANCHING RATIOS TO HEAVY QUARKS ARE TREATED INDEPENDENTLY $R_b^0 = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}}$

$R_c^0 = \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$

THIS IS POSSIBLE WITH THE PRECISE TRACKING DETECTORS IN THE LEP & SLC DETECTORS.

SLD slightly better in heavy quark identification.

* INVISIBLE WIDTH & # NEUTRINOS

ASSUMING LEPTON UNIVERSALITY AND $R_{inv}^0 = \Gamma_{inv}/\Gamma_{\ell\ell}$ WE OBTAIN

$$R_{inv}^0 = \sqrt{\frac{12\pi R_\ell^0}{\sigma_{had}^0 m_Z^2}} - R_\ell^0 - (3 + \delta_Z)$$

effect of Z mass

$\delta_Z \simeq -0.23\%$

HENCE ASSUMING ONLY INVISIBLE DECAYS TO NEUTRINOS AND THE SM PREDICTION FOR $\Gamma_{\nu\bar{\nu}}/\Gamma_{\ell\ell}$ WE CAN ESTIMATE THE NUMBER OF NEUTRINOS

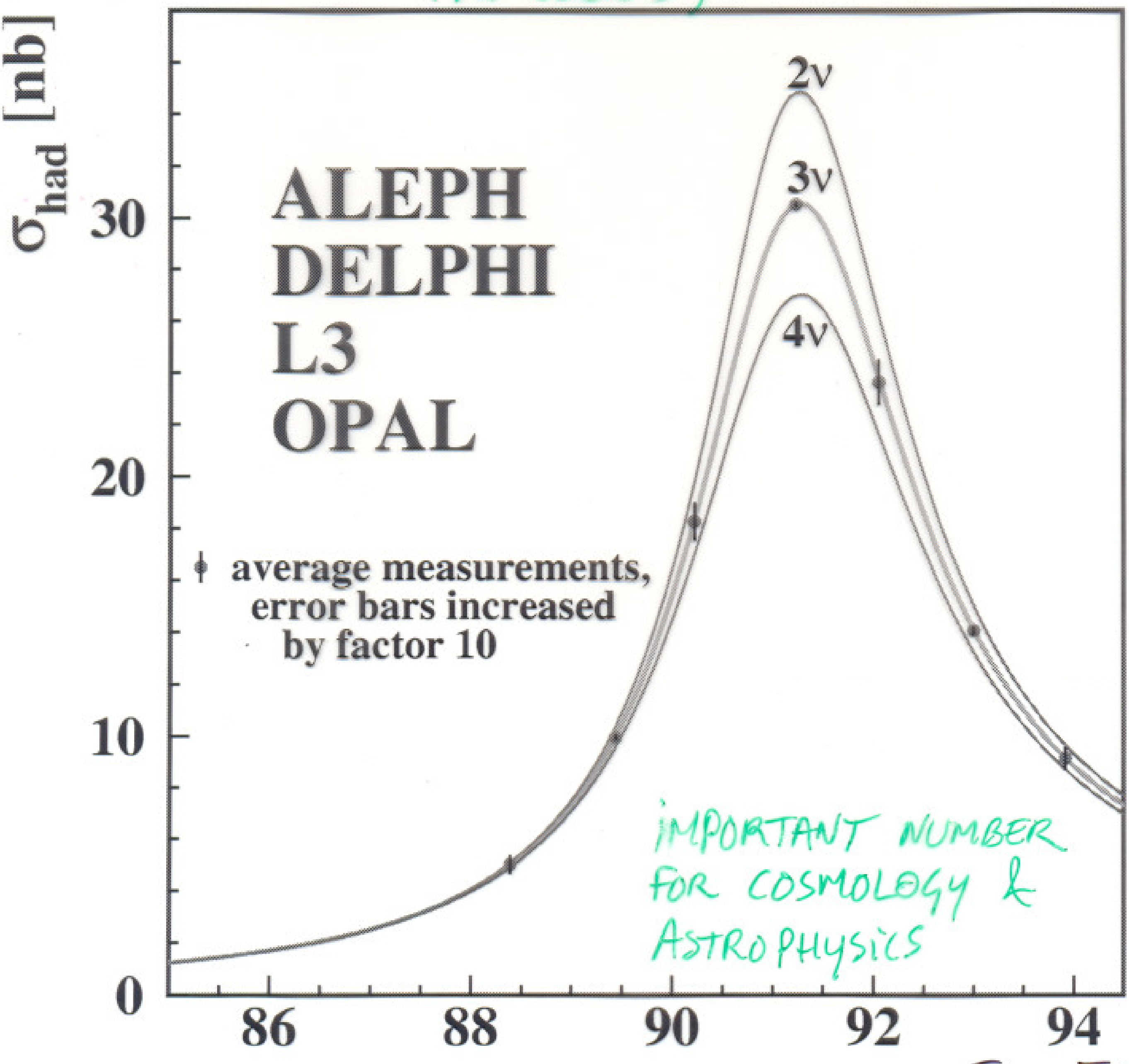
$$R_{inv}^0 = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}}\right)_{SM}$$

DEPENDS ON HADRONIC CROSS SECTION (→ cfr. plot)

DEPENDENCY OF HADRONIC CROSS SECTION ON THE NUMBER OF NEUTRINO SPECIES.

$N_\nu = 2.9840 \pm 0.0082$

(2σ below 3)



E_{cm} [GeV]

* ASYMMETRIES & POLARISATION

ADDITIONAL OBSERVABLES ARE INTRODUCED TO DESCRIBE THE $\cos\theta$ DEPENDENCY IN $d\sigma_{ff}/d\cos\theta$. THEY QUANTIFY THE AMOUNT OF PARITY VIOLATION OF THE NEUTRAL CURRENT, HENCE THE VECTOR & AXIAL-VECTOR COUPLINGS TO THE Z BOSON.

$\Rightarrow$ MEASURE OF $\sin^2\theta^f_{eff}$

(i). EVEN IF THE INITIAL ELECTRONS & POSITRONS ARE NOT POLARISED, THE Z BOSON CAN HAVE A LONGITUDINAL POLARIZATION IN ITS DECAY. THIS BECAUSE THE LEFT- RIGHT-HANDED COUPLING TO FERMIONS ARE UNEQUAL. HENCE THE ANGULAR DISTRIBUTION WILL BE FORWARD-BACKWARD ASYMMETRIC.

THE Z EXCHANGE CROSS SECTION CAN BE WRITTEN AS

$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma^{tot}_{f\bar{f}}\Big[(1-P_e A_e)(1+\cos^2\theta) + 2(A_e - P_e)A_f\cos\theta\Big]$$

electron beam polarisation (assuming no positron polarisation)

WITH

$$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2\,g_{Vf}\,g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2\,\frac{g_{Vf}/g_{Af}}{1+\left(g_{Vf}/g_{Af}\right)^2}$$

WHERE THE LAST TERM CLEARLY SHOWS THE DEPENDENCY ON $\sin^2\theta_W$

WHEN INTEGRATING THE CROSS SECTIONS OVER THE FORWARD OR BACKWARD HEMISPHERE WE OBTAIN

σ_F : forward
σ_B : backward

IDENTICAL FOR RIGHT & LEFT ELECTRON HELICITIES.
THREE BASIC ASYMMETRIES CAN BE MEASURED

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

⇝ picks out the coefficient $A_e A_f$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \cdot \frac{1}{\langle P_e \rangle}$$

⇝ picks out the coefficient A_e

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \cdot \frac{1}{\langle P_e \rangle}$$

⇝ picks out the coefficient A_f

(ii) POLARISATION OF A FINAL-STATE FERMION IS THE DIFFERENCE BETWEEN THE CROSS SECTIONS FOR RIGHT- AND LEFT-HANDED FINAL STATE HELICITIES DIVIDED BY THEIR SUM

$$P_f = \frac{d(\sigma_R - \sigma_L)/d\cos\theta}{d(\sigma_R + \sigma_L)/d\cos\theta}$$

AGAIN WE CAN INTEGRATE OVER FORWARD AND BACKWARD HEMISPHERES :

$$\langle P_f \rangle = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$ ⇝ picks out A_f

$$A_{FB}^{pol} = \frac{(\sigma_R - \sigma_L)_F - (\sigma_R - \sigma_L)_B}{(\sigma_R + \sigma_L)_F + (\sigma_R + \sigma_L)_B}$$ ⇝ picks out A_e

THESE VARIABLES CAN BE OBTAINED FROM A MEASUREMENT OF

$$P_f(\cos\theta) = -\frac{A_f(1+\cos^2\theta) + 2A_e\cos\theta}{(1+\cos^2\theta) + 2A_f A_e \cos\theta}$$

WHICH IS ONLY MEASURED FOR τ-LEPTONS IN THE FINAL STATE OF WHICH WE CAN OBTAIN THE POLARISATION

HENCE ALL TOGETHER WHEN WE MEASURE THE ASYMMETRIES (FORWARD-BACKWARD AND/OR LEFT-RIGHT) WE CAN RELATE ~~THEM~~ TO THE PARAMETERS A_f :

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

$$A_{LR}^{0} = A_e$$

using this LEP can also measure A_f

$$A_{LRFB}^{0} = \frac{3}{4} A_f$$

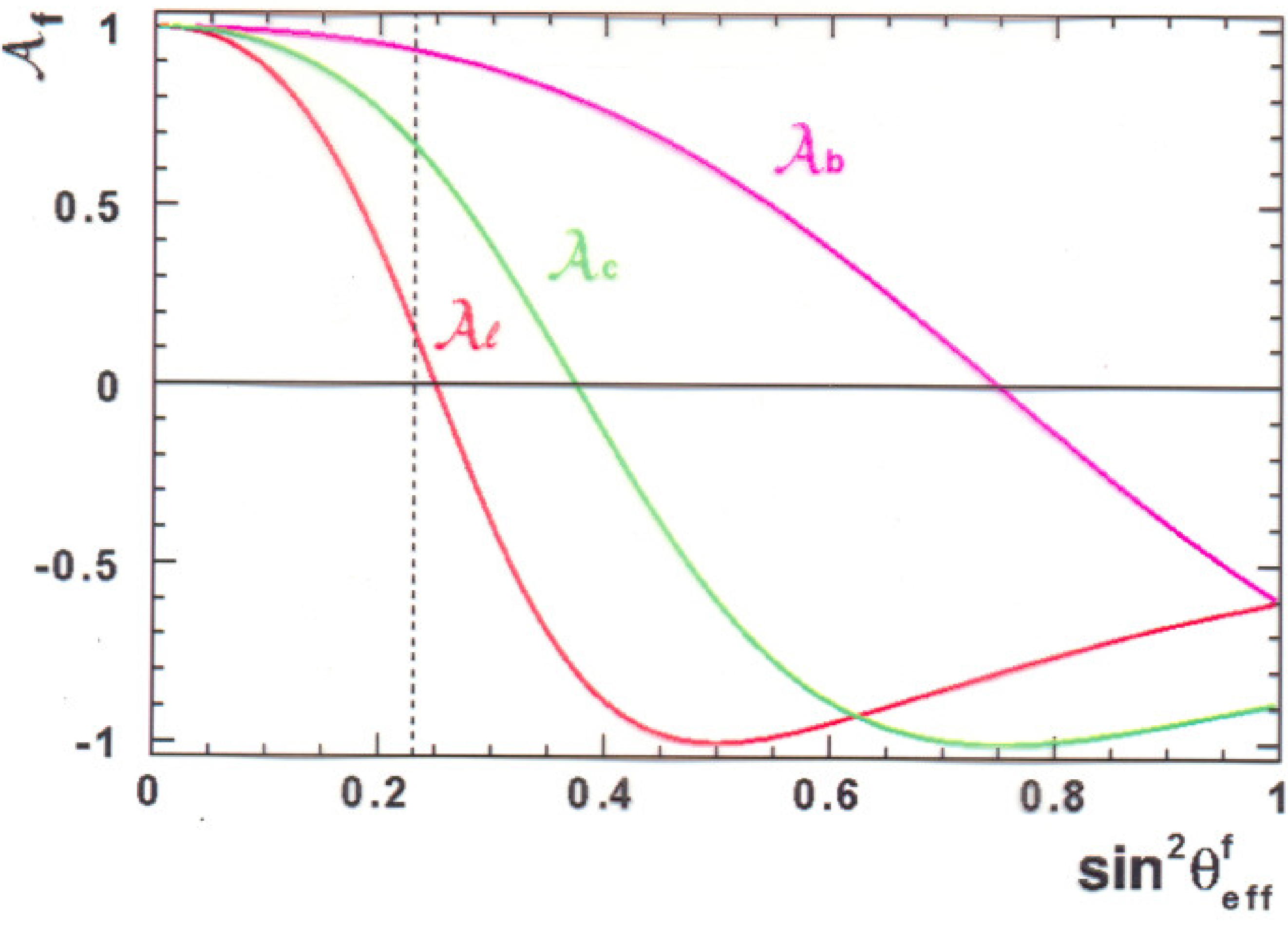
$$\langle P_\tau^0 \rangle = -A_\tau$$

$$A_{FB}^{pol,0} = -\frac{3}{4} A_e$$

LEP: A_{FB}^{0} for all final states & P_τ

SLD: A_{LR}^{0}, A_{LRFB}^{0} for all final states

SENSITIVITY OF $\mathcal{A}_f$ TO $\sin^2\theta^f_{eff}$



FROM THEORY TO EXPERIMENT

THE ABOVE PARAMETERS ARE NOT "REALISTIC OBS" BUT WHICH HAVE SIGNIFICANT THEORY CORRECTIONS

→ PSEUDO-OBSERVABLES

(denoted by superscript o)

eg. { σ_{had} is the measured hadronic cross section
σ^0_{had} is the pole cross-section derived from σ_{had}

{ R_b is the measurement of b-quark cross section divided by the hadronic one $\sigma_{b\bar{b}}/\sigma_{had}$
R^0_b is $\Gamma_{b\bar{b}}/\Gamma_{had}$ derived from this

THE EXPERIMENTAL CROSS SECTIONS & ASYMMETRIES ARE MEASURED IN THE ACCEPTANCE OF THE DETECTOR

→ CORRECT THEM BY EXTRAPOLATING TO PERFECT (= FULL) ACCEPTANCE

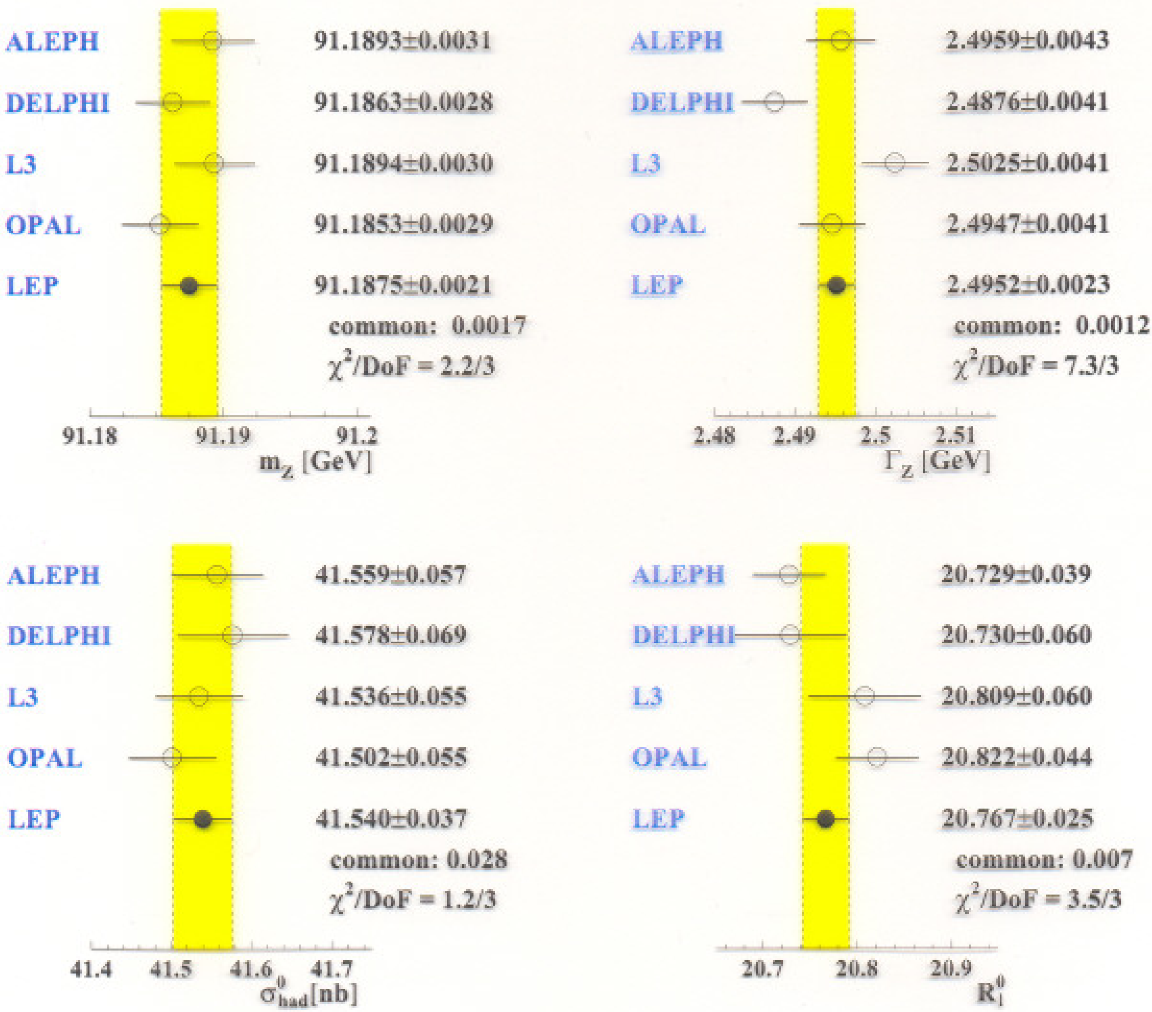
NINE PSEUDO-OBSERVABLES DESCRIBE THE Z RESONANCE IN A MODEL INDEPENDENT WAY.
("THEORY" & "EXPERIMENT" REMAIN DISTINCT)

m_Z, Γ_Z, σ^0_{had}, R^0_ℓ, $A^{0,\ell}_{FB}$

A^0_{LR}, A^0_{LRFB}, $\langle P^0_\tau \rangle$, $A^{pol,0}_{FB}$

need a fit to take into account the correlations between them, only then an interpretation is possible

LEP RESULTS IN THE LEPTON SECTOR



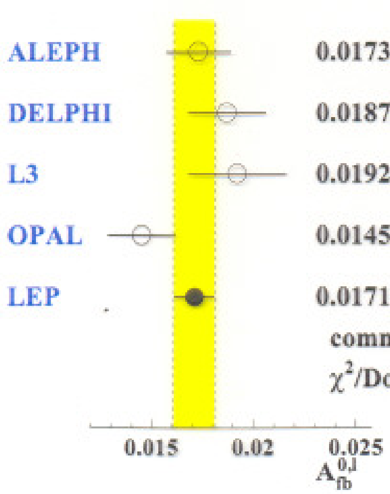


Figure 2.9: Measurements of m_Z, Γ_Z, $\sigma^0_{\rm had}$, R^0_ℓ and $A^{0,\ell}_{\rm FB}$. The averages indicated were obtained using the common errors and combination method discussed in the text. The values of χ^2 per degree of freedom were calculated considering error correlations between measurements of the same parameter, but not error correlations between different parameters.

GOOD COMPARISON BETWEEN LEPTON FLAVOURS

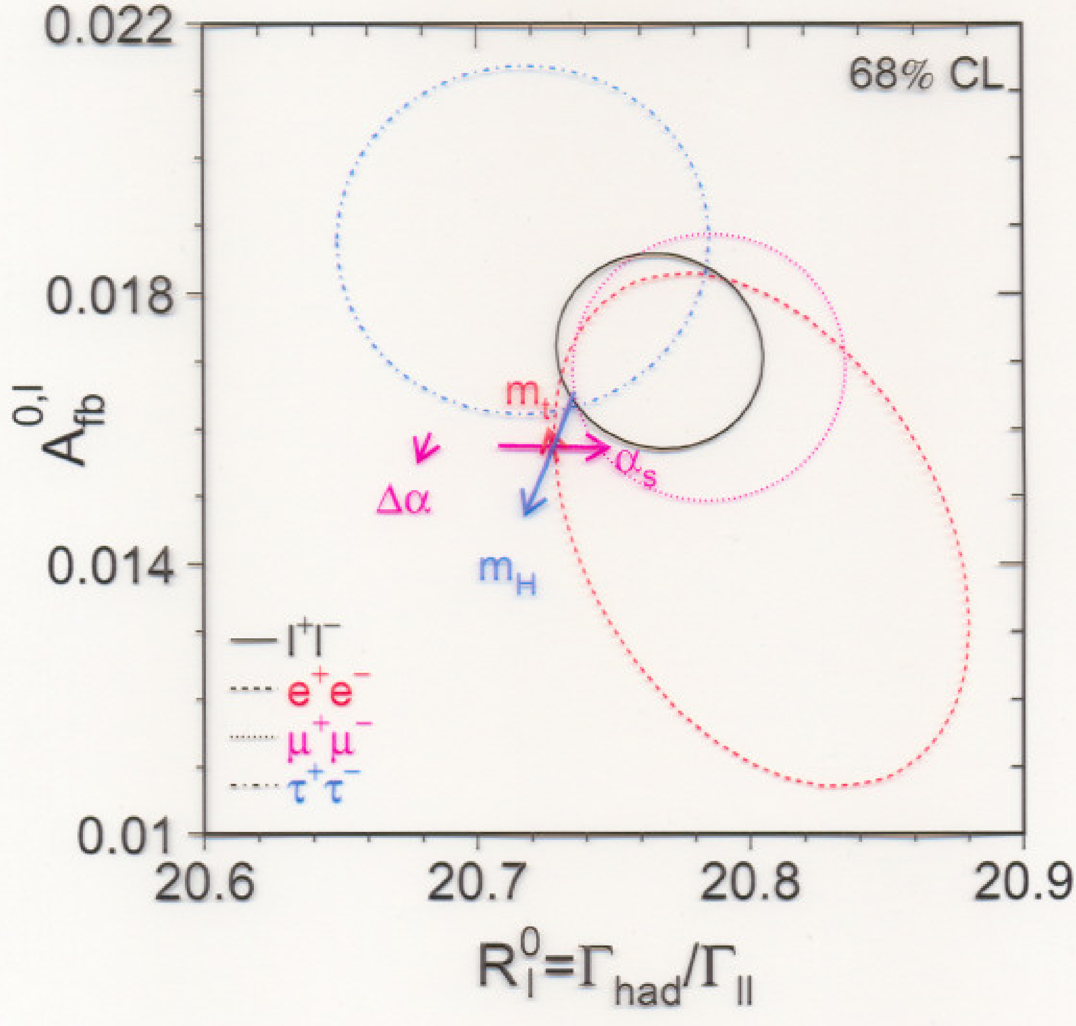


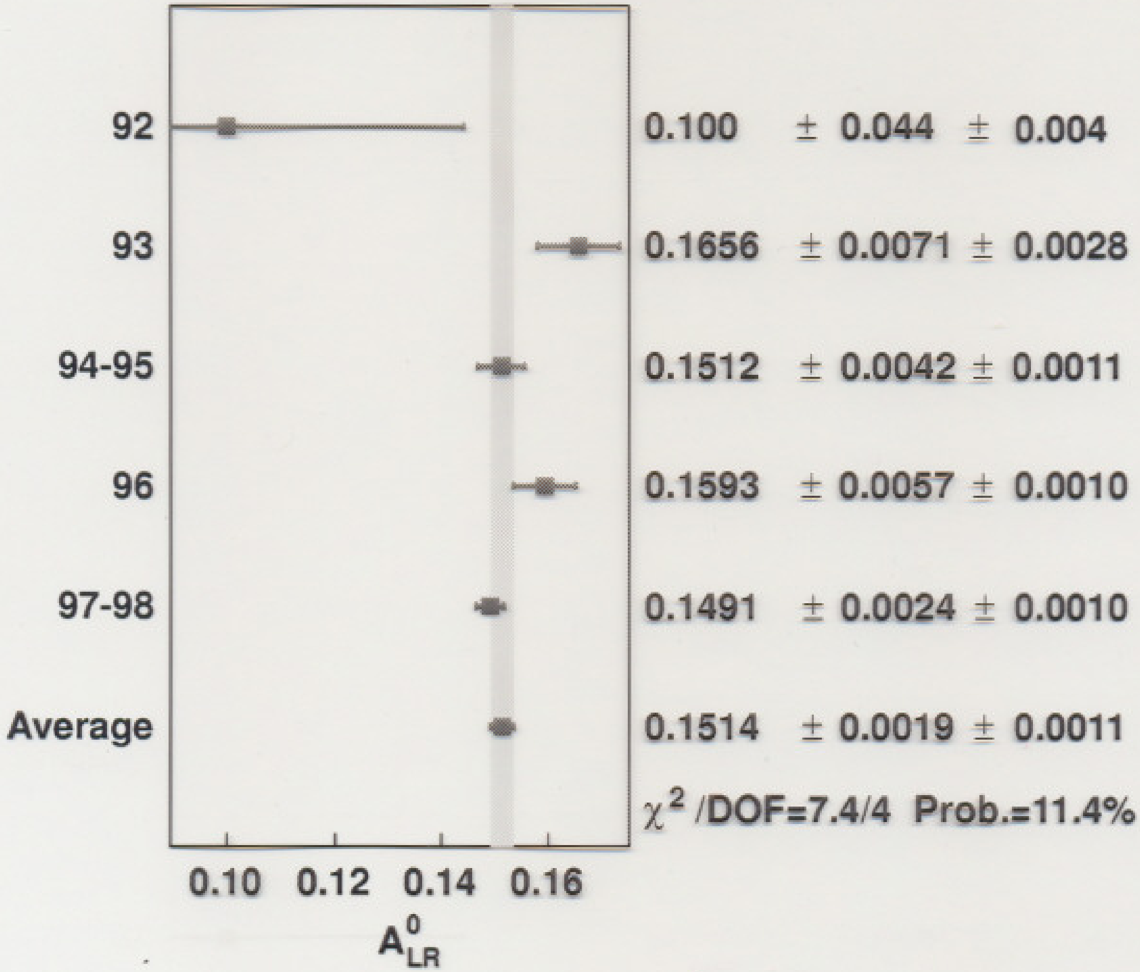
Figure 2.11: Contour lines (68 % CL) in the R_ℓ^0–$A_{\rm FB}^{0,\ell}$ plane for e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states and for all leptons combined. For better comparison the results for the τ lepton are corrected to correspond to the massless case. The SM prediction for $m_Z = 91.1875$ GeV, $m_t = 178.0$ GeV, $m_H = 300$ GeV, and $\alpha_S(m_Z^2) = 0.118$ is also shown as the intersection of the lines with arrows, which correspond to the variation of the SM prediction when m_t, m_H and $\alpha_S(m_Z^2)$ are varied in the intervals $m_t = 178.0 \pm 4.3$ GeV, $m_H = 300^{+700}_{-186}$ GeV, and $\alpha_S(m_Z^2) = 0.118 \pm 0.003$, respectively. The arrow showing the small dependence on the hadronic vacuum polarisation $\Delta\alpha_{\rm had}^{(5)}(m_Z^2) = 0.02758 \pm 0.00035$ is displaced for clarity. The arrows point in the direction of increasing values of these parameters.

MEASUREMENT OF THE LEFT-RIGHT ASYMMETRY BY SLC

NEEDED FOR A PRECISE DETERMINATION OF $\mathcal{A}_e$

COUNT THE NUMBER OF Z BOSONS PRODUCED BY LEFT AND RIGHT LONGITUDINALLY POLARISED ELECTRONS

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{\langle P_e \rangle}$$



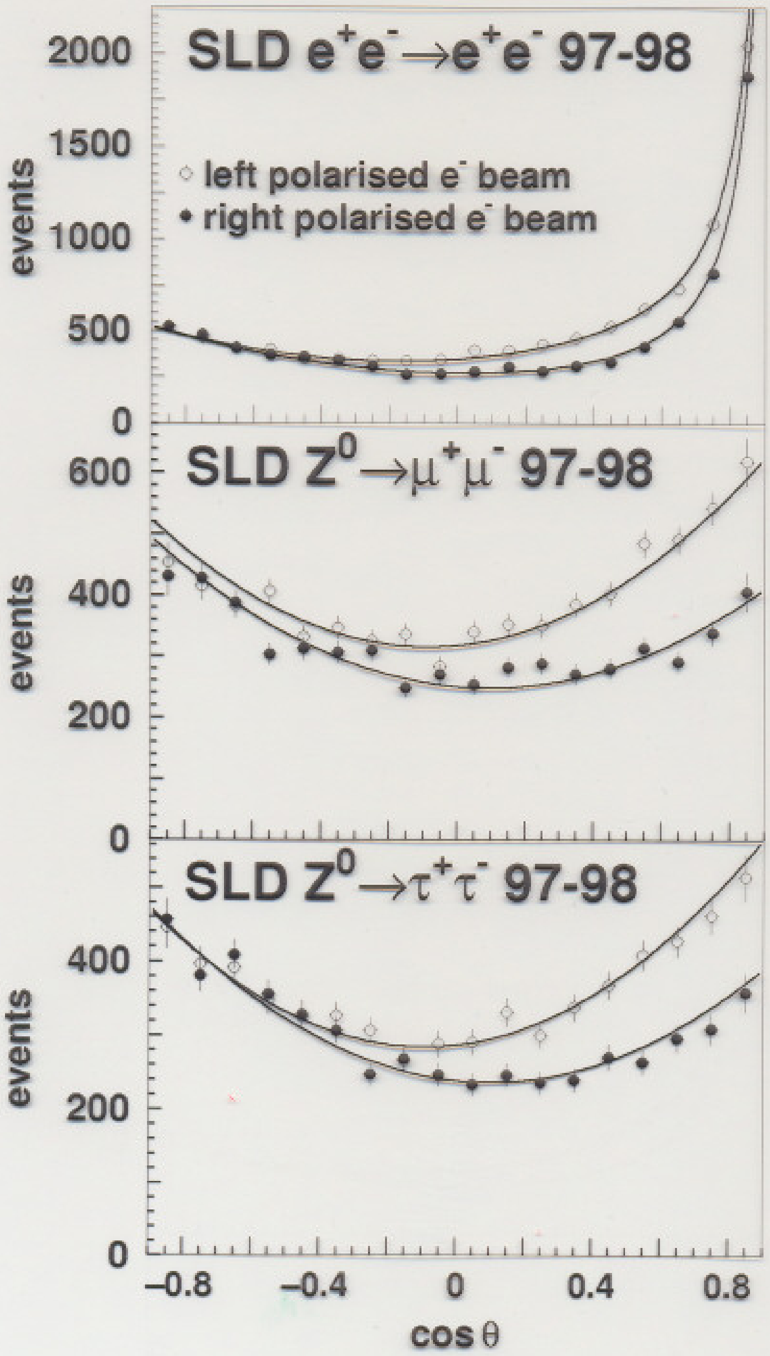
$$A_{LR}^0 = \frac{2\left(1 - 4\sin^2\theta_{eff}^{lept}\right)}{1 + \left(1 - 4\sin^2\theta_{eff}^{lept}\right)^2}$$

$$\Rightarrow \quad \sin^2\theta_{eff}^{lept} = 0.23097 \pm 0.00027$$

LEPTON ASYMMETRY MEASUREMENTS

VIA MEASUREMENTS OF $A^{0,\ell}_{LRFB} = \frac{3}{4}|P_e|A_\ell$

OBTAINED FROM A FIT ON $d\sigma/d\cos\theta$



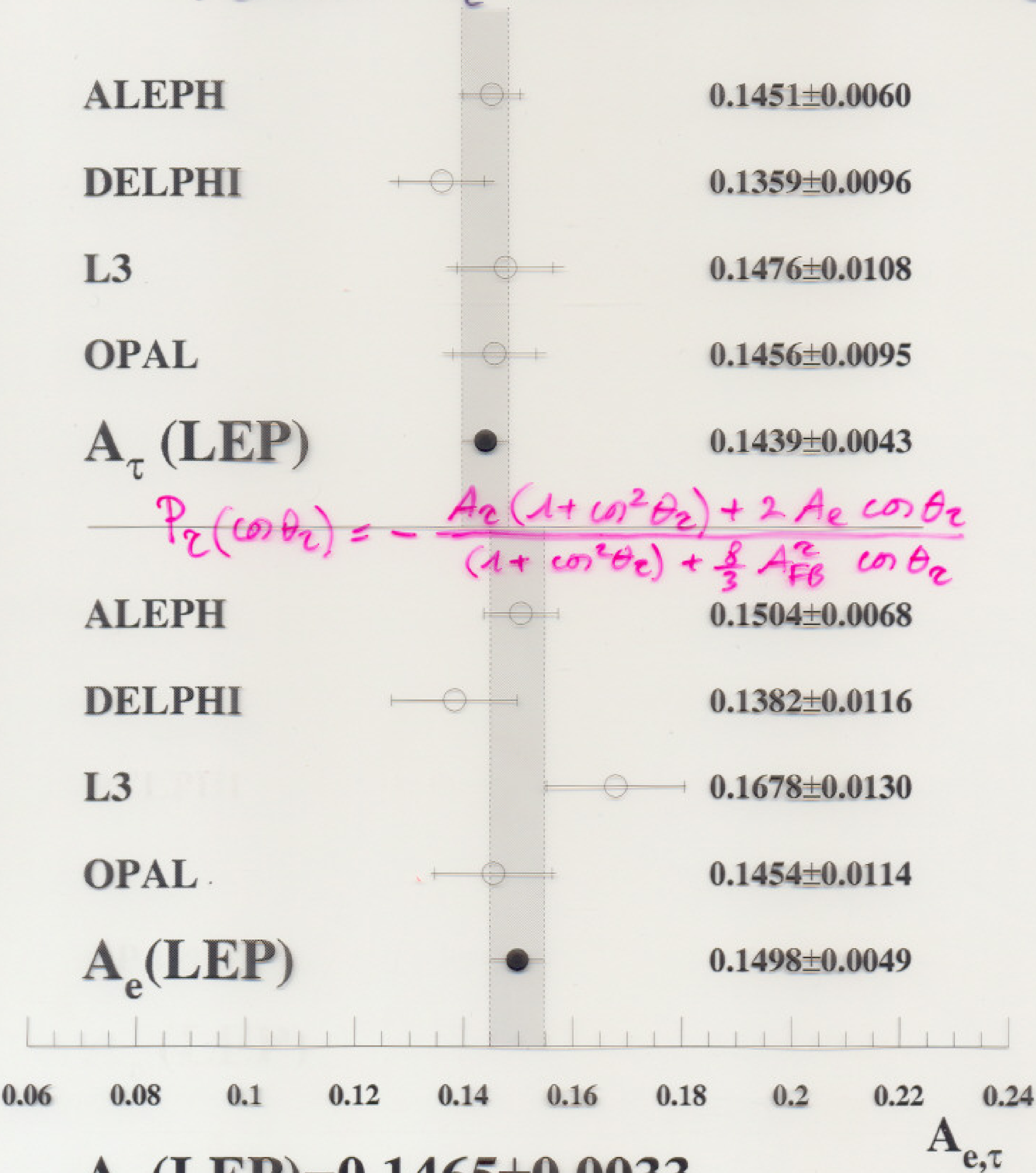
$A_\ell = 0.1513 \pm 0.001$

$\Rightarrow \quad \sin^2\theta^{lept}_{eff} = 0.23098 \pm 0.00026$

THE τ POLARISATION MEASUREMENTS

DEPENDS ON THE DEPENDENCE OF KINEMATIC DISTRIBUTIONS OF THE OBSERVED τ DECAY ON THE ~~H~~ELICITY OF THE PARENT τ LEPTON.

$\Rightarrow$ EXTRACT P_τ AS A FUNCTION OF $\cos\theta_\tau$



$$P_\tau(\cos\theta_\tau) = -\frac{A_\tau(1+\cos^2\theta_\tau) + 2A_e\cos\theta_\tau}{(1+\cos^2\theta_\tau) + \frac{8}{3}A_{FB}^\tau\cos\theta_\tau}$$

A_l (LEP)=0.1465±0.0033

χ^2/DoF=4.7/7

$$\Rightarrow \sin^2\theta_{eff}^{lept} = 0.23159 \pm 0.00041$$

HEAVY FLAVOUR PARTIAL WIDTH
(using b- and c-tagging)

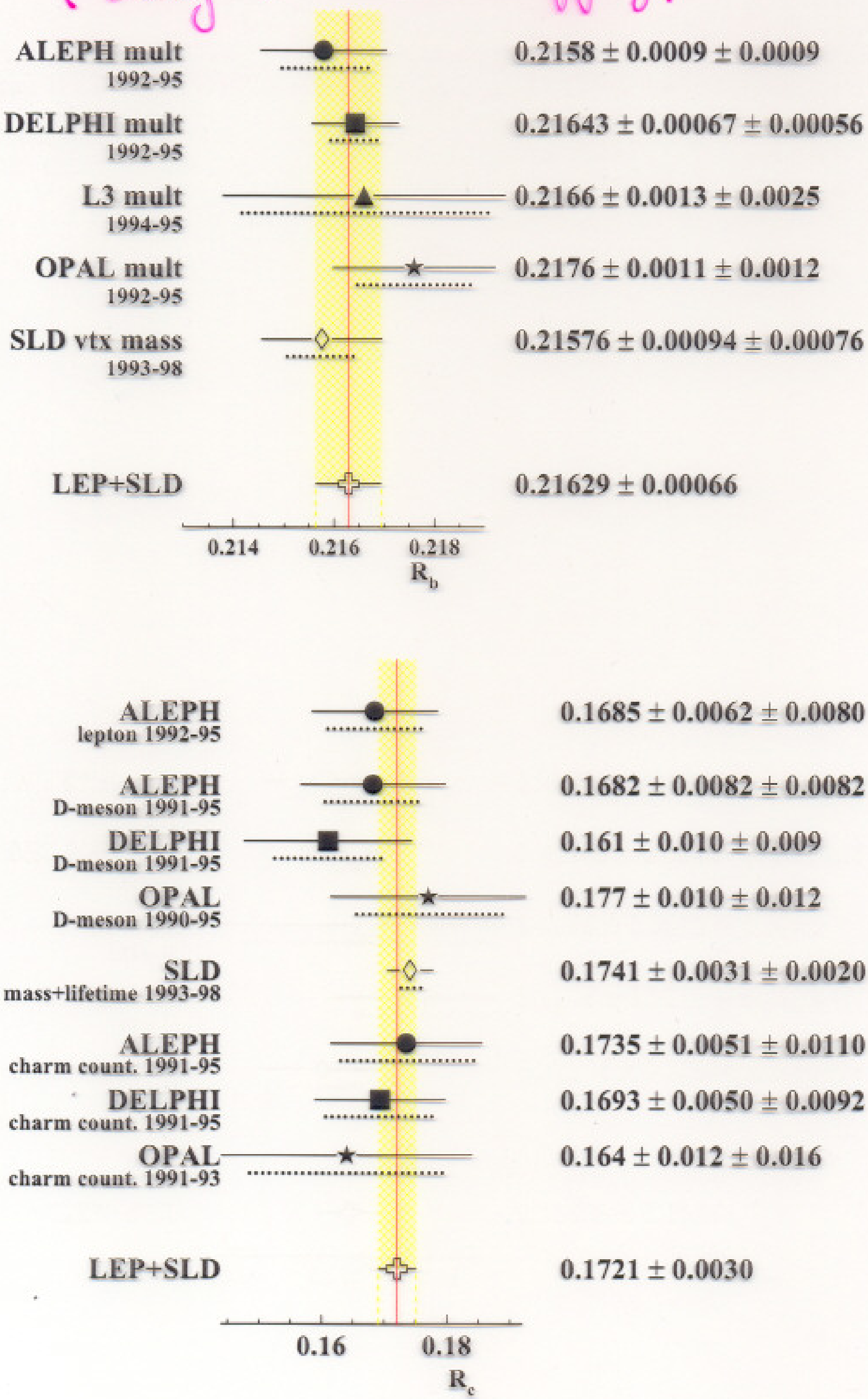
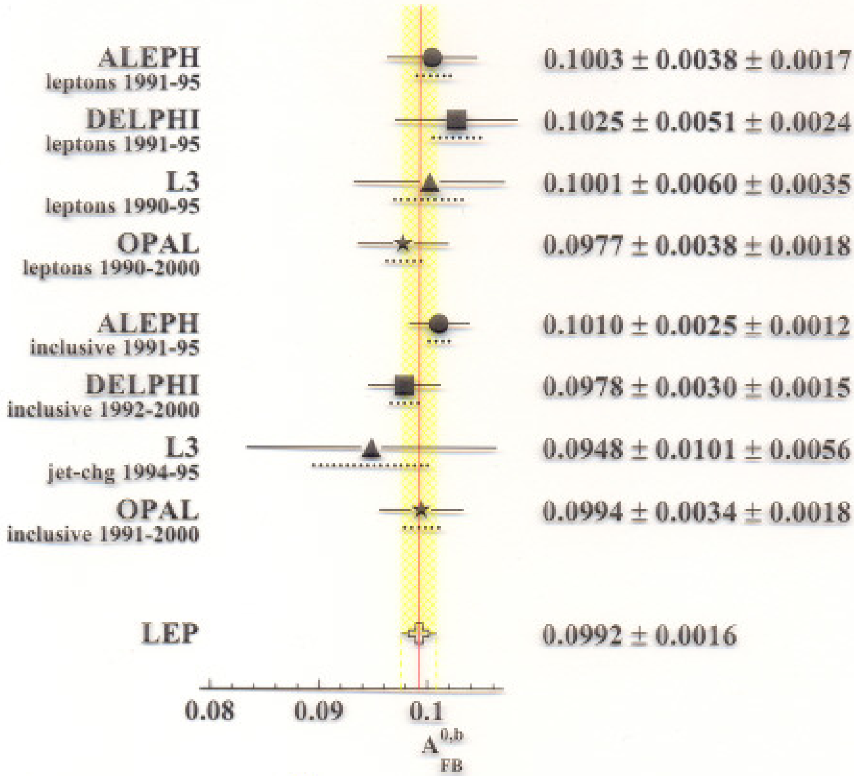


Figure 5.13: R_b^0 and R_c^0 measurements used in the heavy flavour combination, corrected for their dependence on parameters evaluated in the multi-parameter fit described in the text. The dotted lines indicate the size of the systematic error.

HEAVY FLAVOUR ASYMMETRIES



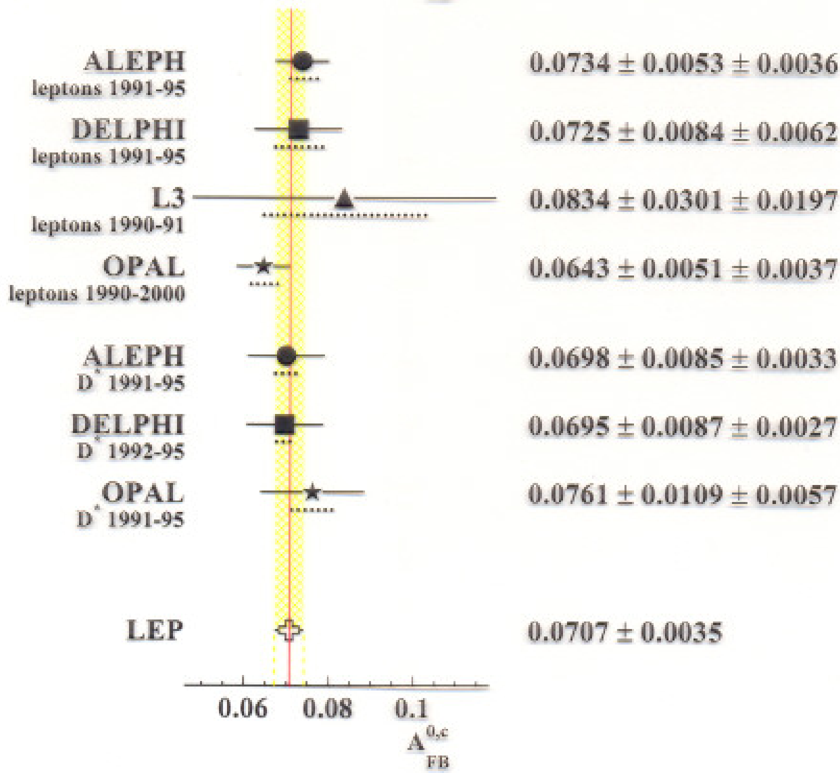


Figure 5.14: $A^{0,b}_{FB}$ and $A^{0,c}_{FB}$ measurements used in the heavy flavour combination, corrected for their dependence on parameters evaluated in the multi-parameter fit described in the text. The $A^{0,b}_{FB}$ measurements with D-mesons do not contribute significantly to the average and are not shown in the plots. The experimental results are derived from the ones shown in Tables C.3 to C.8 combining the different centre of mass energies. The dotted lines indicate the size of the systematic error.

ENERGY DEPENDENCE

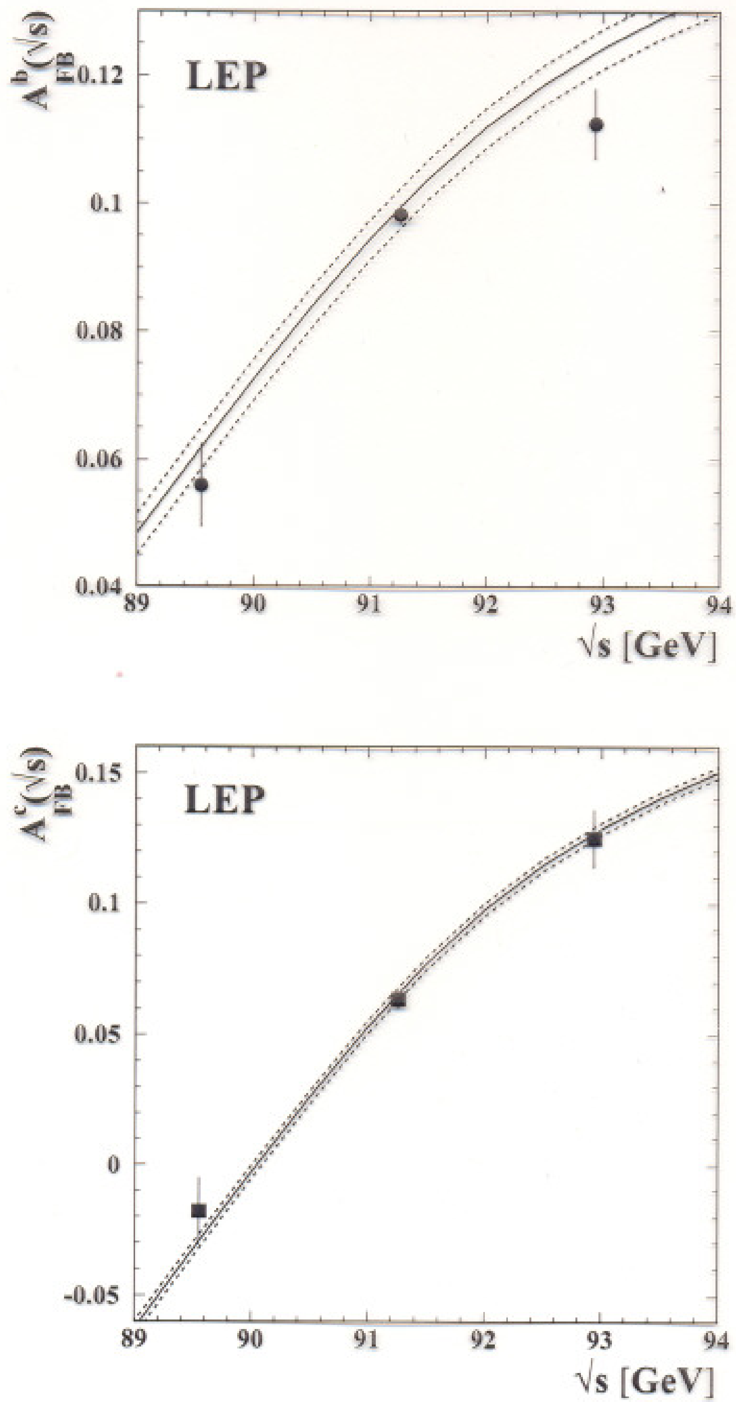


Figure 5.16: Energy dependence of $A^b_{\rm FB}$ and $A^c_{\rm FB}$. The solid line represents the SM prediction for $m_{\rm t} = 178\,{\rm GeV}$, $m_{\rm H} = 300\,{\rm GeV}$, the upper (lower) dashed line is the prediction for $m_{\rm H} = 100\,(1000)\,{\rm GeV}$.

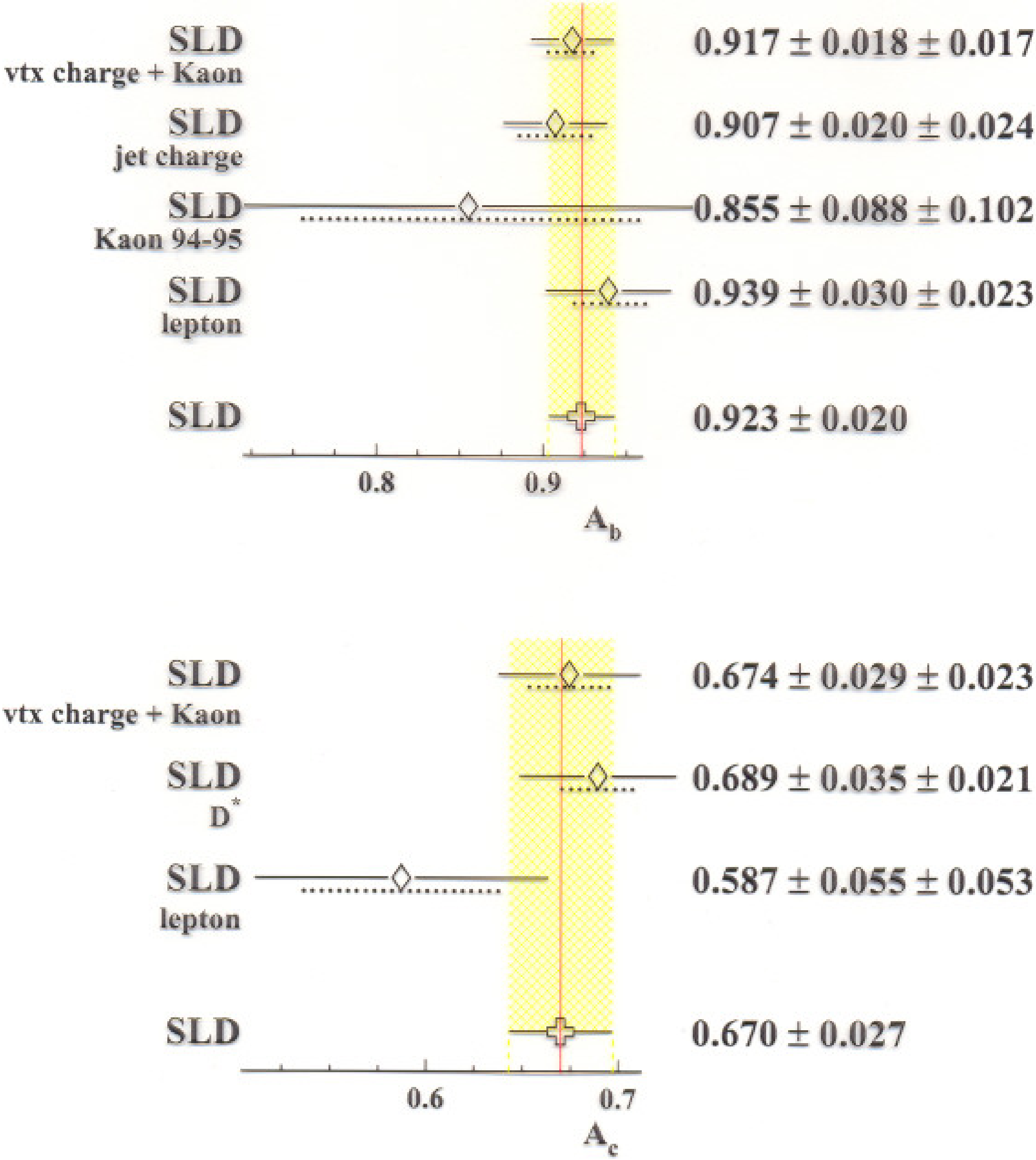
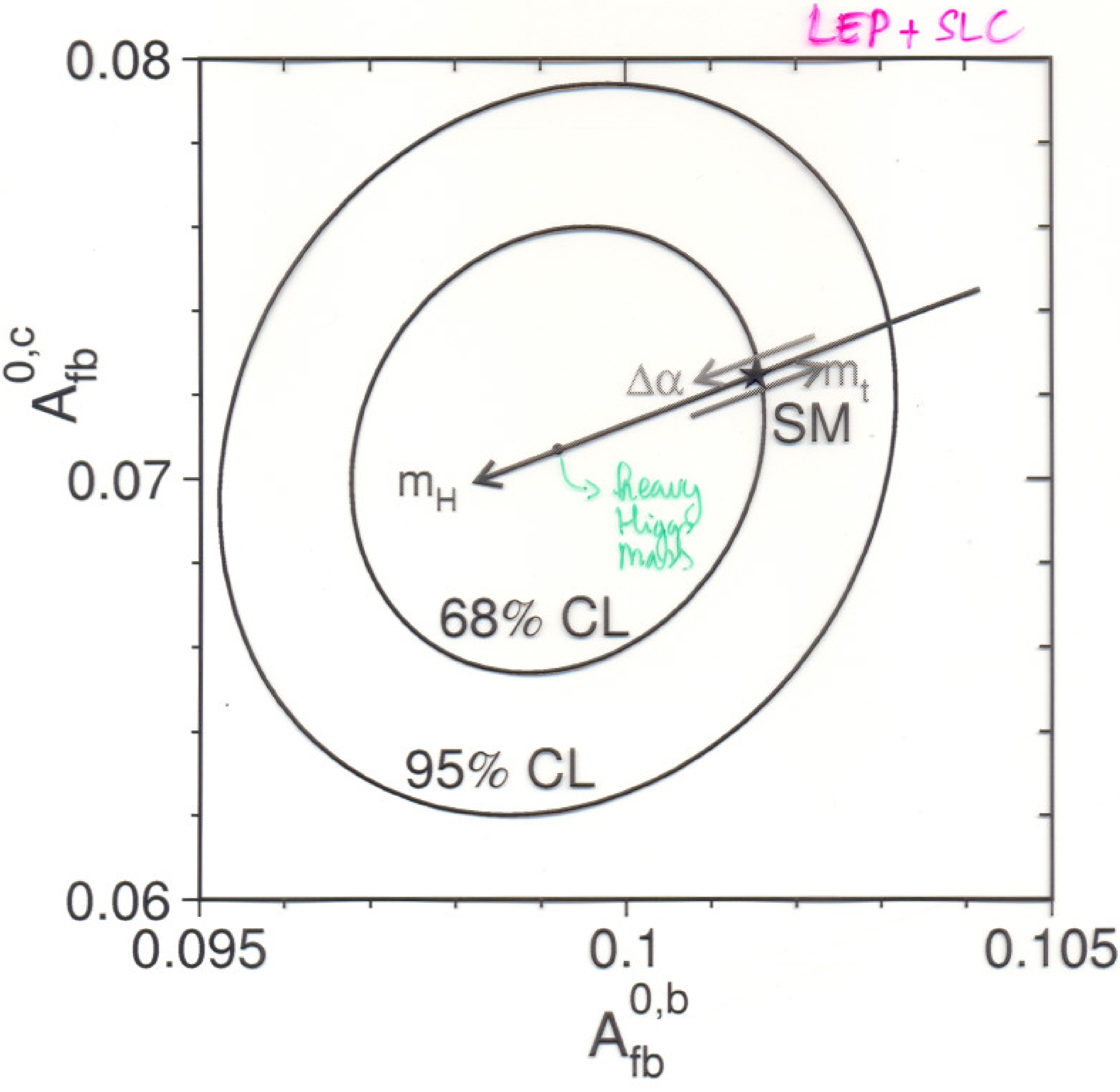


Figure 5.15: $\mathcal{A}_b$ and $\mathcal{A}_c$ measurements used in the heavy flavour combination, corrected for their dependence on parameters evaluated in the multi-parameter fit described in the text. The dotted lines indicate the size of the systematic error.

FINAL VALUES FOR R_b^0, R_c^0, $A_{FB}^{0,b}$, $A_{FB}^{0,c}$, A_b, A_c ARE OBTAIN FROM A MULTIPARAMETER FIT

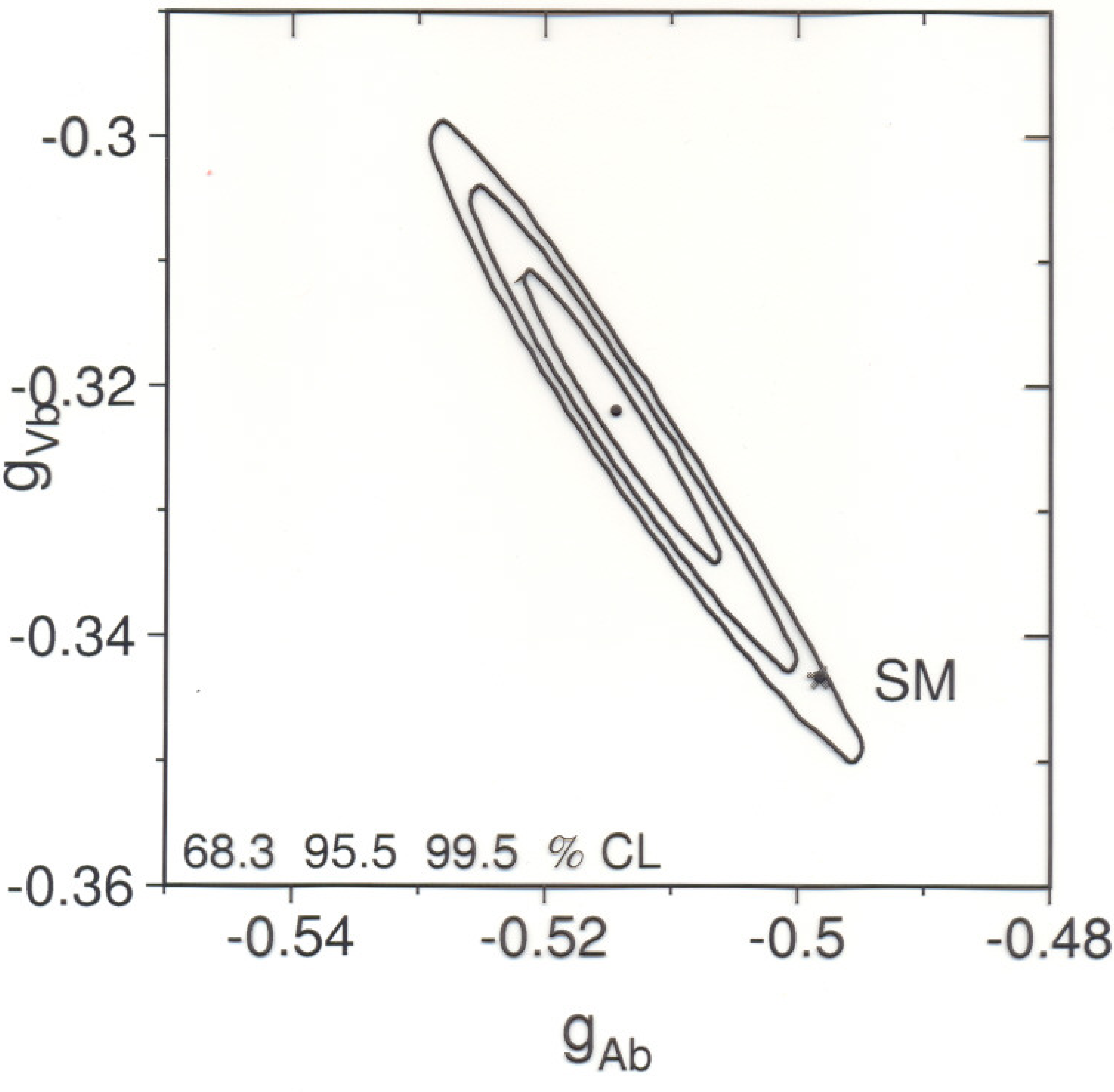
→ GOOD AGREEMENT ILLUSTRATED BELOW

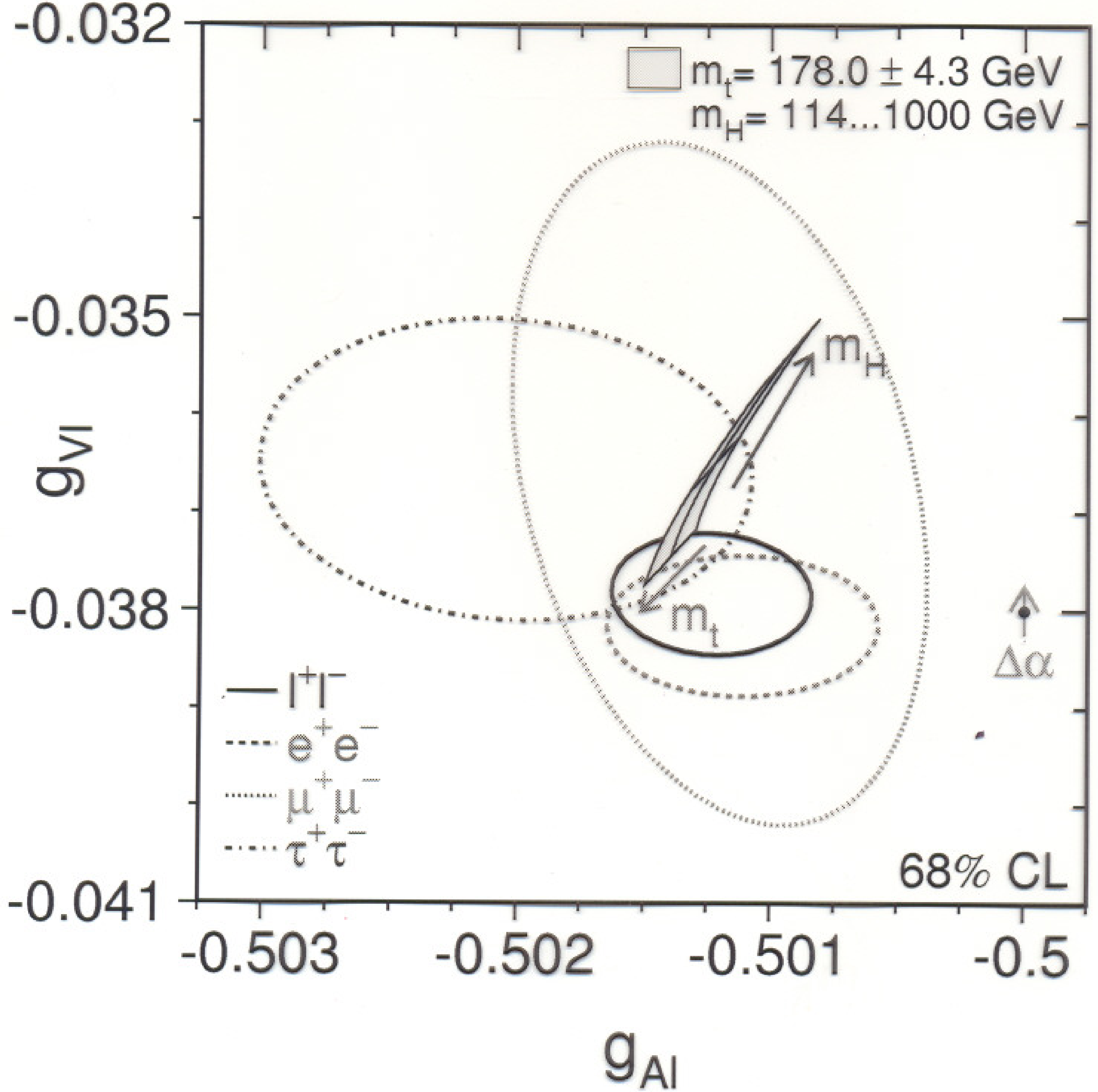


WITH THE SM EQUATIONS WE HAVE SEEN WE CAN TRANSFORM THE PSEUDO-OBSERVABLES INTO EFFECTIVE COUPLINGS OF THE NEUTRAL WEAK CURRENT :

$$A_f\ ,\ (g_{Vf}, g_{Af})\ ,\ (g_{Lf}, g_{Rf})\ ,\ \rho_f\ ,\ \sin^2\theta^f_{eff}$$

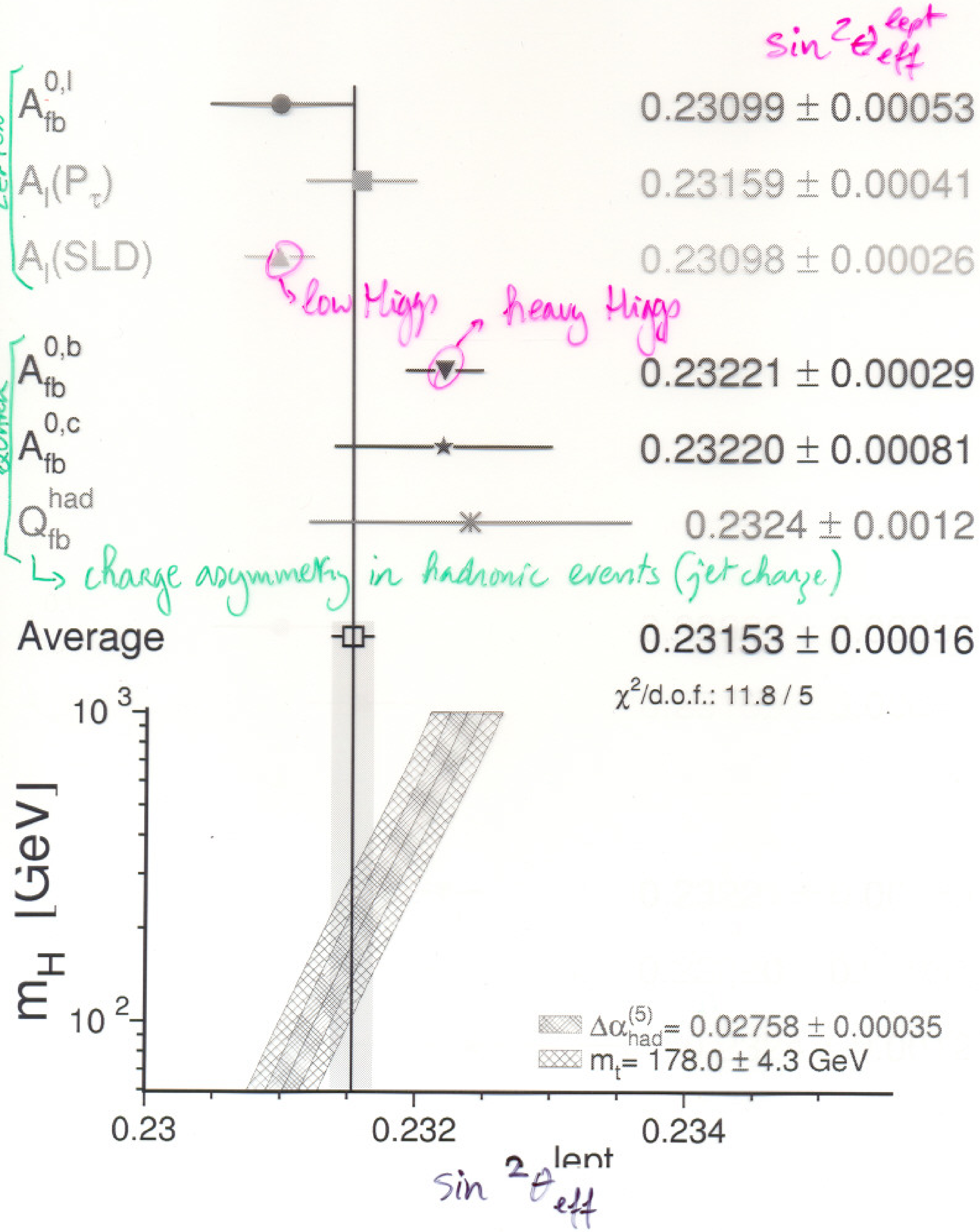
EXAMPLES





$m_t = 178.0 \pm 4.3$ GeV
$m_H = 114...1000$ GeV
m_H
m_t
$\Delta\alpha$
l^+l^-
e^+e^-
$\mu^+\mu^-$
$\tau^+\tau^-$
68% CL
-0.032
-0.035
-0.038
-0.041
-0.503
-0.502
-0.501
-0.5
g_{Vl}
g_{Al}

PUTTING THE ASYMMETRIES TOGETHER



LECTURE 1 : THE Z POLE

TWO KEY EXPERIMENTS : LEP-I (17M Z^0) & SLC (0.6M Z^0)

MEASURABLE TRUE OBSERVABLES

σ_{had}, R_f, A_{FB}, ...

CORRECTIONS QED

SUBSET OF Z-POLE VARIABLES

"PSEUDO-OBSERVABLES"

m_Z, Γ_Z, R_f^0, $A_{FB}^{0,f}$, σ_{had}^0, A_{LR}^0, A_{LRFB}^0, $\langle P_\tau \rangle$, $A_{FB}^{pol,0}$

ZFITTER / TOPAZ

RELEVANT ASYMMETRIES & COUPLINGS.

$\mathcal{A}_f$, g_{Vf}, g_{Af}, ...

STRUCTURE OF NEUTRAL WEAK CURRENT

$\sin^2\theta_{eff}$

MEASUREMENTS OF m_W & m_t

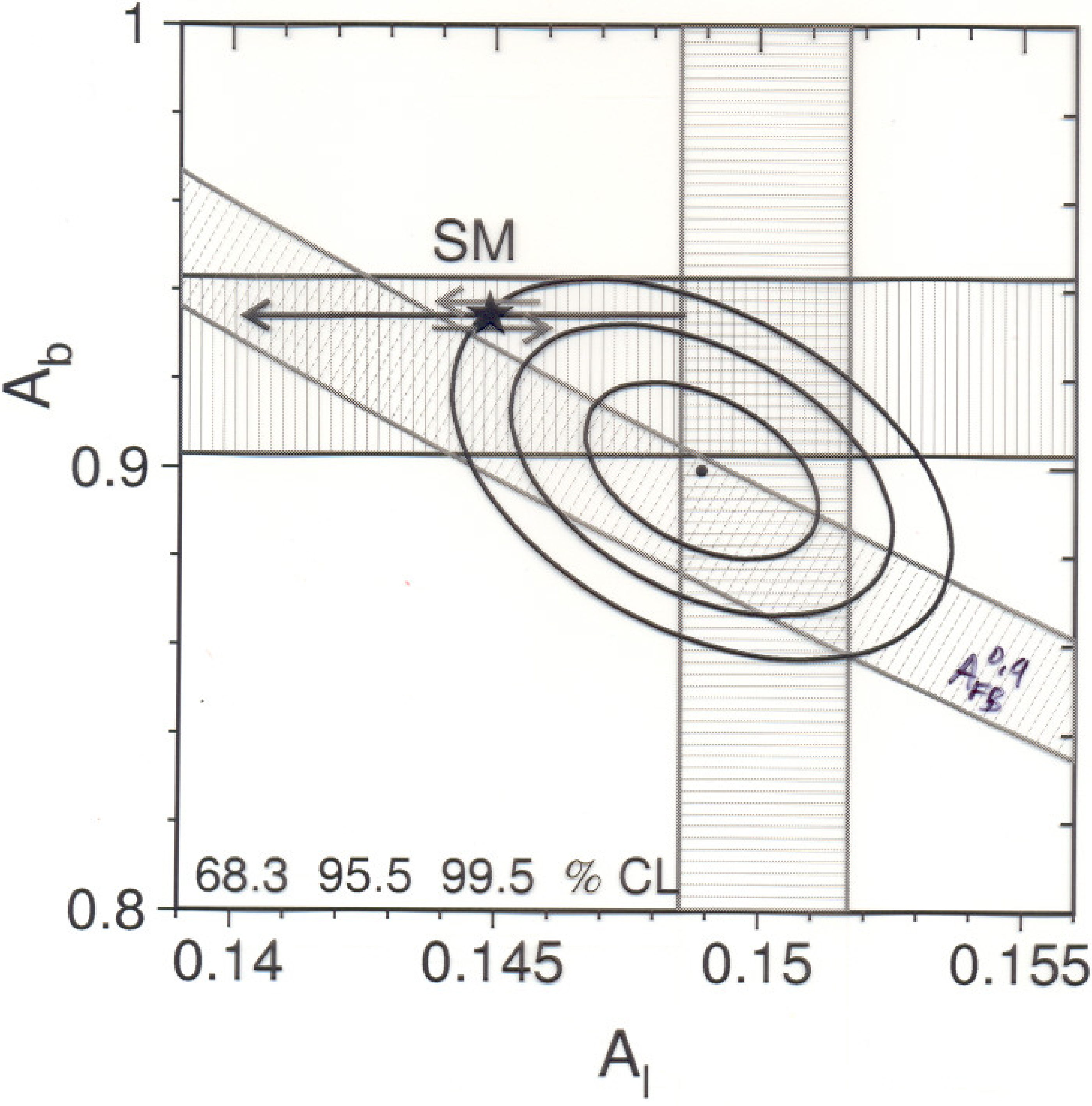
LECTURE 2

ELECTROWEAK FIT USING α, G_F, m_Z, m_t, m_H

(RADIATIVE CORRECTIONS EW)

LECTURE 2

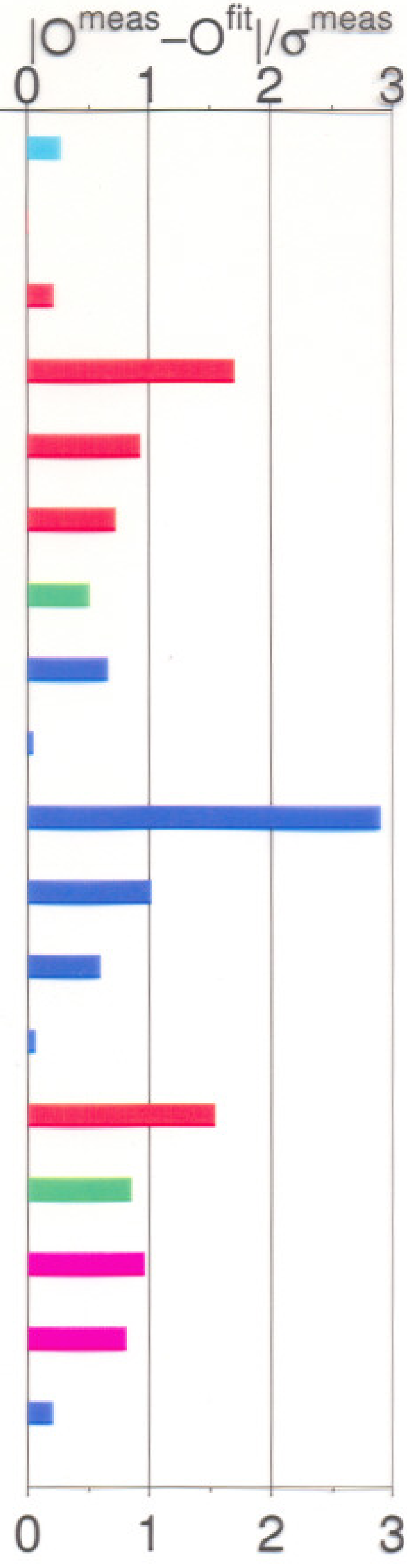
! HIGGS BOSON BLUEBAND PLOT !



SM
68.3 95.5 99.5 % CL
$A_{FB}^{0,q}$
1
0.9
0.8
A_b
0.14
0.145
0.15
0.155
A_l

LECTURE-1 @ THE Z

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	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	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



Discussion

THE Z-POLE OBSERVABLES HAVE BEEN MEASURED WITH HIGH PRECISION. THIS GIVES A COMPLETE PICTURE OF THE NEUTRAL WEAK CURRENT AND THE Z BOSON COUPLINGS.

→ SOME DEVIATIONS BETWEEN A_ℓ (SLC) & $A_{FB}^{0,b}$

THOROUGHLY CHECKED BY EXPERIMENTS AND ASSUMED TO BE A FLUCTUATION

ONLY WITH THE LINEAR COLLIDER WE WILL IMPROVE THIS KNOWLEDGE SIGNIFICANTLY.

→ ALLOWS THE USE OF m_Z AS A PARAMETER FOR INPUT TO SM FITS.

$$(\alpha,\ G_F,\ m_Z,\ m_t,\ m_H)$$

next lecture

to be found.

NEXT LECTURE:

- m_W measurement
- m_{top} measurement
- Global Standard Model fit ⇒ m_H
- interpretation