Standard Model precision measurements
Misure di precisione del modello standard
Lesson 1: Measurements at Z pole

Stefano Lacaprara

INFN Padova

Dottorato di ricerca in fisica
Università di Padova, Dipartimento di Fisica e Astronomia
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Outline

Introduction I

- **Stefano Lacaprara**
  - email: **Stefano.Lacaprara@pd.infn.it**
  - tel: 049 9677100
  - studio: **st 137, Physics Dept. main building,** 1^{st} **floor**
- SM precision measurements 5 lessons, ×2 hours each;
- **G.Simi** will follow covering flavour physics (5x2h)
- **A.Palano** (Bari) will follow covering new exotic states (tetra-penta quark) and Dalitz plot analysis methods in b-physics (6h)
- All the slides available on moodle at https://elearning.unipd.it/dfa/course/view.php?id=756
  - All of you are subscribed to the course on moodle.
- We will also record the class and put the registraton on moodle.

Introduction II

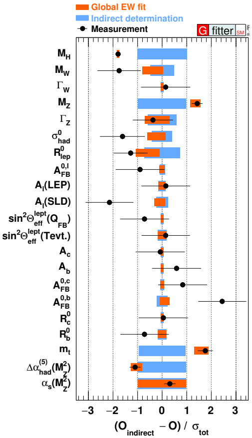
- **Final test:** mandatory as per PhD school rules.
- A short seminar ($\approx 20'$) on one of the topics covered during the course, including discussion with us about topics related to the presentation and the course in general.
  - a list of possible topics will be provided, also topic suggest by students are fine (check with us in advance)
  - the topic should not be the main theme of your PhD work.

Where to start?

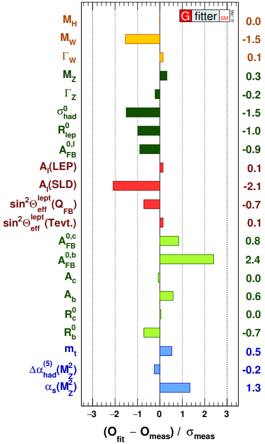
“Begin at the beginning and go on till you come to the end; then stop.” *L.Carrol*

Starting from the end, instead: Global SM fit, *aka* the success of SM.

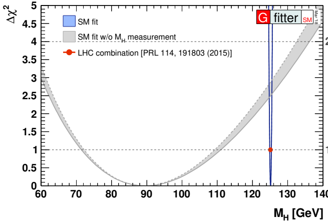
Fit vs indirect vs meas:



Pulls:



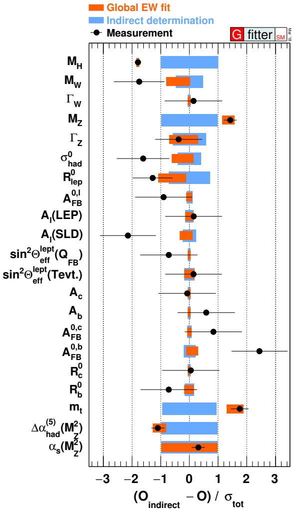
Higgs mass prediction and measurement



Will cover (some) of the experimental aspect of SM precision measurements

Input to global EWK fit

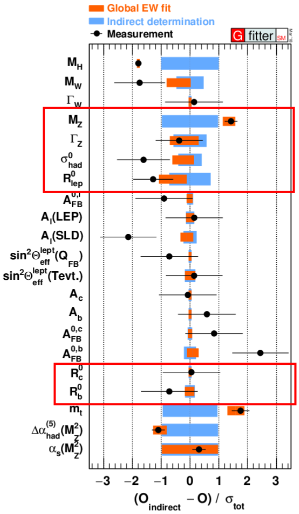
(in parenthesis the order followed in these lessons)



- Higgs mass (5)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron, LHC
- Z-pole observables (1,2)
  - LEP1, SLD
  - M_Z, Γ_Z
  - σ_0^{had}
  - $\sin^2\theta^{lept}_{eff}$ (2)
  - Asymmetries (2)
  - BR $R^0_{lep,b,c} = \Gamma_{had}/\Gamma_{\ell\ell,b\bar{b},c\bar{c}}$
- top mass (4)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$

Input to global EWK fit

(in parenthesis the order followed in these lessons)



- Higgs mass (5)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron, LHC
- Z-pole observables (1,2)
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  - M_Z, Γ_Z
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- top mass (4)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$

Outline

1. Introduction

2. Z-pole observables
    - Standard Model
    - Z lineshape

3. Asymmetries

4. W mass and width

5. Top mass

6. Higgs mass and features

Standard model lagrangian

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu -$$

$$\frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] -$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] -$$

$$g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$

$$\bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 -$$

$$\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 -$$

$$\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$

$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$

$$\partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) -$$

$$\frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Standard model lagrangian

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu -$$

$$\frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] -$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] -$$

$$g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

Just kidding

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$

$$\bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 -$$

$$\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 -$$

$$\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$

$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$

$$\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) -$$

$$\frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

latex from T.Gutierrez, who also noted a sign error somewhere

Standard model lagrangian [1]

$$\mathcal{L} = -\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$\Big\{$ $W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\frac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\frac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu}\right)R$$

$\Big\{$ lepton and quark kinetic energies and interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\frac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\frac{Y}{2}B_{\mu}\right)\phi\right|^2 - V(\phi)$$

$\Big\{$ $W^{\pm}, Z, \gamma,$ and Higgs masses and couplings

$$-G_i(\bar{L}\phi R + \bar{R}\phi^{*\dagger}L).$$

$\Big\{$ lepton and quark masses and coupling to Higgs

gauge fermions Higgs Yukawa

(flavour physics in L and R via CKM (q) and PMNS ν in fermions part)

SM free parameters

masses after spontaneous symmetry breaking:

Free parameters: g, g', $V(\phi) = a\phi^2 + b\phi^4$, G_i

- higgs boson
  - $\nu = \sqrt{\frac{-a}{2b}}$ minimum of Higgs potential (vacuum expectation value)
  - $m_H = 2\sqrt{a}$
- vector bosons
  - $A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}}$, $m_A = 0$;
  - $W^\pm_\mu = \frac{W^1_\mu \mp W^2_\mu}{\sqrt{2}}$, $m_W = \frac{\nu g}{2}$;
  - $Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}}$, $m_Z = \frac{\nu\sqrt{g^2 + g'^2}}{2}$;
- fermions (excluding $\nu' s$)
  - $m_{fermions} = \frac{G_i \nu}{\sqrt{2}}$

Free parameters and boson masses

Excluding the fermion and Higgs masses

g, g', ν OR

electron charge $e = \frac{gg'}{\sqrt{g^2 + g'^2}}$ Millikan experiment

Weinberg angle $\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$ $p\nu$, $p\bar{\nu}$ scattering

or $\sigma(e^-_{pol}d)$ asymmetry

Fermi constant $G_F = \frac{1}{\nu^2\sqrt{2}}$ μ lifetime

Notable SM relations

$$M_W^2 = \frac{e^2}{4G_F\sqrt{2}\sin^2\theta_W} = \frac{\pi\alpha}{\sqrt{2}G_F\sin^2\theta_W}$$

$$M_Z = \frac{M_W}{\cos\theta_W}$$

$$\rho_0 = \frac{M_W^2}{M_Z^2\cos^2\theta_W} = 1$$ Depends only on Higgs sector

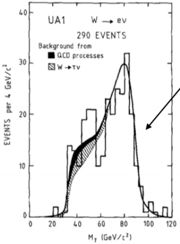
W and Z discovery

Well before LEP

$\sin\theta_W = 0.23 \pm 10\%$, $\alpha = 1/137.035\ldots$, $G_F = 1.16639(1)\cdot 10^{-5}\ GeV^{-2}$o

Prediction: $M_W = 82 \pm 6$ GeV and $M_Z = 92 \pm 5$ GeV

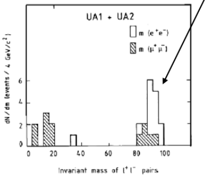
Need a new collider: build $Sp\bar{p}S$ and discover W and Z: UA1[2, 3]/UA2[4, 5]



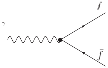
$M_W = 82.7 \pm 1.0_{\text{stat}} \pm 2.7_{\text{syst}}$ GeV

Spot on!

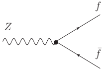
$M_Z = 93.1 \pm 1.0_{\text{stat}} \pm 3.1_{\text{syst}}$ GeV



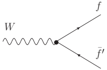
Fermions-vector bosons couplings



$-ieQ^f\gamma_\mu$



$-i\dfrac{g}{\cos\theta_W}\gamma_\mu\dfrac{1}{2}\left(c_V^f - c_A^f\gamma^5\right)$



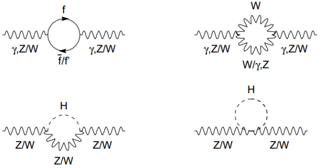
$-i\dfrac{g}{\sqrt{2}}\gamma_\mu\dfrac{1}{2}\left(1-\gamma^5\right)$

Where Q, $c_V^f = \left(T^{(3)} - 2Q\sin^2\theta_W\right)$, and $c_A^f = T^{(3)}$ depends on fermion type:

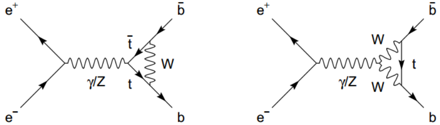
fermion	Q^f	$T^{(3)}$	c_A^f	c_V^f
$(\nu_e,\nu_\mu,\nu_\tau)_L$	0	1/2	1/2	$1/2 = 0.50$
$(e,\mu,\tau)_L$	-1	-1/2	-1/2	$-1/2 + 2\sin^2\theta_W = 0.03$
$(e,\mu,\tau)_R$	-1	0	0	$+2\sin^2\theta_W = 0.47$
$(u,c,t)_L$	2/3	1/2	1/2	$1/2 + 4/3\sin^2\theta_W = 0.19$
$(u,c,t)_R$	2/3	0	0	$4/3\sin^2\theta_W = 0.31$
$(d,s,b)_L$	-1/3	-1/2	-1/2	$-1/2 + 2/3\sin^2\theta_W = 0.34$
$(d,s,b)_R$	-1/3	0	0	$2/3\sin^2\theta_W = 0.16$

Radiative corrections

Correction to propagator



Vertex corrections



Are absorbed using effective (complex) coupling $g_{V/Af}$ and θ_W^{eff}

$$\sin^2\theta_W^{eff} = (1+\Delta\kappa_f)\sin^2\theta_W$$

$$g_{Vf} = \sqrt{(1+\Delta\rho_f)}\,(T^3 - 2Q\sin^2\theta_W^{eff})$$

$$g_{Af} = \sqrt{(1+\Delta\rho_f)}\,(T^3)$$

$$\Delta\rho = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left(\frac{M_t^2}{M_W^2} - \tan^2\theta_W\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right)\right) + \ldots$$

$$\Delta\kappa = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left(\text{cotan}^2\theta_W\frac{M_t^2}{M_W^2} - \frac{10}{9}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right)\right) + \ldots \text{ (extra } \frac{M_f^2}{M_W^2} \text{ for } f = b)$$

Strong dependence on M_{top}, weak on M_H, small dependence to flavour, with exception to b quarks

Radiative corrections (II)

Changes to SM relation due to radiative corrections

(a different way to write the *notable SM relations*)

$$\cos^2\theta_{eff}^{(f)}\sin^2\theta_{eff}^{(f)} = \frac{\pi\alpha(0)}{\sqrt{2}M_Z^2 G_F}\frac{1}{1-\Delta r^{(f)}}$$

where:

$\Delta r^{(f)} = \Delta\alpha + \Delta r_w^{(f)}$ and $\Delta\alpha(s) = \Delta\alpha_{e\mu\tau}(s) + \Delta\alpha_{top}(s) + \Delta\alpha_{had}^{(5)}(s)$

As before, absorb radiative correction using running $\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)}$

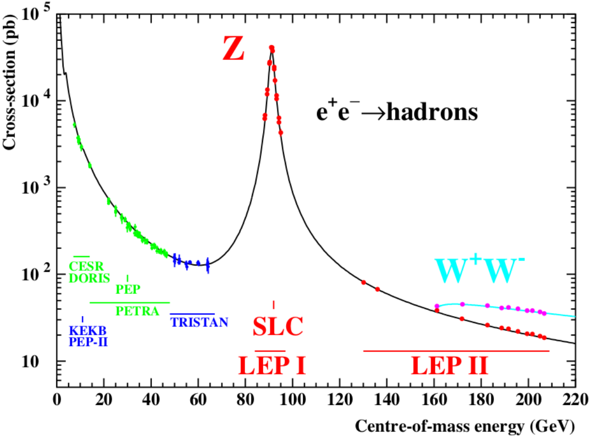
$\alpha(q^2 = 0) = 1/137.035\,999\,76(50) \rightarrow \alpha(M_Z^2) = 1/128.945$

$\Delta r_w^{(f)}$ is weak correction, flavour dependent $\Delta r_w^{(f)} = -\Delta\rho + \ldots$

$\rho = 1 + \Delta\rho$

And now the experimental part... mostly from [6]

Cross sections for Z and W boson production



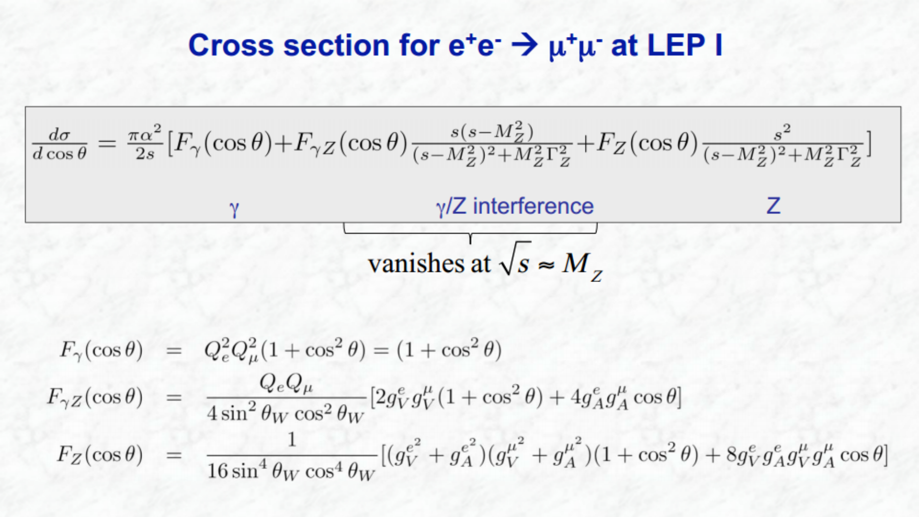
- CLEO@CESR [7]
  - Cornell
- DORIS@DESY [8](Υ)
- PETRA@DESY[9](gluon),
- BABAR@PEP-II [10],
- BELLE@KEKB [11],
- TOPAZ@TRISTAN [12]
  - discovery of $\alpha_{em}(\sqrt{s})$
  - KEK
- SLD@SLC
  - Stanford
- LEP and LEP II

Tristan today at KEK

Cross section for $e^+e^- \rightarrow \mu^+\mu^-$ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\Big[\underset{\gamma}{F_\gamma(\cos\theta)} + \underbrace{\underset{\gamma/Z\text{ interference}}{F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}}_{\text{vanishes at }\sqrt{s}\approx M_Z} + \underset{Z}{F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}\Big]$$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta]
\end{aligned}$$



Cross section for e⁺e⁻ → μ⁺μ⁻ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta)+F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}+F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ γ/Z interference Z

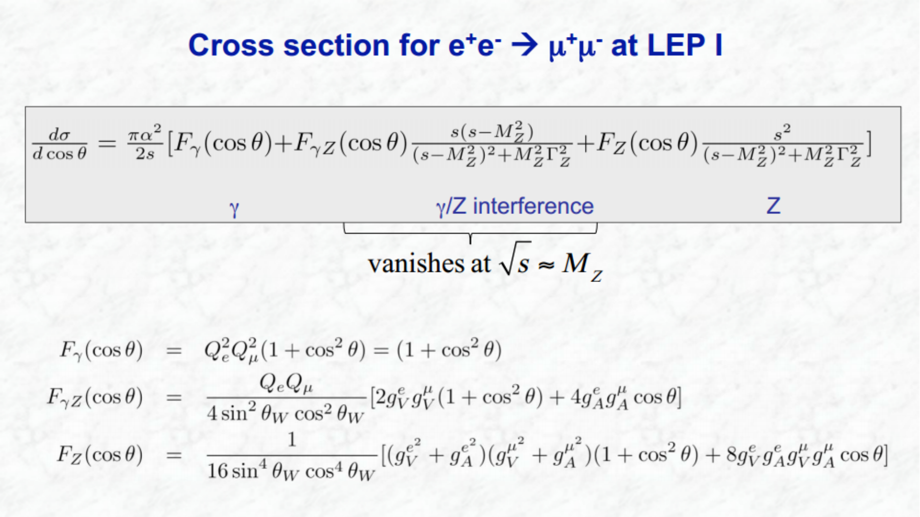
vanishes at $\sqrt{s} \approx M_Z$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W \cos^2\theta_W}[2 g_V^e g_V^\mu (1+\cos^2\theta) + 4 g_A^e g_A^\mu \cos\theta] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W \cos^4\theta_W}[(g_V^{e^2} + g_A^{e^2})(g_V^{\mu^2} + g_A^{\mu^2})(1+\cos^2\theta) + 8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta]
\end{aligned}$$

$\cos\theta$ is the angle between e^- and μ^-

On resonance $\sqrt{s} = M_Z$:

γ/Z vanish ($\sim 0.2\%$ at $\sqrt{s} = M_Z \pm 3 GeV$), $\gamma \sim 1\%$, Z dominates



Cross section for $e^+e^- \to \mu^+\mu^-$ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

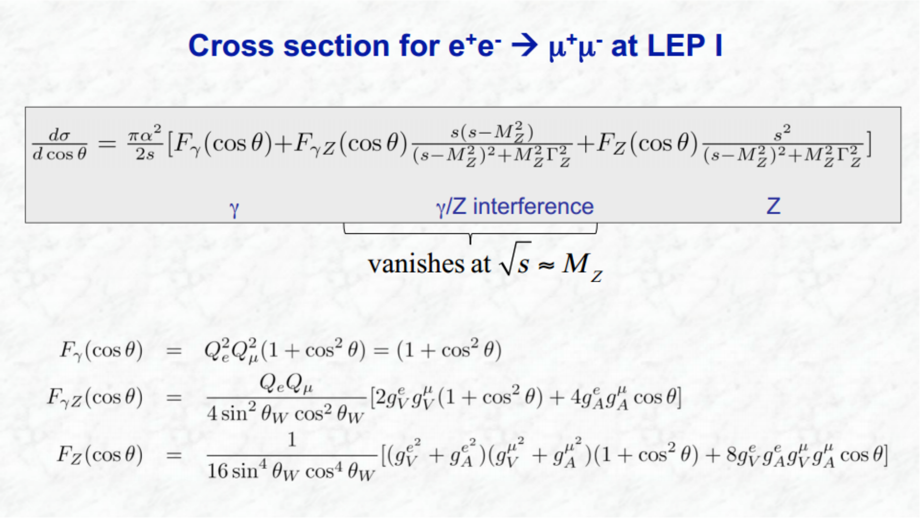
$$\gamma \qquad \underbrace{\gamma/Z\ \text{interference}}_{\text{vanishes at } \sqrt{s}\approx M_Z} \qquad Z$$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta)\\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}\left[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta\right]\\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta\right]
\end{aligned}$$

$\cos\theta$ is the angle between e^- and μ^-

$(1+\cos^2\theta)$ terms contribute to σ_{tot}

$(\cos\theta)$ terms introduce asymmetries forward-backward



Cross section for e⁺e⁻ → μ⁺μ⁻ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ γ/Z interference Z

vanishes at $\sqrt{s} \approx M_Z$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}\left[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta\right] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta\right]
\end{aligned}$$

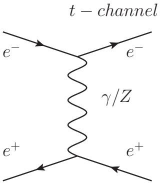
if $e^+e^- \to q\bar{q}$: $\cos\theta$ difficult to know (q vs $\bar{q}$ harder than ℓ vs $\bar{\ell}$)

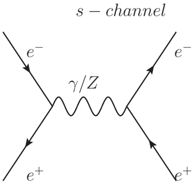
Additional color term $\times N_c$

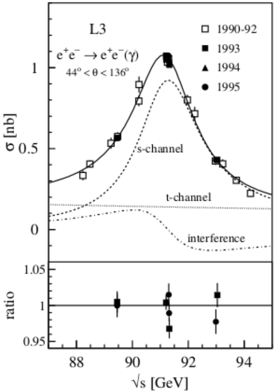
and QCD final state radiative correction $\times(1+\delta_{QCD})$, see later

Cross section for $e^+e^- \rightarrow e^+e^-$

At tree level,
two diagrams:







- s-channel
  - same as $e^+e^- \rightarrow f\bar{f}$;
  - dominates at large angle;
- t-channel
  - Bhabha scattering[a]
  - largely dominates at small scattering angle
    - ★ $\sigma \approx 1/\theta^3$: close to colliding e^- beam
  - very well known QED process;
  - Used to measure LEP luminosity with large angle luminometer

---

[a] Bhabha Homi Jehangir, indian theoretical phys. (Bombay 1909 - m. Bianco 1966)

ISR/FSR

ISR

- Emission of γ from initial state. Important effect (radiative return to Z peak).

$$\sigma(s) = \int_0^1 dz \cdot H_{QED}^{tot}(z,s) \cdot \sigma_{ew}(zs)$$

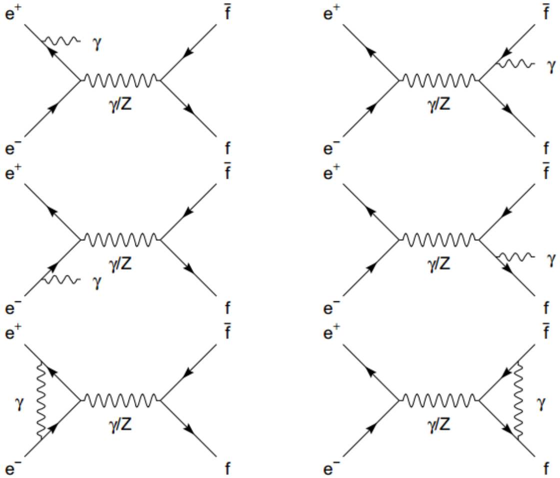
FSR

- both QED and QCD (only for quarks)
- change partial and total width

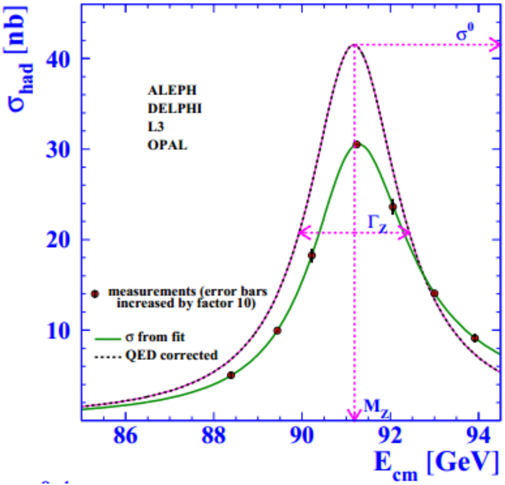
$$\Gamma_h = \Sigma_f \Gamma_0^f (1+\delta_{QED}^f)(1+\delta_{QCD}^f)$$

$$\delta_{QED}^f \approx \frac{3\alpha Q_f^2}{4\pi} \sim 0.17\%,$$

$$\delta_{QCD}^f \approx \frac{\alpha_s(M_Z^2)}{\pi} \sim 3.8\%$$



ISR impact on Z line-shape



- Note the huge importance of ISR radiative (QED) corrections!
- Decrease σ by 30% and shift peak position by $\sim 100\ MeV$
- σ_{had}^{tot} is measured
- value reported and used for electroweak fit, is σ_{had}^{0}, where QED correction are evaluated
- **pseudo-observable**
- Same also for R_f^0, Γ_Z^0, A_{FB}^0, ...

Measurement at the Z line-shape

Considering only hadronic final states:

$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_{had}}{M_Z^2} \frac{s}{(s - M_z^2)^2 + M_Z^2 \Gamma_Z^2}$$ (neglecting the –small– γ contribution)

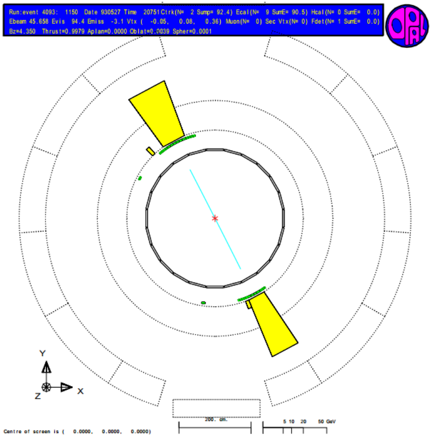
At peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z}$,

where: $\Gamma_{had} = \Sigma_{q \neq t} \Gamma_{q\bar{q}}$ and $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$

We can measure 6+1 parameters:

- Z mass $\mathbf{M_Z}$ from peak position;
- Z total width $\mathbf{\Gamma_Z}$ from peak width;
- hadronic pole cross-section $\sigma_\mathbf{0}$ from peak height;
- Width ratios $\mathbf{R^0_\ell} = \mathbf{R^0_{e,\mu,\tau}} = \mathbf{\Gamma_{had}/\Gamma_{ee,\mu\mu,\tau\tau}}$ from exclusive peak height;
- Width ratios $\mathbf{R^0_b} = \mathbf{\Gamma_{bb}/\Gamma_{had}}$ as above;

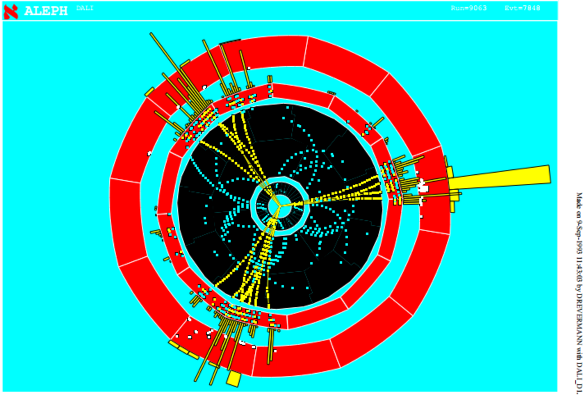
Example of $Z \to ee$ event: OPAL



Very clean environment

Electron ID via tracks and ECAL clusters: $E/p = 1$ ($B = 0.5T$)

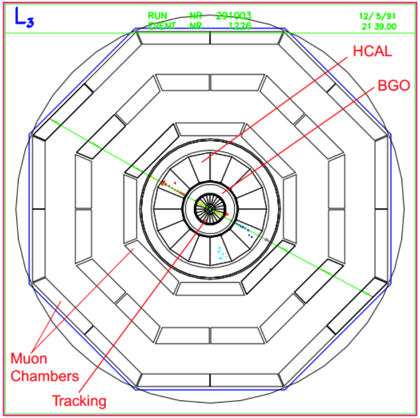
Example of $Z \to qqg$ ALEPH



- This example has 3 jets $e^+e^- \to qqg$

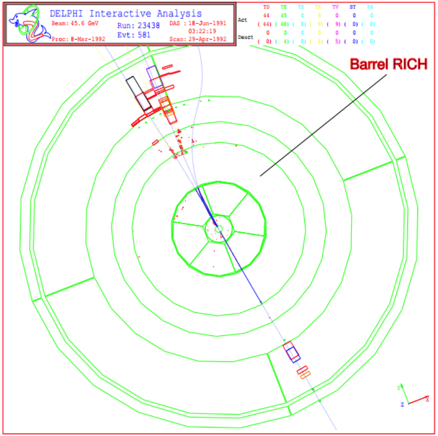
Good example of FSR (QCD): slightly more complex events, larger hadron multiplicity, jet reco (E/HCAL) very good tracker $B = 1.5T$,

Example of $Z \to \mu\mu$ for L3



Even clearer environment: outer tracking detector for μ ID.
L3 had all detectors inside solenoid ($0.5\,T$), excellent ECAL (BGO)

$Z \to \tau\tau$ example for DELPHI

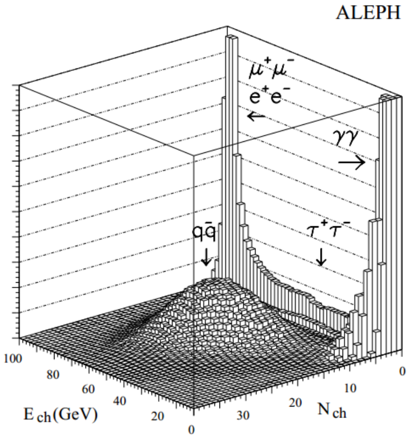


$\tau \to 3h\nu_\tau$ three prong, and $\tau \to h\nu_\tau$ one prong decays

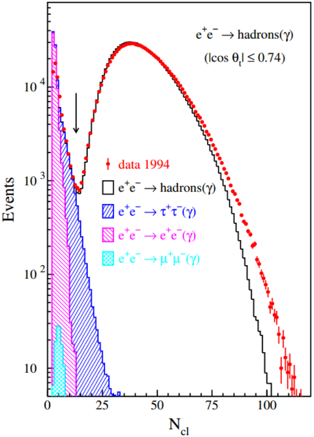
DELPHI had RICH (PID)

Event selection and classification

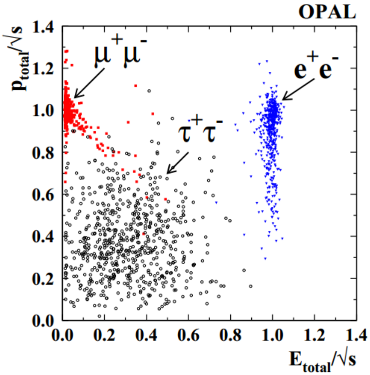
Event selection is quite easy thanks to the very clean environment:
E_{ch} (sum of tracks momenta) vs charged multiplicity.



L3 hadron selection

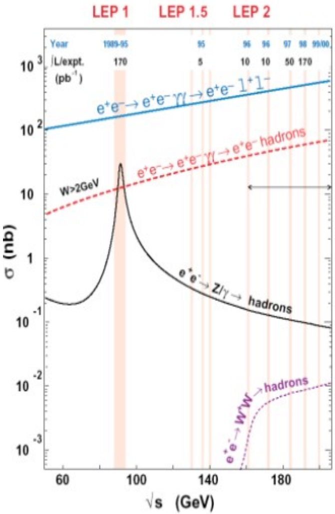


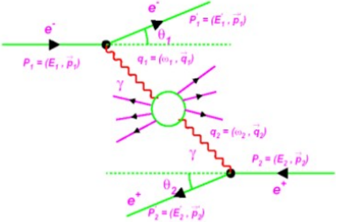
OPAL lepton selection



channel	had	*ee*	$\mu\mu$	$\tau\tau$
efficiency %	99 – 95	98 – 97	98 – 95	70 – 90
background %	0.5	1	1	1 – 3

$\gamma\gamma$ cross section at LEP





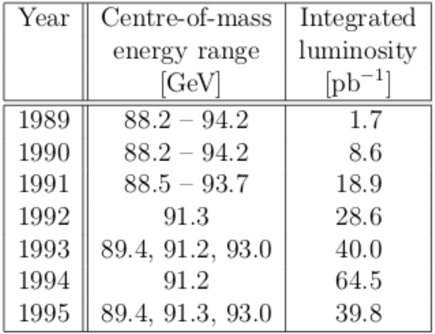
LEP not so clean as one might imagine.

Gamma-Gamma interaction produce a lot of interaction in addition to Z production.

The scattered electrons escape in the beam pipe, undetected.

At Z peak, x-section is ~150nb (vs ~30nb for ee->Z), but it is reduced to ~6nb via pt and $\Delta\phi$ cuts.

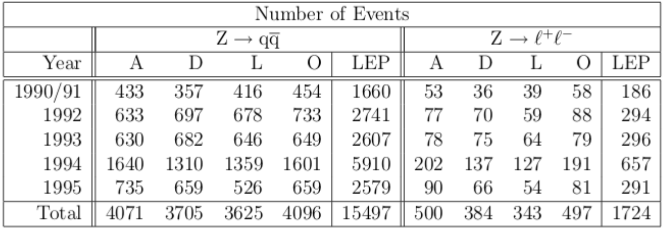
Statistics collected at LEP



Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

In 1990, 91, 93, and 95 a total of $7 + 20\ pb^{-1}$ lumi collected off-peak
Actual $\mathcal{L}$ collected by each experiment $\sim 10 - 15\%$ less

Number of events $\times 1 \cdot 10^3$



Number of Events

	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

Total per experiment:

- 4M $Z \to q\bar{q}$
- 0.5M $Z \to \ell^+\ell^-$

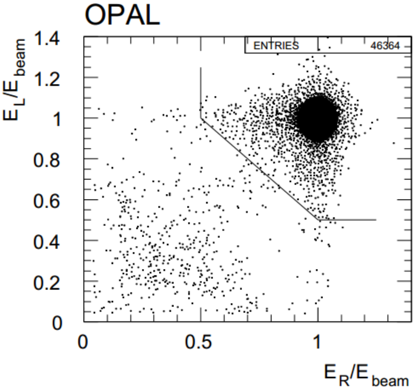
Cross section measurement

$$\sigma_{tot} = \frac{(N_{sel} - N_{bg})}{\epsilon_{sel}\mathcal{L}}$$

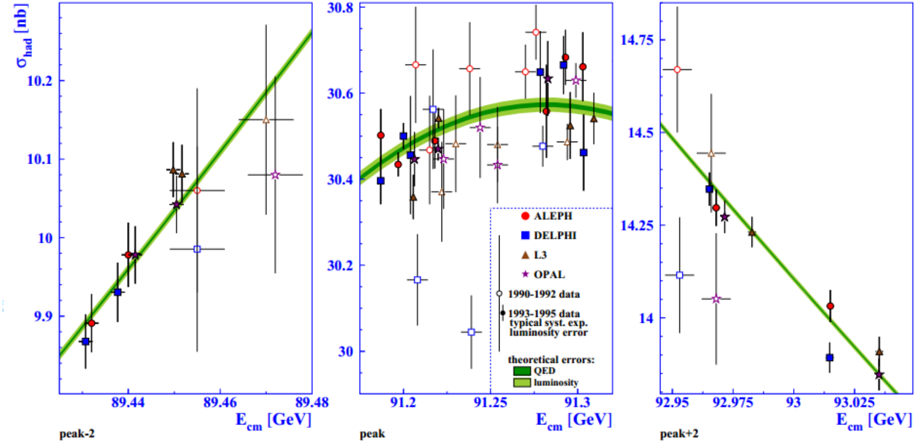
Background and efficiency from MC.

Key issue is luminosity $\mathcal{L}$ measurement

- $e^+e^- \to e^+e^-$ via `t-channel` dominates at low θ.
- Collect Bhabha events with very forward calorimenters 25 to 60 *mrad* from beam.
- x-section goes as $1/\theta^3$: difficult to define the geometrical acceptance of forward calorimeters.
    - common systematic uncert: $\lesssim 0.05\%$,
    - from theory $\sim 0.05\%$.
- at LHC 2.6%, at BelleII 0.7%

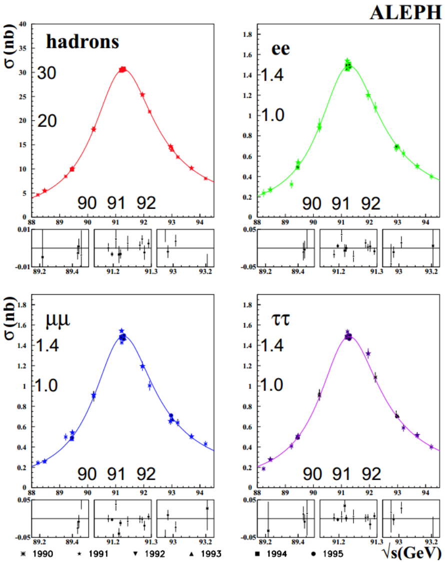


Hadronic cross section vs $\sqrt{s}$

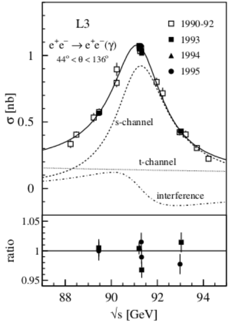


Off-peak measurements $M_Z \pm 2\,\text{GeV}$ are crucial for Γ_Z

Hadronic and leptonic cross-section vs $\sqrt{s}$



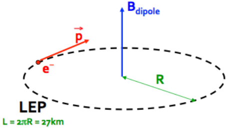
- M_Z from peak position
  - $ee \to ee(\gamma)$ also t-channel and inteference



- Γ_Z from peak width in hadronic final state (larger stats)
- Width ratios R from exclusive cross-sections.
  - $\sigma^0_{had,e,\mu,\tau} \propto \Gamma_e \Gamma_{had,e,\mu,\tau}$
- For M_Z critical is the determination of $\sqrt{s}$ for LEP.

LEP $\sqrt{s}$: resonant depolarization [13]

- Electron with momentum p in uniform vertical magnetic field B



$$E \sim p = eBR = \frac{e}{2\pi} BL$$

- B is not uniform, LEP ring not a circle

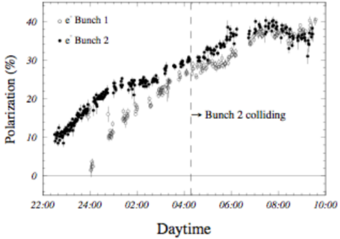
$$E_{beam} = \frac{e}{2\pi} \oint B \cdot d\ell$$

Dipole B field is vertical.

- Electron spin aligns with B
- Sokolov-Ternov theo., patent in '73!.

Due to spin-B interaction: $E_{\uparrow\uparrow} > E_{\uparrow\downarrow}$.

- spin flip due to synchrotron radiation, but flip rate is not symmetric.
- $Pol_{trans} \propto \left(1 - e^{-t/\tau}\right)$, with τ 10h

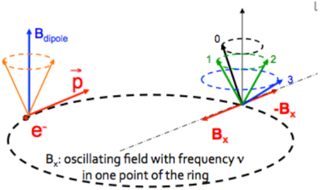


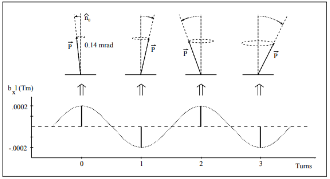
LEP $\sqrt{s}$: resonant depolarization

- spin precess in B field, with a ν proportinal to B (Larmor precession)
  - number of precessions per turn:

$$\nu_s = \frac{g_e - 2}{2} \frac{e}{2\pi m_e} \oint B \cdot d\ell = \frac{g_e - 2}{2} \frac{E_{beam}}{m_e}$$

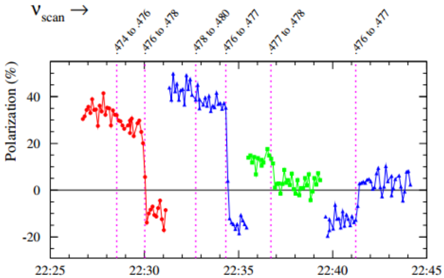
  - ν_s is proportional to E_{Beam}
- apply an additional, radial B field, oscillating with freq ν
  - if $\nu = \nu_s$, the spin is rotated until it becomes horizontal
  - about 10^4 turns (1s) to rotate by 90 deg
  - stochastic sync. rad.: horizonal pol is unstable → destroyed.





LEP $\sqrt{s}$: resonant depolarization

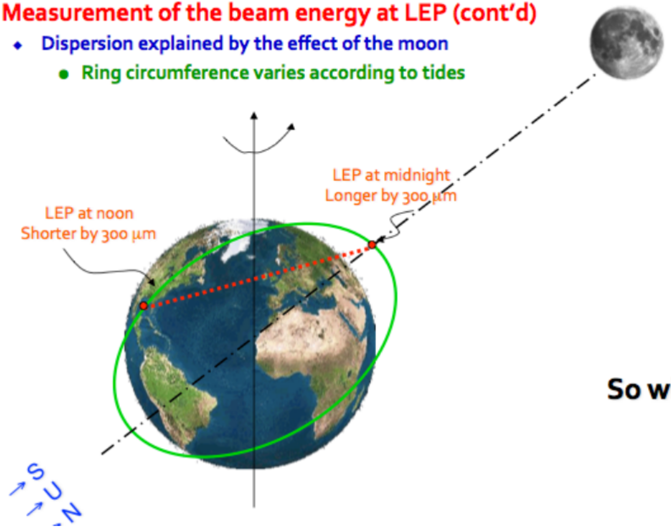
- External freq is: $f_{dep} = (k \pm [\nu]) \cdot f_{rev}$
- where $f_{rev} = 11.25\ kHz$ is that of LEP, k is an integer;
- $[\nu] = \nu_{scan}$ is the non-integer part of the ν of the bending field;
- a freq scan is performed, ν_{scan} is moved slowly
- then the polarization is measured (Compton scattering), then repeat for different bunches



- Process is slow, and can be done only at the end of a fill
- precision (limited to ν_{scan} step) is $\approx 100\,\mathrm{keV}$
- Ultimate LEP $\sqrt{s}$ resolution $\approx 2.2\,\mathrm{MeV}$. Why?

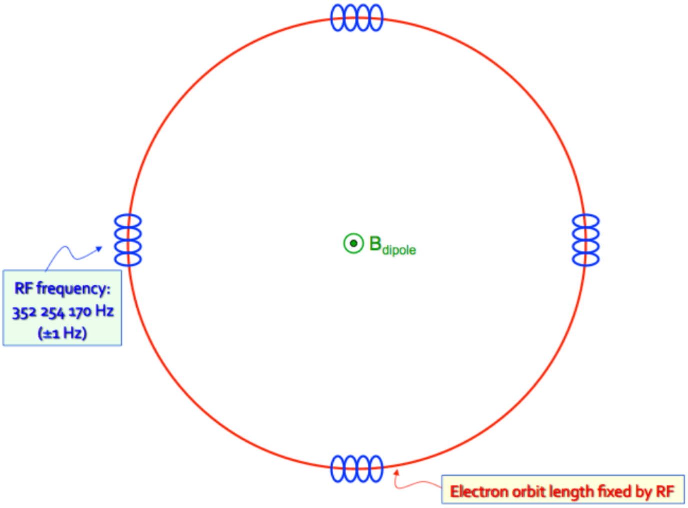
Tidal movement of earth at LEP [14]

- **Measurement of the beam energy at LEP (cont'd)**
  - Dispersion explained by the effect of the moon
    - Ring circumference varies according to tides



So what ?

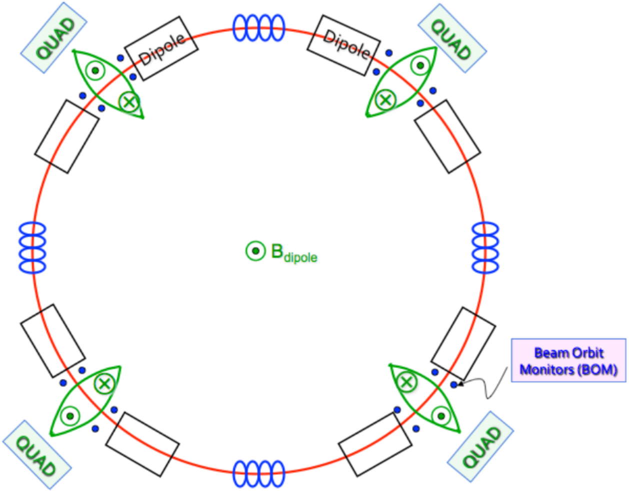
Tidal movement of earth at LEP [14]



RF frequency:
352 254 170 Hz
(±1 Hz)

Electron orbit length fixed by RF

Tidal movement of earth at LEP [14]



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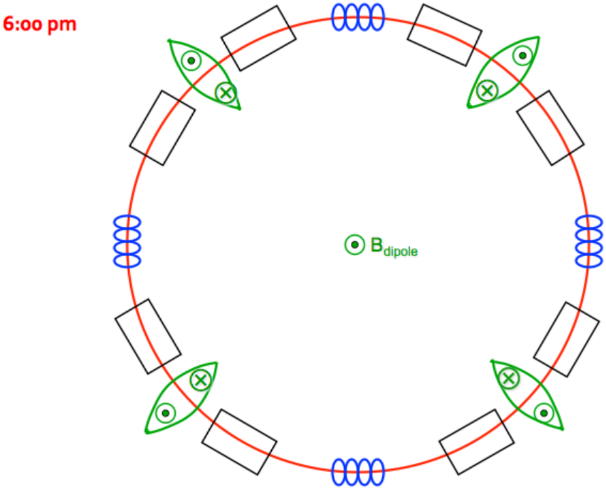

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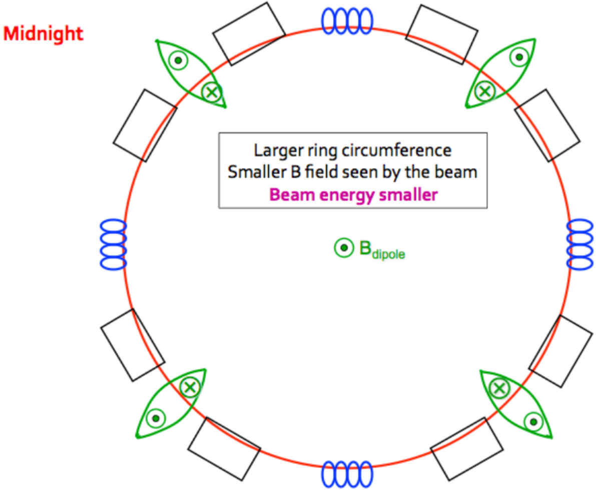
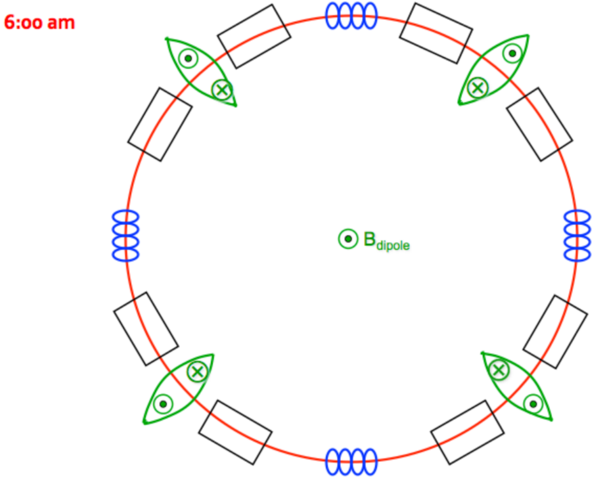


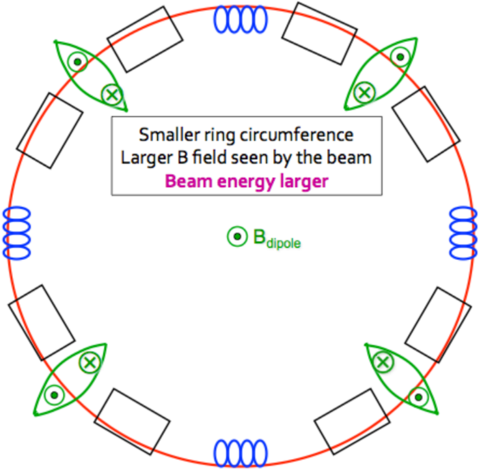
Larger ring circumference
Smaller B field seen by the beam
Beam energy smaller

Tidal movement of earth at LEP [14]



Tidal movement of earth at LEP [14]

Noon



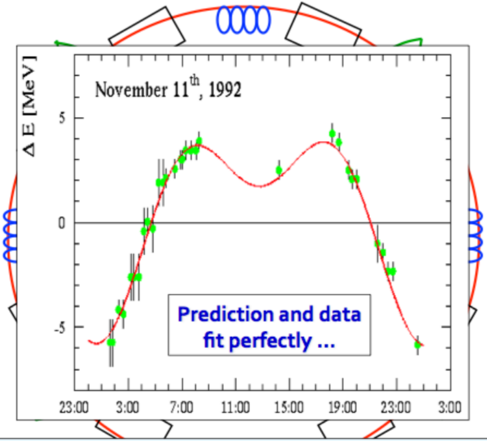
Smaller ring circumference

Larger B field seen by the beam

Beam energy larger

Tidal movement of earth at LEP [14]

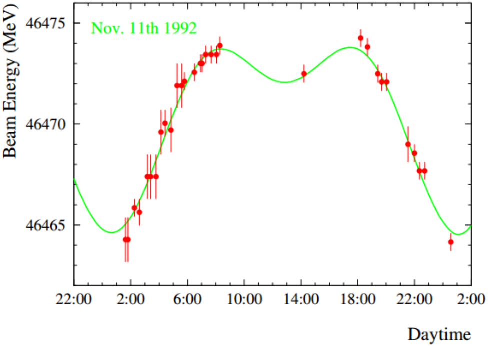
Noon



Prediction and data fit perfectly ...

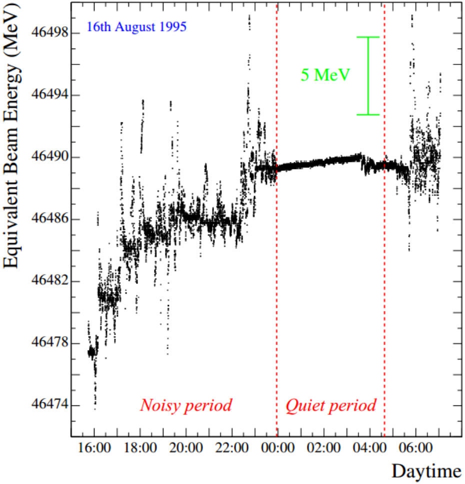
Extrapolation to collision conditions and other time-dependent effects limit the uncertainty on the beam energy to ~1.5 MeV

Tidal movement of earth move the dipole magnets.
Typical displacement 1mm (in 27km), giving a 10 MeV peak-to-peak change.



Other ground distortion from Geneva lake level, heavy rain . . .

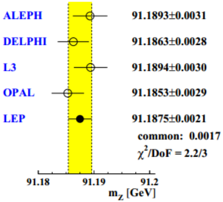
Vagabond electric currents from trains.



Human activity increasing dipole fields during fill: BIAS ≈ 5 MeV

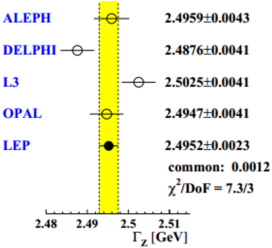
Final M_Z syst from $\sqrt{s}$ about 1.7 MeV

Results



$$M_Z = 91.1875 \pm 0.0021 \;\; GeV \;\; (23ppm)$$

- ± 1.7 MeV LEP $\sqrt{s}$ scale
- ± 0.3 MeV QED corr (ISR)
- ± 0.1 MeV fit parametrization
- ± 0.05 MeV $\mathcal{L}$
- ± 0.05 MeV α_{had}
- Contribution $\gamma - Z$ interference



$$\Gamma_Z = 2.4952 \pm 0.0023 \;\; GeV$$

- ± 1.2 MeV from QED corr (ISR)
- ± 0.2 MeV from QED corr (FSR)
- ± 0.1 MeV from fit parametrization

Lepton universality

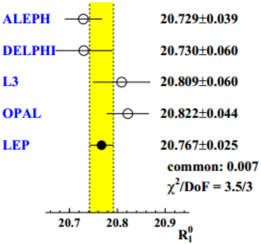
Partial width: $\mathbf{R}^0_\ell = \Gamma_{\text{had}}/\Gamma_\ell$

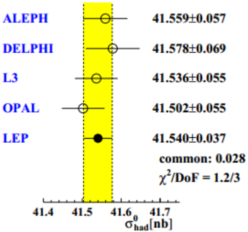
$$R^0_e = 20.804 \pm 0.050$$
$$R^0_\mu = 20.785 \pm 0.033$$
$$R^0_\tau = 20.764 \pm 0.045$$

R^0_τ expected to be smaller due to $m_\tau > m_\mu \gg m_e$

Assuming lepton universality:

$$R^0_\ell = 20.767 \pm 0.25$$
$$\sigma^0_{had} = 41.541 \pm 0.037\ nb$$



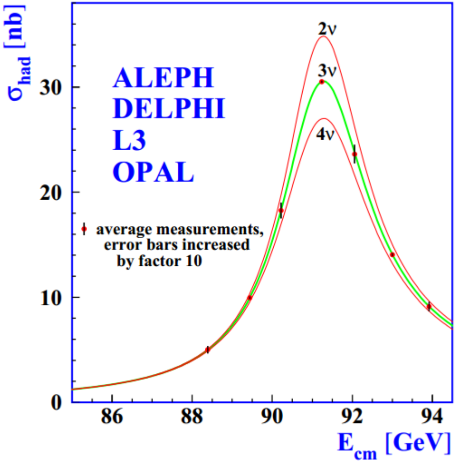


Number of neutrino families

With lepton universality:

$$\begin{aligned}\Gamma_Z &= 2495.2 \pm 2.3 \ MeV \\ \Gamma_{had} &= 1744.4.8 \pm 2.0 \ MeV \\ \Gamma_\ell &= 83.895 \pm 0.086 \ MeV \\ \Gamma_{inv} &= 499.0 \pm 1.5 \ MeV\end{aligned}$$

- $\Gamma_{inv}^{SM} = 501.7 \pm 0.2^{+0.1}_{-0.9}(m_H) \ MeV$
- $\Gamma_{inv}^{x} = -2.7^{+1.8}_{-1.5} \ MeV$
- $N_\nu = 2.9840 \pm 0.0082$
- $\delta N_\nu \approx 10.5 \frac{\delta n_{had}}{n_{had}} \oplus 3.0 \frac{\delta n_{lep}}{n_{lep}} \oplus 7.5 \frac{\delta \mathcal{L}}{\mathcal{L}}$



$R_{b,c}$

It is not possible, in general, to distinguish quark flavour, with the exception of b and c-quarks, using different techniques:
Useing two features: long b (and c) lifetime and exclusive b and c decays.

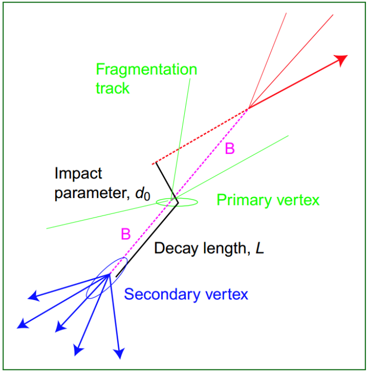
- lifetime tagging;
  - $c\tau$ for b is $\sim 450 \mu m$ (in lab $\times\gamma$)
  - $c\tau$ for c is $\sim 150 \mu m$ (in lab $\times\gamma$)
  - detect displaced secondary vertex via impact parameter or decay length measurements
- exclusive decays:
  - leptonic decay;
  - decay with D mesons;

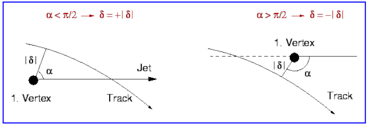
Correction to $R_{b,c}$ from QCD (gluon radiation from final state quarks), in addition to QED correction and LEP energy scale.

lifetime tagging

Heavy hadrons have long lifetime and large boost at LEP

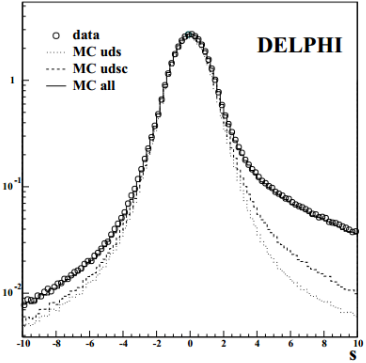
- Impact Parameter (d_0):
  - d_0 is the distance of closest approach from the primary vertex of the extrapolated track;
  - the resolution depends on the track reconstruction and primay vertex knowledge;
  - silicon microvertex close to beam pipe for resolution, PV depends on accelerator (SLC better than LEP);
  - **a signed quantity** wrt the jet dir.
    - badly measured track can intercept the "wrong-side" of the beam-spot;
  - $d_0^{sign} = d_0/\sigma(d_0)$;
- Decay length (L)
  - Signed as well



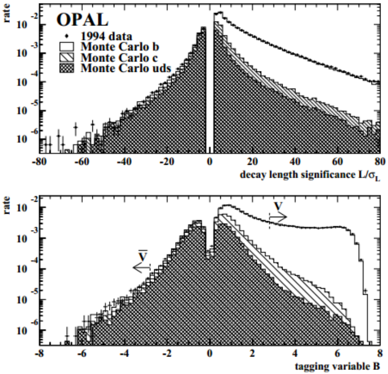


lifetime tagging

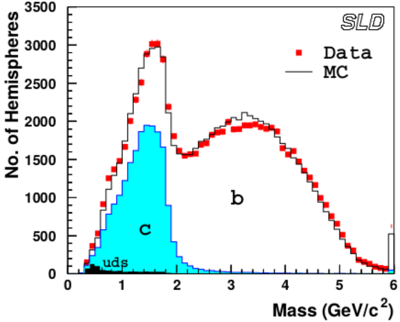
d_0 significance



L significance and NN



$b \leftrightarrow c$ separation via M_{vtx}



Resolution

$\delta_{IP} \sim 16 - 100\mu m \; (R\phi/Z)$,

$\delta_b \sim 300\mu m$

b-tagging performance

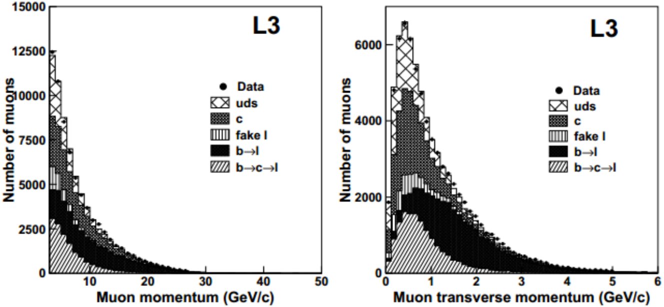
	ALEPH	DELPHI	L3	OPAL	SLD
b Purity [%]	97.8	98.6	84.3	96.7	98.3
b Efficiency [%]	22.7	29.6	23.7	25.5	61.8

Lepton tagging

A lepton inside a jet is a stong indication of a *b* or *c* flavour.

To distinguish from b to $\bar{b}$ use semileptonic decay of b quarks.

- $b \to \ell^-$; $\approx 10\%$
- $c \to \ell^+$; $\approx 13\%$
- $b \to c \to \ell^+$ cascade decay ;



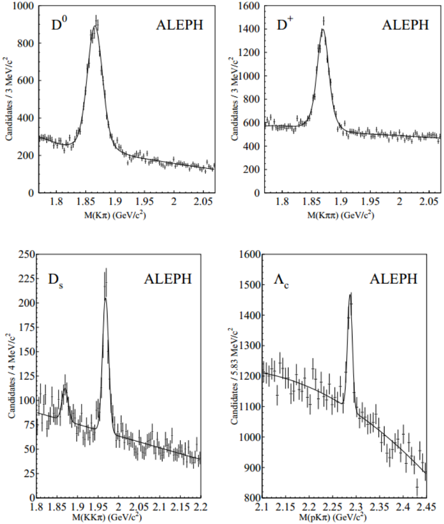
- Distinguish between direct and cascade decay using lepton p_T and p
- lower purity and efficiency wrt lifetime tagger

D-Meson Tags

Tagging via reconstruction of charmed meson and barions in jet:

direct evidence of a jet originated by an heavy quark.

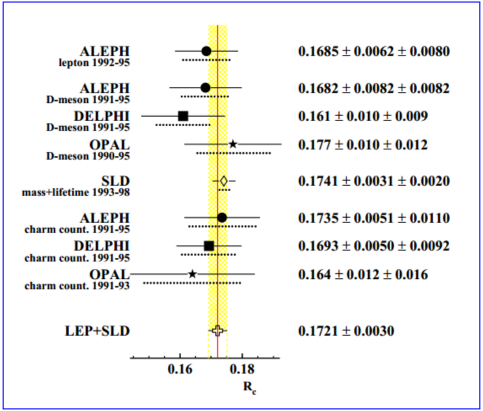
- low $\mathcal{B} \sim \mathcal{O}(\%)$
- $b \to c$ fragmentation is small
- distinguish c from b decay by charmed mesons momentum;
  - $D_0 \to K^- \pi^+$
  - $D^+ \to K^- \pi^+ \pi^+$
  - $D_s \to K^+ K^- \pi^+$
  - $\Lambda_c^+ \to p K^- \pi^+$
  - $D^{*+} \to \pi^+ D^0$
    - slow π^+, no need for PID



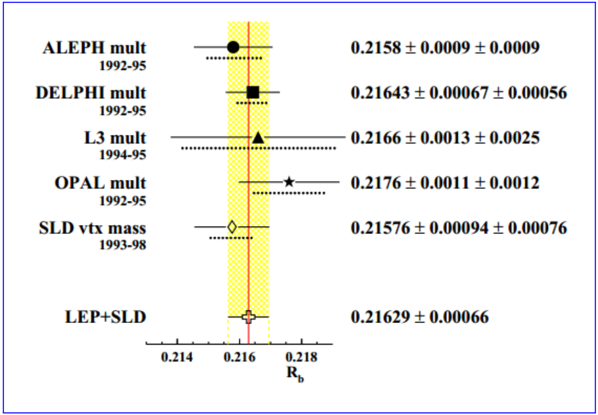
R_q for b and c

Single-tag (one b/c) or double-tag methods (both sides: allows to extract tag ε from data)

charm R_c



beauty R_b

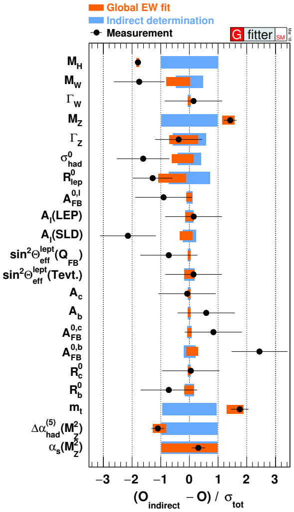


Dotted line is systematic uncertainties

Contribution from SLD (next lesson): smaller interaction region, better b-tagging, smaller uncertainties

Input to global EWK fit

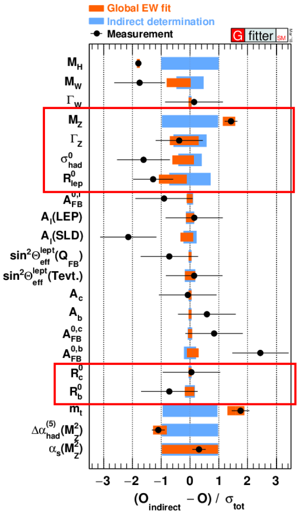
(in parenthesis the order followed in these lessons)



- Higgs mass (5)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron, LHC
- Z-pole observables (1,2)
  - LEP1, SLD
  - M_Z, Γ_Z
  - σ_0^{had}
  - $\sin^2\theta_{eff}^{lept}$
  - Asymmetries (2)
  - BR $R^0_{lep,b,c} = \Gamma_{had}/\Gamma_{\ell\ell,b\bar{b},c\bar{c}}$
- top mass (4)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$

Input to global EWK fit

(in parenthesis the order followed in these lessons)



- Higgs mass (5)
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Further Reading I

- F. Halzen and A. D. Martin, *Quarks and Leptons: an introductory course in modern particle physics*. Wiley, New York, USA, 1984.
- G. Arnison, A. Astbury, B. Aubert, C. Bacci, G. Bauer, A. Bézaguet, R. Böck, T. Bowcock, M. Calvetti, T. Carroll, P. Catz, P. Cennini, S. Centro, F. Ceradini, S. Cittolin, D. Cline, C. Cochet, J. Colas, M. Corden, D. Dallman, M. DeBeer, M. D. Negra, M. Demoulin, D. Denegri, A. D. Ciaccio, D. DiBitonto, L. Dobrzynski, J. Dowell, M. Edwards, K. Eggert, E. Eisenhandler, N. Ellis, P. Erhard, H. Faissner, G. Fontaine, R. Frey, R. Frühwirth, J. Garvey, S. Geer, C. Ghesqui‘ere, P. Ghez, K. Giboni, W. Gibson, Y. Giraud-H’eraud, A. Givernaud, A. Gonidec, G. Grayer, P. Gutierrez, T. Hansl-Kozanecka, W. Haynes, L. Hertzberger, C. Hodges, D. Hoffmann, H. Hoffmann, D. Holthuizen, R. Homer, A. Honma, W. Jank, G. Jorat, P. Kalmus, V. Karimaki, R. Keeler, I. Kenyon, A. Kernan, R. Kinnunen, H. Kowalski, W. Kozanecki, D. Kryn, F. Lacava, J.-P. Laugier, J.-P. Lees, H. Lehmann, K. Leuchs, A. Lévêque, E. Linglin, E. Locci, M. Loret, J.-J. Malosse, T. Markiewicz, G. Maurin, T. McMahon, J.-P. Mendiburu, M.-N. Minard, M. Moricca, H. Muirhead, F. Muller, A. Nandi, L. Naumann, A. Norton, A. Orkin-Lecourtois, L. Paoluzi, G. Petrucci, G. Mortari, M. Pimia, A. Placci, E. Radermacher, J. Ransdell, H. Reithler, J.-P. Revol, J. Rich, M. Rijssenbeek, C. Roberts, J. Rohlf, P. Rossi, C. Rubbia, B. Sadoulet, G. Sajot, G. Salvi, J. Salvini, J. Sass, A. Saudraix, A. Savoy-Navarro, D. Schinzel, W. Scott, T. Shah, M. Spiro, J. Strauss, K. Sumorok, F. Szoncso, D. Smith, C. Tao, G. Thompson, J. Timmer, E. Tscheslog, J. Tuominiemi, S. V. der Meer, J.-P. Vialle, J. Vrana, V. Vuillemin, H. Wahl, P. Watkins, J. Wilson, Y. Xie, M. Yvert, and E. Zurfluh, “Experimental observation of isolated large transverse energy electrons with associated missing energy at s=540 gev,” *Physics Letters B* **122** no. 1, (1983) 103 – 116. http://www.sciencedirect.com/science/article/pii/0370269383911772.
- **UA1** Collaboration, G. Arnison *et al.*, “Experimental Observation of Lepton Pairs of Invariant Mass Around 95-GeV/c**2 at the CERN SPS Collider,” *Phys. Lett.* **B126** (1983) 398–410. [,7.55(1983)].
- M. Banner, R. Battiston, P. Bloch, F. Bonaudi, K. Borer, M. Borghini, J.-C. Chollet, A. Clark, C. Conta, P. Darriulat, L. D. Lella, J. Dines-Hansen, P.-A. Dorsaz, L. Fayard, M. Fraternali, D. Froidevaux, J.-M. Gaillard, O. Gildemeister, V. Goggi, H. Grote, B. Hahn, H. Hanni, J. Hansen, P. Hansen, T. Himel, V. HungerbÃ$\frac{1}{4}$hler, P. Jenni, O. Kofoed-Hansen, E. Lançon, M. Livan, S. Loucatos, B. Madsen, P. Mani, B. Mansoulie, G. Mantovani, L. Mapelli, B. Merkel, M. Mermikides, R. MÃ¸llerud, B. Nilsson, C. Onions, G. Parrour, F. Pastore, H. Plothow-Besch, M. Polverel, J.-P. Repellin, A. Rothenberg, A. Roussarie, G. Sauvage, J. Schacher, J. Siegrist, H. Steiner, G. Stimpfl, F. Stocker, J. Teiger, V. Vercesi, A. Weidberg, H. Zaccone, and W. Zeller, “Observation of single isolated electrons of high transverse momentum in events with missing transverse energy at the cern pp collider,” *Physics Letters B* **122** no. 5, (1983) 476 – 485. http://www.sciencedirect.com/science/article/pii/0370269383916052.

Further Reading II

- **UA2** Collaboration, P. Bagnaia *et al.*, “Evidence for Z0 —¿ e+ e- at the CERN anti-p p Collider,” *Phys. Lett.* **B129** (1983) 130–140. [,7.69(1983)].
- **ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group** Collaboration, “Precision electroweak measurements on the Z resonance,” *Phys.Rept.* **427** (2006) 257–454, `arXiv:hep-ex/0509008 [hep-ex]`.
- **CLEO** Collaboration, “Measurement of the Total Hadronic Cross Section in e+e- Annihilations below 10.56-GeV,” *Phys. Rev.* **D76** (2007) 072008, `arXiv:0706.2813 [hep-ex]`.
- H. Albrecht, R. Childers, C. Darden, G. Drews, H. Hasemann, W. Schmidt-Parzefall, H. Schröder, H. Schulz, F. Selonke, E. Steinmann, R. Wurth, W. Hofmann, A. Markees, D. Wegener, K. Schubert, J. Stiewe, R. Waldi, S. Weseler, P. Böckmann, L. Jönsson, M. Danilov, Y. Semenov, I. Tichomirov, and Y. Zaitsev, “The hadronic cross section of electron-positron annihilation at 9.5 gev and the υ and υ' resonance parameters,” *Physics Letters B* **116** no. 5, (1982) 383 – 386. `http://www.sciencedirect.com/science/article/pii/0370269382903057`.
- P. Söding, “On the discovery of the gluon,” *The European Physical Journal H* **35** no. 1, (Jul, 2010) 3–28. `https://doi.org/10.1140/epjh/e2010-00002-5`.
- **BaBar** Collaboration, “Measurement of $e^+e^- \to$ hadrons cross sections at BABAR, and implication for the muon $g-2$,” *PoS* **Hadron2013** (2013) 126, `arXiv:1402.0618 [hep-ex]`.
- H. Nakazawa, “Measurement of hadronic cross sections with isr/two-photon processes at belle,” *Nuclear and Particle Physics Proceedings* **260** (2015) 98 – 101. `http://www.sciencedirect.com/science/article/pii/S2405601415000796`. The 13th International Workshop on Tau Lepton Physics.
- I. Levine, D. Koltick, B. Howell, E. Shibata, J. Fujimoto, T. Tauchi, K. Abe, T. Abe, I. Adachi, K. Adachi, M. Aoki, M. Aoki, K. Emi, R. Enomoto, H. Fujii, K. Fujii, T. Fujii, N. Fujiwara, H. Hayashii, H. Hirano, H. Ikeda, H. Ikeda, Y. Inoue, S. Itami, R. Itoh, H. Iwasaki, M. Iwasaki, R. Kajikawa, K. Kaneyuki, S. Kato, S. Kawabata, H. Kichimi, M. Kobayashi, H. Mamada, K. Miyabayashi, A. Miyamoto, K. Nagai, K. Nakabayashi, M. Nakamura, E. Nakano, O. Nitoh, S. Noguchi, A. Ochi, F. Ochiai, N. Ohishi, Y. Ohnishi, Y. Ohshima, H. Okuno, T. Okusawa, A. Sugiyama, S. Suzuki, K. Takahashi, T. Takahashi, T. Tanimori, Y. Teramoto, M. Tomoto, T. Tsukamoto, T. Tsumura, S. Uno, K. Watanabe, Y. Watanabe, A. Yamamoto, and M. Yamauchi, “Measurement of the electromagnetic coupling at large momentum transfer,” *Phys. Rev. Lett.* **78** (Jan, 1997) 424–427. `http://link.aps.org/doi/10.1103/PhysRevLett.78.424`.

Further Reading III

- L. Arnaudon, B. Dehning, P. Grosse-Wiesmann, R. Jacobsen, M. Jonker, J. Koutchouk, J. Miles, R. Olsen, M. Placidi, R. Schmidt, J. Wenninger, R. Assmann, and A. Blondel, "Accurate determination of the lep beam energy by resonant depolarization," *Zeitschrift für Physik C Particles and Fields* **66** no. 1-2, (1995) 45–62. `http://dx.doi.org/10.1007/BF01496579`.
- L. Arnaudon, R. Assmann, A. Blondel, B. Dehning, G. E. Fischer, P. Grosse-Wiesmann, A. Hofmann, R. Jacobsen, J. P. Koutchouk, J. Miles, R. Olsen, M. Placidi, R. Schmidt, and J. Wenninger, "Effects of terrestrial tides on the LEP beam energy." SL Divisional Reports - 1994, http://cds.cern.ch/record/90793.
- R. N. Cahn and G. Goldhaber, *The Experimental Foundations of Particle Physics*.
  Cambridge University Press, second ed., 2009.
  `http://dx.doi.org/10.1017/CBO9780511609923`.
  Cambridge Books Online.

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