LEP Results - 1

Pippa Wells – CERN

1: Z Resonance

- The LEP machine, beam energy, detectors
- Z lineshape: cross-sections, luminosity
- Lepton Forward-Backward asymmetry, polarised asymmetries
- Number of light neutrinos, lepton couplings

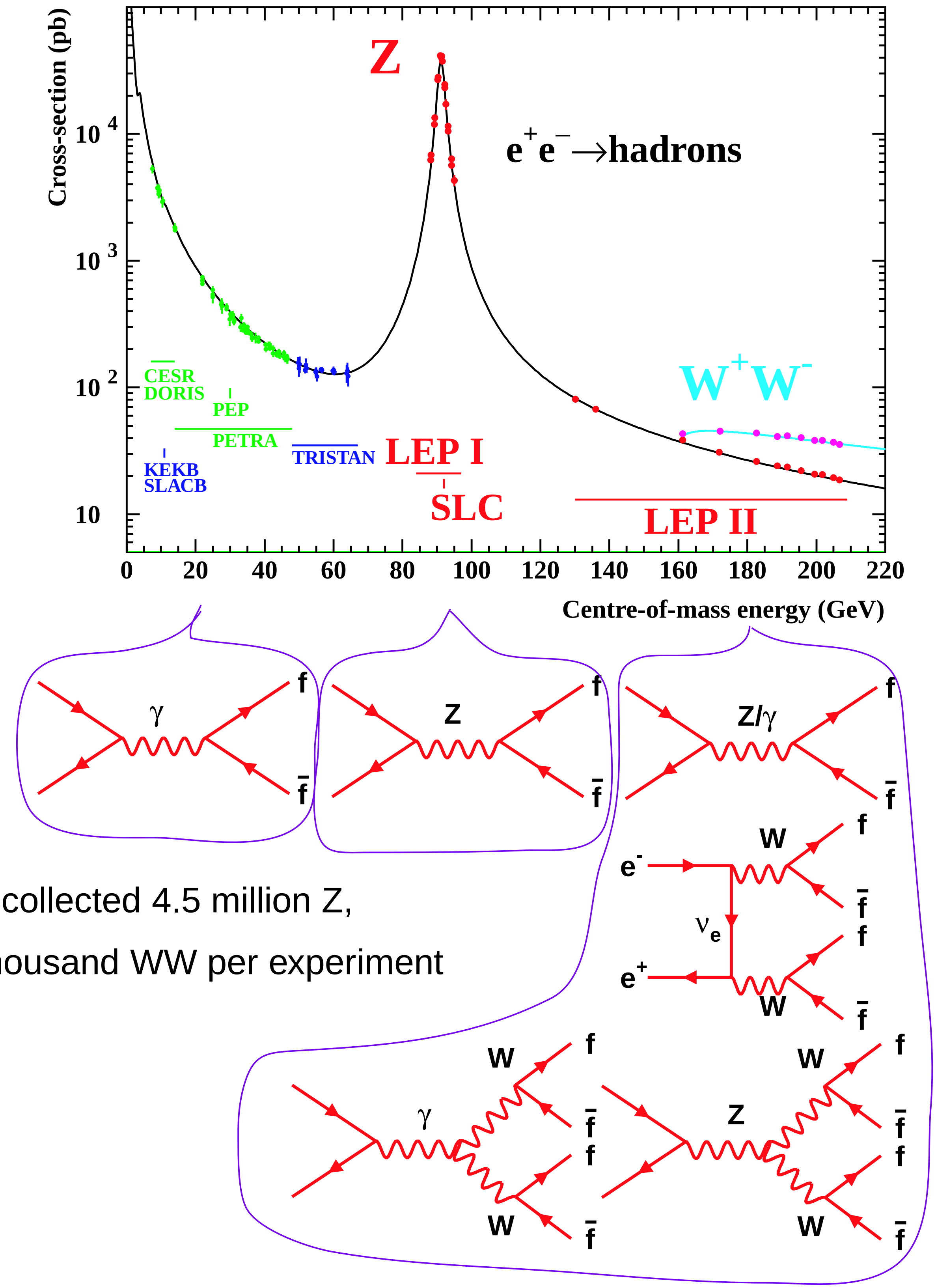
2: LEP2 Results

- WW and ZZ physics at LEP2
- b-tagging, electroweak physics with heavy flavours (b and c)
- Global electroweak fits
- Standard Model Higgs boson - a hint?

LEP Time Line

1960's	Glashow-Weinberg-Salam $SU(2) \times U(1)$ theory of electroweak interactions, prediction of W and Z gauge bosons.
1972	$SU(3)_{\rm colour}$ QCD theory of strong interactions
1976	CERN study group considers Large Electron-Positron storage ring, $\sqrt{s} = 2 \times 100$ GeV, $\mathcal{L} \approx 10^{32}$cm^{-2}s^{-1}
1979	Observation of gluon at PETRA.
	December: 27 km design approved by CERN council
1983	Chose LEP experiments.
	W and Z observed at CERN SPS
1989	Scooped! $\mathrm{e^+e^-}$ collisions at Z in MARK II at SLC.
	First collisions in LEP with $\sqrt{s} \approx M_{\rm Z}$
1995	Gradual installation of LEP2 SC RF system starts
	Energy raised to $\sqrt{s} = 140$ GeV at end of year.
	Top quark observation at Fermilab confirmed
1996	W pair threshold crossed at LEP...
1999	Nobel Prize for 't Hooft and Veltman for "for elucidating the quantum structure of electroweak interactions in physics"
2000	Last year of LEP running with $\sqrt{s}$ up to 209 GeV.

Electron-positron annihilation



LEP collected 4.5 million Z,

12 thousand WW per experiment

Z resonance lineshape

To measure the Z mass, total width and cross-section, partial widths (branching ratios) and couplings:

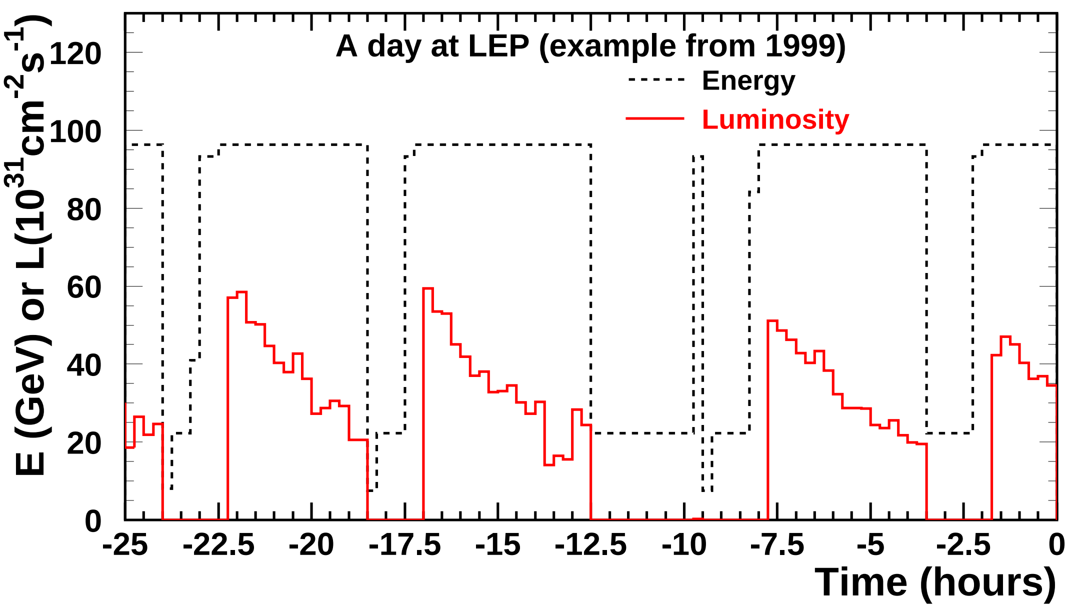
- LEP machine gives $\mathrm{e^+e^-}$ collisions at a few energies on and near the Z peak and precise measurement of E_{beam}
- Detectors ALEPH, DELPHI, L3, OPAL distinguish Z final states and measure the luminosity from QED t-channel process $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}$ (Bhabha scattering)

$$\sigma(\sqrt{s}) = (N_{\mathrm{observed}} - N_{\mathrm{background}})/\epsilon\mathcal{L}$$

- Monte Carlo simulation of the signal efficiency and background.
- Theoretical prediction of the lineshape
- Match precision from 4.5 million Z events per experiment - relative statistical error about 5×10^{-4}.
- Several thousand people involved
- $\sigma(M_{\mathrm{Z}}) \approx 340$ MeV from UA2+CDF in 1989. Hoped to reduce to ≈ 10 MeV (limited by beam energy precision)
- Count the number of generations. 2.5 generations were known in 1989, top quark and ν_τ not yet established. Number of light neutrinos limited by big bang nucleosynthesis to $\lesssim 4$. Expected precision of about ± 0.2 on the number.

The LEP Collider

A good fill lasts around 10 h (LEP1 at Z) or 3 h (LEP2)



Beam energy - resonant depolarisation

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

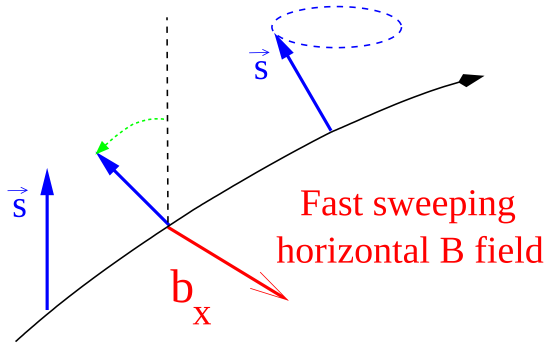
Spin of electrons aligns with vertical B field due to synchrotron radiation. Slow (hours) build up of transverse polarisation IF beam orbit sufficiently smooth.

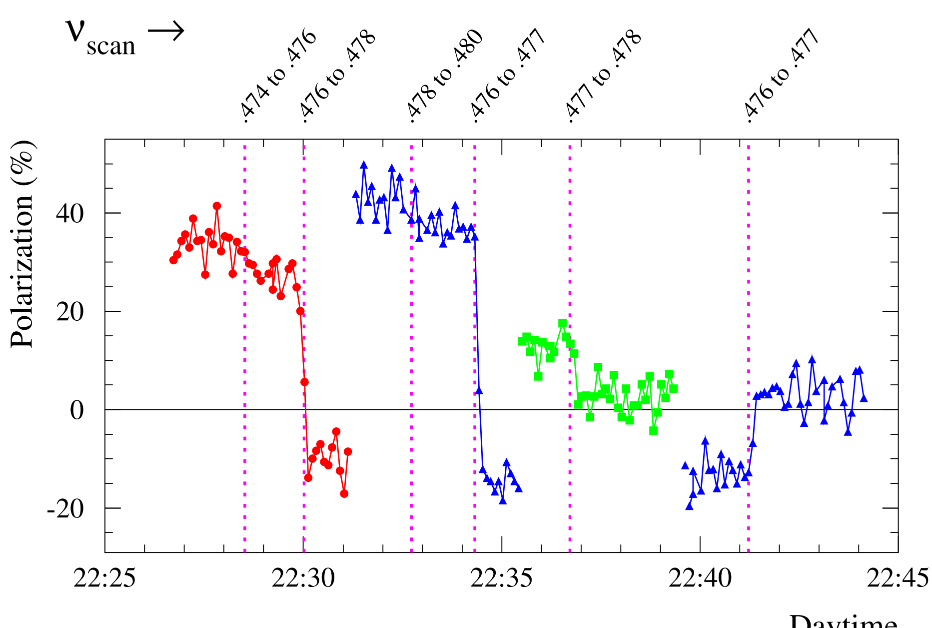
Spins precess in B field. Number of precessions per turn of LEP:

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

$\nu_s \approx$ 101.5, 103.5, 105.5 at $\sqrt{s} =$ peak-2, peak, peak+2

Apply oscillating horizontal B field, ν, at one place. Scan ν.
If $\nu = \nu_s$, polarisation is destroyed.

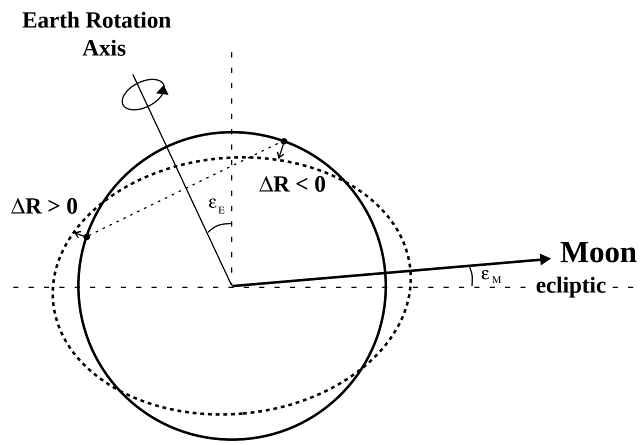




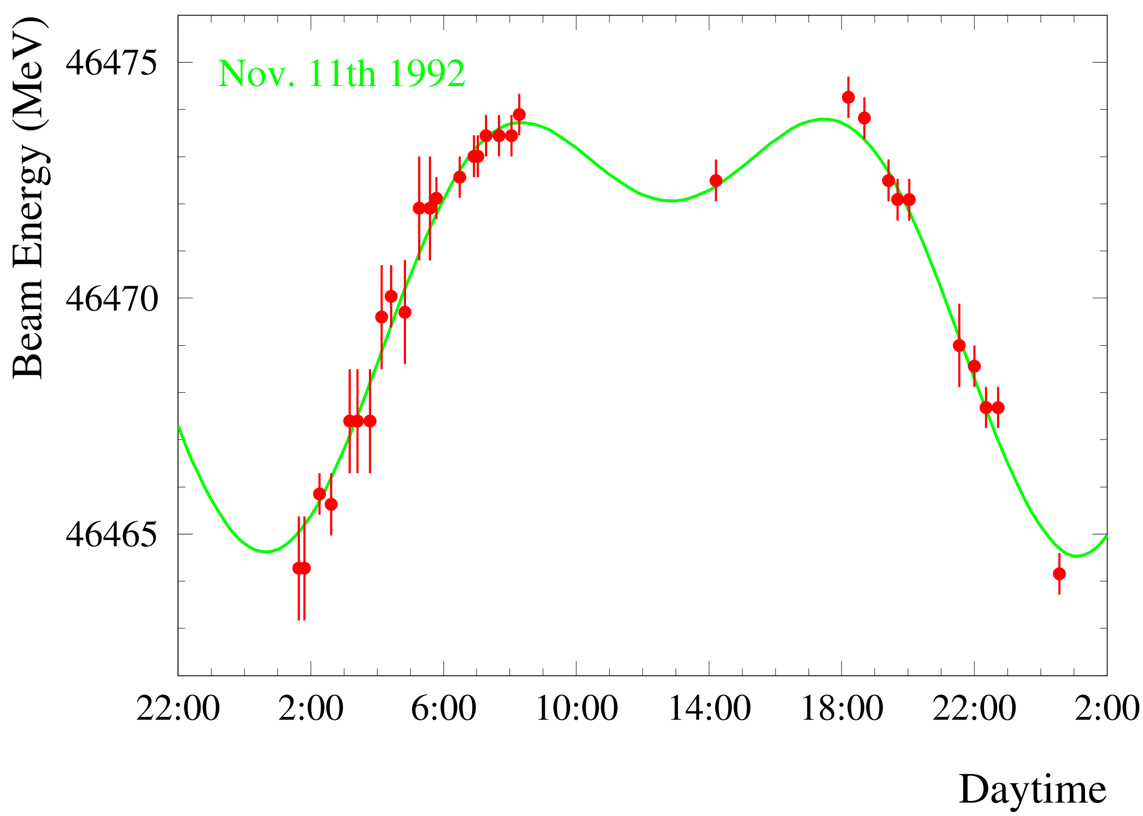
Instantaneous precision $\approx$100 keV. In 1986 expected limit from magnetic stability $\delta M_Z \approx 10$ MeV

Stability? Quadrupole movements...

1991 - first calibrations saw fluctuations of order 10 MeV. Earth tides driven by moon and sun.



Length of orbit fixed by RF system, but magnets move with ground. Beam no longer goes through centre of quadrupoles. Sensitive to 1mm change in 27 km, typical 10 MeV peak-to-peak.

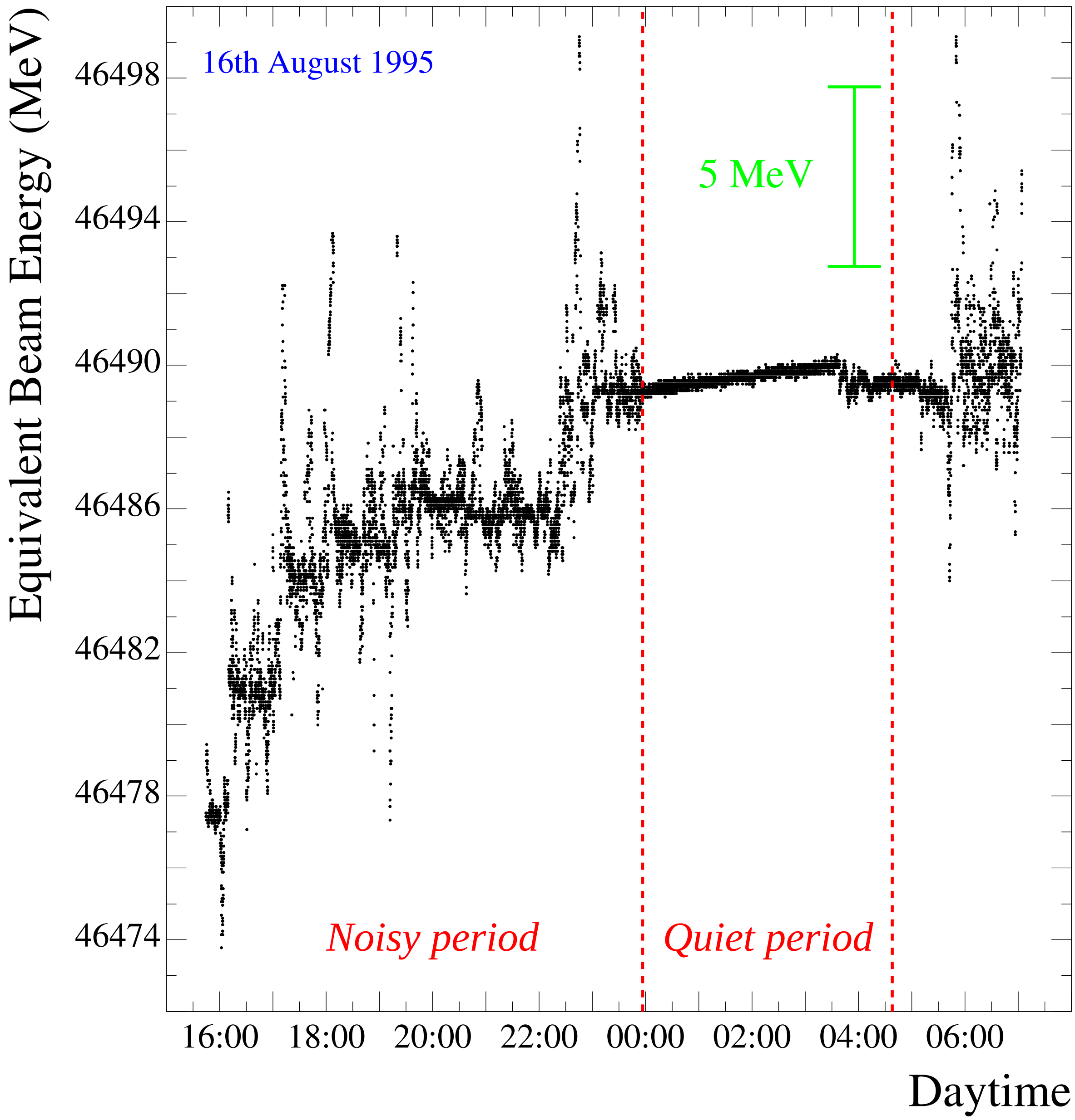


Also see ground distortion due to lake level, heavy rain...

Stability? Dipole fields...

1993: Measured energy at the end of many fills

1995: Measurements of B field in tunnel dipoles



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

Long investigation revealed cause - Vagabond electric currents from nearby trains. Correct earlier years using model of average train behaviour. Final $M_{\rm Z}$ systematic of 1.7 MeV

LEP1 data samples

Approximate luminosity delivered per year.

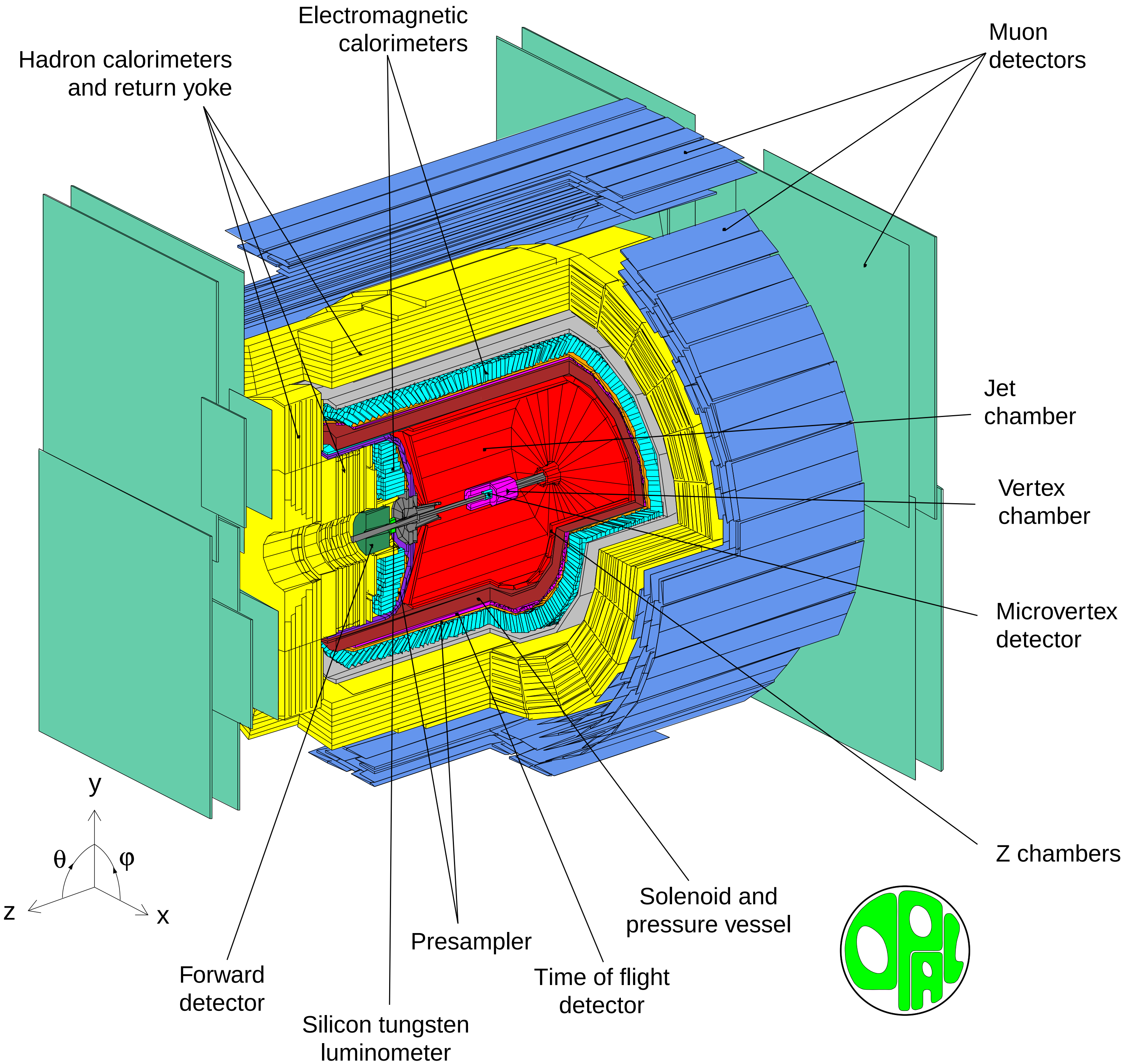
(Experiments collect 10–15% less)

year	centre-of-mass energies [GeV]	total luminosity [pb^{-1}]	off-peak luminosity [pb^{-1}]
1989	88.2 – 94.2	2	1
1990	88.2 – 94.2	9	4
1991	88.5 – 93.7	19	7
1992	91.3	29	0
1993	89.4, 91.2, 93.0	40	20
1994	91.2	65	
1995	89.4, 91.3, 93.0	40	20

In 1989-1991, 6 off-peak points were measured.

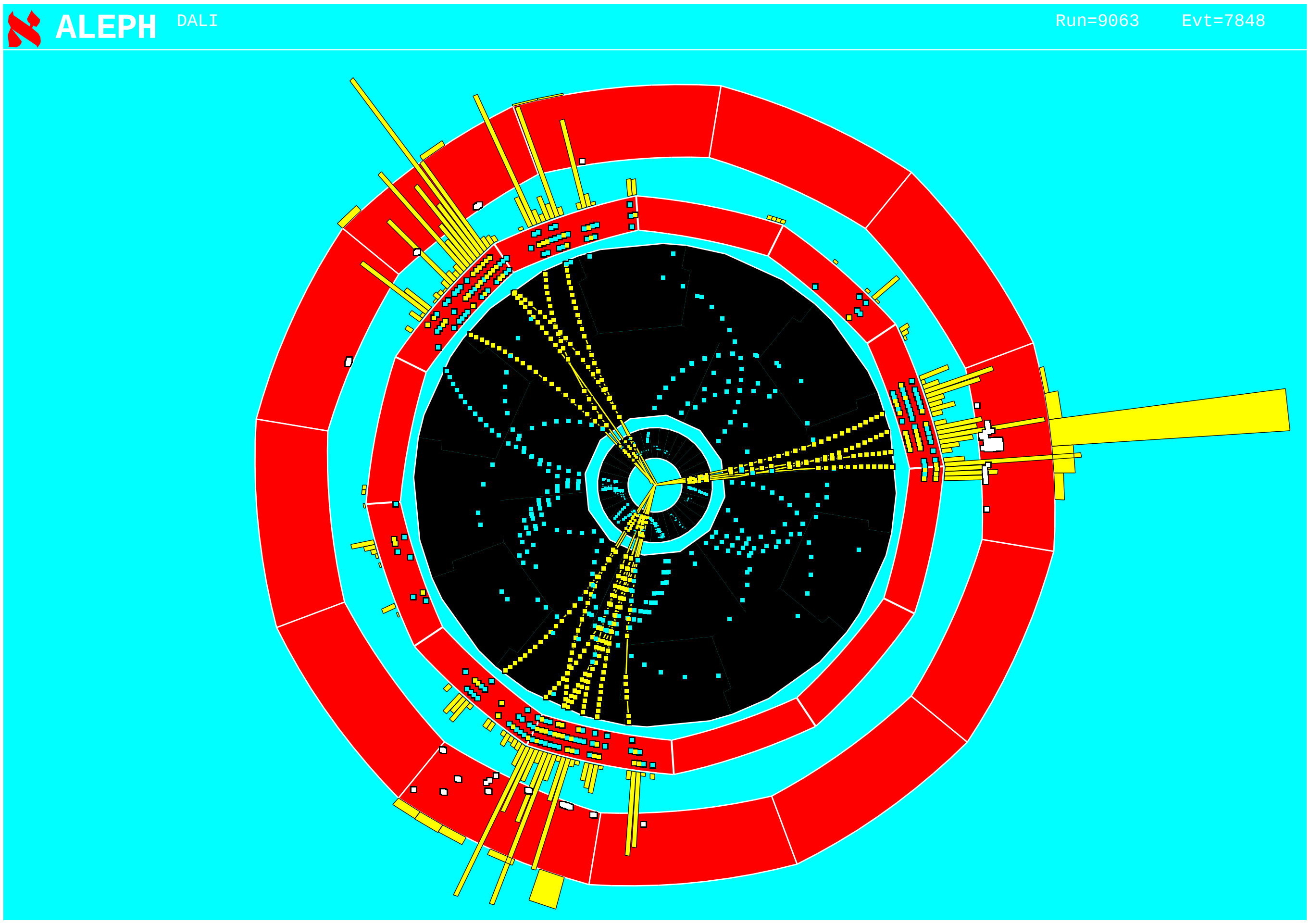
In 1993 and 1995 only 2 off-peak points were selected, to maximise the statistical precision. The exact values of the energies are chosen to allow resonant depolarisation at the end of each fill.

Cut-away view of OPAL



Overall size $12 \times 12 \times 12$ m

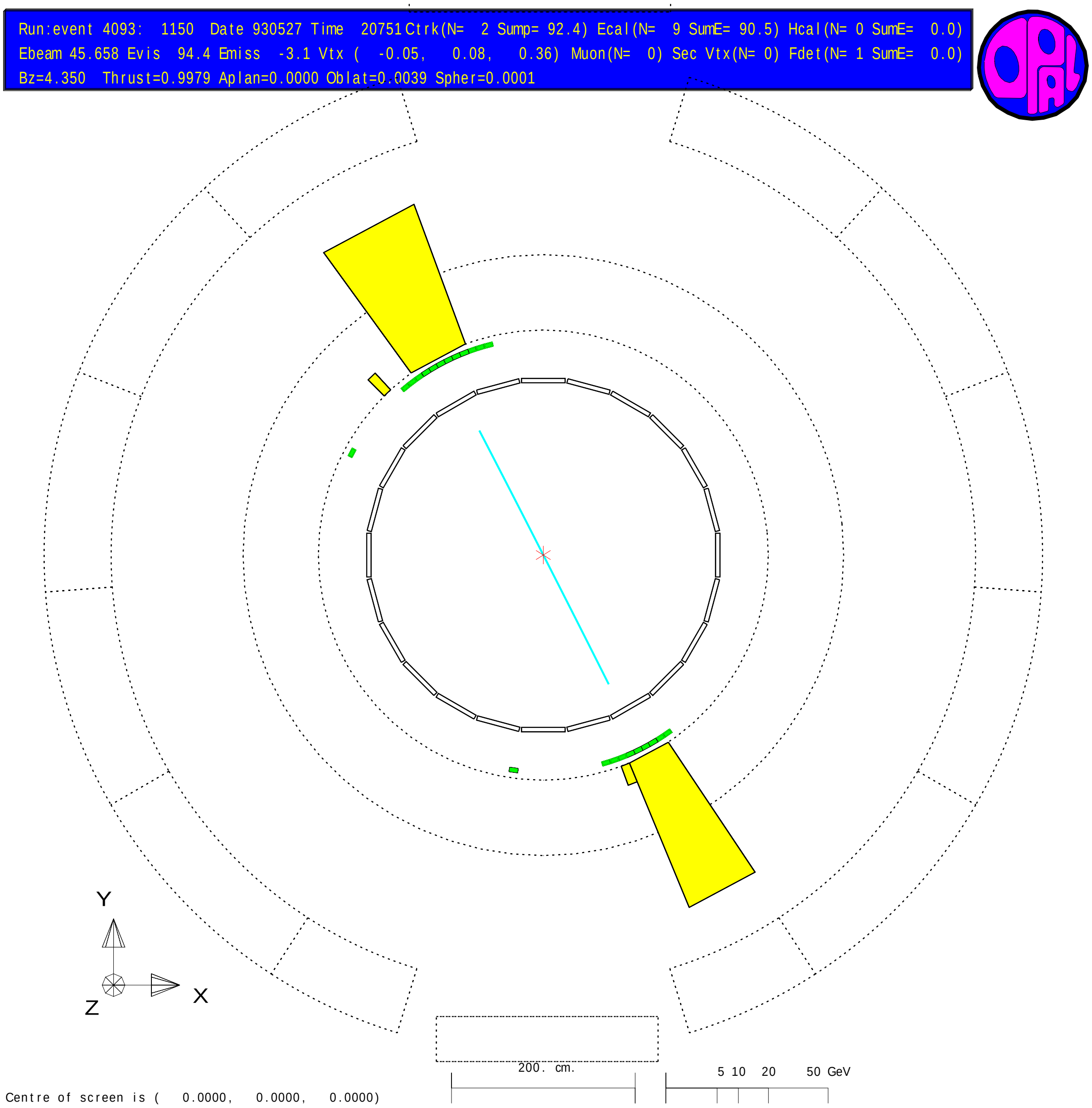
Hadronic event in ALEPH



Made on 9-Sep-1993 11:43:03 by DREVERMANN with DALI_D1.

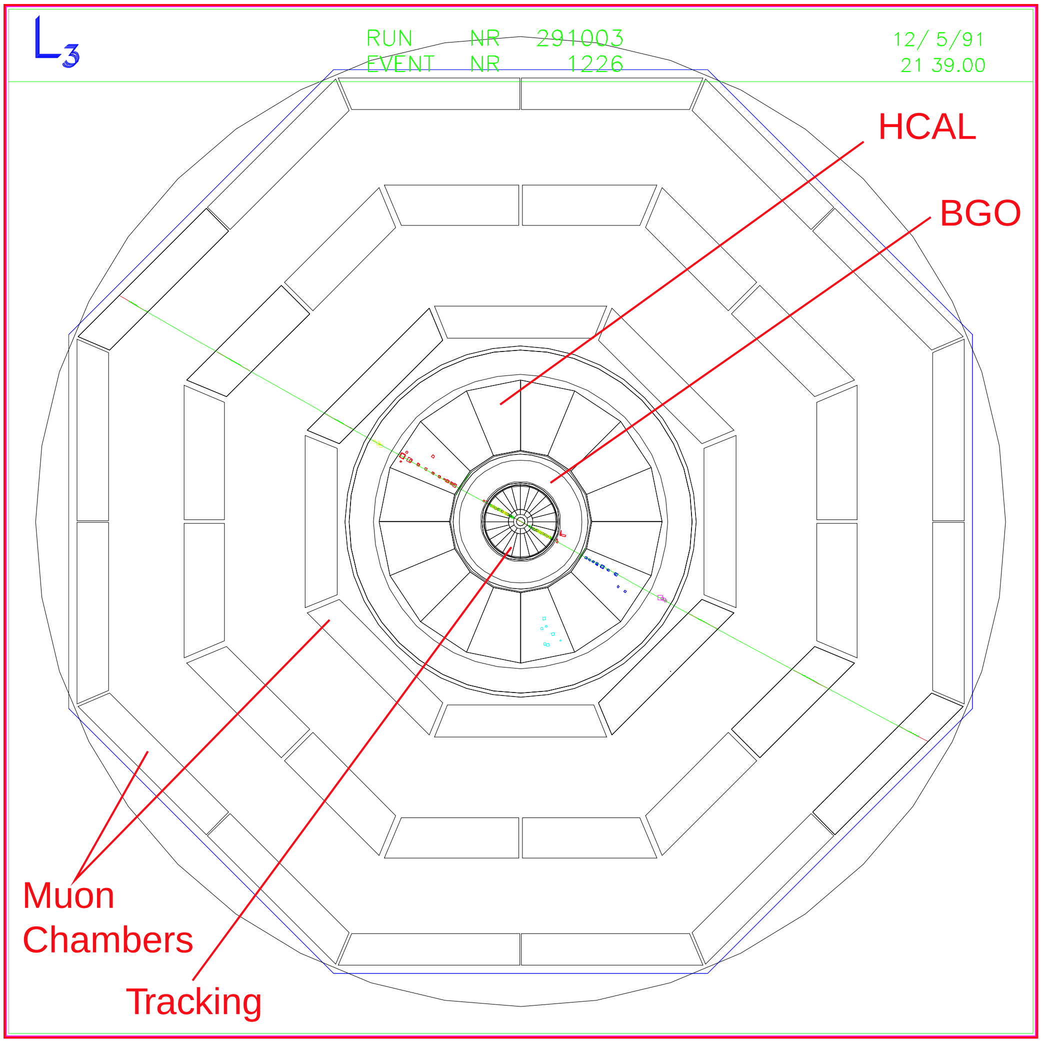
- This example has 3 jets $e^+e^- \rightarrow qqg$
- Curved tracks in B field (ALEPH and DELPHI have superconducting solenoids - B field about 1.5 T compared to about 0.5 T in OPAL and L3)
- Many tracks and clusters in calorimeters

$e^+e^- \longrightarrow e^+e^-$ event in OPAL



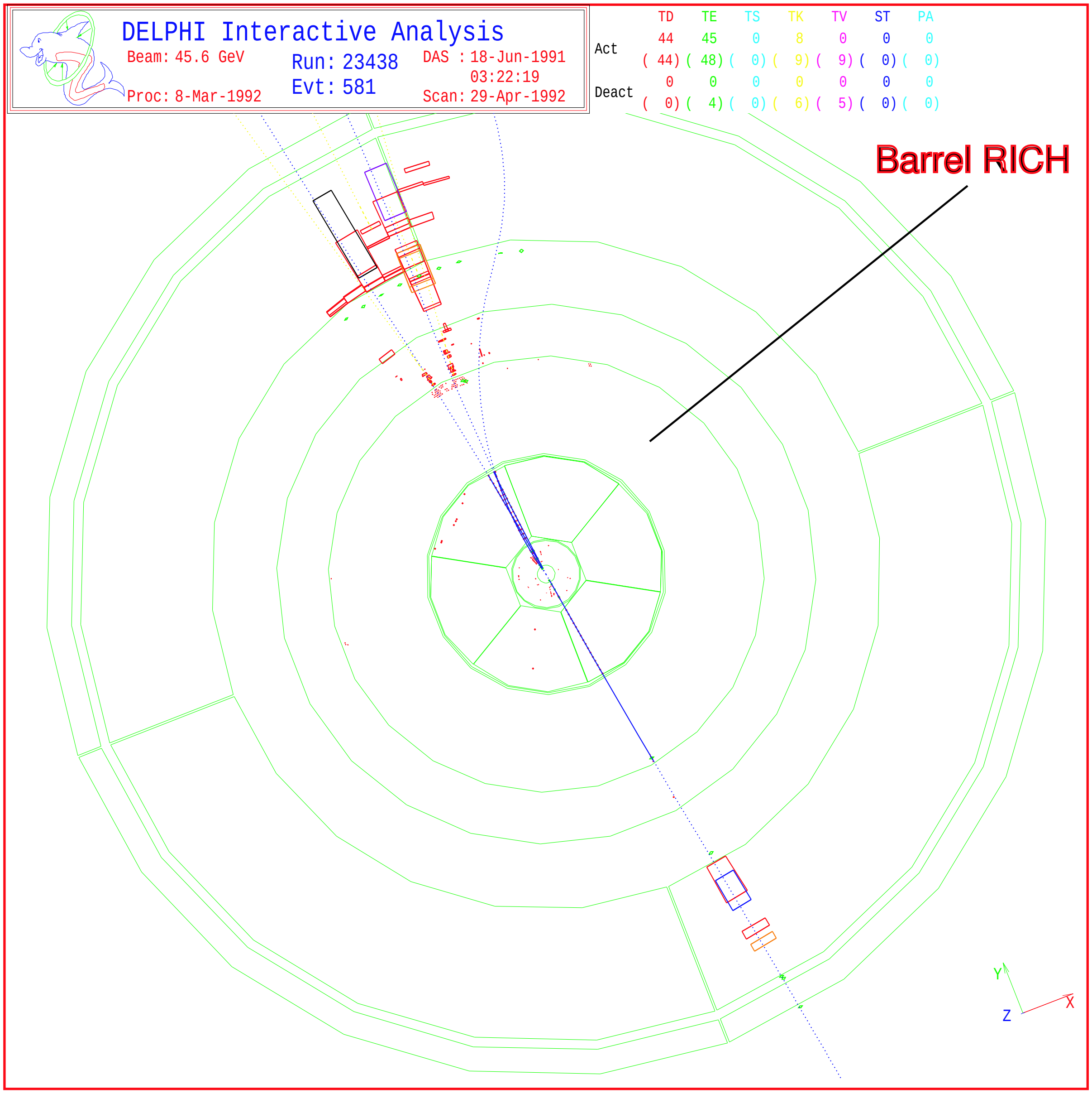
- Lepton pair events have low multiplicity
- Electrons are identified by a track in the central detector, and a large energy deposit in the electromagnetic calorimeter, $E/p = 1$.

$e^+e^- \longrightarrow \mu^+\mu^-$ event in L3



- Muons penetrate the entire detector, and leave little energy in the calorimeters.
- L3 detector emphasizes lepton and photon id with a precise BGO crystal ECAL, and large muon spectrometer.
- The tracking volume is relatively small (radius 1m)
- ALL detectors inside 6m radius solenoid, field 0.5T.

$e^+e^- \longrightarrow \tau^+\tau^-$ event in DELPHI



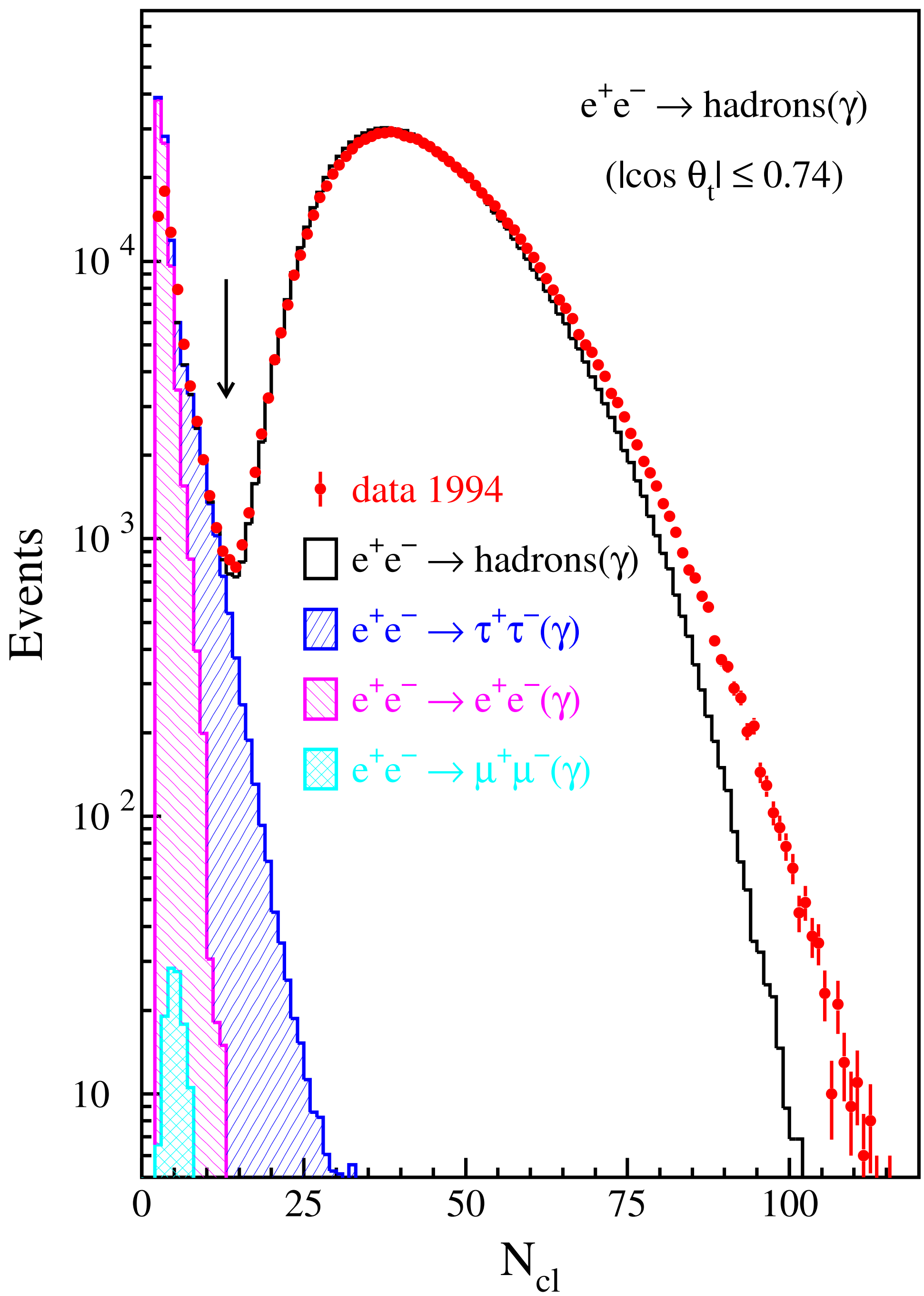
- Tau lepton decays dominated by 1 and 3 charged tracks, with or without neutrals, missing neutrino(s), back-to-back very narrow “jets”.
- DELPHI has extra particle ID detectors, RICH.

Event selection

A few very simple cuts can distinguish hadronic, e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ events, and also background from $\gamma\gamma$, cosmic rays...

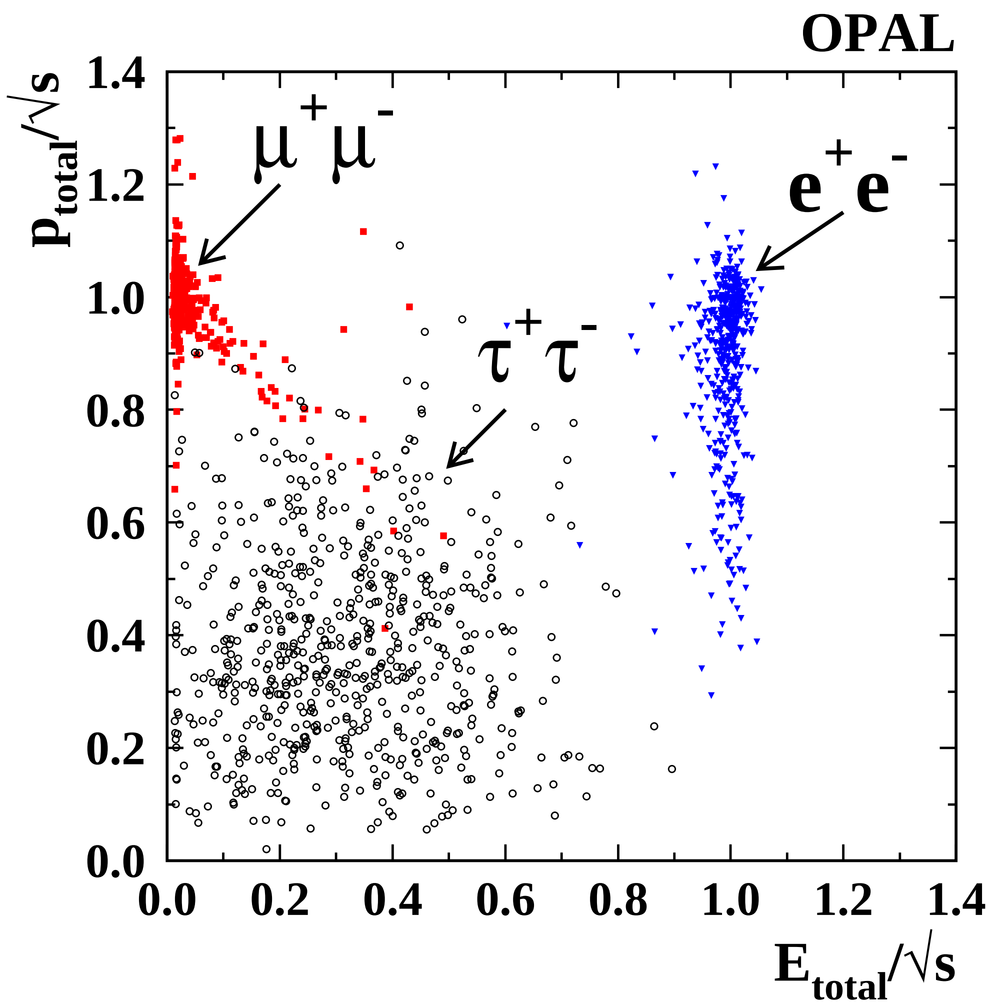
The difficult task is to control systematic errors - how good is Monte Carlo description of data?

Example 1: Hadronic event selection from L3



Event selection

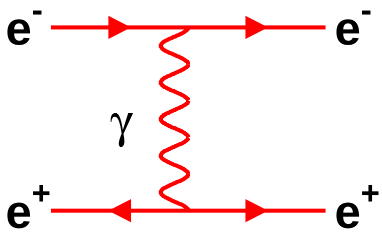
Example 2: $\Sigma|p_{\mathrm{tracks}}|$ vs $\Sigma E_{\mathrm{clusters}}$ for leptons



Representative values (vary from experiment to experiment)

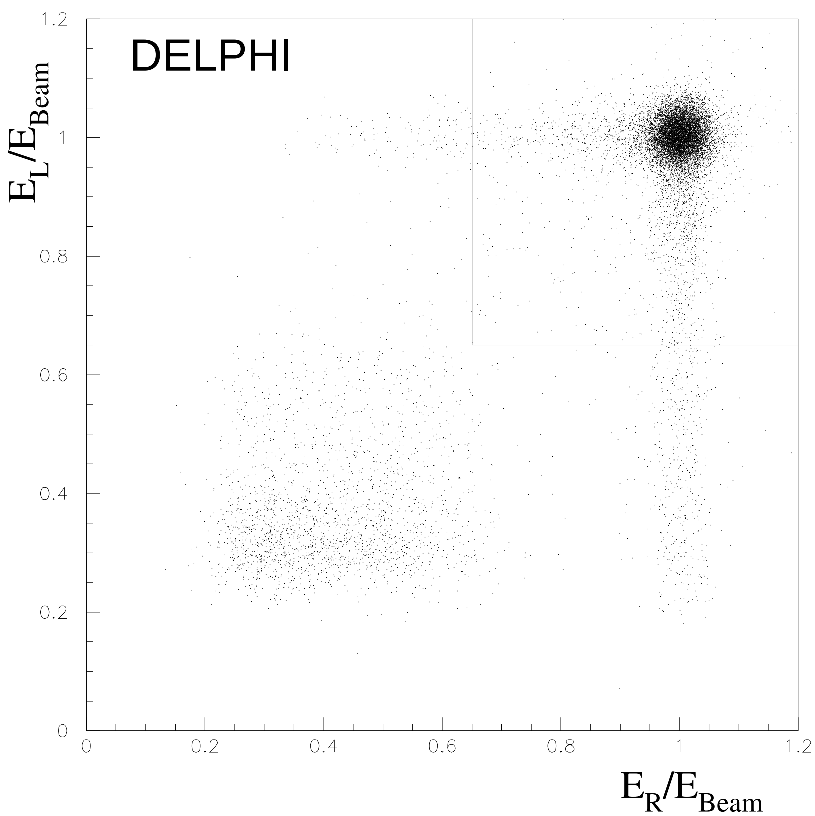
Channel	hadron	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$
Efficiency %	99	98	98	80
Background %	0.5	1	1	2
Syst error %	0.07	0.2	0.1	0.4

Luminosity Measurement



The t-channel contribution to $e^+e^- \longrightarrow e^+e^-$ dominates at small angles. Detectors typically 25 to 60 mrad from beam.

Very clear electron signal in forward detectors (calorimeters).



Accepted cross section at least $2 \times \sigma_{\rm had}$. $1/\theta^3$ variation.

Experimental difficulty: define geometric edge of acceptance to give cross-section precision $\lesssim 0.05\%$.

Common theory error of $\sim 0.05\%$ (cf $\sim 1\%$ in 1989).

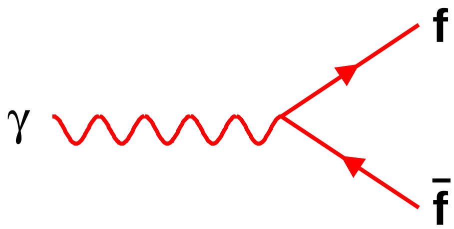
(BHLUMI program: S. Jadach, B.F.L. Ward et al.)

Standard Model relationships

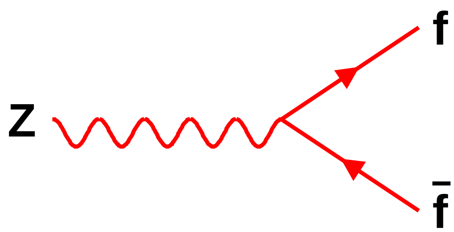
Masses of heavy gauge bosons and their couplings to fermions depend on SAME mixing angle

$$\cos\theta_{\mathrm{W}} = M_{\mathrm{W}}/M_{\mathrm{Z}}$$

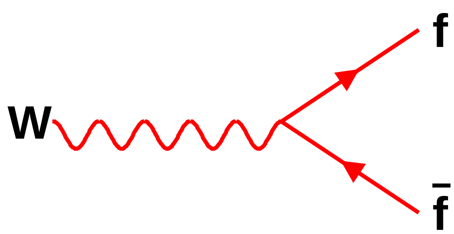
$SU(2) \times U(1)$ coupling constants, g, g', proportional to electric charge e: $g = e\sin\theta_{\mathrm{W}}$, $g' = e\cos\theta_{\mathrm{W}}$



$$-ieQ\gamma_\mu$$



$$ie\gamma_\mu(g_v - g_a\gamma_5)\frac{1}{2\sin\theta_{\mathrm{W}}\cos\theta_{\mathrm{W}}}$$



$$ie\gamma_\mu(1 - \gamma_5)\frac{1}{2\sqrt{2}\sin\theta_{\mathrm{W}}}$$

where Q, g_a and g_v depend on fermion type, with

$$g_a = \quad T^3 \quad = \pm\frac{1}{2}$$

$$g_v = \quad (T^3 - 2Q\sin^2\theta_W) \quad = \pm\frac{1}{2}(1 - 4|Q|\sin^2\theta_W)$$

g_v/g_a gives $\sin^2\theta_W$ if you know $|Q|$.

Standard Model relationships

Relate e, $\sin\theta_{\mathrm{W}}$ and M_{W} to the best measured parameters:

$$\alpha \equiv \frac{e^2}{4\pi} = 1/137.035\,999\,76(50)$$

$$G_{\mathrm{F}} \equiv \frac{\pi\alpha}{\sqrt{2}M_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}}} = 1.166\,39(1)\times 10^{-5}\ \text{GeV}^{-2}$$

$$M_{\mathrm{Z}} = 91.1875(21)\ \text{GeV}$$

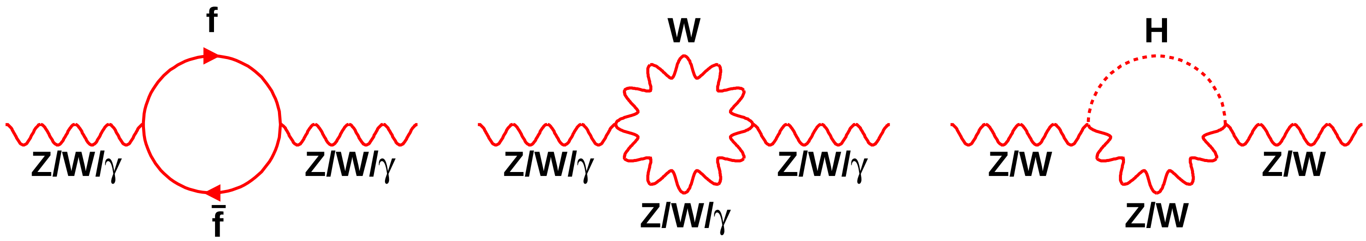
G_{F} measured from muon decay; M_{Z} from LEP.

These relations are true at tree level, but to check that they are valid, must take into account radiative corrections, which give sensitivity to virtual heavy particles, and possibly new physics!

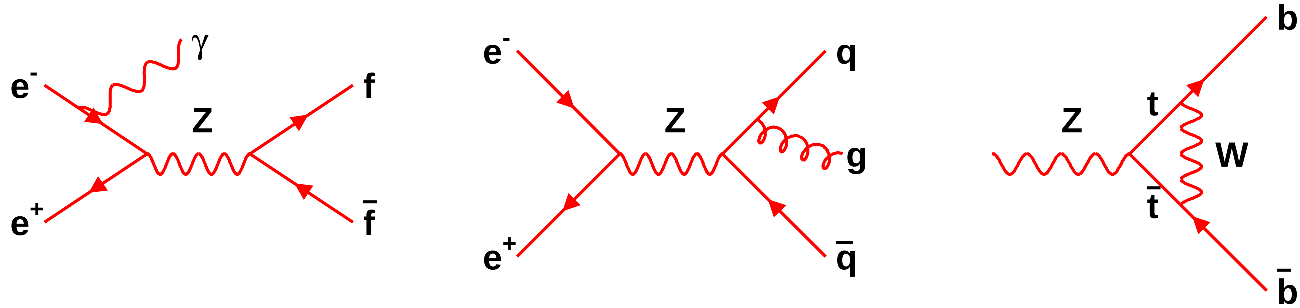
Aside: Other SM inputs needed are fermion masses, Higgs mass, CKM matrix (quark mass eigenstates are not weak eigenstates), strong coupling constant, α_s

Radiative corrections

Propagator corrections are the same for each fermion type.



QED, QCD and vertex corrections give fermion dependent terms.



Electroweak corrections absorbed into effective couplings:

$$
\begin{aligned}
g_{\mathrm{V}} \equiv g_{\mathrm{V}}^{\mathrm{eff}} &= \sqrt{(1+\Delta\rho)}(T^3 - 2Q\sin^2\theta_{\mathrm{eff}}) \\
g_{\mathrm{A}} \equiv g_{\mathrm{A}}^{\mathrm{eff}} &= \sqrt{(1+\Delta\rho)}T^3 \\
\sin^2\theta_{\mathrm{eff}} &= (1+\Delta\kappa)\sin^2\theta_{\mathrm{W}}
\end{aligned}
$$

$$
\begin{aligned}
\Delta\rho &= \frac{3G_{\mathrm{F}}M_{\mathrm{W}}^2}{8\sqrt{2}\pi^2}\left(\frac{M_{\mathrm{t}}^2}{M_{\mathrm{W}}^2} - \tan^2\theta_{\mathrm{W}}\left[\ln\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}^2} - \frac{5}{6}\right]\right) + \cdots \\
\Delta\kappa &= \frac{3G_{\mathrm{F}}M_{\mathrm{W}}^2}{8\sqrt{2}\pi^2}\left(\cot^2\theta_{\mathrm{W}}\frac{M_{\mathrm{t}}^2}{M_{\mathrm{W}}^2} - \frac{11}{9}\left[\ln\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}^2} - \frac{5}{6}\right]\right) + \cdots
\end{aligned}
$$

Extra $M_{\mathrm{t}}^2/M_{\mathrm{W}}^2$ contributions for b quark

Radiative corrections

The value of G_{F} is also modified:

$$G_{\mathrm{F}} = \frac{\pi\alpha}{\sqrt{2} M_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}}} \frac{1}{1 - \Delta r}$$

where

$$\Delta r = \Delta\alpha + \Delta r_{\mathrm{w}} = \Delta\alpha - \Delta\kappa + \cdots$$

$\Delta\alpha$ term incorporates the running of the electromagnetic coupling due to fermion loops in the photon propagator. The difficult part of the calculation is to account for all the hadronic states. Use experimental measurement of $\mathrm{e^+e^-} \to \mathrm{hadrons}$ at low $\sqrt{s}$.

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

$\alpha(0) = 1/137.035\,999\,76(50)$; $\alpha(M_{\mathrm{Z}}) = 1/128.936(46)$

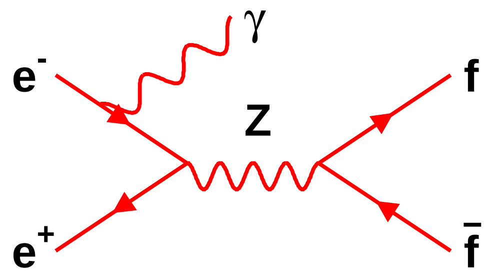
Quadratic dependence on M_{t}
Logarithmic dependence on M_{H}
Can fit both M_{t} and M_{H}

Use programs such as ZFITTER (D Bardin et al.) and TOPAZ0 (G Montagna et al.) for calculations to higher order.

Leading order expressions above are for large M_{H}.

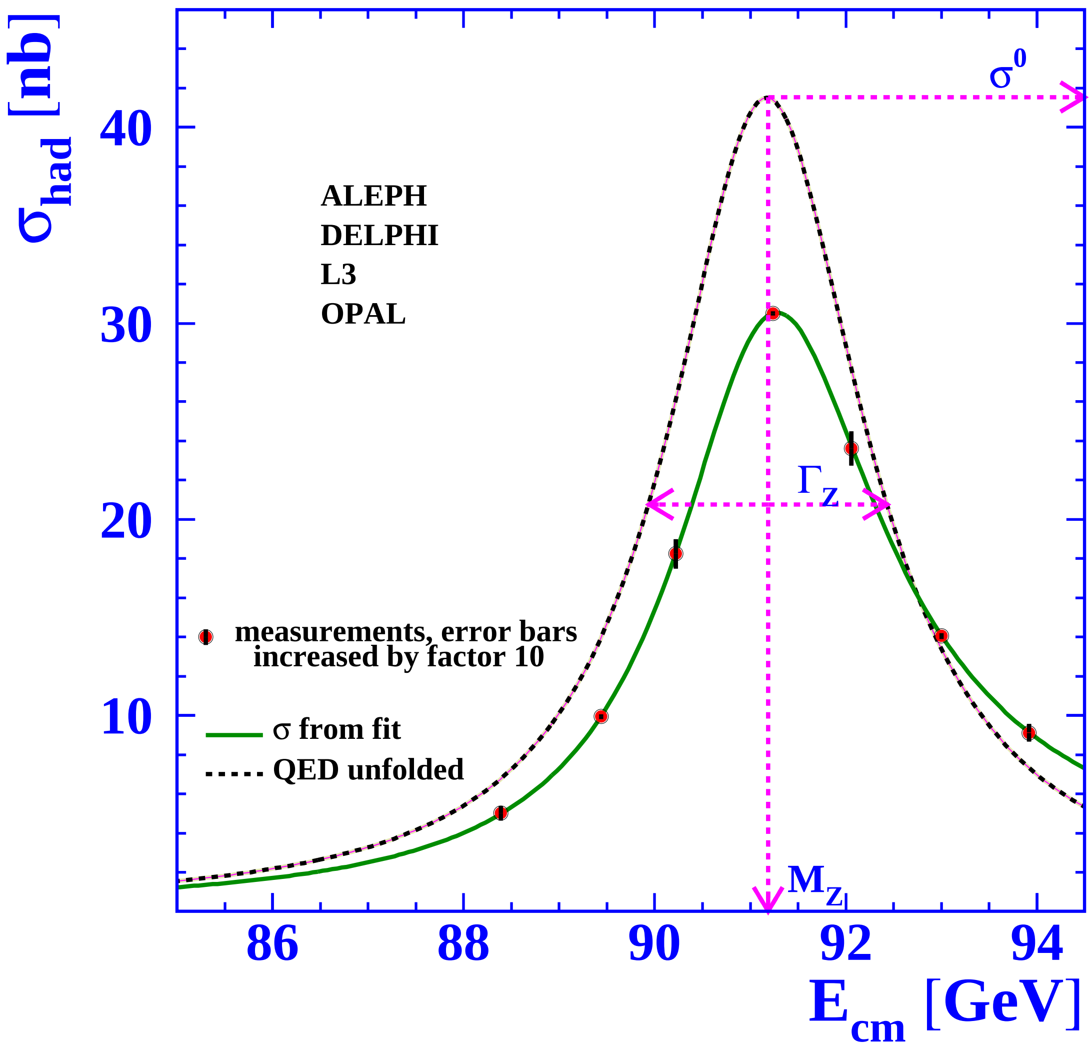
QED corrections

Dominant QED correction from initial state radiation.



Accounted for by radiator function H. We want $\sigma_{\rm ew}(s)$

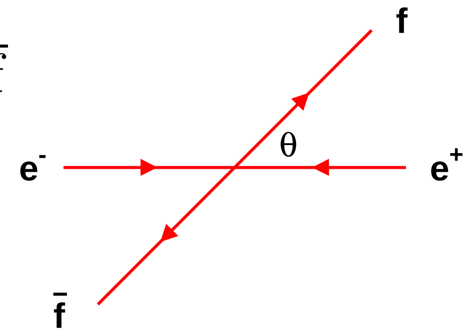
$$\sigma(s) = \int_{4m_{\rm f}^2/s}^{1} dz H_{\rm QED}^{\rm tot}(z,s)\sigma_{\rm ew}(zs).$$



Differential cross-section

Improved Born Approximation for $\mathrm{e^+e^-} \longrightarrow \mathrm{f\bar{f}}$

(Ignoring fermion masses, QED/QCD ISR/FSR ...)



$$\frac{d\sigma_{\mathrm{ew}}}{d\cos\theta} = \frac{\pi N_c^{\mathrm{f}}}{2s} 16|\chi(s)|^2 \times$$
$$\left[(g_{\mathrm{Ve}}^2 + g_{\mathrm{Ae}}^2)(g_{\mathrm{Vf}}^2 + g_{\mathrm{Af}}^2)(1+\cos^2\theta) + 8 g_{\mathrm{Ve}} g_{\mathrm{Ae}} g_{\mathrm{Vf}} g_{\mathrm{Af}} \cos\theta\right]$$
$$+[\gamma \text{ exchange}] \;+\; [\gamma Z \text{ interference}]$$

Where

$$\chi(s) = \frac{G_{\mathrm{F}} M_{\mathrm{Z}}^2}{8\pi\sqrt{2}} \frac{s}{s - M_{\mathrm{Z}}^2 + is\Gamma_{\mathrm{Z}}/M_{\mathrm{Z}}}$$

$|\chi(s)|^2$ gives lineshape as a function of s.

Even term in $\cos\theta$ gives total cross-section

$$\sigma_{\mathrm{ff}} \propto (g_{\mathrm{Ve}}^2 + g_{\mathrm{Ae}}^2)(g_{\mathrm{Vf}}^2 + g_{\mathrm{Af}}^2)$$

Odd term in $\cos\theta$ leads to forward-backward asymmetry:

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

where $\sigma_{\mathrm{F}} = \int_0^1 (d\sigma/d\cos\theta) d\cos\theta$. At the Z peak:

$$A_{\mathrm{FB}}^{0,\mathrm{f}} = \frac{3}{4} \frac{2 g_{\mathrm{Ve}} g_{\mathrm{Ae}}}{g_{\mathrm{Ve}}^2 + g_{\mathrm{Ae}}^2} \frac{2 g_{\mathrm{Vf}} g_{\mathrm{Af}}}{g_{\mathrm{Vf}}^2 + g_{\mathrm{Af}}^2} \equiv \frac{3}{4} \mathcal{A}_{\mathrm{e}} \mathcal{A}_{\mathrm{f}}$$

A_{FB} depends on $g_{\mathrm{Vf}}/g_{\mathrm{Af}}$, i.e. on $\sin^2\theta_{\mathrm{eff}}$

Cross-section plus A_{FB} allow g_{Vf} and g_{Af} to be derived.

Polarised asymmetries

Final state fermions in $\mathrm{e^+e^-} \longrightarrow \mathrm{f\bar{f}}$ are polarised. Polarisation can be measured for τ lepton final states at LEP.

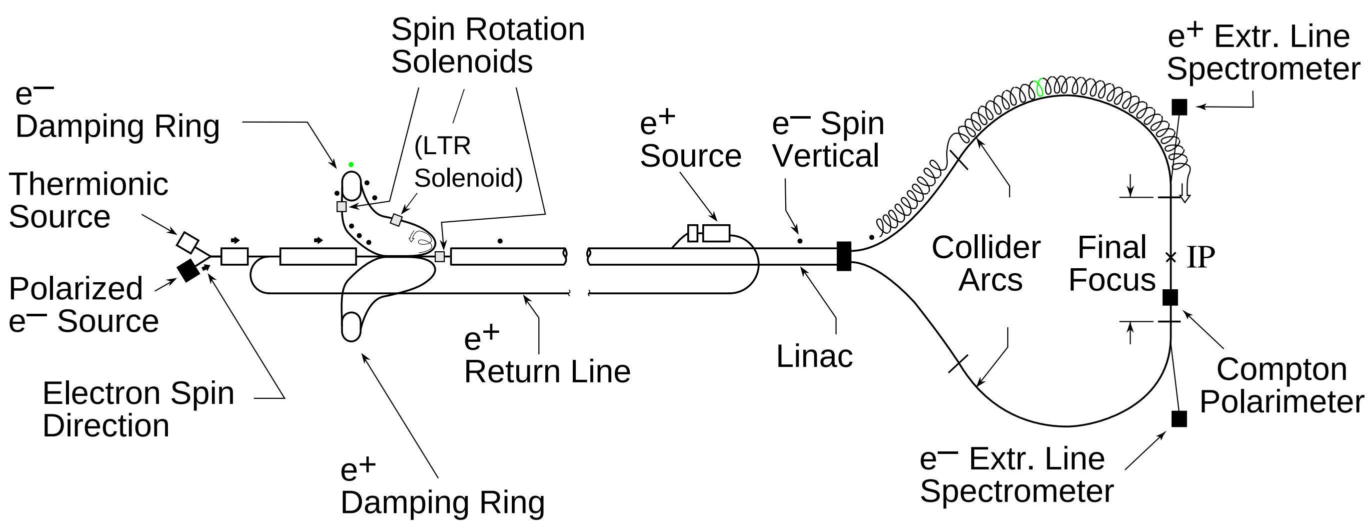
$$\mathcal{P}_\tau \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

where $\sigma_{+(-)}$ cross section for producing + (-) helicity τ^- leptons.

Eg. $\tau \longrightarrow \pi\nu$, momentum of the π depends on the τ helicity

Initial state: LEP beams are unpolarised (except for special energy calibration conditions)

Stanford Linear Collider - longitudinally polarised electron beam to detector SLD. Electron beam $\approx$ 75% polarised from 1994–1998.



Knowing polarisation of final (τ) or initial (SLD) state, can construct left-right, left-right-forward-backward... asymmetries, and measure $\mathcal{A}_\mathrm{e}$ or $\mathcal{A}_\mathrm{f}$, eg.

$$A_\mathrm{LR}(s) = \frac{N_\mathrm{L} - N_\mathrm{R}}{N_\mathrm{L} + N_\mathrm{R}} \frac{1}{\langle \mathcal{P}_\mathrm{e} \rangle} \;, \quad A^0_\mathrm{LR} \equiv \mathcal{A}_\mathrm{e}$$

Cross-section and partial widths

Cross-section as a function of s (from $|\chi(s)|^2$): “Z lineshape”

$$\sigma_{\mathrm{ff}}(s) = \sigma^0_{\mathrm{ff}} \frac{s\Gamma_{\mathrm{Z}}^2}{(s - M_{\mathrm{Z}})^2 + s^2\Gamma_{\mathrm{Z}}^2/M_{\mathrm{Z}}^2}$$

where pole cross-section is

$$\sigma^0_{\mathrm{ff}} = \frac{12\pi}{M_{\mathrm{Z}}^2} \frac{\Gamma_{\mathrm{ee}}\Gamma_{\mathrm{f\bar{f}}}}{\Gamma_{\mathrm{Z}}^2}.$$

with $\Gamma_{\mathrm{f\bar{f}}}/\Gamma_{\mathrm{Z}} = \mathrm{BR}(\mathrm{Z} \to \mathrm{f\bar{f}})$ and partial width is

$$\Gamma_{\mathrm{f\bar{f}}} = N_c^{\mathrm{f}} \frac{G_{\mathrm{F}} M_{\mathrm{Z}}^3}{6\sqrt{2}\pi} \left(g^2_{\mathrm{Af}} + g^2_{\mathrm{Vf}}\right)$$

+ QED/QCD corrections eg. QCD: $\Gamma_{\mathrm{q\bar{q}}} \to \Gamma_{\mathrm{q\bar{q}}}(1 + \alpha_s/\pi + \cdots)$

Total width of Z

$$\Gamma_{\mathrm{Z}} = \Gamma_{\mathrm{had}} + 3\Gamma_{\ell\ell} + \Gamma_{\mathrm{inv}} = \Sigma\Gamma_{\mathrm{q\bar{q}}} + 3\Gamma_{\ell\ell} + N_\nu\Gamma_{\nu\nu}$$

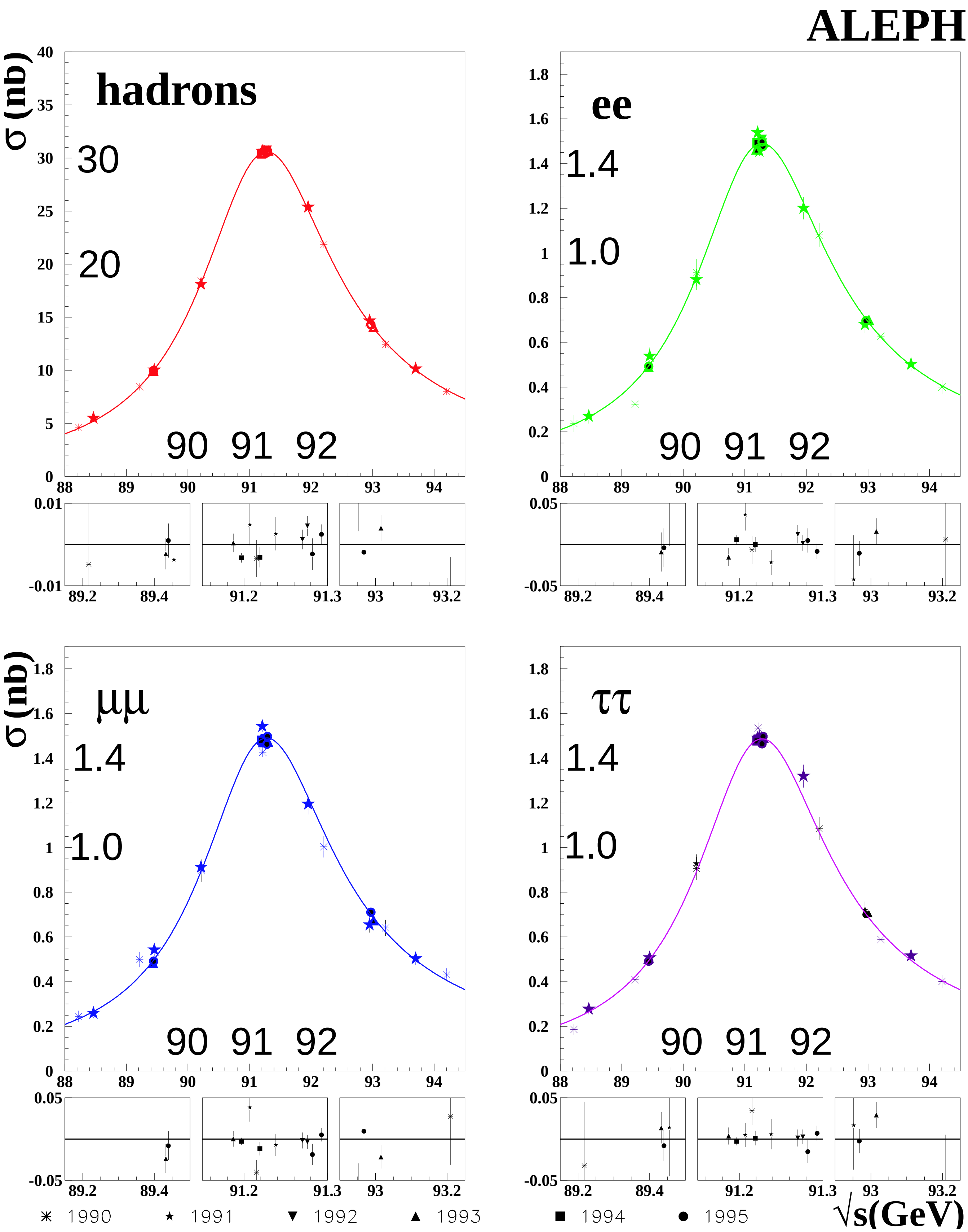
Comparing total width to partial width gives N_ν

Cross-sections and widths correlated. Choose to fit:

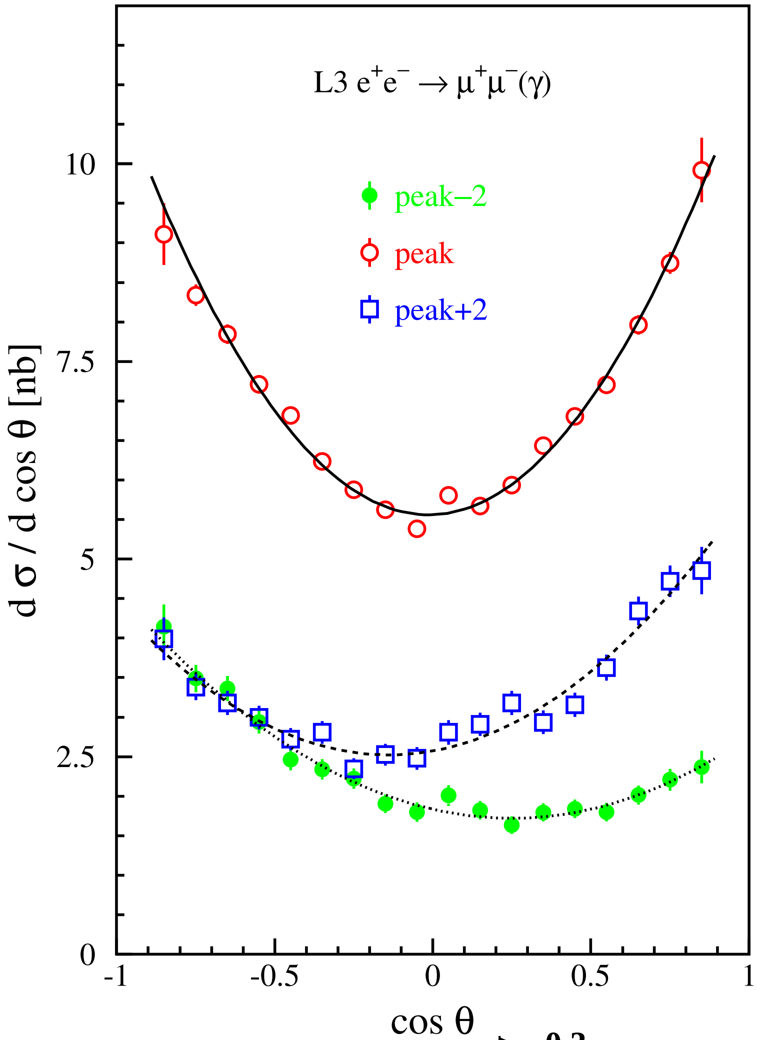
- $M_{\mathrm{Z}}, \Gamma_{\mathrm{Z}}, \sigma^0_{\mathrm{h}}$
- Ratios: $R^0_{\mathrm{e}} \equiv \Gamma_{\mathrm{had}}/\Gamma_{\mathrm{ee}}$, $R^0_\mu \equiv \Gamma_{\mathrm{had}}/\Gamma_{\mu\mu}$, $R^0_\tau \equiv \Gamma_{\mathrm{had}}/\Gamma_{\tau\tau}$ or $R^0_\ell \equiv \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell}$
- Asymmetries: $A^{0,\mathrm{e}}_{\mathrm{FB}}$, $A^{0,\mu}_{\mathrm{FB}}$ and $A^{0,\tau}_{\mathrm{FB}}$ or $A^{0,\ell}_{\mathrm{FB}}$

Extra information from tagging some quark flavours (lecture 2).

Cross-sections vs $\sqrt{s}$

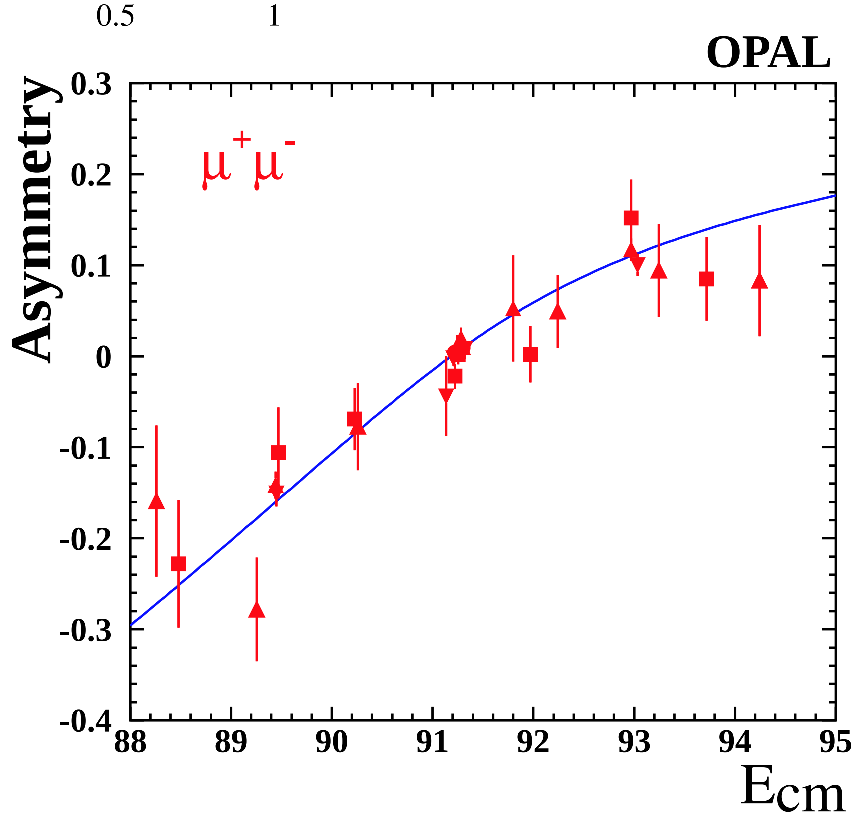


Lepton forward-backward asymmetries



Forward-backward asymmetry for lepton pairs is straightforward to measure. Charge of lepton from tracking.

Asymmetry varies with centre-of-mass energy.



Lepton Universality

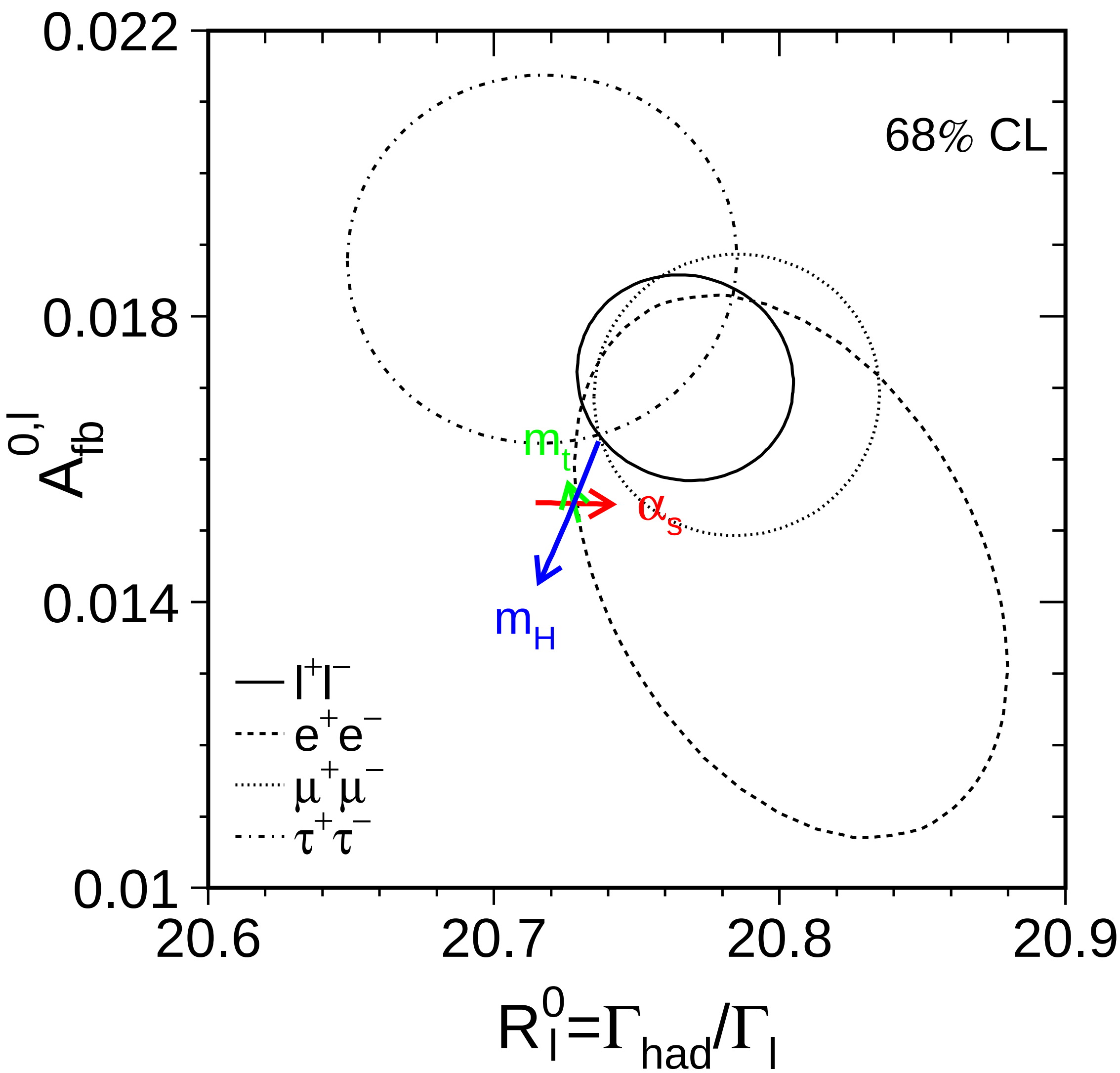
Plot $A_{\mathrm{FB}}^{0,\ell}$ vs. $R_\ell^0 = \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell}$. Contours contain 68% probability.

Lepton universality OK. Results agree with SM (arrows)

$M_{\mathrm{t}} = 174.3 \pm 5.1$ GeV

$M_{\mathrm{H}} = 300^{+700}_{-186}$ GeV (low M_{H} preferred)

$\alpha_s(M_{\mathrm{Z}}^2) = 0.118 \pm 0.002$



Next lecture: interpretation of asymmetries in terms of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

LEP combined results

Z resonance parameters - recall pre-LEP hopes:

- $\sigma(M_{\rm Z}) \approx 10$ MeV (limited by beam energy precision)
- Number of generations $\sigma(N_\nu) \approx 0.2$

Fitted	$M_{\rm Z}$ [GeV]	91.1875 $\pm$ 0.0021
	$\Gamma_{\rm Z}$ [GeV]	2.4952 $\pm$ 0.0023
	$\sigma^0_{\rm h}$ [nb]	41.540 $\pm$ 0.037
	R^0_ℓ	20.767 $\pm$ 0.025
	$A^{0,\,\ell}_{\rm FB}$	0.0171 $\pm$ 0.0010
Derived	$\Gamma_{\rm inv}$ [MeV]	499.0 $\pm$ 1.5
	$\Gamma_{\rm had}$ [MeV]	1744.4 $\pm$ 2.0
	$\Gamma_{\ell\ell}$ [MeV]	83.984 $\pm$ 0.086
	N_ν	2.984 $\pm$ 0.008

Summary - Very precise measurements of Z mass, width, cross-sections, partial widths and lepton forward-backward asymmetries.

High statistics data samples. Careful control of systematic errors.