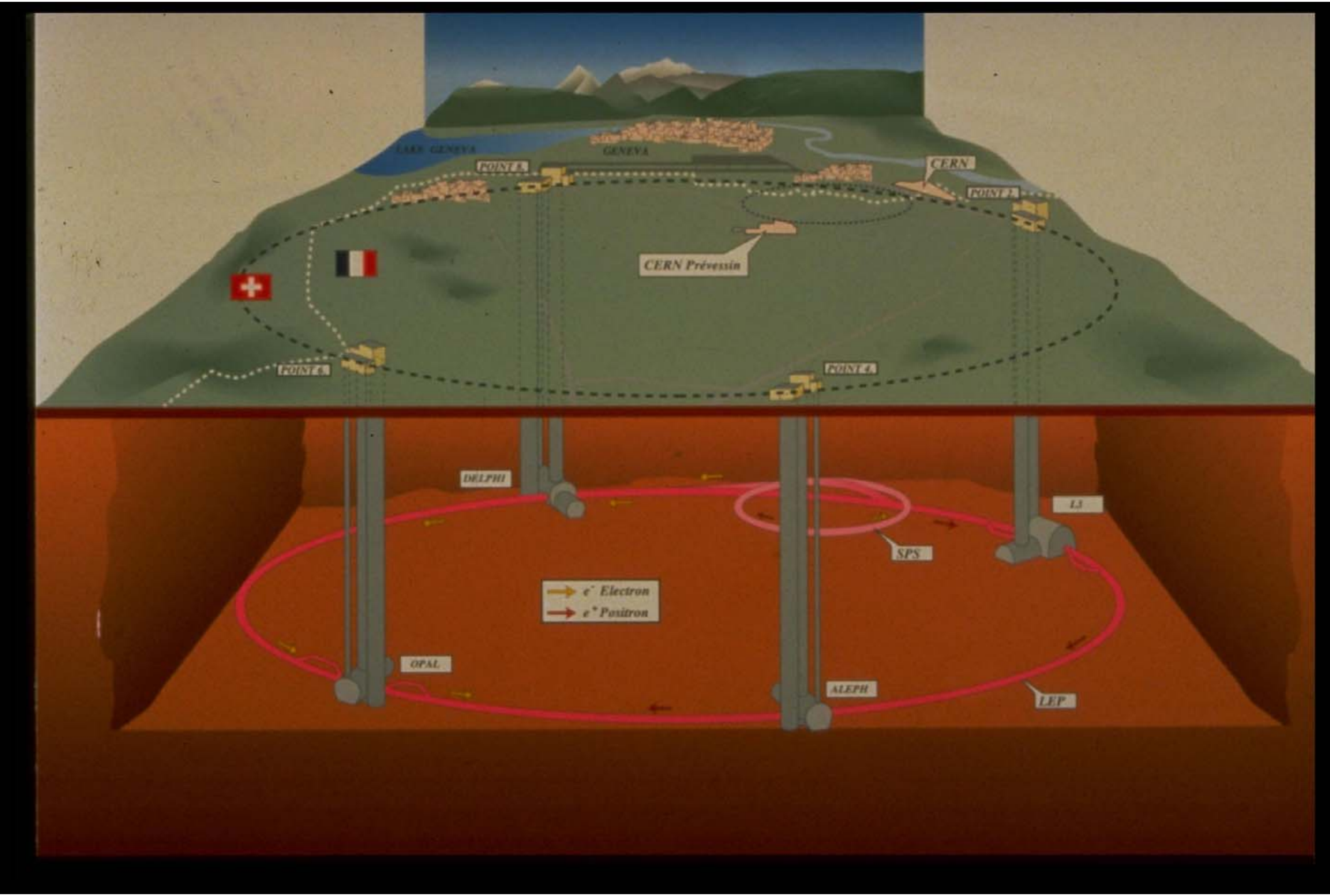
Experimentelle Tests des elektro-schwachen Standard-Modells bei LEP + SLC

Klaus Desch, 10.12.2003

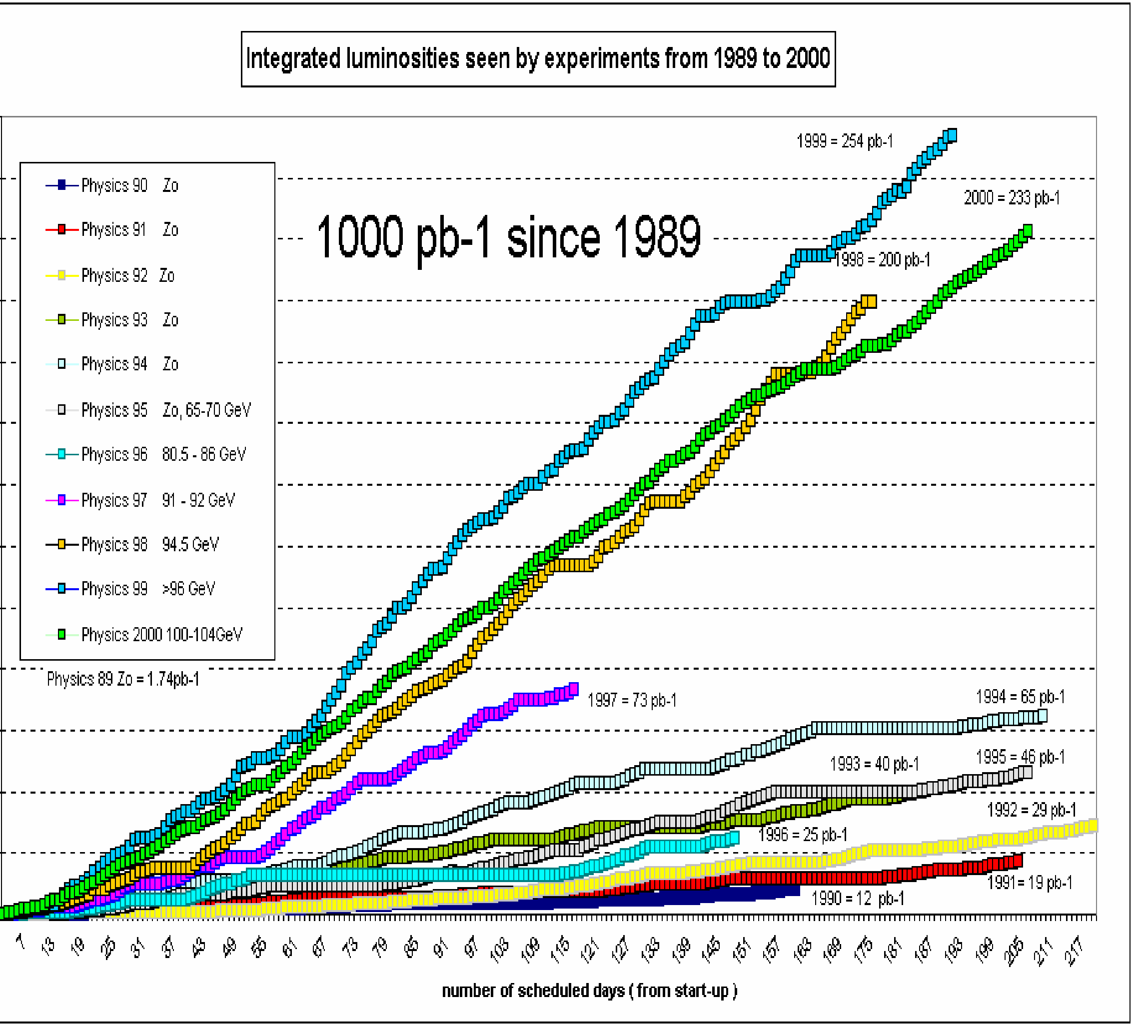
Der LEP Collider am CERN



Der LEP Collider am CERN

Umfang	~27 km
Schwerpunktsenergie	92.1 GeV(LEP1) to 209 GeV(LEP 2)
Beschleunigungs-Gradient	bis 7 MV/m (SC cavities)
Anzahl Bunches	4 x 4
Strom pro Bunch	~ 750 μA
Luminosität (Z0)	~ $24 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (~1 Z0/s)
Luminosität (LEP2)	~ $50 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (3 WW/h)
Wechselwirkungszonen	4 (ALEPH,DELPHI,L3,OPAL)
Energie-Kalibration	< 1 MeV (Z0)

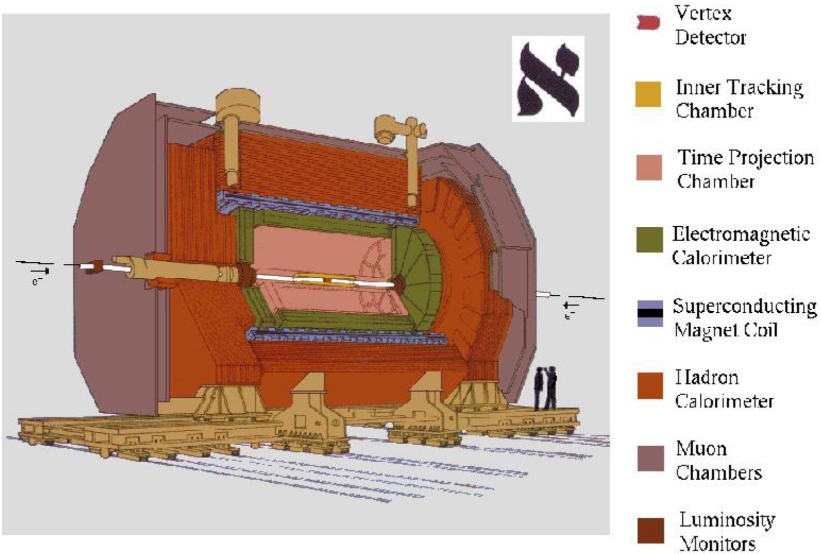
Der LEP Collider am CERN



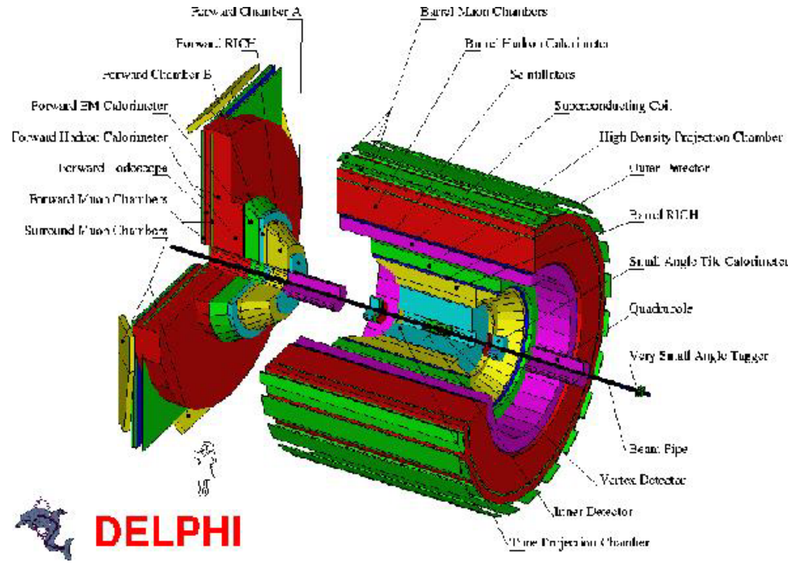
LEP 1	1990-1995	~91 GeV 4 Millionen Z0's
LEP 2	1995	Testphase für LEP2: 130 GeV
	1996	161-172 GeV: WW-Schwelle
	1997	183 GeV 1000 W-Paare
	1998	189 GeV 2500 W-Paare
	1999	192-200 GeV 3000 W-Paare
	2000	200-209 GeV 3000 W-Paare

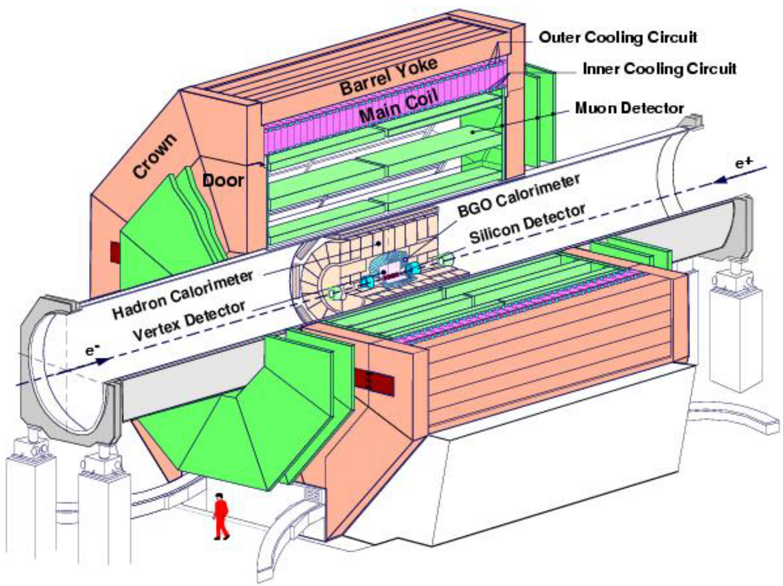
Im Nov 2000 wurde LEP abgeschaltet um für den LHC Platz zu machen

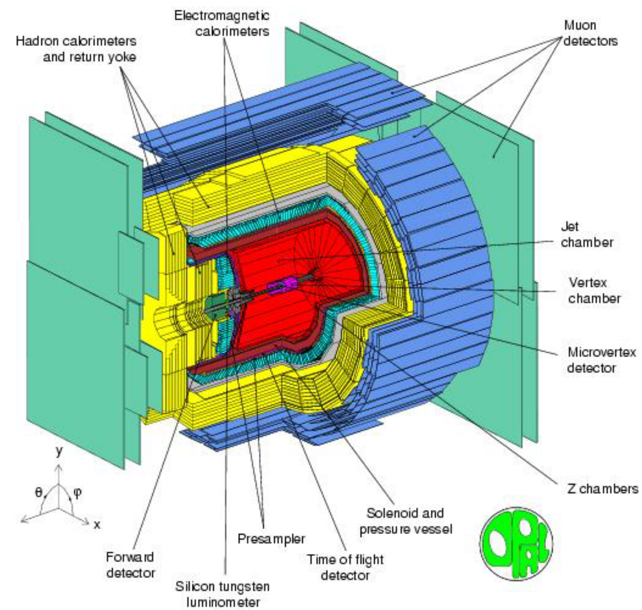
Detektoren



The ALEPH Detector

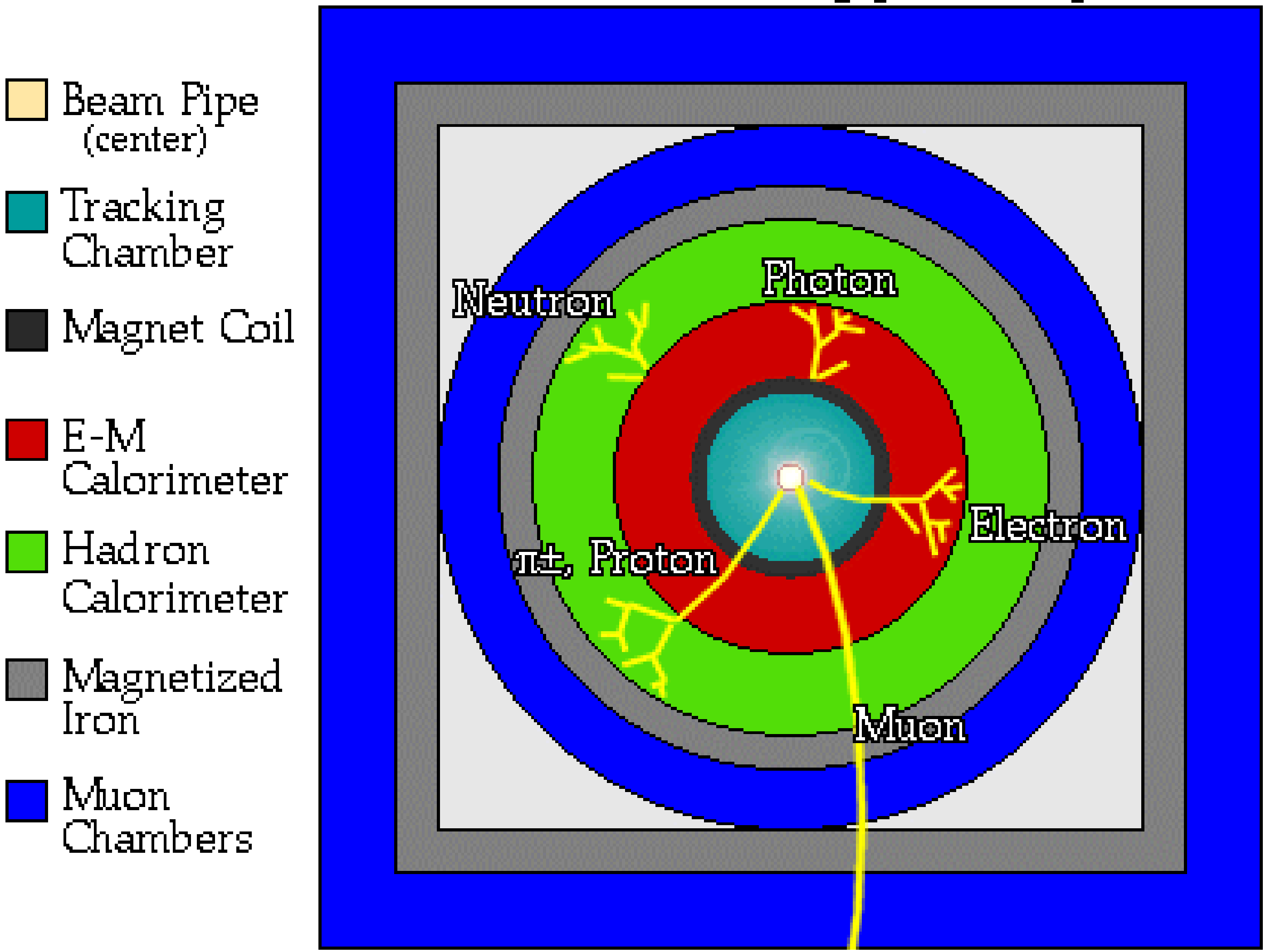




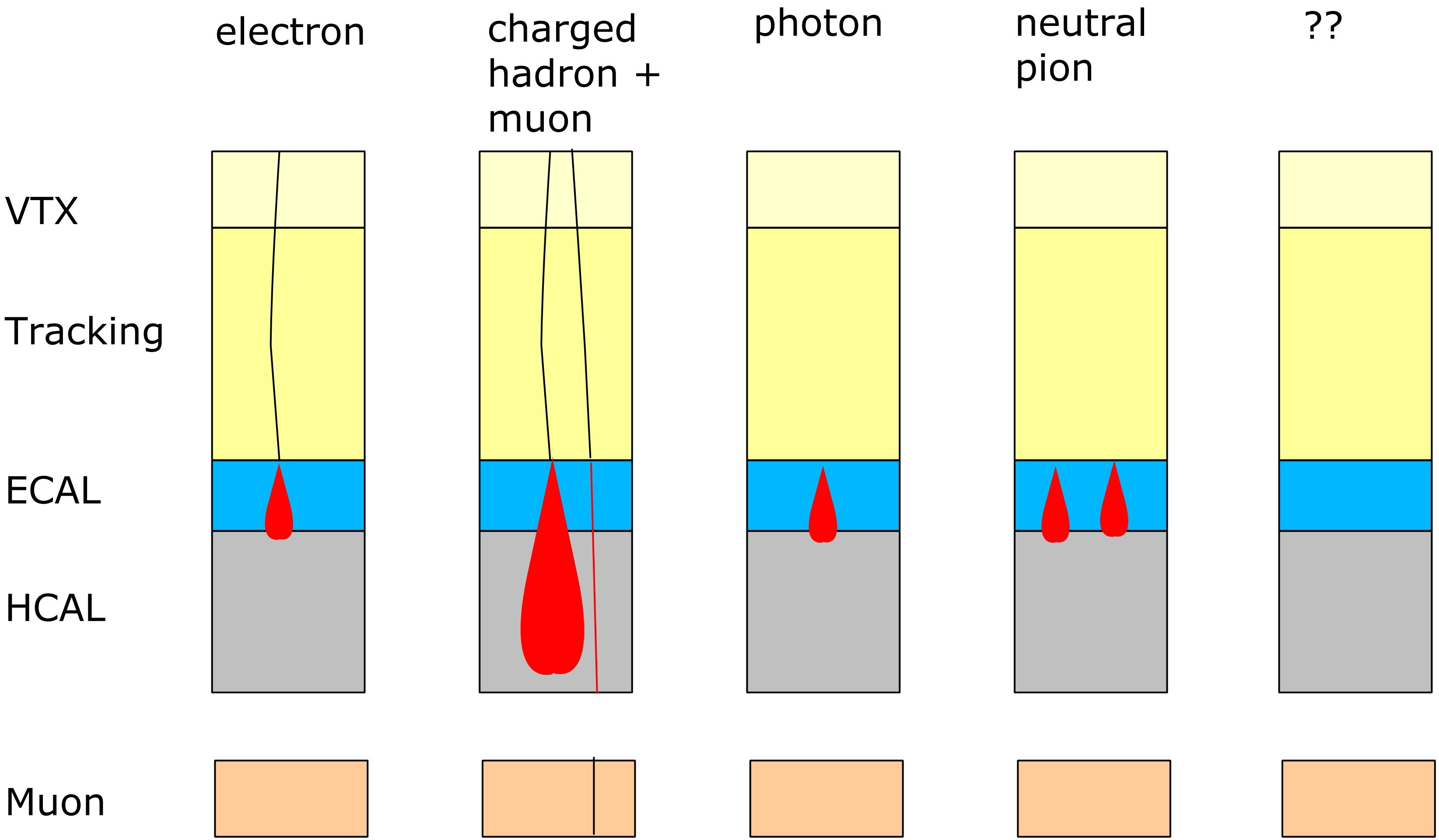


Detektoren

A detector cross-section, showing particle paths

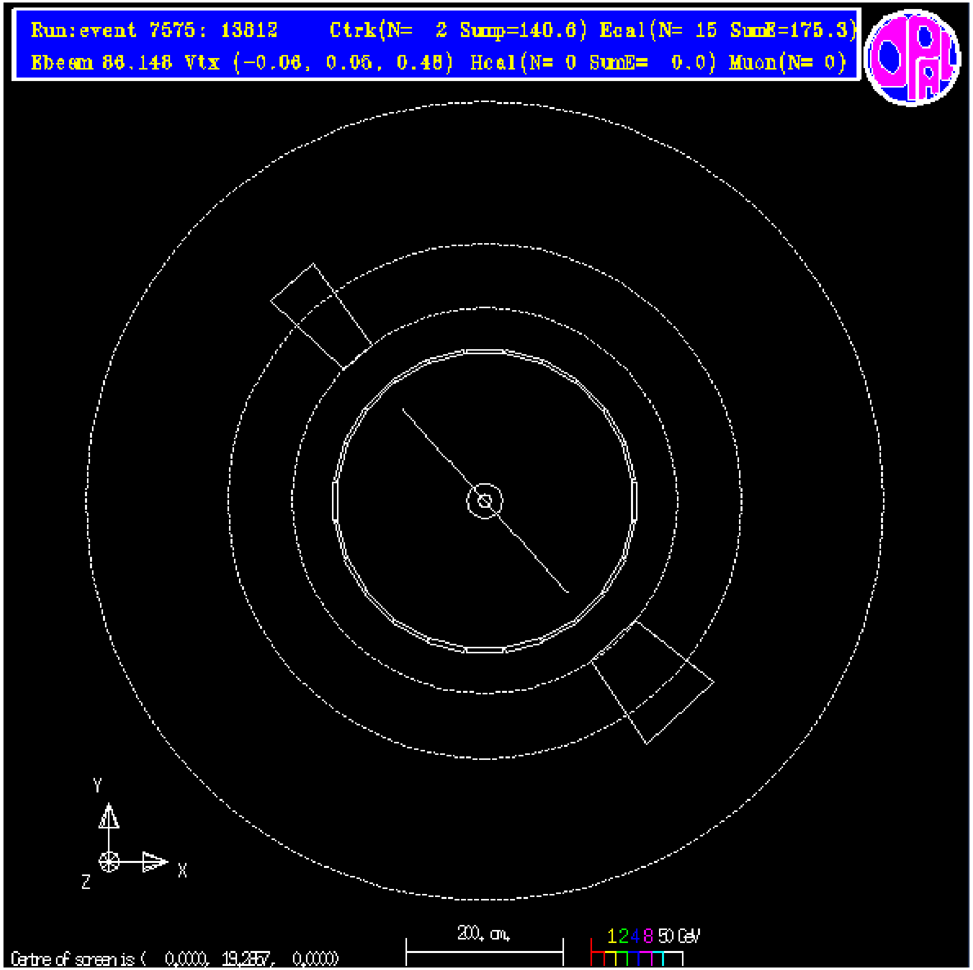


Detektoren


electron
charged hadron + muon
photon
neutral pion
??
VTX
Tracking
ECAL
HCAL
Muon

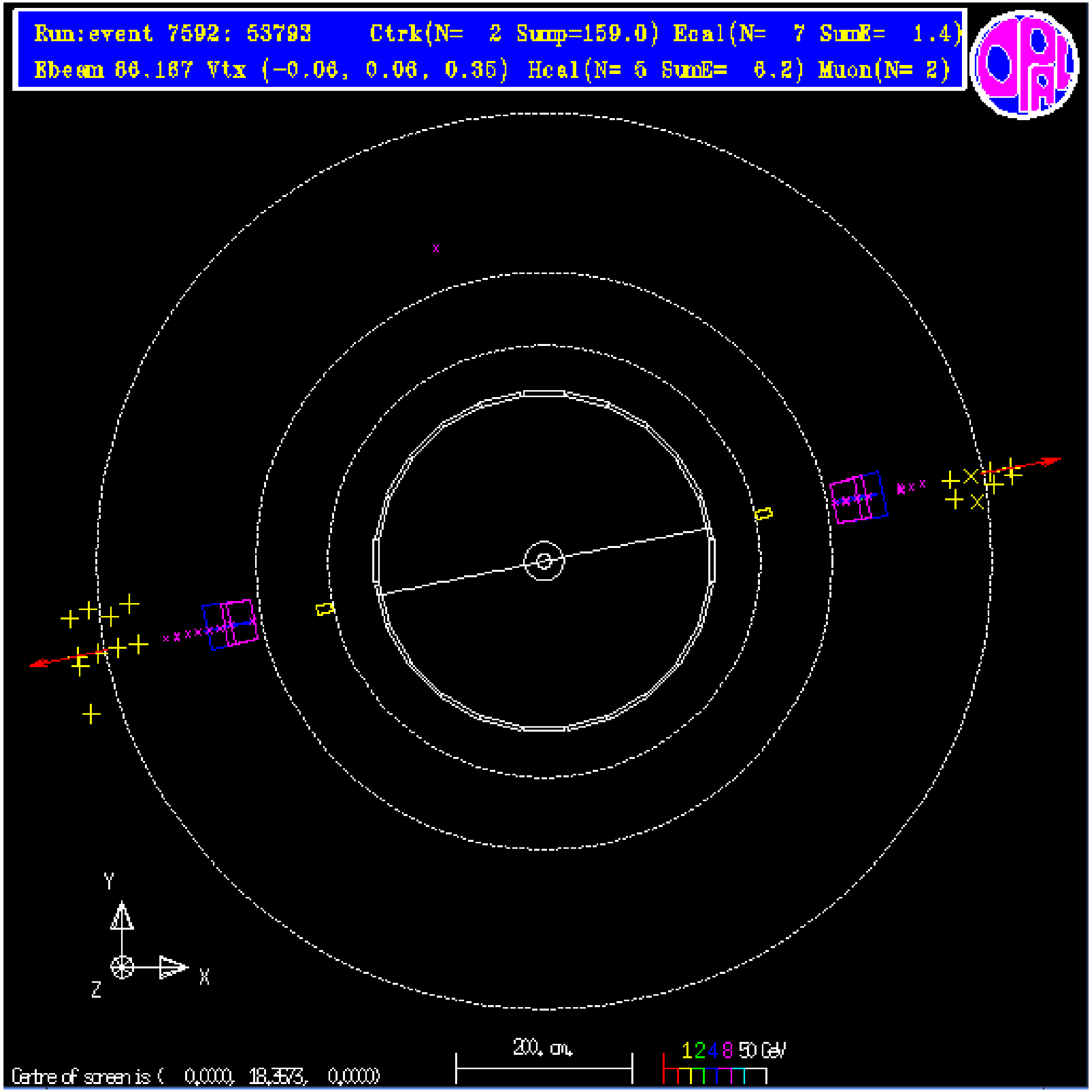
Ereignisse identifizieren

http://www.hep.man.ac.uk/~events/home.html



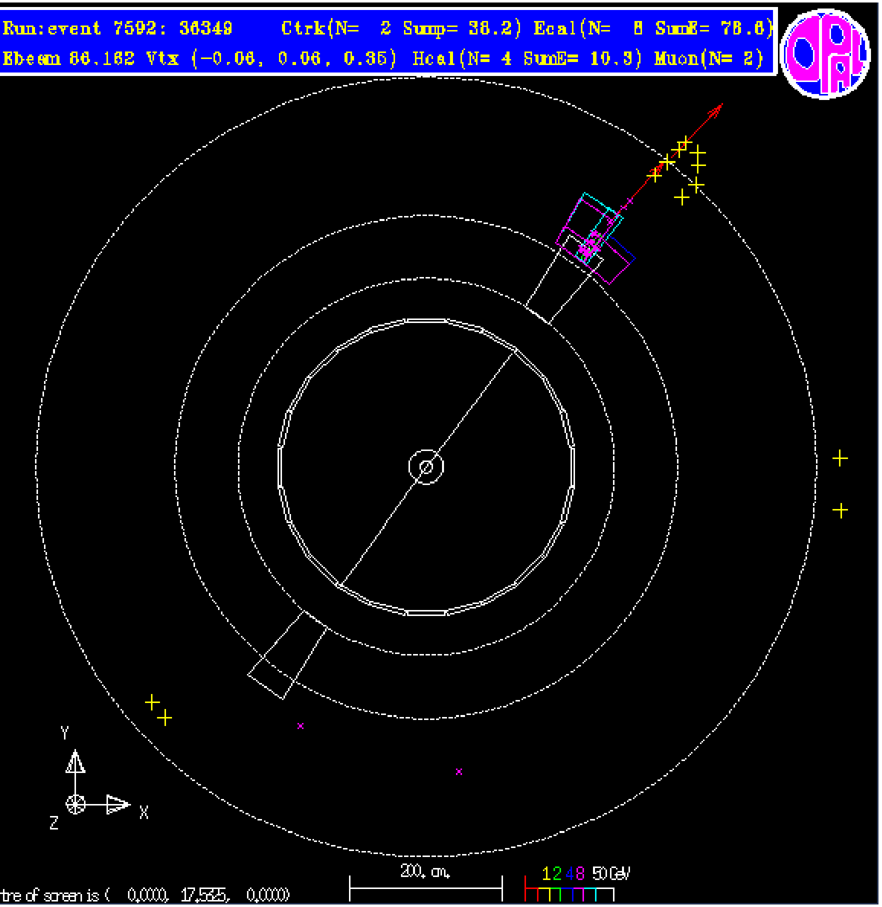
$$e^+e^- \rightarrow e^+e^-$$

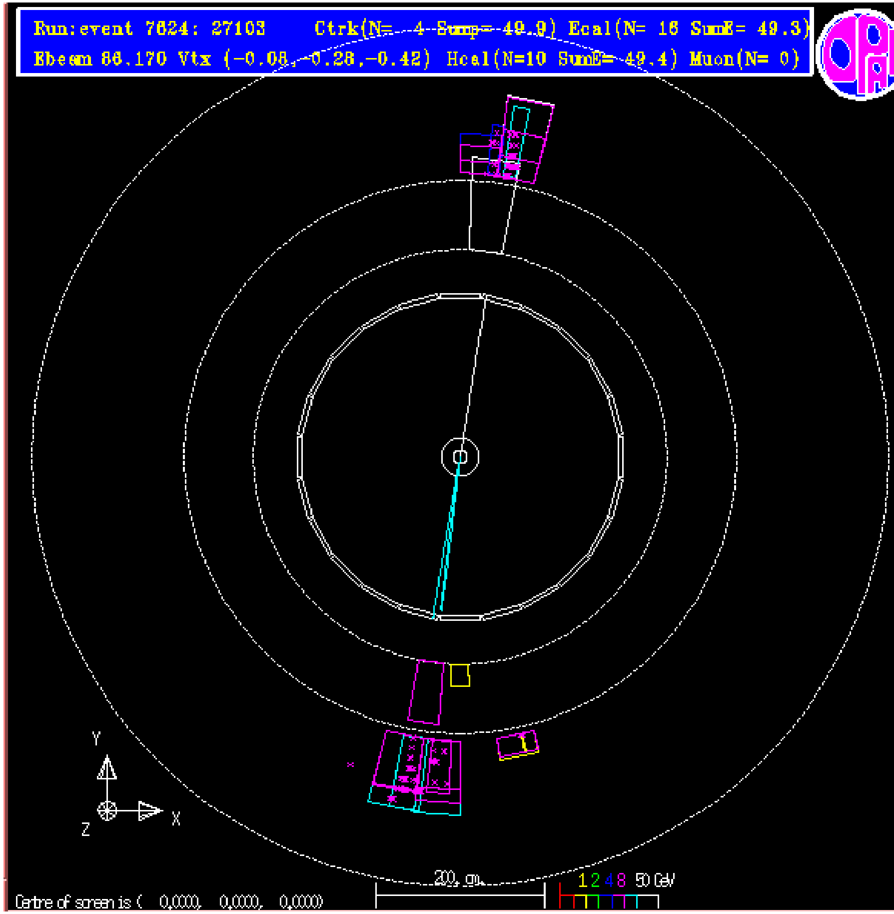
Ereignisse identifizieren



$$e^+e^- \rightarrow \mu^+\mu^-$$

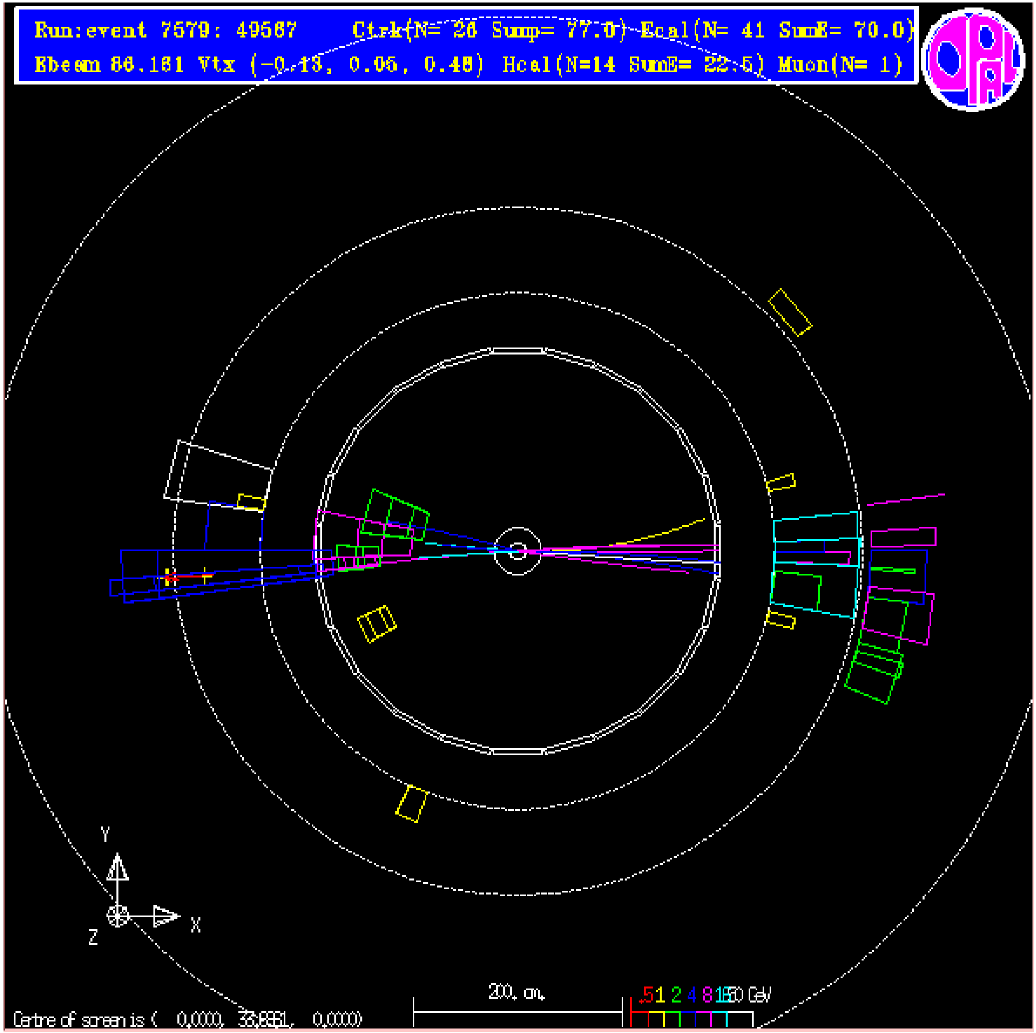
Ereignisse identifizieren





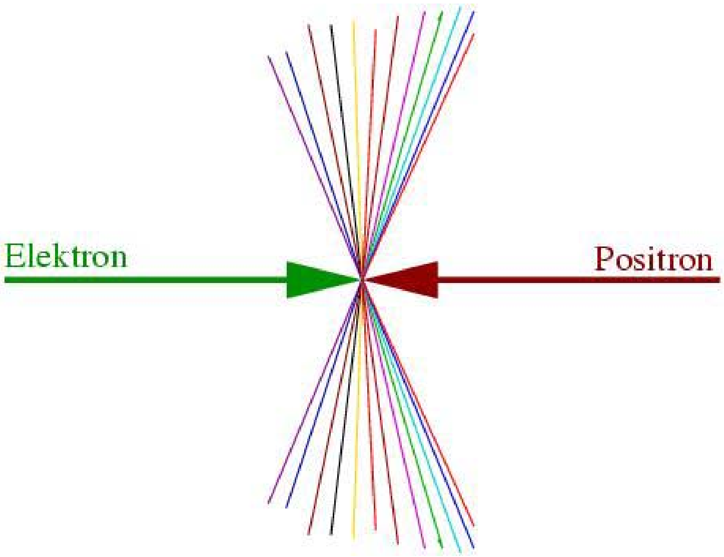
$$e^+e^- \rightarrow \tau^+\tau^-$$

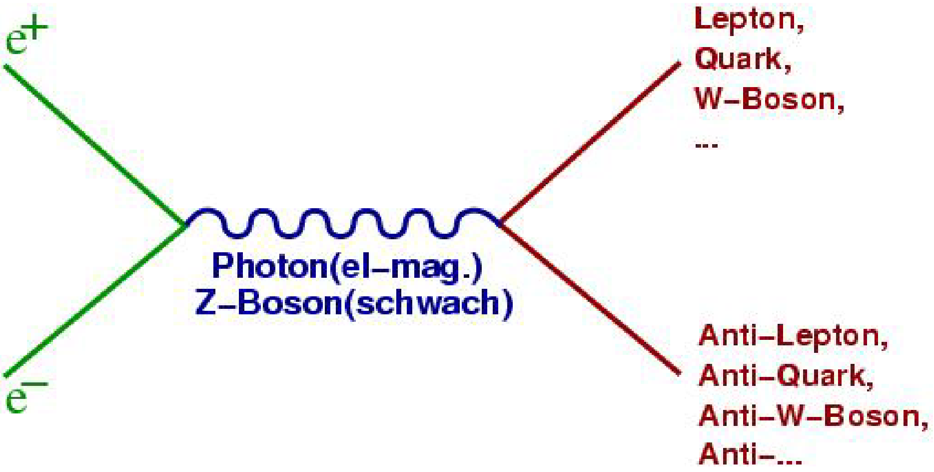
Ereignisse identifizieren



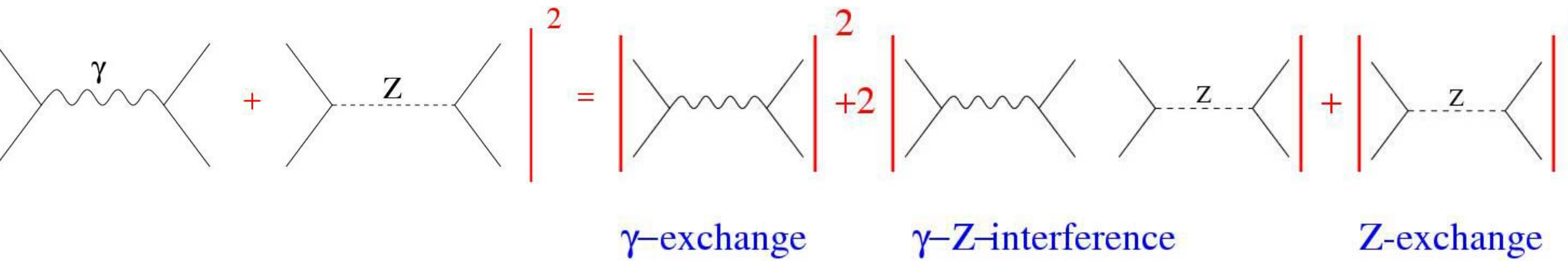
$$e^+e^- \rightarrow q\bar{q}$$

Der wichtigste Prozess bei LEP1





Der Wirkungsquerschnitt

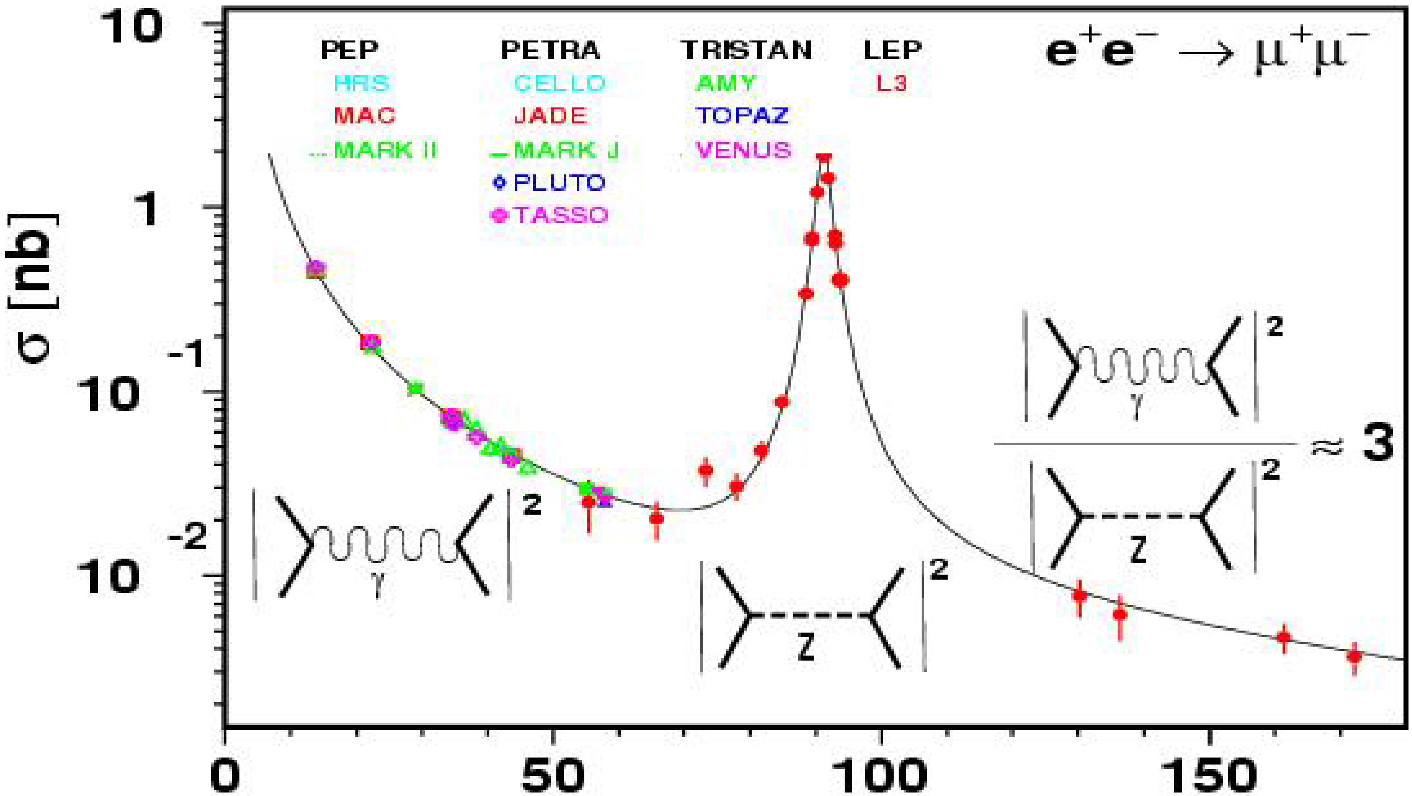


$$\frac{d\sigma}{d\Omega} = N_c \frac{\alpha^2}{4s} \quad \{(1+\cos^2\theta)\,[Q_f^2 - 2\chi_1 v_e v_f Q_f - \chi_2\,(a_e^2+v_e^2)\,(a_f^2+v_f^2)]$$

$$+2\cos\theta\,[-2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f]\}$$

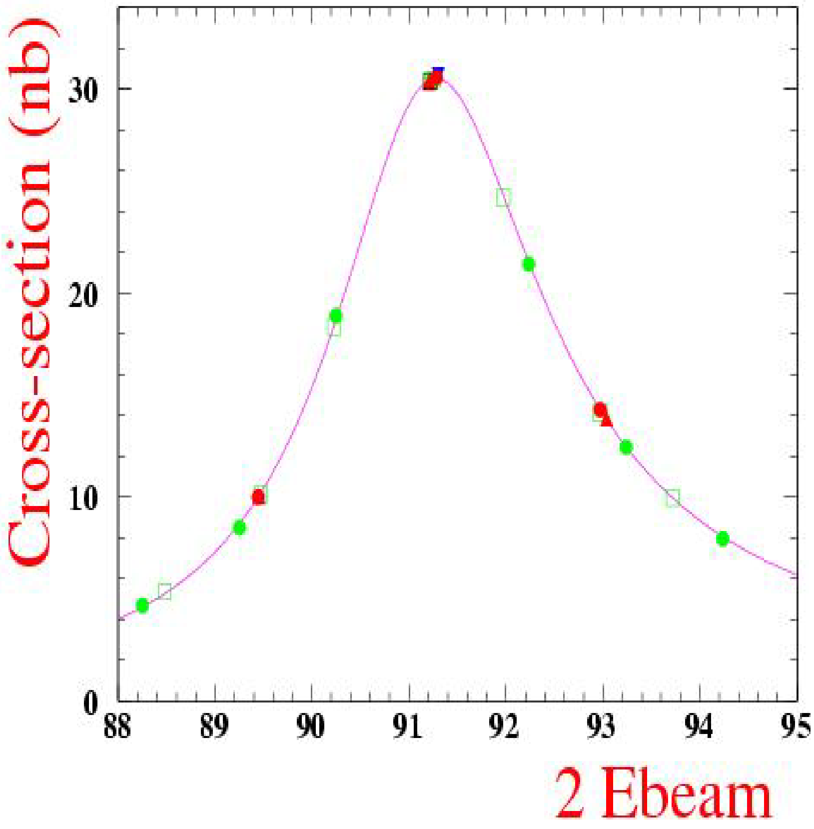
$$\begin{aligned}
\chi_1 &= \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\,\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} \\
\chi_2 &= \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\,\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} \\
a_e &= -1 \\
v_e &= -1+4\sin^2\theta_W \\
a_f &= 2T_{3f} \\
v_f &= 2T_{3f} - 4Q_f\sin^2\theta_W
\end{aligned}$$

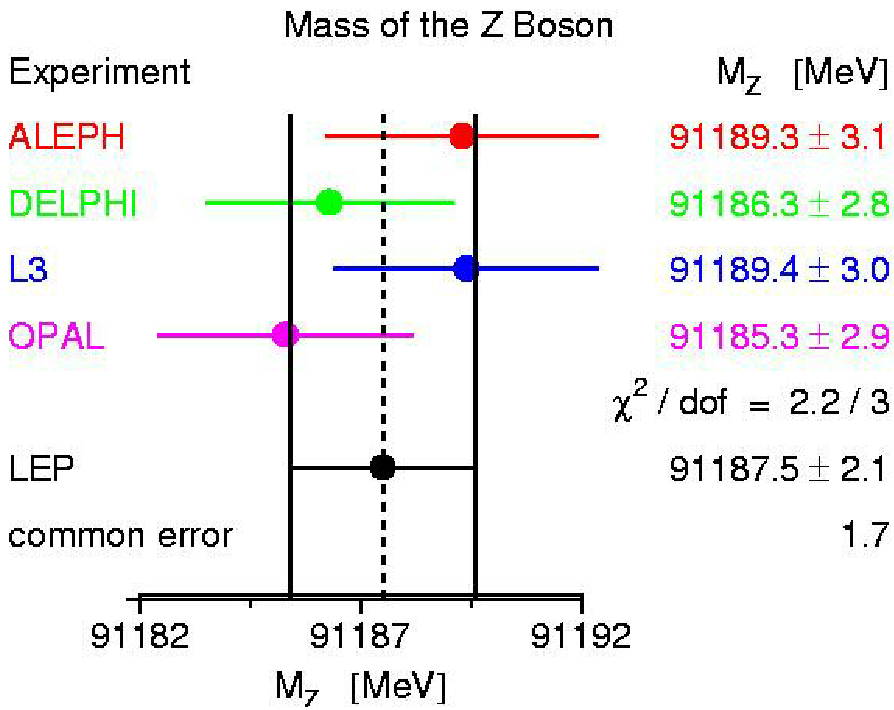
Der Wirkungsquerschnitt



- γ-exchange dominant for low $\sqrt{s}$
- Z^0 is a dramatic resonance !
- Theory curve describes the data extremely well
- Theory curve is not the one from previous page but includes higher-order corrections

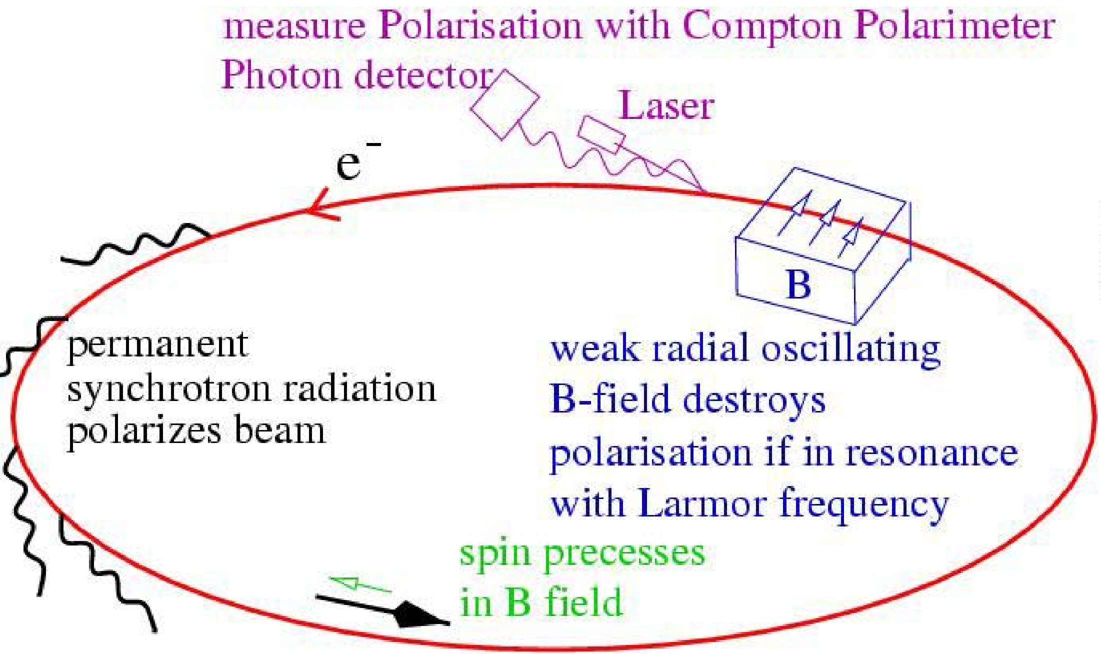
Die Masse des Z-Bosons



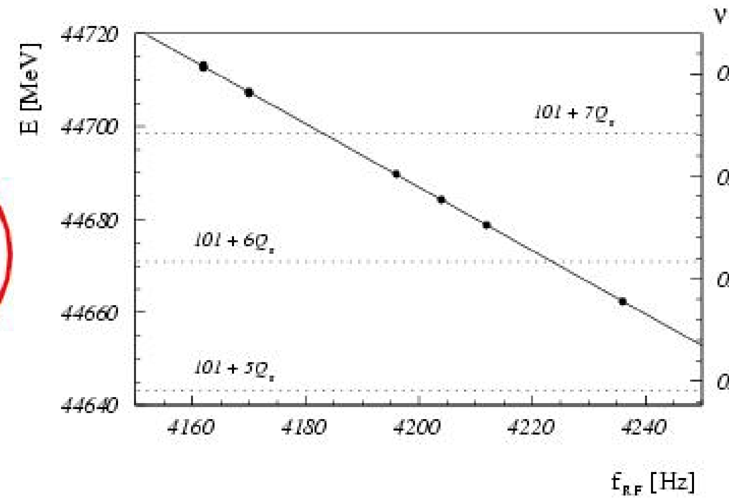


Fehler nur 2.1 MeV!
Benötigt Verständnis vieler kleiner theoretischer + experimenteller Effekte
Wichtig: Strahlenergie

Strahlenergiemessung

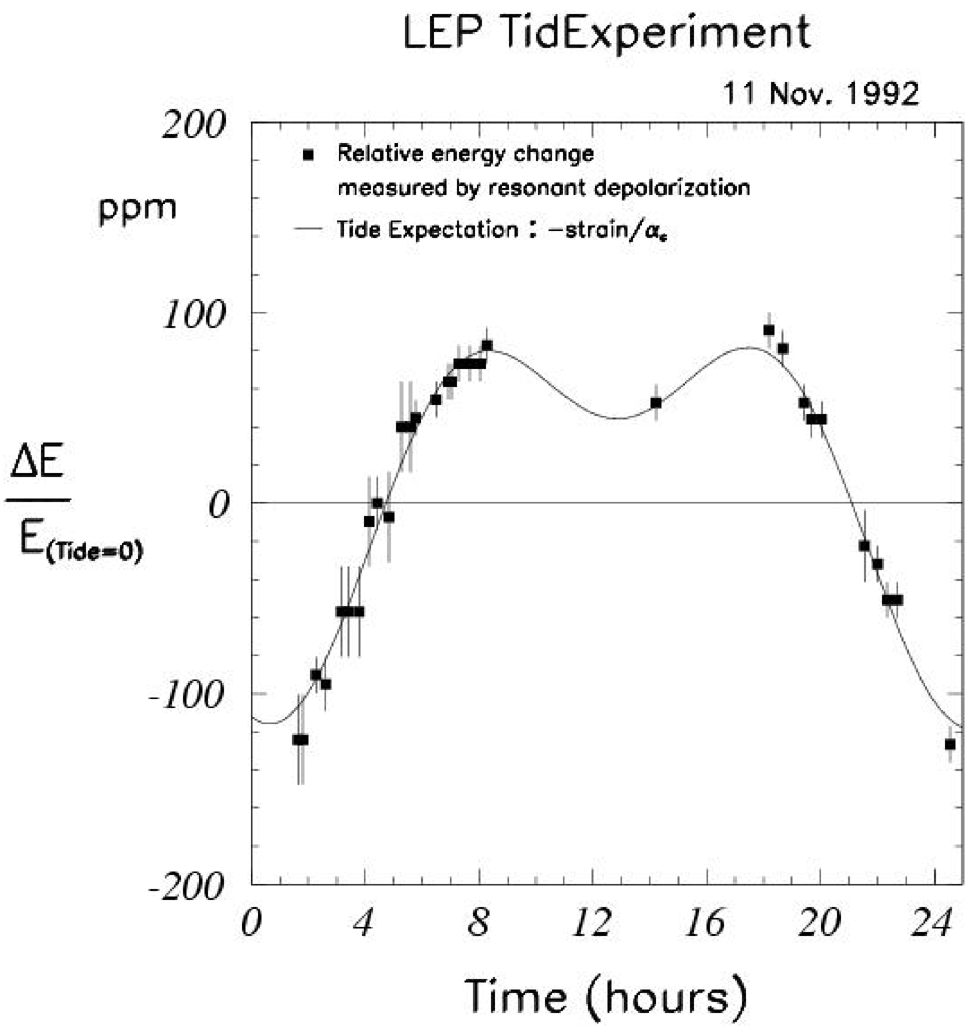


$$\nu = \frac{g-2}{2}\,\frac{E}{mc^2}$$ (Larmor frequency)



Erreichte Präzision: ~ 1 MeV !

Strahlenergiemessung:kleine Effekte

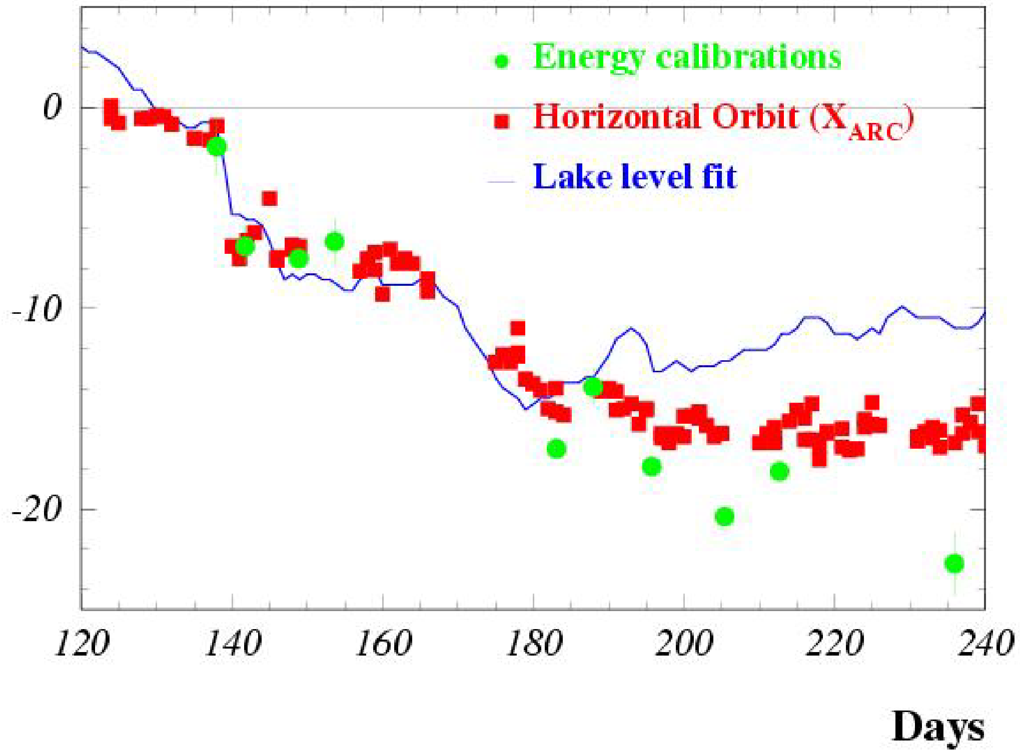


Moon pulls the LEP ring

→ change ring radius by 1 mm

→ 10 MeV energy change

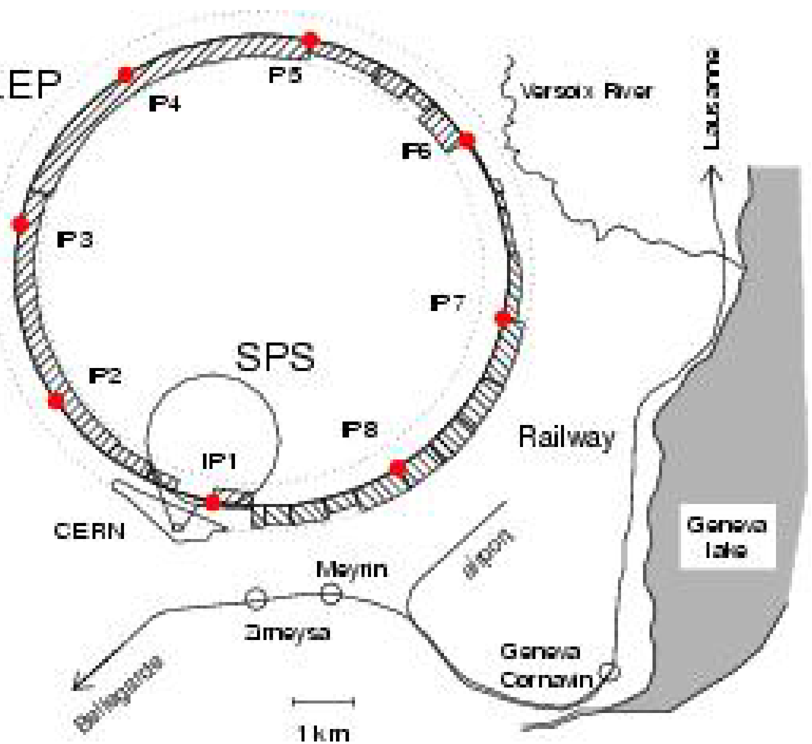
Strahlenergiemessung: sehr kleine Effekte

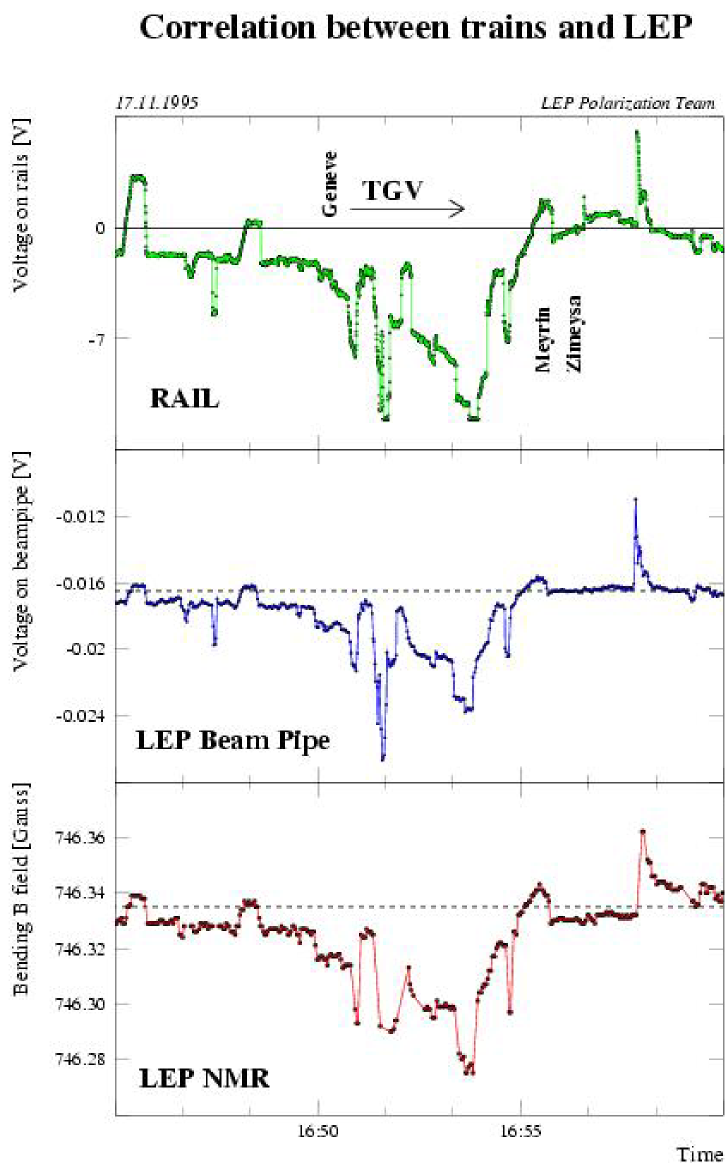


Water level in lake Geneva causes deformation of LEP ring

$\longrightarrow$ up to 20 MeV energy change

Strahlenergiemessung: sehr kleine Effekte





Nächster Schritt: Ereignisse klassifizieren

SM macht genaue Vorhersagen der Z-Verzweigungsverhältnisse:

$$\Gamma_{\nu\nu} = \frac{\mathrm{G_F M_Z^3}}{12\pi\sqrt{2}} \approx 167\ \mathrm{MeV}$$ für jede Neutrinofamilie

$$\Gamma_{ee} = \Gamma_{\mu\mu} = \Gamma_{\tau\tau} = 4x_W^2 \Gamma_{\nu\nu} \approx 84\ \mathrm{MeV}$$

$$\Gamma_{uu} = \Gamma_{cc} = 3\left(\frac{32}{9}x_W^2 - \frac{8}{3}x_W + 1\right)\Gamma_{\nu\nu} \approx 287\ \mathrm{MeV}$$

$$\Gamma_{dd} = \Gamma_{ss} = \Gamma_{bb} = 3\left(\frac{8}{9}x_W^2 - \frac{4}{3}x_W + 1\right)\Gamma_{\nu\nu} \approx 370\ \mathrm{MeV}$$

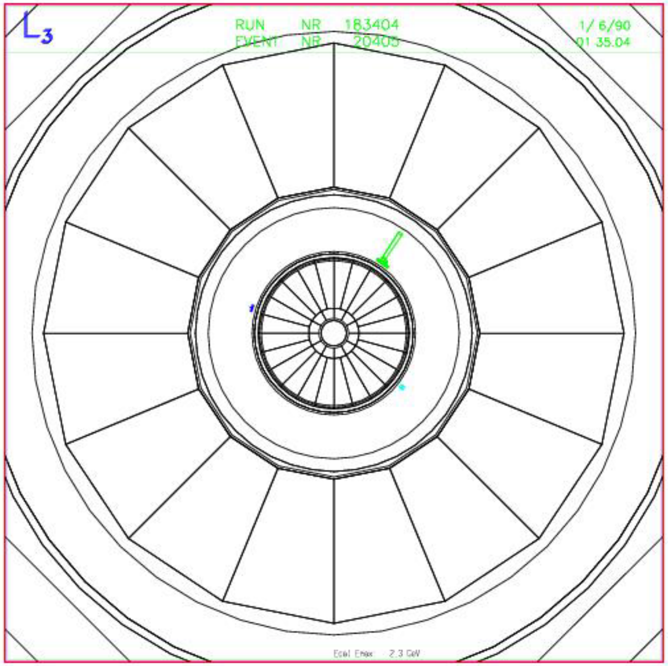
(Quarkmassen vernachlässigt)

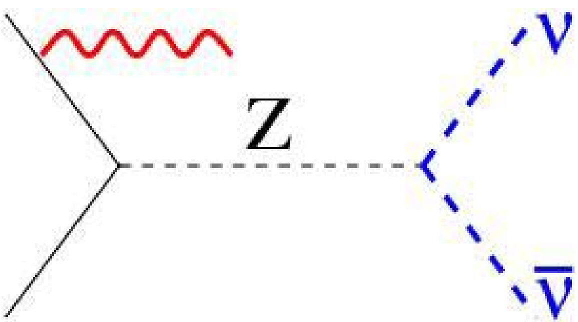
$$(x_W = \sin^2\theta_W)$$

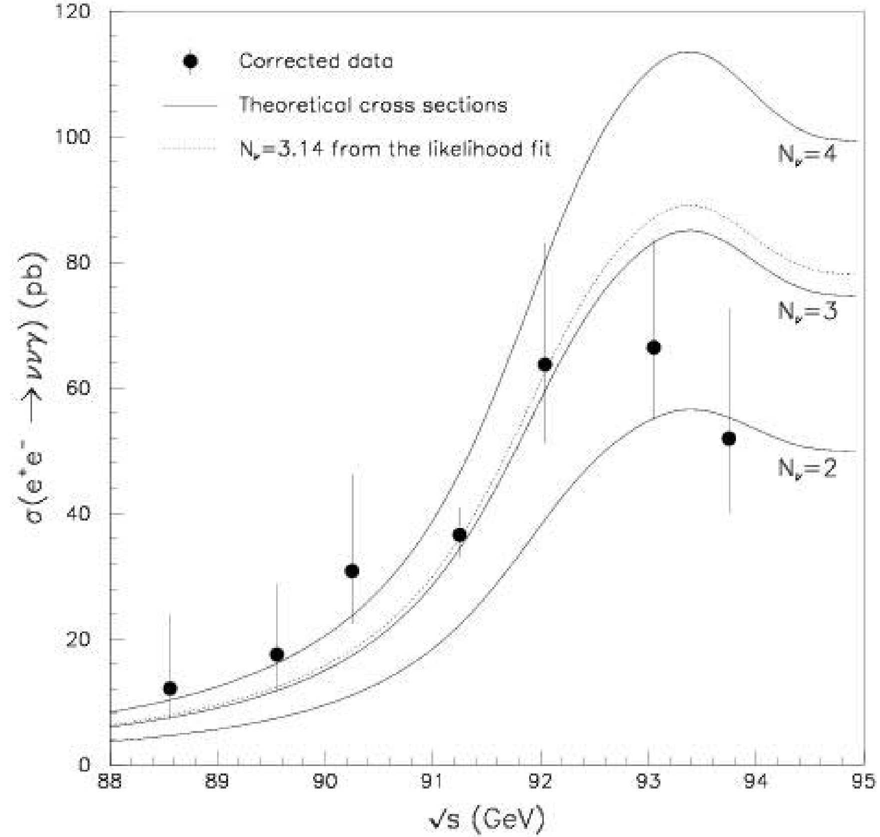
Wie kann man $\Gamma_{\nu\nu}$ messen ?

$$BR(Z \to X) = \frac{\Gamma_X}{\Gamma_{tot}}$$

Neutrinos zählen





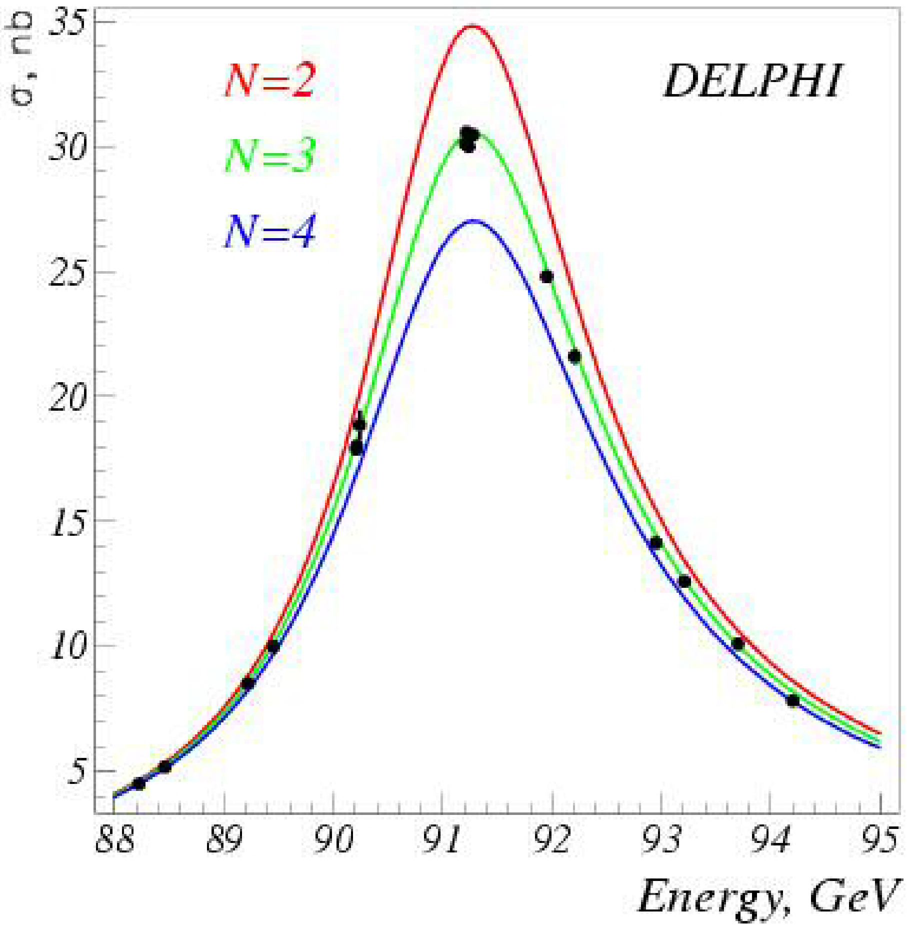


3 Familien bevorzugt, aber großer Fehler…

Neutrinos zählen – etwas schlauer…

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{qq} + N_{families}\Gamma_{\nu\nu}$$

d.h. die Anzahl der Familien hängt von der totalen Breite ab



Ergebnis:

$$N_{families} = 2.9841 \pm 0.0083$$

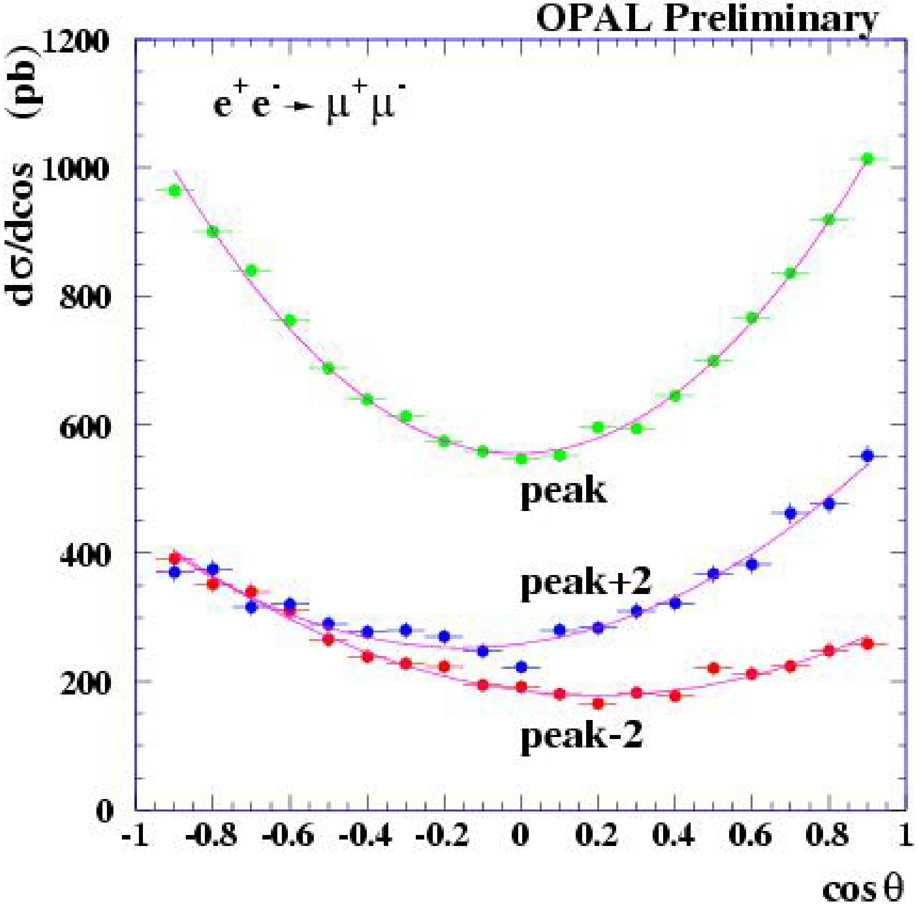
vor LEP:

$$N_{families} < 5.9$$

Noch ein Schritt weiter: Winkelverteilungen

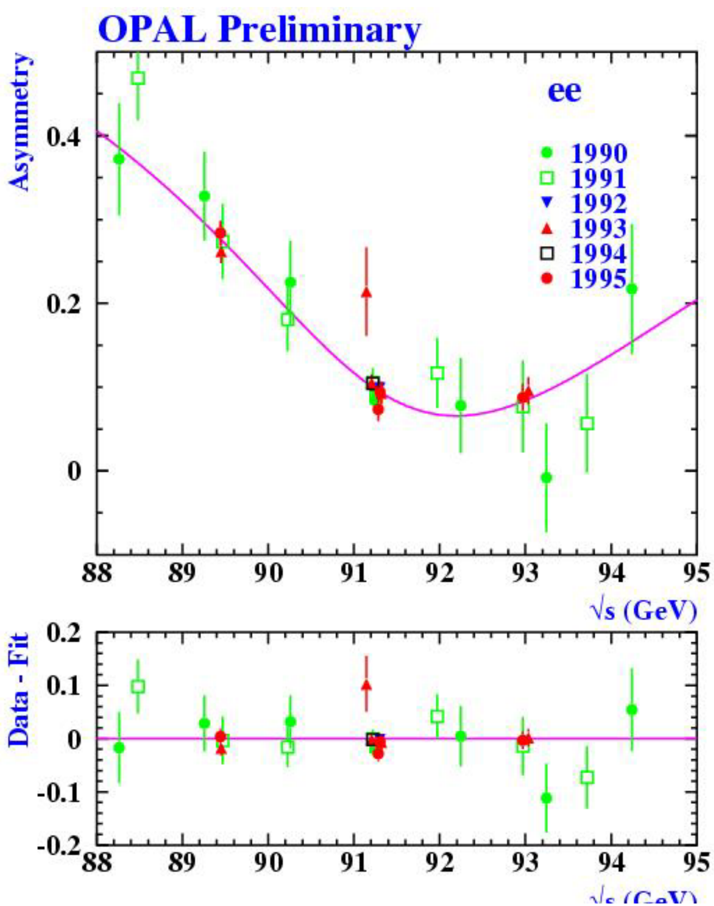
Linearer Term in cos(θ) führt zu Vorwärts-Rückwärtsassymetrie:

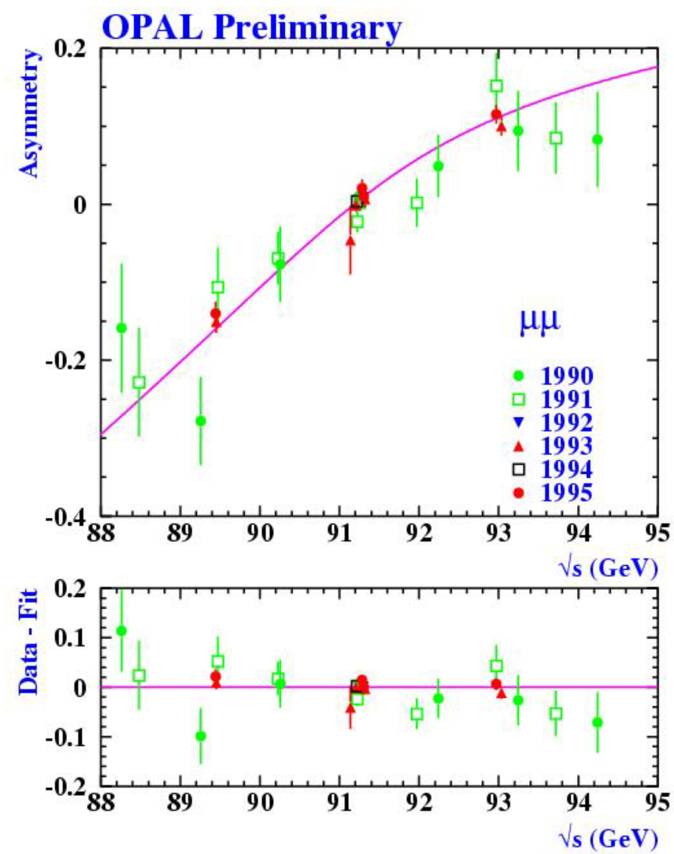
$$A_{FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

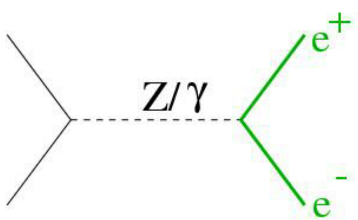


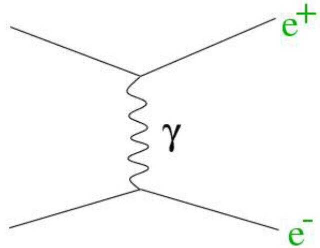
besser
(kleinere Systematik) als
fit der ganzen Verteilung
da die Detektoreffizienz
keine Rolle spielt
(nur vorwärts-rückwärts-
symmetrischer Detektor)

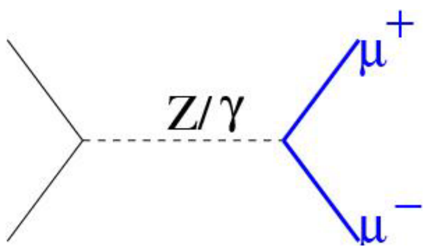
Noch ein Schritt weiter: Winkelverteilungen









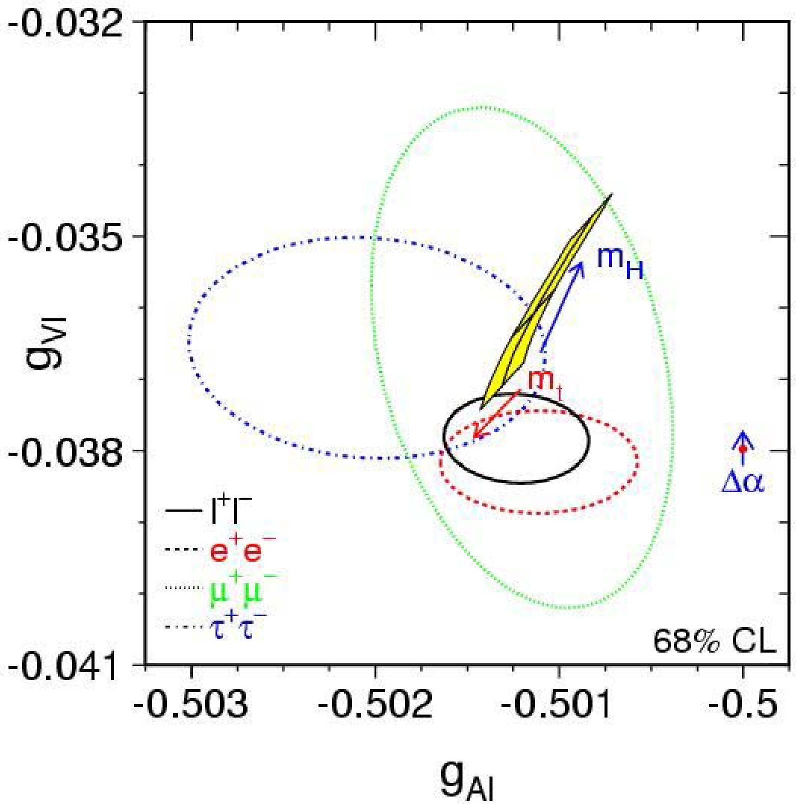


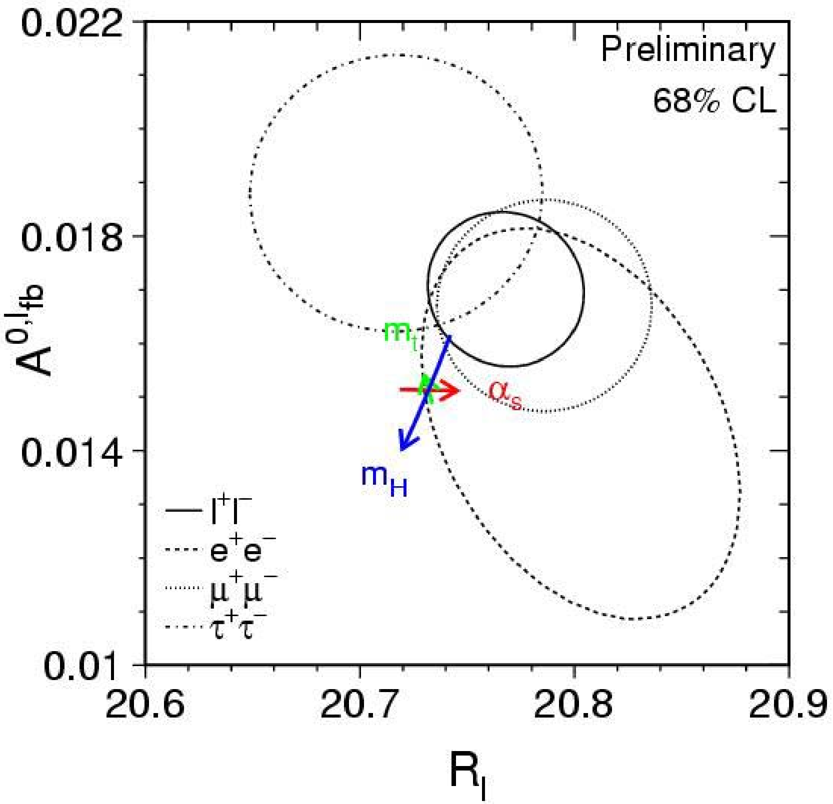
Noch ein Schritt weiter: Winkelverteilungen

FB Asymmetrien ermöglichen Bestimmung der Vektor- and Axialvekt

Kopplungen der Fermionen an das Z.

Test der Leptonuniversalität!





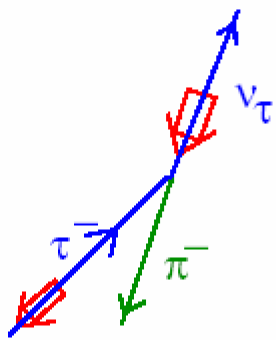
Another degree of freedom: polarisation

Measure polarisation of final state:

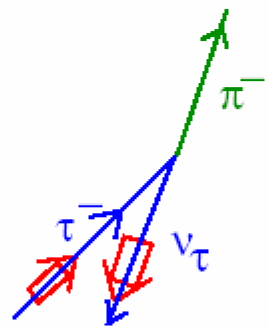
Need a spin analyser: impossible for e^+e^-, $\mu^+\mu^-$

$\longrightarrow$ **would need a "4π-Stern-Gerlach-Exp."**

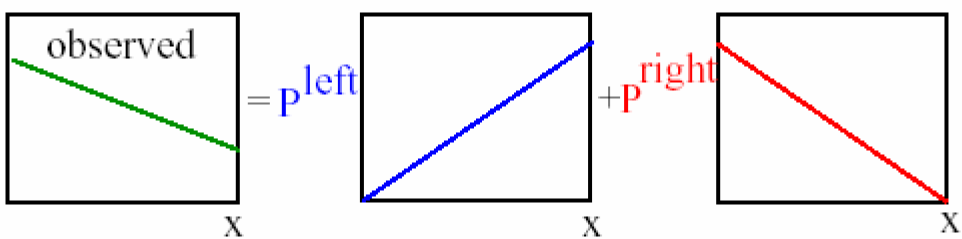
$\longrightarrow$ **but τ-leptons are their own spin alalyser, through their decay:**



left-handed tau:
neutrino emitted
in tau flight direction



right-handed tau:
neutrino emitted
against tau flight direction



Tau polarisation

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

From the $\cos\theta$ dependence of P_τ the so called Asymmetry Parameters A_e and A_τ can be calculated:

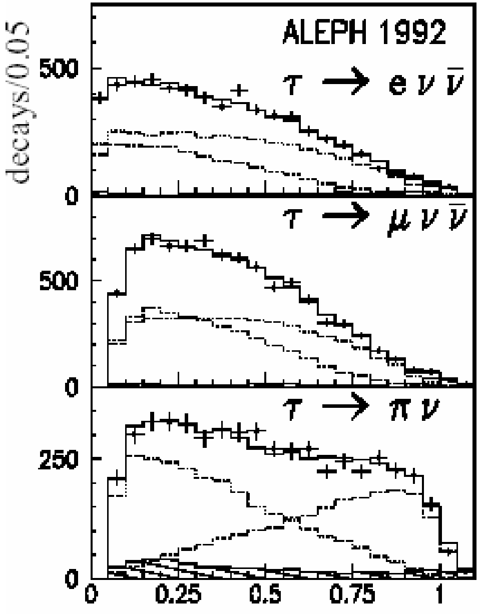
$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta) + A_e(2\cos\theta)}{(1+\cos^2\theta) + A_\tau A_e(2\cos\theta)}$$

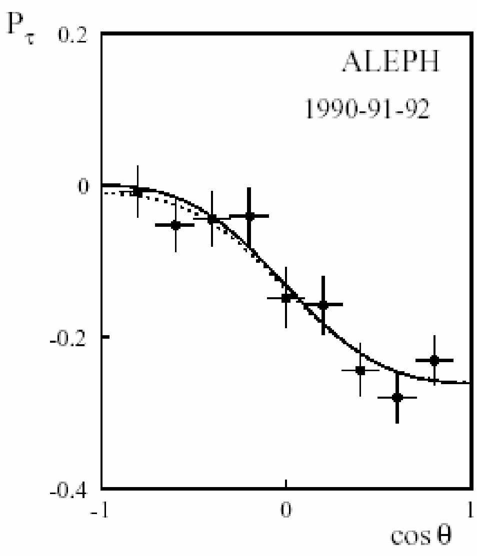
which in turn are functions of the axial- and vector coupling to the Z^0:

$$A_\ell = \frac{2 v_\ell a_\ell}{v_\ell^2 + a_\ell^2}$$

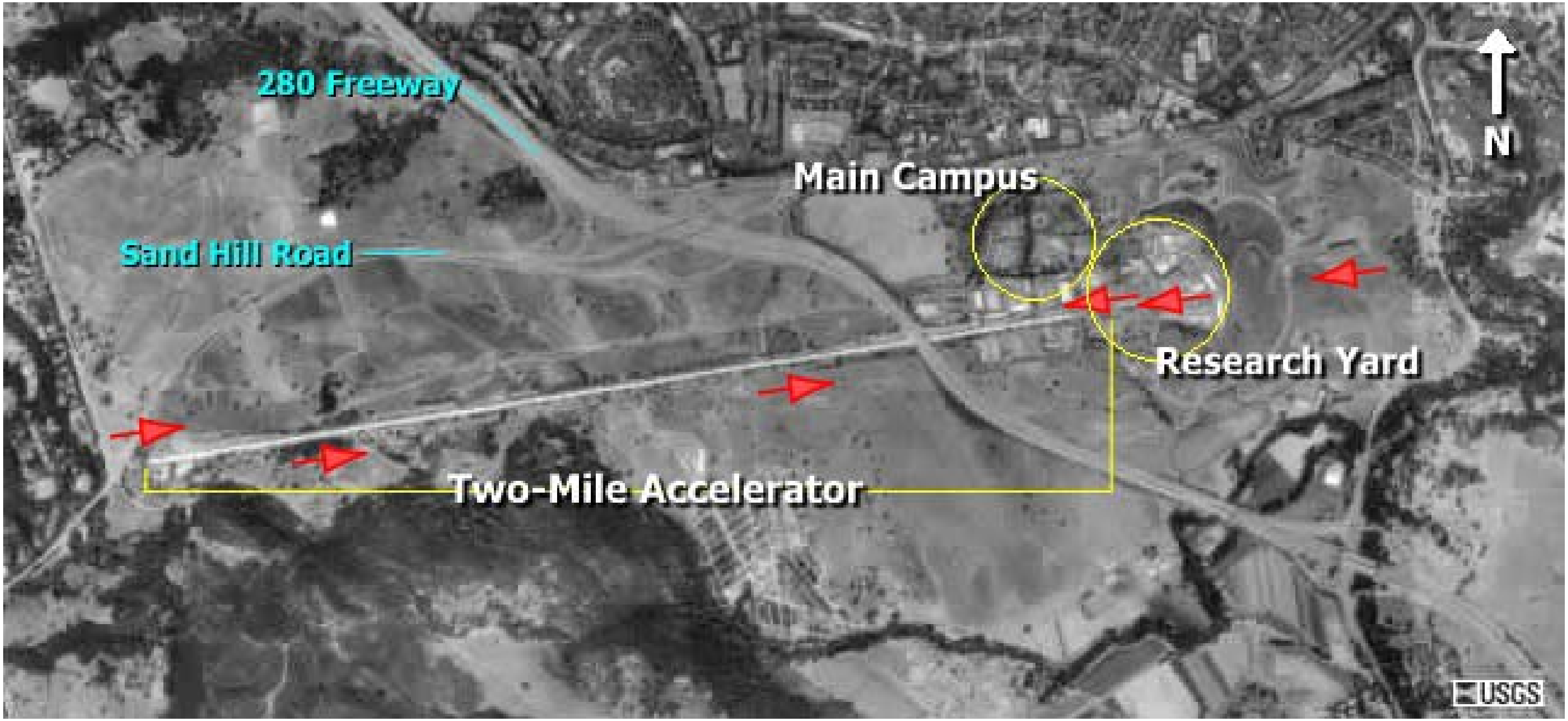
which measure the electro-weak mixing angle:

$$\sin^2\theta_W^{eff} = \frac{1}{4}\left(1 - \frac{v_\ell}{a_\ell}\right)$$

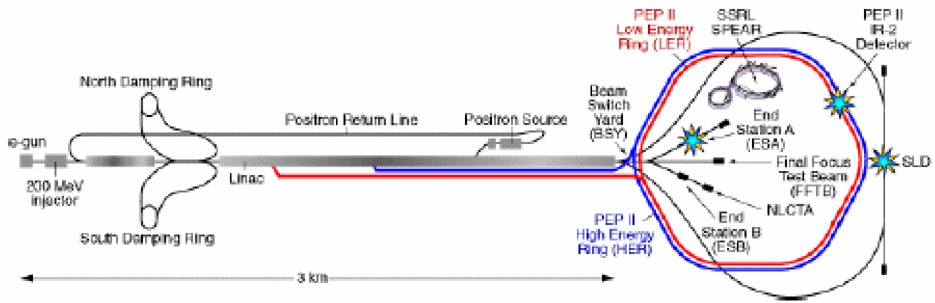


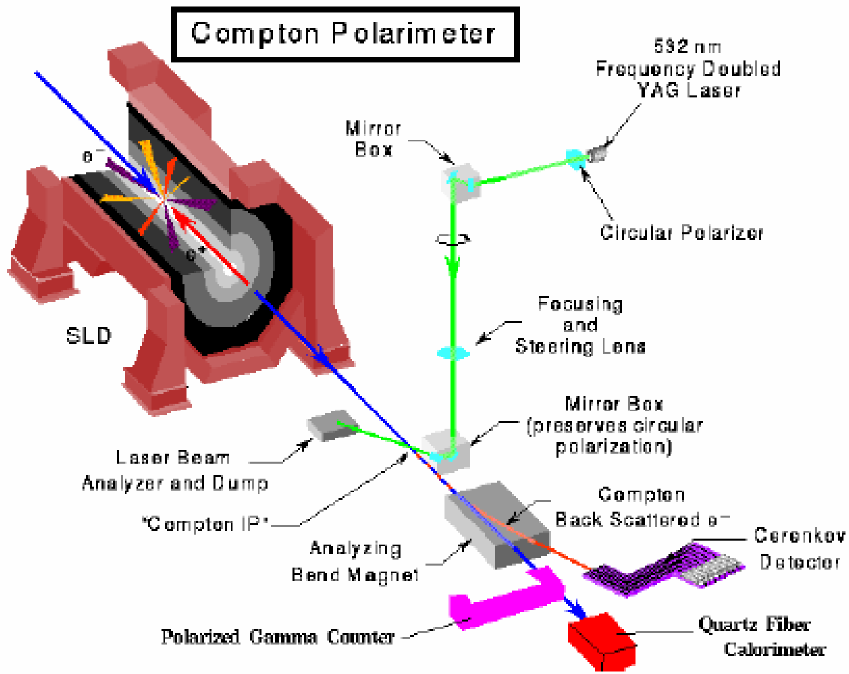


Excursion across the Atlantic



Excursion across the Atlantic





Left-Right Asymmetry

With longitudinally polarised e^- beam, the left-right Asymmetry can be measured:

$$A_{LR} = \frac{\sigma(e_L^- e_R^+) - \sigma(e_R^- e_L^+)}{\sigma(e_L^- e_R^+) + \sigma(e_R^- e_L^+)}$$

Note that $\sigma(e_L^- e_L^+) = \sigma(e_R^- e_R^+) = 0$ for anihilation!

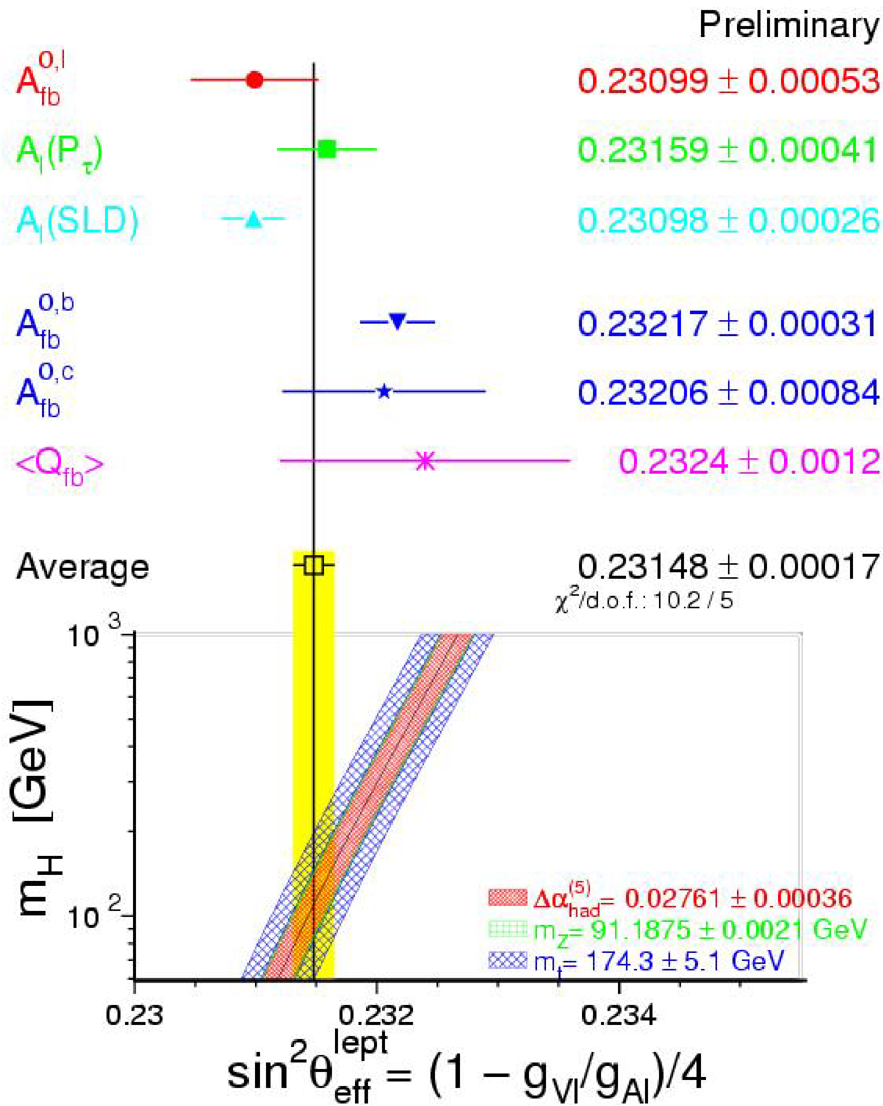
It is again directly related to the electrweak mixing angle:

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

The result:

$$\boxed{A_{LR}(m_Z) = 0.1656 \pm 0.0071(\mathrm{stat.}) \pm 0.0028(\mathrm{syst.})}$$

Interpretation of the Asymmetries



Asymmetry measurements
Can be interpreted as
Measurement of the
Electro-weak mixing angle

$$\sin^2 \theta_W$$

Too precise measurements! – Radiative corrections

The measured observables can be predicted in the SM as a function
Of the following parameters:

$$\mathcal{O} = \mathcal{O}(m_Z, m_t, m_H, \alpha(m_Z), \alpha_s(m_Z); G_F)$$

LEP

- Lineshape $m_Z, \Gamma_Z, \sigma_h^0, R_\ell, A_{FB}^{0,\ell}$
- $P(\tau)$ $\mathcal{A}_e, \mathcal{A}_\tau$
- b, c $R_b, R_c, A_{FB}^{0,b}, A_{FB}^{0,c}$
- Q_{FB} $\sin^2\theta_{eff}^{lept}$

SLD

- b, c $R_b, R_c, A_{FB}^{0,b}, A_{FB}^{0,c}$
- L-R asym $\mathcal{A}_\ell, \mathcal{A}_b, \mathcal{A}_c$

$p\bar{p}$, LEP2

- m_t, m_W

νN

- $\sin^2\theta_W$

$$R_\ell = \Gamma_{had}/\Gamma_\ell$$

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$\mathcal{A}_f = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

$$g_{V\ell}/g_{A\ell} = 1 - 4\sin^2\theta_{eff}^{lept}$$

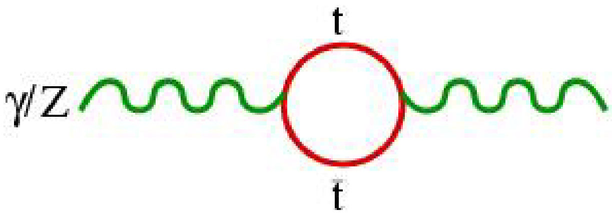
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Too precise measurements! – Radiative corrections

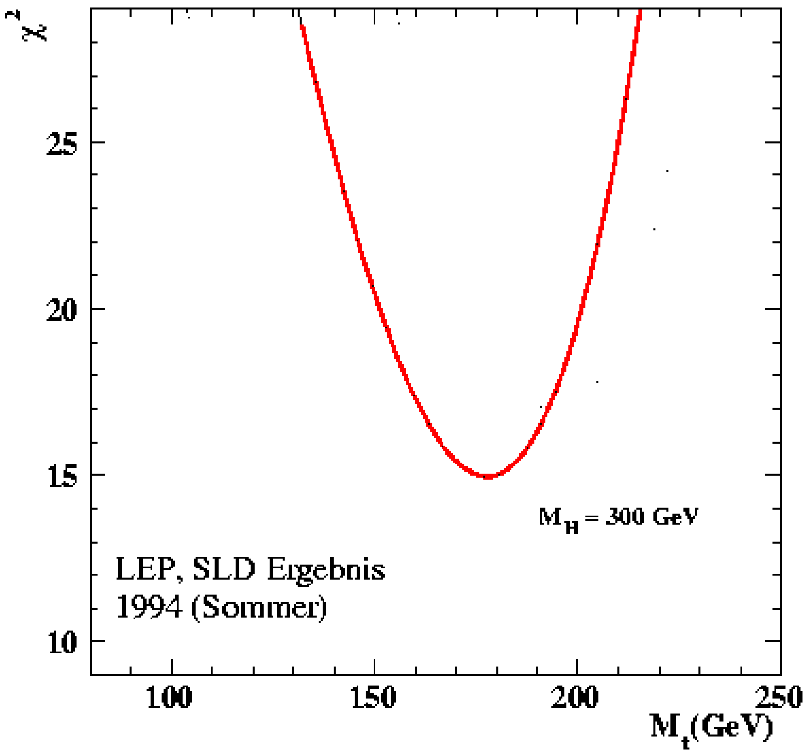
They depend on the unknown parameters

m_{top} linearly

m_{Higgs} only logarithmically

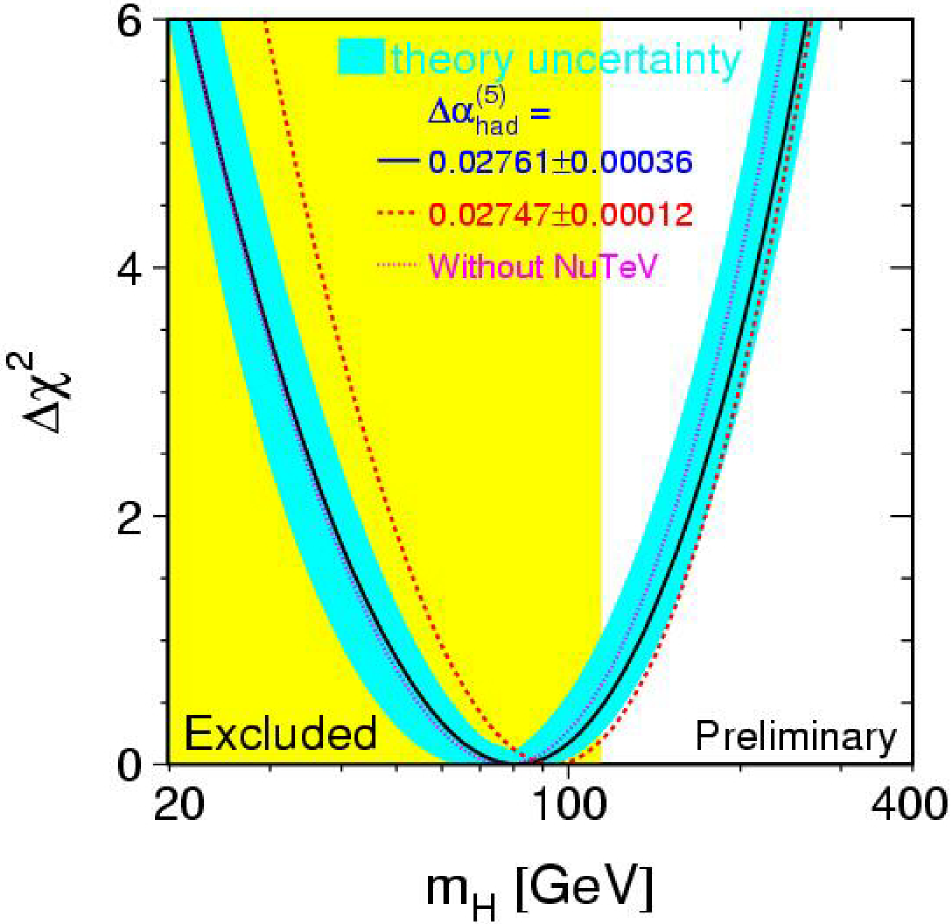


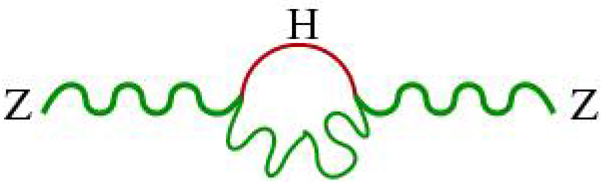
Lead to prediction of top-mass before its discovery:



Sensitivity to the last SM particle: the Higgs

Perform a global fit to all measurements within the SM to obtain the most likely Higgs mass:





M(Higgs) <~ 200 GeV at 95% C.L.

What is the yellow bar?

Particle Physics Today

excellent:

Impressive agreement between experimental results and thoeretical predictions:

A major part of these Results comes from LEP and SLD!

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84