Electroweak measurements
– The quest for even higher precision –

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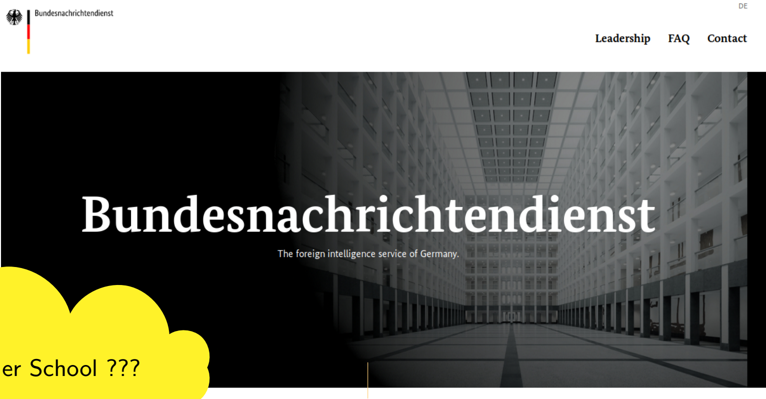
Albert-Ludwigs Universität Freiburg

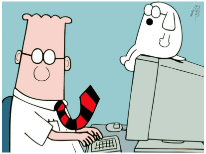
– BND summer school 2019 –



Bundesnachrichtendienst

The foreign intelligence service of Germany.

BND Summer School ???



What are your questions?

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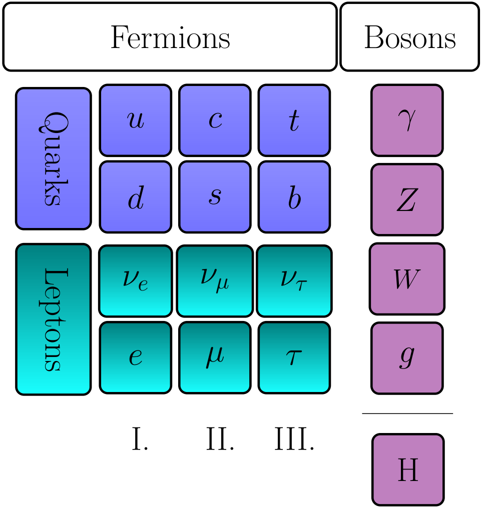
And put in the code I'll give you. You can write down **questions** any time!

Will also use this page for a **Quiz** and **feedback**.

The Standard Model of Particle Physics



	Fermions			Bosons
Quarks	u	c	t	γ
	d	s	b	Z
Leptons	ν_e	ν_μ	ν_τ	W
	e	μ	τ	g
	I.	II.	III.	H

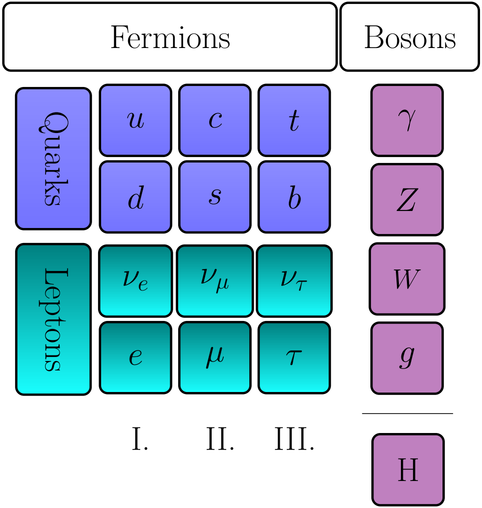
➔ electromagnetic interaction

➔ neutral weak interaction

➔ charged weak interaction

➔ strong interaction

The Standard Model of Particle Physics



➔ electromagnetic interaction

➔ neutral weak interaction

➔ charged weak interaction

➔ strong interaction

➔ 4th July 2012: Observation of *Higgs-like* Boson at the LHC

The free parameters of the Standard Model

- α_{EM}: electromagnetic coupling constant
- α_S: strong coupling constant
- G_F: weak coupling constant

- 6 quark masses
- 3 charged lepton masses
- Z_0 mass
- Higgs mass

- 3 mixing angles and 1 complex phase (CKM matrix)

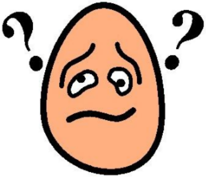
➔ for non-vanishing neutrino masses: 7 add. parameters (masses and mixing)

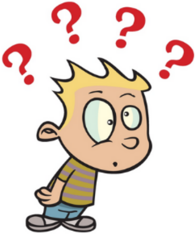
Why is the Higgs-boson special in the SM?

- ➔ neither quark nor lepton, which are building blocks of other matter
- ➔ also not a gauge boson, so it does not carry any force
- ➔ only scalar in the SM
- ➔ mechanism postulated long before many SM particles were known!

xkcd.com

Now a question for you!





Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz!

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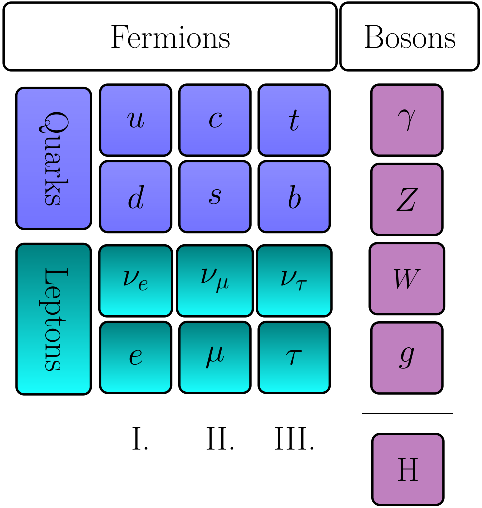
So from our nice list of elementary particles here...

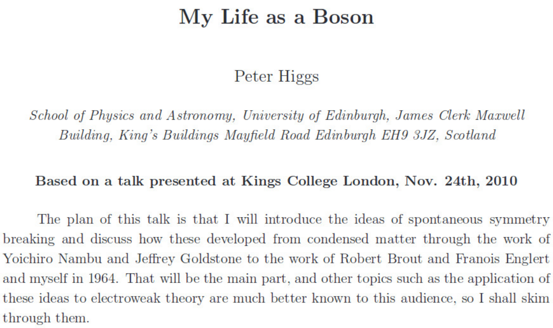


Fermions				Bosons
Quarks	u	c	t	γ
	d	s	b	Z
Leptons	ν_e	ν_μ	ν_τ	W
	e	μ	τ	g
	I.	II.	III.	H

… only these were known (postulated) in 1964

A little (pre)-history

Historical context



My Life as a Boson

Peter Higgs

School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell
Building, King's Buildings Mayfield Road Edinburgh EH9 3JZ, Scotland

Based on a talk presented at Kings College London, Nov. 24th, 2010

The plan of this talk is that I will introduce the ideas of spontaneous symmetry breaking and discuss how these developed from condensed matter through the work of Yoichiro Nambu and Jeffrey Goldstone to the work of Robert Brout and Franois Englert and myself in 1964. That will be the main part, and other topics such as the application of these ideas to electroweak theory are much better known to this audience, so I shall skim through them.

➔ nice summary of the history of SSB from Peter Higgs ▸ Link to full transcript

Question 2

Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz!

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Spontaneous symmetry breaking papers

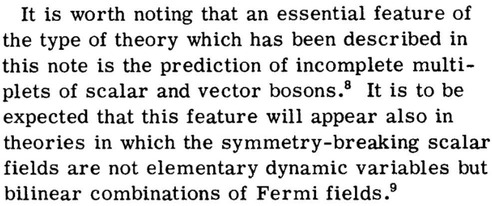
What is the difference between the approaches?

When approaches are equivalent, why “Higgs”-boson?

➔ one reason: people got order wrong and cited Higgs paper first

➔ then: first version of Higgs paper got rejected

↪ when revising the paper for resubmission, Higgs added the following:



It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

➔ first explicit mentioning of the scalar boson

➔ nowadays: Brout-Englert-Higgs (BEH) Boson!

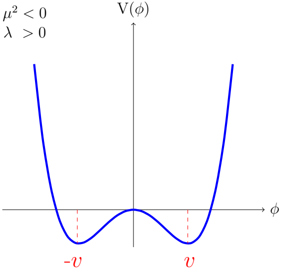
The BEH mechanism in simpler form

Introduce a doublet of complex, scalar fields ϕ:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad .$$

The corresponding Higgs potential is of the form:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$



⇒ get a non-vanishing vacuum-expectation value $v = \sqrt{-\mu^2/\lambda}$

Breakdown of Lagrangian for $\mathrm{SU(2)_L \times U(1)_Y}$

$$\mathcal{L}_{\mathrm{SU(2)_L \times U(1)_Y}} = \underbrace{-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{\mathcal{L}_{\mathrm{Gauge}}} + \underbrace{\bar{\psi_L}\gamma^{\mu}(iD^{\mu})\psi_L + \bar{\psi_R}\gamma^{\mu}(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu})\psi_R}_{\psi_{\mathcal{L}}\,_{\mathrm{Fermions}}}$$

$$+ \underbrace{|(iD^{\mu})\phi|^2 - V(\phi)}_{\mathcal{L}_{\mathrm{Higgs}}} - \underbrace{(\lambda_l\bar{\psi_L}\phi\psi_R + \lambda_q\bar{\psi_L}\phi\psi_R + h.c.)}_{\mathcal{L}_{\mathrm{Yukawa}}}$$

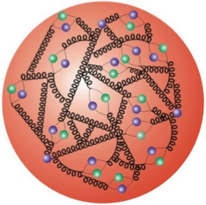
➔ **We will look into many parts of this today and tomorrow**

Mistake often made:

➔ The Higgs boson is NOT the origin of mass!

↪ it allows for massive elementary particles in the theory

Example proton:



➔ mass proton: 938 MeV

➔ $2 \cdot m_{\mathrm{u-quark}} + m_{\mathrm{u-quark}} + m_g \approx 11.5$ MeV

⇒ missing a factor of ≈ 82 !

⇒ proton mass comes mainly from QCD confinement

What happened after papers were published?

1965 Higgs:

➔ Full review paper published ▸ Phys.Rev 145 1156

➔ Ideas were shown by all authors in seminars

➔ Many people thought the idea was wrong, since the Goldstone theorem had been fully proven.

1967: Glashow, Weinberg, Salam

➔ applied SSB to electroweak theory

1970/1: Veltman and t' Hooft

➔ proof that Yang-Mills theories with masses from SSB in scalar fields are renormalizable

Electroweak theory

- introduced by Glashow, Weinberg and Salam (GWS)
- gauge group is the SU(2)$_\mathrm{L}\times$U(1)$_\mathrm{Y}$
- SU(2): non-abelian SU(2), U(1) abelian U(1)
- four generators: lead to four massless fields:

  $\hookrightarrow$ W$_1^\mu$,W$_2^\mu$,W$_3^\mu$ generated by the weak isospin

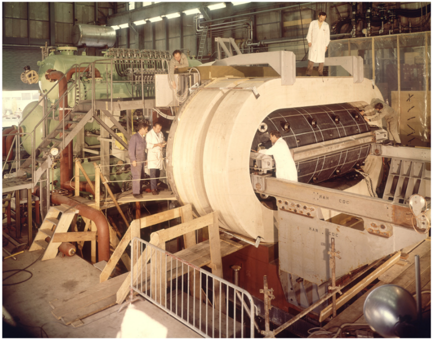
  $\hookrightarrow$ B$_\mu^0$ generated by the hypercharge Y

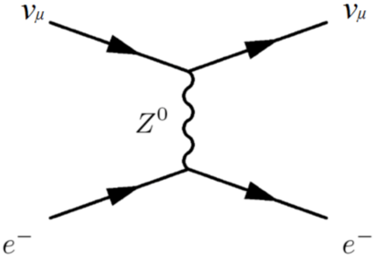
Physical particles are mixtures of these massless bosons:

$$\begin{pmatrix} Z^0 \\ \gamma \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W_3^\mu \end{pmatrix}$$

Search for W and Z bosons ▸ Dieter Haidt

First sign of neutral currents: discovery at Gargamelle (bubble chamber) 1973:





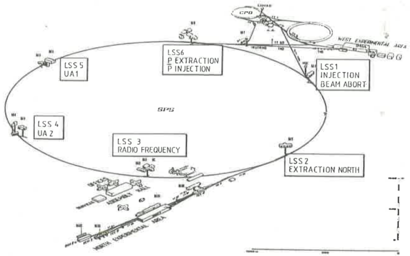
From neutrino experiments: measurement of electroweak-mixing angle $\sin\theta_W$:

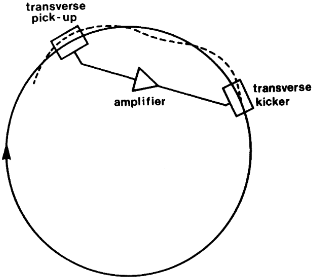
↪ allows a first constraint of the W boson mass:

$$m_W = \sqrt{\frac{\pi\alpha_{\mathrm{EM}}}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W} = \frac{37\mathrm{GeV}}{\sin\theta_W} \approx 70\ \mathrm{GeV}$$

Search for W and Z bosons at the $Sp\bar{p}S$

First estimate of W-boson mass gave motivation to build $Sp\bar{p}S$!

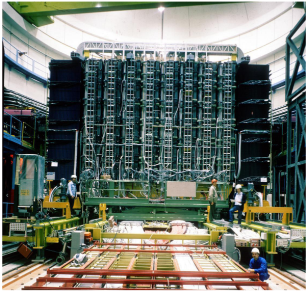




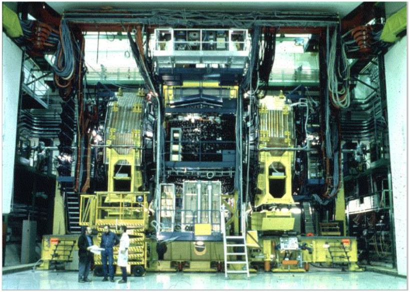
- production via $u\bar{d}$, $\bar{u}d$, $u\bar{u}$ and $d\bar{d}$
- the three valence quarks account for $\approx 50\%$ of the proton momentum
  $\hookrightarrow$ each valence quark carries therefore about 1/6
  $\hookrightarrow$ the collider needs an energy at least 6 times the boson mass
- 1981: start with $\sqrt{s} = 540$ GeV, running until 1991: $\sqrt{s} = 900$ GeV

The two main experiments at the $Sp\bar{p}S$

– UA1 experiment –



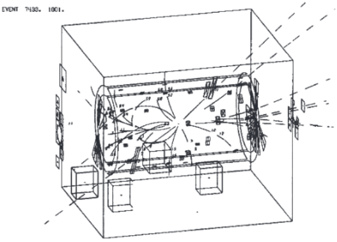
– UA2 experiment –



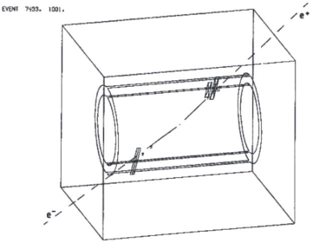
- UA1: general purpose detector, 5.8 m long, 4.6 m high ▸ Details
- UA2: focused on electron detection, no muon detection ▸ Details

↪ high-granularity calorimeters for very precise measurements

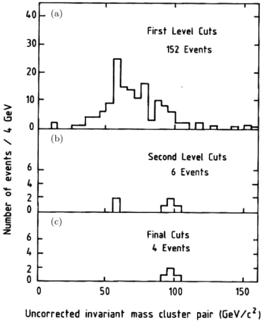
Discovery of W and Z bosons in 1983



(a)



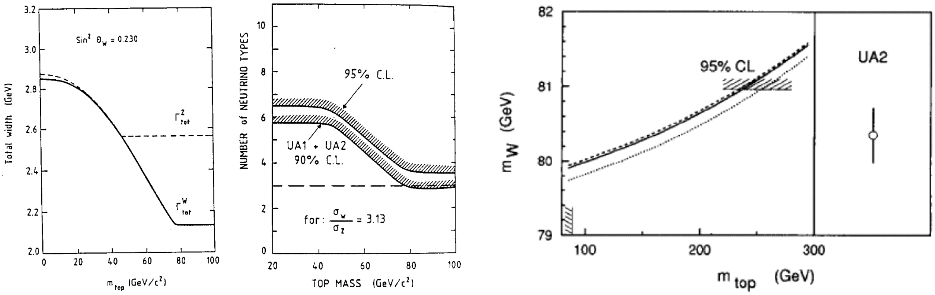
(b)



- January 1983: first 10 W boson events available
- June 1983: Z boson discovery in $Z \to ee$ and $Z \to \mu\mu$
- nobel prize in 1984 for Carlo Rubbia and Simon van der Meer

First limits on the m_{top} mass

▸ Paper



- UA2 measured the ratio m_W/m_Z with very high precision
- take now also into account high precision m_Z measurement from LEP:

$$m_Z(\mathrm{LEP})\frac{m_W}{m_Z}(\mathrm{UA1}) = 80.35 \pm 0.33 \pm 0.17\ \mathrm{GeV}$$

Allows to set limit on m_{top}: $m_{\mathrm{top}} = 160^{+50}_{-60}$ GeV

Relations in the EW sector

▸ Phys.Rept.427, 2006

Fermi constant:

$$G_F = \frac{\alpha_{\mathrm{EM}}\pi}{\sqrt{2} m_W^2 \sin^2\theta_W^{\mathrm{tree}}}$$

ρ_0 parameter (1 in the SM):

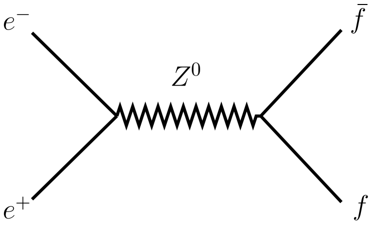
$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W^{\mathrm{tree}}}$$

and

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

↪ can determine everything if we know α_{EM}, m_Z and G_F

Relations in the EW sector ▸ Phys.Rept.427, 2006



Coupling of fermions to Z-boson:

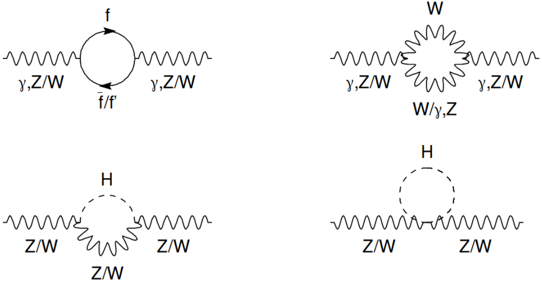
$$g_L^{\text{tree}} = \sqrt{\rho_0}(T_3^f - Q_f \sin^2\theta_W^{\text{tree}})$$
$$g_R^{\text{tree}} = -\sqrt{\rho_0} Q_f \sin^2\theta_W^{\text{tree}}$$

$\hookrightarrow$ T_3: third component of weak isospin, Q: electric charge.

Expressed as vector and axial-vector couplings:

$$g_V^{\text{tree}} = \sqrt{\rho_0}(T_3^f - 2Q_f \sin^2\theta_W^{\text{tree}})$$
$$g_A^{\text{tree}} = \sqrt{\rho_0}\, T_3^f$$

Now need to include radiative corrections ▸ Phys.Rept.427, 2006



Propagator self-energies and flavour-dependent vertex corrections:

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

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

Radiative corrections

Real effective couplings:

$$g_{Vf} = \sqrt{\rho_f}\left(T_3^f - 2Q_f \sin^2\theta_{\mathrm{eff}}^f\right)$$
$$g_{Af} = T_3^f$$

Effective mixing angle:

$$\sin^2\theta_{\mathrm{eff}}^f = \kappa_f \sin^2\theta_W$$

with:

- form-factor for overall scale: $\rho_f = 1 + \Delta\rho_{se} + \Delta\rho_f$
- form-factor for EW mixing angle: $\kappa_f = 1 + \Delta\kappa_{se} + \Delta\kappa_f$

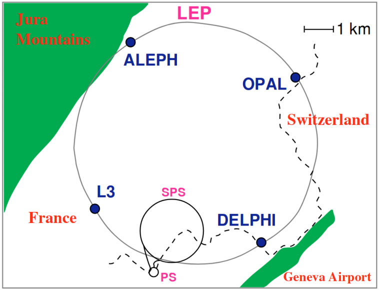
Observables to measure at the Z-pole

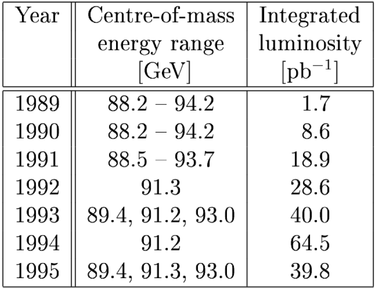
- m_Z, Γ_Z
- $\Gamma(\mathrm{had})$, $\Gamma(\mathrm{inv})$, $\Gamma(\ell^+\ell^-)$
- σ_{had}
- R_e, R_μ, R_τ, R_b, R_c
- $\sin^2\theta^\ell$
- several forward-backward asymmetries A_{FB}
- A_e, A_μ, A_τ, A_b, A_c, A_s

Measurements at the Z-pole

1. LEP: Large electron-positron collider, Run 1 from 1989 – 1995
   - ↪ circular collider
   - ↪ 4 experiments
   - ↪ different CME around Z-pole
   - ↪ no longitudinal polarisation
2. SLC: Stanford linear collider, 1989 – 1998
   - ↪ linear collider
   - ↪ Mark-II detector 1989–1991, SLD from 1992-1998
   - ↪ running on Z-pole
   - ↪ electron beam longitudinally polarised (up to $\approx$ 80 %)

Experimental setup at LEP I





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

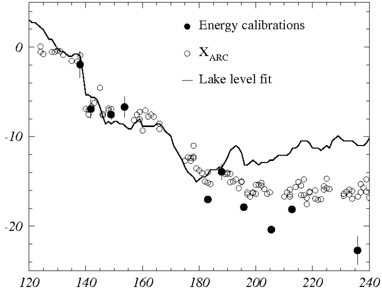
First data taking period: LEP I

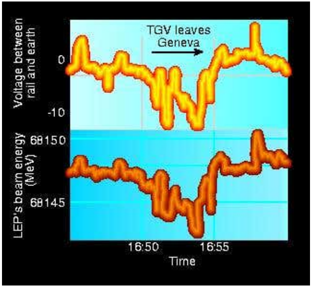
- make scan of Z line shape: different CME
- for each new fill of collider: change CME → more stable!
- in 1995: lumi so high that one gets 1000 events per hour per experiment
- for all experiments together: about 17 million Z events
- precision in CME: only 2 MeV

What can affect the beam?

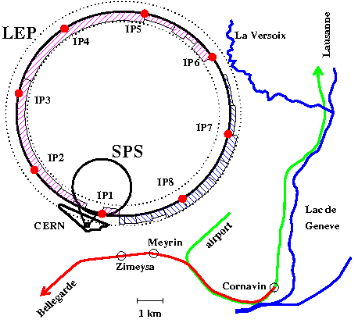
Many different phenomena can play a role:

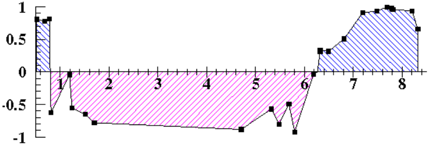
- affected by tide (sun, moon) ▸ NIM A paper
- geological changes in region after long raining periods
- water level in lake Geneva ▸ newscientist
- TGV: causes leakage currents → impact on dipole magnets





What can affect the beam?

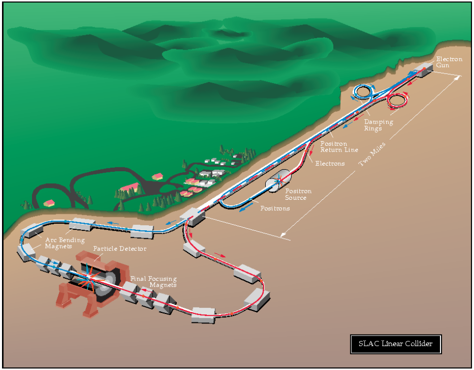




Correlation versus IP

▸ Paper ref.

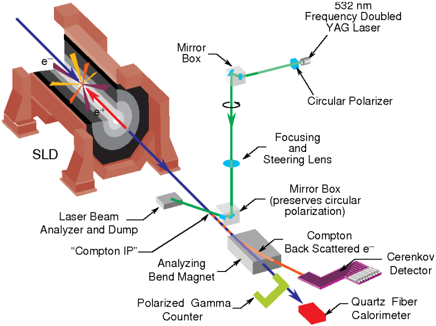
Experimental setup at SLC ▸ Paper

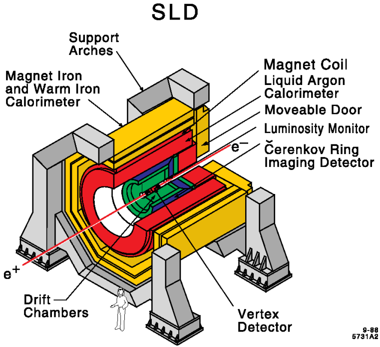


Stanford Linear Collider

- first linear e^+e^- collider, 120 Hz
- positrons created by colliding electrons with target
- bunch energy is ≈ 46.5 GeV $\rightarrow$ loose about 1 GeV in arcs

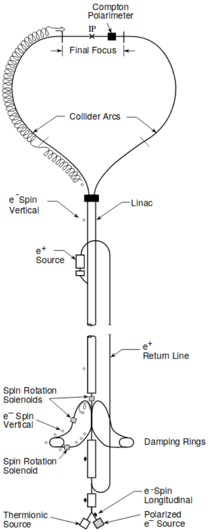
Experimental setup at SLC ▸ Paper



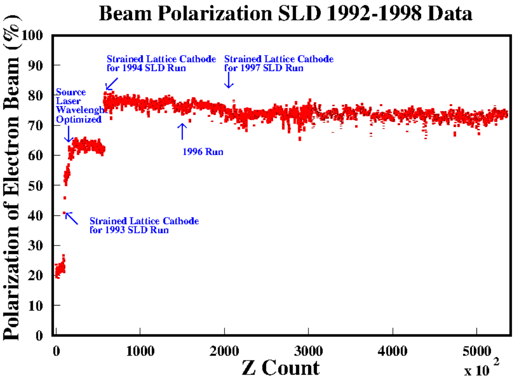


- very good vertex detector
- from 1992 - 98: 600.000 Z events recorded by SLD
- important difference to LEP: electron beam longitudinally polarised!

Advantage at SLC: beam polarisation



arXiv:hep-ex/9611006



- large improvement in electron polarisation:
  ↪ above 70% for most data
- polarisation allows to enhance/suppress specific processes
- polarisation needs to be well known

Question 3

Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz!

Now:

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What quantities to measure?

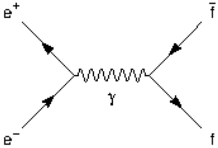
$$\sigma = \frac{N_{\mathrm{sel}} - N_{\mathrm{bkg}}}{\epsilon_{\mathrm{sel}}\ \mathrm{A}\ \mathcal{L}}$$

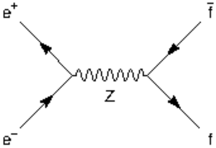
- N_{sel}: number of selected events
- N_{bkg}: number of expected background events
- ϵ_{sel}: selection efficiency
- A: acceptance
- $\mathcal{L}$: luminosity → precise knowledge important!

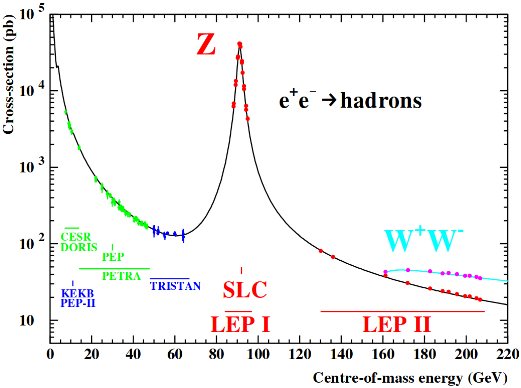
➔ measure total cross-section for different CME: line shape

Measurement of the Z-line shape

▸ LEP EWWG

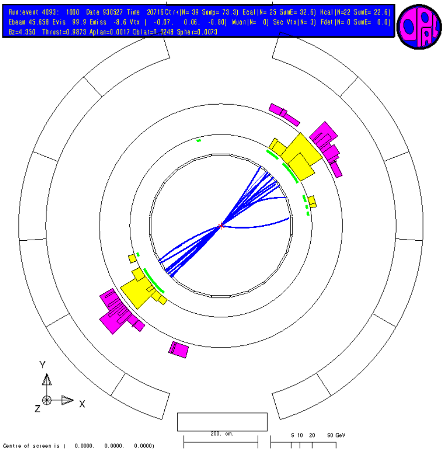


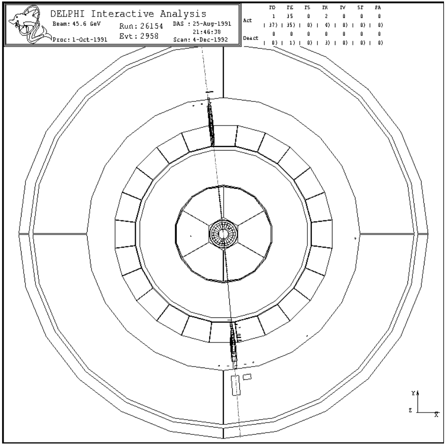




Year	Centre-of-mass energy range [GeV]	Integrated luminosity $[\mathrm{pb}^{-1}]$
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

Event displays LEP ▸ LEP EWWG

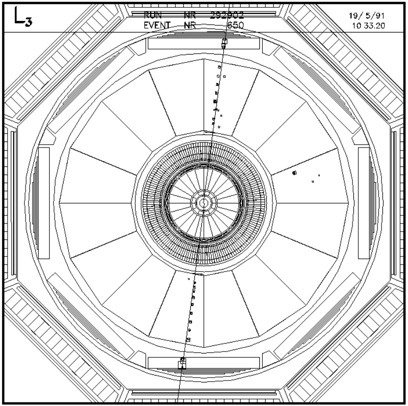




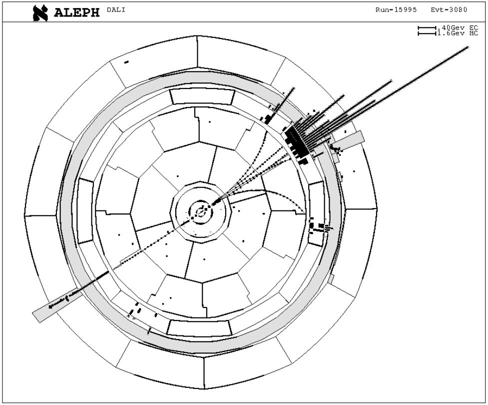
➔ $Z \rightarrow q\bar{q}$

➔ $Z \rightarrow e^+e^-$

Event displays LEP ▸ LEP EWWG



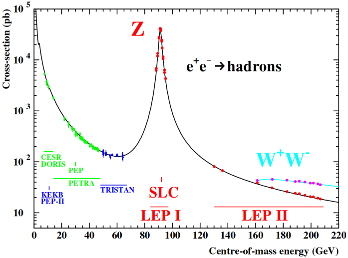
➔ $Z \to \mu^+\mu^-$



➔ $Z \to \tau^+\tau^-$

The components of the $e^+e^- \to f\bar{f}$ production ▸ LEP EWWG

$$\frac{2s}{\pi}\frac{1}{N_c^f}\frac{d\sigma_{ew}}{d\cos\theta}(e^+e^- \to f\bar{f}) = \sigma_\gamma + \underbrace{\sigma_{\gamma/Z}}_{\text{interference}} + \sigma_Z$$



- $\sigma_\gamma \propto (1+\cos^2\theta)$
- $\sigma_{\gamma/Z} \propto \chi(s)[\text{factor}_1 \cdot (1+\cos^2\theta) + \text{factor}_2 \cdot \cos\theta]$
- $\sigma_Z \propto |\chi(s)|^2[\text{factor}_3 \cdot (1+\cos^2\theta) + \text{factor}_4 \cdot \cos\theta]$

with: $\chi(s) = \frac{G_F m_Z^2}{8\pi\sqrt{2}} \frac{s}{s - m_Z^2 + i\,s\,\Gamma_Z/m_Z}$

$\hookrightarrow$ $(1+\cos^2\theta)$: contributes to total cross-section

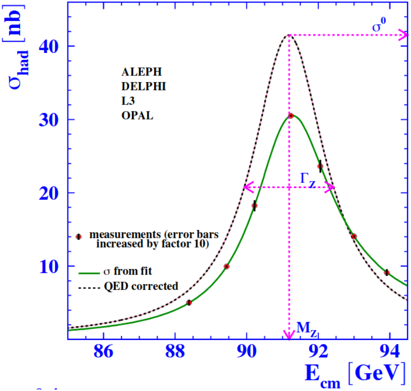
$\hookrightarrow$ $\cos\theta$: contributes to forward-backward asymmetries

Cross-section of the $e^+e^- \to Z \to f\bar{f}$ production ▸ LEP EWWG

$$\sigma^Z_{f\bar{f}} = \frac{1}{R_{\mathrm{QED}}} \underbrace{\frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}}_{\sigma^0_{f\bar{f}}} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

From fit to line shape can obtain:

- m_Z
- Γ_Z
- $\sigma^0_{\mathrm{had}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\mathrm{had}}}{\Gamma_Z^2}$
- $R^0_\ell = \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell}$



Number of neutrino generations ▸ LEP EWWG

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{inv}}$$
$$= \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \sum_{q\neq t} \Gamma_{q\bar{q}} + N_\nu \Gamma_{\nu\nu}$$

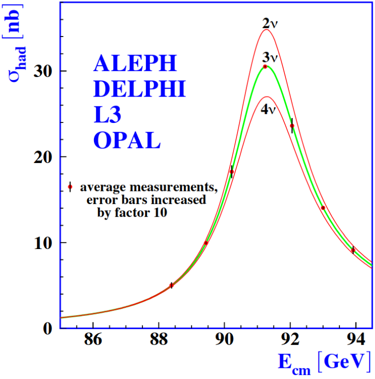
$$R^0_{\mathrm{inv}} = \sqrt{\left(\frac{12\pi R^0_\ell}{\sigma^0_{\mathrm{had}} m_Z^2}\right) - R^0_\ell - (3+\delta_\tau)}$$

Compare measurement with SM expectation:

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

$\Rightarrow N_\nu \approx 2.984 \pm 0.008$

↪ no additional light neutrino generation!



Z-coupling: $V - A$

$$\text{vertex factor} = \frac{-ig_Z}{2}\gamma^\mu(g_V^f - g_A^f\gamma^5)$$

Can now measure the effective mixing-angle from the ratio:

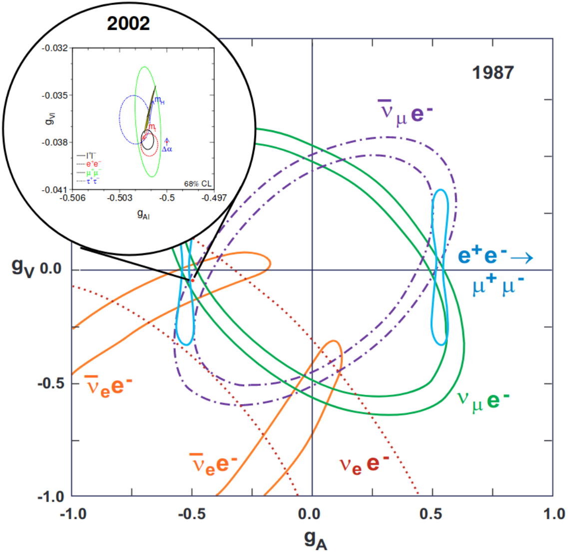
$$\frac{g_V^f}{g_A^f} = 1 - 2\frac{Q_f}{T_3^f}\sin^2\theta_{W,\text{eff}}^f = 1 - 4|Q_f|\sin^2\theta_{W,\text{eff}}^f$$

and also define the asymmetry parameter $\mathcal{A}_f$ (final-state):

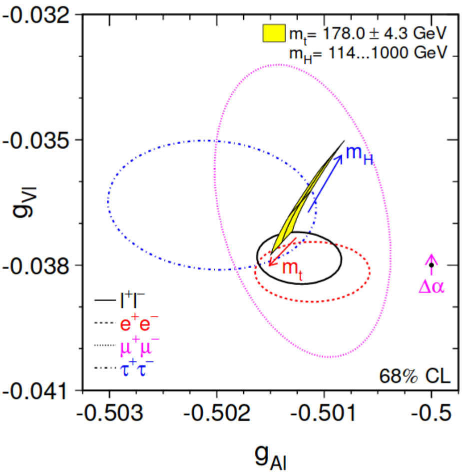
$$\mathcal{A}_f = 2\frac{g_V^f/g_A^f}{1+(g_V^f/g_A^f)^2}$$

Vector/axial-vector couplings from electron-neutrino scattering

▸ LEP EWWG

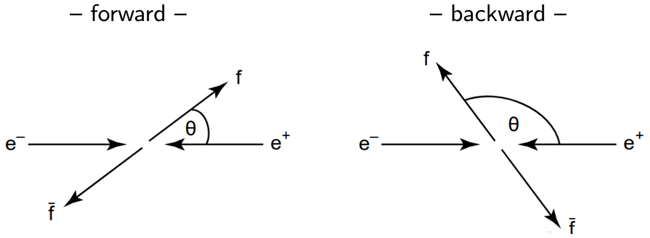


Vector/axial-vector couplings from LEP/SLD ▸ LEP EWWG



➔ Z-coupling compatible for three lepton generations!

Measurement of asymmetries



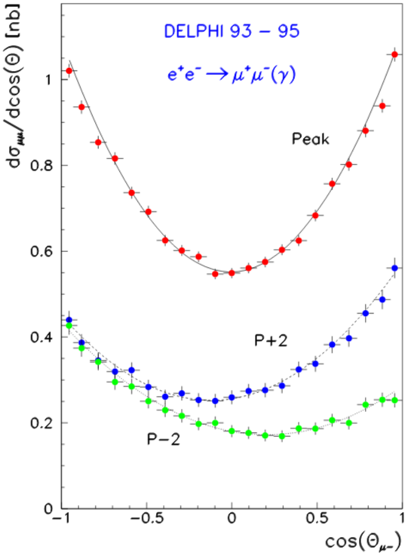
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

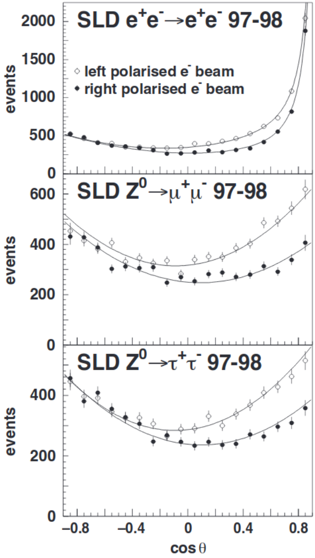
can be also expressed as product of asymmetry parameters:

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

Measurement of angular distributions

▸ LEP EWWG





How to measure the polarisation

Chirality: handedness

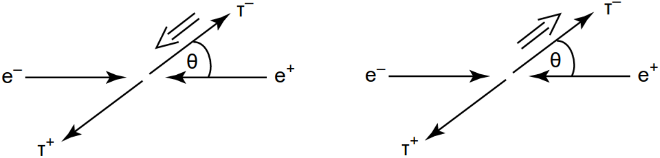
$$\Psi_R = \frac{1}{2}(1+\gamma^5)\Psi, \;\; \Psi_L = \frac{1}{2}(1-\gamma^5)\Psi$$

Helicity: projection of spin in direction of momentum

$$h = \frac{\vec{s}\vec{p}}{|\vec{p}|}$$

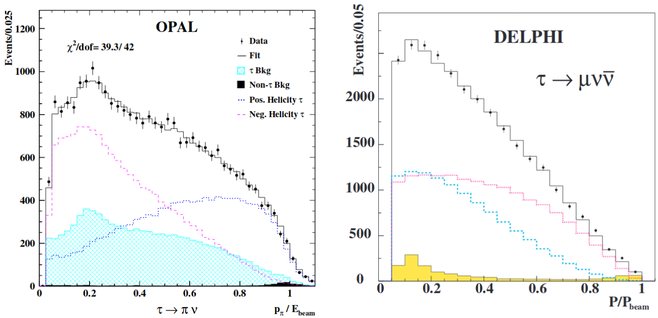
For $E >> m$:

- right-handed chirality ≙ positive helicity
- left-handed chiralicty ≙ negative helicity



$$\mathcal{P}_f(\cos\theta) = -\frac{\mathcal{A}_f(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_f\mathcal{A}_e\cos\theta}$$

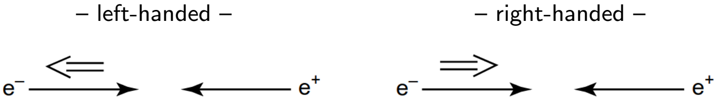
At LEP: can only measure τ polarisation → decays very quickly (≈ 0.3 ps).



Perform template fit to distribution:

- easier in decays with hadrons, especially two-body decays like $\tau \rightarrow \pi\nu_\tau$
- leptonic tau decays have 3 final-state particles, two of them invisible

Measurement of left-right asymmetry at SLD



– left-handed – – right-handed –

$$A_{LR} = \frac{N_L - N_R}{N_L + N_R} \frac{1}{< P_e >} = \mathcal{A}_e$$

↪ with P_e being the magnitude of the electron polarisation.

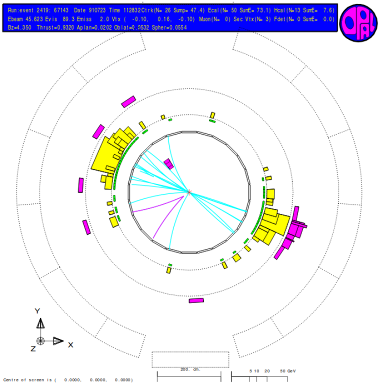
A_{LR} only depends on the initial state!

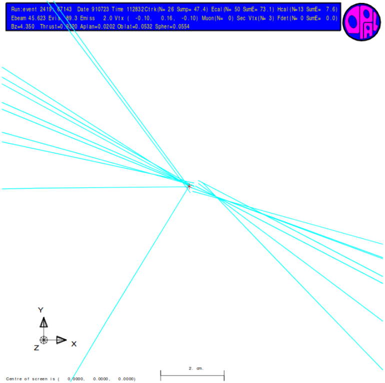
Also accessible:

$$A^f_{FB,LR} = \frac{N^f_{LF} + N^f_{RB} - N^f_{LB} - N^f_{RF}}{N^f_{LF} + N^f_{RB} + N^f_{LB} + N^f_{RF}} = \frac{3}{4}\mathcal{A}_f$$

➔ in both cases: simple counting experiments

Measurement of A_{FB}^{b} using b-jet identification ▸ LEP EWWG

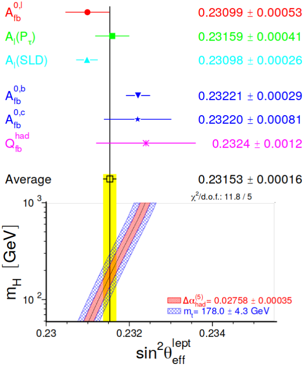




➔ A_{FB}^{b} result from LEP differs by about 3σ from SLD result

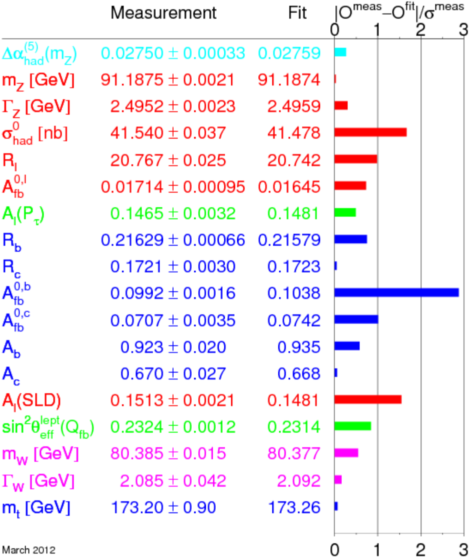
Results asymmetry measurements

observable	collider	value	total unc.	SM expectation	pull	corresponding $\sin^2\theta^l_{\text{eff}}$
A_e	LEP	0.1498	0.0049	0.1473 ± 0.0012	0.5	$0.23117 \pm 0.00062^*$
A_τ	LEP	0.1439	0.0043	0.1473 ± 0.0012	−0.8	0.23192 ± 0.00055
$A^{0,e}_{\text{FB}}$	LEP	0.0145	0.0025	0.01627 ± 0.00027	−0.7	$0.23254 \pm 0.0015^*$
$A^{0,\mu}_{\text{FB}}$	LEP	0.0169	0.0013	0.01627 ± 0.00027	0.5	$0.23113 \pm 0.0007^*$
$A^{0,\tau}_{\text{FB}}$	LEP	0.0188	0.0017	0.01627 ± 0.00027	1.5	$0.23000 \pm 0.0009^*$
$A^{0,l}_{\text{FB}}$	LEP	0.0171	0.001	0.01627 ± 0.00027	0.8	0.23099 ± 0.00053
$A^{0,c}_{\text{FB}}$	LEP	0.0699	0.0036	0.07378 ± 0.00068	−1.1	0.23220 ± 0.00081
$A^{0,b}_{\text{FB}}$	LEP	0.0992	0.0017	0.10324 ± 0.00088	−2.4	0.23221 ± 0.00029
A_e	SLD	0.1516	0.0021	0.1473 ± 0.0012	2.0	$0.23094 \pm 0.00027^*$
A_μ	SLD	0.142	0.015	0.1473 ± 0.0012	−0.4	$0.23216 \pm 0.002^*$
A_τ	SLD	0.136	0.015	0.1473 ± 0.0012	−0.8	$0.23259 \pm 0.002^*$
A_l	SLD	0.1513	0.0021	0.1473 ± 0.0012	1.9	0.23098 ± 0.00026
A_c	SLD	0.67	0.027	0.66798 ± 0.00055	0.1	$0.231 \pm 0.008^*$
A_b	SLD	0.923	0.02	0.93462 ± 0.00018	−0.6	$0.25 \pm 0.03^*$



- can translate asymmetry measurements into electroweak mixing angle
- A^b_{FB} result from LEP differs by about 3σ

Compare measured values with result from EW fit



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

March 2012

Question 4

Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz! Quiz!

Now:

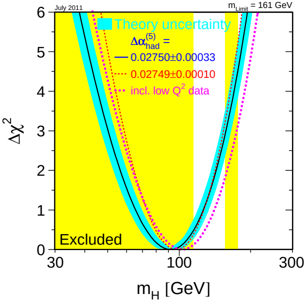
Open a new tab in your browser

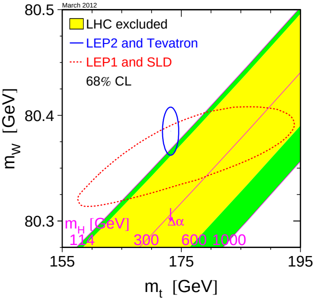
Go to: www.menti.com

Put in new code!

What do we gain from the LEP I and SLC results?

- so: need high precision measurements
  - ↪ 15 observables from LEP-EWWG (m_Z, Γ_Z, ...)
  - ↪ + m_Z, Γ_Z, m_{top} and low-energy observables
- from indirect searches: Higgs mass most likely around 100 GeV
  - ↪ would be still in reach for LEP experiments!

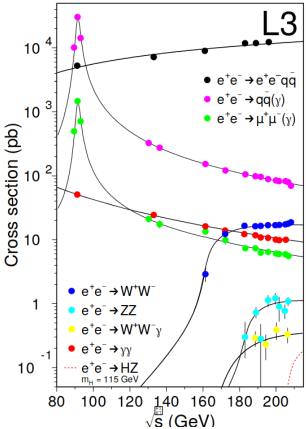




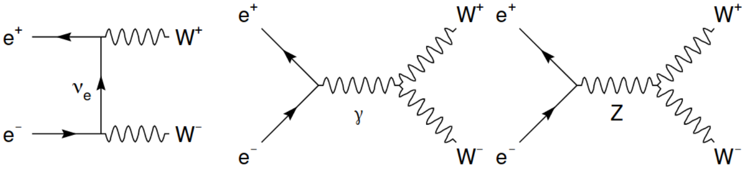
The LEP-II upgrade: a rich physics programme

- LEP-II: running from 1995 – 2000, total lumi all experiments: 3 fb-1
- required update of cavities: replace copper RF cavities by superconducting cavities
  ↪ replacement done over several years

Year	Mean energy $\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
1995, 1997	130.3	6
	136.3	6
	140.2	1
1996	161.3	12
	172.1	12
1997	182.7	60
1998	188.6	180
1999	191.6	30
	195.5	90
	199.5	90
	201.8	40
2000	204.8	80
	206.5	130
	208.0	8
Total	130 – 209	745



WW pair production



Measurement of m_W and Γ_W: two approaches

① at *WW* threshold: only 3% of data statistics

$\hookrightarrow \sigma \propto \beta = \sqrt{1 - 4m_W^2/s}$

$\hookrightarrow m_W(\text{threshold}) = 80.42 \pm 0.20(\text{stat.}) \pm 0.03(E_{\text{LEP}})$ GeV

② direct reconstruction:

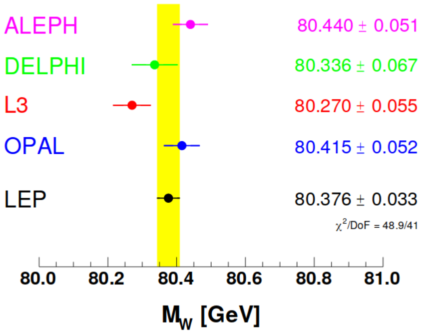
$\hookrightarrow$ mainly $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\bar{\nu}_\ell$ final state

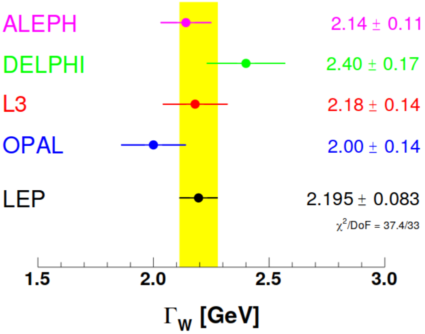
$\hookrightarrow$ $\ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$ stats limited, but no uncertainties from jets

$\hookrightarrow$ unbinned LH fit to data, combination of results with BLUE method

$\hookrightarrow m_W(\text{direct}) = 80.376 \pm 0.025(\text{stat.}) \pm 0.022(\text{syst.})$ GeV

High precision also for the *W* boson

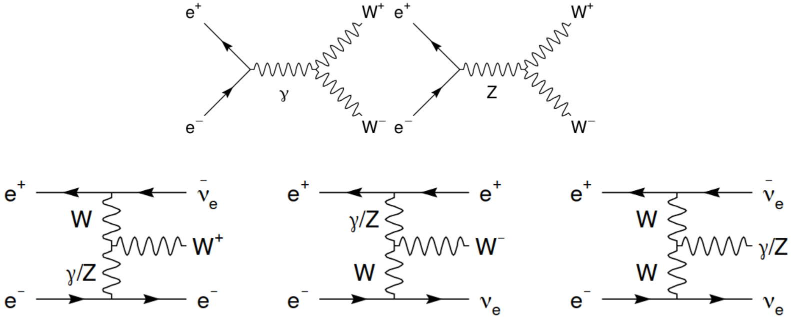




rel. uncertainty: 0.04 %

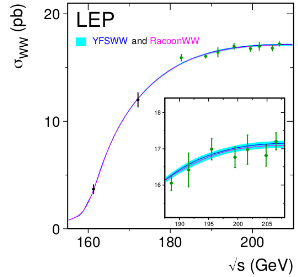
rel. uncertainty: 3.8 %

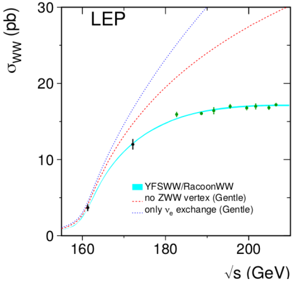
Triple gauge boson couplings

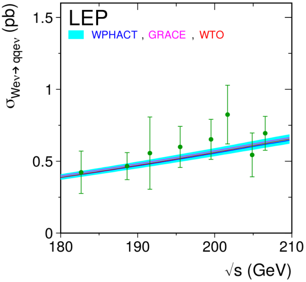


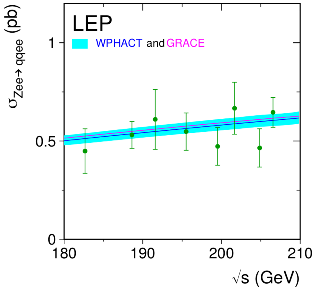
- ➔ can measure di-boson or single boson production
- ➔ can express via 5 independent couplings: $g_1^Z, \kappa_g amma, \kappa_Z, \lambda_\gamma, \lambda_Z$
- ➔ in SM: $g_1^Z = \kappa_\gamma = \kappa_Z = 1, \;\; \lambda_\gamma = \lambda_Z = 0$

Cross-section measurements

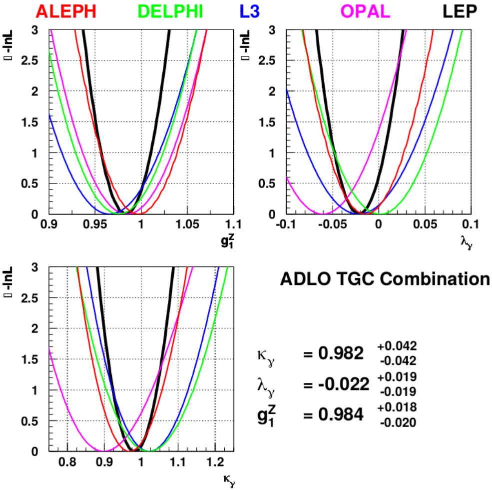








Single parameter fits for charged TGC



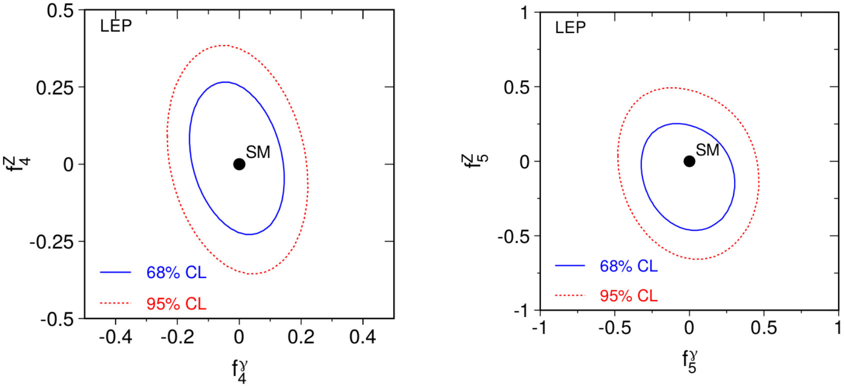
$$\kappa_\gamma = 0.982 \begin{smallmatrix}+0.042\\-0.042\end{smallmatrix}$$

$$\lambda_\gamma = -0.022 \begin{smallmatrix}+0.019\\-0.019\end{smallmatrix}$$

$$g_1^Z = 0.984 \begin{smallmatrix}+0.018\\-0.020\end{smallmatrix}$$

➔ charged triple-gauge couplings in agreement with SM prediction

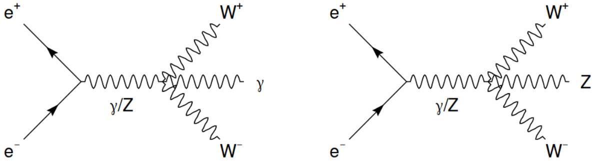
Search for neutral triple-gauge couplings

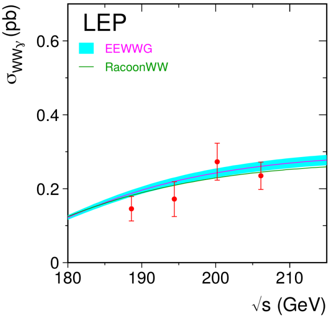


- no neutral triple gauge-coupling present at tree-level in SM

  ↪ no evidence found in two-parameter fits, everything is consistent with zero

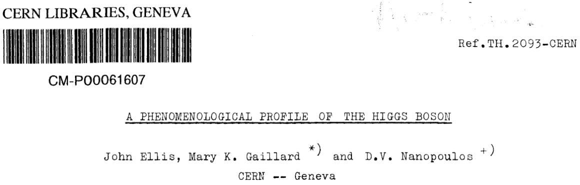
Quartic gauge boson couplings





1975/76: The hunt begins...

Paper on Higgs profile: Link Paper

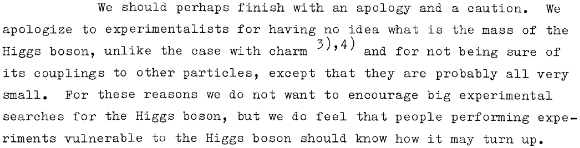


Ref.TH.2093-CERN

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

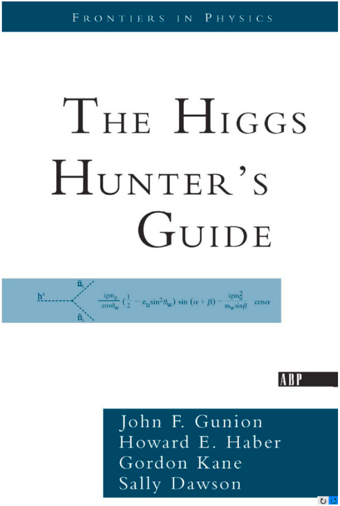
John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

Summary:



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

The hunt begins...



FRONTIERS IN PHYSICS

THE HIGGS HUNTER'S GUIDE

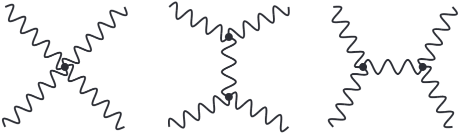
ABP

John F. Gunion
Howard E. Haber
Gordon Kane
Sally Dawson

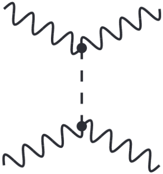
- mass: free parameter, no prediction
- spin/parity: $J^{CP} = 0^{++}$
- couplings, production/decay modes:
  $\hookrightarrow$ depend on m_H!

What if the Higgs boson did not exist?

- Higgs field has 4 degrees of freedom
  ↪ after W and Z bosons get mass: 1 degree of freedom left
- look at scattering of longitudinal W bosons: $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$



➔ if the Higgs boson does not exist, cross-section diverges!



Indirect Higgs searches at LEP

- assume: search for new particle at accelerators

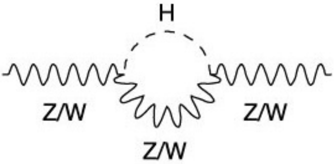
  ↪ too heavy to be directly produced and observed

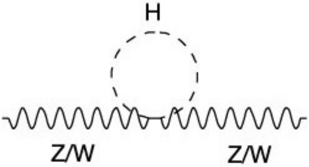
- but: if particle appears in higher-order loop corrections

  ↪ will alter the actual measured quantities

- effect quite small here (< 1 %)

  ↪ but constraints possible in high-precision measurements!





Direct searches at LEP

- since Higgs seemed to be still in reach for LEP:

  ↪ upgraded accelerator to reach up to 206 GeV

- since Higgs coupling increases with particle mass:

  ↪ search for associated production with Z-boson

- with $\sqrt{s} \leq 206$ GeV and $m_Z \approx 91$ GeV

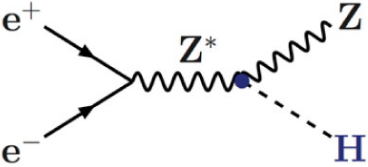
  ↪ can only find Higgs if $m_H \approx 115$ GeV

- $\Gamma(H \to b\bar{b}) \approx 70$ %

- $\Gamma(H \to \tau^+\tau^-) \approx 8$ %

- combine data taken at ALL LEP experiments

➔ reached a lower limit of ≈ 115 GeV



Summary for today

Electroweak sector

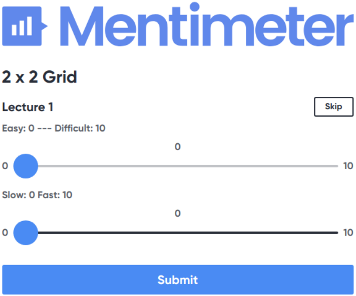
- observation of W and Z bosons at SPPS
- high-precision measurements of particle masses at LEP and SLD
- see discrepancy for weak mixing angle between LEP and SLD
- measurements show that the SM is consistent so far

What did these measurements tell us?

- could establish number of light neutrino generations
- first bounds on top mass already
- lower limit for Higgs mass from LEP II

↪ indirect measurements give promising outlook for future colliders

Just one more minute...



2 x 2 Grid

Lecture 1

Easy: 0 --- Difficult: 10

Slow: 0 Fast: 10

Now:

Open a new tab in your browser, Go to: www.menti.com, Put in new code!

- both scales are between 0 and 10
- 0: too easy/ too slow
- 10: too difficult/ too fast