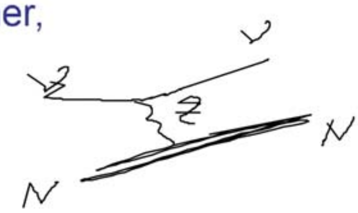
Übersicht: Entdeckung und präzise Vermessung des Z^0

- 1973, Gargamelle Blasenkammer, CERN: neutrale Ströme
  $\nu_\mu + e_0^- \to \nu_\mu + e^-$
  $\nu + N_0 \to \nu +$ Hadronen

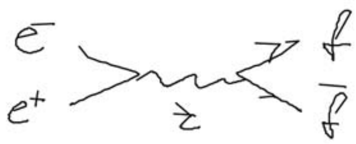


- Anfang der 80er:
  Beginn der Planung von LEP
- 1981,PETRA e^+e^-Kollider,DESY:
  Vorwärts-Rückwärts-Asymmetrie in
  $e^+e^- \to \mu^+\mu^-$
- 1983,UA1,SppS Kollider, CERN:
  Entdeckung des Z
  bis 1988 ca. 30 Ereignisse
- 1989-1998, Stanford Linear Collider (SLC), SLAC
  $\sim 0.6 \times 10^6 Z^0$, A_{LR} Messung
- 1989-1995, Large Electron Positron Collider (LEP), CERN
  Je $6 \times 10^6 Z^0$ an 4 Experimenten

s- Kanal - Resonanzen, Interferenzen

Beispiel $e^+e^- \to f\bar{f}$

+



$\mathcal{M}_\gamma \sim \frac{1}{q^2}$ $\mathcal{M}_Z \sim \frac{1}{q^2 - m_Z^2}$

+ endl. Lebensdauer des Z : $\Gamma = \frac{1}{\tau} > 0$

$\longrightarrow \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma}$

Warum?

Ruhesystem des Z $E = m,\ p = 0$

$\psi \sim e^{i(\vec{p}\vec{r} - Et)} = e^{-ip_\mu x^\mu} = e^{-imt}$

↳ $m \sim$ Phasenfrequenz

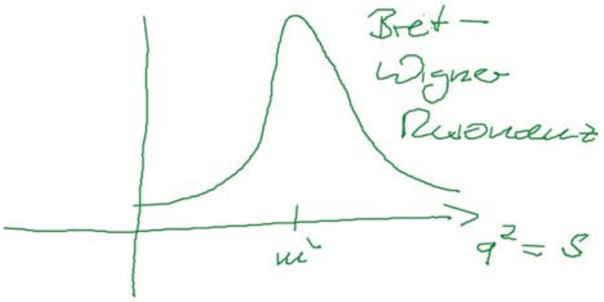
instabil $\psi\psi^* \sim e^{-\frac{t}{\tau}} = e^{-\Gamma t}$

$\hookrightarrow \psi \sim e^{-imt}\, e^{-\frac{\Gamma}{2}t} = e^{-i(m-i\frac{\Gamma}{2})t}$!

$m \to m - i\frac{\Gamma}{2}$

$\to$ Propagator $\dfrac{1}{q^2-(m-i\frac{\Gamma}{2})^2} = \dfrac{1}{q^2-m^2+im\Gamma+\cancel{\frac{\Gamma^2}{4}}} = \chi$ $\quad \Gamma \ll m$

$|\chi|^2 \sim \dfrac{1}{(q^2-m^2)^2+m^2\Gamma^2}$



analog
erzwungene Schwingung

$A \sim \dfrac{1}{(\omega^2-\omega_0^2)^2+\omega_0^2\gamma^2}$

Resonanz in der Phasenfrequenz von ψ
$\to$ virtuelle Teilchen schwingen mit von außen aufgezwungenen Phasenfrequenz $m_a = \sqrt{q^2}$ (z.B. $m_a = \sqrt{s}$)
$u, t < 0 \Rightarrow$ keine Resonanz im u t - Kanal

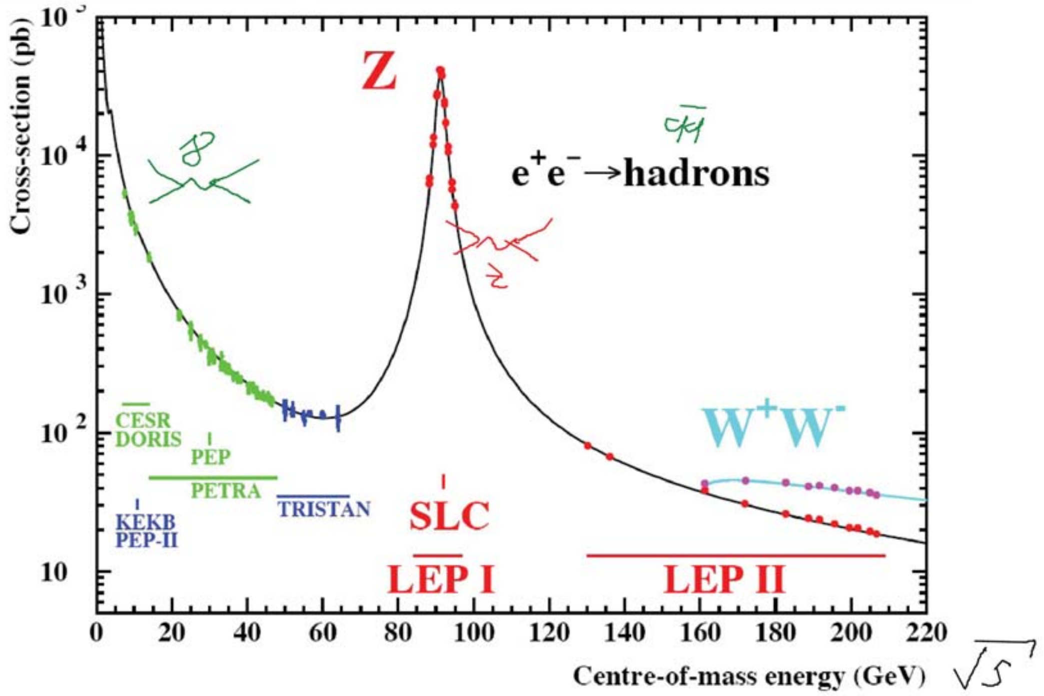
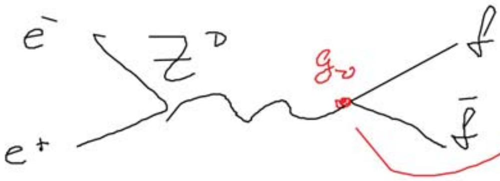


Figure 1.2: The hadronic cross-section as a function of centre-of-mass energy. The solid line is the prediction of the Standard Model, and the points are the experimental measurements. Also indicated are the energy ranges of various e^+e^- accelerators. The cross-sections have been corrected for the effects of photon radiation.

Gesamter Wirkungsquerschnitt



$= -ie\gamma^\mu (v_f - a_f \gamma^5)$

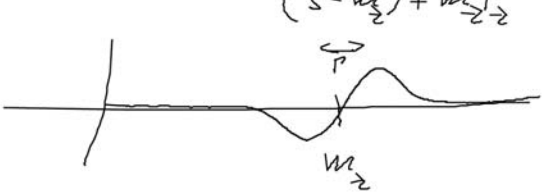
$j^\mu = \bar\psi \gamma^\mu \psi$ Vektor Kopplung

$j_A^\mu = \bar\psi \gamma^\mu \gamma^5 \psi$ Axial Vektorkopplung

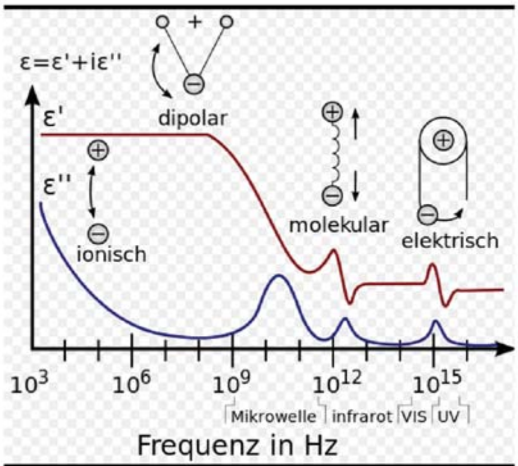
$$\sigma = \frac{4\pi}{3}\frac{\alpha^2}{s}\left\{ Q_f^2 - 2Q_f \,\mathrm{Re}\,\chi(s)\, v_e v_f + |\chi(s)|^2 (v_e^2 + a_e^2)(v_f^2 + a_f^2) \right\}$$

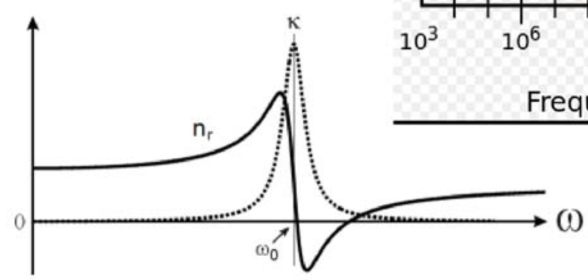
$$\mathrm{Re}\,\chi(s) = \frac{s(s-m_Z^2)}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \qquad |\chi(s)|^2 = \frac{s^2}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

max bei
$s = (m \pm \Gamma)^2$



Analog:
optischer Brechungsindex über
Real- und Imaginärteil
der elektrischen Permittivität
https://de.wikipedia.org/wiki/Permittivität

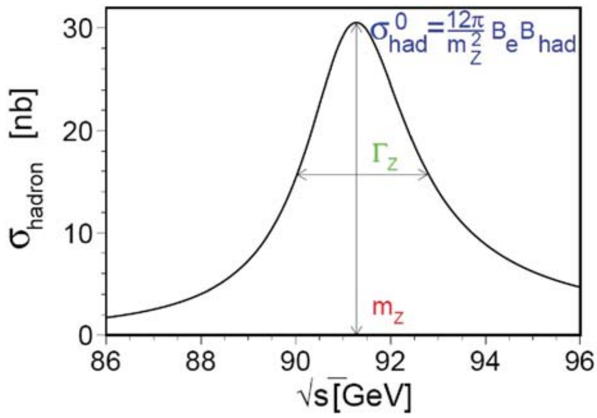




Brechzahl $n(\omega)$ in Abhängigkeit von ω aufgespalten in Realteil n_r und Imaginärteil κ. Anormale Dispersion ($dn_r/d\omega<0$) tritt genau dort auf wo die Absorption maximal ist.

VII.3.Präzisionsmessungen auf der Z-Resonanz

- Methodik der Messgrößen



$Z \rightarrow \underbrace{q\bar{q}(u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b})}_{70\%}, \underbrace{\nu\bar{\nu}(\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau)}_{20\%}, \underbrace{l\bar{l}(e^+e^-, \mu^+\mu^-, \tau^+\tau^-)}_{10\%}$

$$\sigma(2E_{\text{Strahl}}) = \frac{\text{N(Ereignisse) - N(Untergrund)}}{\text{Akzeptanz} \times \text{Luminosität}}$$

Meßgrößen	Akzeptanz	Luminosität	E_{Strahl}
$\sigma_i, B_i = \Gamma_i/\Gamma_Z$	●	●	●
$R_i = B_i/B_{\text{had}}$	●		
m_Z, Γ, A_{FB}			●

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Messsung der Strahlenergie über Depolarisation des Strahls

- Selbstständige Transvers. Polarisation: Sokolov-Ternov Effekt
- Unterschiedliche Spin-Flip WQ für Synchrotronstrahlung

$$\sigma\left(e^-_\uparrow \rightarrow e^-_\downarrow \gamma\right) \neq \sigma\left(e^-_\downarrow \rightarrow e^-_\uparrow \gamma\right)$$

$$\tau_{\text{ST}} = \frac{8}{5\sqrt{3}} \frac{m\rho^2 R}{r\hbar\gamma^5},$$

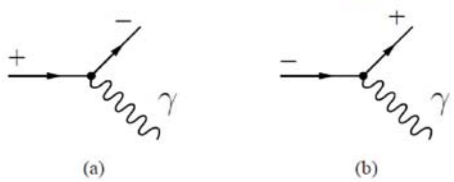


Figure 2-2: *The two spin-flip Feynman diagrams that contribute to the Sokolov-Ternov effect. In (a) an electron in the 'spin up' state gets flipped to the 'spin down' state, while in (b) an electron in the 'spin down' state gets flipped to the 'spin up' state; after emitting a photon due to synchrotron radiation induced by bending in a magnetic field. The cross-sections for these two processes are not equal and as such there will be a gradual buildup of polarization in the beam, known as the Sokolov-Ternov effect.*

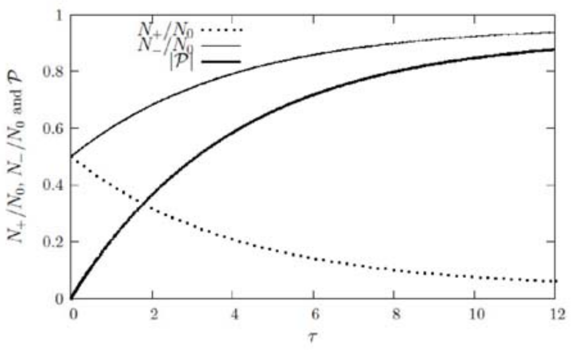


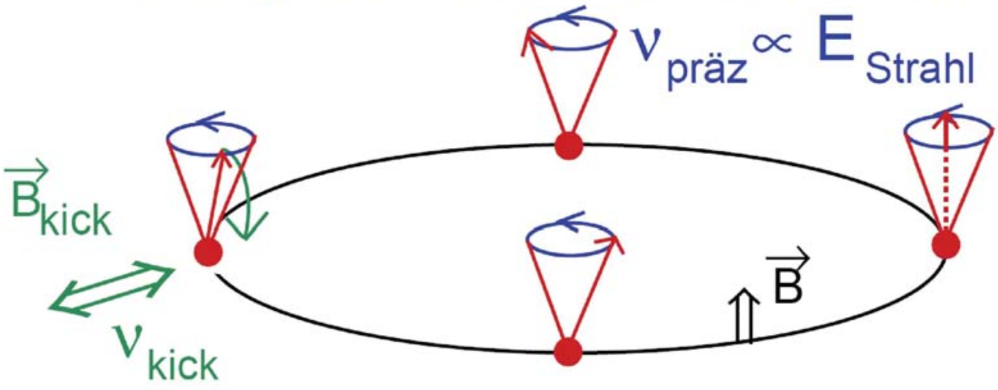
Figure 5-1: *A schematic graph of the Sokolov-Ternov effect, showing that the num particles in the 'spin up' state (N_+) decreases with time while the number of parti the 'spin down' state (N_-) increases with time. Hence $|\mathcal{P}| = |(N_+ - N_-)/(N_+ + N_-$ absolute value of the beam polarization, increases with time. One sees that the re $\mathrm{d}N_+/\mathrm{d}\tau = -\mathrm{d}N_-/\mathrm{d}\tau$ and $N_+ + N_- = N_0$ are satisfied throughout. The graph just general trends, therefore we do not specify the units of the time axis.*

	Electron storage rings			Proton storage rings	
	LEP	TRISTAN	HERA	LHC	SSC
E [GeV]	46.5	30	27.521	7000	20000
$\gamma = \sqrt{1-\beta^2}$	90999	58710	53858	7462	21317
R [m]	4243	480	1008	4243	12096
ρ [m]	3096.2	246.5	575	3096.2	10108
N_γ	6039	3896	3574	567	1429
τ_{ST} [min]	308	2	35	2.8×10^{14}	4.5×10^{13}

Table 2.1: *Properties of some high energy electron storage rings, and proposed proton storage rings. E is the kinetic energy of the beam, $\gamma = \sqrt{1-\beta^2}$ is the relativistic Lorentz factor, R the mean radius of the storage ring consisting of identical bending magnets of bending radius ρ separated by straight sections combining to give a total circumference*

Messung von m_Z <-> Bestimmung von E_{Strahl}

- Messung durch resonante Depolarisation



res. Depolarisation: $\nu_{präz} = i \cdot \nu_{kick}$

- jeweils an **Ende** einer Füllung
- ca. jeden zweiten Tag
- intrinsische Genauigkeit: 5×10^{-6}
- Extrapolation zum WW-Punkt: $12 \times 10^{-6} \cong 1.1$ MeV auf $\sqrt{s}$

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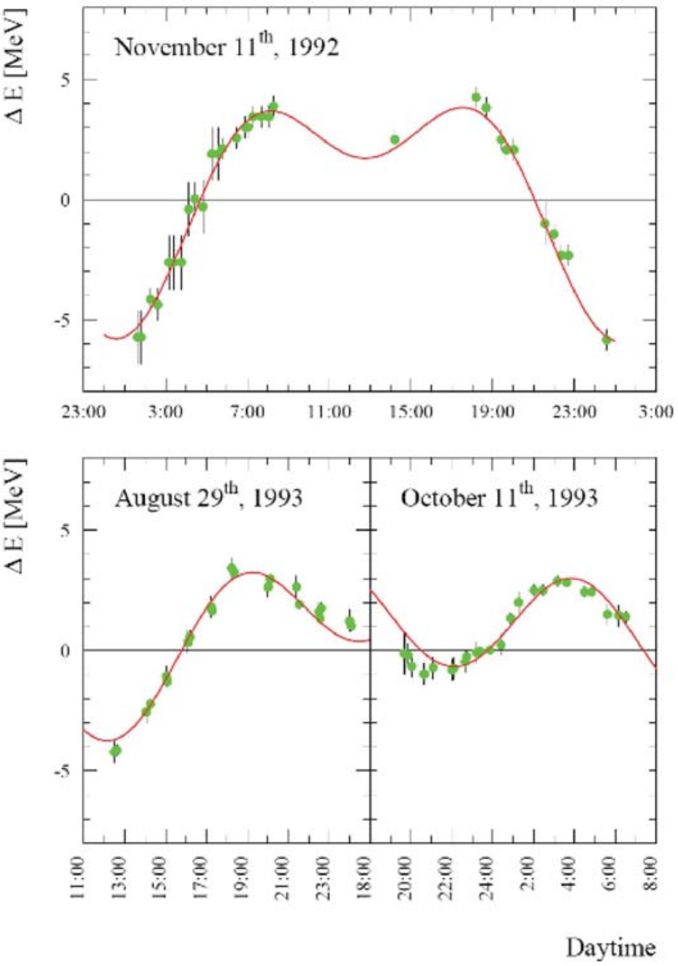
Fortschreibung durch indirekte Messung

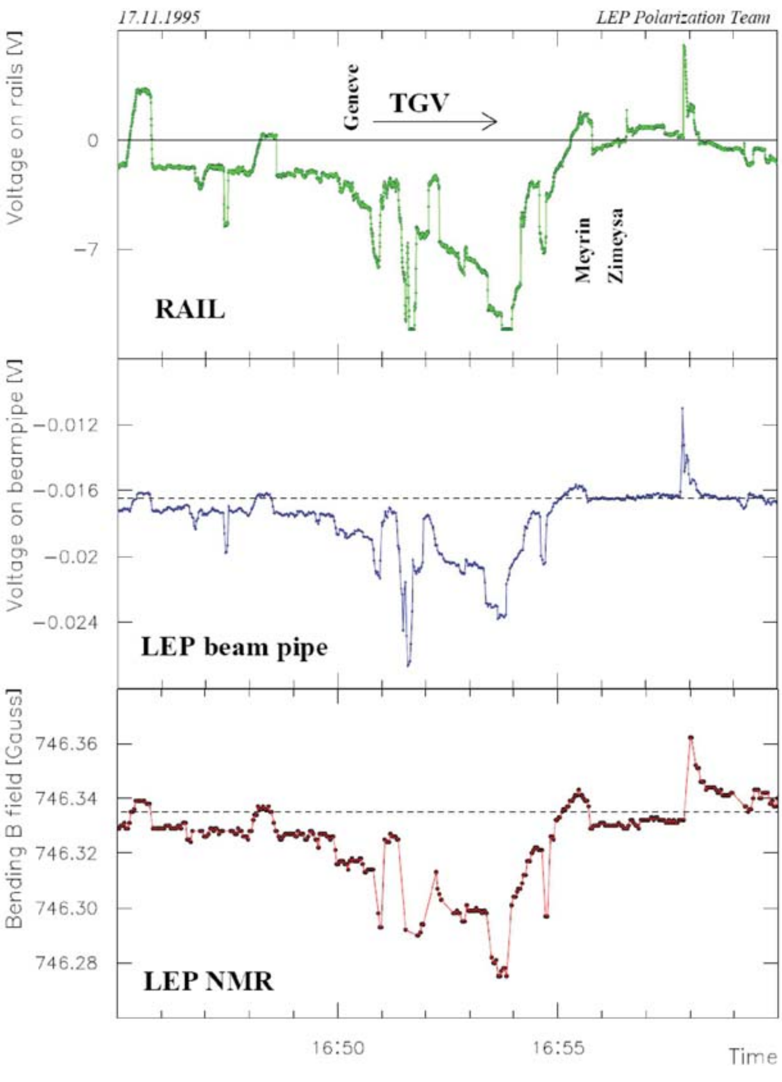
$$\boxed{E_{\mathrm{Strahl}} \propto \oint_{\mathrm{Ring}} B \times \mathrm{d}l}$$

- NMR B-Feld Messung in Referenzdipolmagneten
- Kenntnis der genauen Bahn notwendig
  - 30 μm Bahn Offset in Quadrupolen $\cong$ 5 MeV Offset in $\sqrt{s}$

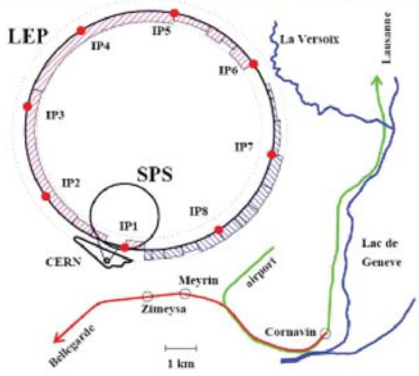
- Problem
  - Verformung des LEP-Rings durch
    - Wasserstand des Genfer Sees
    - Temperatur
    - Mond...

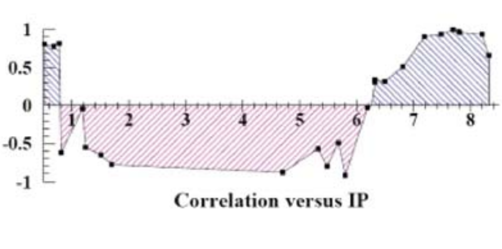


Mondgezeiten: ~ 10 MeV in $\sqrt{s}$



TGV: ~ 4 MeV in $\sqrt{s}$





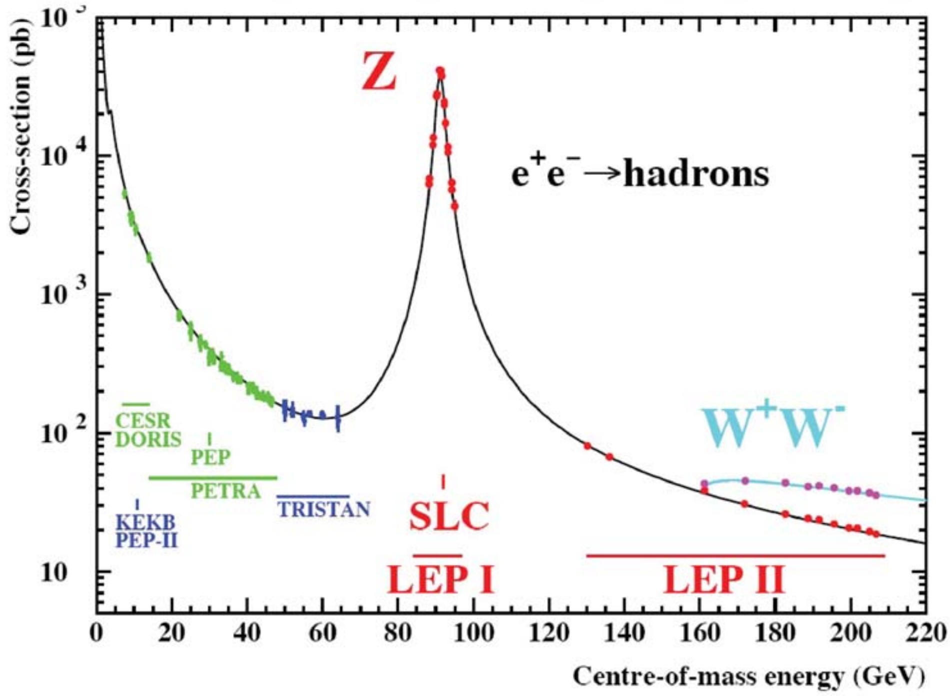


Figure 1.2: The hadronic cross-section as a function of centre-of-mass energy. The solid line is the prediction of the Standard Model, and the points are the experimental measurements. Also indicated are the energy ranges of various e^+e^- accelerators. The cross-sections have been corrected for the effects of photon radiation.

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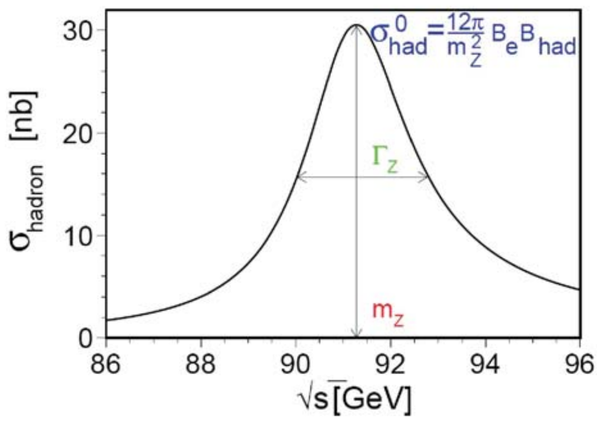

$$Z \to \underbrace{\bar{q}q(\bar{u}u,\ \bar{d}d,\ \bar{s}s,\ \bar{c}c,\ \bar{b}b)}_{70\%},\ \underbrace{\bar{\nu}\nu(\bar{\nu}_e\nu_e\ \bar{\nu}_\mu\nu_\mu\ \bar{\nu}_\tau\nu_\tau)}_{20\%},\ \underbrace{\bar{l}l(e^+e^-\ \mu^+\mu^-\ \tau^+\tau^-)}_{10\%}$$

$$\sigma(2E_{\mathrm{Strahl}}) = \frac{\text{N(Ereignisse) - N(Untergrund)}}{\text{Akzeptanz} \times \text{Luminosität}}$$

Meßgrößen	Akzeptanz	Luminosität	E_{Strah}
$\sigma_i, B_i = \Gamma_i/\Gamma_Z$	●	●	●
$R_i = B_i/B_{\mathrm{had}}$	●		
$m_Z, \Gamma, A_{\mathrm{FB}}$			●

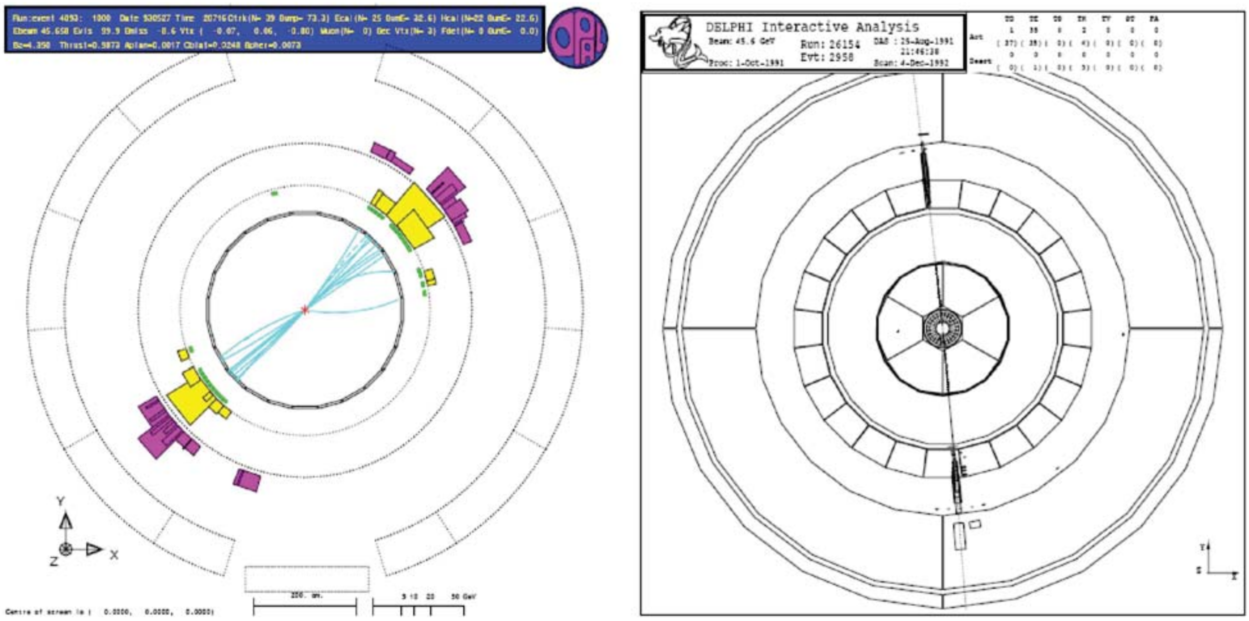

Figure 1.7: Pictures of $q\overline{q}$, e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states, visualised with the event displays of the OPAL, DELPHI, L3 and ALEPH collaborations, respectively. In all views, the electron-positron beam axis is perpendicular to the plane of the page.

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τ — ν

1 1 3

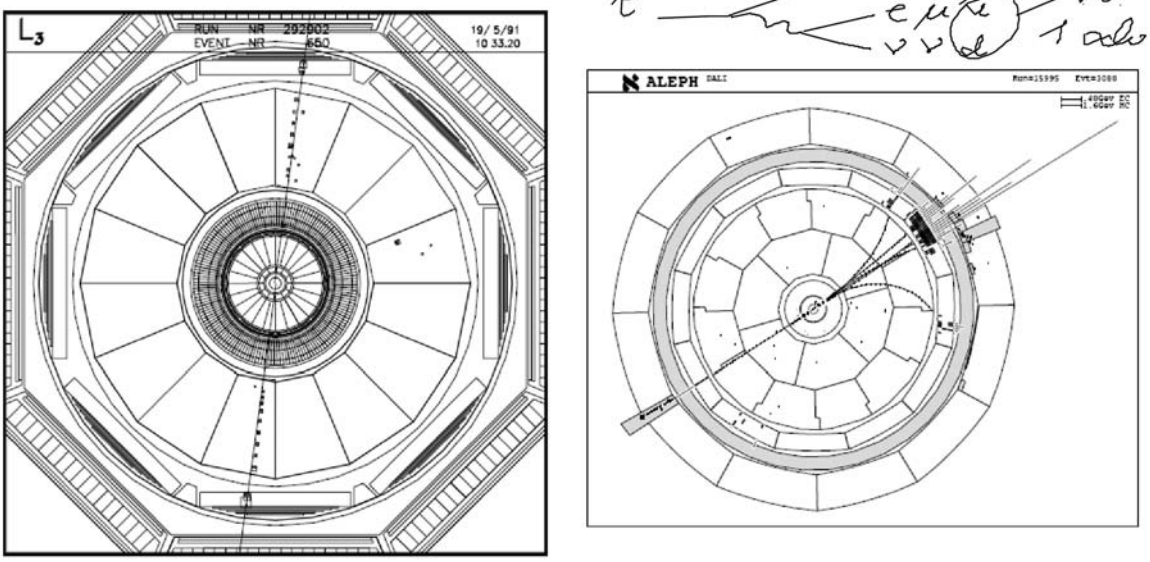
e μ π

ν ν ν

i.a. 1 oder 3 geladene π

+ n π^0

0,1,2



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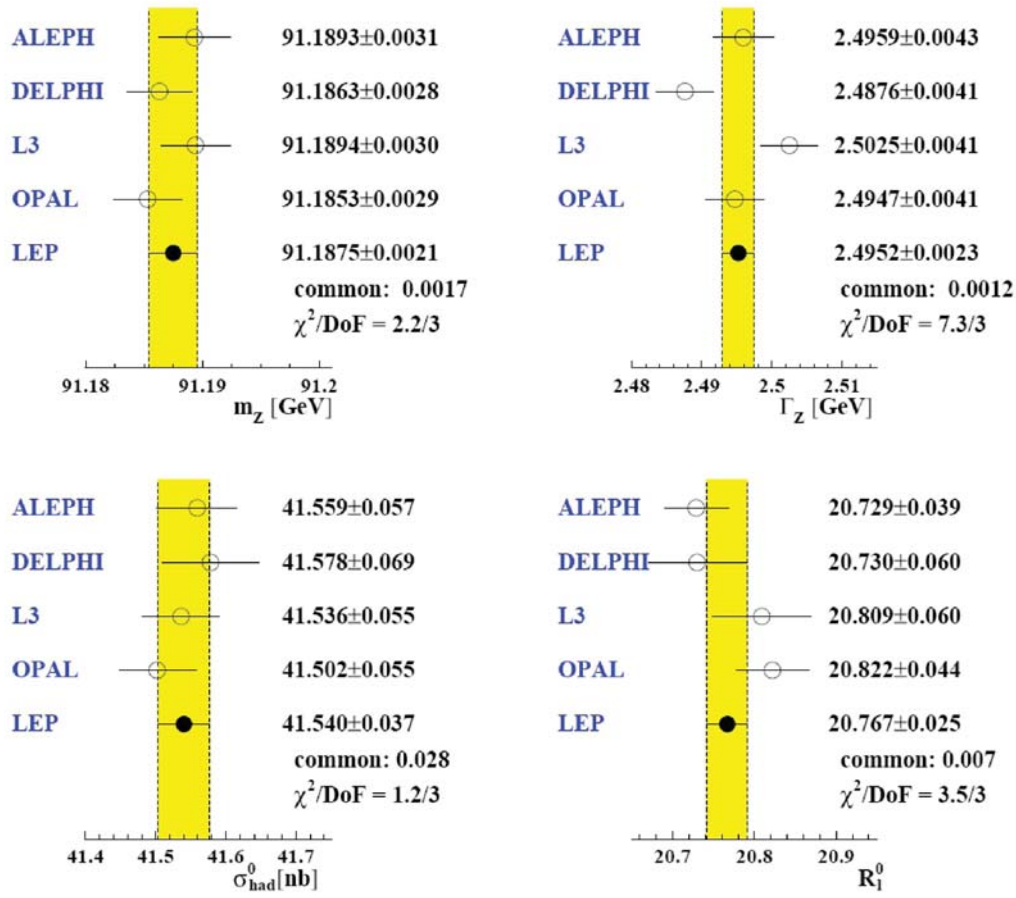
$\sim 10^{-5}$



$\sim 10^{-3}$

$\frac{B_{qq}}{B_{\mu\mu}} = R$

$\sim 10^{-3}$

$\sim 10^{-4}$

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Zahl der Neutrino Generationen

$\rightarrow$
3 (leichte)
Neutrino
Generationen
$m_\nu < \frac{m_Z}{2}$

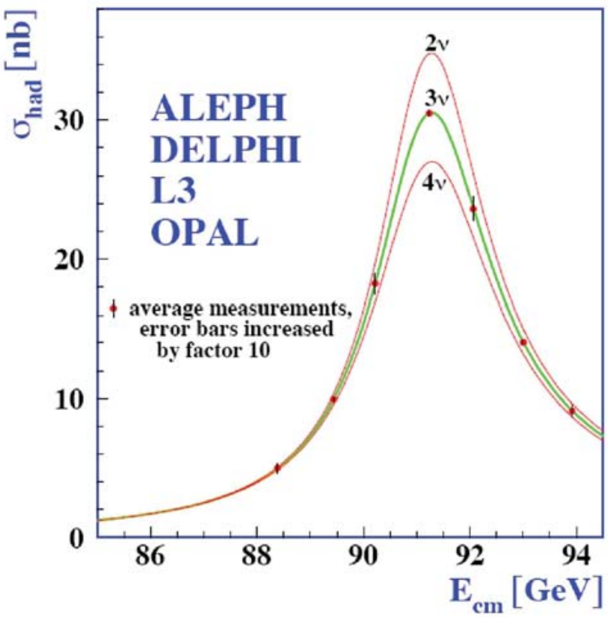
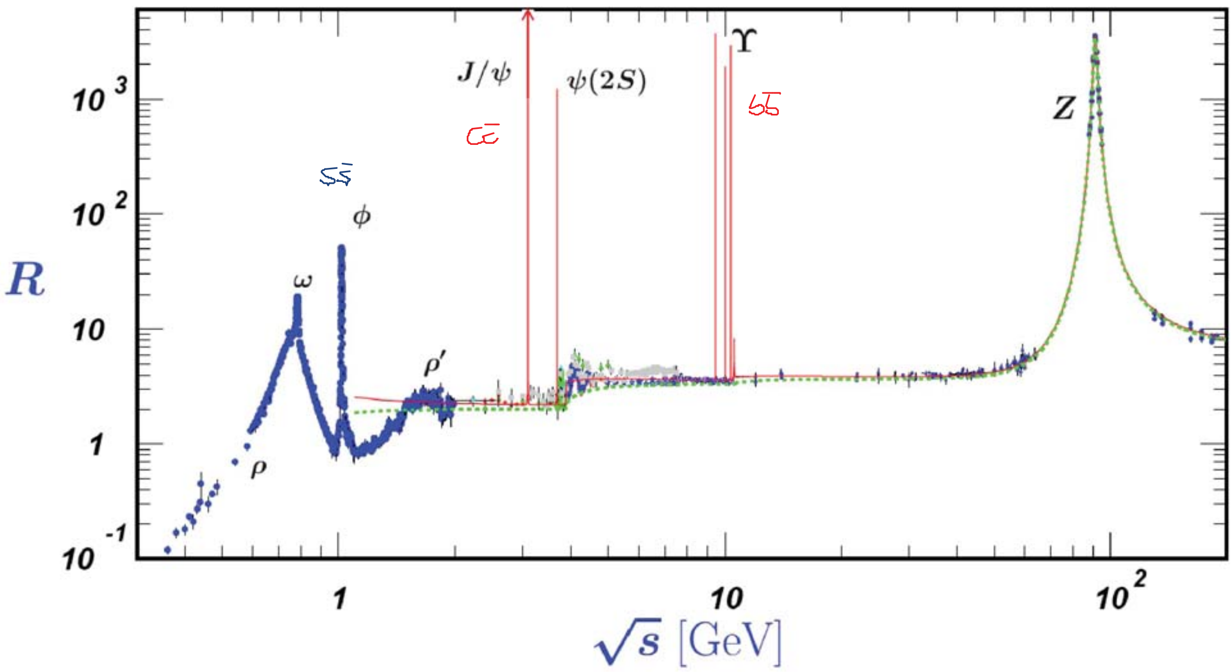


Figure 1.13: Measurements of the hadron production cross-section around the Z resonance. The curves indicate the predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass.

Vergleich der Breiten der verschiedenenen Resonanzen in e+e-
R = WQ(e+e- --> qq) / WQ(e+e- --> μ+μ-)



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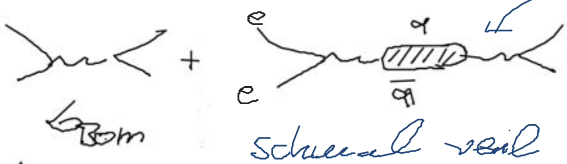
$c\bar{c}$

Test: Interferenz nur wenn $b\bar{b}$

$J^{PC} = 1^{--}$ = $J^{PC} = 1^{--}$

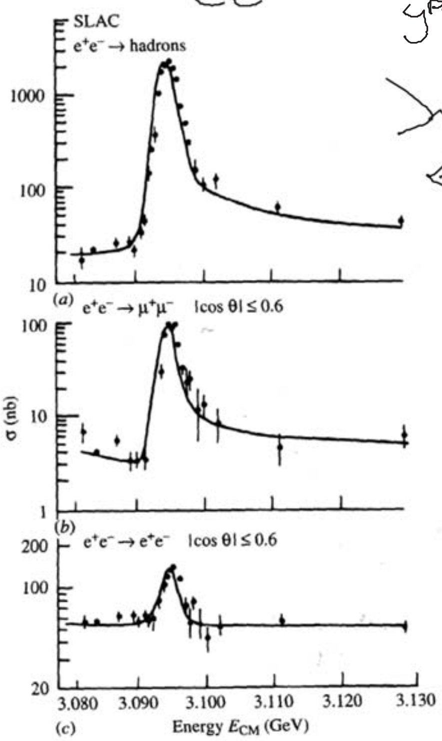
$q^2 \sim m_r^2$



schmal weil unterhalb offener $q\bar{q}$ Schwelle

$m_r < 2 m_B$

$\tau \sim 10^{-20}$ s



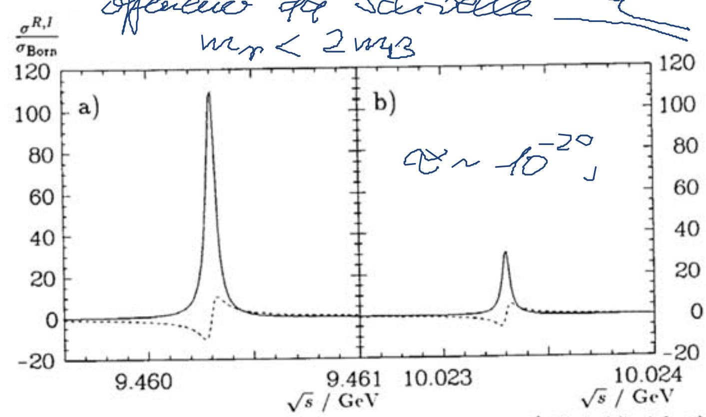
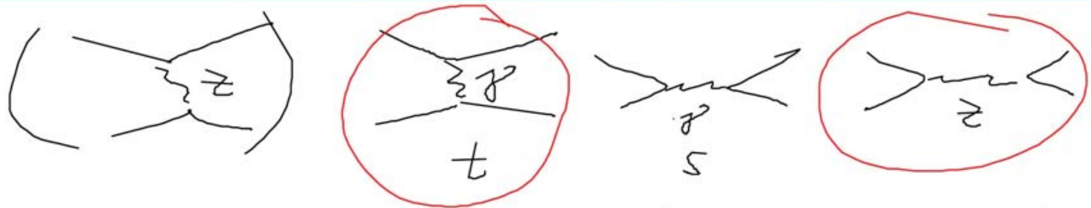


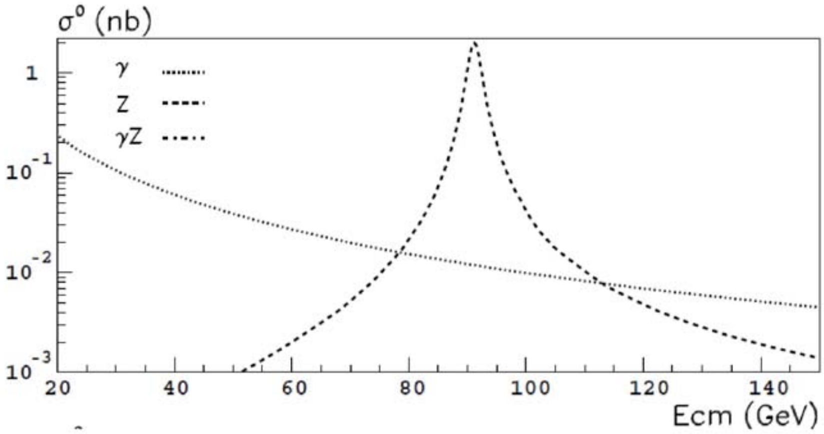
Figure 2.9: Resonance term σ^R (solid line) and interference term σ^I (dashed line) for the $\Upsilon(1S)$ (a) and the $\Upsilon(2S)$ (b) in units of the Born cross-section for $e^+e^- \to \mu^+\mu^-$.

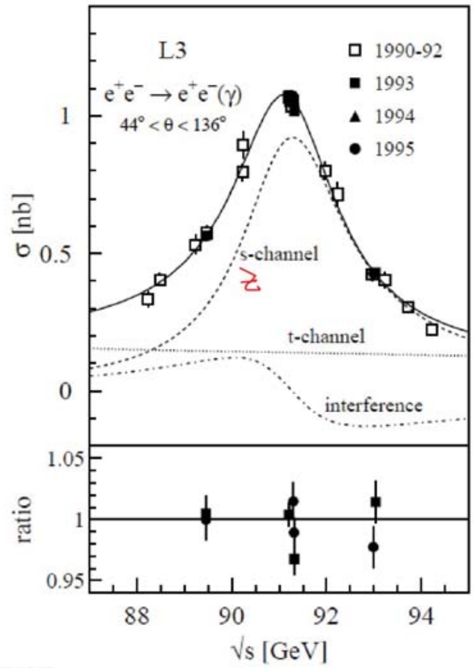
gamma-J/Psi Interferenz (mit exper. Auflösung)

gamma-Y Interferenz (ohne exper. Auflösung) jeweils beschränkt auf m +- Γ



Links: s-Kanal
Die gamma-Z Interferenz is kleiner als 10^-3





Rechts: s- und t-Kanal für e+e- --> e+e-
die s-t-Kanal Z-gamma interferenz trägt stark bei
und hat umgekehrtes Vorzeichen von s-s Interferenz

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V.1. Axial- und Vektorkopplungen der Eichbosonen

- Links- und Rechts-Chirale Kopplungen
  $-i\gamma^\mu c_L \frac{1}{2}(1-\gamma^5)$ und $-i\gamma^\mu c_R \frac{1}{2}(1+\gamma^5)$

$w^{\pm} = \frac{1}{\sqrt{2}}(w_1 \mp i w_2)$

Vektorboson V	γ	$W^\pm$	Z^0
$c_L(V)$	eQ	$\sqrt{2}\, g_W I_3^W$	$g_W/\cos\theta_W\,(I_3^W - Q\sin^2\theta_W)$
$c_R(V)$	eQ	0	$g_W/\cos\theta_W\,(\quad - Q\sin^2\theta_W)$
	gleich	nur links	L und R unterschiedlich

vorderste Seite

-

- Mit

V	γ	$W^\pm$	Z^0
g(V)	e	$\sqrt{2}\, g_W$	$g_W/\cos\theta_W$

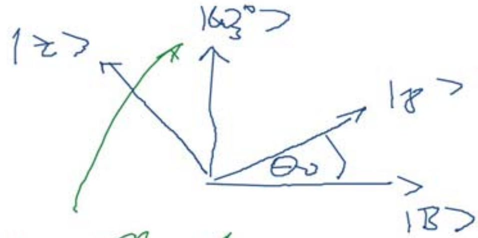
kann man definieren:

Ladung

Kopplung * Ladung

- Vektorkopplung $c_V := (c_L + c_R)/g$
- Axialkopplung $c_A := (c_L - c_R)/g$

$$\left.\begin{matrix} c_V := (c_L + c_R)/g \\ c_A := (c_L - c_R)/g \end{matrix}\right\} \Leftrightarrow \left\{\begin{matrix} c_L := (c_V + c_A)g/2 \\ c_R := (c_V - c_A)g/2 \end{matrix}\right.$$



$$|Z\rangle = \cos\theta_W |W_3^0\rangle - \sin\theta_W |B\rangle$$

$|B\rangle \leftarrow$ koppelt mit g_Y an Y

koppelt mit g_W an I_3^W

Kopplung des Z: $\cos\theta_W\, g_W I_3^W - \sin\theta_W\, g_Y Y$

$$= \cos\theta_W\, g_W I_3^W - \sin\theta_W \frac{\sin\theta}{\cos\theta} g_W (Q - I_3^W)$$

$Y = Q - I_3^W$

$\frac{g_Y}{g_W} = \tan\theta_W$

$$= \frac{g_W}{\cos\theta_W}\left((\cos^2\theta_W + \sin^2\theta_W) I_3^W - Q\sin^2\theta_W\right)$$

$$= \underbrace{\frac{g_W}{\cos\theta_W}}_{= g_Z}\left(I_3^W - Q\sin^2\theta_W\right)$$

- Axial- und Vektor-Kopplungen: $-\iota g \tfrac{1}{2}(c_V\gamma^\mu - c_A\gamma^\mu\gamma^5)$

Vektorboson V	γ	$W^\pm$	Z^0
$c_V(V)$	2Q	I_3^W	$I_3^W - 2Q\sin^2\theta_W$
$c_A(V)$	0	I_3^W	I_3^W
	"V"	"V-A"	"$c_V V - c_A A$"

$\bar{\psi}\gamma^\mu\psi$: Vektor-Viererstrom

$\bar{\psi}\gamma^\mu\gamma^5\psi$: Axialvektor-Viererstrom

Bedeutung: Möglichkeit der Messung von $\sin^2\theta_W$ über c_V