Introduction to Electroweak Physics

(Theory for Precision Tests)

W. Hollik

- Theoretical basis
- Higher order perturbation theory
- The vector-boson masses
- Physics at the Z resonance
- Physics above the Z resonance
- Higgs bosons

Quantum Field Theory

fields = Operators, act on particle states

field quanta = particles (mass, spin, charge, ...)

Lagrangian based on

– space–time symmetry (Lorentz invariance)

– internal symmetry (gauge invariance)

suitable formulation of micro-dynamics for the fundamental interactions

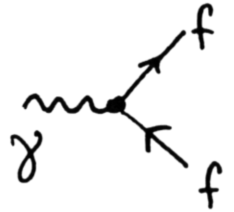
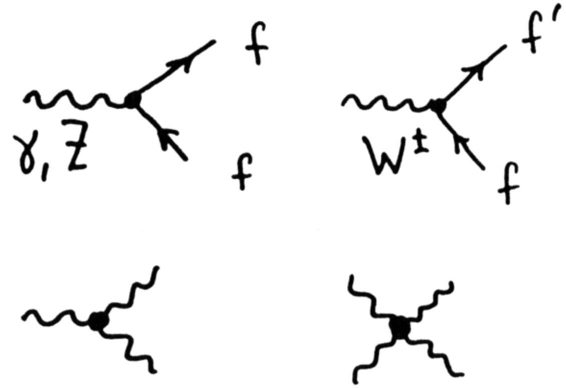
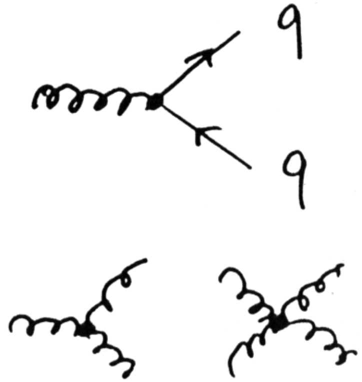
- elektromagnetic: **Quantum Electrodynamics**

- weak: unified with e.m. $\rightarrow$ **e.w. Standard Model**
- strong: **Quantum Chromodynamics**

guidance:

– successful gauge principle

– empirically known symmetry properties

	electromagnetic	electroweak	strong
Symmetry	$\mathcal{U}(1)_{em}$	$SU(2) \times \mathcal{U}(1) \supset \mathcal{U}(1)_{em}$	$SU(3)$
Charges	Q	I_+, I_-, I_3, Y	$T_1, \dots T_8$
Vector fields	A_μ	$W^+_\mu, W^-_\mu, \underbrace{W^0_\mu, B_\mu}$ $\downarrow \Theta_W$ A_μ, Z_μ	$G^1_\mu, \dots G^8_\mu$
coupling constant	e	g_2, g_1 $e = g_2 \sin \Theta_W$	g_s
types of couplings			

W propagators

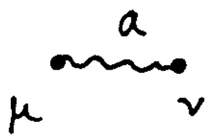
[exact gauge symmetry

problem like in QED:

massless vector field $\rightarrow$ propagator?

gauge fixing term is required:

$$\mathcal{L}_{fix} = -\frac{1}{2\xi_a}\left(\partial_\mu W^{\mu,a}\right)^2 \qquad \text{(sum over a)}$$



$$\frac{i}{k^2+i\varepsilon}\left[-g_{\mu\nu}+(1-\xi_a)\frac{k_\mu k_\nu}{k^2}\right]$$

non-abelian:

S-matrix elements ξ-dependent with these propagators

additional auxiliary fields are required: ghosts

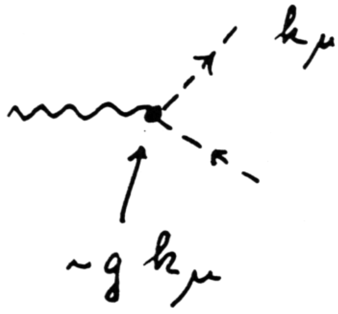
Faddeev-Popov ghosts

compensate unphysical polarization states

New fields u^a $(\longleftrightarrow W_\mu^a)$ with

$$\mathcal{L}_{Gh} = \mathcal{L}_{kin} + \mathcal{L}_{int}$$

propagators



extra (-1) for 

$\Rightarrow$
- S-matrix unitary
- gauge independent
- renormalizable theory

- gauge fields are <u>massless</u>

- mass term $M_a^2 \, W_\mu^a W^{\mu, a}$

  $\rightarrow$ spoils renormalizability

massive propagator:

$$\frac{i}{k^2 - M_a^2 + i\varepsilon} \left[-g_{\mu\nu} + \frac{k_\mu k_\nu}{M_a^2} \right]$$

bad behaviour for $k_\mu \rightarrow \infty$: $\sim$ con

$M_A = 0$: $\sim \frac{1}{k^2}$

$\boxed{\text{loop diagrams:}}$

$$\int d^4k \, \frac{1}{k^2 - M_a^2} \left(\frac{k_\mu k_\nu}{M_a^2} + \cdots \right.$$

divergences worse

more loops $\longrightarrow$ more propagators

$\rightarrow$ higher degrees of divergences

not under control

Problem: $W^{\pm}, Z$ are massive

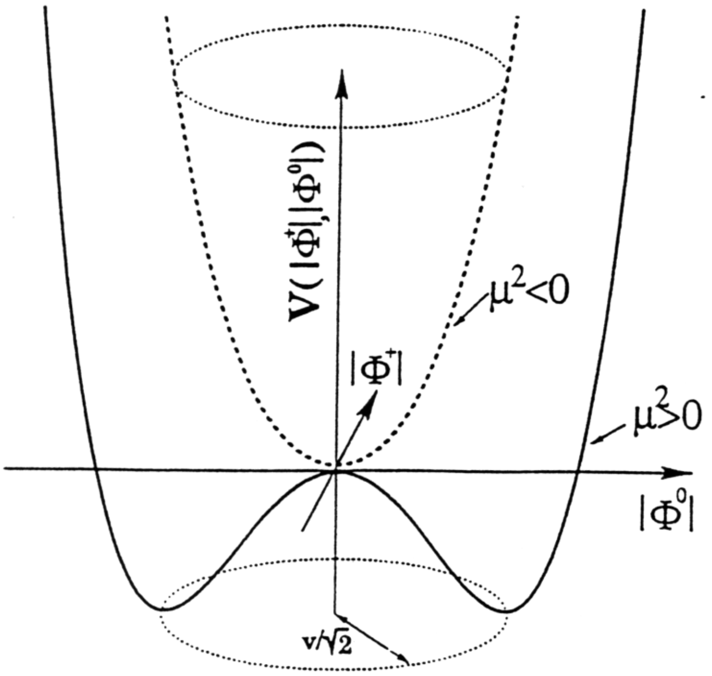
Explicit mass terms ↯ renormalizability

Standard Model solution: Higgs mechanism

$$\mathcal{L}_H = \mathcal{L}_{\mathrm{kin}} - V$$

$$V = -\mu^2 \, |\Phi|^2 + \lambda \, |\Phi|^4$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$ isospin-doublet of scalar fields



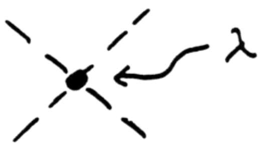
$$\boxed{\phi^0 = v + H}$$

$$v \sim \sqrt{\frac{\mu^2}{\lambda}} \neq 0 \quad \text{for } \mu^2 > 0$$

- <u>Higgs bosons:</u> quanta of H field

neutral, spin 0

mass: $M_H = v \cdot \sqrt{\lambda}$



self-coupling

$\lambda \sim M_H^2$

M_H: free parameter

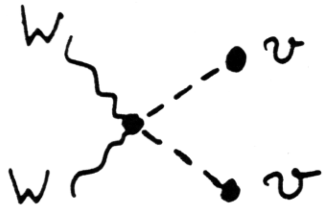
exp: $M_H > 113$ GeV LEP

[95% C.L.]

$M_H = 115$ GeV ? LEP

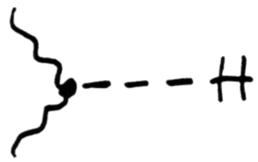
Nov. 20

- $\boxed{\text{Gauge interaction}}$ Higgs $\leftrightarrow$ W, Z

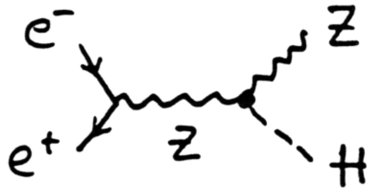


$$M_W^2 = g_2^2 \, v^2$$

mass term

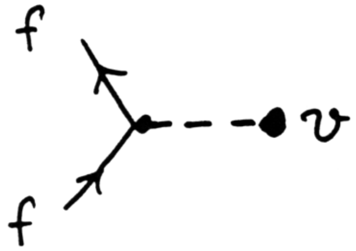


residual H $\leftrightarrow$ W, Z interaction

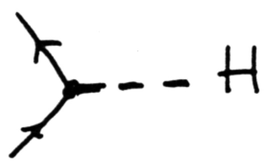
$\Rightarrow$ 

Higgs production
exp. search in e^+e

- $\boxed{\text{Yukawa interaction}}$ $\rightarrow$ fermion mas



$$m_f = g_f \cdot v$$



residual Yukawa in
Higgs $\leftrightarrow$ fermion

propagators of massive gauge bosons

$$\left(-g_{\mu\nu} + (1-\xi)\frac{k_\mu k_\nu}{k^2-\xi M^2} \right) \frac{1}{k^2-M^2}$$

$$\xrightarrow{\text{large } k_\mu} \frac{1}{k^2}$$ like massless case

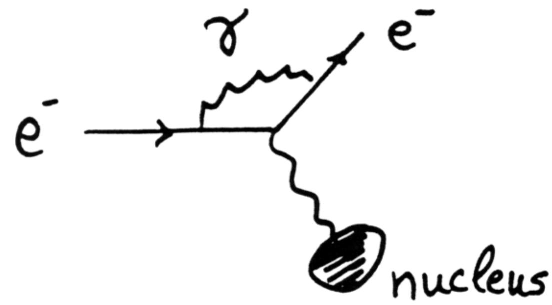
$\Longrightarrow$

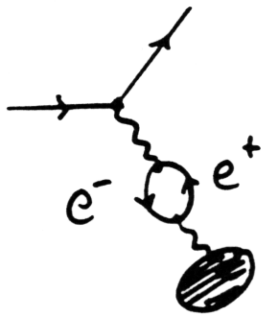
- same structure of divergences as in the massless gauge theory
- theory is renormalizable

Quantum Effects and Precision Tests

quantum effects: beyond Born approximation

historically: **QED**





$\Rightarrow$ Lamb shift

$\Rightarrow \quad g-2 \neq 0$

$\boxed{\text{Theory}} \longrightarrow \; ? \; \longleftarrow \boxed{\text{Experiments}}$

precise predictions

measurement with high accuracy

Experiments at particle accelerators

LEP	$e^- e^+$	CERN ALEPH, DELPHI, L3, OPAL
SLC	$e^- e^+$	Stanford SLD
Tevatron	p-$\bar{p}$	Fermi National Lab. CDF, DØ
HERA	$e^- p$	DESY H1, ZEUS

<u>Future</u>:

Tevatron Run II (2001)

LHC (CERN) p-p (2006)

e^+e^- Linear Collider (?)

- **Elektroschwache Präzisionsmessungen:**
  - LEP1/SLC: e^+e^- Vernichtung an der Z-Boson Resonanz

    LEP1: $\sim 4 \times 10^6$ Ereignisse/Exp. ('89 – '95)
  - LEP2: $e^+e^- \to W^+W^-$
  - Tevatron: $q\bar{q}' \to W \to l\bar{\nu},\ q\bar{q}'$

    $q\bar{q} \to t\bar{t},\ t \to W^+b \to \ldots$
  - Niederenergieexperimente

$M_{\mathrm{Z}}[\mathrm{GeV}]$	$=$	91.1871 ± 0.0021	0.002%
$\Gamma_{\mathrm{Z}}[\mathrm{GeV}]$	$=$	2.4944 ± 0.0024	0.10%
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$=$	0.23151 ± 0.00017	0.07%
$M_{\mathrm{W}}[\mathrm{GeV}]$	$=$	80.394 ± 0.042	0.05%
$m_{\mathrm{t}}[\mathrm{GeV}]$	$=$	174.3 ± 5.1	2.9%
$G_\mu[\mathrm{GeV}^{-2}]$	$=$	$1.16637(2)\,10^{-5}$	0.002%

Effekte, die bei LEP berücksichtigt werden müssen:
Gezeiten, Wasserstand des Genfer Sees,
Fahrplan des TGV Genf – Paris

- **Quanteneffekte der Theorie:**

  $\sim \mathcal{O}(1\%) \Rightarrow$ Schleifenkorrekturen

Standard Model is renormalizable

→ quantum effects are calculable

Nobel Prize 19:
→ 't Hooft
Veltman

- lowest order (Born approximation)

← $g = \mathcal{O}(e)$

- next order (1-loop):

all particles of the SM
(virtual states)

top: $\sim m_t^2$, Higgs: $\sim \log M_H$

top

⇓

determination of top mass

Higgs

⇓

constraints on Higgs-boson mass

SM quantum effects, renormalization

well defined Feynman rules ($\epsilon, M_W, M_Z, M_H, m_f$)

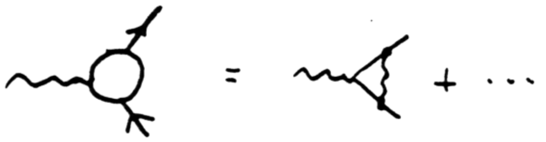
$\rightarrow$ calculate diagrams with loops

In 4-fermion processes () with $m_f \ll M_i$

①  γ, W, Z

 f

propagator corrections

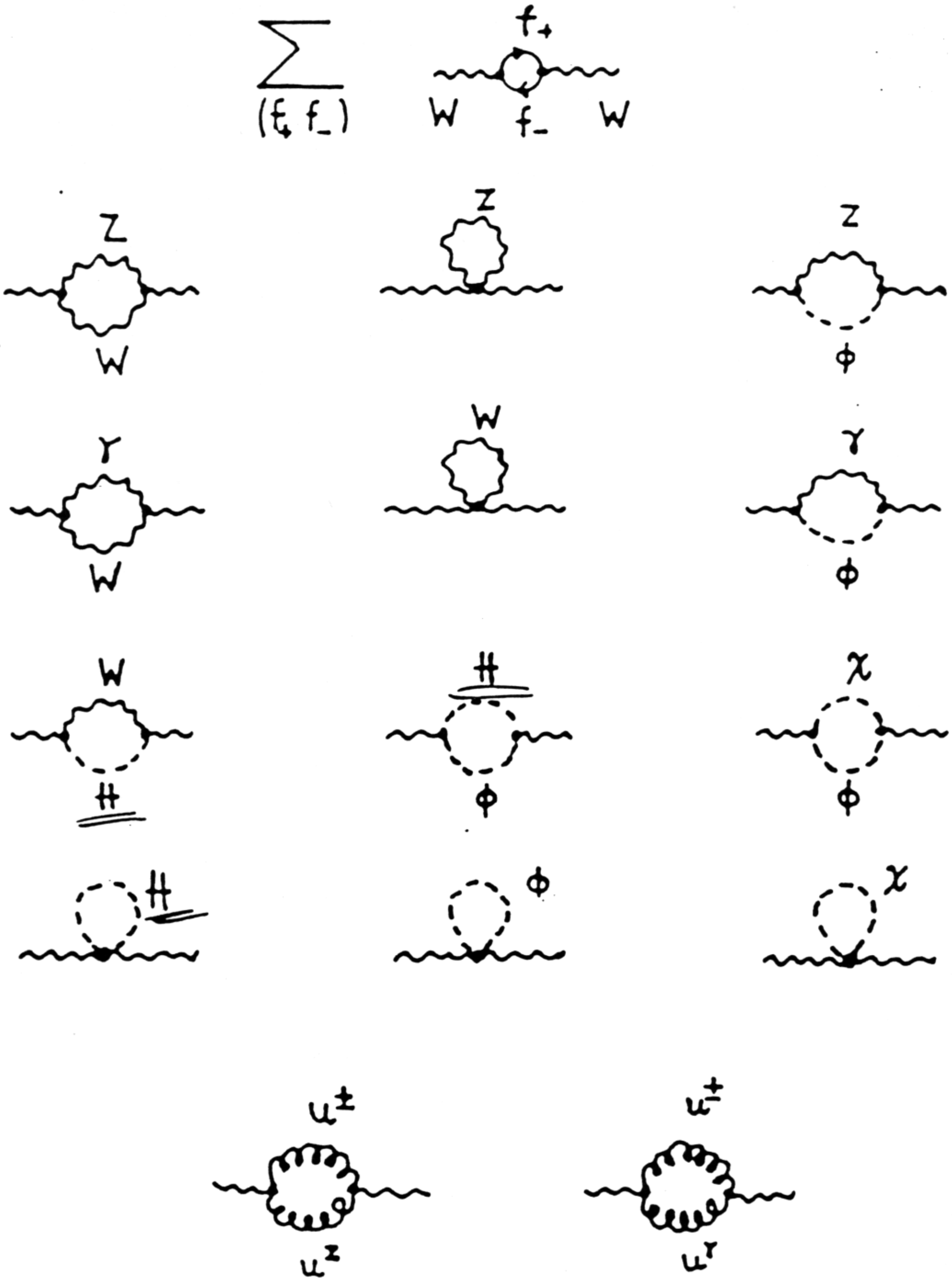
② 

vertex corrections

③ 

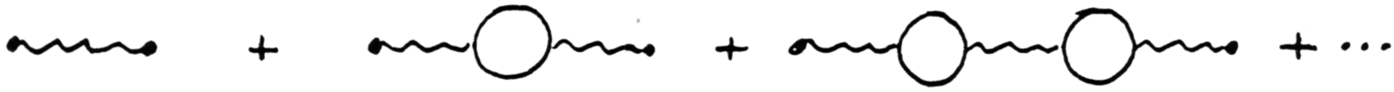
box diagrams

W Self energy



W propagator with 1-loop self energy

("dressed" propagator)



$$\frac{1}{k^2-M_W^2} + \frac{1}{k^2-M_W^2}\left(-\Sigma_W\right)\frac{1}{k^2-M_W^2} + \frac{1}{k^2-M_W^2}\left(-\Sigma_W\right)\frac{1}{k^2-M_W^2}\left(-\Sigma_W\right)\frac{1}{k^2-M_W^2} +$$

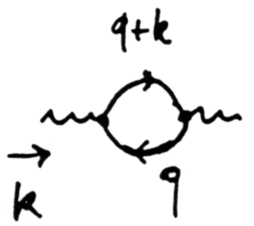
$$= \frac{1}{k^2-M_W^2}\underbrace{\left\{ 1 + \left(\frac{-\Sigma_W}{k^2-M_W^2}\right) + \left(\frac{-\Sigma_W}{k^2-M_W^2}\right)^2 + \dots \right\}}_{= \frac{1}{1+\frac{\Sigma_W}{k^2-M_W^2}}}$$

$$= \frac{1}{k^2-M_W^2+\Sigma_W(k^2)}$$

<u>Observations</u>:

(1) $\Im m\, \Sigma_W(k^2=M_W^2) \neq 0 \Rightarrow$ finite width ✓

(2) $\mathrm{Re}\, \Sigma_W$ is divergent: needs regularization
= procedure to make integral finite



$$\int d^4q \frac{1}{(q^2-m_1^2)[(q+k)^2-m_2^2]} \sim \int \frac{d^4q}{q^4}$$ divergent (UV

Result of regularization:

→ $\Sigma_W(k^2)$ is mathematically well defined

→ dependent on unphysical dimension D

way out:

---

mass renormalization

lowest order: $\frac{1}{k^2 - M_W^2}$ pole at $k^2 = M_W^2$

Quantum Field Theory: pole ↔ physical mas

For unstable particles: Re(pole) ↔ physical mass

higher order: $\frac{1}{k^2 - M_W^2 + \Sigma_W(k^2)}$ but $\mathrm{Re}\,\Sigma_W(M_W^2) \neq 0$

pole is somewhere else!

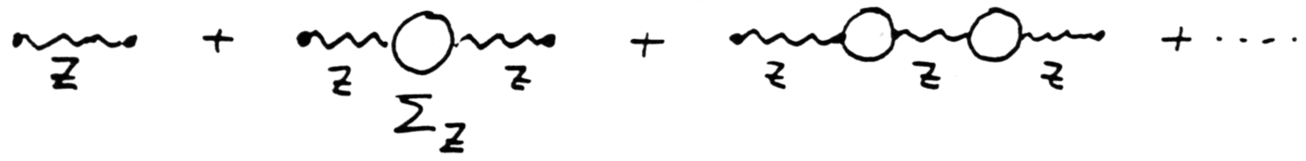
hence: M_W in $\mathcal{L}$ is not the physical mass
but "bare" mass M_W^0

Replace $M_W^2 \rightarrow M_W^{0\,2} = \underbrace{M_W^2}_{\text{physical}} + \underbrace{\delta M_W^2}_{\text{counter term}}$

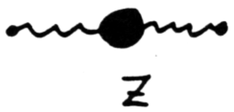
Condition:

$$\mathrm{Re}\left[k^2 - M_W^2 - \delta M_W^2 + \Sigma_W(k^2)\right]_{k^2 = M_W^2} = 0 \quad \Leftrightarrow \quad \boxed{\delta M_W^2 = \mathrm{Re}\,\Sigma_W(M_W^2)}$$

same procedure for Z propagator:



$$= \frac{1}{k^2 - M_Z^{0\,2} + \Sigma_Z(k^2)} \quad =:$$



$M_Z^{0\,2} = M_Z^2 + \delta M_Z^2$ $\qquad$ M_Z : physical Z mass

$\boxed{\delta M_Z^2 = \mathrm{Re}\,\Sigma_Z(M_Z^2)}$ $\qquad$ renormalization condition

Charge renormalization:

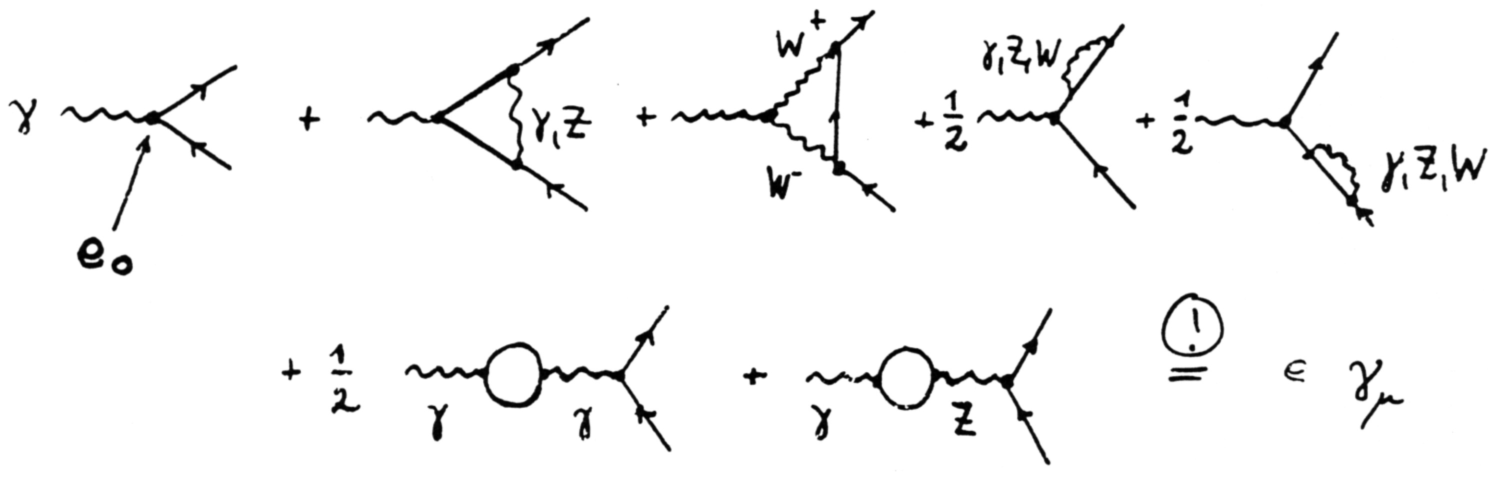
e is defined in γ-e-scattering in the classical limit (Thomson scattering)

$$k^2 = 0, \quad k^0 \to 0 \quad (\lambda \to \infty)$$

lowest order:

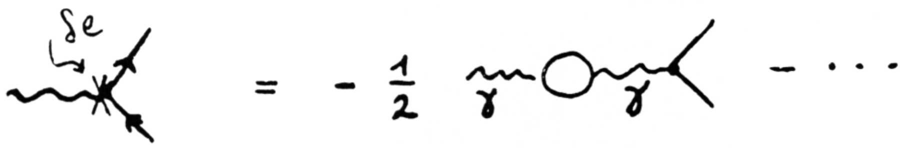
$$= e\,\gamma_\mu \Rightarrow \sigma_{\text{Compton}} \to \sigma_{Th} = \frac{e^4}{6\,m_e^2}$$

one-loop order (always with $k^2=0$, $k^0 \to 0$)



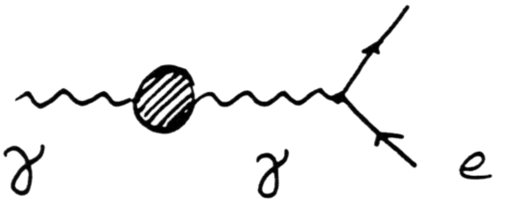
$$\overset{!}{=} e\,\gamma_\mu$$

"bare" charge: $e_0 = \underset{\substack{\uparrow \\ \text{physical}}}{e} + \delta e$



$$\boxed{\frac{\delta e}{e} = \frac{1}{2}\Pi_\gamma(0) - \frac{\sin\theta_W}{\cos\theta_W}\cdot\frac{\Sigma_{\gamma Z}(0)}{M_Z^2}}$$

Large effects from charge and mass renormalization :

(i) 

$$2\frac{\delta e}{e} = \Pi^{\gamma}(0) +$$

$$\Pi_\gamma(0) = \underbrace{\Pi_\gamma(0) - \Pi_\gamma(M_Z^2)}_{\Delta\alpha\text{, finite}} + \Pi_\gamma(M_Z^2)$$

$$\sim Q_f^2 \log\frac{M_Z}{m_f}, \qquad \sim \frac{M_Z^2}{m_{top}^2} \text{ small}$$

light

(ii) $$\sin^2\Theta_W = 1 - \frac{M_W^2}{M_Z^2} \longrightarrow 1 - \frac{M_W^2 + \delta M_W^2}{M_Z^2 + \delta M_Z^2}$$

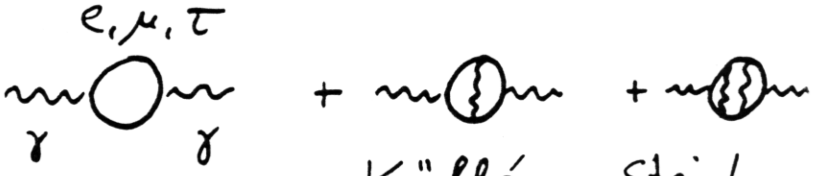
$$= 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\underbrace{\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right)}_{\Delta\rho + \cdots}$$

m_t^2, $\log M_H$

(i)

$$\Delta\alpha = (\Delta\alpha)_{lep} + (\Delta\alpha)^{(5)}_{had} + (\Delta\alpha)_{top}$$

$$(\Delta\alpha)_{lept} = \sum$$

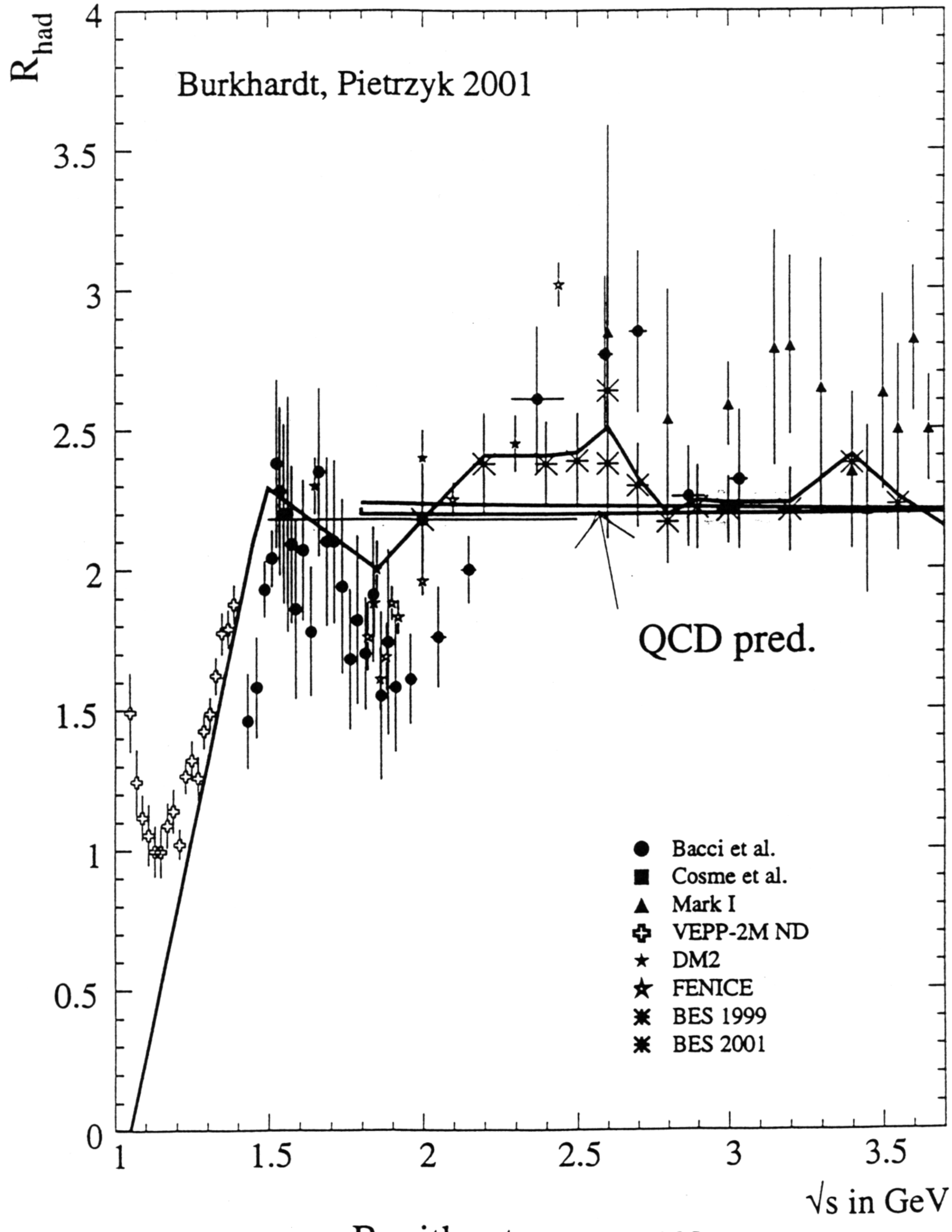


Källén, Sabry (1955)

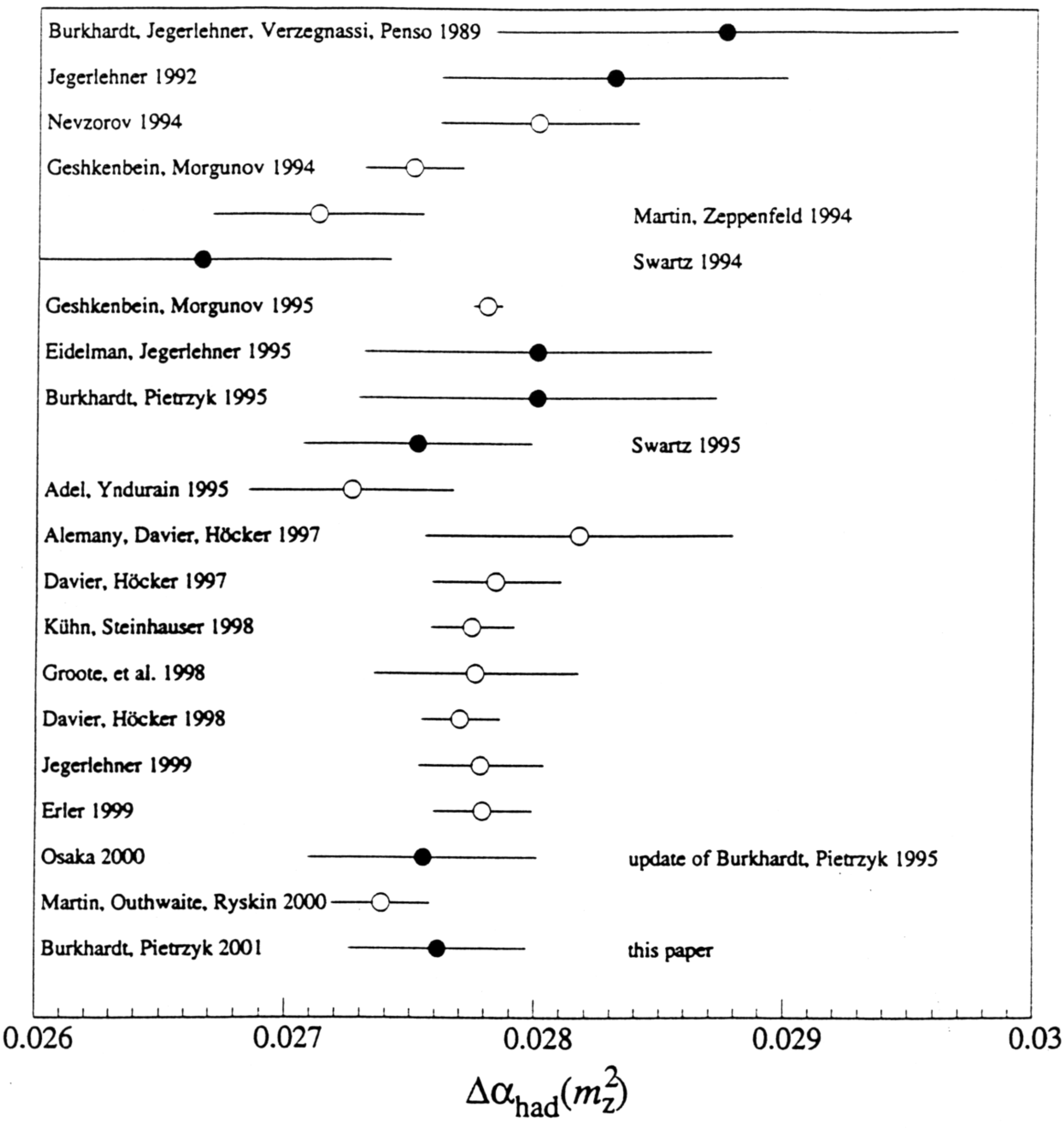
Steinhauser (1998)

$$(\Delta\alpha)^{(5)}_{had} = -\frac{M_Z^2}{4\pi^2\alpha}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{\boxed{\sigma(e^+e^-\to had)}}{s-M_Z^2-i\varepsilon}$$

$$\boxed{\alpha(M_Z) = \frac{\alpha}{1-\Delta\alpha}} = \alpha\left[1+\Delta\alpha+\Delta\alpha^2+\cdots\right.$$



R without resonances



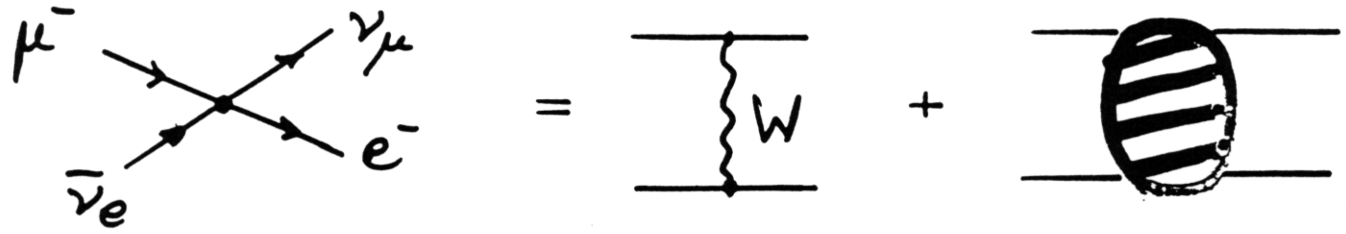
Burkhardt, Jegerlehner, Verzegnassi, Penso 1989
Jegerlehner 1992
Nevzorov 1994
Geshkenbein, Morgunov 1994
Martin, Zeppenfeld 1994
Swartz 1994
Geshkenbein, Morgunov 1995
Eidelman, Jegerlehner 1995
Burkhardt, Pietrzyk 1995
Swartz 1995
Adel, Yndurain 1995
Alemany, Davier, Höcker 1997
Davier, Höcker 1997
Kühn, Steinhauser 1998
Groote, et al. 1998
Davier, Höcker 1998
Jegerlehner 1999
Erler 1999
Osaka 2000
update of Burkhardt, Pietrzyk 1995
Martin, Outhwaite, Ryskin 2000
Burkhardt, Pietrzyk 2001
this paper
0.026
0.027
0.028
0.029
0.03
$\Delta\alpha_{had}(m_Z^2)$

Masses of W and Z bosons

correlated via muon lifetime $\leftrightarrow$ Fermi constant G_μ

$$\frac{1}{\tau_\mu} = \frac{G_\mu^{\,2}\, m_\mu^5}{192\pi^3}\left(1 - \frac{8m_e^2}{m_\mu^2}\right)\cdot(1+\delta_{\mathrm{QED}})$$

$$G_\mu = 1.16637(1)\cdot 10^{-5}\ \mathrm{GeV}^{-2}$$



Fermi Model

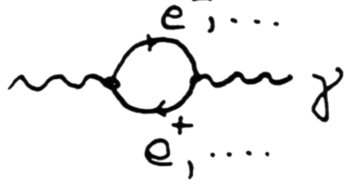
Standard Model

$$G_\mu = \frac{\pi}{\sqrt{2}}\cdot\frac{\alpha}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\cdot\frac{1}{1-\Delta r}$$

$$\Delta r = \Delta\alpha + \Delta r_W(m_t, M_H)$$

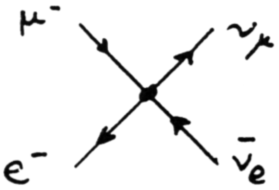
6%

[QED]



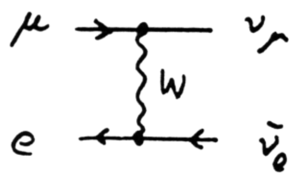
μ decay and "Δr" ($M_W \leftrightarrow M_Z \leftrightarrow \sin^2\theta_W$

- **Fermi model** + QED corrections



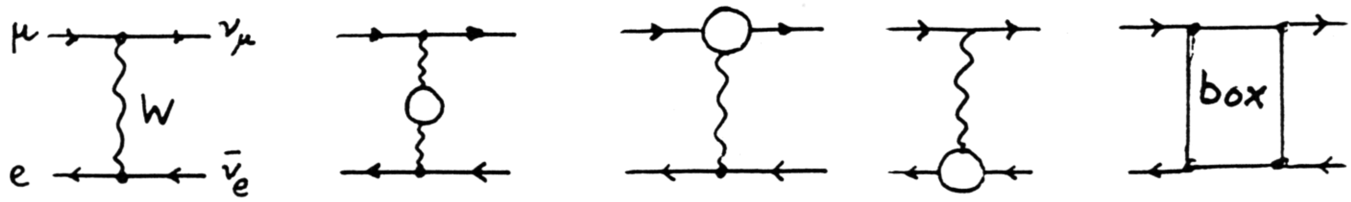
$$\frac{1}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3}\left(1 - \frac{8m_e^2}{m_\mu^2}\right)\Big\{1 + \overbrace{\frac{\alpha}{2\pi}\left(\frac{25}{4} - \pi^2\right) + 0.28\left(\frac{\alpha}{\pi}\right)^2}^{\delta_{QED}}$$

- **Standard Model, Born** $\longleftrightarrow$ Fermi, Born



$$\frac{e^2}{8\sin^2\theta_W} \cdot \frac{1}{M_W^2} = \frac{G_\mu}{\sqrt{2}}$$

- **Standard Model, 1-loop** $\longleftrightarrow$ Fermi, Born



$$\frac{e_0^2}{8\sin^2\theta_W^{0\,2} M_W^{0\,2}}\left\{1 + \frac{\Sigma_W(0)}{M_W^2} + (\text{vertex, box})\right\} = \frac{G_\mu^{exp}}{\sqrt{2}}$$

$$\left(\sin^2\theta_W^{0\,2} = 1 - M_W^{0\,2}/M_Z^{0\,2}\right)$$

Expansion up to one-loop order:

$$e_0^2 = (e+\delta e)^2 = e^2\left(1+2\frac{\delta e}{e}\right)$$

$$M_W^{0\,2} = M_W^2\left(1+\frac{\delta M_W^2}{M_W^2}\right)$$

$$\sin^2\theta_W^0 = 1-\frac{M_W^2+\delta M_W^2}{M_Z^2+\delta M_Z^2} \qquad \left(s_W^2 \equiv \sin^2\theta_W = 1-M_W^2/M_Z^2\right)$$

$$= \sin^2\theta_W\left[1+\frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\frac{\delta M_Z^2}{M_Z^2}-\frac{\delta M_W^2}{M_W^2}\right)\right]$$

insert in

$$\frac{G_\mu}{\sqrt{2}} = \frac{e_0^2}{8\sin^2\theta_W^0 M_W^{0\,2}}\left\{1+\frac{\Sigma_W(0)}{M_W^2}+(\text{vertex, box})\right\}$$

$$= \frac{e^2}{8\sin^2\theta_W M_W^2}\left\{1+\underbrace{2\frac{\delta e}{e}-\frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\frac{\delta M_Z^2}{M_Z^2}-\frac{\delta M_W^2}{M_W^2}\right)+\frac{\Sigma_W(0)-\delta M_W^2}{M_W^2}+(V,B)}_{=:\ \Delta r\,(e,\,M_W,\,M_Z,\,M_H,\,m_f)}\right\}$$

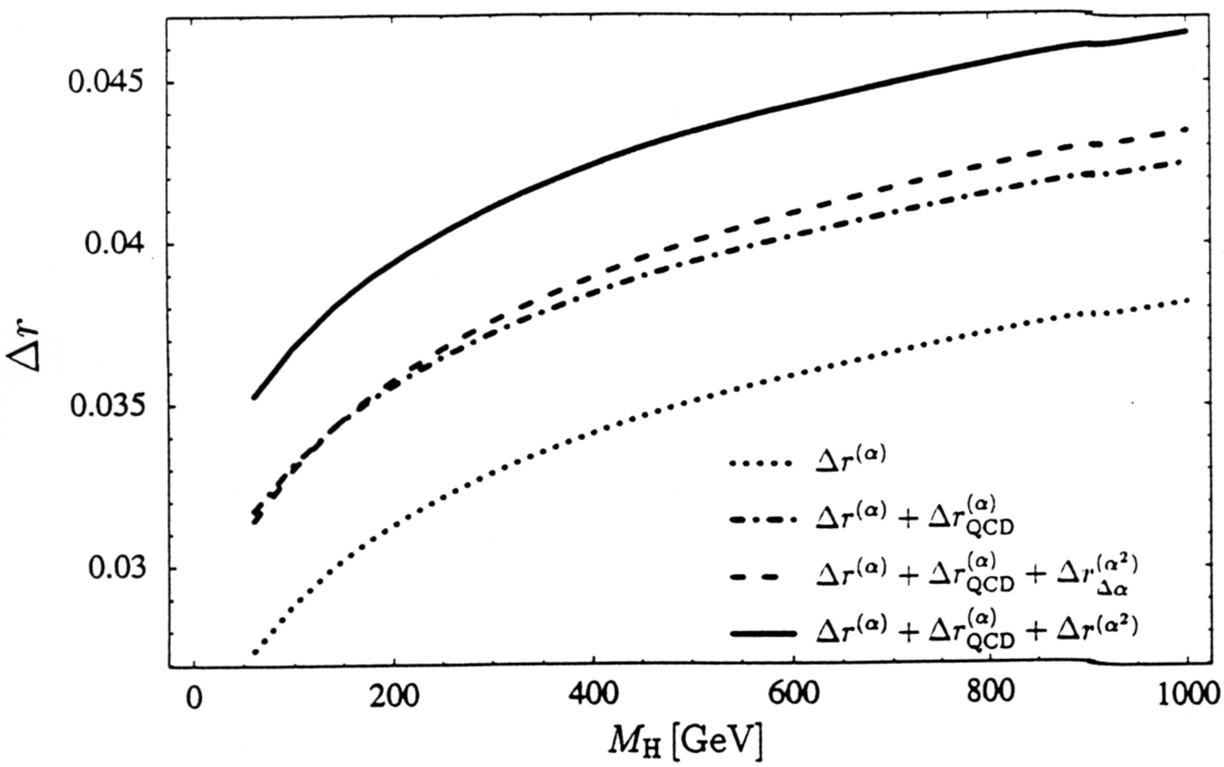
$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8\sin^2\theta_W M_W^2} \cdot \Bigg\{ 1 + \underbrace{2\frac{\delta e}{e} - \frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right) + \frac{\Sigma_W(0) - \delta M_W^2}{M_W^2} + (V,B)}_{\equiv \Delta r\,(e,\, M_W,\, M_Z,\, m_f,\, M_H)}$$

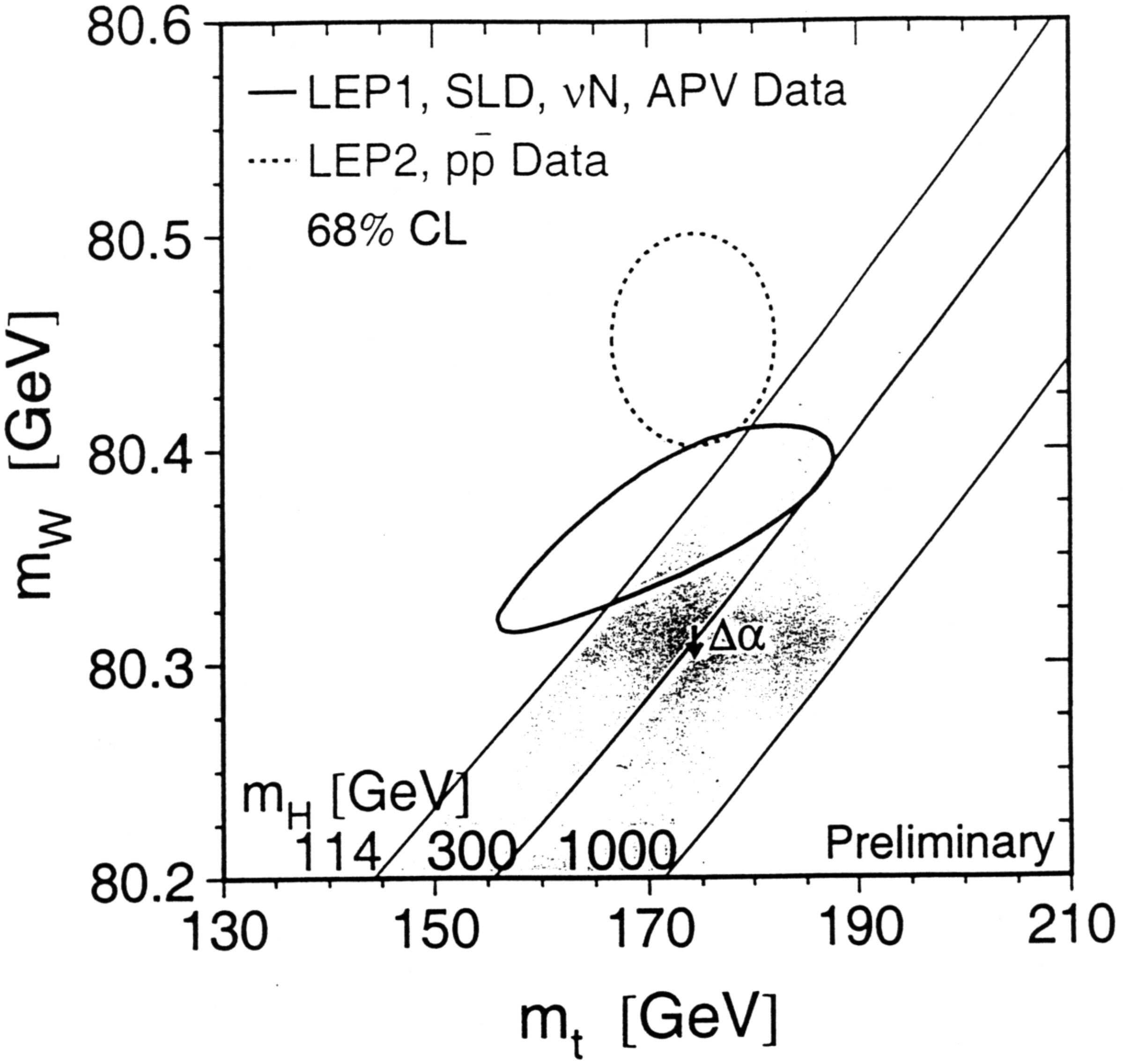
- $$\frac{\delta e}{e} = \underbrace{\Pi^\gamma(0) - \Pi^\gamma(M_Z^2)}_{\Delta\alpha \cong \frac{\alpha}{3\pi}\sum_f Q_f^2 \log\frac{M_Z^2}{m_f^2}} + \Pi^\gamma(M_Z^2) + \ldots$$

  $[6\%]$

- $$\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2} = \underbrace{\frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}}_{\Delta\rho \cong \frac{3 m_t^2}{M_Z^2} \cdot \frac{\alpha}{16\pi\sin^2\theta_W}} + \ldots$$

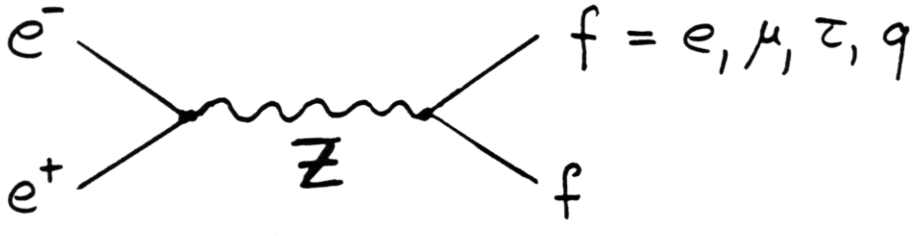
  $[1\%]$


0.045
0.04
0.035
0.03
Δr
$\Delta r^{(\alpha)}$
$\Delta r^{(\alpha)} + \Delta r^{(\alpha)}_{\mathrm{QCD}}$
$\Delta r^{(\alpha)} + \Delta r^{(\alpha)}_{\mathrm{QCD}} + \Delta r^{(\alpha^2)}_{\Delta\alpha}$
$\Delta r^{(\alpha)} + \Delta r^{(\alpha)}_{\mathrm{QCD}} + \Delta r^{(\alpha^2)}$
0
200
400
600
800
1000
M_{H} [GeV]



80.6
80.5
80.4
80.3
80.2
LEP1, SLD, νN, APV Data
LEP2, pp̄ Data
68% CL
m_W [GeV]
$\Delta\alpha$
m_H [GeV]
114
300
1000
Preliminary
130
150
170
190
210
m_t [GeV]

$\boxed{Z \text{ resonance}}$



$\sim 16 \cdot 10^6$ at LEP (1989 – 1995)

$$\sigma(s) = 12\pi \frac{\Gamma(Z \to e^+e^-) \cdot \Gamma(Z \to f\bar{f})}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

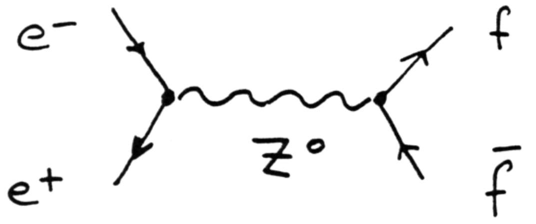
$s \uparrow E^2_{CMS}$

Breit-Wigner

width: $\Gamma_Z = \underbrace{\Gamma(e,\mu,\tau)}_{\text{lept.}} + \underbrace{\sum_q \Gamma(q\bar{q})}_{\text{hadron.}} + \underbrace{N_\nu \Gamma(\nu\bar{\nu}}_{\text{invisibl}}$

- Line shape $\to M_Z, \Gamma_Z$
- σ_{peak} $\to$ partial widths $\Gamma_{lept}, \Gamma_{had}$
- angular distributions, polarization asymmetries $\to \sin^2\Theta_W$

Z physics



$$J_\mu^{(e)} \frac{g^{\mu\nu}}{q^2 - M_Z^2 + i M_Z \Gamma_Z} J_\nu^{(f)}$$

- $$\left.\frac{d\sigma}{d\Omega}\right|_{unpol} \sim (v_e^2 + a_e^2)(v_f^2 + a_f^2) \cdot (1 + \cos^2\theta) + 2 v_e a_e \cdot 2 v_f a_f \cdot 2\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} \cdot \frac{2 v_e a_e}{v_e^2 + a_e^2} \cdot \frac{2 v_f a_f}{v_f^2 + a_f^2}$$

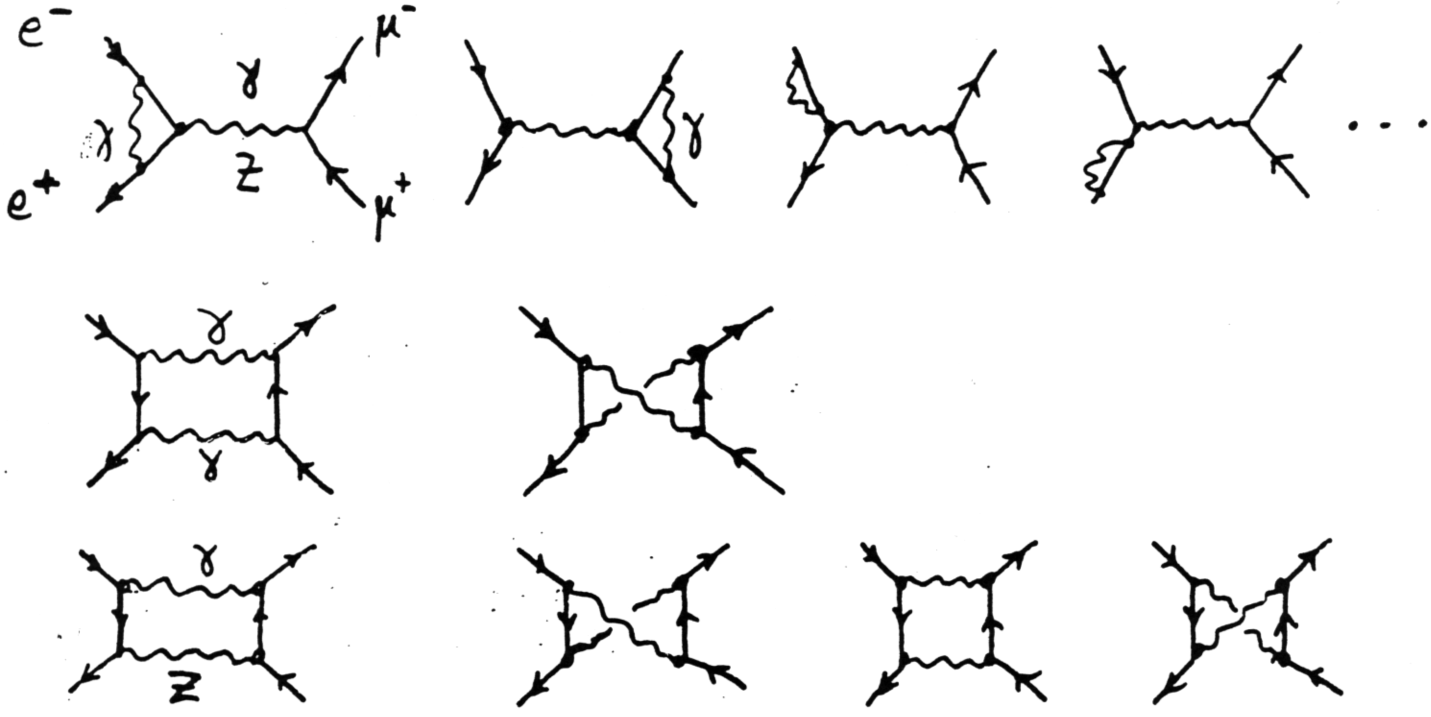
$$\frac{v_f}{a_f} = 1 - 4 |Q_f| \sin^2\theta_W$$

- Polarized e^- (longitudinal):

$$A_{LR} = \frac{\sigma(e_L) - \sigma(e_R)}{\sigma(e_L) + \sigma(e_R)} = \frac{2 v_e a_e}{v_e^2 + a_e^2}$$

$$\frac{v_e}{a_e} = 1 - 4 \sin^2\theta_W$$

QED (or photonic) corrections



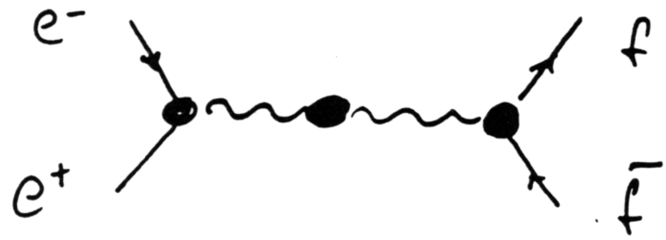
* UV finite, gauge invariant
* IR divergent (→ real bremsstrahlung)

ISR

FSR

real photon bremsstrahlung

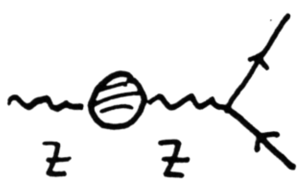
Z amplitude with effective coupling

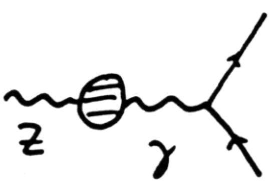


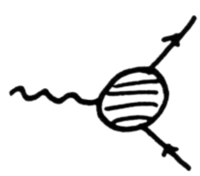
$$(\text{Norm.}) \cdot J_\mu^{(e)} \, \frac{g^{\mu\nu}}{s - M_Z^2 + i \frac{s}{M_Z^2} \Gamma_Z M_Z} \, J_\nu^{(f)}$$

$$(\text{Norm.}) = G_\mu M_Z^2 \sqrt{2} \qquad \left(\leftarrow \frac{e^2}{s_W^2 c_W^2} \right)$$

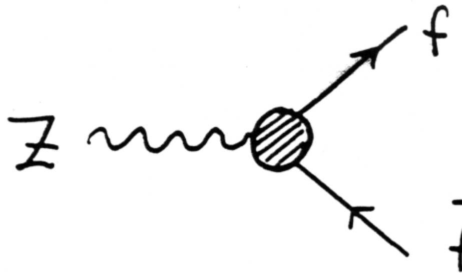
$$\boxed{J_\mu = \gamma_\mu \left(g_V^f - g_A^f \gamma_5 \right)}$$

$\frac{1}{2}$ 

$+$ 

$+$ 

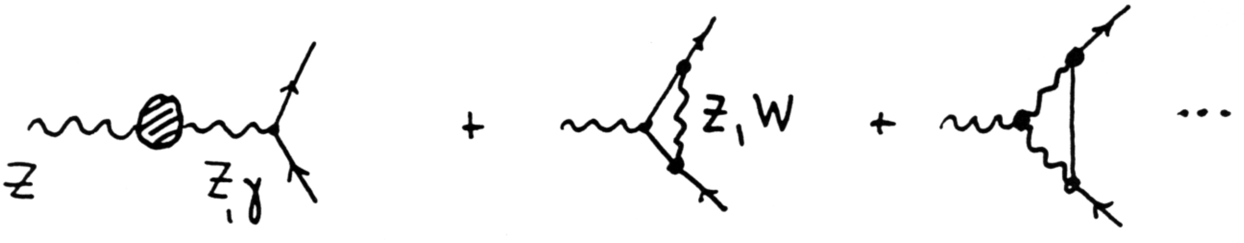
$+ \frac{1}{2}$ 
$+ \frac{1}{2}$ 
$+$ Counter terms



$$\boxed{\begin{aligned} g_A^f &= \sqrt{\rho_f}\; I_3^f \\ g_V^f &= \sqrt{\rho_f}\; \left(I_3^f - 2 Q_f \sin^2\Theta_f \right) \end{aligned}}$$

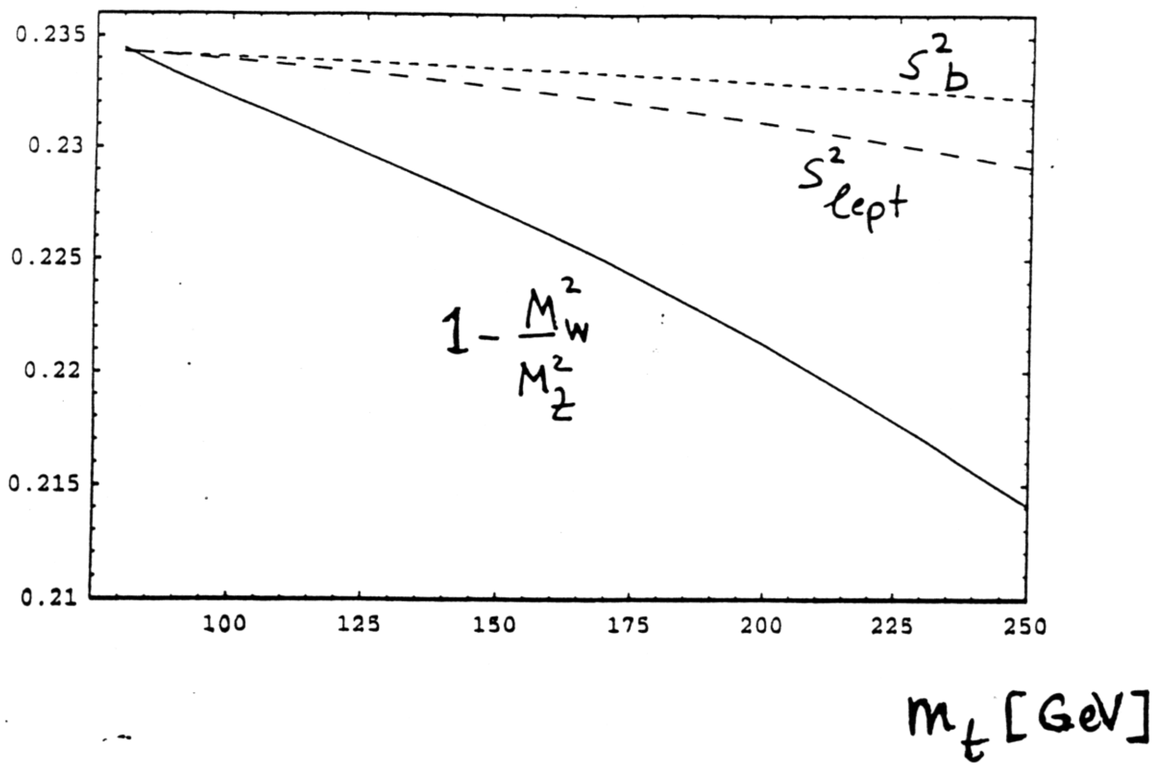
$$\rho_f(m_t, M_H, \alpha_s) = \frac{1}{1-\Delta\rho} + \cdots$$

$$\sin^2\Theta_f(m_t, M_H, \alpha_s) = s_W^2 + \Delta\rho \cdot c_W^2 + \cdots$$

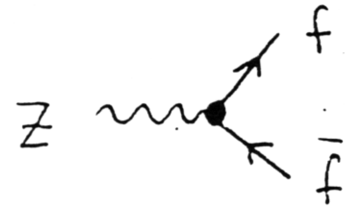


non-universal

Mixing angles, $M_H = 300$ GeV



Z boson observables



g_V^f, g_A^f and $(G_\mu M_Z^2)$ normalizat

$$\Gamma_{Z\to f\bar{f}} = N_c^f \frac{\sqrt{2}\, G_\mu M_Z^3}{12\pi} \left[(g_V^f)^2 + (g_A^f)^2 \right] \left(1 + \frac{3\alpha}{4\pi} Q_f^2\right) \cdot K_{QCD}$$

$$A_{FB}^f = \frac{3}{4} \cdot \frac{2 g_V^e g_A^e}{g_V^{e\,2} + g_A^{e\,2}} \cdot \underbrace{\frac{2 g_V^f g_A^f}{g_V^{f\,2} + g_A^{f\,2}}}_{= A_f}$$

$$P_\tau = \frac{2 g_V^\tau g_A^\tau}{g_V^{\tau\,2} + g_A^{\tau\,2}}$$

$$A_{LR} = \frac{2 g_V^e g_A^e}{g_V^{e\,2} + g_A^{e\,2}}$$

depend on ratio $\dfrac{g_V^f}{g_A^f} \leftrightarrow \sin^2\theta_f$

b-quark asymmetry:

$$A_{FB}^b = \frac{3}{4} \underbrace{A_e}_{\Downarrow\ \sin^2\theta_e} \cdot \underbrace{A_b}_{\simeq \text{ const in SM}}$$

0.935 ± 0.001

FORTRAN Code

$$(m_t, M_H) \to \boxed{\text{ZFITTER}} \to \text{Präzisions-Observable}$$

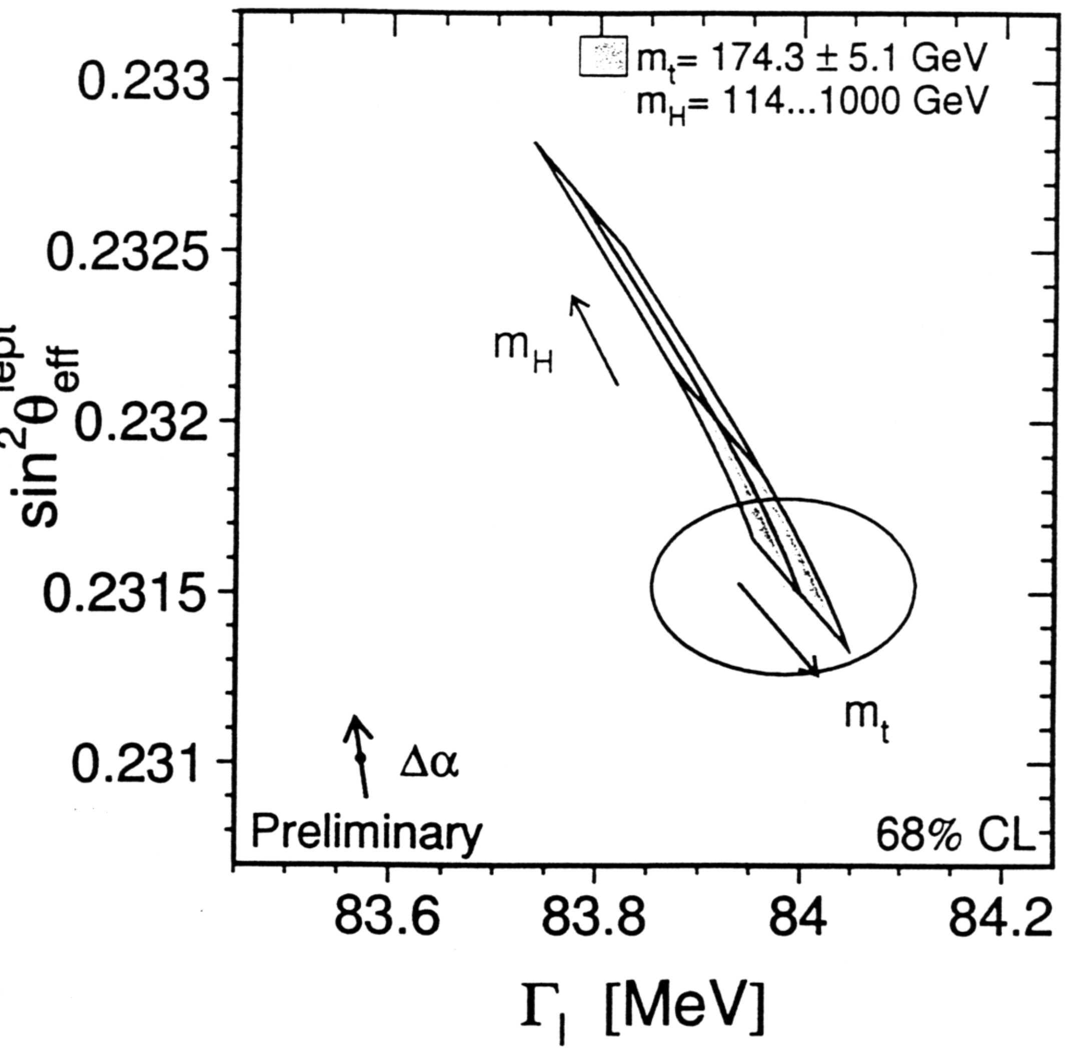
Bardin, Riemann, ... — Dubna, Zeuther

enstanden in > 10 Jahren Zusammenarbeit
mit Beiträgen von

Passarino, ...	Torino
WH, Kühn, Chetyrkin, ...	KA
Steinhauser	KA / HH
Kniehl	HH
Jegerlehner, ...	Zeuthen
Barbieri, --	Pisa
Degrassi, ...	Padova
Sirlin	New York
⋮	

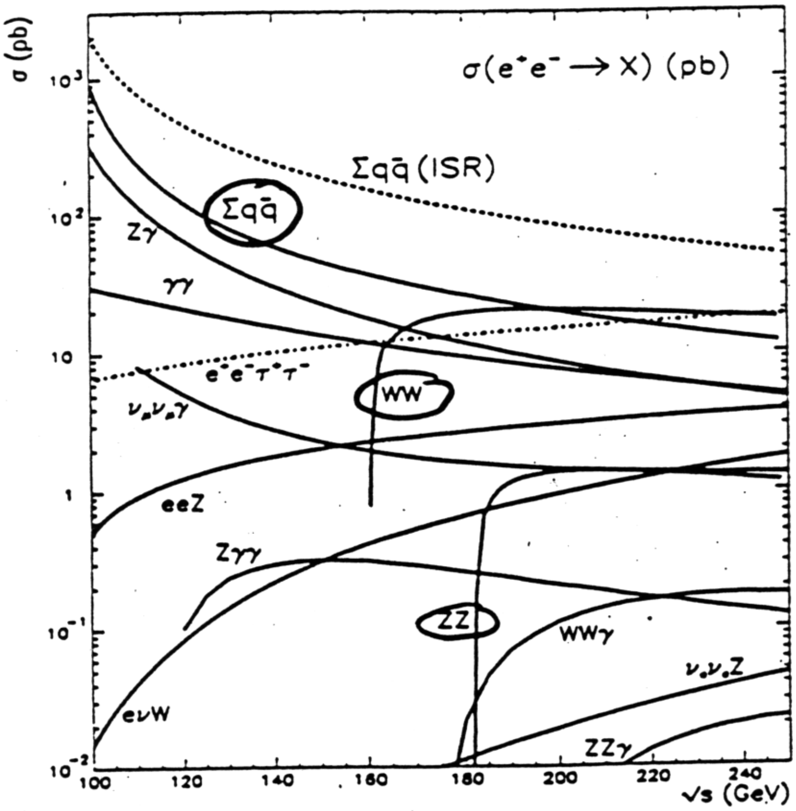
at work:

Freitas, Walter, Weiglein, WH

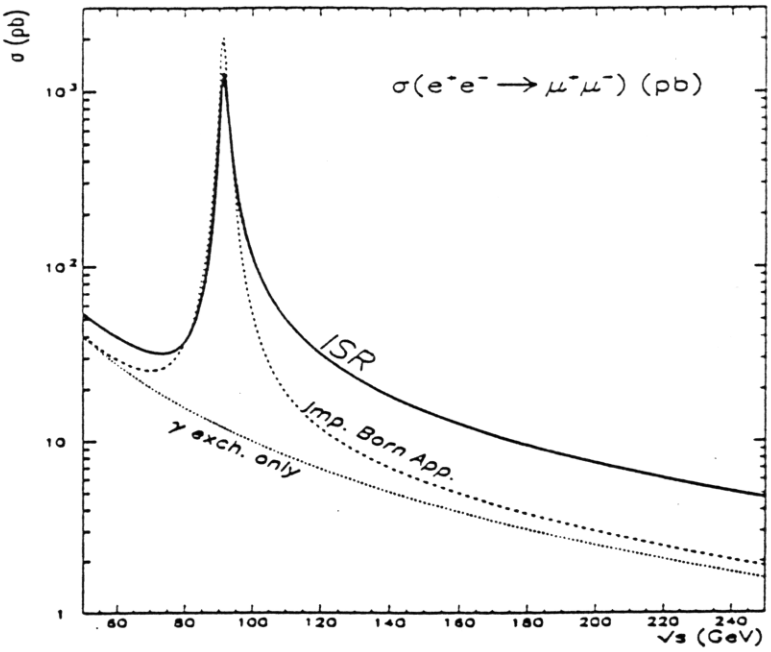


m_t= 174.3 ± 5.1 GeV
m_H= 114...1000 GeV
0.233
0.2325
0.232
0.2315
0.231
sin²θ_eff^lept
m_H
m_t
Δα
Preliminary
68% CL
83.6
83.8
84
84.2
Γ_l [MeV]

Above the Z resonance



$e^+e^- \to f\bar{f}$ above the Z



CERN 96-01
"LEP200 Report"

Boudjema,
Mele et al.
"Standard model processes"

- one of the dominant processes at LEP

  $\sigma_{had} > \sigma_{WW}$

- observables measureable with good precisio
  - 0.7 % for σ_{had}
  - 1.2 % for $\sigma_{\mu\mu}$

- box diagrams are important

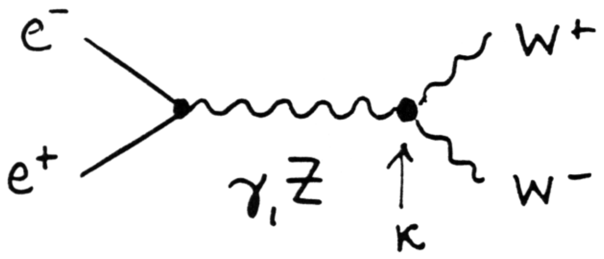
  Bardin, W.H., Passarino

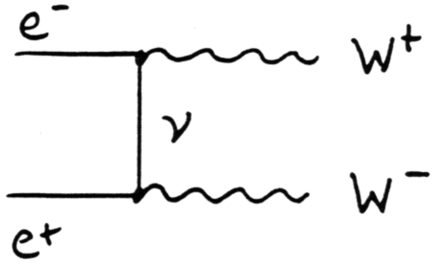
  

- large QED corrections
  initial state radiation → tail effect

- theoretical precision ~ 0.5 % required
  under control ZFITTER, TOPAZ0, KORALZ

$e^+e^- \longrightarrow W^+W^-$

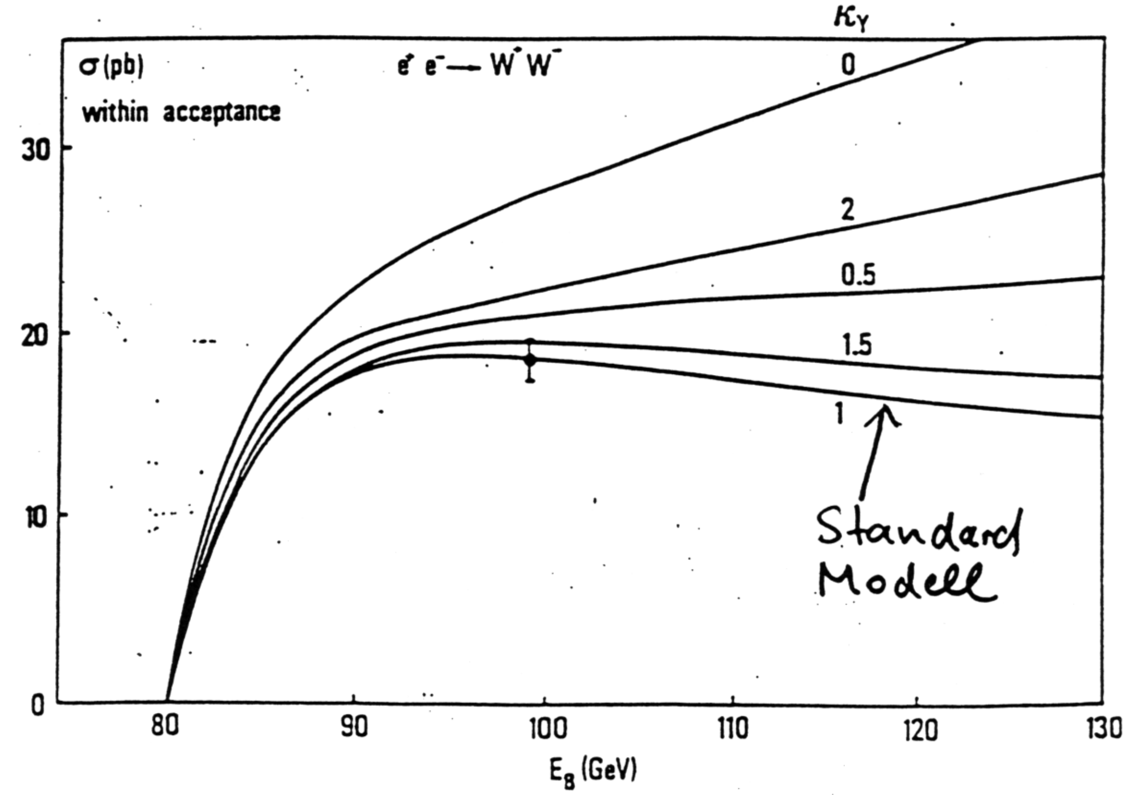




(i) precise measurement of M_W

$\Delta M_W \simeq 40$ MeV

(ii) test of trilinear coupling



$WW\gamma/Z$ triple couplings

$$\mathcal{L}_{WW\gamma/Z} =$$

$$e \Big\{ (\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) W^{-\mu} \underline{A}^\nu$$

$$+ \kappa_\gamma \, W_\mu^+ W_\nu^- \, \underline{F}^{\mu\nu}$$

$$+ \frac{\lambda_\gamma}{M_W^2} \, W^+_{\rho\mu} W^{-\mu}{}_\nu \, \underline{F}^{\rho\nu} \quad + \quad h.c. \Big\}$$

$$+ \, e \cot\theta_W \Big\{ (\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) W^{-\mu} \underline{Z}^\nu$$

$$+ \kappa_Z \, W_\mu^+ W_\nu^- \, \underline{Z}^{\mu\nu}$$

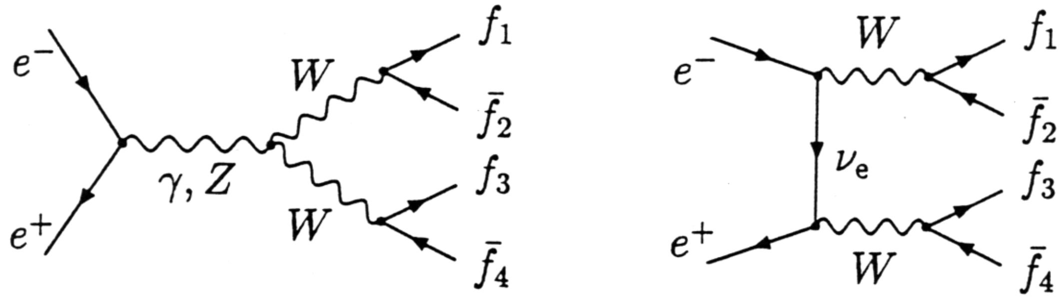
$$+ \frac{\lambda_Z}{M_W^2} \, W^+_{\rho\mu} W^{-\mu}{}_\nu \, \underline{Z}^{\rho\nu} \quad + h.c. \Big\}$$

Standard Model: $\kappa_\gamma = \kappa_Z = 1$

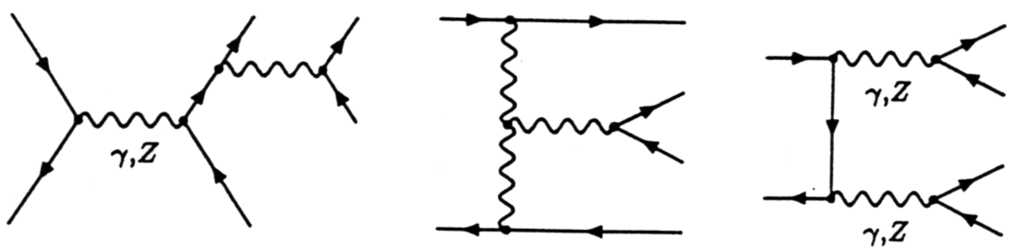
$\lambda_\gamma = \lambda_Z = 0$

Lowest-order four-fermion cross section

Signal diagrams: two resonant W bosons



Background diagrams: at most one resonant W



etc.

Typical size $\approx \frac{\Gamma_W}{M_W} \approx 2.5\%$

Monte Carlo generator RacoonWW

$\mathcal{O}(\alpha)$ corrections with RacoonWW

Denner, Dittmaier, Roth, Wackeroth '99,

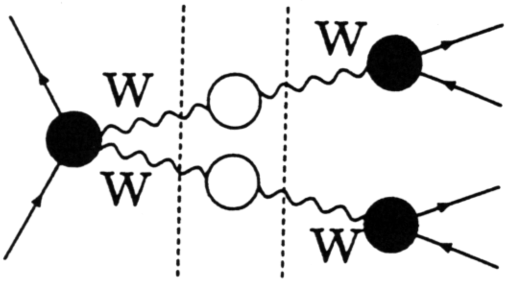
virtual

real

$e^+e^- \to 4f + \gamma$ (tree level):
Full matrix element

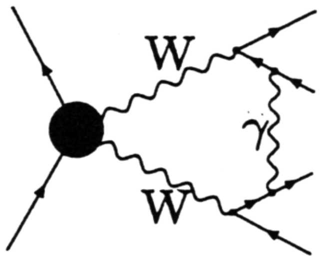
$e^+e^- \to WW \to 4f$ (1 loop):
Double-pole approximation

Factorizable corrections



building blocks:
- W-pair production
- W decay

Non-factorizable corrections



etc.

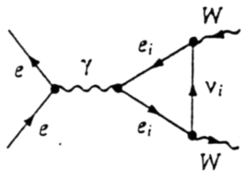
γ-exchange between production- and decay-subprocesses with $E_\gamma \lesssim \Gamma_W$

Würzburg: Böhm, Denner, Sack

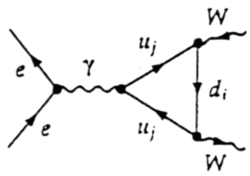
Leiden: Beenakker, Berends, Kuijf

FeynArts 3

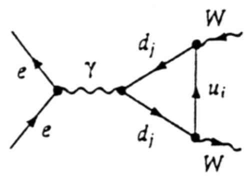
$e^+ e^- \to W^+ W^-$



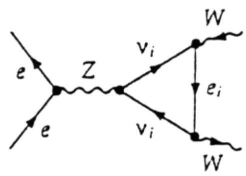
T1 C1 N1



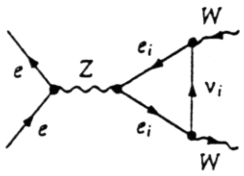
T1 C2 N2



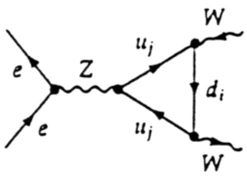
T1 C3 N3



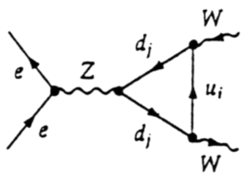
T1 C4 N4



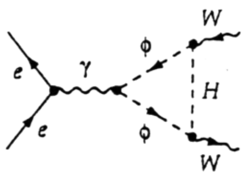
T1 C5 N5



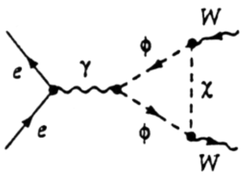
T1 C6 N6



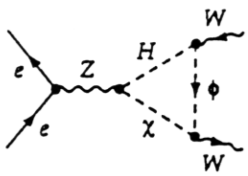
T1 C7 N7



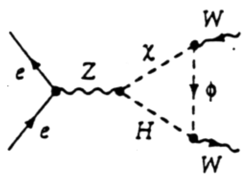
T1 C1 N8



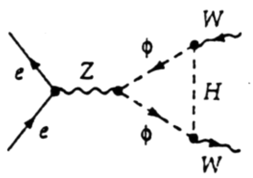
T1 C2 N9



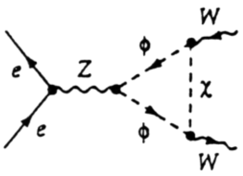
T1 C3 N10



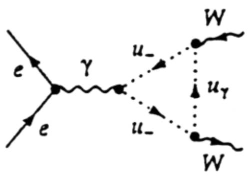
T1 C4 N11



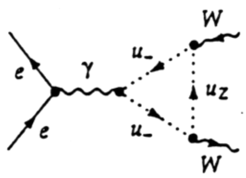
T1 C5 N12



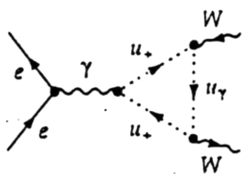
T1 C6 N13



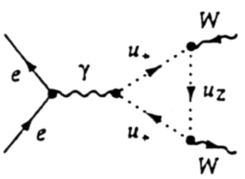
T1 C1 N14



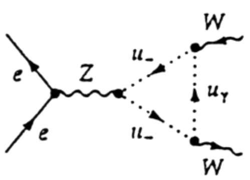
T1 C2 N15



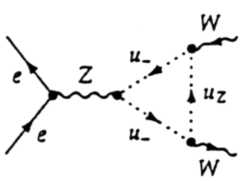
T1 C3 N16



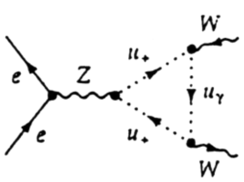
T1 C4 N17



T1 C5 N18

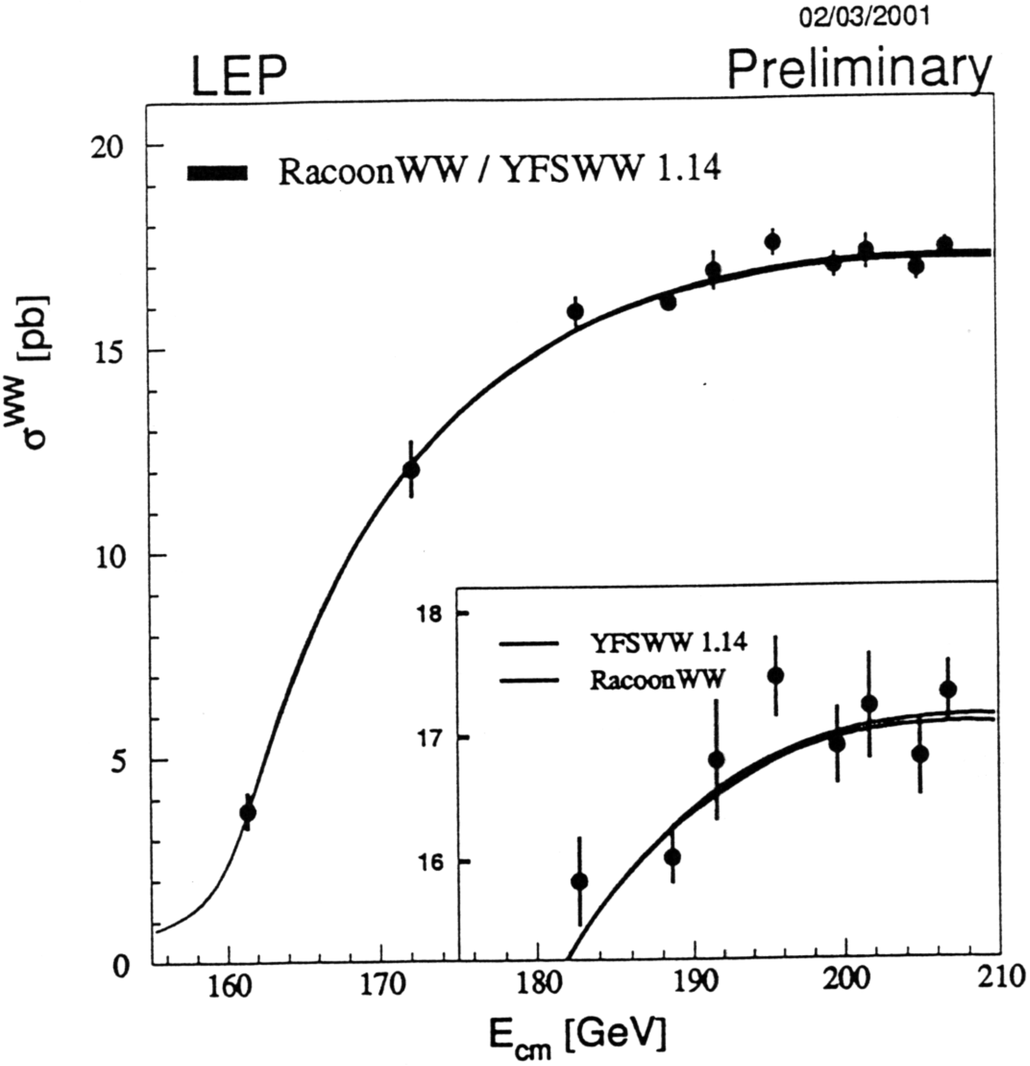


T1 C6 N19



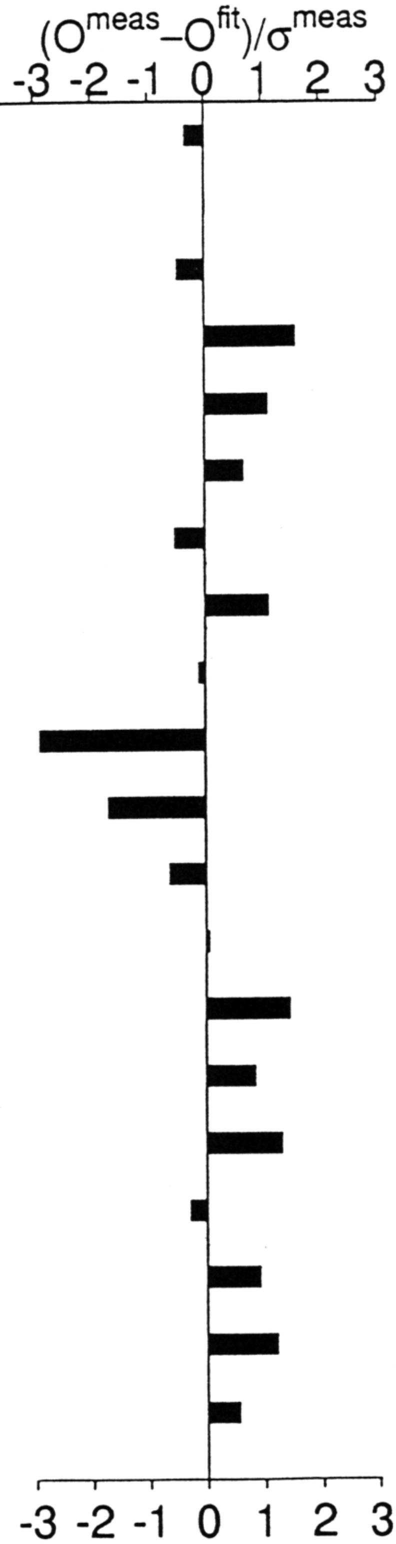
T1 C7 N20

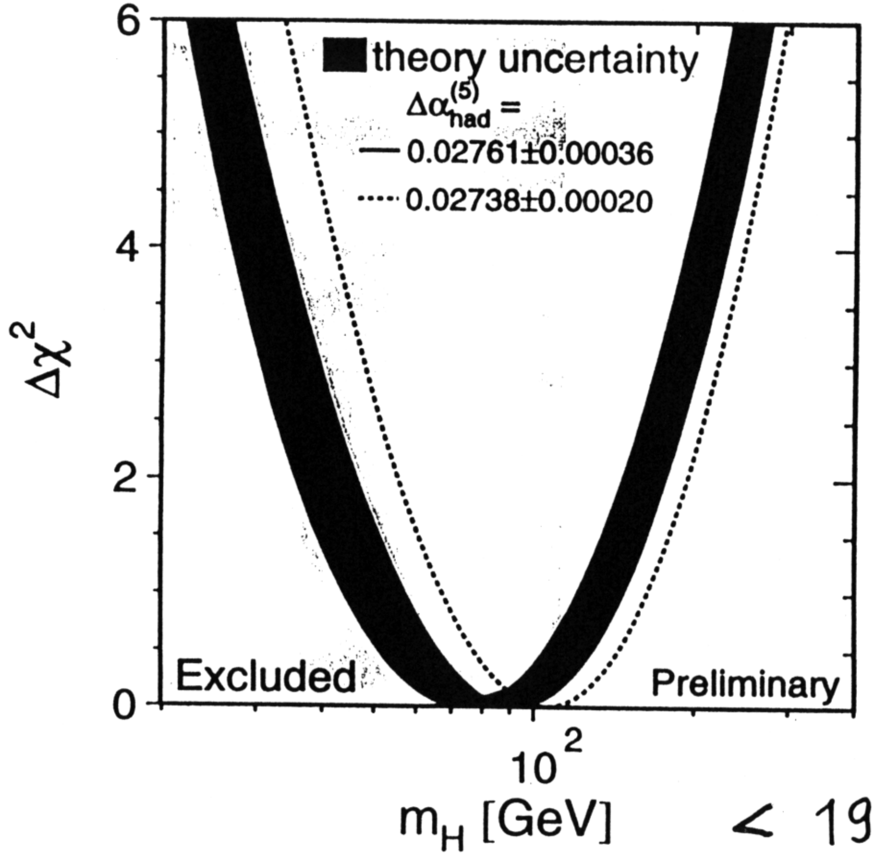
W-pair production at LEP2



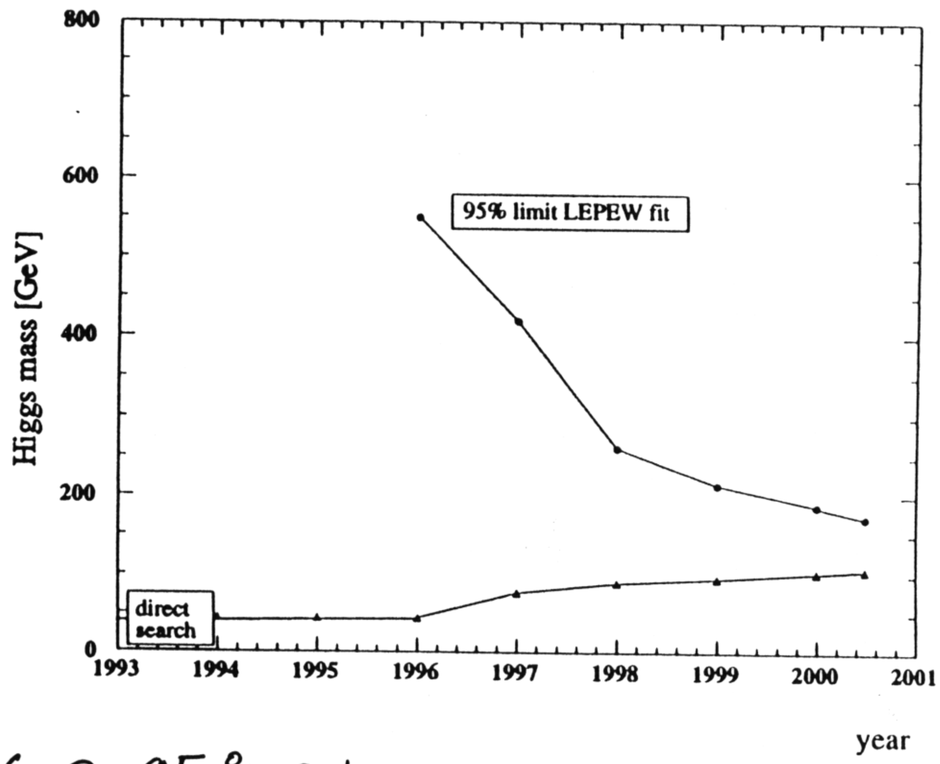
Summer 2001

	Measurement	Pull
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ_{had}^{0} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A_{fb}^{0,l}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A_{fb}^{0,b}$	0.0990 ± 0.0017	-2.90
$A_{fb}^{0,c}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
Q_W(Cs)	-72.50 ± 0.70	.56




theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02761±0.00036
0.02738±0.00020
Excluded
Preliminary
$\Delta\chi^2$
0
2
4
6
10^2
m_H [GeV]

< 196 @ 95% C.L.


95% limit LEPEW fit
direct search
Higgs mass [GeV]
0
200
400
600
800
1993
1994
1995
1996
1997
1998
1999
2000
2001
year

Hambye, Riesselmann