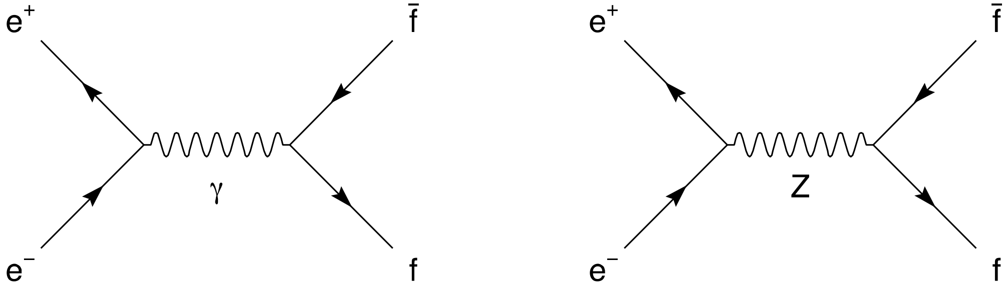
# 11. Experimentelle Tests der elektroschwachen Wechselwirkung

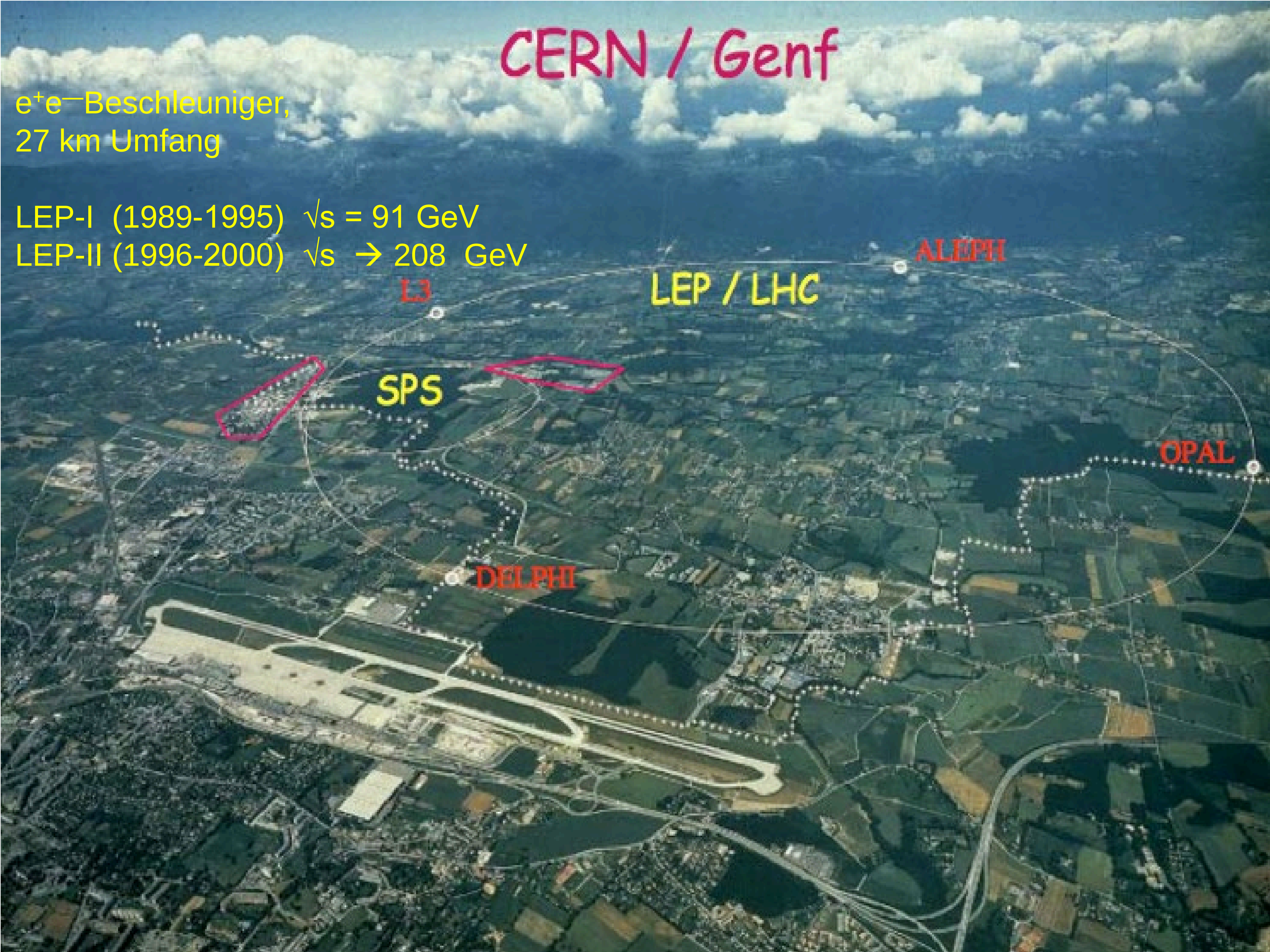
11.1 Fermi-Theorie der schwachen Wechselwirkung im Grenzfall niedriger Energie

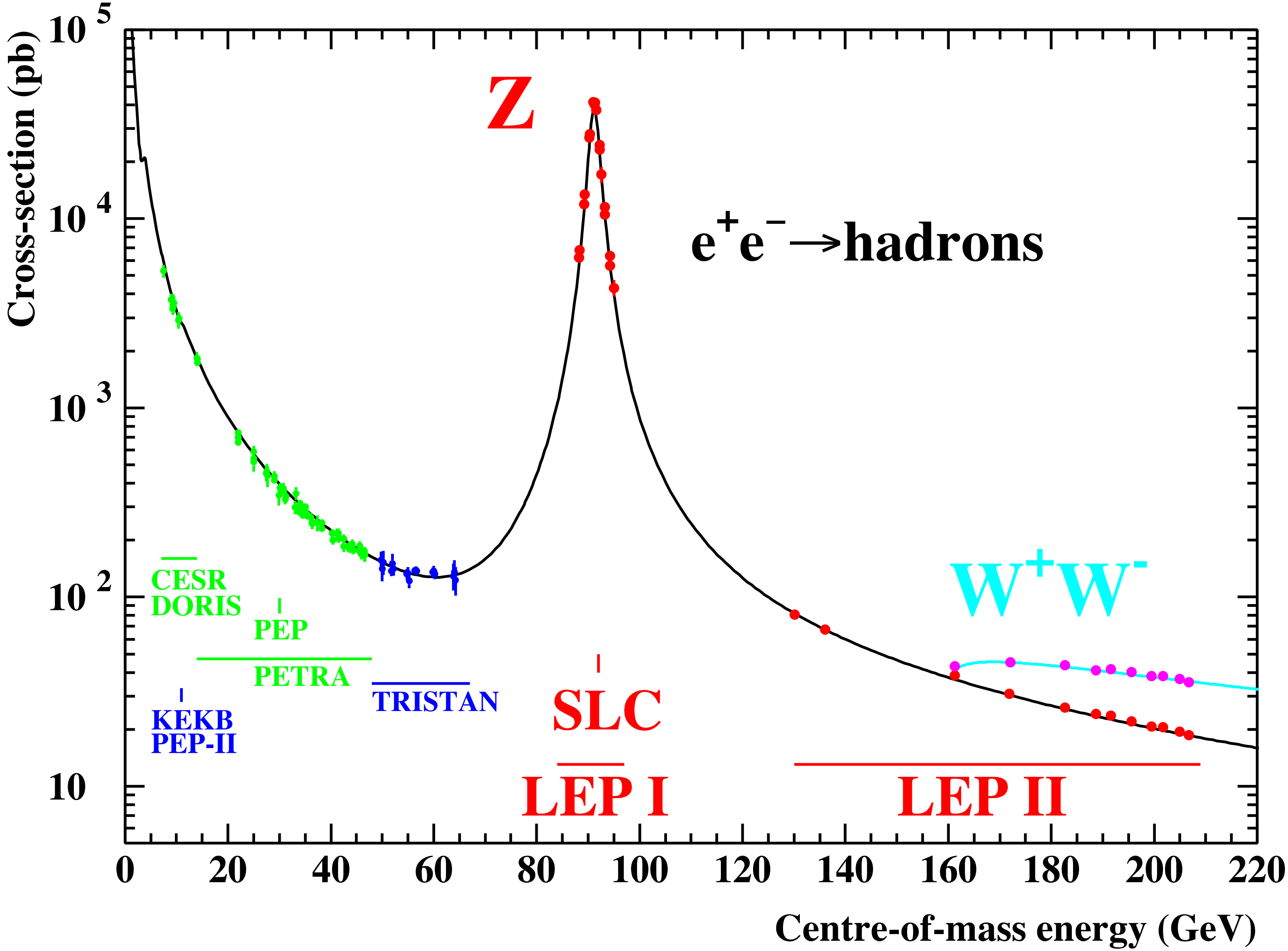
11.2 Elektroschwache Vereinheitlichung (Glashow, Salam, Weinberg)

11.3 Vorhersagen der elektroschwachen Theorie

11.4 Test der elektroschwachen Theorie bei LEP

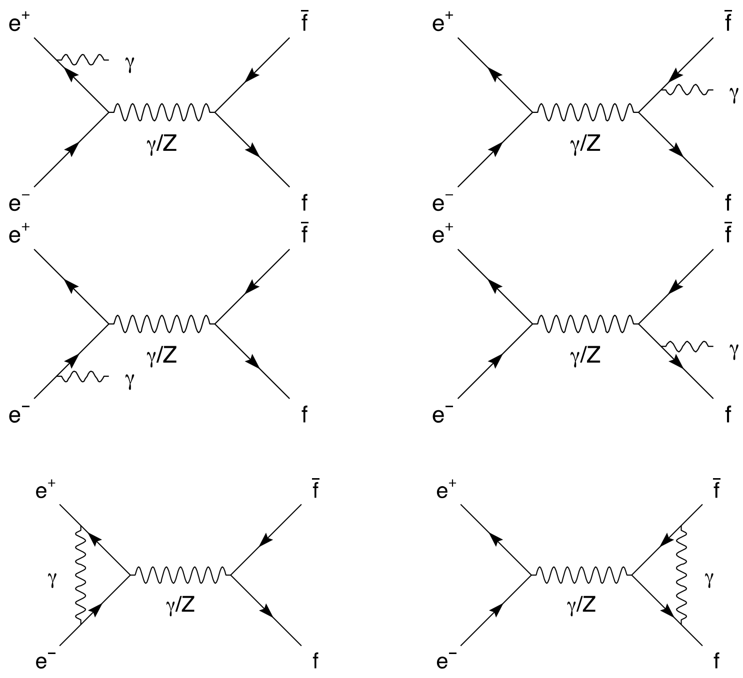


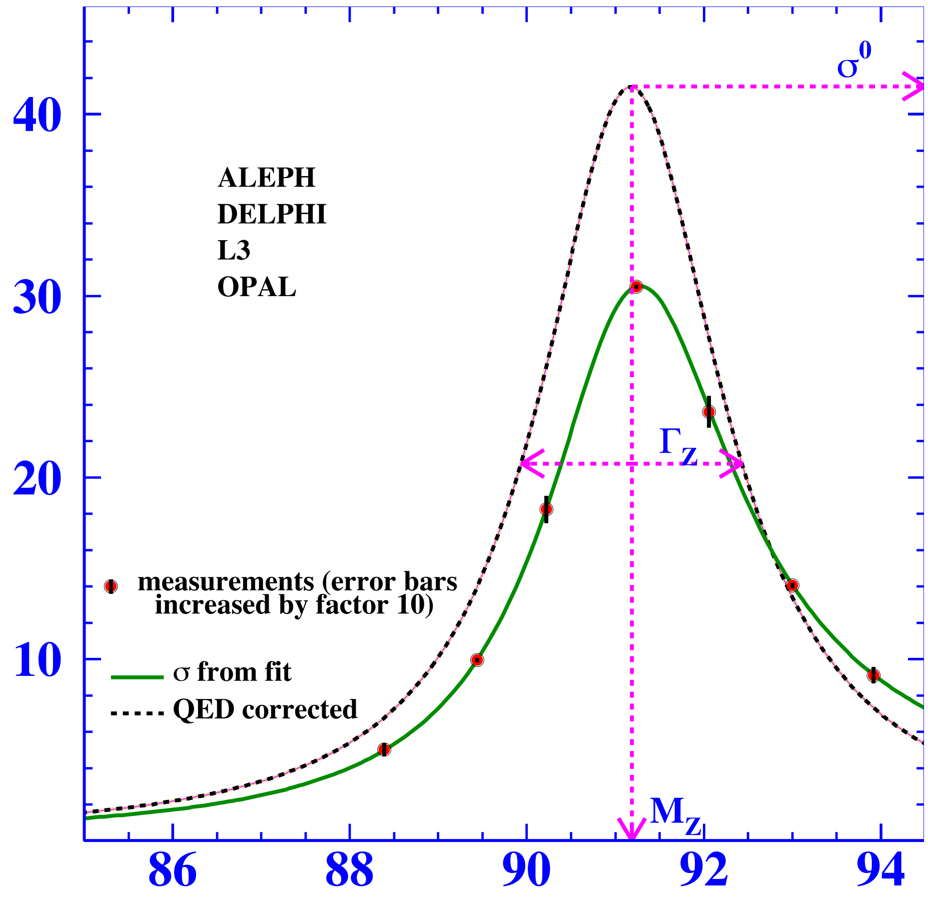

CERN / Genf
$e^+e^-$–Beschleuniger,
27 km Umfang
LEP-I (1989-1995) $\sqrt{s}$ = 91 GeV
LEP-II (1996-2000) $\sqrt{s}$ → 208 GeV
ALEPH
L3
LEP / LHC
SPS
OPAL
DELPHI



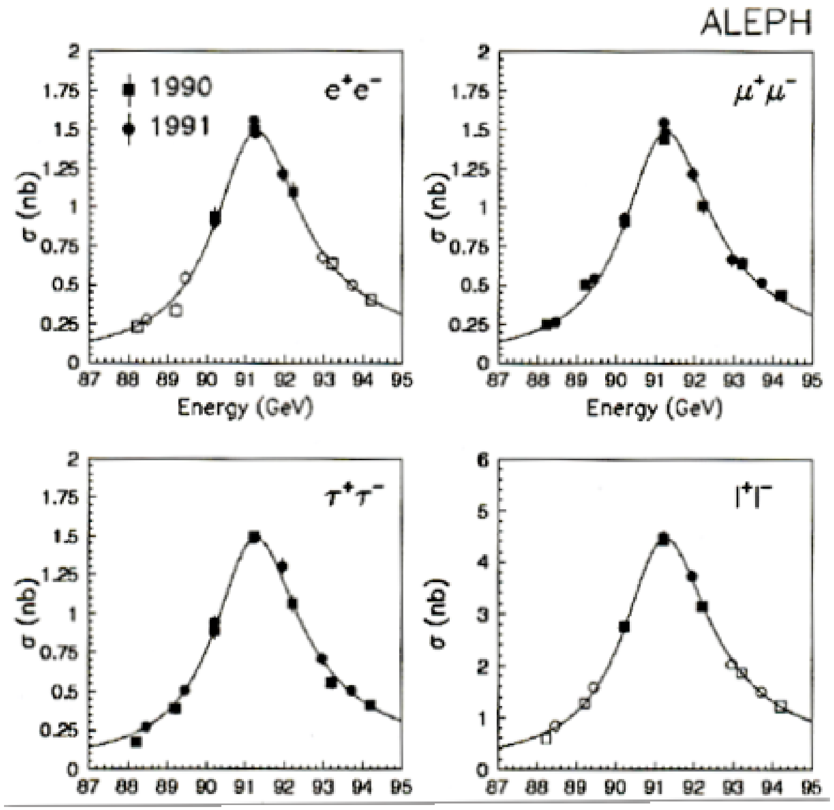
Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
e+e-→hadrons
W+W-
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

# Effects of radiative corrections (photon radiation, processes of higher order)

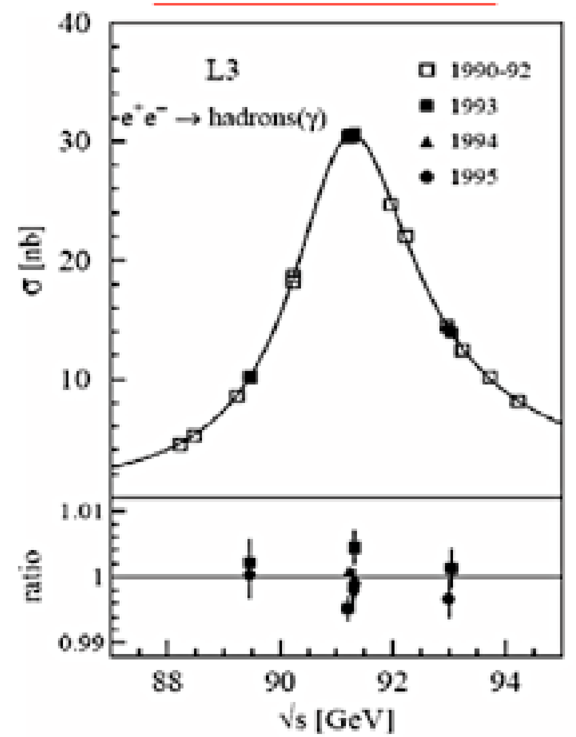


# Lepton-Universalität




# Hadronischer Wirkungsquerschnitt




Quark-Flavor i.a. nicht exp. trennbar
(Ausnahme: c,b → Lebendsdauer)
⇒ had. Breite: $\Gamma_{had} = \Gamma_u+\Gamma_d+\Gamma_s+\Gamma_c+\Gamma_b$

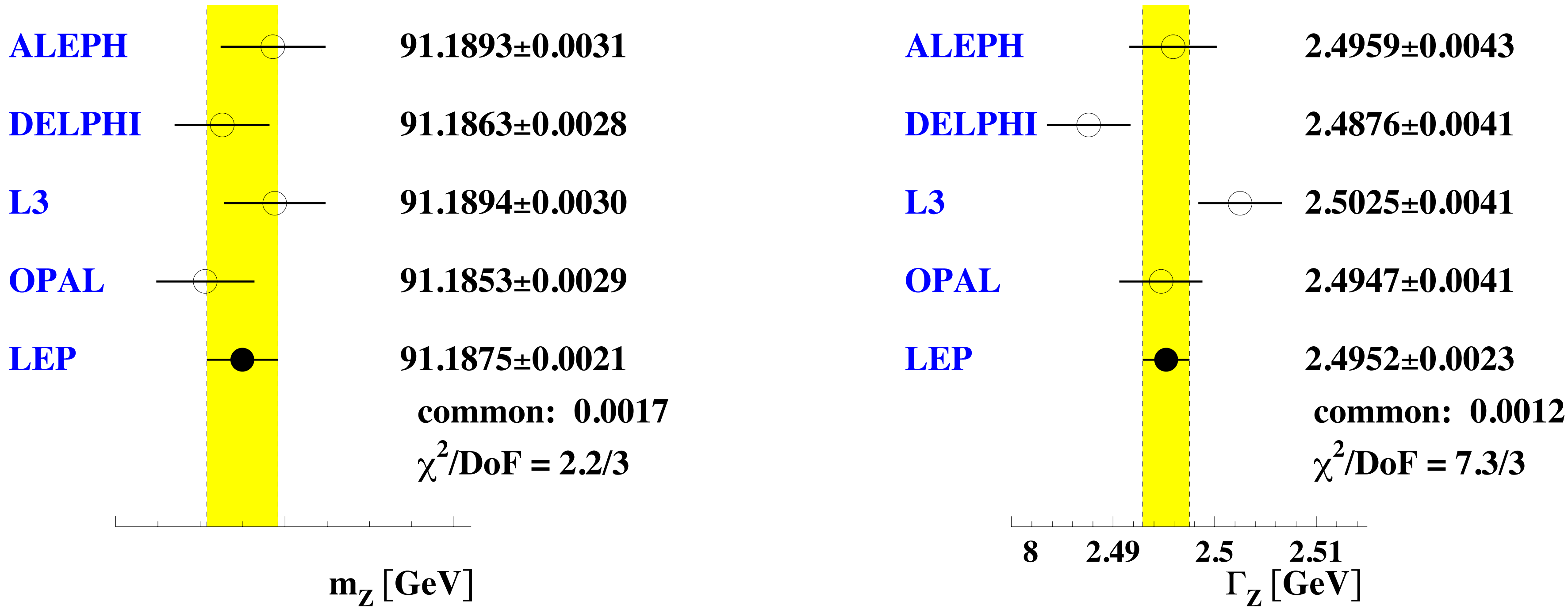
Messe Verhältnisse der Pol-WQ:

$$R_l^0 \equiv \frac{\Gamma_{had}}{\Gamma_{ll}} \qquad l = e, \mu, \tau$$

$$R_q^0 \equiv \frac{\Gamma_{qq}}{\Gamma_{had}} \qquad q = b, c$$

- Keine Unterschiede für verschiedene Leptonarten
  → Lepton-Universalität
- Form der Resonanzkurve für alle Endzustände gleich

# Gemessene Parameter des Z-Bosons




$$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

## Parameter der Z-Resonanzkurve

$m_Z = 91.1875 \pm 0.0021$ GeV ($\pm$23 ppm (*))

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

$\Gamma_{had} = 1.7458 \pm 0.0027$ GeV

$\Gamma_e = 0.08392 \pm 0.00012$ GeV

$\Gamma_\mu = 0.08399 \pm 0.00018$ GeV

$\Gamma_\tau = 0.08408 \pm 0.00022$ GeV

$\pm$0.09 %

3 leptons are treated independently

test of lepton universality

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

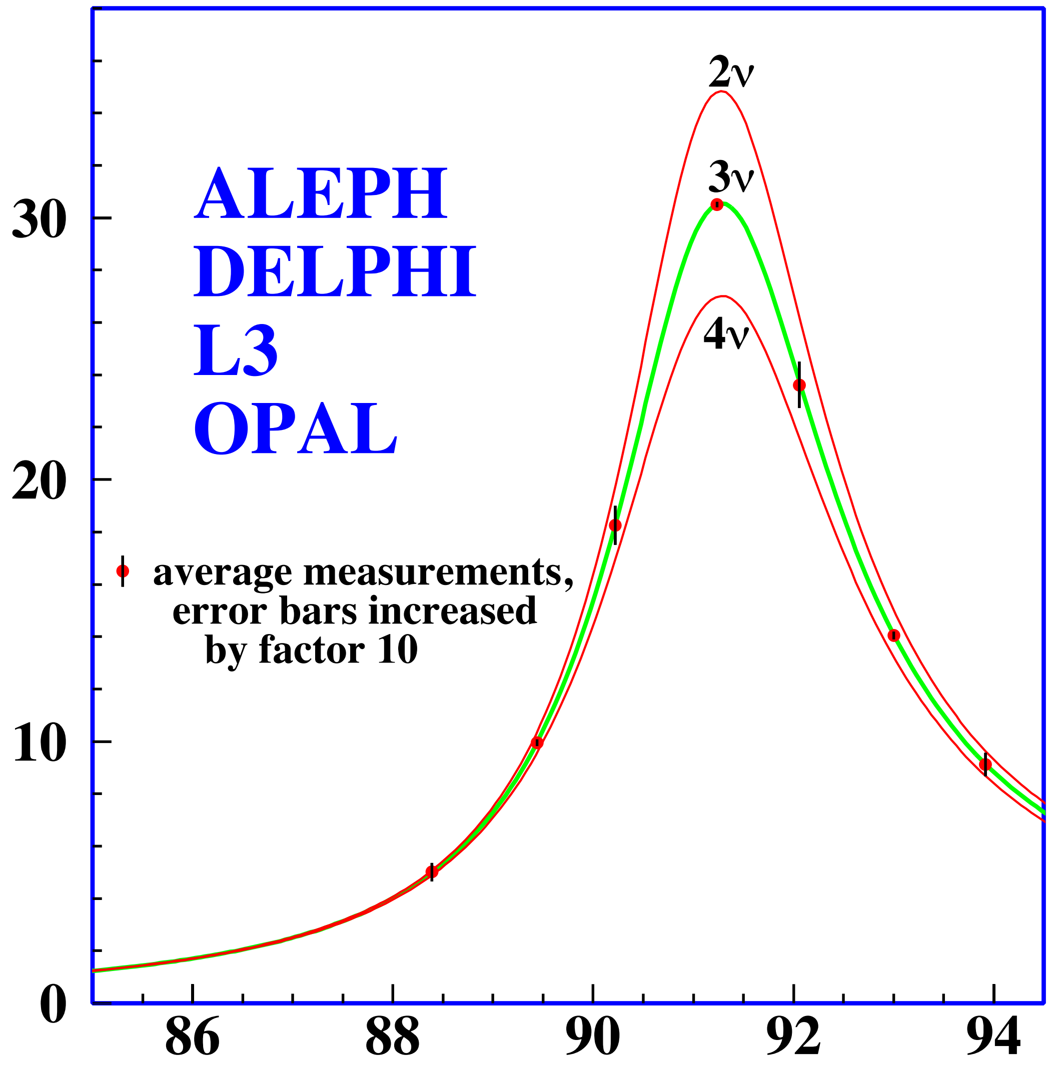
$\Gamma_{had} = 1.7444 \pm 0.0022$ GeV

$\Gamma_e = 0.083985 \pm 0.000086$ GeV

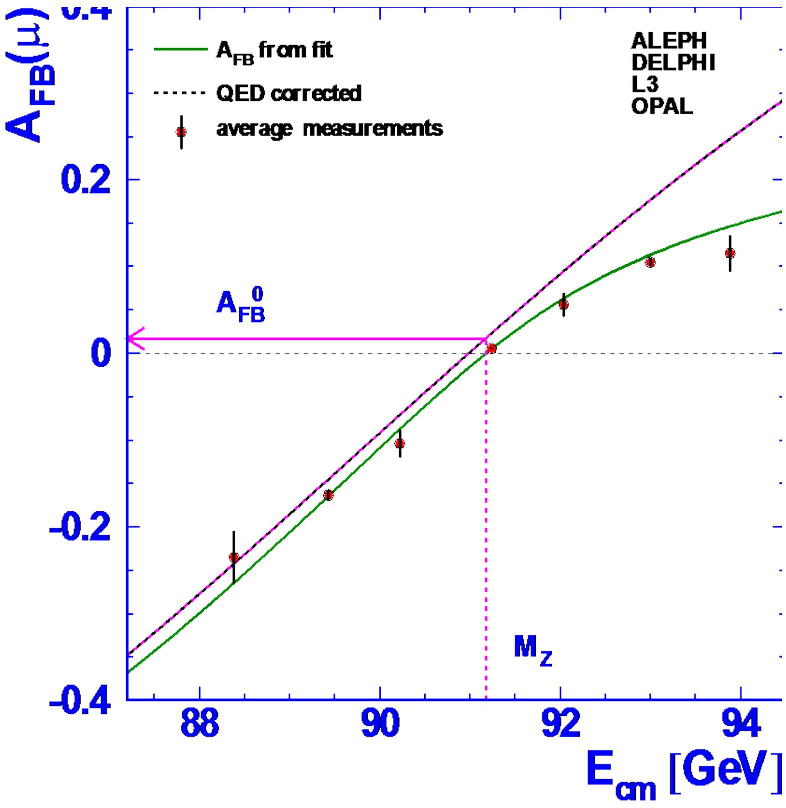
Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$

*) error of the LEP energy determination: $\pm$1.7 MeV (19 ppm)

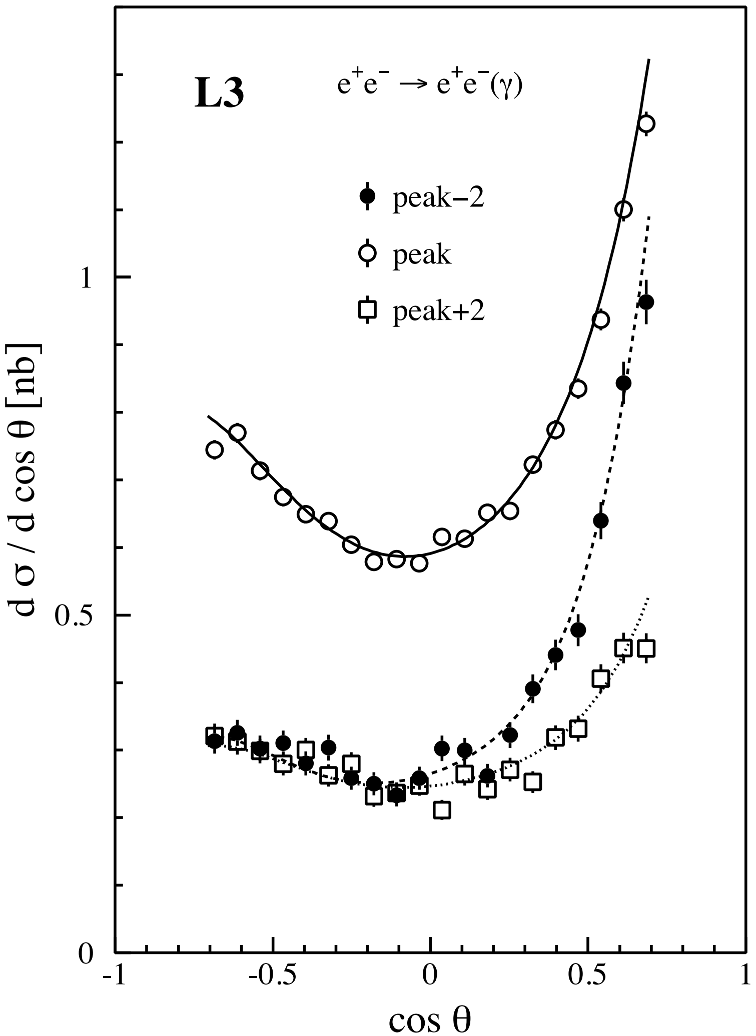
# Messung der Zahl der Neutrinos

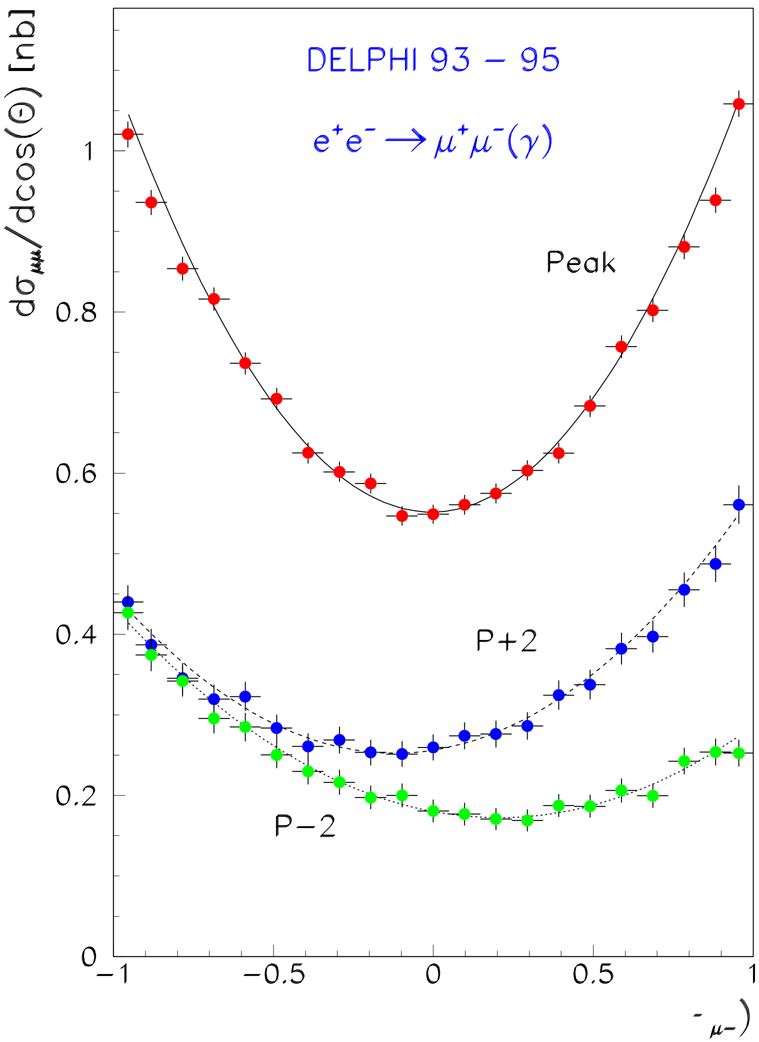


# Vorwärts- Rückwärts-Asymmetrien

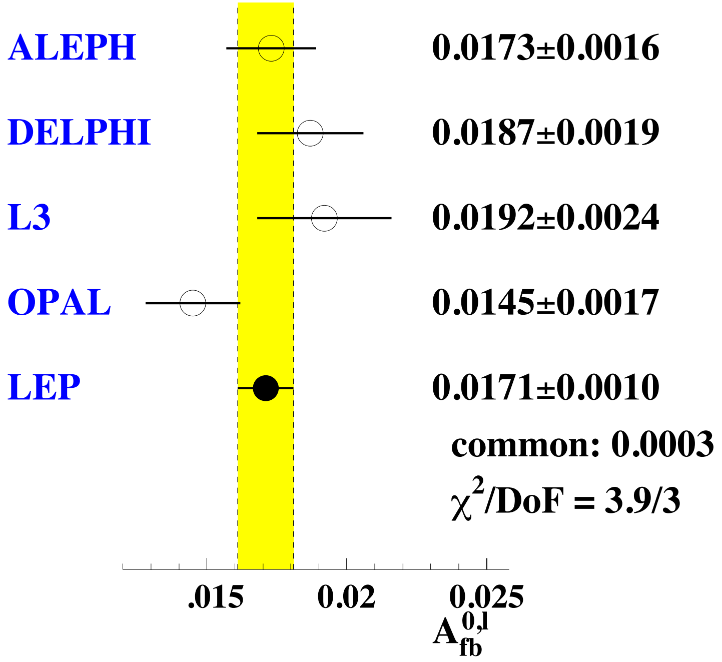


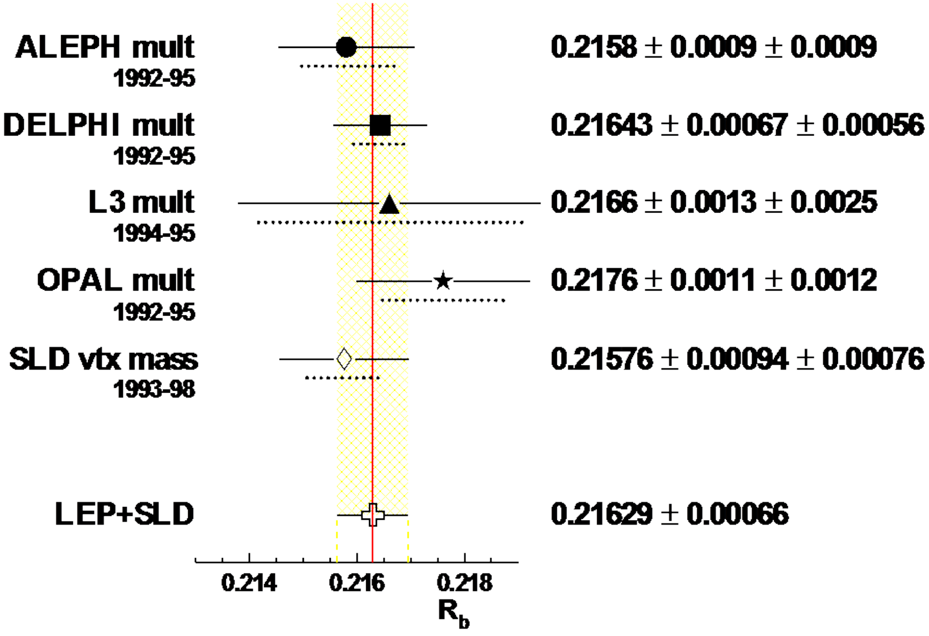
# cos θ- Abhängigkeit des Wirkungsquerschnitts



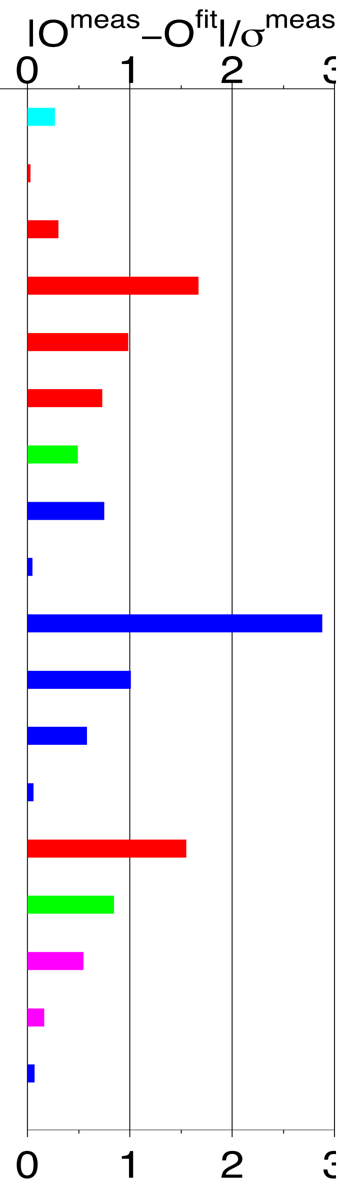
# Gemessene Parameter des Z-Bosons



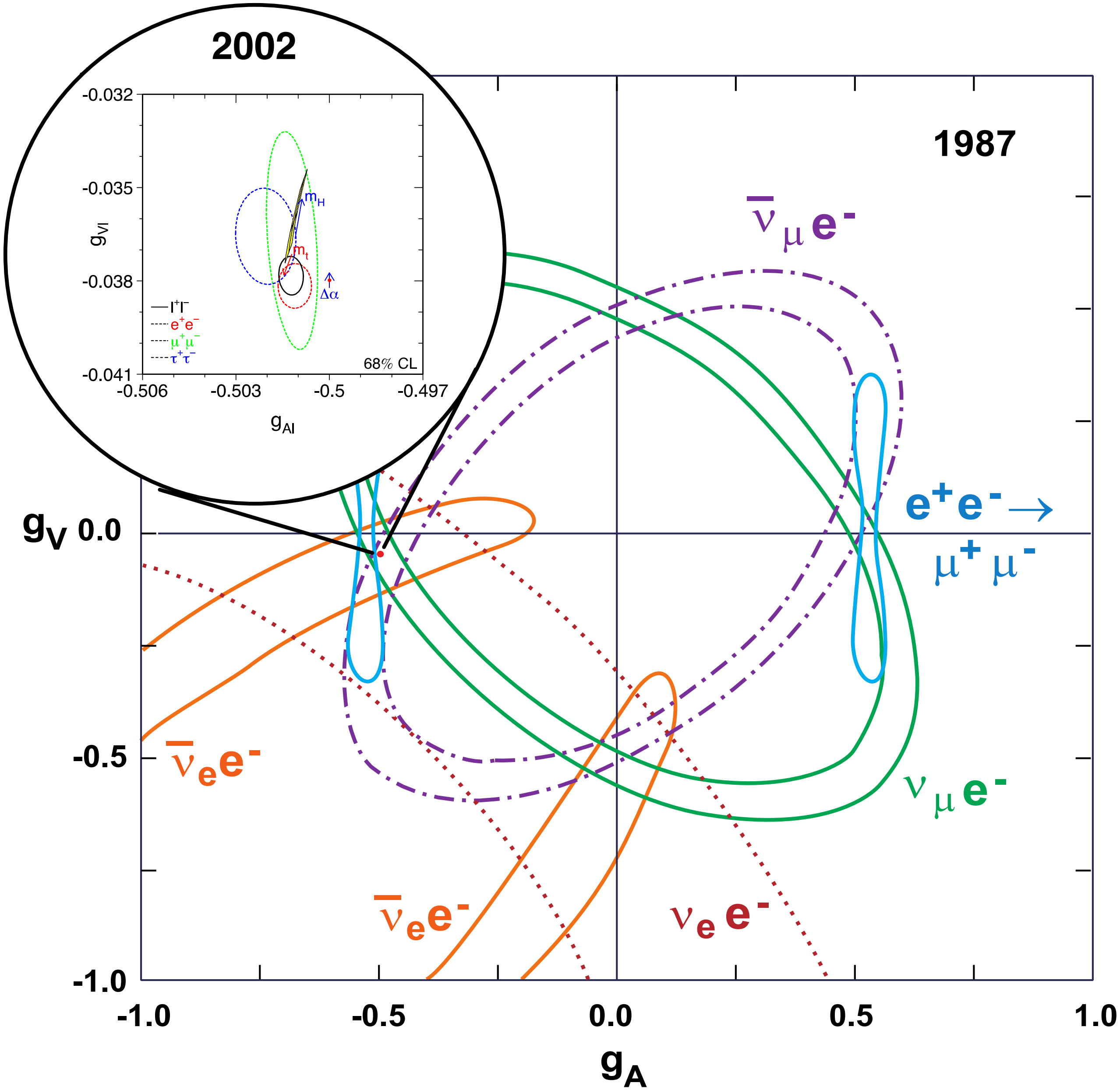
# LEP-Messungen im Vergleich zu den Vorhersagen des Standardmodells

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02750 ± 0.00033 | 0.02759 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^0$ [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 |
| $\Gamma_W$ [GeV] | 2.085 ± 0.042 | 2.092 |
| $m_t$ [GeV] | 173.20 ± 0.90 | 173.26 |

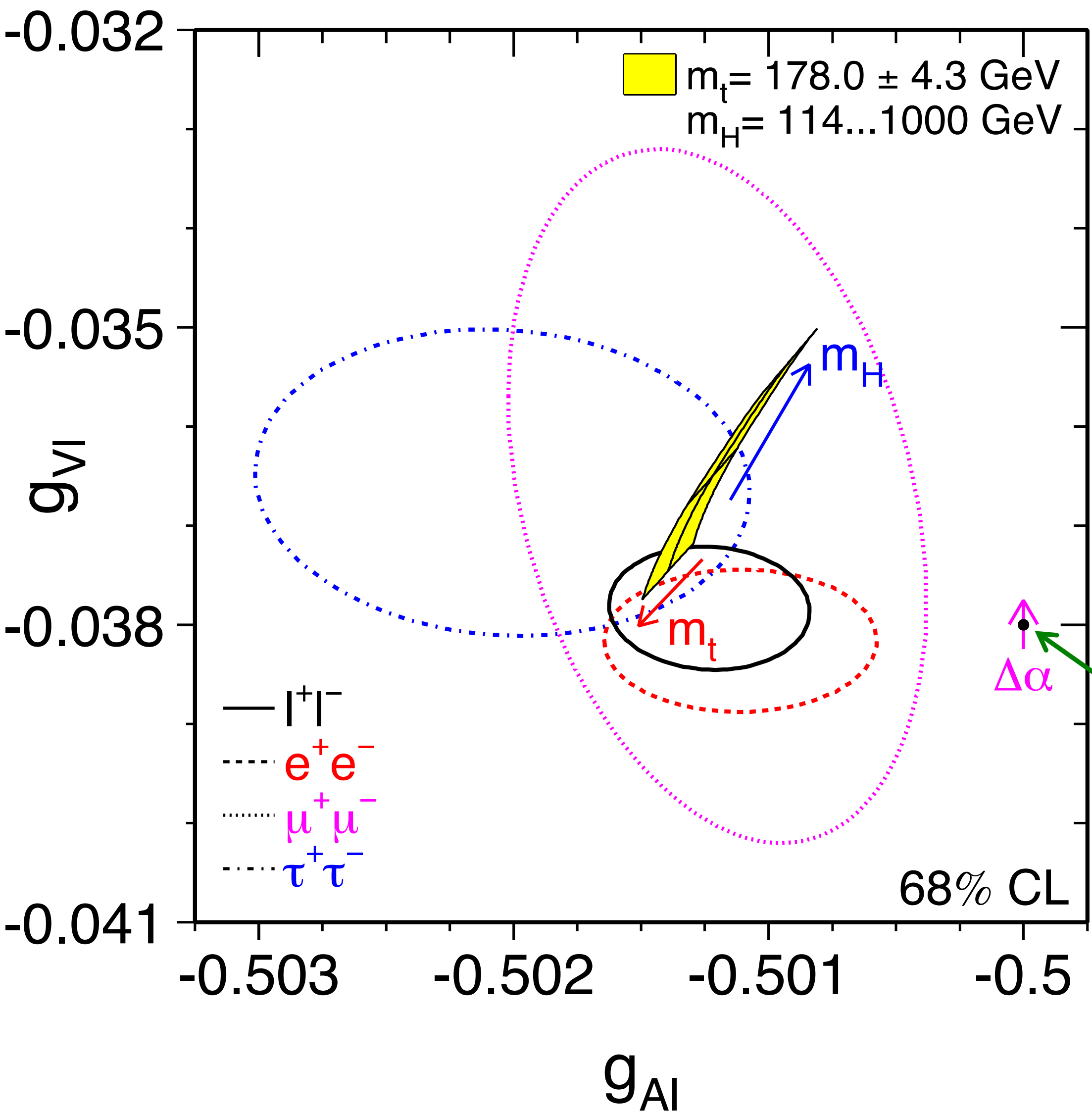



March 2012

# Fortschritte in den Messungen der elektroschwachen Kopplungen

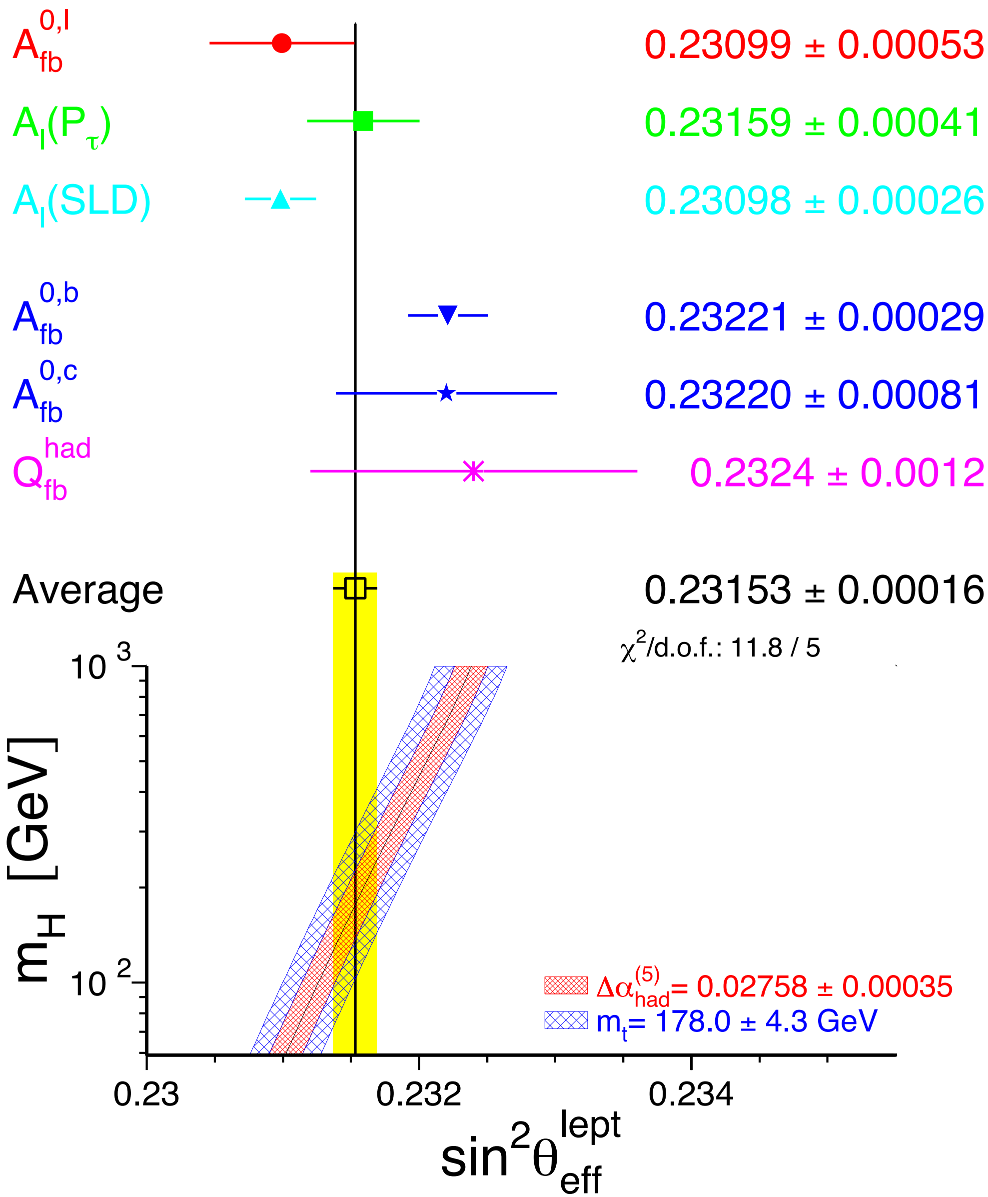


# Fortschritte in den Messungen der elektroschwachen Kopplungen

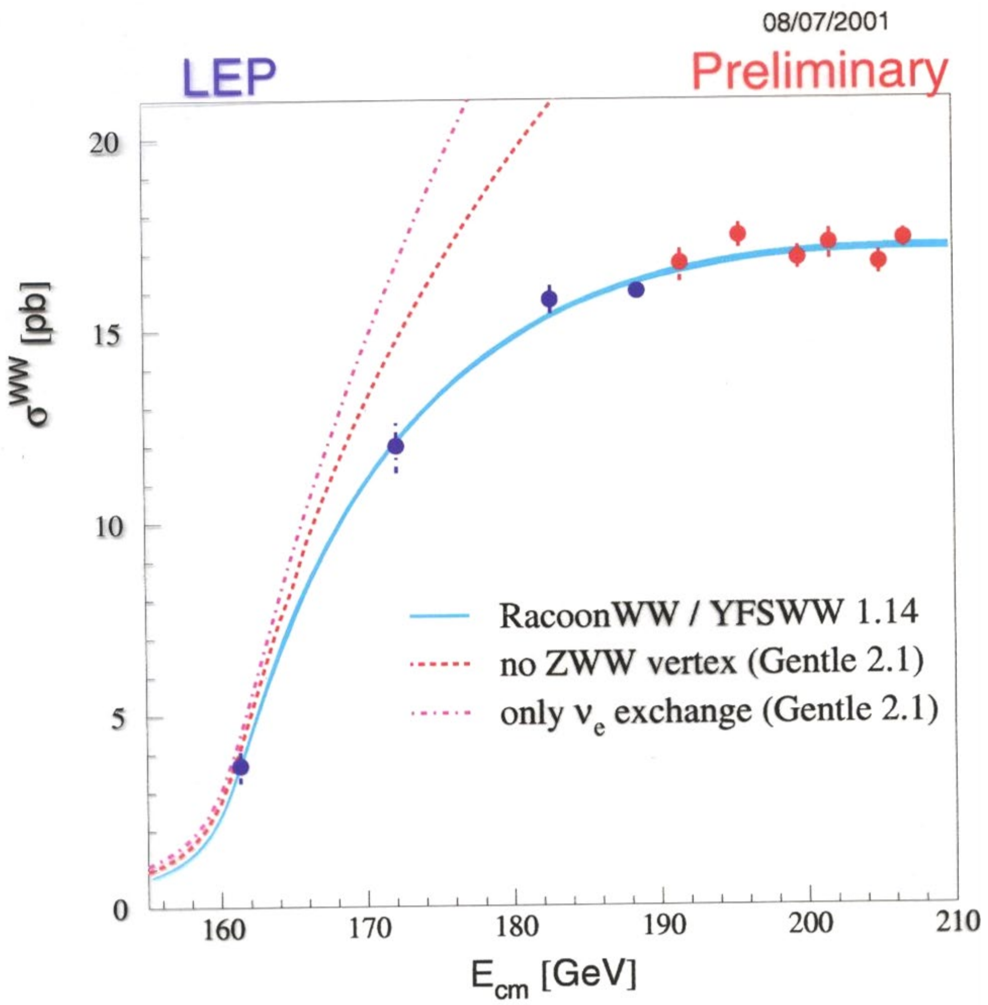



Standardmodell-Vorhersage
ohne Quantenkorrekturen:
$g_A = T_3$
$g_V = T_3 - 2\,Q\,\sin^2\theta_W$

# Messungen des schwachen Mischungswinkels



# Wirkungsquerschnitt für die W-Paarproduktion, LEP-II



# Precision measurements of $m_W$ and $m_{top}$

Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between $m_W$, $m_t$ and $m_H$

Electromagnetic constant measured in atomic transitions, $e^+e^-$ machines, etc.

$$m_W = \left( \frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Fermi constant measured in muon decay

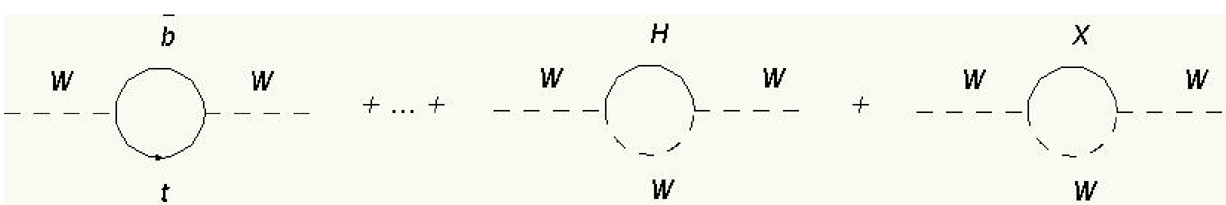
weak mixing angle measured at LEP/SLC

radiative corrections
$\Delta r \sim f\,(m_{top}^2, \log m_H)$
$\Delta r \approx 3\%$

$G_F$, $\alpha_{EM}$, $\sin\theta_W$

are known with high precision

Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory, radiative corrections)

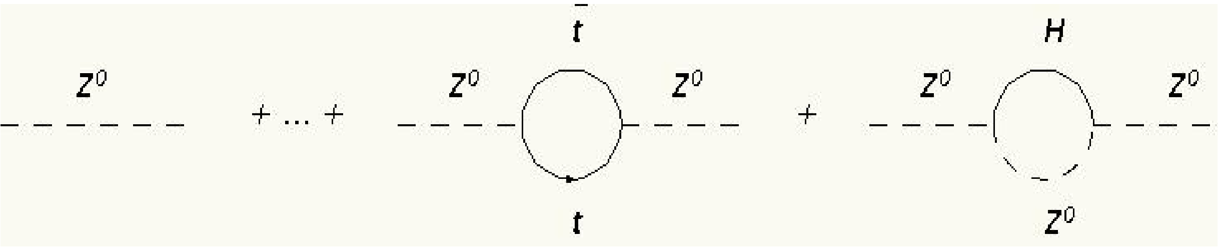


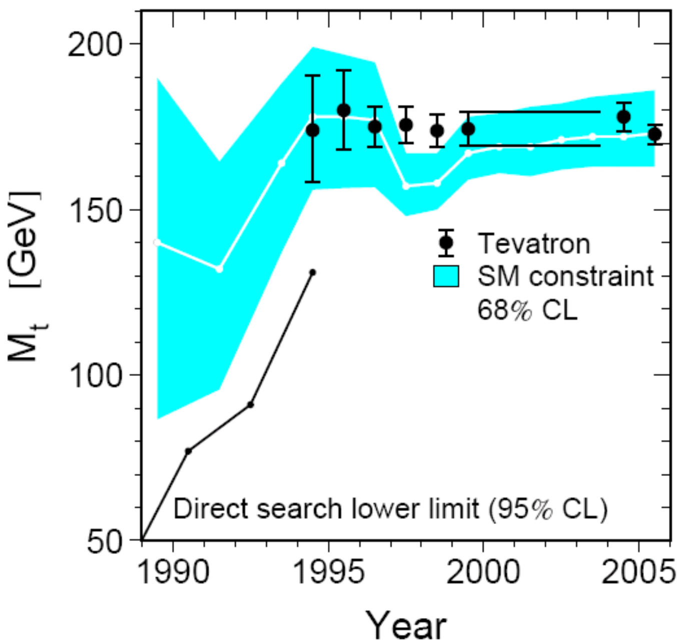
## Indirekte Grenzen (aus Präzisionsmessungen):

- Im Standardmodell sind alle Wechselwirkungen der Teilchen untereinander (Kopplungsstärken) exakt festgelegt

- In der Quantenfeldtheorie müssen auch Quantenkorrekturen in der Berechnung von Streuprozessen, Massen, .... etc. berücksichtigt werden. Hierbei treten Beiträge von sog. virtuellen Teilchen auf, d.h. Teilchen machen sich bereits weit unterhalb ihrer Energie/Massenskala bemerkbar.

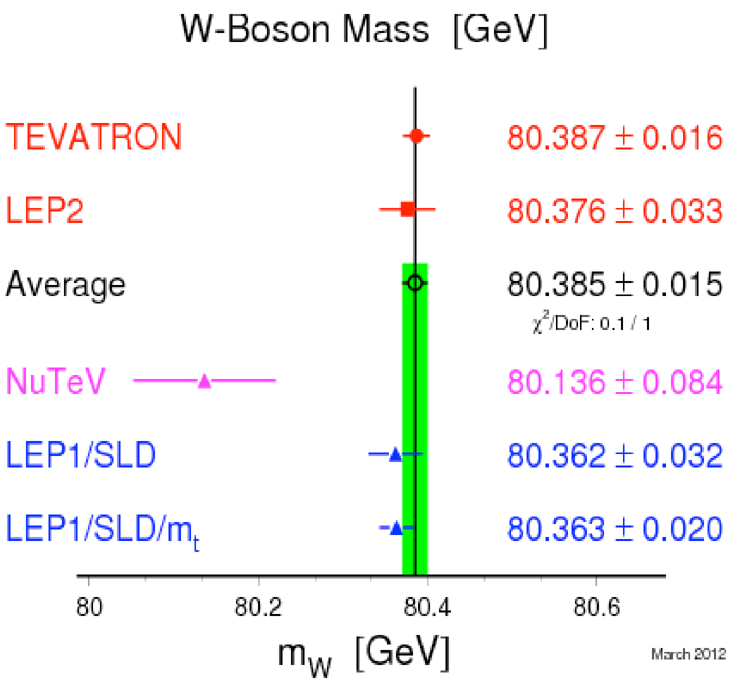
Beispiel: Einfluss des Top-Quarks auf die $Z^0$-Masse (LEP, 1990er Jahre)

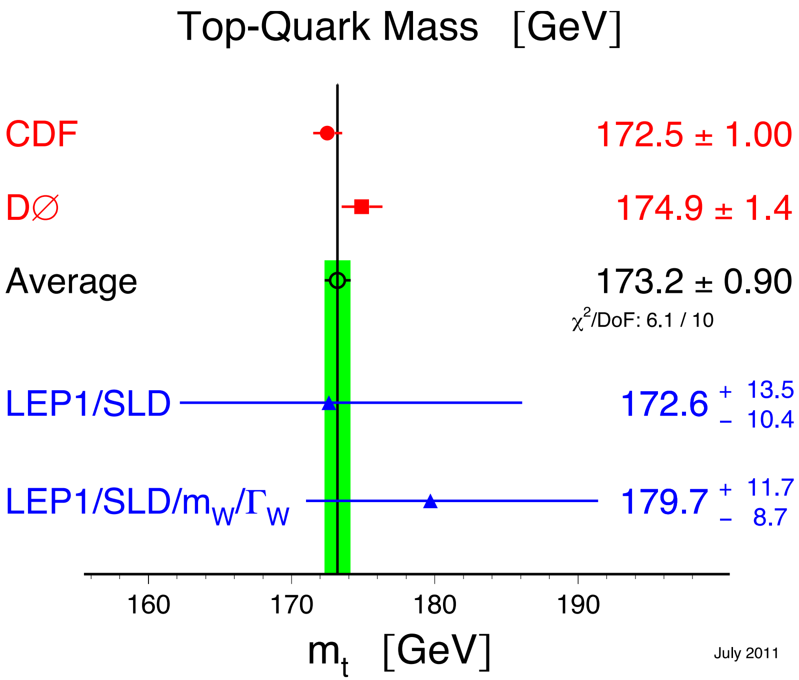


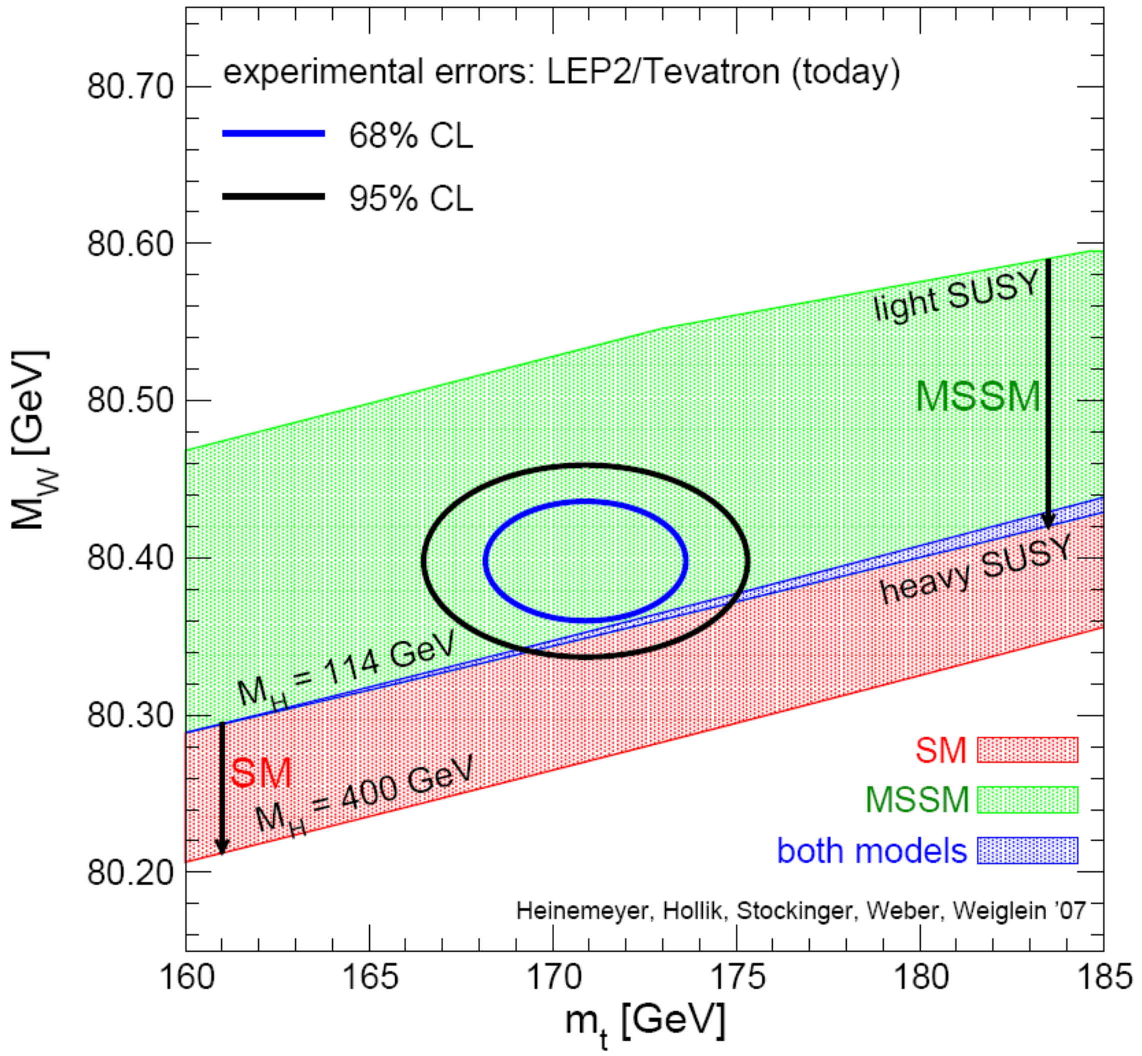




$$m_Z^2 = m_Z^2(0) \cdot (1 + \Delta(m_t, m_H, ...))$$

$$\Delta = .... + c_1 \cdot m_t^2 + .... + c_2 \cdot \ln m_H + ....$$


W-Boson Mass [GeV]
TEVATRON
80.387 ± 0.016
LEP2
80.376 ± 0.033
Average
80.385 ± 0.015
χ²/DoF: 0.1 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.362 ± 0.032
LEP1/SLD/m_t
80.363 ± 0.020
80
80.2
80.4
80.6
m_W [GeV]
March 2012


Top-Quark Mass [GeV]
CDF
172.5 ± 1.00
D∅
174.9 ± 1.4
Average
173.2 ± 0.90
χ²/DoF: 6.1 / 10
LEP1/SLD
172.6 + 13.5 − 10.4
LEP1/SLD/m_W/Γ_W
179.7 + 11.7 − 8.7
160
170
180
190
m_t [GeV]
July 2011

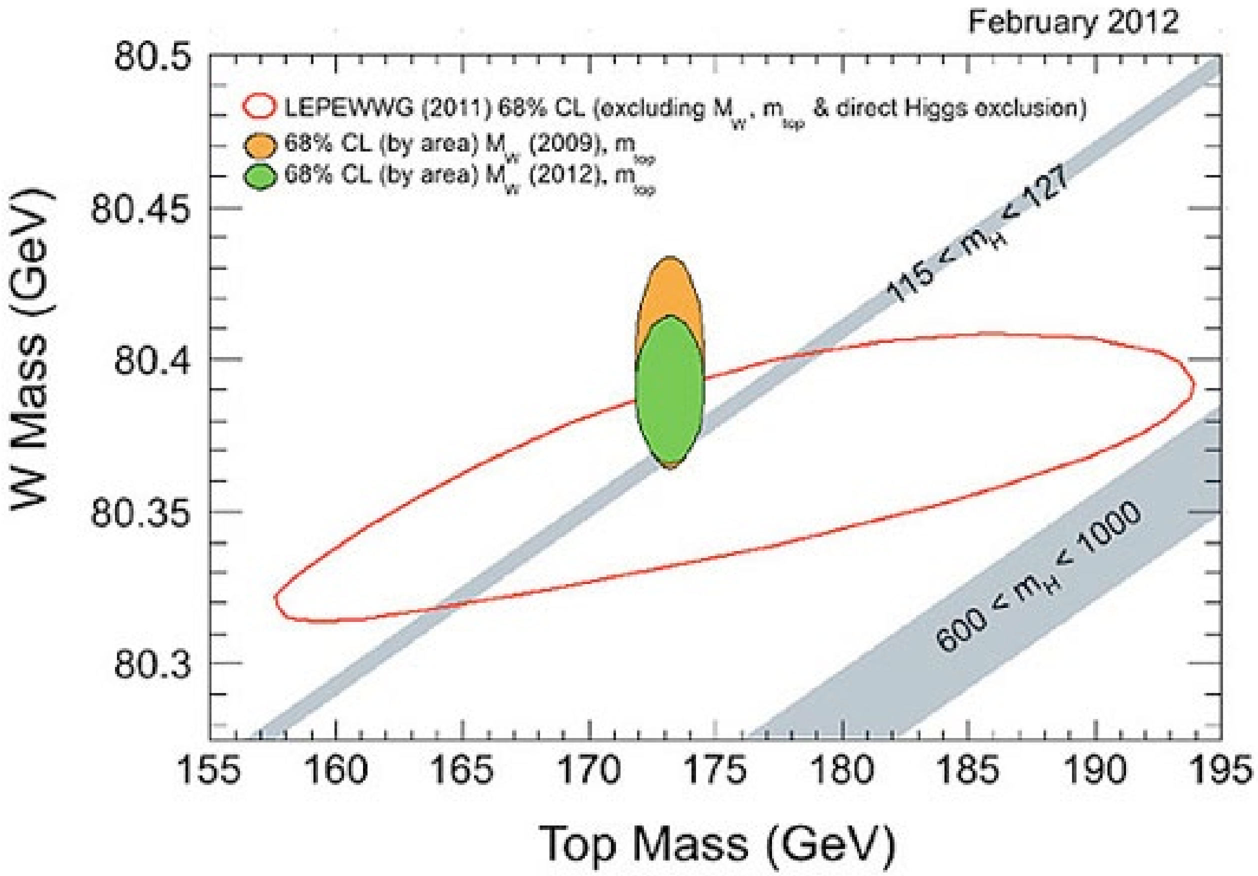


experimental errors: LEP2/Tevatron (today)
68% CL
95% CL
80.70
80.60
80.50
80.40
80.30
80.20
$M_W$ [GeV]
light SUSY
MSSM
heavy SUSY
$M_H$ = 114 GeV
SM
$M_H$ = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '07
160
165
170
175
180
185
$m_t$ [GeV]


2007

(vor LHC)

# Konsistenz der experimentellen Messungen im Rahmen des Standardmodells




Feb. 2012

LEP am CERN / Genf

$e^+e^-$-Beschleuniger,
27 km Umfang

LEP-I (1989-1995) $\sqrt{s}$ = 91 GeV
LEP-II (1996-2000) $\sqrt{s} \rightarrow$ 208 GeV