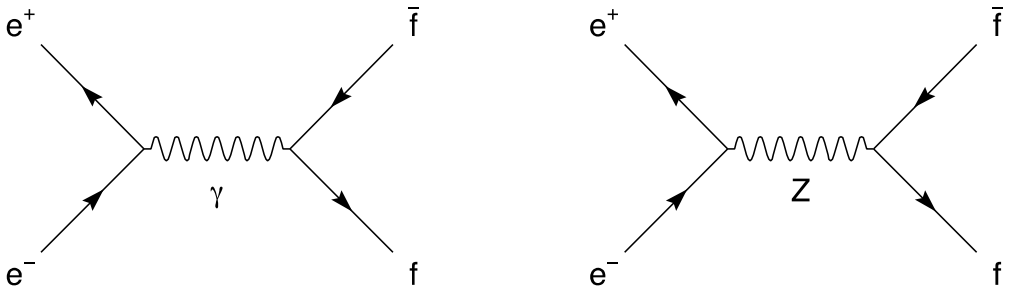
11. Experimentelle Tests der elektroschwachen Wechselwirkung

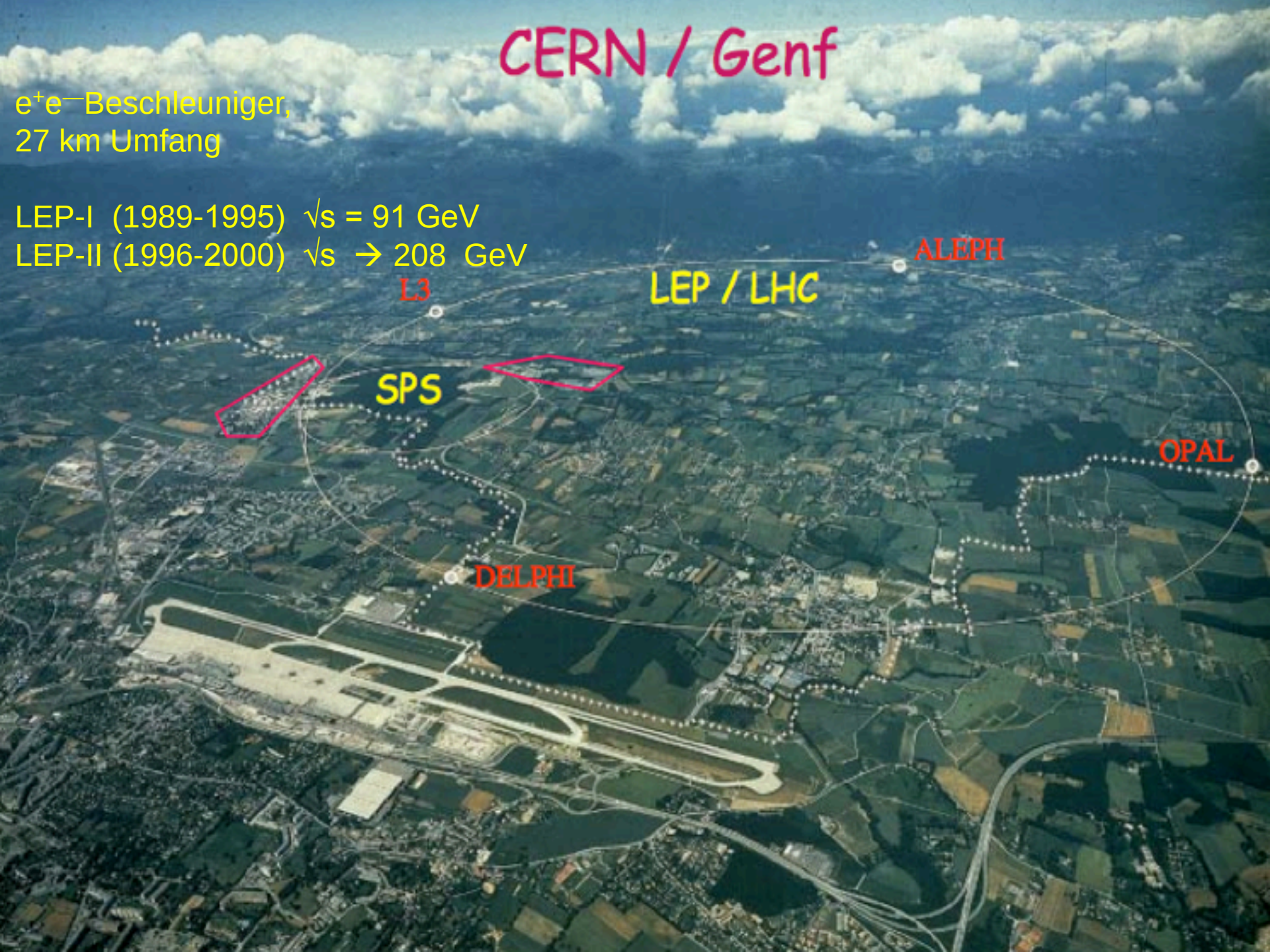
11.1 Fermi-Theorie der schwachen Wechselwirkung im Grenzfall niedriger Energie

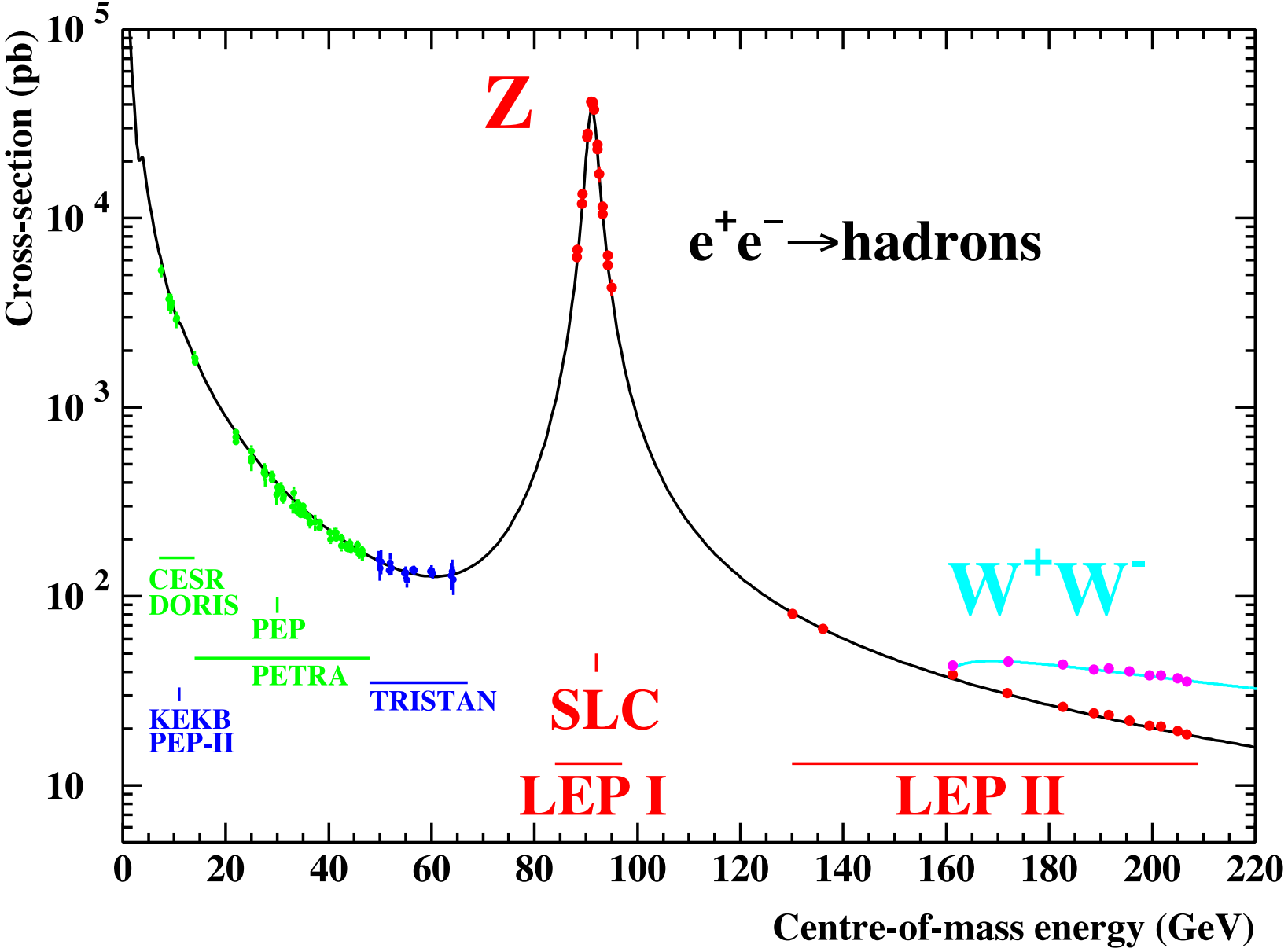
11.2 Elektroschwache Vereinheitlichung (Glashow, Salam, Weinberg)

11.3 Vorhersagen der elektroschwachen Theorie

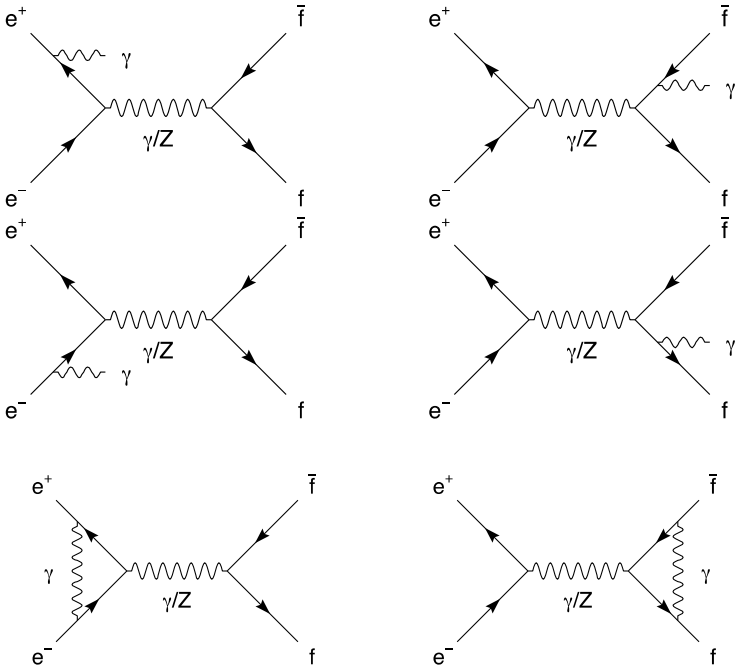
11.4 Test der elektroschwachen Theorie bei LEP

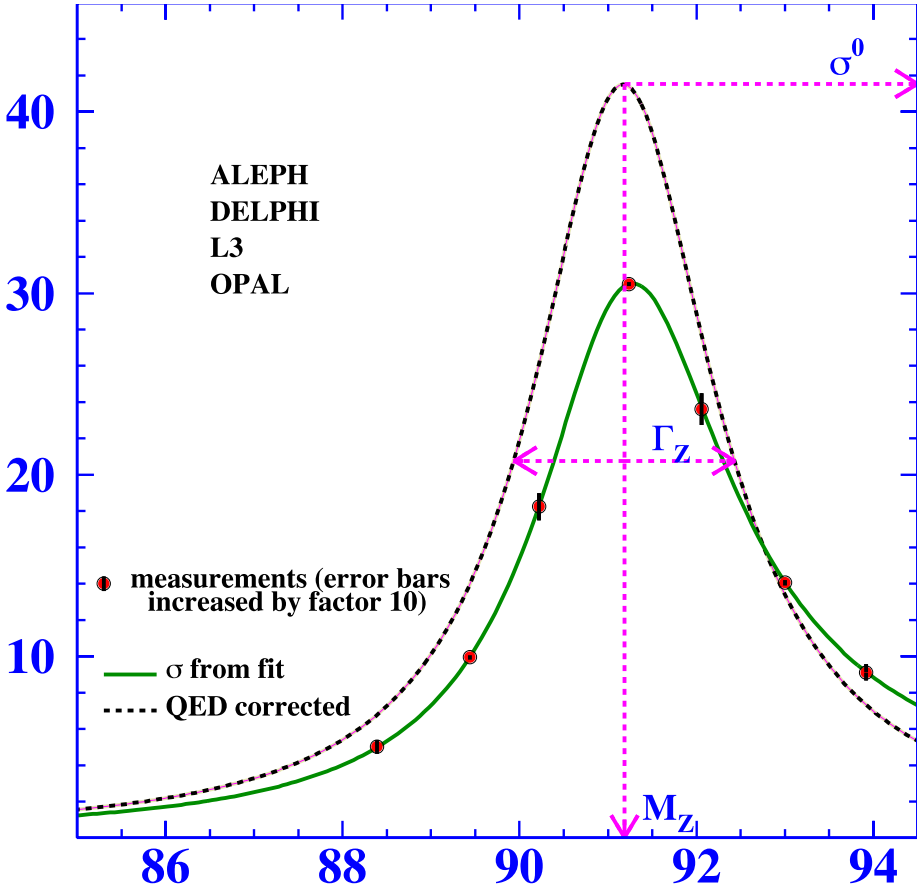



CERN / Genf
e+e−Beschleuniger,
27 km Umfang
LEP-I (1989-1995) √s = 91 GeV
LEP-II (1996-2000) √s → 208 GeV
ALEPH
L3
LEP / LHC
SPS
OPAL
DELPHI

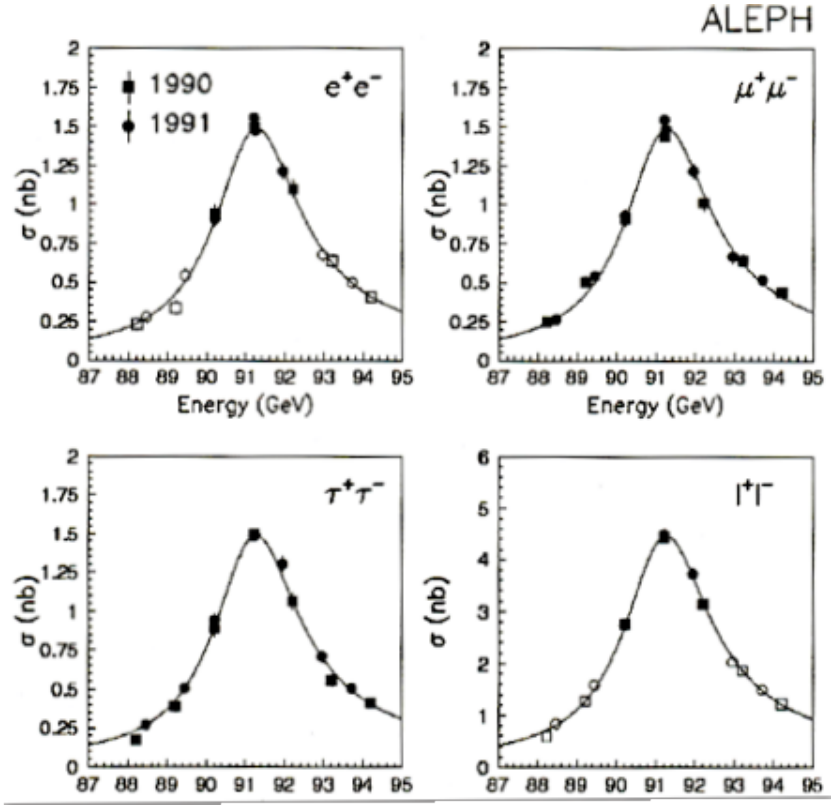

Cross-section (pb)
10 5
10 4
10 3
10 2
10
Z
e+e−→hadrons
W+W-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

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



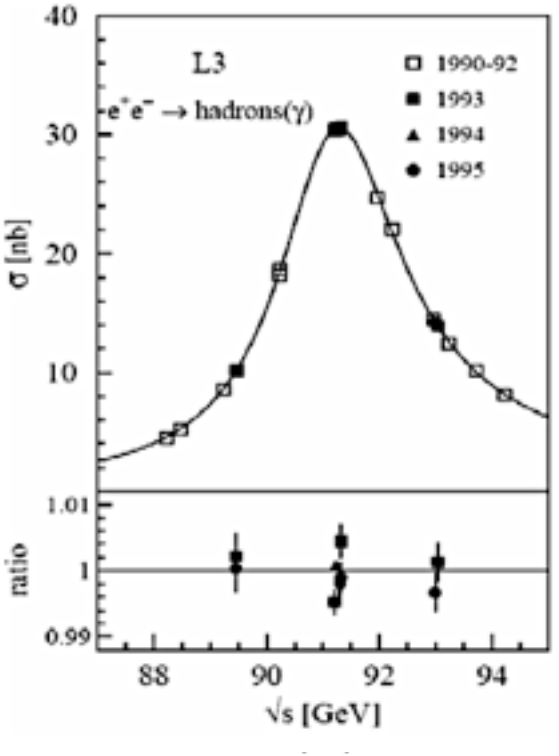


Lepton-Universalität



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

Hadronischer Wirkungsquerschnitt



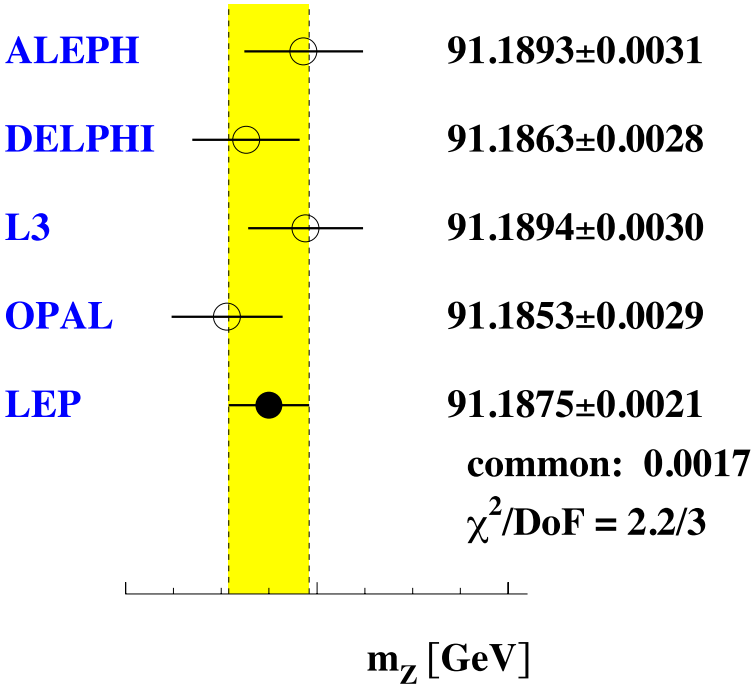
Quark-Flavor i.a. nicht exp. trennbar
(Ausnahme: c,b → Lebendsdauer)
⇒ had. Breite: $\Gamma_{had} = \Gamma_u+\Gamma_d+\Gamma_s+\Gamma_c+\Gamma_b$

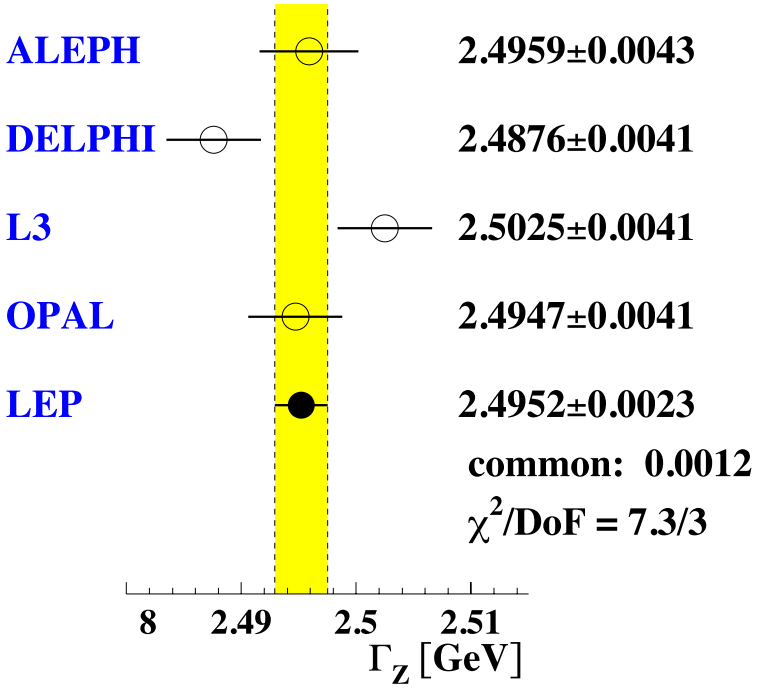
Messe Verhältnisse der Pol-WQ:

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

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

Gemessene Parameter des Z-Bosons





$m_Z = 91.1875 \pm 0.0021$ GeV

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV

Parameter der Z-Resonanzkurve

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

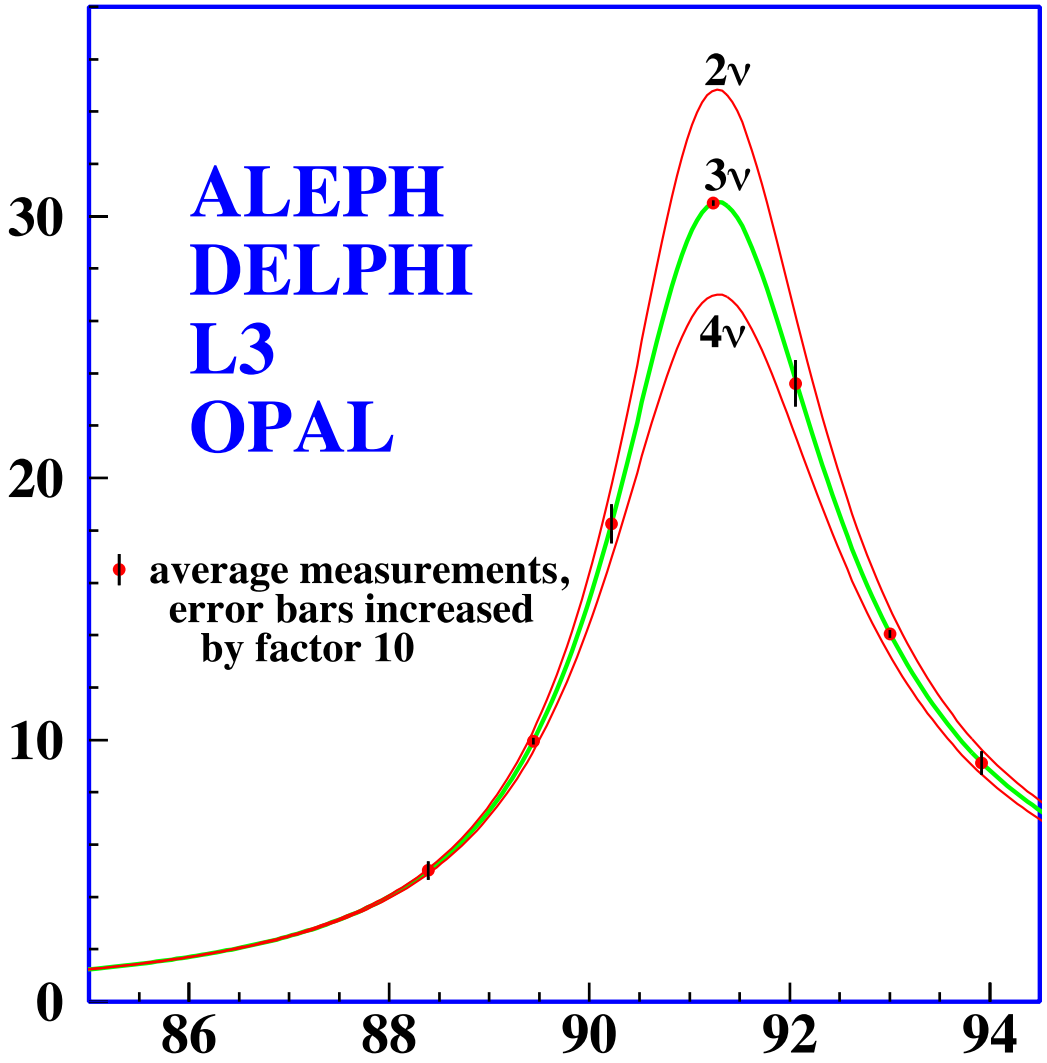
Γ_Z	$= 2.4952 \pm 0.0023$ GeV	± 0.09 %
Γ_{had}	$= 1.7458 \pm 0.0027$ GeV	
Γ_e	$= 0.08392 \pm 0.00012$ GeV	3 leptons are treated independently
Γ_μ	$= 0.08399 \pm 0.00018$ GeV	
Γ_τ	$= 0.08408 \pm 0.00022$ GeV	

test of lepton universality

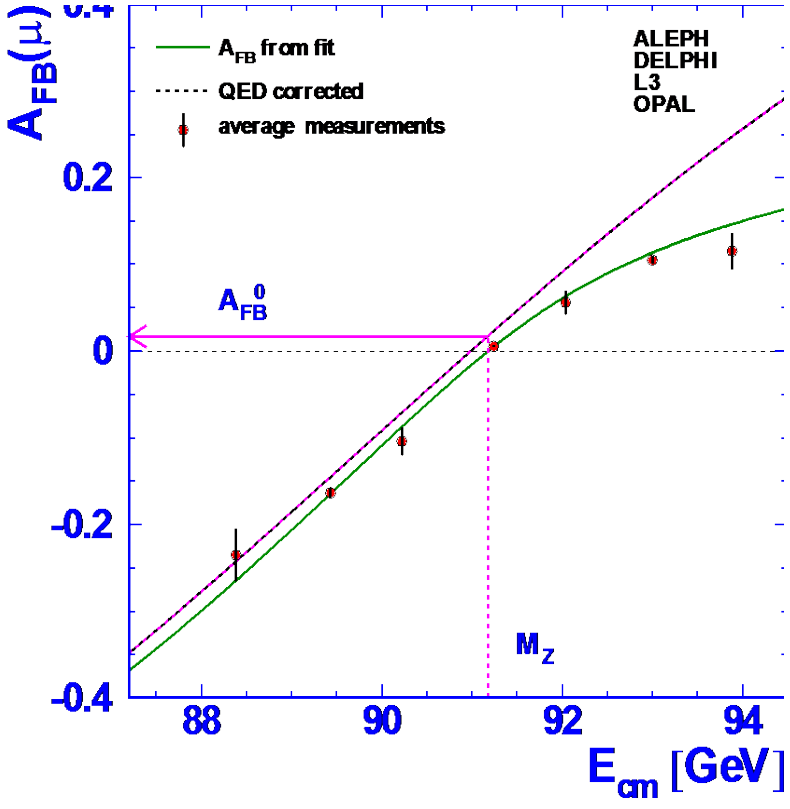
Γ_Z	$= 2.4952 \pm 0.0023$ GeV	Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
Γ_{had}	$= 1.7444 \pm 0.0022$ GeV	
Γ_e	$= 0.083985 \pm 0.000086$ GeV	

*) error of the LEP energy determination: ± 1.7 MeV (19 ppm)

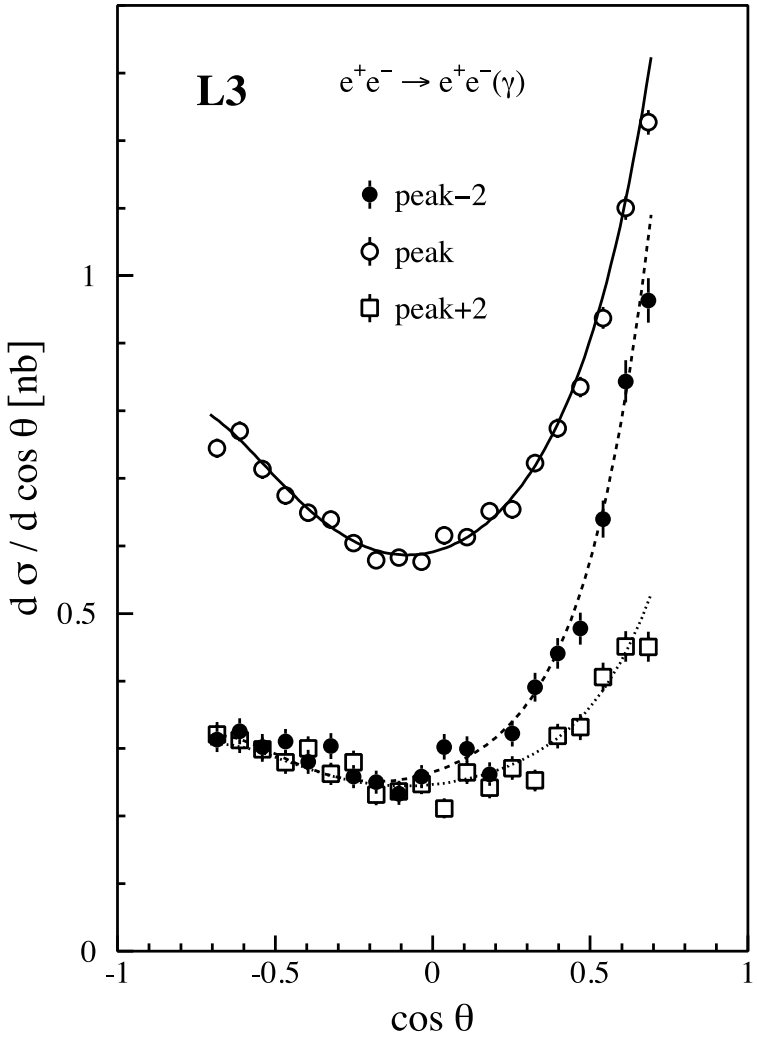
Messung der Zahl der Neutrinos

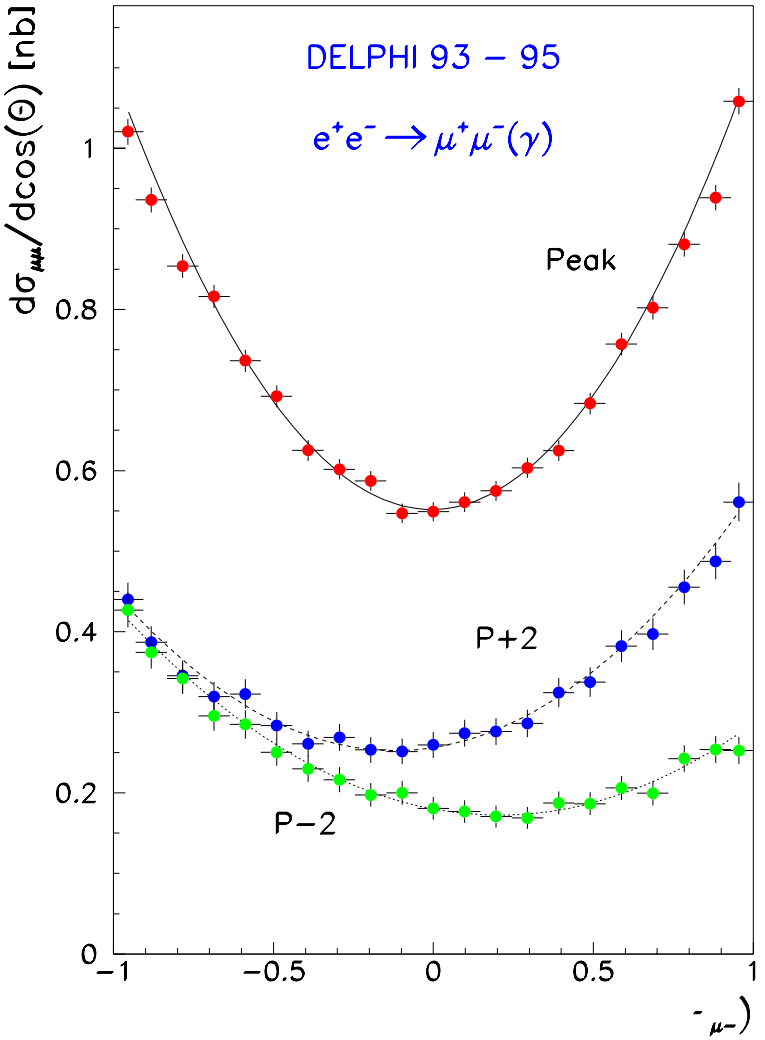


Vorwärts- Rückwärts-Asymmetrien

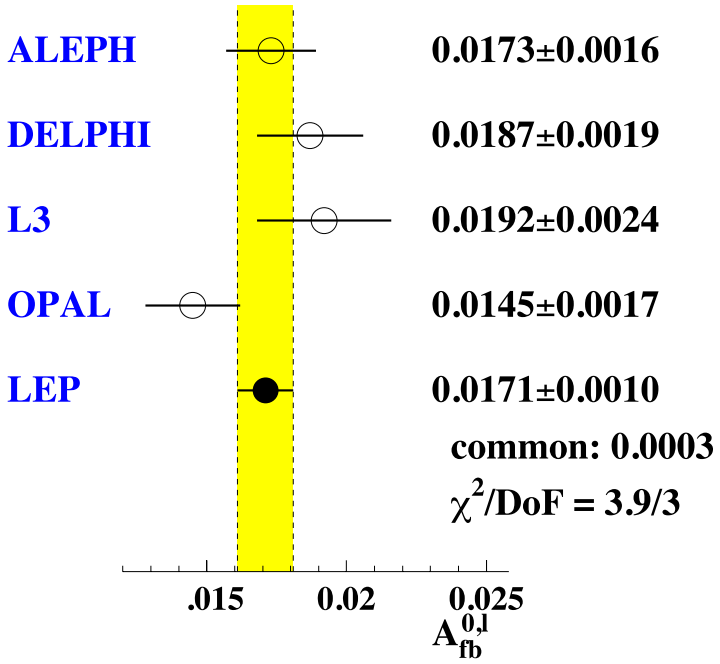


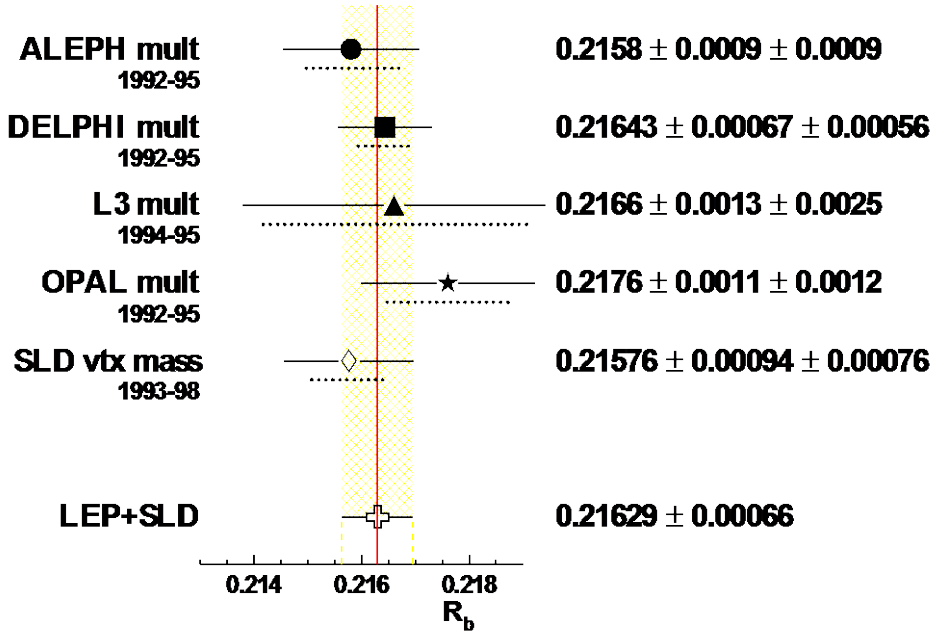
cos θ- Abhängigkeit des Wirkungsquerschnitts



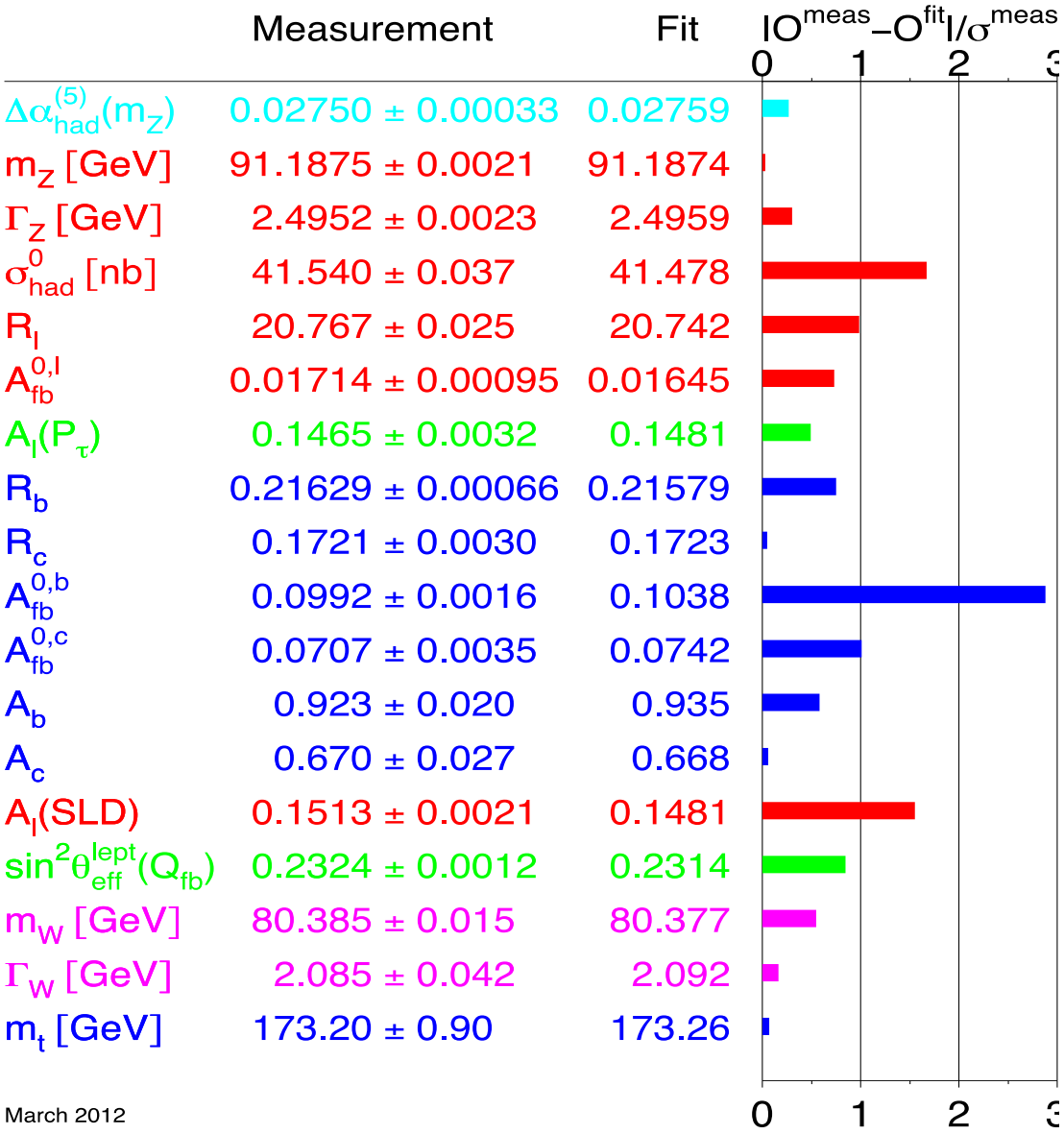


Gemessene Parameter des Z-Bosons

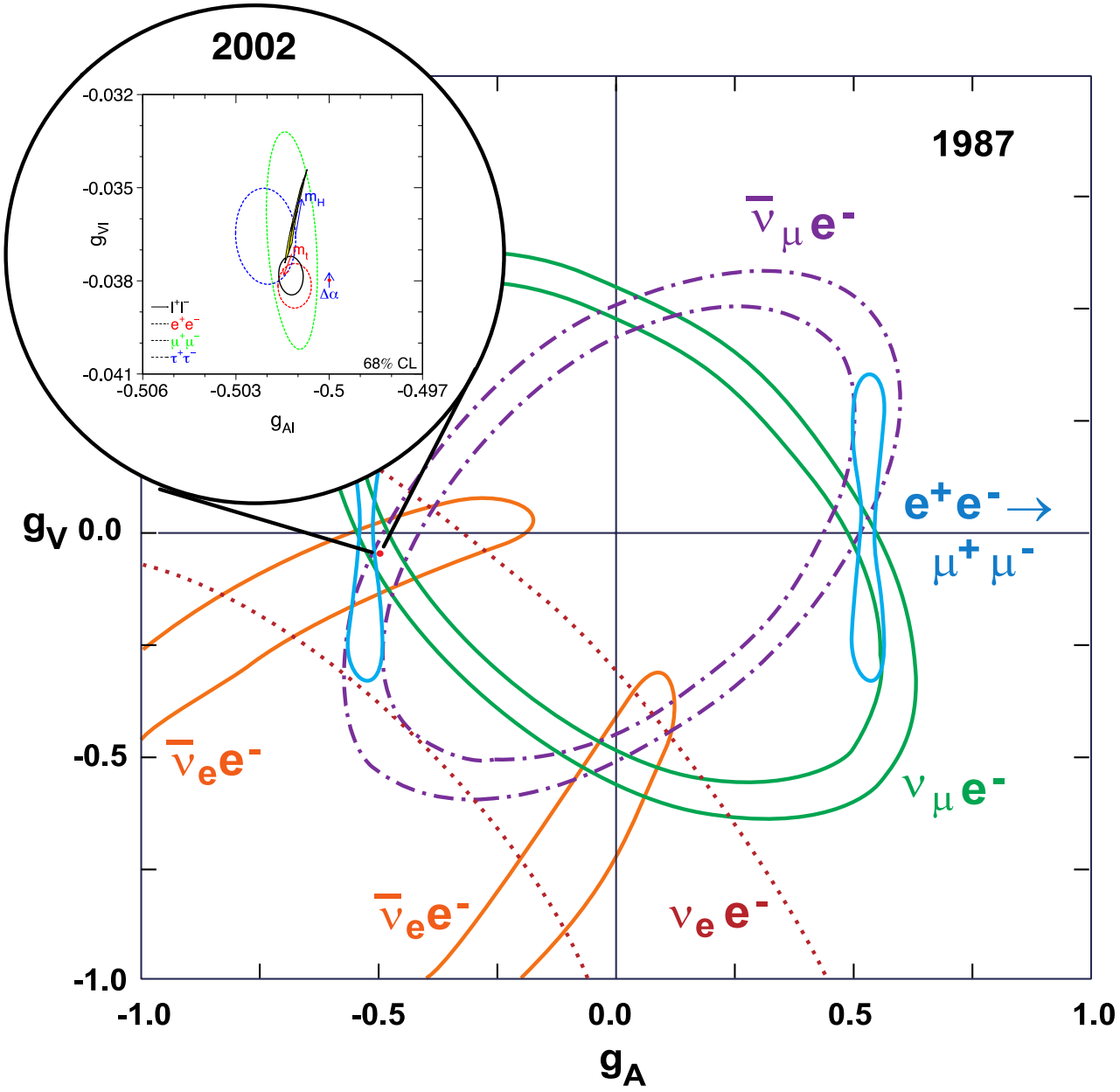




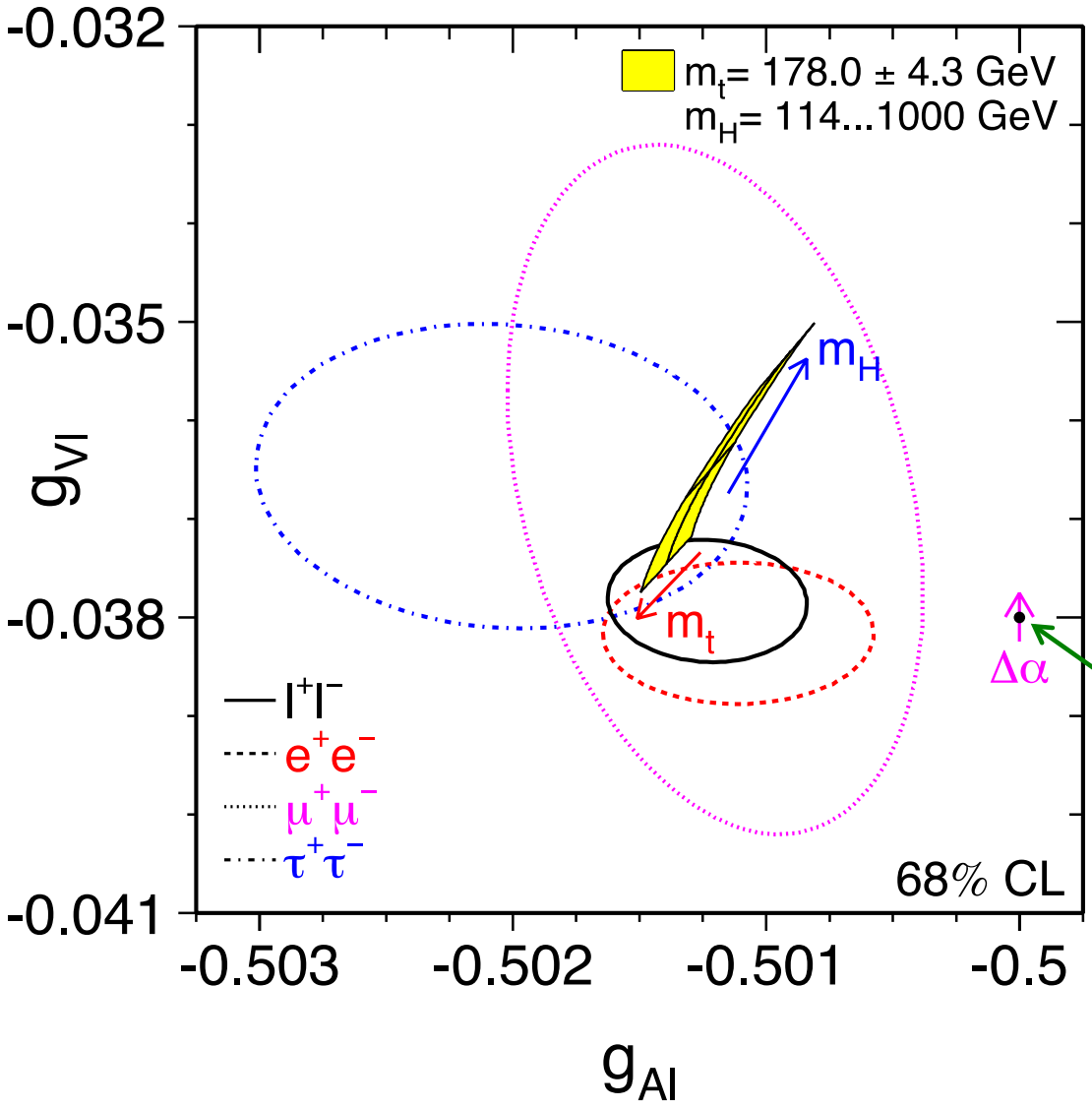
LEP-Messungen im Vergleich zu den Vorhersagen des Standardmodells



Fortschritte in den Messungen der elektroschwachen Kopplungen



Fortschritte in den Messungen der elektroschwachen Kopplungen

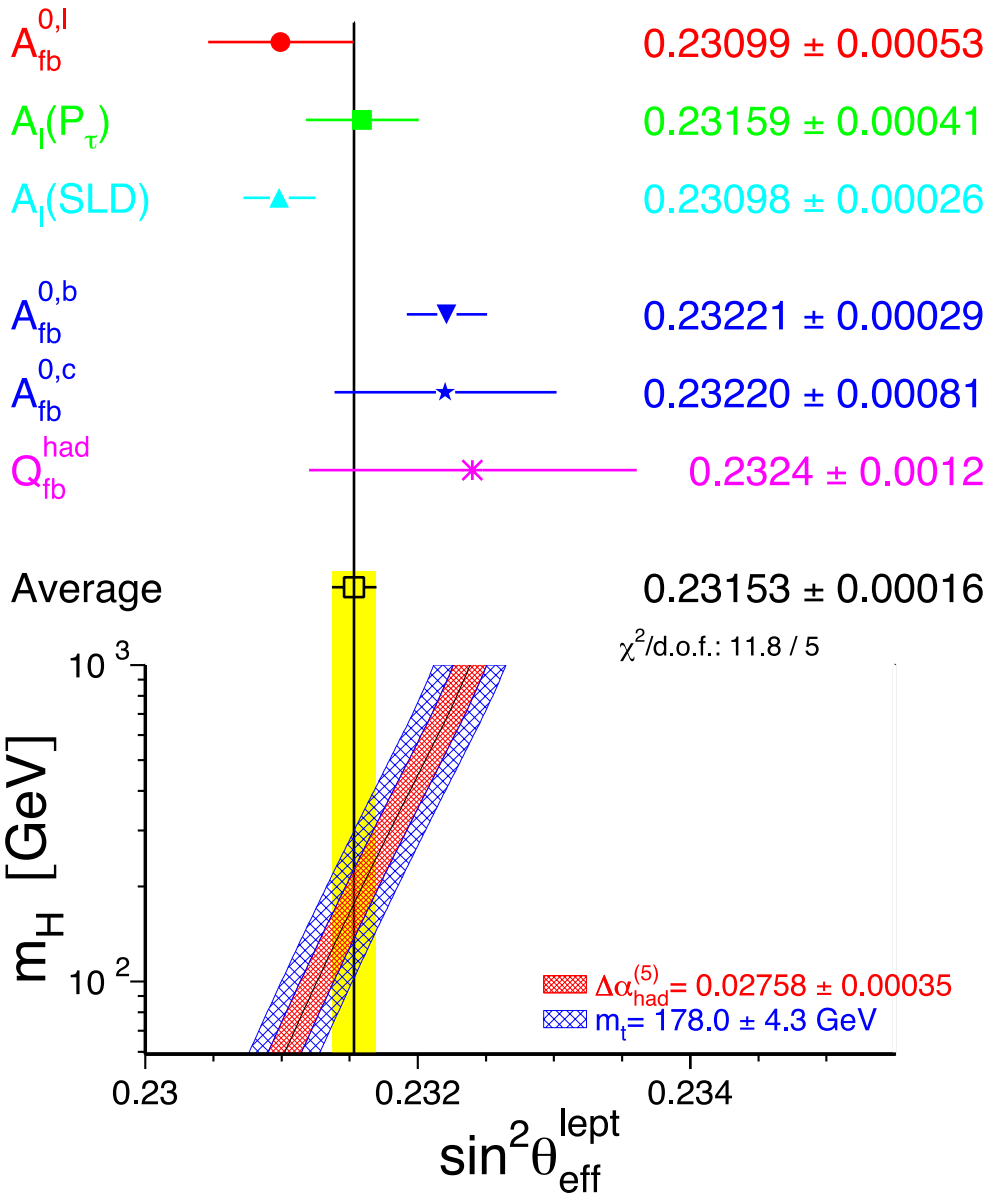


Standardmodell-Vorhersage ohne Quantenkorrekturen:

$g_A = T_3$

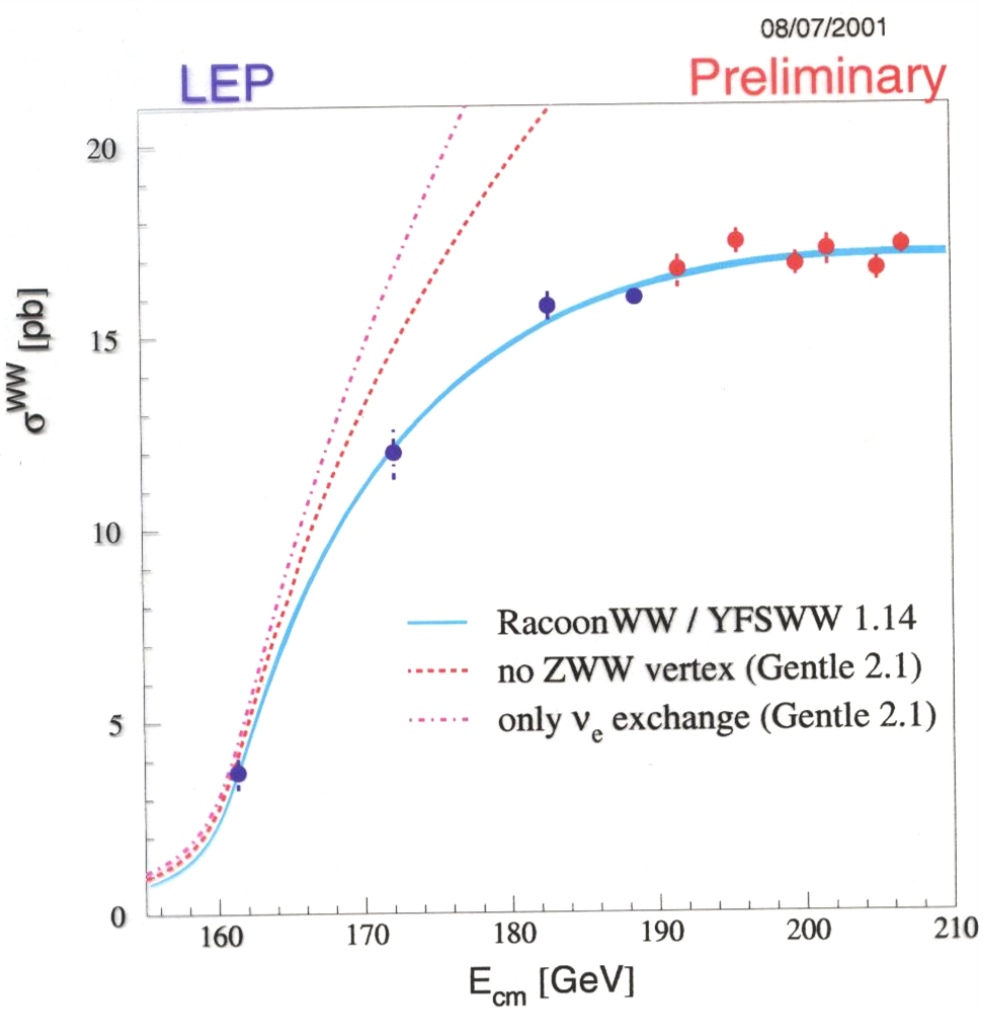
$g_V = T_3 - 2\,Q \sin^2 \theta_W$

Messungen des schwachen Mischungswinkels




LEP am CERN / Genf
e+e--Beschleuniger,
27 km Umfang
LEP-I (1989-1995) √s = 91 GeV
LEP-II (1996-2000) √s → 208 GeV

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

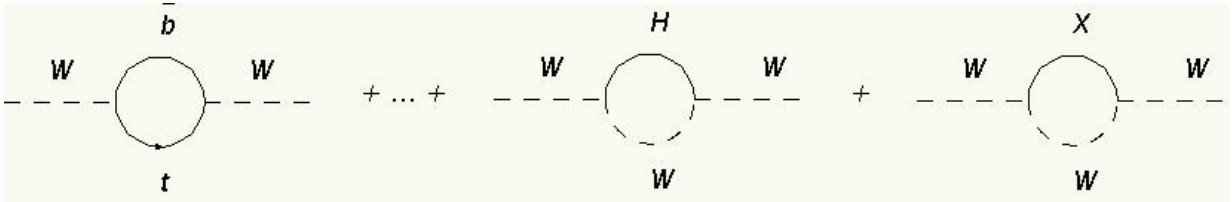
weak mixing angle
measured at LEP/SLC

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

G_F, α_{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)

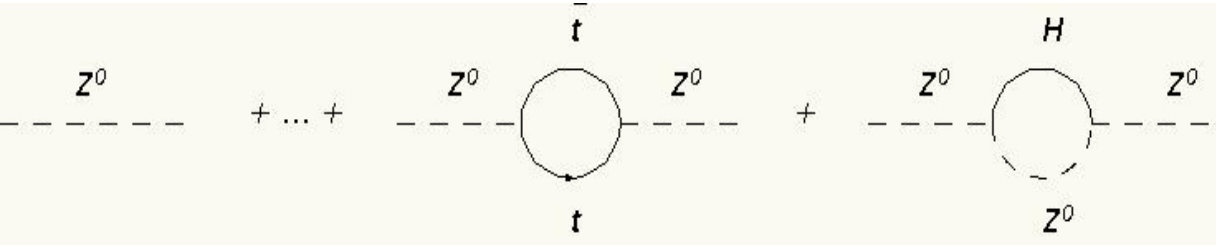


Indirekte Grenzen (aus Präzisionsmessungen):

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

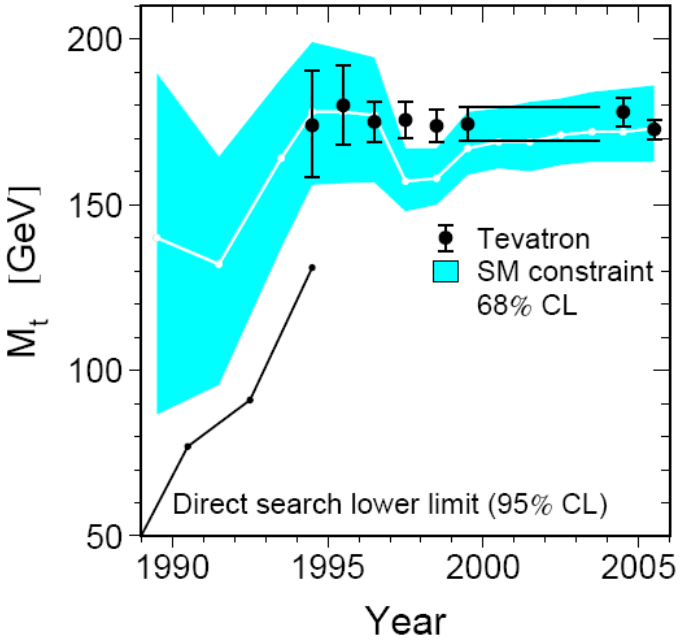
- In der Quantenfeldtheorie müssen auch Quantenkorrekturen in der Berechnung von Streuprozessen, Massen, ... etc. berücksichtigt werden. Hierbei treten Beiträge von sog. virtuellen Teilchen auf, d.h. Teilchen machen sich bereits weit unterhalb ihrer Energie/Massenskala bemerkbar.

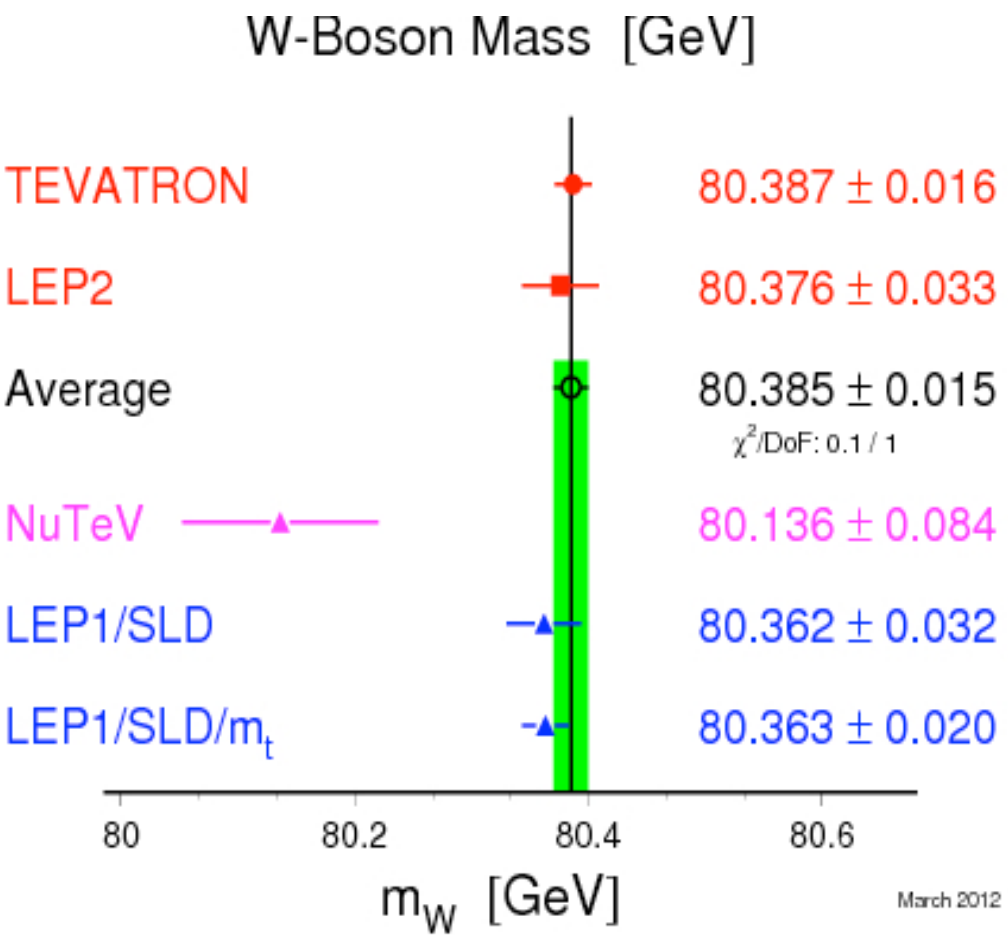
Beispiel: Einfluss des Top-Quarks auf die Z^0-Masse (LEP, 1990er Jahre)

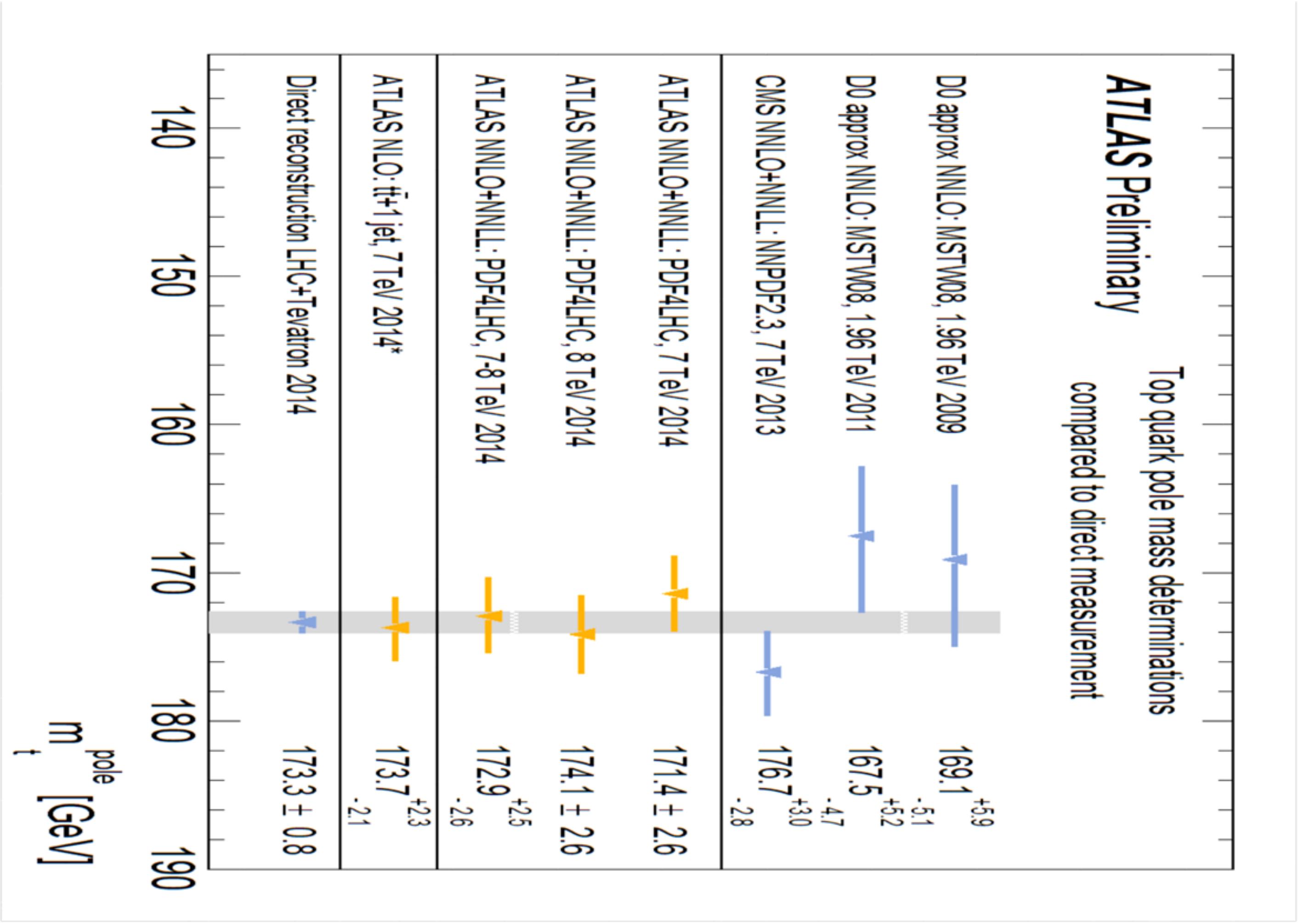


$$m_Z^2 = m_Z^2(0) \cdot (1 + \Delta(m_t, m_H, ...))$$

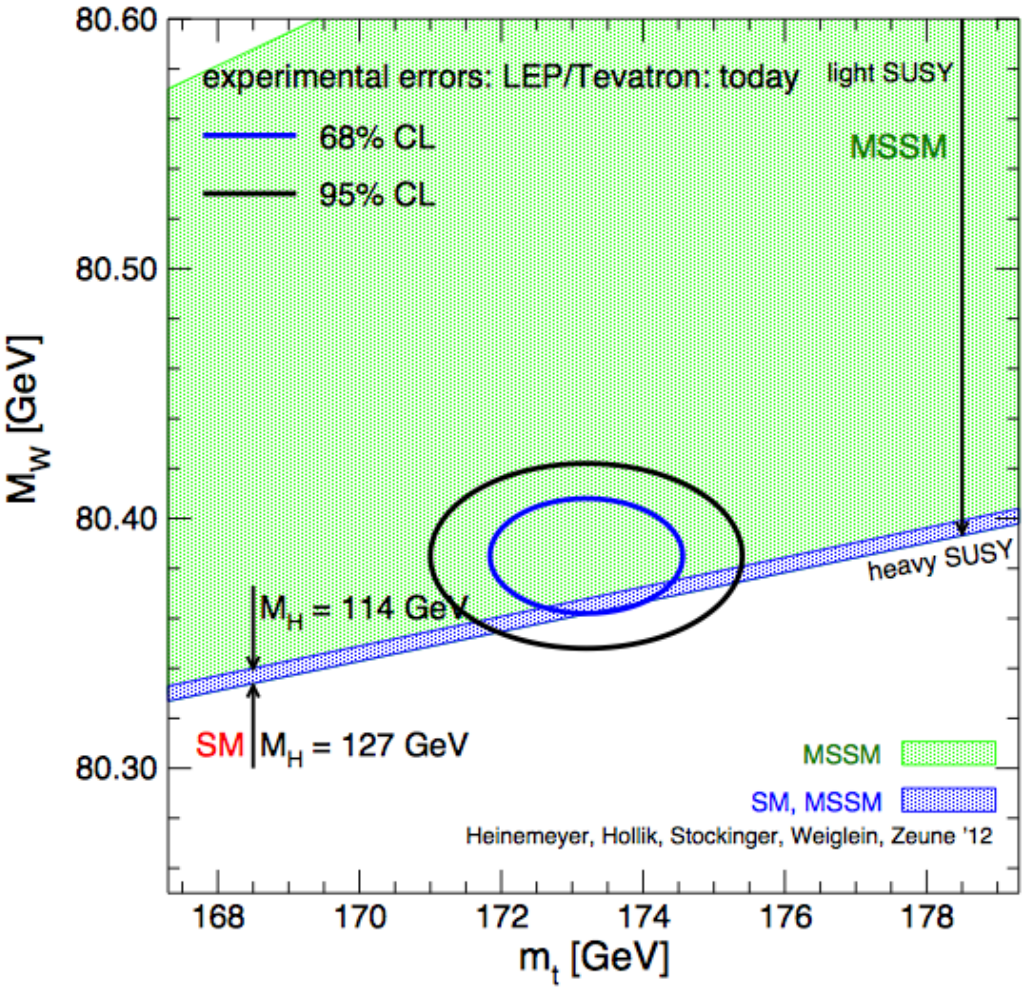
$$\Delta = ... + c_1 \cdot m_t^2 + ... + c_2 \cdot \ln m_H + ...$$



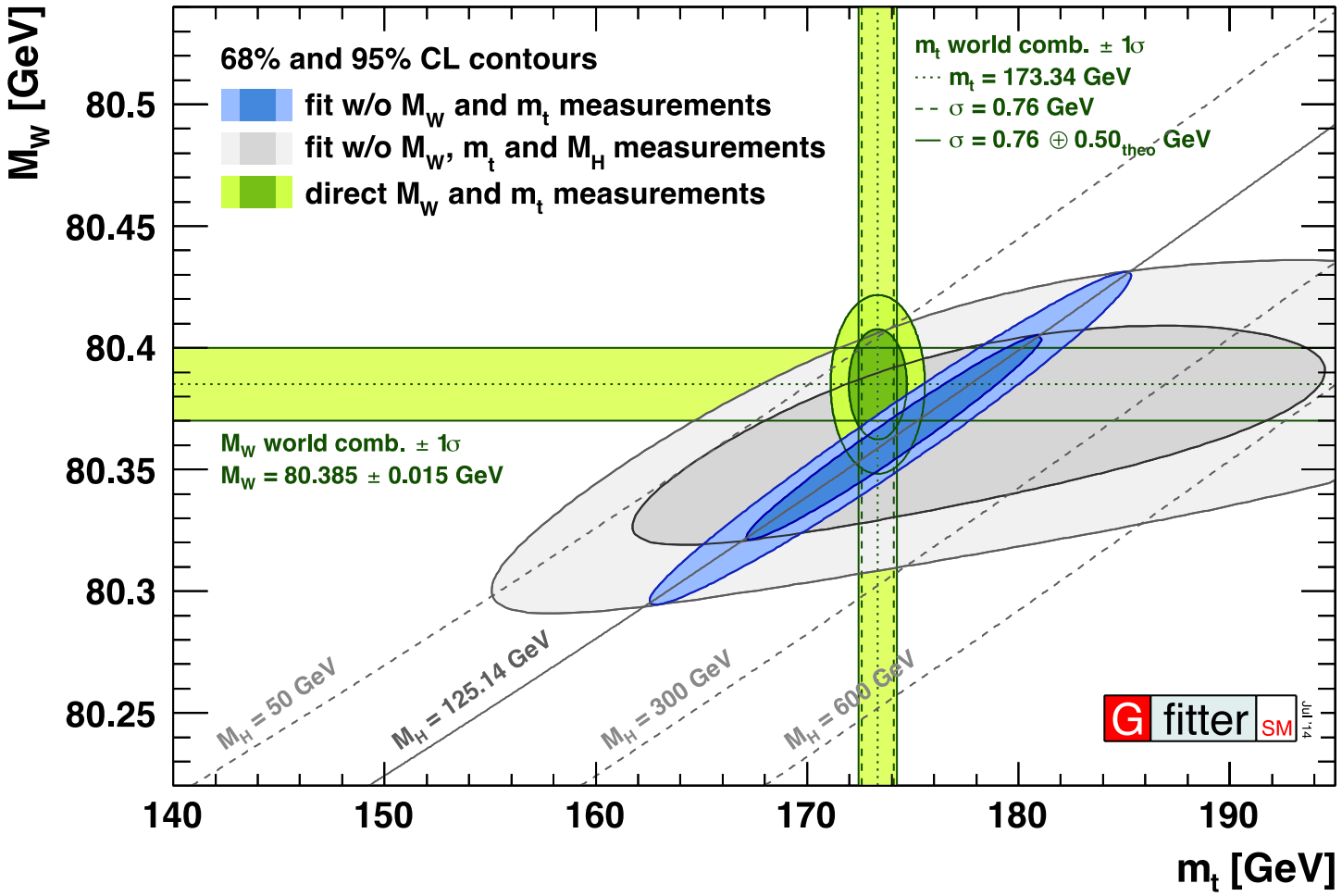

W-Boson Mass [GeV]
TEVATRON
80.387 ± 0.016
LEP2
80.376 ± 0.033
Average
80.385 ± 0.015
χ²/DoF: 0.1 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.362 ± 0.032
LEP1/SLD/m_t
80.363 ± 0.020
80
80.2
80.4
80.6
m_W [GeV]
March 2012



ATLAS Preliminary
Top quark pole mass determinations
compared to direct measurement
D0 approx NNLO: MSTW08, 1.96 TeV 2009
169.1 +5.9 -5.1
D0 approx NNLO: MSTW08, 1.96 TeV 2011
167.5 +5.2 -4.7
CMS NNLO+NNLL: NNPDF2.3, 7 TeV 2013
176.7 +3.0 -2.8
ATLAS NNLO+NNLL: PDF4LHC, 7 TeV 2014
171.4 ± 2.6
ATLAS NNLO+NNLL: PDF4LHC, 8 TeV 2014
174.1 ± 2.6
ATLAS NNLO+NNLL: PDF4LHC, 7-8 TeV 2014
172.9 +2.5 -2.6
ATLAS NLO: tt̄+1 jet, 7 TeV 2014*
173.7 +2.3 -2.1
Direct reconstruction LHC+Tevatron 2014
173.3 ± 0.8
140
150
160
170
180
190
m_t^pole [GeV]


80.60
80.50
80.40
80.30
M_W [GeV]
experimental errors: LEP/Tevatron: today
68% CL
95% CL
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 127 GeV
MSSM
SM, MSSM
Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '12
168
170
172
174
176
178
m_t [GeV]

2012


68% and 95% CL contours
fit w/o M_W and m_t measurements
fit w/o M_W, m_t and M_H measurements
direct M_W and m_t measurements
m_t world comb. ± 1σ
m_t = 173.34 GeV
σ = 0.76 GeV
σ = 0.76 ⊕ 0.50$_{theo}$ GeV
M_W world comb. ± 1σ
M_W = 80.385 ± 0.015 GeV
M_H = 50 GeV
M_H = 125.14 GeV
M_H = 300 GeV
M_H = 600 GeV
G fitter SM
Jul '14
M_W [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
m_t [GeV]