ELECTROWEAK PRECISION DATA AND THE HIGGS MASS
Workshop summary

Klaus Mönig

DESY-Zeuthen

Introduction

Questions of the workshop:

- Can we believe the precision data?
- Can we believe the theoretical calculations?
- Are the data consistent within the model?

The starting point: (winter2003)

- χ^2 of the global electroweak fit:

$$\begin{aligned} \chi^2/\mathrm{ndf} &= 25.5/15 \\ \Rightarrow \ \mathrm{Prob} &= 4.4\% \end{aligned}$$

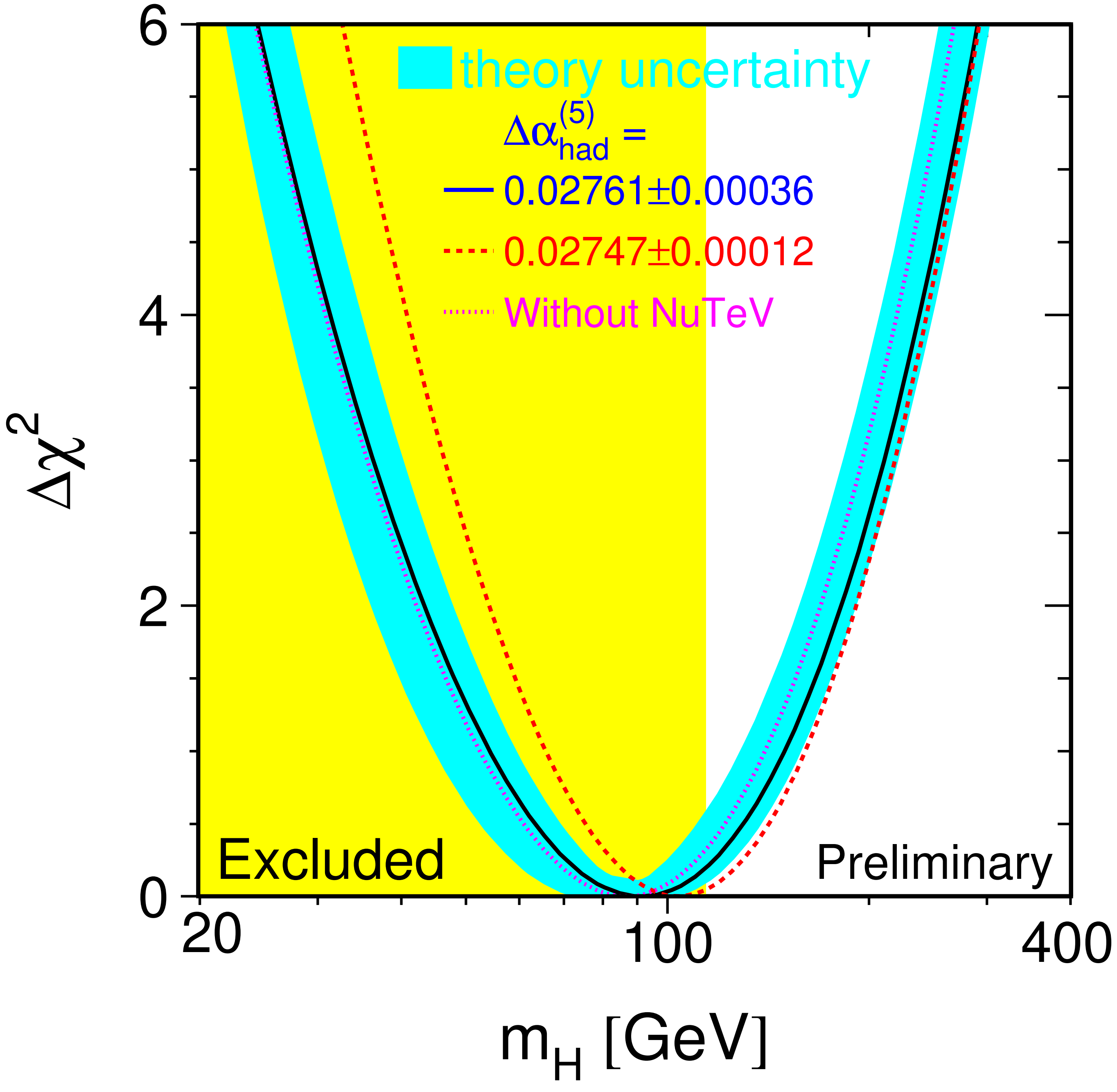
- fit result:

$$\begin{aligned} m_{\mathrm{t}} &= 174.0 \pm 4.5\,\mathrm{GeV} \\ \alpha_s(m_{\mathrm{Z}}^2) &= 0.1185 \pm 0.0027 \\ \log(m_{\mathrm{H}}) &= 1.96 \pm 0.22 \\ \Rightarrow m_{\mathrm{H}} &< 211\,\mathrm{GeV}\ (95\%\mathrm{c.l.}) \end{aligned}$$

➡ A light Higgs just beyond LEP2 is preferred

➡ However the fit quality is marginal

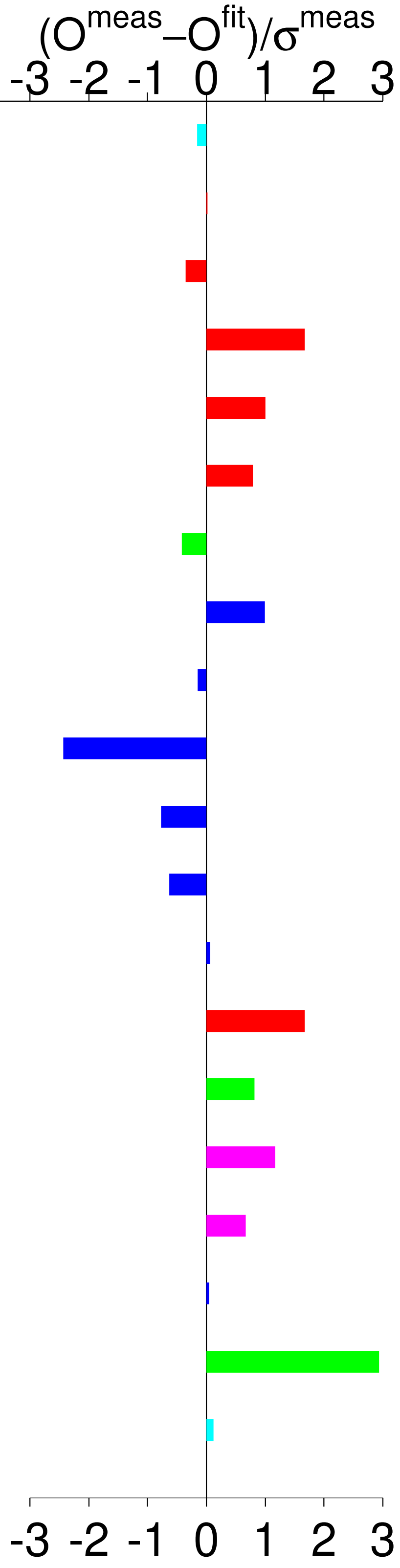
$\Delta\chi^2$ of the electroweak fit as function of m_{H}



Deviation of observables from electroweak fit

Winter 2003

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ^0_{had} [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.43
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
$Q_W(Cs)$	-72.83 ± 0.49	0.12



The worrying observables:

	value	stat	exp. syst	theo. syst	pull
$\sin^2\theta(\nu N)$	0.2277	0.0013	0.0006	0.0006	2.9
A_{FB}^{b}	0.0995	0.0015	0.0005	0.0004	2.4
A_{LR}	0.1513	0.0018	0.0010	0	1.7
m_W	80.449	0.024	0.019	0.017	1.2

(The m_W error breakdown is unofficial)

- The largest deviation is 2.9σ
- In all cases statistics is the largest error source
- For m_W the errors are made out of many sources
- For A_{LR} the exp. error contains mainly two sources where one is of statistical nature

Mike's Argumentation

The Standard Model is wrong!

Either all data are correct:

$$\begin{aligned} \chi^2/\mathrm{ndf} &= 25.5/15 \\ \Rightarrow \ \mathrm{Prob} &= 4.4\% \end{aligned}$$

is unacceptable

Or $A_{\mathrm{FB}}^{\mathrm{b}}$ (and $\sin^2\theta(\nu N)$) is wrong:

$$m_{\mathrm{H}} = (53^{+39}_{-23})\,\mathrm{GeV}$$

is inconsistent with the direct searches

This workshop was meant to discuss if his argumentation is valid

Warning: Any argumentation with χ^2 probabilities in the 1-20% range (including mine) is necessarily subjective

$\sin^2\theta(\nu N)$

- $\sin^2\theta(\nu N)$ is obtained from charged to neutral current ratio in νN and $\bar{\nu}N$
- $\sin^2\theta(\nu N)$ has only little sensitivity to m_{H}:
  - with NuTeV: $\log(m_{\mathrm{H}}) = 1.96 \pm 0.22$
  - without NuTeV: $\log(m_{\mathrm{H}}) = 1.94 \pm 0.22$

$\Rightarrow$ can treat $\sin^2\theta(\nu N)$ in isolation

- three possibilities
  - the measurement or a theoretical assumption is wrong
    ➡ continue without NuTeV
  - 3σ is a statistical fluctuation
    ➡ also can continue without NuTeV
  - the 3σ deviation is a real effect
    ➡ the whole SM fit breaks down

$$\begin{aligned}\sin^2\theta(\nu N) = 0.2277 &\pm 0.0013(\mathrm{stat.})\\ &\pm 0.0006(\mathrm{exp.\,syst.})\\ &\pm 0.0006(\mathrm{theo.\,syst.})\end{aligned}$$

Is the measurement correct?

No reason to doubt this

Are the theoretical assumptions correct?

QCD of the nucleon

- the present analysis is leading order
- some suggested effects like isospin-violation or $s-\bar{s}$ asymmetry analyzed and found to be small
- a framework for NLO structure functions including errors exists and should be tested
- it would be good if NuTeV structure functions could be included in the PDF fits

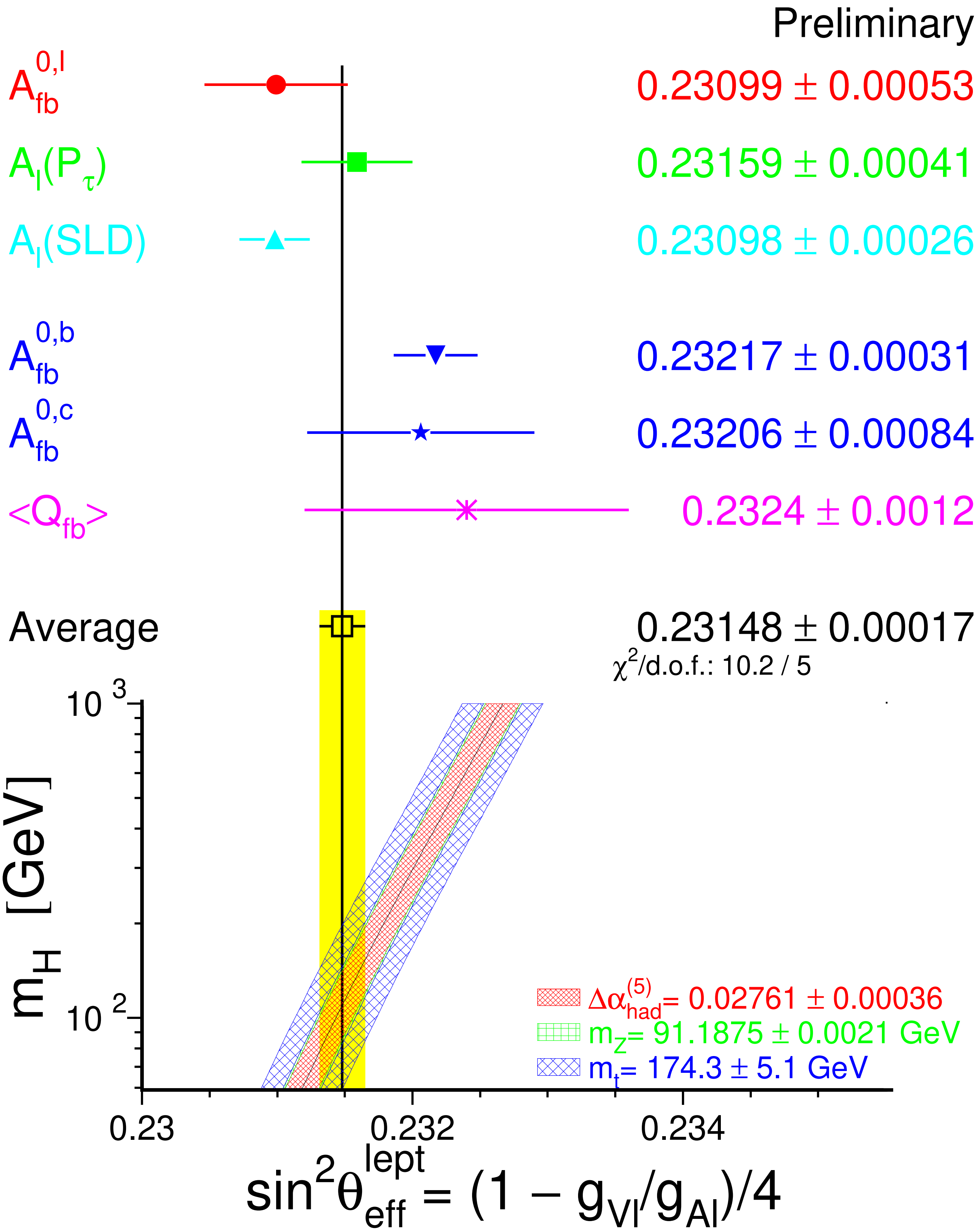
QCD of the nucleus

- in principle different nuclear effects for ν-CC and ν-NC can explain the discrepancy
- however nuclear effects for ν-CC and ℓ-MC agree

QED corrections are large and should be cross checked

In summary no obvious problem but, given the importance of the deviation, every possible check has to be done

The $\sin^2\theta^l_{eff}$ Problem



The fact

- $\sin^2\theta^l_{eff}$ combination:

$$\chi^2/\mathrm{ndf} = 10.2/5 \quad \Rightarrow \mathrm{Prob} = 7\%$$

- $\frac{\sin^2\theta^l_{eff}(A^{\mathrm{b}}_{\mathrm{FB}}) - \sin^2\theta^l_{eff}(A_{\mathrm{LR}})}{\sigma(\sin^2\theta^l_{eff}(A^{\mathrm{b}}_{\mathrm{FB}}) - \sin^2\theta^l_{eff}(A_{\mathrm{LR}}))} = 3$

The folklore:

There is a difference between $\sin^2\theta^l_{eff}$ from leptonic and from hadronic observables

observable	$\Delta A_{\mathrm{LR}}[\sigma]$	$\Delta A^{\mathrm{b}}_{\mathrm{FB}}[\sigma]$
A^{ℓ}_{FB}	0	-1.9
$\mathcal{P}_\tau$	$+1.3$	-1.1
$A^{\mathrm{c}}_{\mathrm{FB}}$	$+1.2$	-0.1
$< Q_{FB} >$	$+1.2$	$+0.2$

- average without $A^{\mathrm{b}}_{\mathrm{FB}}$:
  $\chi^2/\mathrm{ndf} = 3.8/4 \quad \Rightarrow \mathrm{Prob} = 43\%$
- average without A_{LR}:
  $\chi^2/\mathrm{ndf} = 4.4/4 \quad \Rightarrow \mathrm{Prob} = 36\%$

The other $\sin^2\theta^l_{eff}$ measurements don't distinguish between A_{LR} and $A^{\mathrm{b}}_{\mathrm{FB}}$

How consistent are the data?

$\sin^2\theta(\nu N)$ already discussed

Take as basis high energy data
(=LEPEW fit – $\sin^2\theta(\nu N)$ – APV)

$$\begin{aligned} \chi^2/\mathrm{ndf} &= 16.6/13 \\ \Rightarrow \mathrm{Prob} &= 22\% \\ \log(m_\mathrm{H}) &= 1.94 \pm 0.22 \end{aligned}$$

certainly not unacceptable

Take out worrying observables one by one

left out	$\log(m_\mathrm{H})$	χ^2/ndf	Prob
A_FB^b	1.72	9.2/12	69%
A_LR	2.09	13.1/12	36%
m_W	2.00	15.2/12	24%
A_LR & m_W	2.24	9.6/11	58%

- all fits acceptable
- within SM m_W favors A_LR compared to A_FB^b
- even without A_LR and m_W Higgs stays relatively light

Does theory affect the consistency within the SM?

- all uncertainties affecting specific observables are included in the χ^2 definition (e.g. luminosity error, QCD corrections to $A_{\mathrm{FB}}^{\mathrm{b}}$, PDFs in $\sin^2\theta(\nu N)$ and m_{W})
- (however they are all assumed to be Gaussian)
- the errors in the electroweak prediction are shown as the thickness of the blue band however they are not included in the χ^2
- two representative tests:
  - apply recent correction to m_{W} by Freitas et al (AMT4=5)
    $\Rightarrow \chi^2$ decreases by 0.3
  - shift in addition $\sin^2\theta^l_{eff}$ by $8 \cdot 10^{-5}$
    $\Rightarrow \chi^2$ decreases by additional 0.5

➠ no dramatic effects

$A_{\mathrm{FB}}^{\mathrm{b}}$

Two methods:

- leptons
- jet charge/vertex charge

Two main ingredients

- flavor tagging
- charge tagging

Leptons

- flavor and charge tagging with lepton (p, p_t) spectra
- flavor tagging sometimes helped by lifetime tag
- spectra calibrated opposite to a lifetime tag and with double lepton tag

jet charge/vertex charge

- flavor tag: lifetime tag, calibrated with single/double tagging technique

- charge tag: combination of jet charge and vertex charge either with a weighting method or with a cut method
- in all cases charge tag is calibrated with data

Both cases

- the signal is mainly calibrated with data
- only small backgrounds and hemisphere correlations have to be taken from simulation

LEP/SLD combination

- $\mathcal{O}(100)$ measurements of $\mathcal{O}(10)$ observables
- many potentially correlated systematics (particle lifetimes, BRs, decay models...)
- careful combination taking correlations into account

$$\begin{aligned} A_{\mathrm{FB}}^{\mathrm{b}} = 0.0995 & \pm 0.0015(\mathrm{stat}) \\ & \pm 0.0005(\mathrm{exp\ syst}) \\ & \pm 0.0004(\mathrm{cor\ syst}) \end{aligned}$$

- in the end one of the EW observables with the smallest systematic errors

QCD uncertainties in $A_{\mathrm{FB}}^{\mathrm{b}}$

Full acceptance (using thrust axis):

$$A_{\mathrm{FB}}^{\mathrm{b}} = A_{\mathrm{FB}}^{\mathrm{b}}(\mathrm{no\,QCD}) \cdot (1 - 0.0354 \pm 0.0063)$$

Effect of QCD corrections on final result

$$\frac{\Delta A_{\mathrm{FB}}^{\mathrm{b}}(\mathrm{QCD})}{\Delta A_{\mathrm{FB}}^{\mathrm{b}}} = 0.21$$

- ambiguity to define direction
  1) quark direction after gluon radiation
  2) thrust direction signed by quark projection
- 1st order massive calculation exists for both definitions
- two 2nd order massless calculations exist for quark direction (Ravindran/van Neerven, Catani/Seymour)
- both calculations agree within the required precision
- however the Catani/Seymour calculation contains a $\log(Q^2/m_b^2)$ divergence which makes it unusable for light quarks

- the Catani/Seymour calculation exists also for the thrust direction
  $\Rightarrow$ default in the analyzes
- the LEPHF group has tried to estimate the error conservatively, taking into account higher orders, mass effects etc.
- the experiments see on average only about half the QCD corrections, since the selection biases towards high energy b-quarks
- especially all colinear effects are absorbed in the measurement of the charge tagging efficiency
- this bias is estimated with PYTHIA which describes the total correction well
- in summary it seems impossible that QCD corrections can bring $A_{\mathrm{FB}}^{\mathrm{b}}$ close to A_{LR}

A_{LR}

$$A_{\mathrm{LR}}(\sqrt{s}) = \frac{1}{\mathcal{P}} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

- event counting: solid hadronic selection
  $\Rightarrow$ no problem
- $\mathcal{L}_L = \mathcal{L}_R$ by construction and experimentally verified
- challenge: polarimetry
  - average beam polarization understood to 0.5%
  - other polarization related effects (difference average beam polarization – luminosity weighted polarization, positron polarization etc.) add up to $< 0.2\%$
- correction $A_{\mathrm{LR}}(\sqrt{s}) \rightarrow A^0_{\mathrm{LR}}$ using ZFITTER
  - main effect is $\gamma - Z$ interference (0 on peak)
  - ➠ $\Delta A_{\mathrm{LR}}/A_{\mathrm{LR}} = 0.4\%$ from knowledge of E_b (statistics of miniscan)

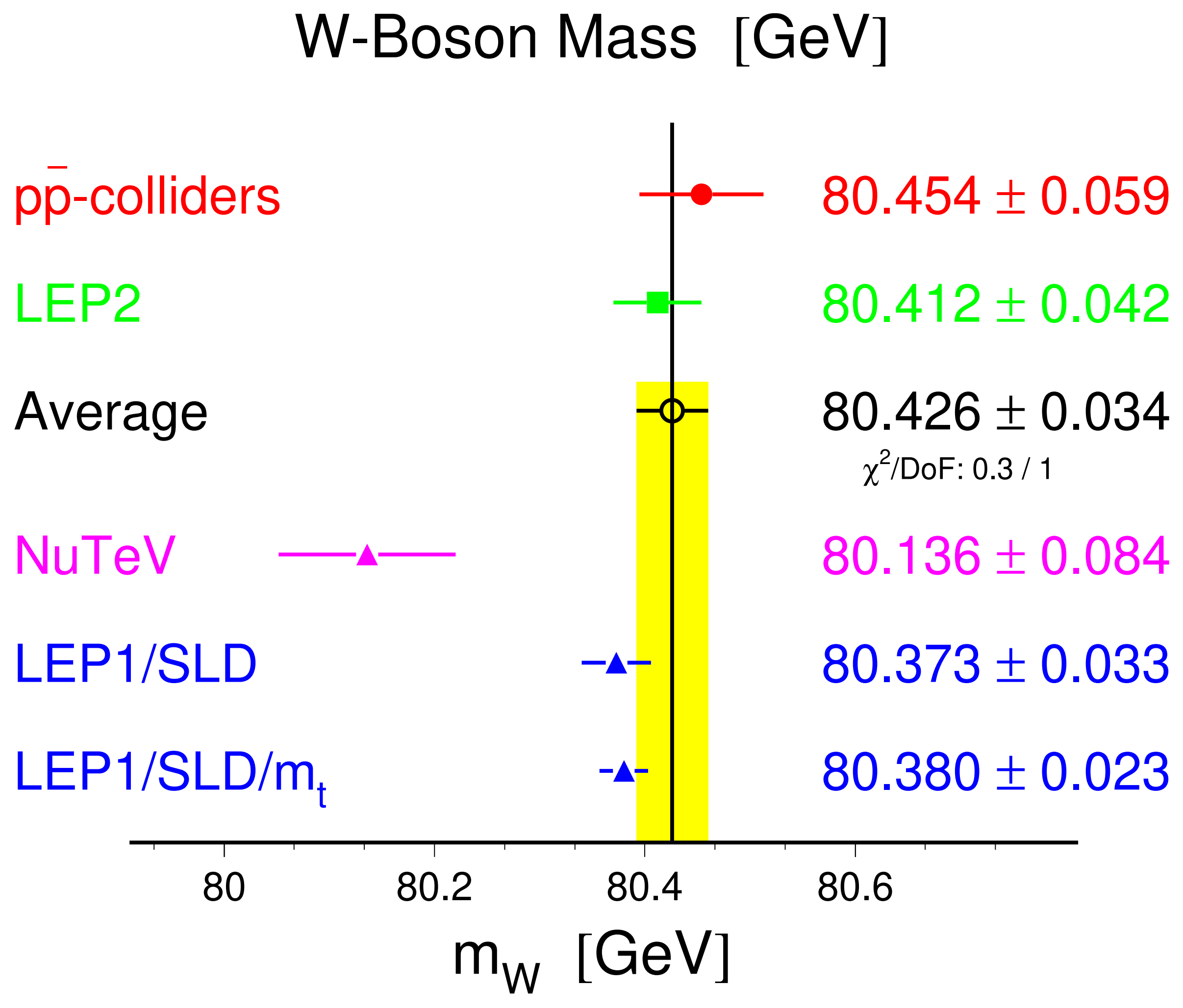
$$
\begin{aligned}
A^0_{\mathrm{LR}} &= 0.1514 \pm 0.0019(\mathrm{stat}) \pm 0.0010(\mathrm{syst}) \\
&= 0.1514 \pm 0.0022
\end{aligned}
$$

Adding lepton asymmetries

$$\mathcal{A}_{\mathrm{e}}x = 0.1513 \pm 0.0021$$

A_{LR} looks like a robust measurement with basically no theoretical uncertainties

m_W



LEP

- all results are still preliminary
- dominant systematics:
  - fragmentation: 18 MeV (interplay between fragmentation and acceptance)
  - LEP beam energy: 17 MeV (hope for some improvements in final version)
  - QED corrections: 8 MeV

– final state interaction in 4q: 10 MeV

  * error is 90 MeV in 4q channel
  * at present basically deweights the 4q channel
  * lots of work going on to understand it

- LEP aim: $\Delta m_{\mathrm{W}} = 35\,\mathrm{MeV}$

Summary LEP

- $m_{\mathrm{W}} = 80.426 \pm 0.042\,\mathrm{GeV}$
- systematics dominated, but many different sources
- the only worrying error (4q final state interactions) only increases the statistical error but plays no real role in the end

Tevatron:

main method: transverse mass

$$m_T = \sqrt{2p_t^{\ell}p_t^{\nu}(1-\cos\phi)}$$

need to reconstruct hadronic recoil for p_t^{ν}

Calibration of energy scale and hadronic recoil with Z events

$\Rightarrow$ main systematics is from Z statistics

Theoretical uncertainties:

- PDFs: 15 MeV (mainly from edge effects) PDF error might increase using new PDF fits with errors
- higher order QED $10 - 20$ MeV
- $p_t(W)$ model 5 MeV (extrapolation from Z to W)

Summary Tevatron

- $m_\mathrm{W} = 80.454 \pm 0.059\,\mathrm{GeV}$
- systematics dominated, however largest part from Z statistics
- PDF error might be underestimated, but only 15 MeV

$\alpha(m_Z)$

All uncertainties in $\alpha(m_Z)$ come from the light hadronic contribution $\Delta\alpha^{(5)}_{\mathrm{had}}$

"official" number:

$$\begin{aligned} \Delta\alpha^{(5)}_{\mathrm{had}} &= 0.02761 \pm 0.00036 \\ (\Rightarrow \Delta \sin^2\theta^l_{eff} &= 0.00013 \\ \Delta m_{\mathrm{W}} &= 6.6\,\mathrm{MeV}) \end{aligned}$$

(Burhardt, Pietrzyk, data driven including preliminary CMD2)

Equivalent analysis from Jegerlehner:

$$\Delta\alpha^{(5)}_{\mathrm{had}} = 0.027896 \pm 0.000395$$

Is there a 0.8σ uncertainty from the analysis method?

Updated analysis from Jegerlehner including final CMD2:

$$\Delta\alpha^{(5)}_{\mathrm{had}} = 0.027572 \pm 0.000359$$

Should become new "official" value

The $e^+e^- - \tau$ problem:

- for $g-2$ the hadronic contribution differs by 3σ if e^+e^- or τ data are used in the ρ region
- for $\Delta\alpha^{(5)}_{\mathrm{had}}$ this would mean 0.8σ

If $2 \times 0.8\sigma$ is added to the $\Delta\alpha^{(5)}_{\mathrm{had}}$ uncertainty, the error on $\log(m_{\mathrm{H}})$ increases by 10%

"Theory driven" analyzes

- theory driven analyzes improve error by ~factor two
- within the errors the data driven analysis agrees with all theory driven ones
- however it is not clear if the theory driven analyzes agree amongst each other

Conclusions on $\alpha(m_Z)$

- the general conclusions of the electroweak fit are not affected by problems with $\alpha(m_Z)$
- however some progress highly desirable:
  - data driven:
    * understand the differences in the "equivalent" analyzes
    * understand the $e^+e^- - \tau$ problem
  - theory driven
    * do the numbers agree?
    * can we agree on one method which we could use as the "official number"?

Luminosity Theory

- $\mathcal{L}$ is measured from low angle Bhabha scattering
- in the LEP parameterization $\mathcal{L}$ affects only σ_0
- the luminosity calculation is done with Bhlumi plus some additional calculations (2nd order sub-leading contributions plus light pairs)
- present error 0.06%, included in fit χ^2
  dominant error sources:
  - technical precision 0.03%
  - missing photonic correction 0.03%
  - light pairs 0.03% (0.01%)
  - hadronic vacuum polarization 0.04%

  The Vpol error could be reduced to 0.025%
  Attention:
  - this would change the central value
  - the dominant contribution comes from the ρ-region ($e^+e^- - \tau$-problem)
- a 0.1% change in σ_0 would change χ^2 by 2 and α_s by $< 0.5\sigma$, (and N_ν by 0.9σ) rest unaffected
- the present error estimate looks solid although a cross check would be desirable

Pseudo Observables

3-step procedure:

experimental signals → realistic observables → pseudo-observables

- experimental signals: what is measured in the detector, per definition no theory uncertainty
- realistic observables: cross sections, asymmetries within simple cuts, necessarily some dependence on QED, QCD (+exotic models)
- pseudo-observables: "particle properties" of Z, W: masses partial width g_V/g_A (via asymmetry parameter $\mathcal{A}_f$) model dependence: additional QED, QCD corrections, γ-exchange, γ-Z-interference (partly), imaginary parts of couplings

Within SM:

- theoretical uncertainties on pseudo-observables typically less than 1/10th of the experimental error
- fits of m_{H}, m_{t}, α_s to realistic observables and to pseudo-observables derived form these realistic observables give identical results

Uncertainties in the Electroweak Predictions

- Most important observables are m_{W} and $\sin^2\theta^l_{eff}$
- m_{W} from m_{Z} and G_{F} now complete to 2nd order
  estimated precision $m_{\mathrm{W}} =\approx 5\,\mathrm{MeV}$
- For $\sin^2\theta^l_{eff}$ important 2-loop parts missing
  uncertainty from extrapolating m_{W} 2-loop effects: $\Delta\sin^2\theta^l_{eff} = 8\cdot 10^{-5}$
  (1/2 the experimental error!)
- 2-loop effects for other observables (e.g. Γ_f) of minor importance
- These errors are included in the blueband width

Going beyond the SM: MSSM Fit

- heavy SUSY = SM with light Higgs
- SUSY can fit m_W (summer02) and g-2 better than SM
- no improvement for $\sin^2\theta(\nu N)$ and $A^\mathrm{b}_\mathrm{FB} - A_\mathrm{LR}$ discrepancy
- overall χ^2 probability similar
- The theoretical uncertainties within the MSSM a about a factor two larger than in the SM

The data are definitely compatible with Supersymmetry

However they don't prefer the MSSM over the SM

The Summary of the Summary

- All data are consistent with the SM on the 4% level
- The largest deviation (2.9σ) is $\sin^2\theta(\nu N)$
  - it is still not impossible that this is a fluctuation
  - but definitely a large effort is needed to understand this number
- For the electroweak quantities the predictions seem reliable
  - for m_W the full 2-loop is available
  - the error estimate for $\sin^2\theta^l_{eff}$ isn't frightening
  - nevertheless it is very important to get a prediction for $\sin^2\theta^l_{eff}$ on the same level as m_W
- Also $\alpha(m_\mathrm{Z})$ cannot alter the conclusions but progress is still important
- All in all the light Higgs prediction seems rather robust