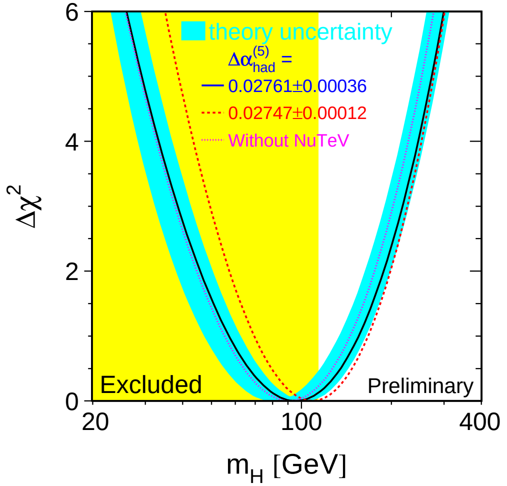
# ELECTROWEAK FIT

Günter Quast, Universität Karlsruhe
ALEPH experiment & LEP electroweak working group




EPS, Aachen, July 17 - 23, 2003

Session:Tests of the Standard Model

**Precision (pseudo-)observables $O_i$** depend on
**Standard Model parameters** $\alpha_{em}(m_Z)$, $m_Z$, $\alpha_s$, $m_t$ and on the Higgs mass $m_H$
(and on $G_F$ and on all fermion masses)

With the exception of $m_H$, all input parameters are constrained by measurements
($\alpha_s$ constrained with high precision by $\Gamma_{had}$ from LEP 1)

**Four classes of precision measurements ...**

| | | | | |
|---|---|---|---|---|
| $\rho_{eff}^{lept}$ | = | $1.0049 \pm 0.0010$ | $\Gamma_{\ell\ell}$ (& $\Gamma_{inv}$) | LEP 1 |
| $\sin^2\theta_{eff}^{lept}$ | = | $0.23150 \pm 0.00016$ | $A_{FB}$, $A_{LR}$, $\tau$-Pol. | LEP 1, SLD |
| $R_b$ | = | $0.21638 \pm 0.00066$ | $\Gamma_{b\bar{b}} / \Gamma_{had}$ | LEP 1, SLD |
| $m_W$ | = | $80.426 \pm 0.034$ GeV | | LEP 2, CDF, D0 |

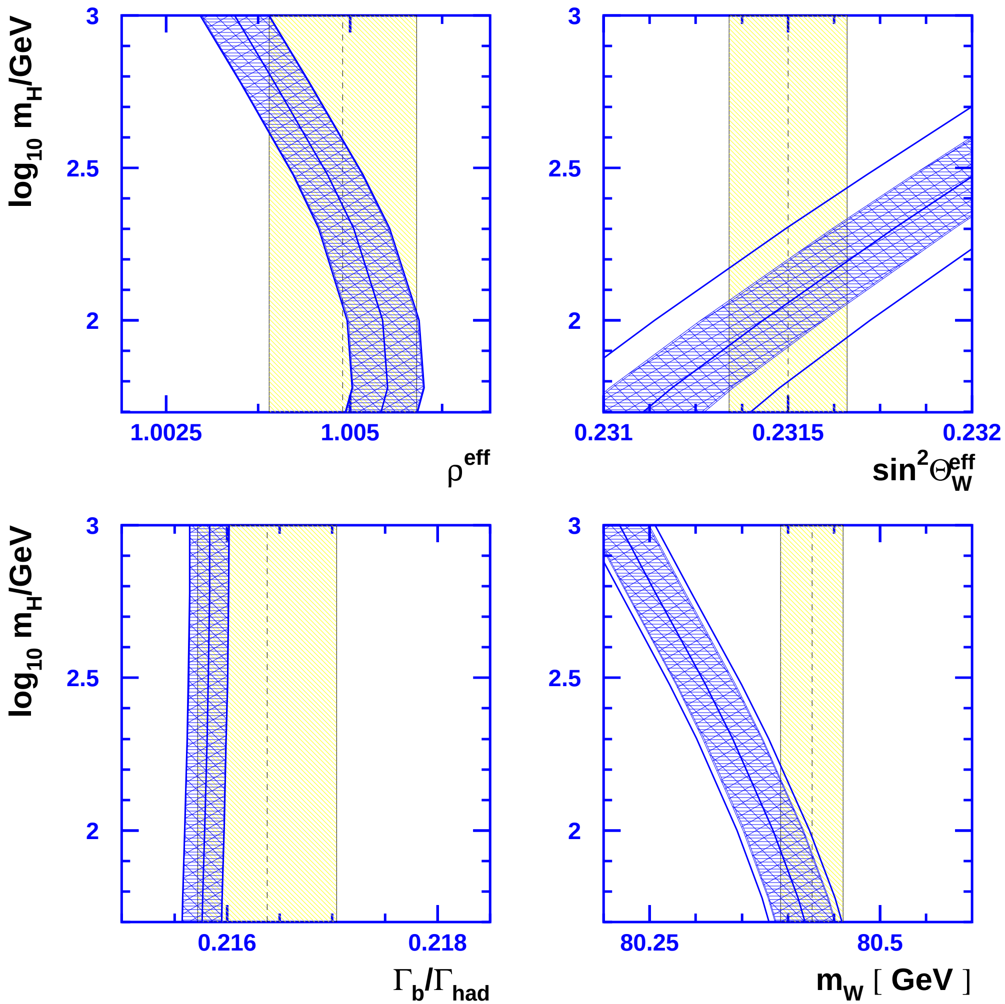
... plus a few others **are used in the "electroweak fit" to**

- test the consistency
- predict the Higgs boson mass within the framework

of the Standard Model

**LEP EWWG combines measurements and performs the ew fits**

## Comparison with Standard Model



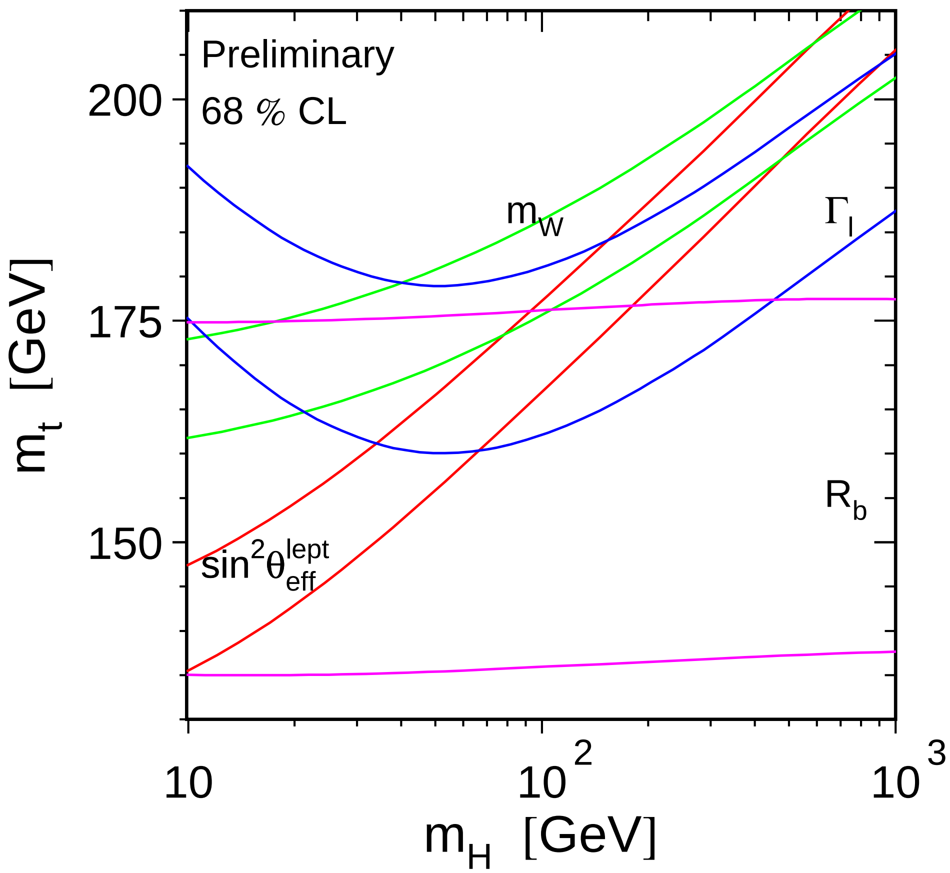

no $\alpha_S$ dependence in these observables

dark hatched: $m_t$ dependence, for $m_t = 174.3 \pm 5.1$ GeV

light area: $\alpha(m_Z)$ dependence for $1/\alpha^5(m_Z) = 128.936 \pm 0.049$

$(\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036)$

### Bands in the $m_H - m_t$ plane



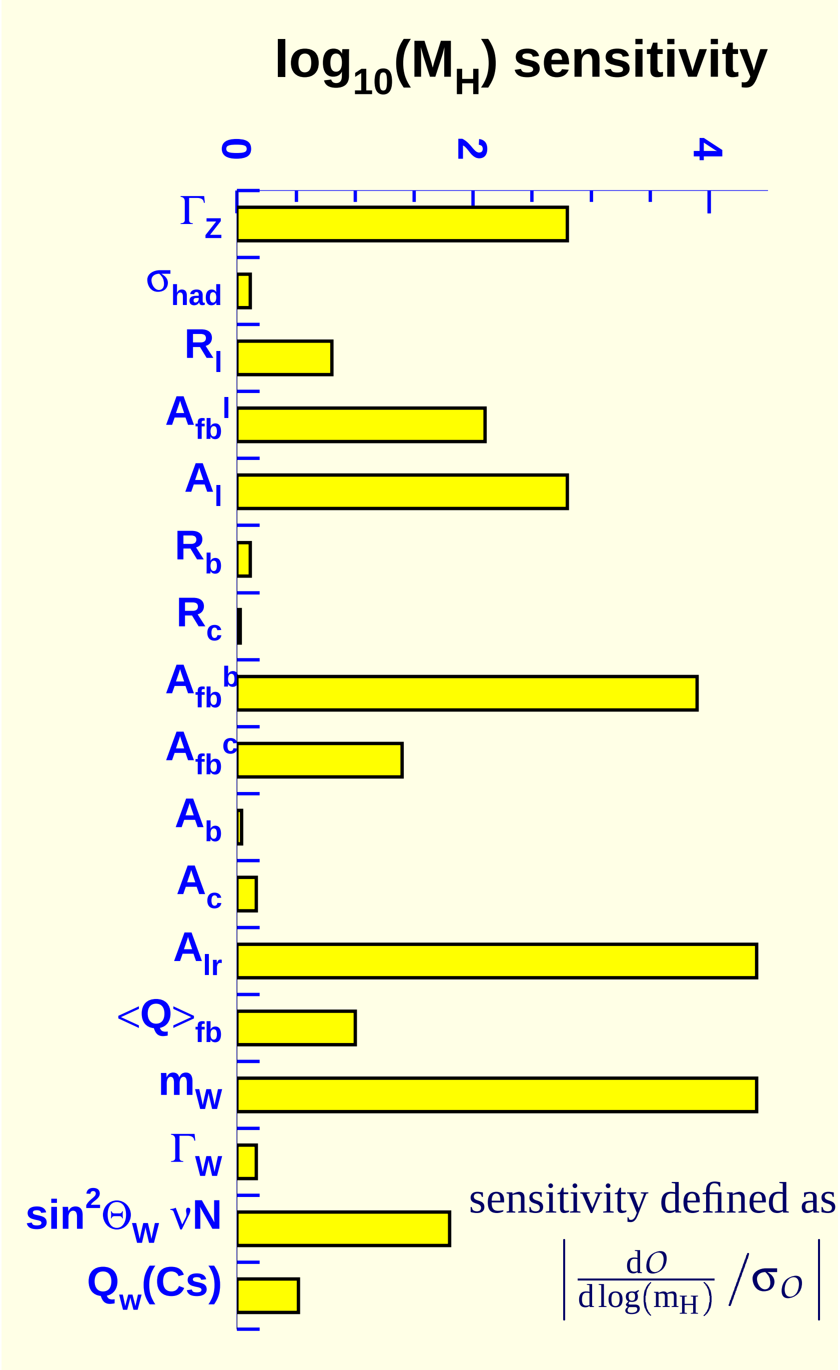

**Note:** Real Higgs-strahlung neglected; modifies $\Gamma_Z$ and partial widths, depends on experimental acceptance. **Important only for** $m_H < 50$ GeV

## More than 100 measurements ...

... reduced to 20 precision observables:

- $m_Z$, $\alpha(m_Z)$, $m_t$ **(published)** SM input
- lineshape LEP 1 **(published)**
  +correlation matrix
- $\tau$ polarisation LEP 1 **(final)**
- heavy flavour LEP 1, SLD **(almost final)**
  +correlation matrix (upd. summer '03)
- $A_{LR}$ SLD **(published)**
- $Q_{FB}$ LEP 1 **(final)**
- $m_W, \Gamma_W$ LEP 2 & Tevatron **(preliminary)**
  new LEP result winter '03
- $\sin^2\theta_W(\nu N)$ NuTev **(published)**
- atomic parity violation **(published)**
  new theory corrections, very small change)

Not all measurements are highly sensitve to EW corrections ⟶



Comparision with Standard Model at best-fit point of $m_Z$, $\alpha_{em}(m_Z)$, $\alpha_s$, $m_t$ and $m_H$ →

$\chi^2 = 25.4/15$ d.o.f, probability 4.5 %

very low prob., needs deeper discussion !

**largest contributions to $\chi^2$:**

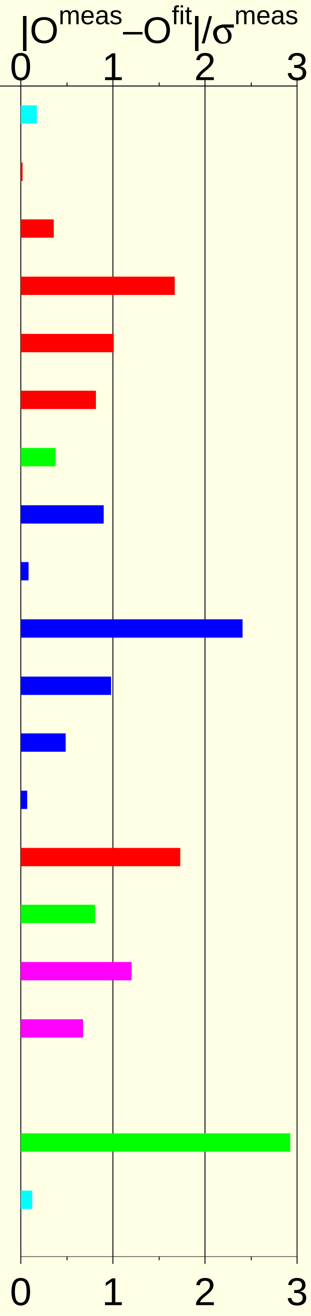
- $\sin^2\theta_W(\nu N)$ NuTeV

  relatively low sensitivity

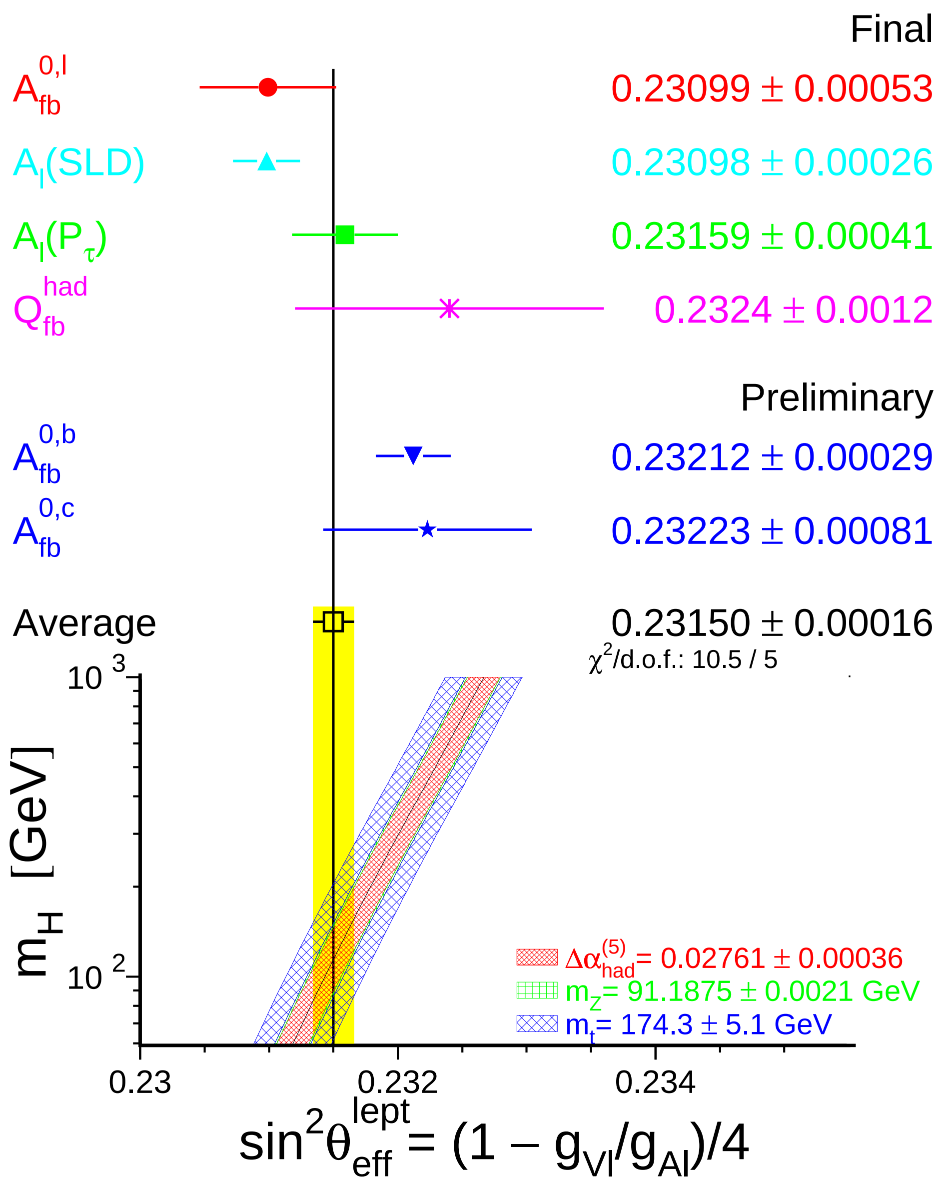
- $A_{FB}^{0,b}$ LEP 1
- $A_{LR}$ SLD

  among the largest sensitivities, both are measurements of the same quantity, $\sin^2\theta_{eff}^{lept}$

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02761 ± 0.00036 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1875 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4960 |
| $\sigma_{had}^0$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01636 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1477 |
| $R_b$ | 0.21638 ± 0.00066 | 0.21579 |
| $R_c$ | 0.1720 ± 0.0030 | 0.1723 |
| $A_{fb}^{0,b}$ | 0.0997 ± 0.0016 | 0.1036 |
| $A_{fb}^{0,c}$ | 0.0706 ± 0.0035 | 0.0740 |
| $A_b$ | 0.925 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.026 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1477 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.426 ± 0.034 | 80.385 |
| $\Gamma_W$ [GeV] | 2.139 ± 0.069 | 2.093 |
| $m_t$ [GeV] | 174.3 ± 5.1 | 174.3 |
| $\sin^2\theta_W(\nu N)$ | 0.2277 ± 0.0016 | 0.2229 |
| $Q_W$(Cs) | -72.84 ± 0.46 | -72.90 |



## The $\sin^2\theta_{\rm eff}$ problem




Assuming **lepton universality**, there are 6 input measurements.

- $\chi^2$ of combination is 10.5/5 d.o.f, probability only 6.2 %
- two most precise measurements, $\mathcal{A}_\ell$(SLD) and $A_{FB}^{0,b}$, deviate by 2.9 $\sigma$
- problem is not new, many checks done
- average w.o. $\mathcal{A}_\ell$(SLD) $\Rightarrow$ prob=39 %
  average w.o. $A_{FB}^{0,b}$ $\Rightarrow$ prob=37 %
  $\Longrightarrow$ **other measurements don't discriminate between $\mathcal{A}_\ell$(SLD) and $A_{FB}^{0,b}$**

**No convincing model known that might explain the $\mathcal{A}_\ell$(SLD) – $A_{FB}^{0,b}$ discrepancy.**

To continue,

**assume reason is statistical fluctuation**

Global fit with average $\sin^2\theta_{\rm eff}^{\rm lept}$

$\Longrightarrow \chi^2 = 15/10$ d.o.f, **probability = 13 %**

## $\sin^2\theta_W(\nu N)$ **problem** - $\mu_\nu(\overline{\mu_\nu})\ q$ scattering, charged (CC) and neutral (NC) current

Paschos-Wolfenstein relation for iso-scalar target:

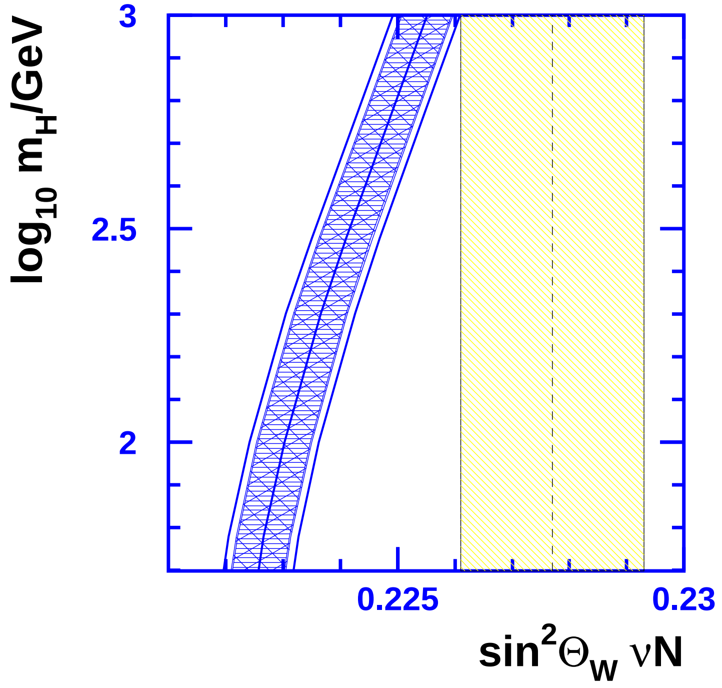
$$R_- = \frac{\sigma_{NC}(\nu)-\sigma_{NC}(\bar\nu)}{\sigma_{CC}(\nu)-\sigma_{CC}(\bar\nu)} = 4\,g_{L\nu}{}^2 \sum_{q\nu}\left[g_{Lq}{}^2 - g_{Rq}{}^2\right] =$$

$$\rho_\nu\,\rho_{ud}\left[\tfrac{1}{2}\sin^2\theta_W{}^{(on-shell)}\right] + \text{electroweak corrections}$$

Measurement of eff. couplings at $< Q^2 > \simeq 20\,\mathrm{GeV}^2$,
historically quoted as $\sin^2\theta_W = 1 - m_W^2/m_Z^2$

**Factor two more precise than old world average**

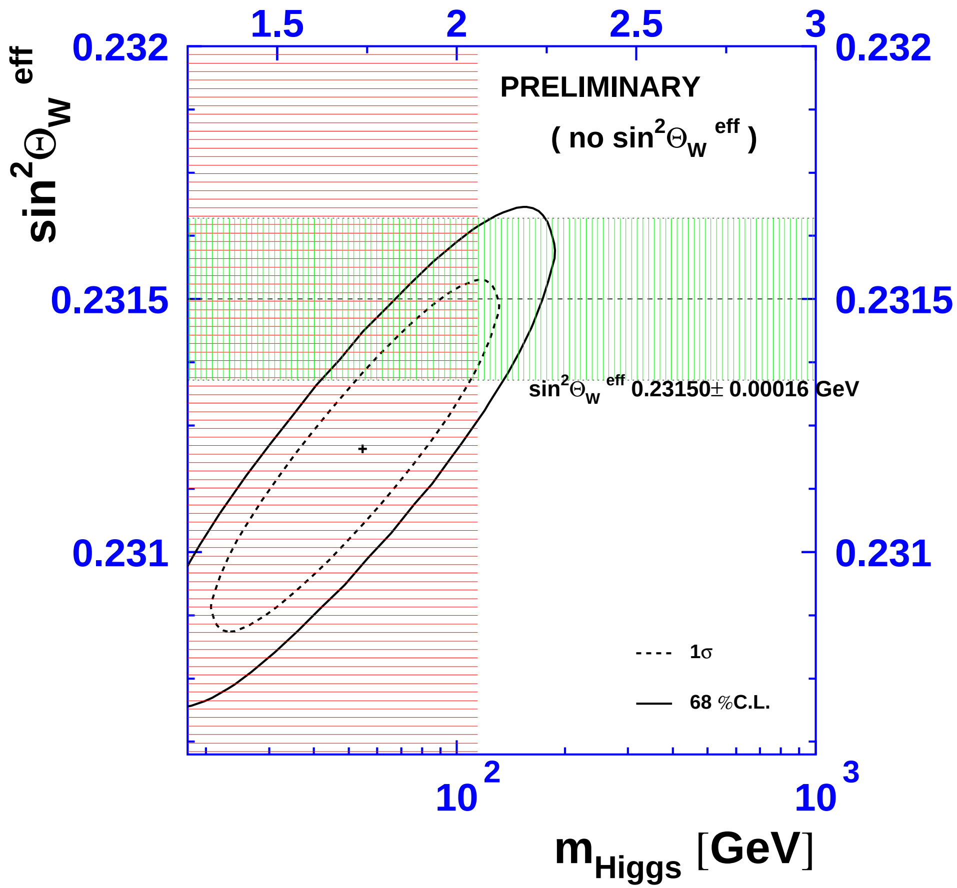
$2.9\,\sigma$ **away from SM prediction !**

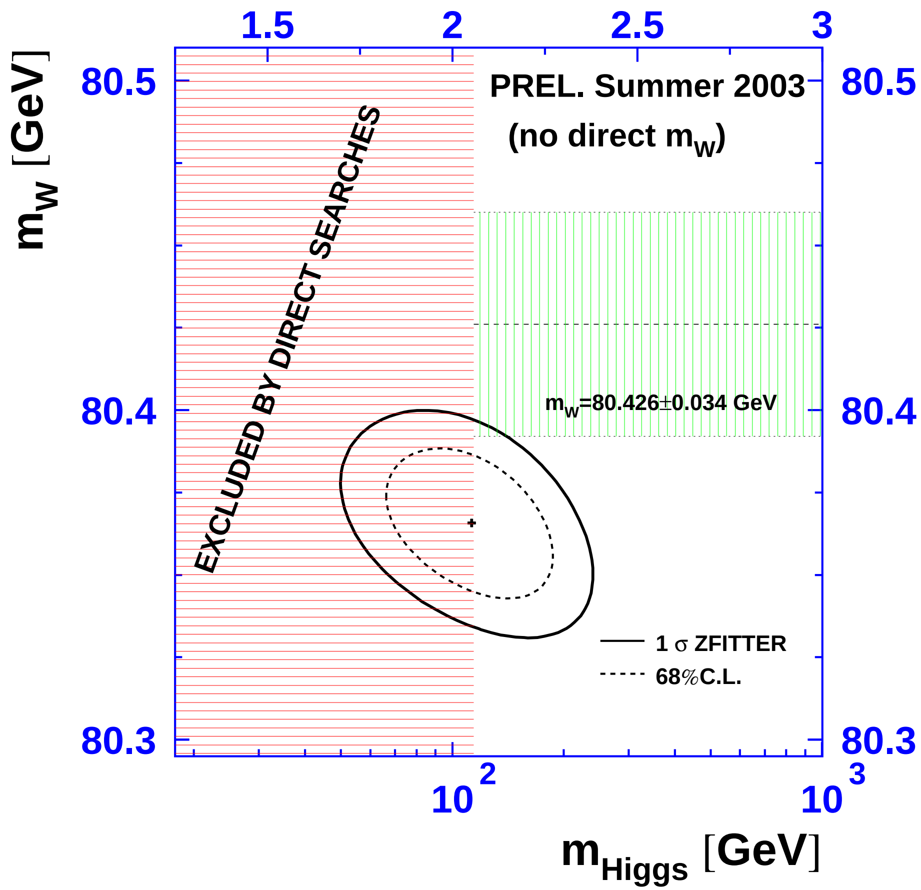



- Perform e.w. fit **without** $\sin^2\theta_W(\nu N) \Rightarrow$ $\chi^2$ probability = 28 %
  - – shift in $m_H$ of only -5 GeV
  - – error $\Delta\log(m_H)$ increases only slightly (from 0.21 to 0.22)

$\Longrightarrow$ “problem” factorises out from global EW fit !

## Indirect vs. direct measurements - $\sin^2\theta_{eff}^{lept}$ and $m_W$




indirect $\sin^2\theta_{eff}^{lept} = 0.23120 \pm 0.00038$

indirect $m_W = 80.373 \pm 0.023$ GeV

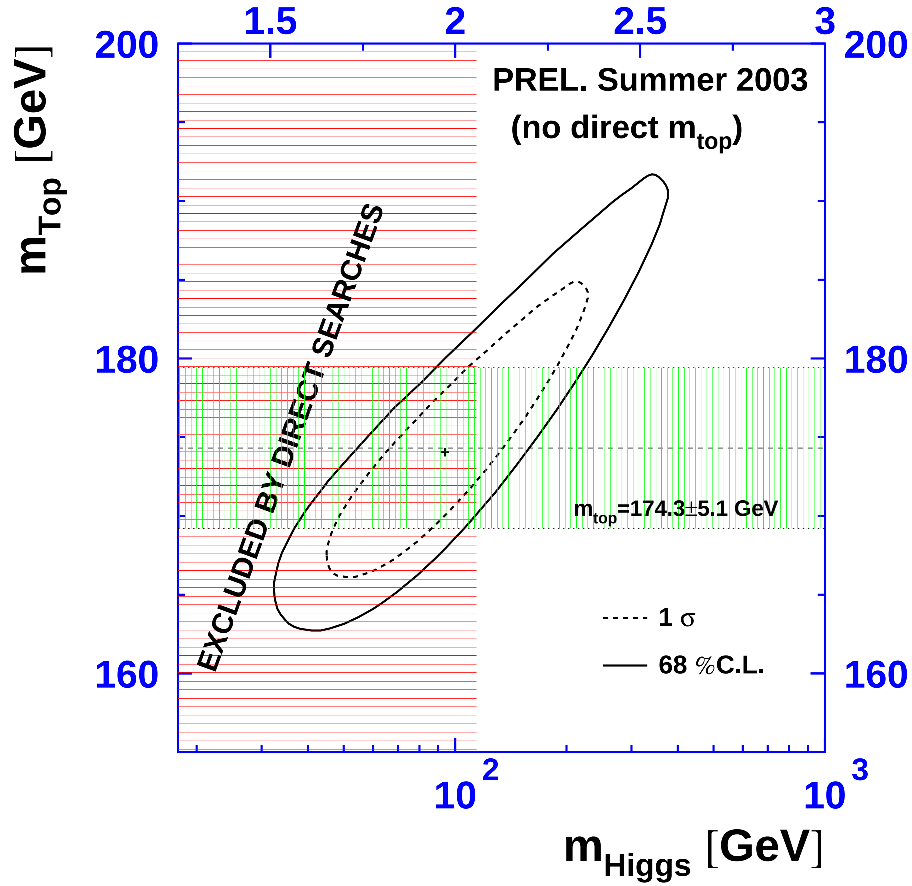
**consistent** √

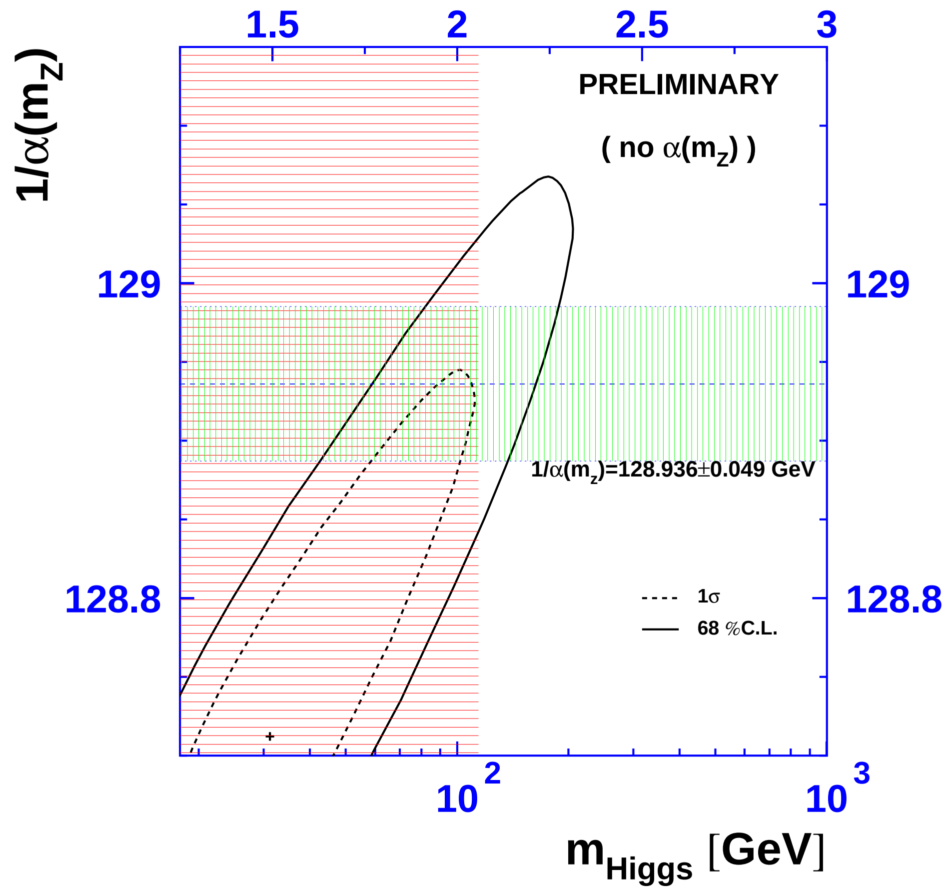
**direct measurement much more precise**

**consistent** √

**direct measurement still less precise**

## Indirect vs. direct measurements - $m_t$ and $\alpha(m_Z)$




indirect $m_t = 174.0^{+11}_{-8}$ GeV

**very consistent** √

**improvements on top mass from Tevatron soon !**

indirect $1/\alpha(m_Z) = 128.71 \pm 0.17$

**consistent** √

**improvements on experiment-driven evaluation very soon**

## A first conclusion:

The almost 3 $\sigma$ discrepancy of $\sin^2\theta_W(\nu N)$ from the Standard Model expectation is the main reason for the low probability of the overall fit.
Its sensitivity to (known) electroweak corrections is small.

The 2nd largest single contribution is the 3 $\sigma$ discrepancy between $\mathcal{A}_\ell(\text{SLD}) - A_{FB}^{0,b}$.

All other measurements are very consistent with each other and with SM!

- global fit with average $\sin^2\theta_{\text{eff}}^{\text{lept}}$ and w.o. $\sin^2\theta_W(\nu N)$
  $\Rightarrow \chi^2 = 6.4/9\,\text{d.o.f}$, **probability = 70 %** **more than satisfying !**

All possible checks of the $\sin^2\theta_W(\nu N)$ result
must be performed to see if the problem is
experimental, theoretical, just a fluctuation or “new physics” !

## Results - from fit to **all** data

Fit with ZFITTER 6.36

$\chi^2/N_{df} = 25.4/15$, **prob=4.5%**

| observable | fit | input |
|---|---|---|
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | $91.1875 \pm 0.0021$ |
| $m_t$ [GeV] | $174.3 \pm 4.5$ | $174.3 \pm 5.1$ |
| $\Delta\alpha^{(5)}_{had}$ | $0.02767 \pm 0.00035$ | $0.02761 \pm 0.00036$ |
| $m_H$ [GeV] | $96\ ^{+60}_{-38}$ | |
| $\alpha_s$ | $0.1186 \pm 0.0027$ | |
| derived: | | |
| $\sin^2\theta^{lept}_{eff}$ | $0.23143 \pm 0.00014$ | |
| $m_W$ [GeV] | $80.385 \pm 0.019$ | |

largest correlations: $m_H - m_t$: 71 % $m_H - \Delta\alpha^{(5)}_{had}$: 48 %

(high value of $\chi^2$ discussed already)

## Strong coupling constant

$\alpha_s$ from $R_\ell$ only

$$\alpha_s = 0.1224 \pm 0.00038 \left(\begin{matrix}+0.0033\\-0.000\end{matrix}\right)_{m_\mathrm{H}}$$

$\alpha_s$ from $\sigma^o_{\mathrm{lept}}$

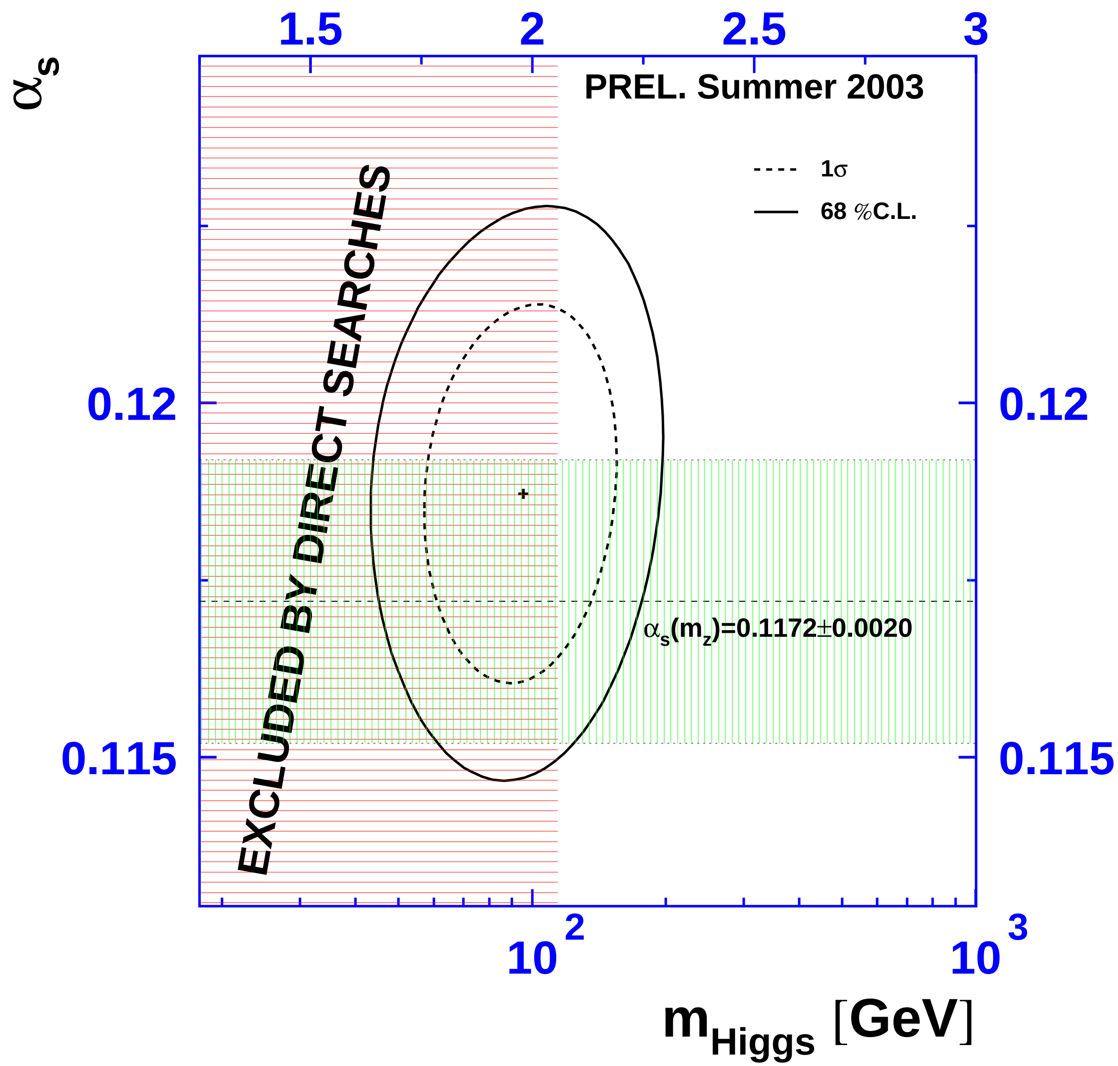
$$\alpha_s = 0.1180 \pm 0.0030 \left(\begin{matrix}+0.0026\\-0.000\end{matrix}\right)_{m_\mathrm{H}}$$

for $m_\mathrm{H} = 100^{+900}_{-0}$ GeV

$\alpha_s$ from **fit to all data**

$$\alpha_s = 0.1186 \pm 0.0027$$

**Note:** systematic QCD error ranging between ~0.0005 and ~0.003 (!!) still to be added




good agreement with PDG average! √

## Theoretical uncertainties - origin of the "blue band"

two fit programs:

- ZFITTER vers. 6.36 (June 21, 2001) D. Bardin et al.
- TOPAZ0 vers. 4.4 (February 22, 2001) G. Passarino et al.

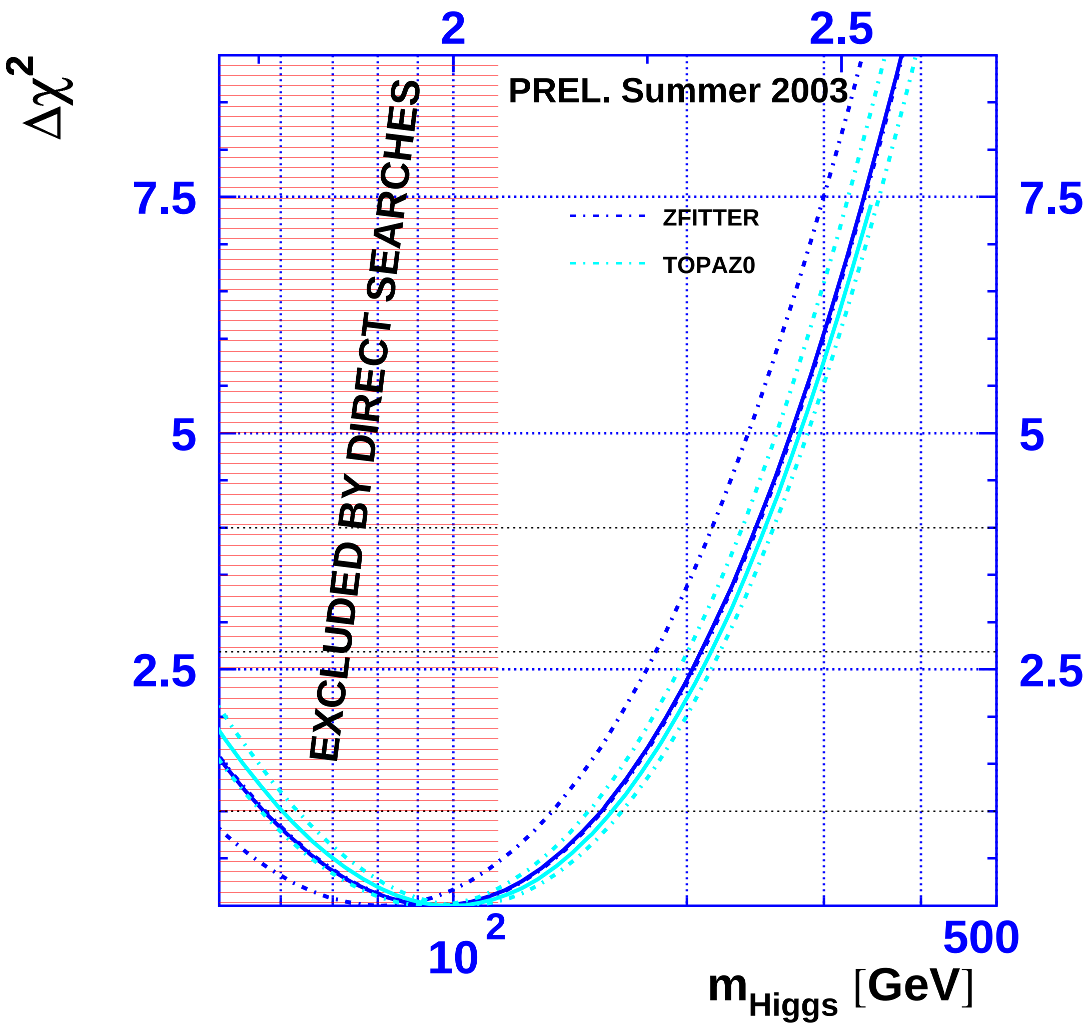
TOPAZ0-ZFITTER diference at minimum: **2** GeV

**Vary options one by one - extremes as uncertainty**

limiting curves:

low side:
2-loop $m_W$ (Freitas *et al.*)

high side:
TOPAZ0 w. special option




Note: two-loop corrections on $m_W$ complete, missing for $\sin^2\theta_{eff}^{lept}$, leading three-loop for $m_W$ and $\sin^2\theta_{eff}^{lept}$ ready (see talk by G. Weiglein)

Upgrade of fit programs this year!?

## Higgs limit

Fit to all data:

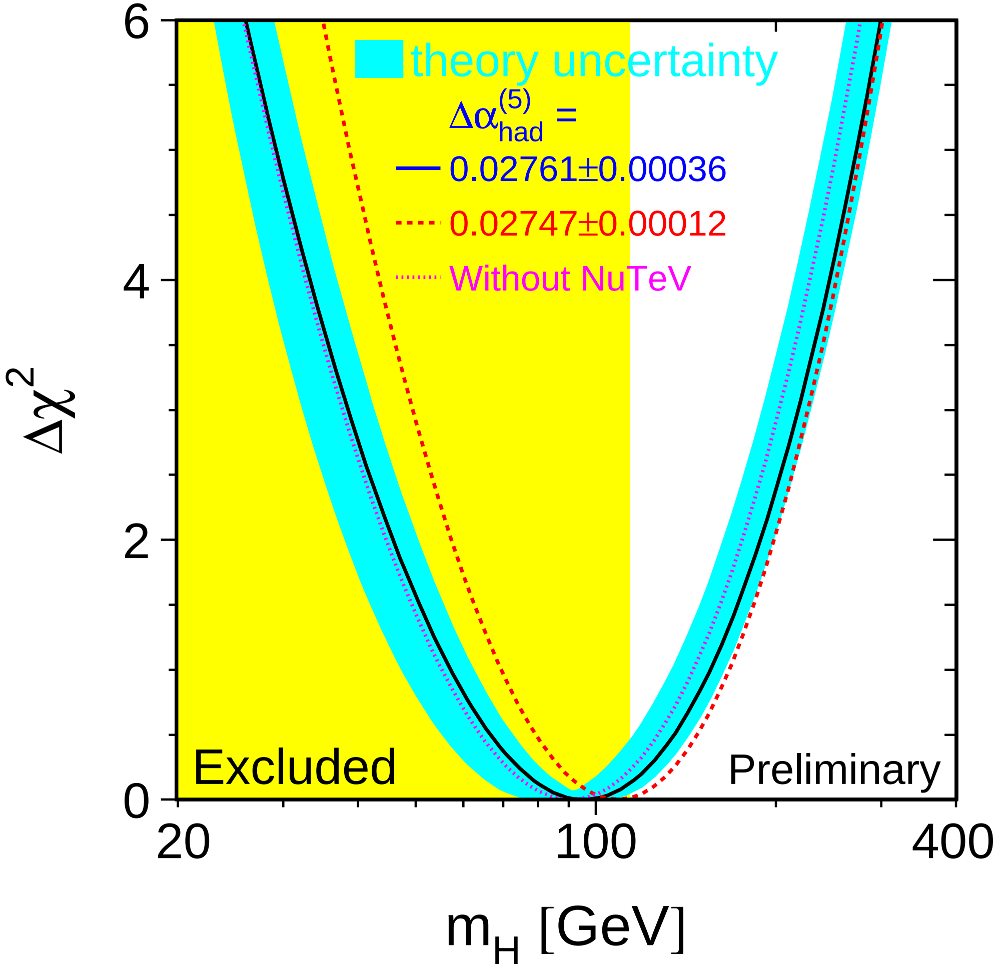
– dark-blue: ZFITTER 6.36

– one-sided 95 % CL limit at
  $\Delta\chi^2 = 2.69$ (1.64 $\sigma$)

– light-blue band: syst. theory error

– dashed magenta: without NuTeV
  small effect: limit ∼15 GeV lower

– dashed red: theory-driven $\alpha(m_Z)$
  curve shifted, smaller error, limit almost unchanged




$$m_H = 96^{+60}_{-38}\,\text{GeV}$$

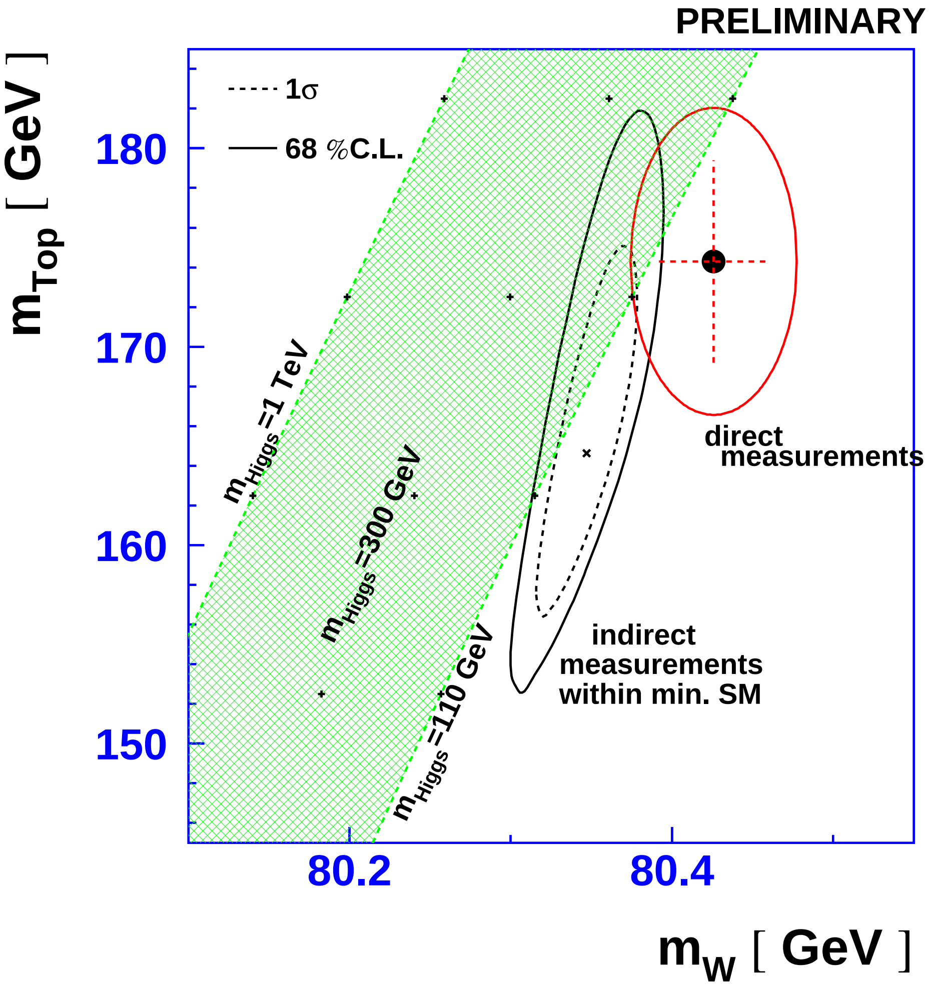
$$m_H < 219\,\text{GeV @ 95 \%CL (1-sided)}$$

## $m_W$ and $m_t$ - direct vs. indirect

- Measurements of $m_W$ preliminary
- marginal agreement of direct measurements with indirect determination
- new round of $m_W$ and $m_t$ measurements (soon) from Tevatron

**Note:** Area right of the green band better accommodated by Supersymmetry

**Where will $m_W$ & $m_t$ finally end up?**




$$\text{indirect } m_W = 80.347 \pm 0.031\,\text{GeV}$$

$$\text{indirect } m_t = 164.6\ ^{+10.}_{-8.2}\ \text{GeV}$$

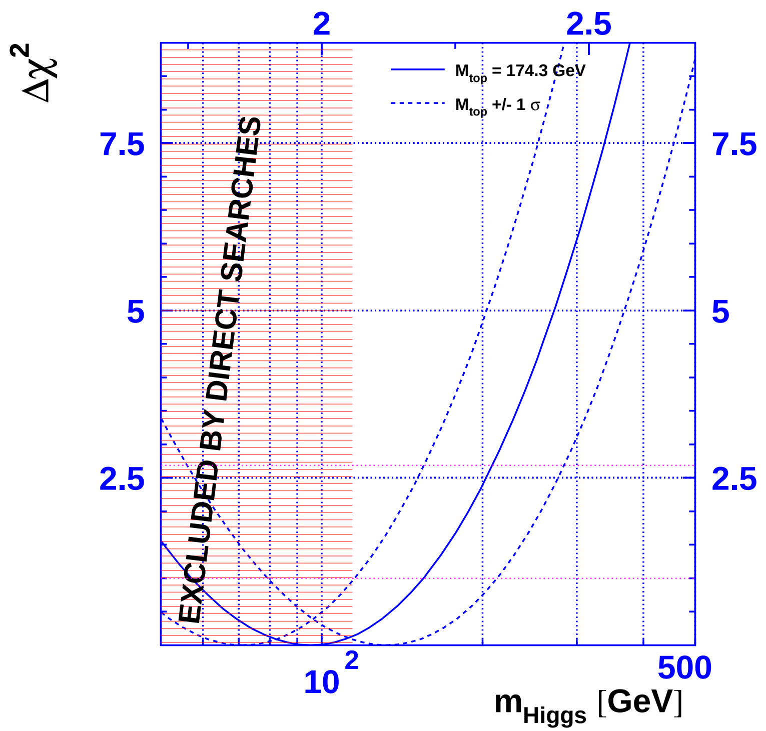
correlation 82 %

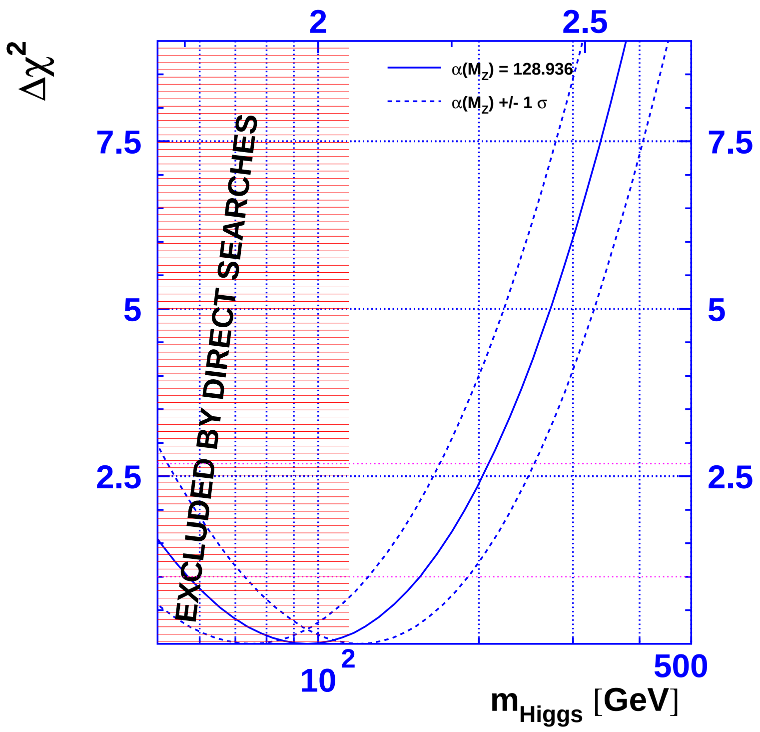
## Dependence on Standard model INPUT - $m_t$ and $\alpha(m_Z)$

Changes of **SM input parameters** in the near future:

- CDF and D0 at Tevatron: $m_t$
- CMD 2, Novosibirsk and Kloe at Daphne: $\alpha(m_Z)$

**Fit results are VERY sensitive !**




$$\frac{d\log(m_H/GeV)}{d\,m_t} = 0.026\,/\mathrm{GeV}$$

$$\frac{d\log(m_H/GeV)}{d\,\Delta\alpha^{(5)}_{\mathrm{had}}} = -0.028/0.00010$$

## Conclusion:

- Despite two almost-three-$\sigma$ effects

  the Standard Model looks rather healthy.
- most precision results from LEP final or becoming final
- a new round of precision physics ahead of us

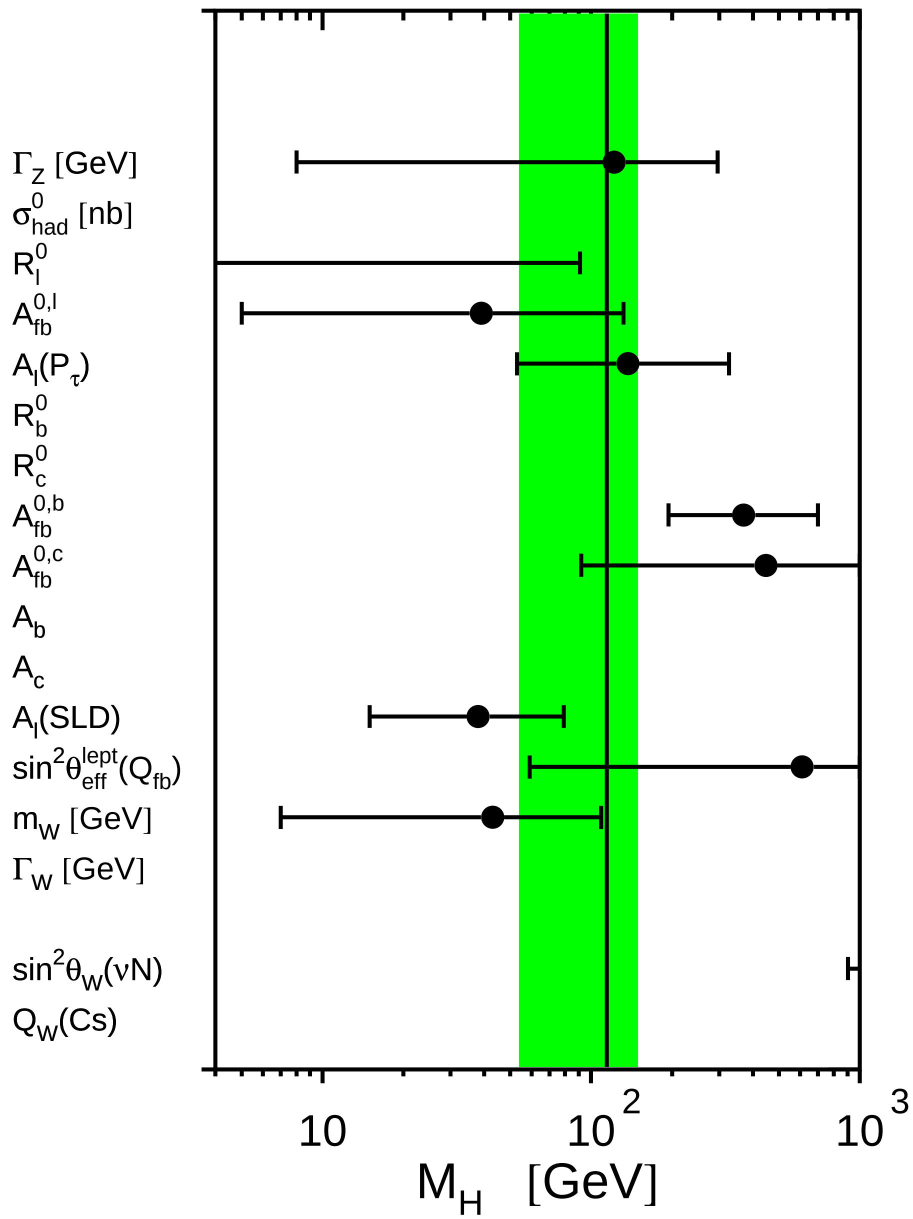
  – expect changes of / improvements on $m_W$, $m_t$
- job of the EWWG as a LEP dominated group approaching a natural end

  – who takes over ?

Thanks to my colleagues from the LEP EWWG
for averaging results, performing fits, producing plots ...
and for many years of fruitful collaboration.

Particular thanks to Martin Grünewald for group coordination
and for taking a large part of the bi-annual work load.

## *MH* from each measurement



## Change in $\Delta\alpha_{had}^{(5)}$

by including recent re-evaluation of radiative corrections by CMD-2

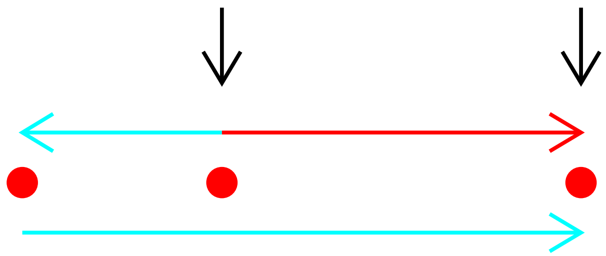
Contributed Paper, Abstract ID-126
by B. Pietrzyk and H. Burkhardt

Effect on $m_H$

– mean value 4 GeV lower
– 95 % mass limit 9 GeV lower

**Burkhardt, Pietrzyk**

| | 2001 published | 2003 preliminary |
|---|---|---|
| $\Delta\alpha_{had}$ | 0.02761±0.00036 | 0.02768±0.00036 |



**CMD2 2001 published -10%** | **1999 prelimary** | **2003 revised +18%**

**of total uncertainty on $\Delta\alpha_{had}$**