Title

Electro-weak Measurements from Z^0 production

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The nearly final measurement of
M_Z and Γ_Z

Cross section measurements (briefly)

R_b and R_c

Consistency of leptonic and hadronic asymmetries

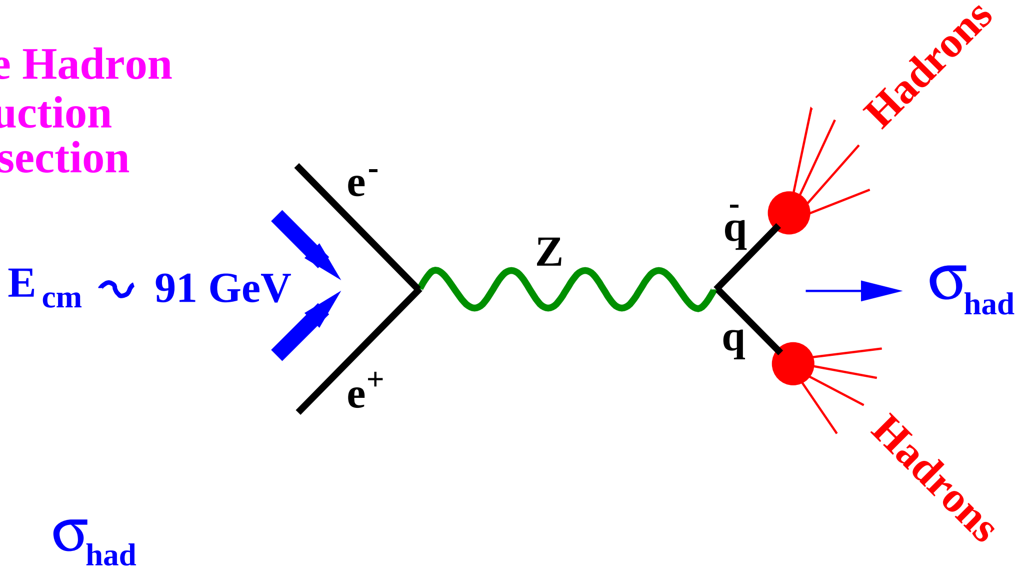
Interpretation
&
constraints upon M_H

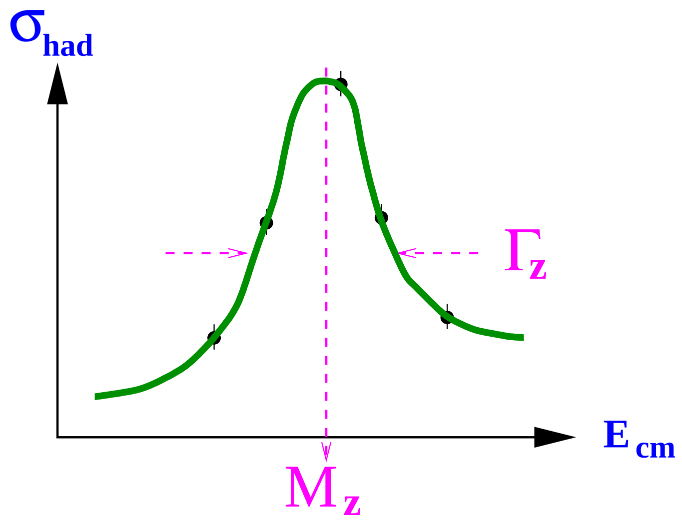
Results from
LEP: ALEPH, DELPHI, L3, OPAL
SLC: SLD
Tevatron: CDF, D0

Many thanks to
- the experiments
- the theoretical community
- the LEP electroweak group
(for combinations and many nice plots)

Measurement of M_Z and Γ_Z

Measure Hadron production cross-section





Ingredients:

Lep

Hadron events

Luminosity measurement

Beam energy calibration

Theoretical and experimental fitting tools

LEP History

Year	Int. Lumi. (pb^{-1}) on-peak	Int. Lumi. (pb^{-1}) off-peak
1989	1.3	
1990	6.8	
1991	8	5
1992	25	-
1993	16	18
1994	47	-
1995	9	18
Total:	100	50

History

Old energy calibration

Experiments install precision luminometers

High luminosity

"Pretzel"

Resonant depolarisation

Precision scan !

Bunch Trains

New NMR instrumentation

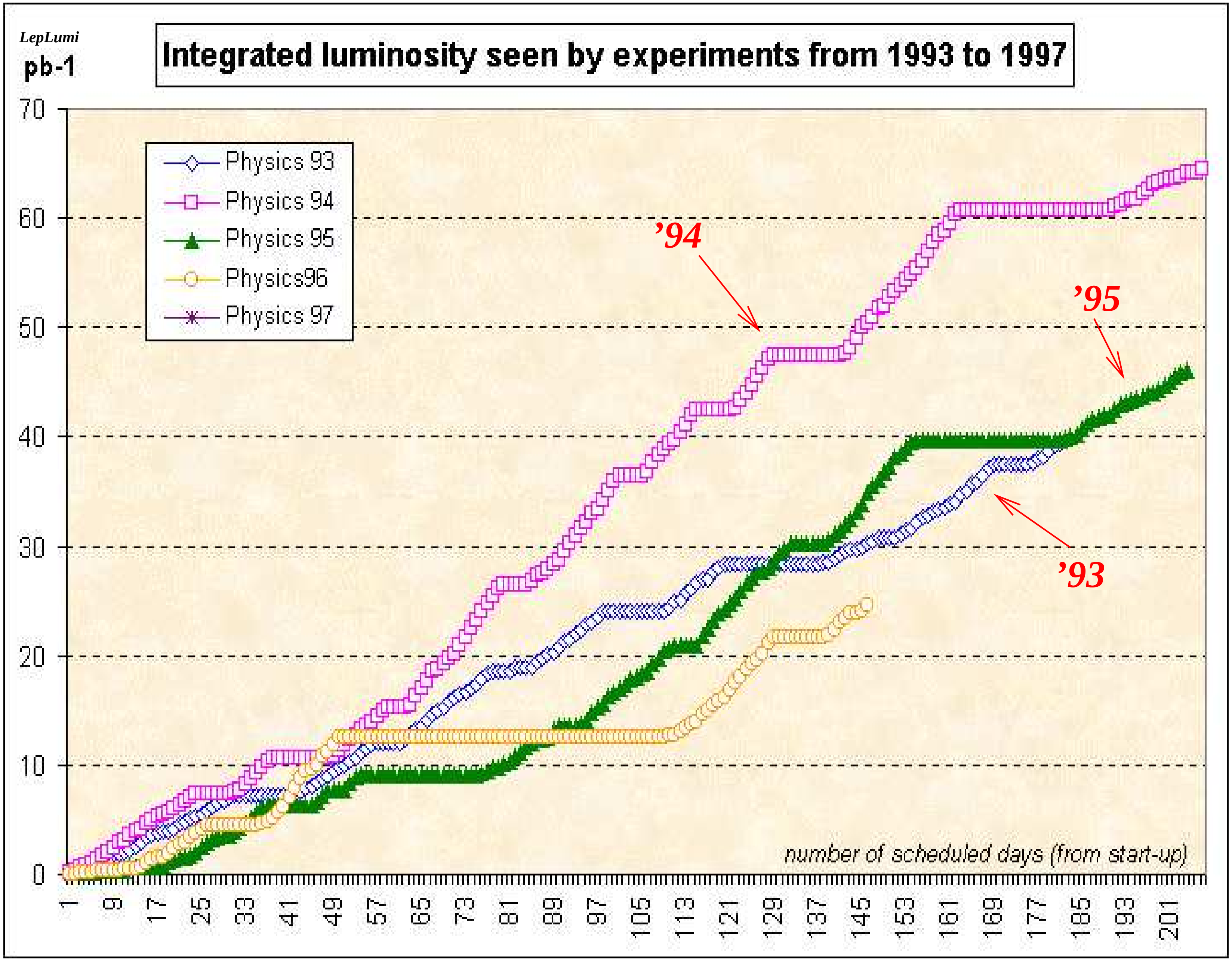
Precision scan !

⇒ 4 M hadronic events/exp.

- Experimental statistical precision:

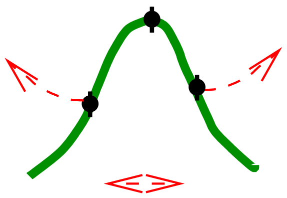
$$\Delta M_Z = 1.2 \text{ MeV}$$

$$\Delta \Gamma_Z = 2.0 \text{ MeV}$$


LepLumi
pb-1
Integrated luminosity seen by experiments from 1993 to 1997
0
10
20
30
40
50
60
70
Physics 93
Physics 94
Physics 95
Physics96
Physics 97
'94
'95
'93
number of scheduled days (from start-up)
1
9
17
25
33
41
49
57
65
73
81
89
97
105
113
121
129
137
145
153
161
169
177
185
193
201

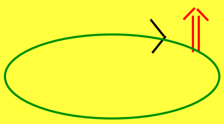
Lep Beam Energy Measurement

Error on energy scale affects M_Z



Anticorrelated error affects Γ_Z

• Resonant Spin Depolarisation



Very precise calibration: < 0.5 MeV

30% of fills calibrated in 1993 ⇒ *70% of fills calibrated in 1995*

- ***Precise measurements made infrequently***
  -> model needed to interpolate

- ***Many important effects on beam energy during fill:***

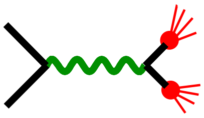
	Approx error on E_{cm}
-Field rise due to TGV	1.0
-Field rise due to temperature	1.0
-Horizontal correctors	0.3
-Tide	0.4
-Orbit drifts	0.5
-RF corrections	1.0
-Dispersion	0.7

Total
~ 1.5 MeV

- ***Present preliminary LEP energy errors:***

$$\Delta M_Z = 1.5 \text{ MeV}$$
$$\Delta \Gamma_Z = 1.7 \text{ MeV}$$

⇒ ***Final LEP energy calibration imminent !!***

Measurement of $Z^0 \rightarrow$ hadrons 

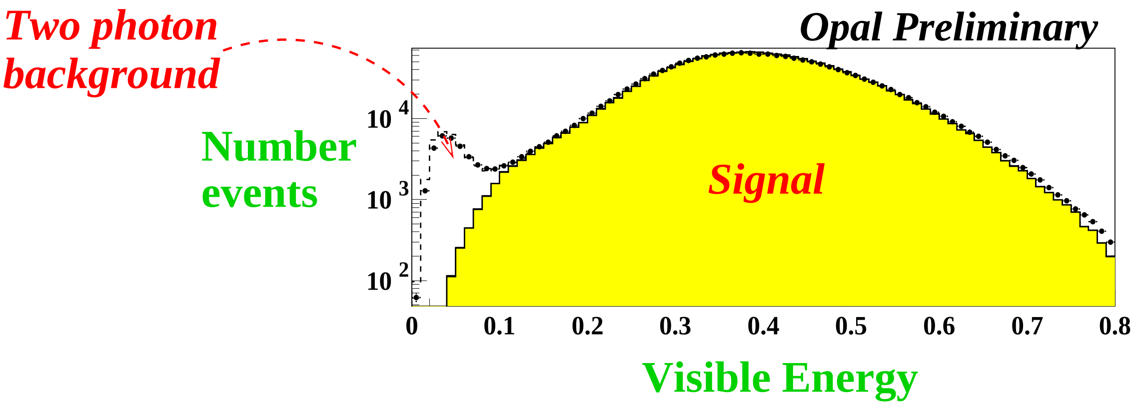
- **Selections:**
  - *-High multiplicity of tracks and clusters*
  - *-High visible energy*
  - *-Low momentum imbalance*

	Aleph	Delphi	L3	Opal
Acceptance (%)	99.1	96	99.4	99.5
Syst. error (%)	0.07	0.10	0.05	0.08

[Statistical precision 0.05% / exp]

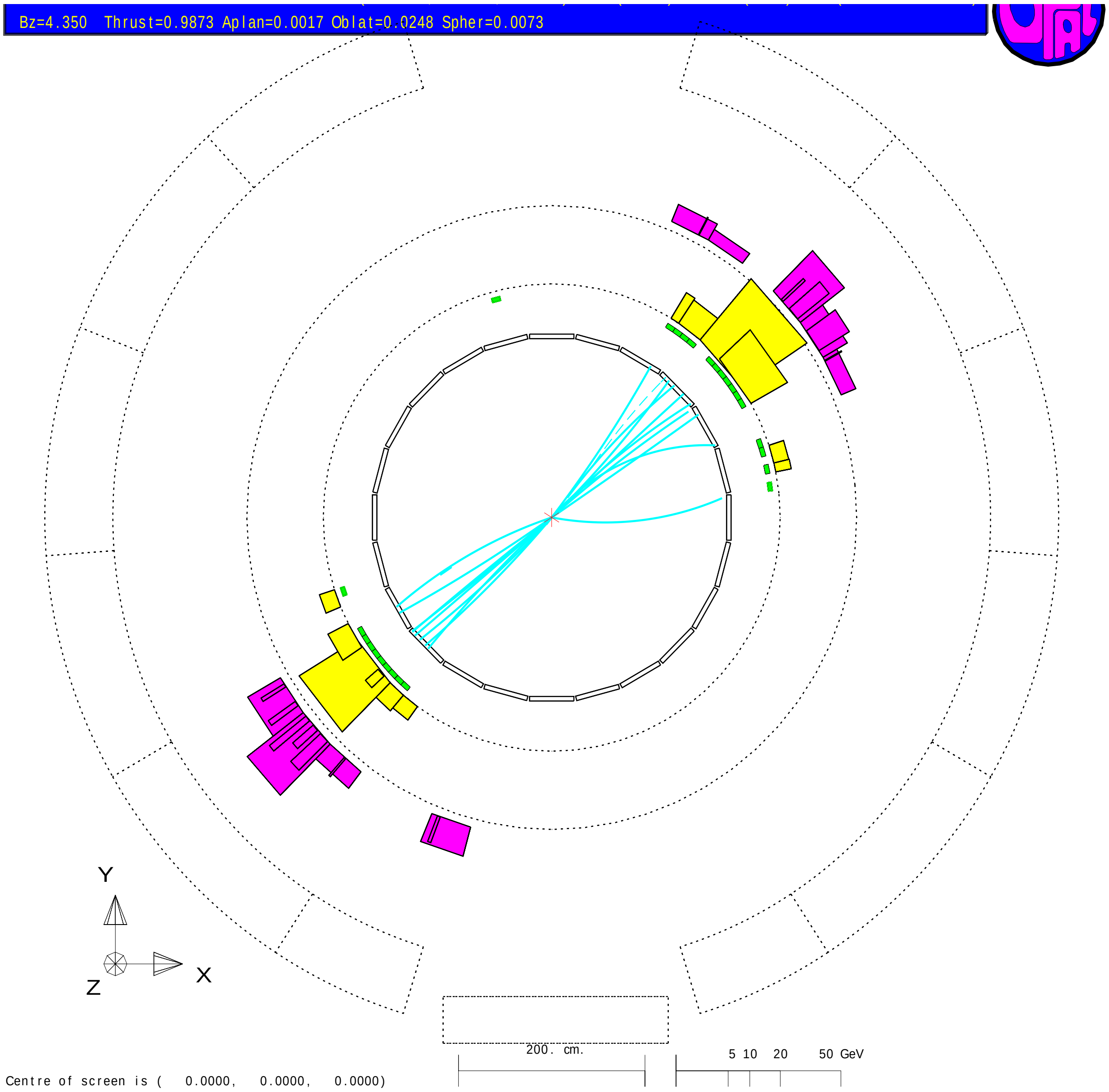
- **Backgrounds:**
  - *non-resonant (two-photon)* 0.2%
  - *ee -> $\tau\tau$* 0.2%

- **Data quality:**



- **Luminosity measurement:**
  - *- low angle Bhabha scattering*
  - *- precision Silicon position measurement + calorimeters*

-> typical experimental uncertainty 0.08%
-> theoretical uncertainty in Bhabha cross section 0.11%



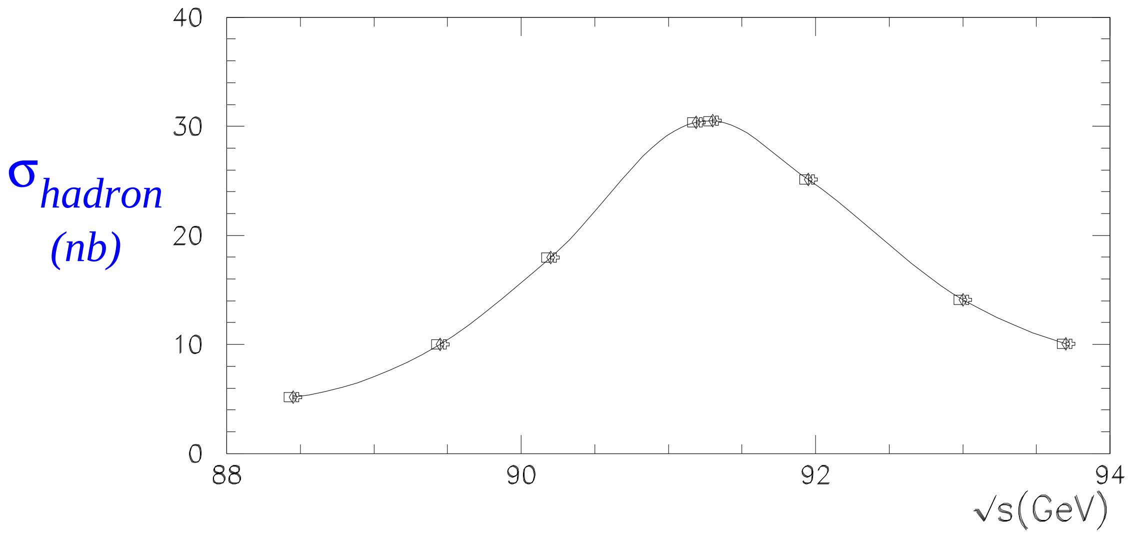
Bz=4.350 Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
Y
Z
X
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)

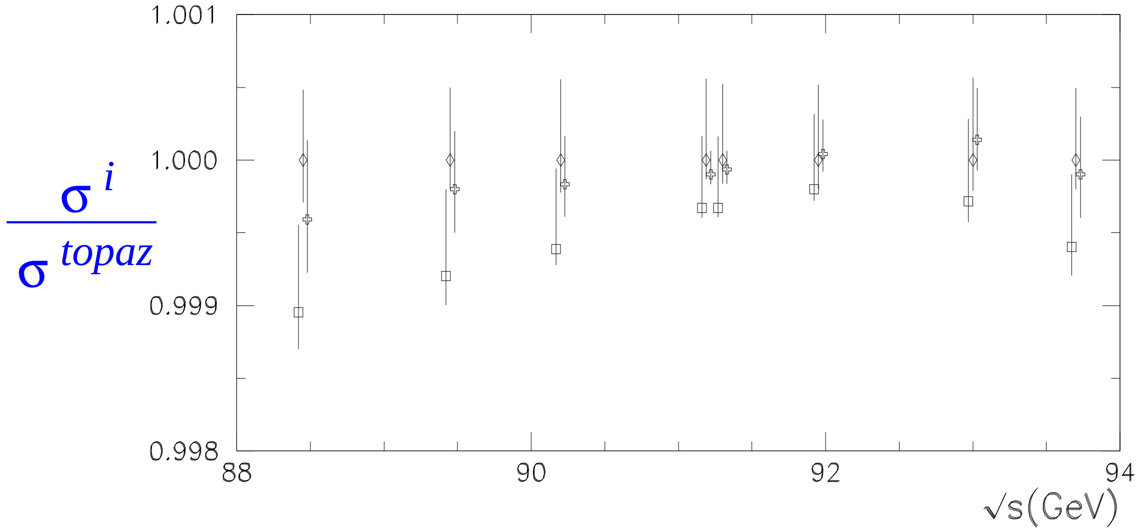
Theoretical Tools

- ***Large theoretical effort***
  -> 1995 "Precision Calculations Workshop"

Several programs used to fit to lineshape:
-> agree well

ZFITTER (Bardine et. al.)
TOPAZ0 (Montagna et. al.)
BHM (Burgers et. al.)



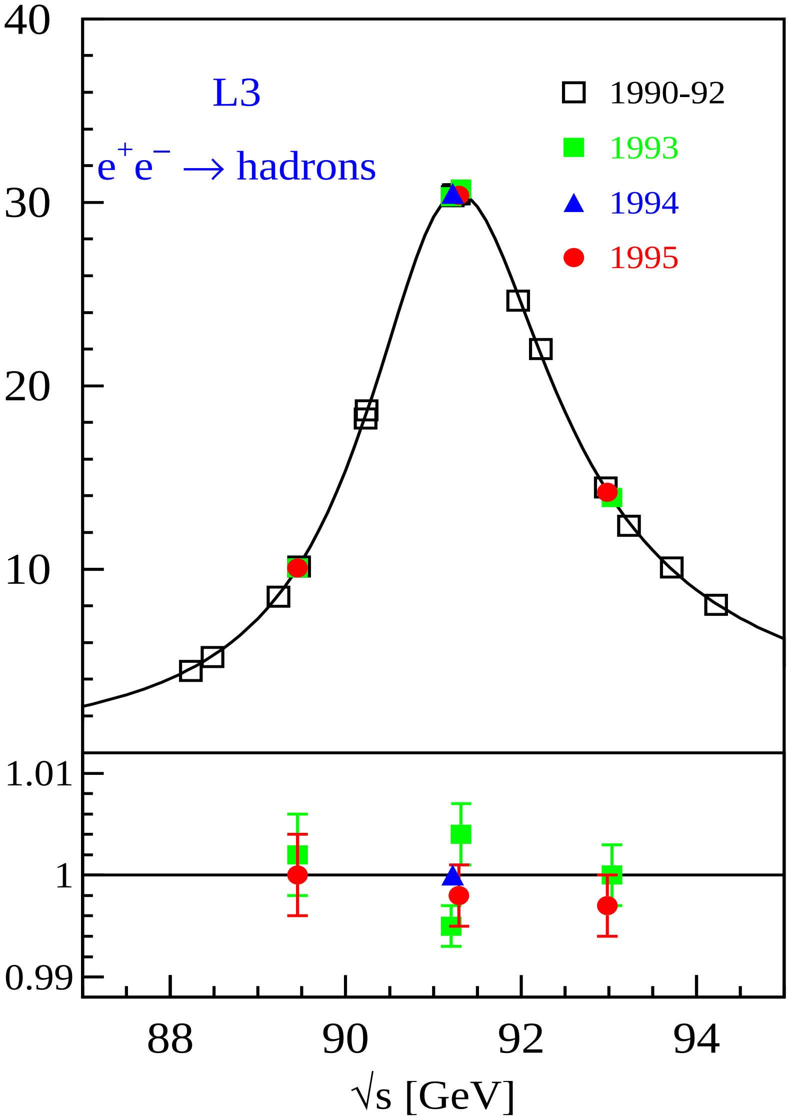


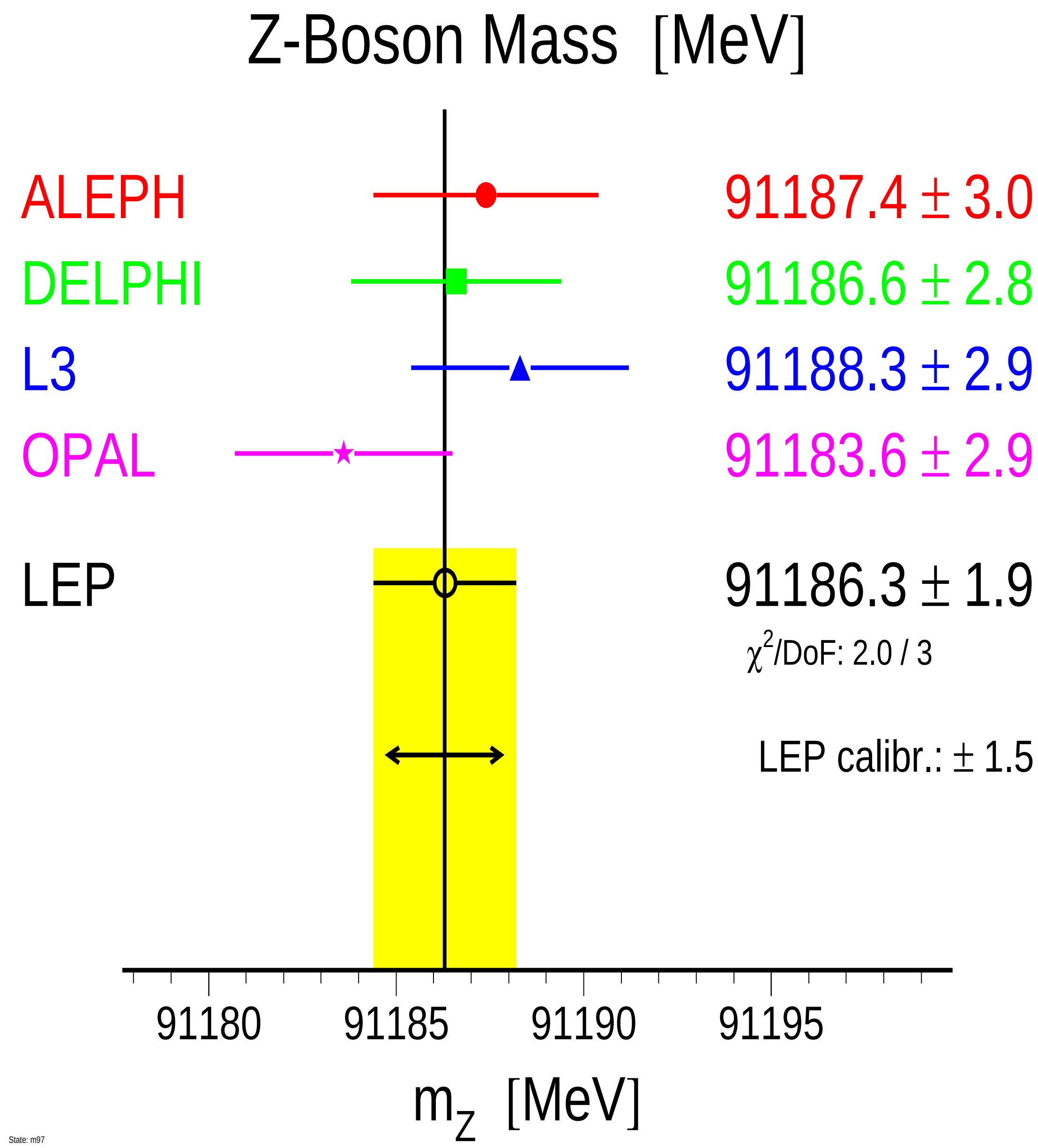
Results

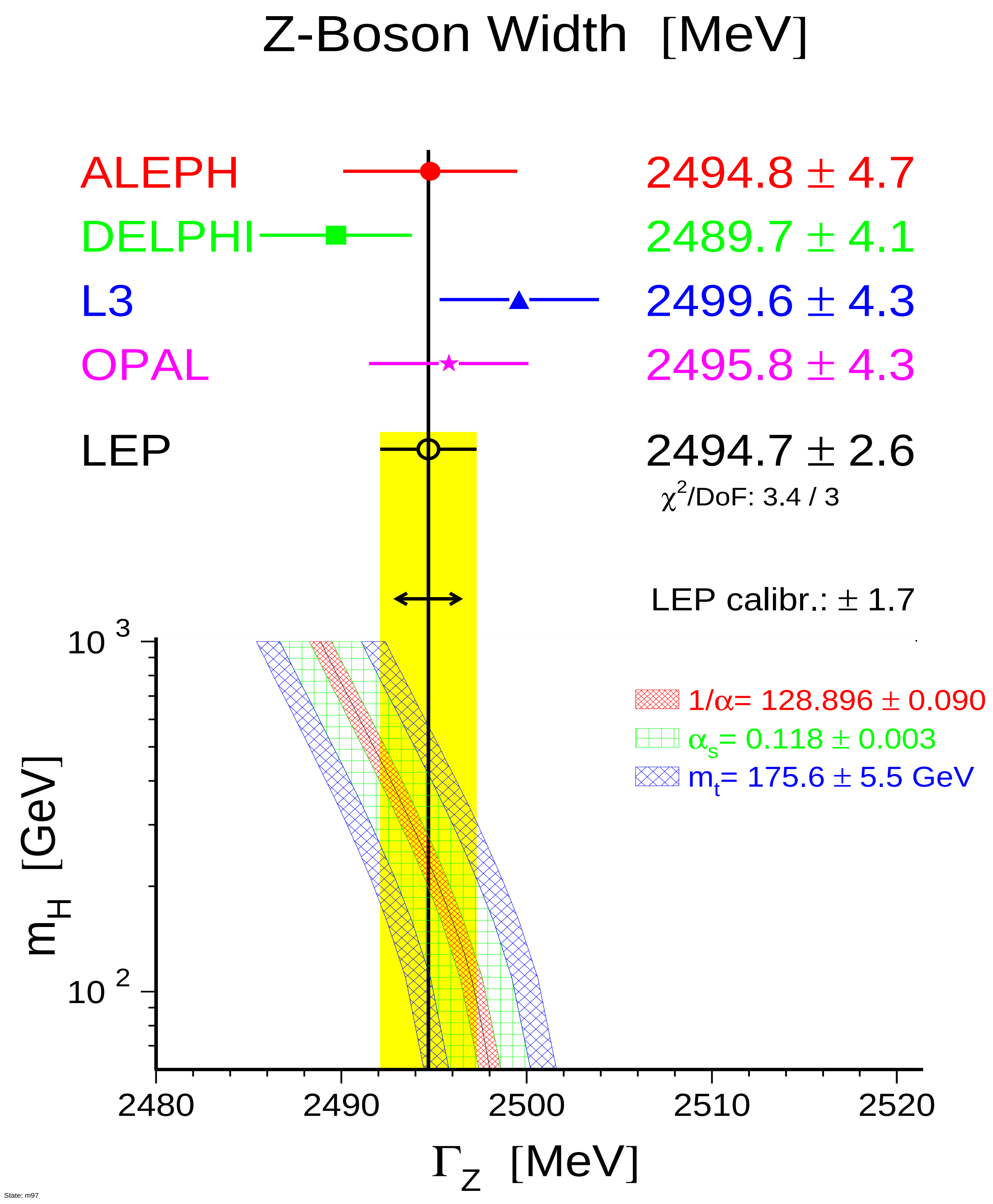
L3 preliminary results

Measured hadron cross-section (nb)

Ratio:




Z-Boson Mass [MeV]
ALEPH
91187.4 ± 3.0
DELPHI
91186.6 ± 2.8
L3
91188.3 ± 2.9
OPAL
91183.6 ± 2.9
LEP
91186.3 ± 1.9
χ²/DoF: 2.0 / 3
LEP calibr.: ± 1.5
91180
91185
91190
91195
m_Z [MeV]
State: m97


Z-Boson Width [MeV]
ALEPH
2494.8 ± 4.7
DELPHI
2489.7 ± 4.1
L3
2499.6 ± 4.3
OPAL
2495.8 ± 4.3
LEP
2494.7 ± 2.6
χ²/DoF: 3.4 / 3
LEP calibr.: ± 1.7
1/α= 128.896 ± 0.090
αs= 0.118 ± 0.003
mt= 175.6 ± 5.5 GeV
10 3
10 2
mH [GeV]
2480
2490
2500
2510
2520
ΓZ [MeV]
State: m97

Cross sections and partial widths

- ***Hadron and lepton cross sections at $\sqrt{s} = M_Z$ measured at same time as mass and width***

Approximately 400,000 leptons per experiment (e, μ, τ)

$$\sigma_{had} \Longleftrightarrow \Gamma_{had}$$

$$\sigma_e \Longleftrightarrow \Gamma_e \Longleftrightarrow R_e$$

$$\sigma_\mu \Longleftrightarrow \Gamma_\mu \Longleftrightarrow R_\mu$$

$$\sigma_\tau \Longleftrightarrow \Gamma_\tau \Longleftrightarrow R_\tau$$

$$\sigma_f \sim \frac{\Gamma_e \, \Gamma_f}{\Gamma_Z^2} \qquad R_l = \frac{\Gamma_{had}}{\Gamma_l}$$

No recent changes

$$\Gamma_{had} = 1743.5 \; \pm \; 2.4 \; MeV$$

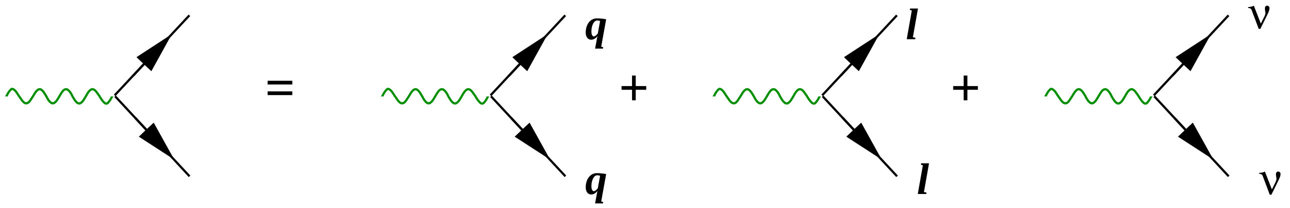
$$\Gamma_e = 83.94 \; \pm \; 0.15 \; MeV$$

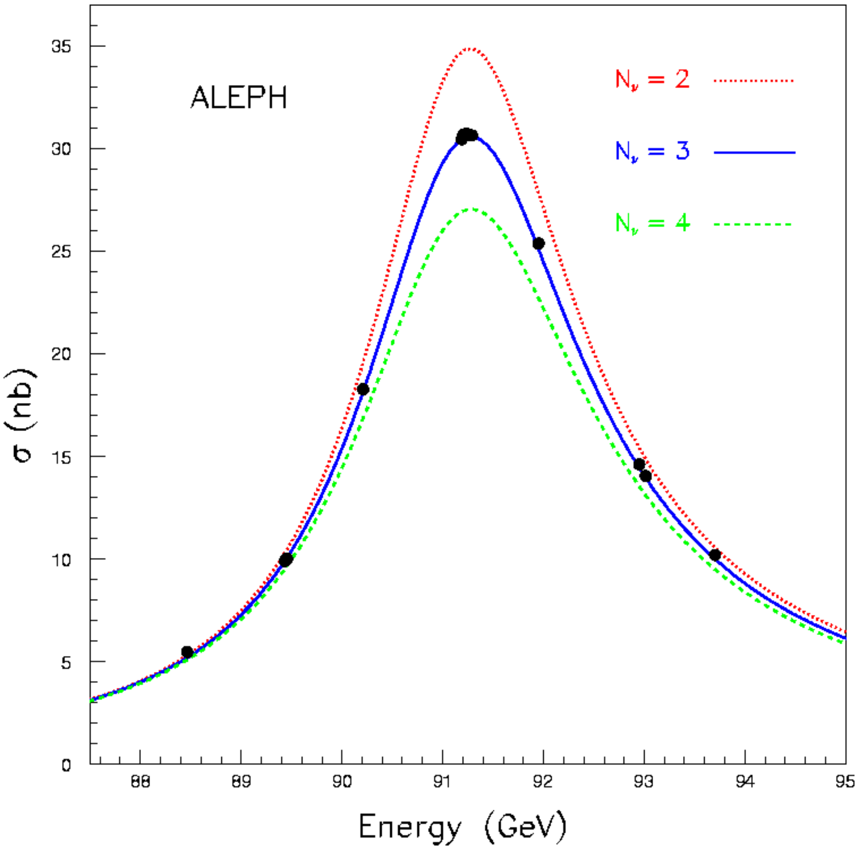
$$\Gamma_\mu = 83.79 \; \pm \; 0.21 \; MeV$$

$$\Gamma_\tau = 83.64 \; \pm \; 0.26 \; MeV$$

Number of light neutrino species

Γ_z Γ_{had} Γ_{lepton} $\Gamma_{invisible}$





$\Gamma_{invisible}$ = 499.8 +- 1.9 MeV

$N_{\nu\nu}$ = 2.992 +- 0.011

RbDefinition

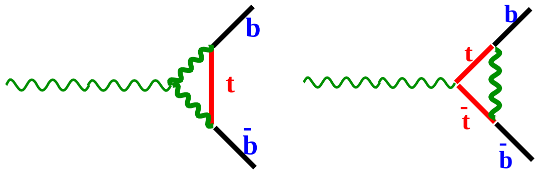
R_b and R_c

- R_q *is defined, for quark q, as:*

$$R_q = \frac{\Gamma(\; q\bar{q} \;)}{\Gamma(\; \text{all hadrons} \;)}$$

⇨ *Most dependence upon virtual corrections cancels out*

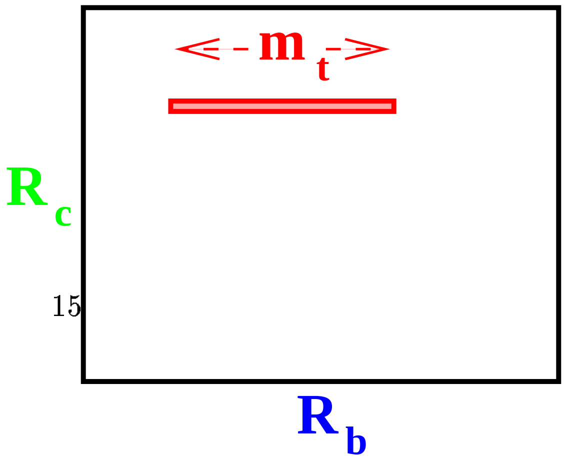
- *Uniquely for b quarks:*



$$R_b = \frac{\Gamma(\; b\,\bar{b} \;)\cdot(1 + ..m_t^2)}{\Gamma(\; \text{all hadrons} \;)}$$

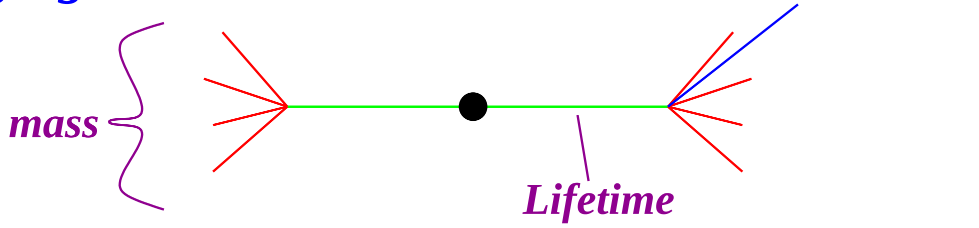
⇨ *Sensitive to extra* m_t *correction*

Therefore we expect:



R_b Analyses

- ***b tagging methods:***



- ***Double tag technique:***

$$N_b \propto \Gamma_{bb} \quad \varepsilon$$

$$N_{bb} \propto \Gamma_{bb} \quad \varepsilon^2$$

Solve for Γ_{bb} and ε from data

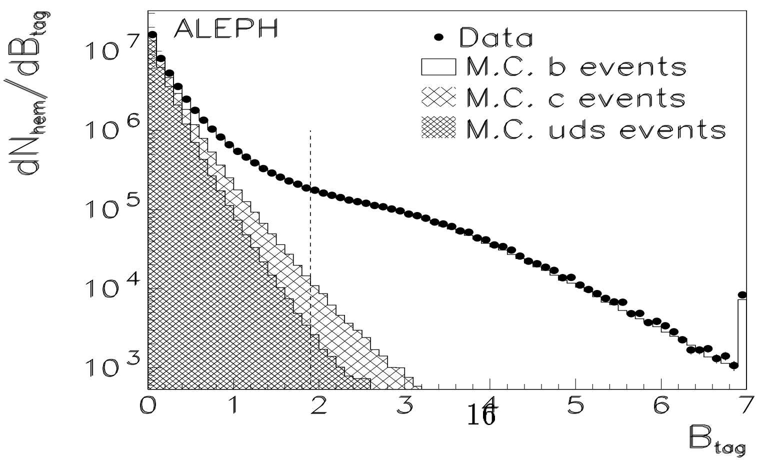
- ***Main systematic errors:***

  - Charm background /modelling
  - Hemisphere tag correlations

- ***Recent advances:***

  - Pioneering use of mass information (SLD / ALEPH)
  - Use of multiple tags
  - Better understanding of correlations

⇨ Systematic errors reduced by factor 2
(typical syst: 0.05% / stat: 0.05%)

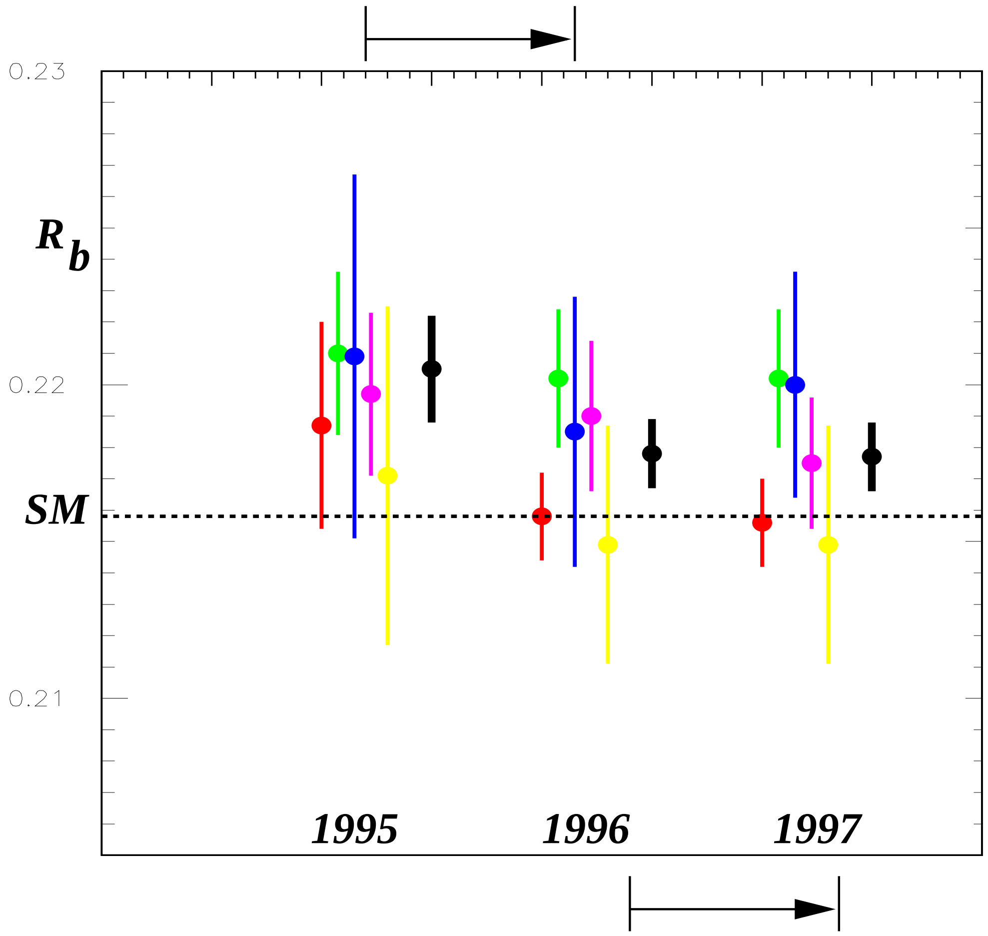


Efficiency -> 25%

Purity -> 98%

History of R_b

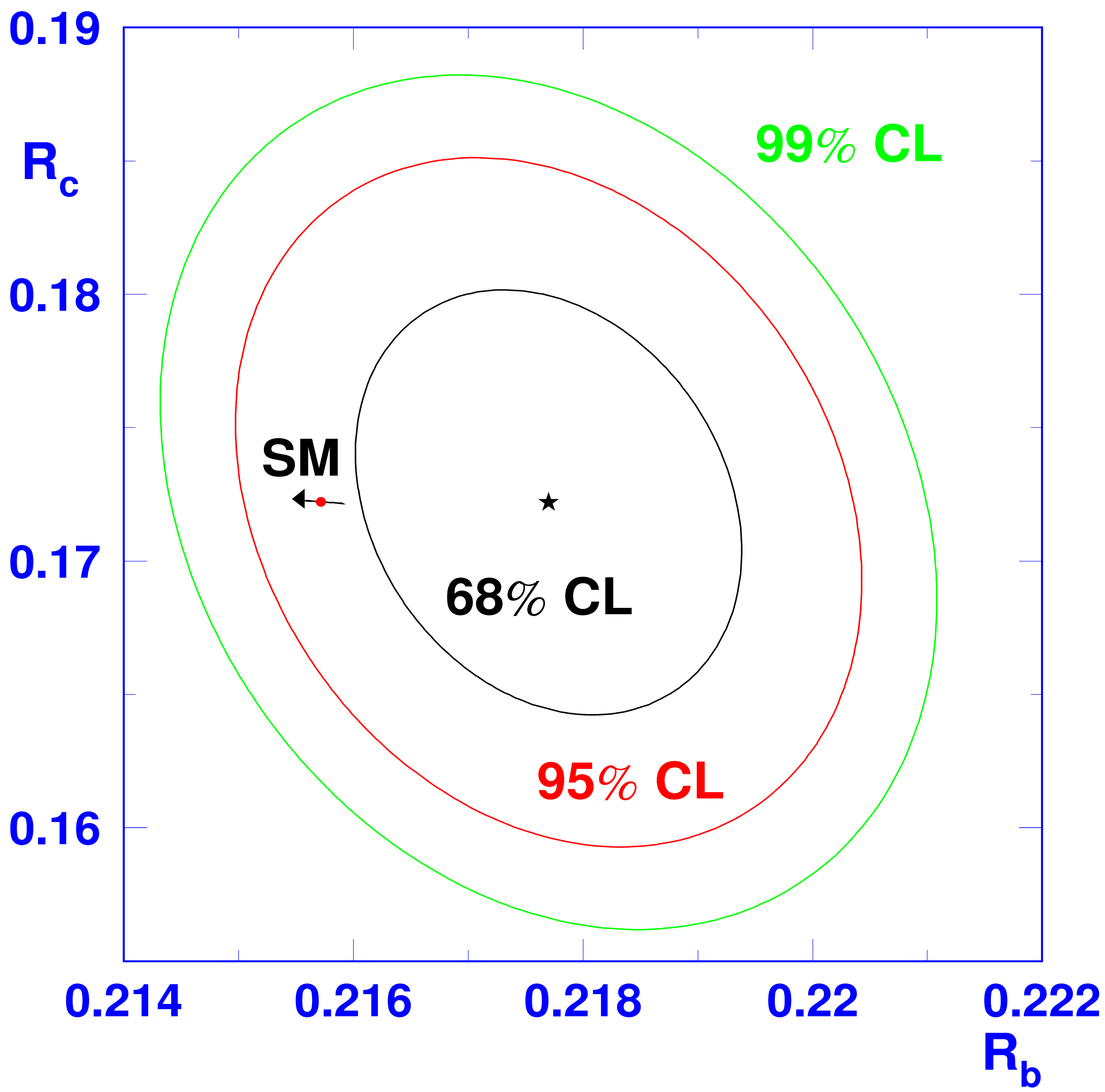
-Aleph introduce pure/multiple method ->1995
-Delphi add 1994 data
-L3 introduce lifetime tag ->1994
-Sld introduce new pure mass tag analysis
-Some changes to related params.
(Rc - 0.0008, gluon splitting -0.0003)



-Aleph finalise ->1995
-L3 introduce lepton analysis->1995
-Opal finalise -> 1994
-Sld update analysis

Aleph *Delphi* *L3* *Opal* *Sld*

R_b -vs- R_c



LEP/SLD

R_b^0 = 0.2177 +- 0.0011

R_c^0 = 0.1722 +- 0.0053

(R_b is approx eqivalent to mt = 105 +45 -?? GeV)

Asymmetries ($\sin^2\theta_w$)

All asymmetries measure vector and axial-vector coupling combination:

$$v_f \rightarrow I_3 - 2\,Q_f \sin^2\theta_w$$

$$A_f = 2\,\frac{v_f\,a_f}{v_f^2 + a_f^2}$$

Lepton Forward-Backward asymmetry

τ polarisation

Left-Right asymmetry from SLD

b,c quark Forw.-Back. asymmetry

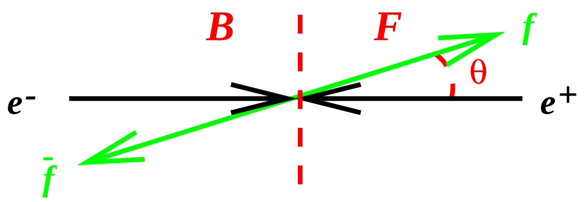
b,c quark polarised asymmetries from SLD

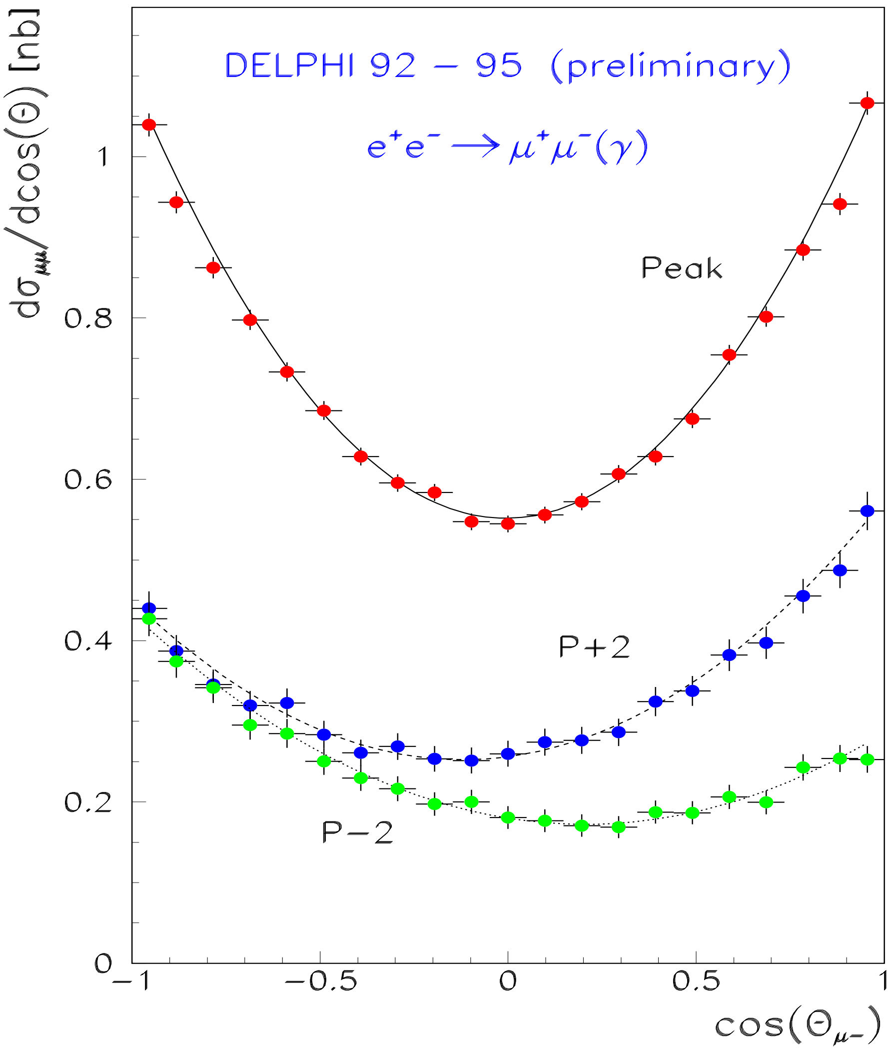
All measure A_{lepton}

measures $A_{lepton} \cdot A_{b,c}$

measures $A_{b,c}$

Lepton Forward - Backward Asymmetries



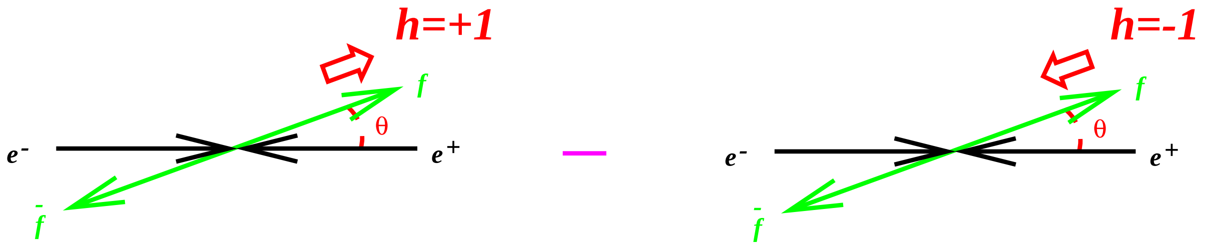


LEP Average

$$A_l^{fb} = 0.0177 \pm 0.0010$$

$$\to A_l = 0.1536 \pm 0.0043$$

Tau polarisation asymmetry:



- measure helicity through decay products
- measure A_e and A_t independantly through angular variation of h

LEP Average

A_τ = 0.1401 +- 0.0067

A_e = 0.1382 +- 0.0076

Left - Right asymmetry:

- use all hadronic and some leptonic events to measure $\sigma_L - \sigma_R$
- required precise measurement of electron beam polarisation
- measures A_e (independent of final state detected)

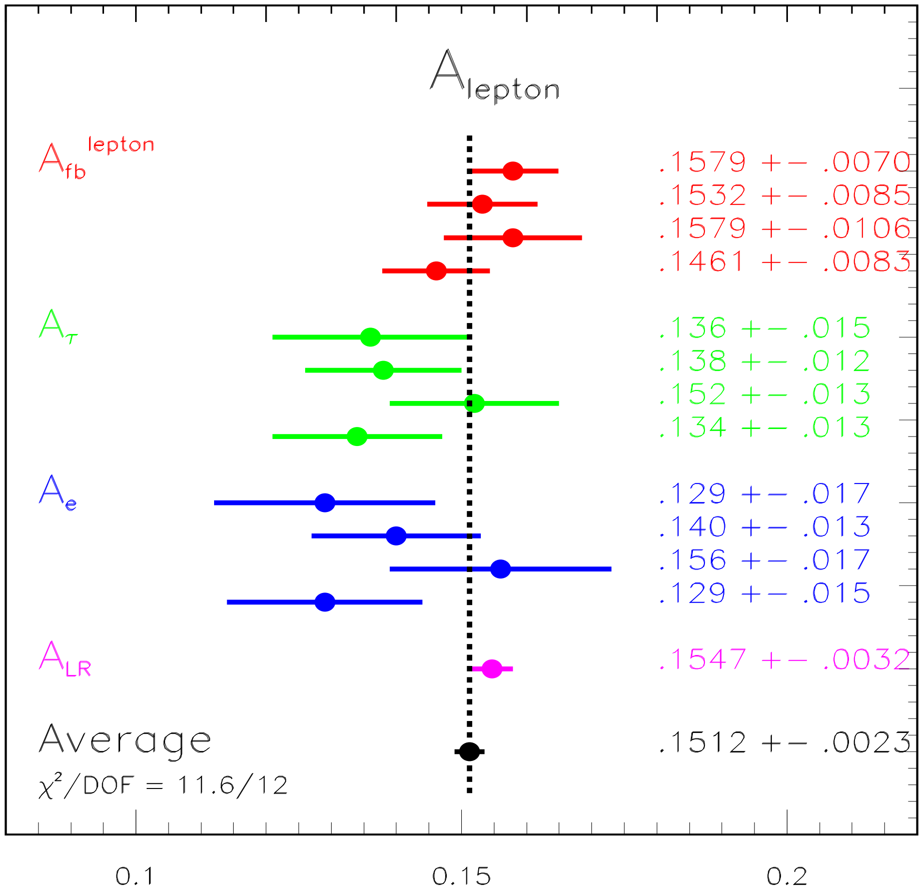
SLD

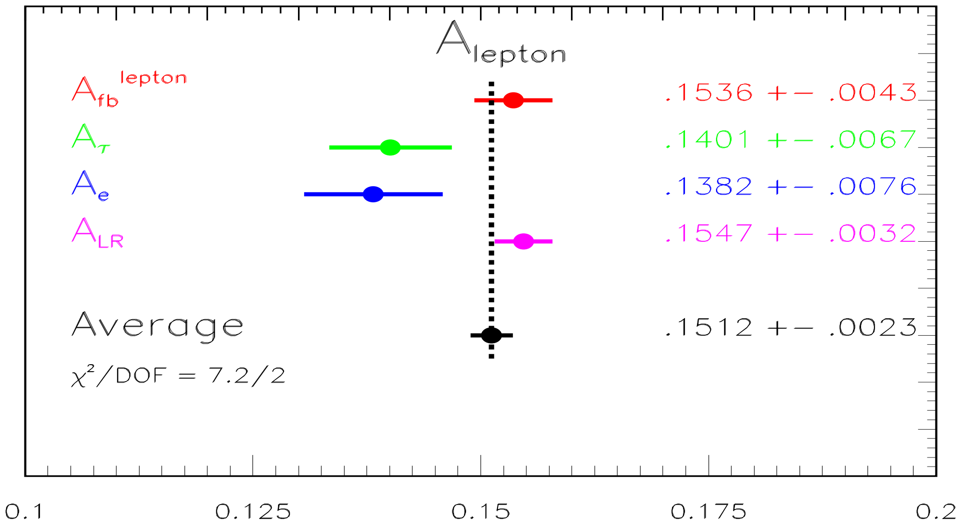
A_e = 0.1547 +- 0.0032

Comparison of measurements of A_l

A
D
L
O

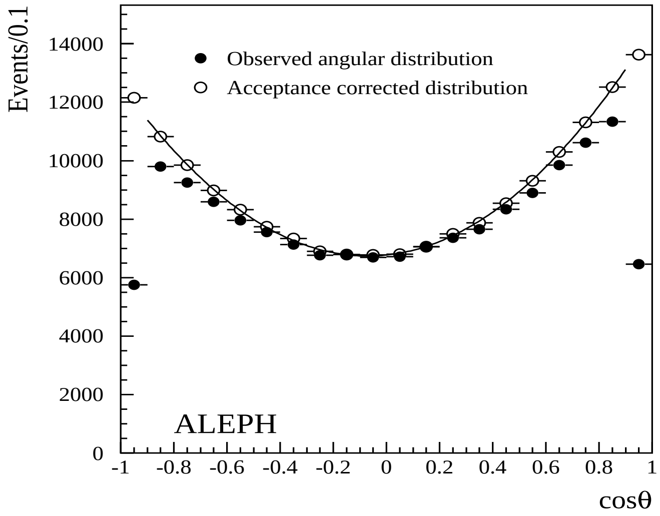
SLD





b quark asymmetries

- *b quark Forward - Backward asymmetry:*



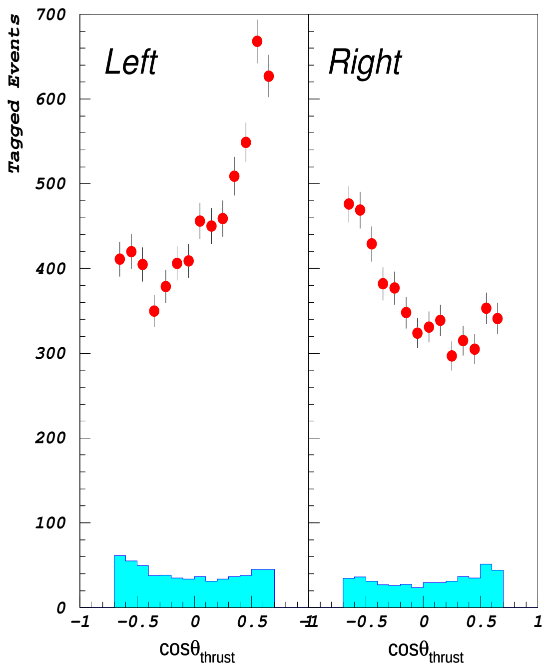
LEP Average

$A^{0,b}_{fb}$

= 0.0985 +- 0.0022

- *b quark polarised Forward - Backward asymmetry:*

A_b from Jet-Charge, SLD 1993-1995

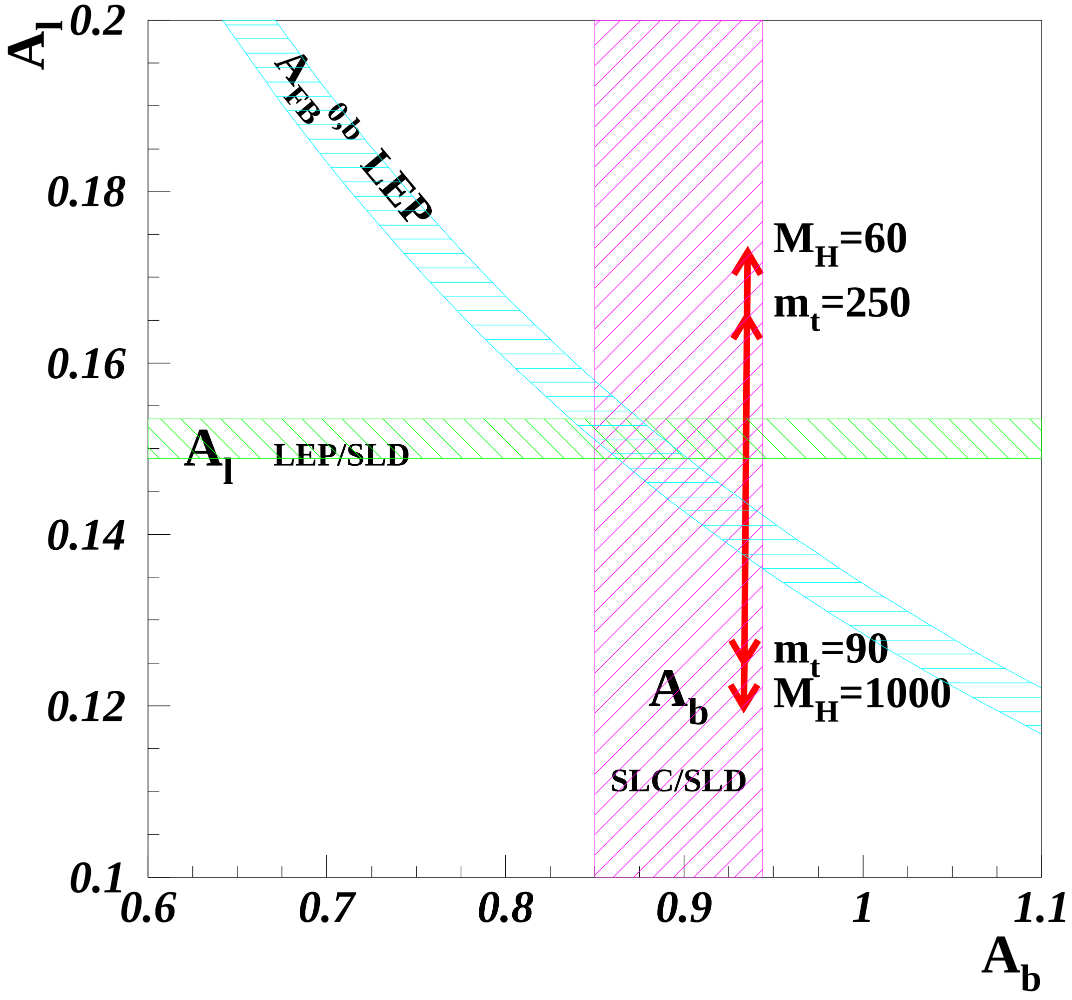


SLD

A_b

= 0.897 +- 0.0038

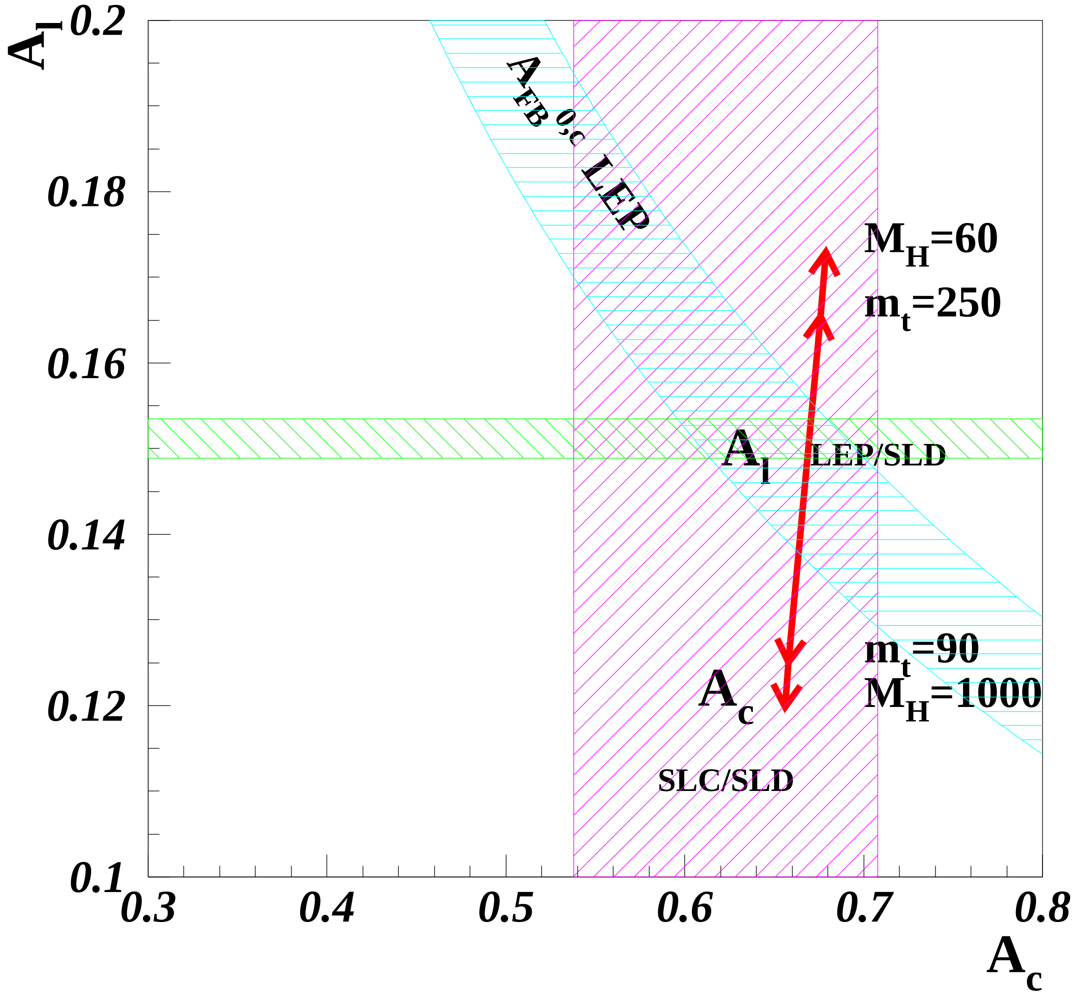
Constraints on A_l and A_b



Fit for A_b *yields*

A_b = 0.875 +- 0.021 (SM value 0.935)

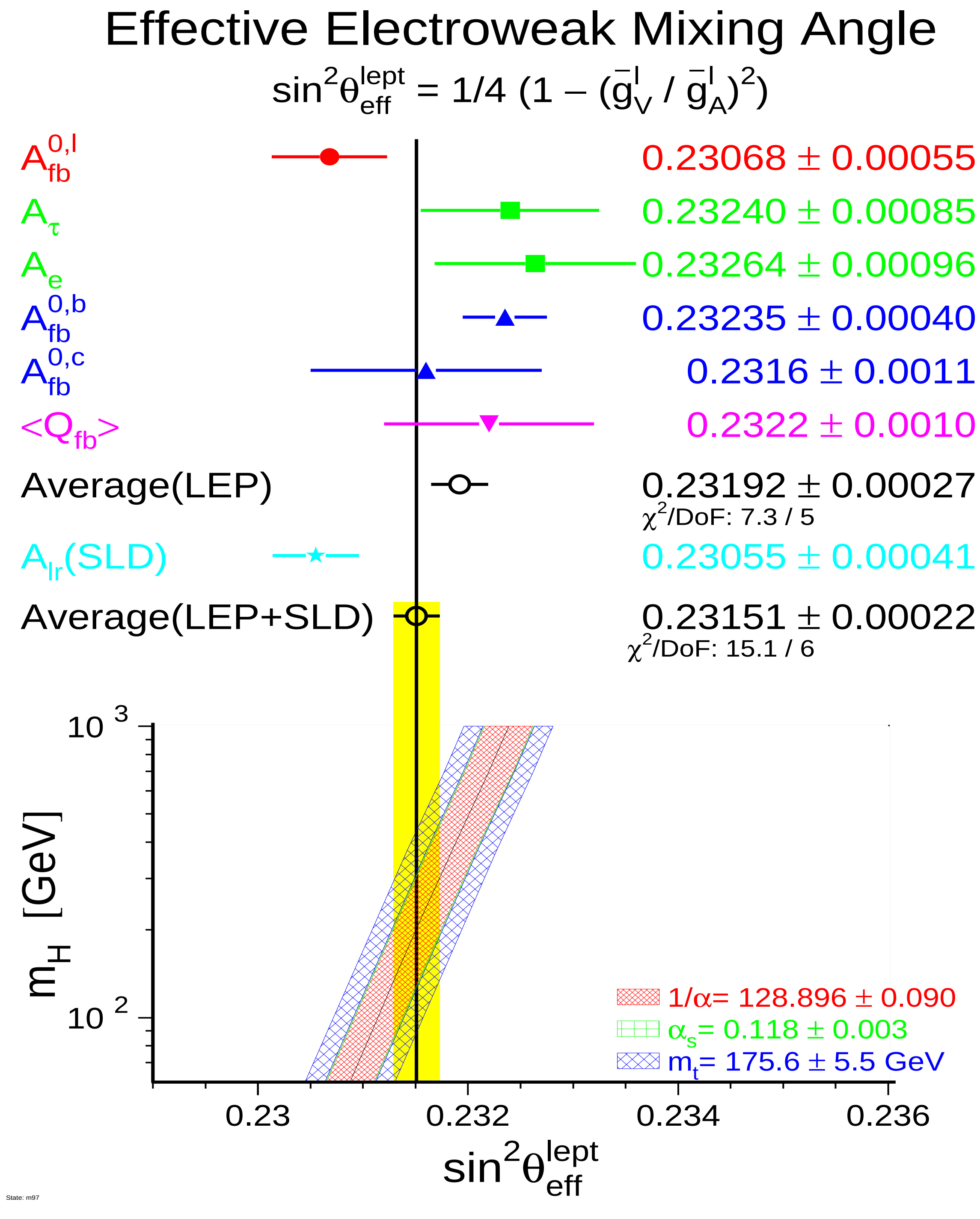
Constraints on A_l and A_c

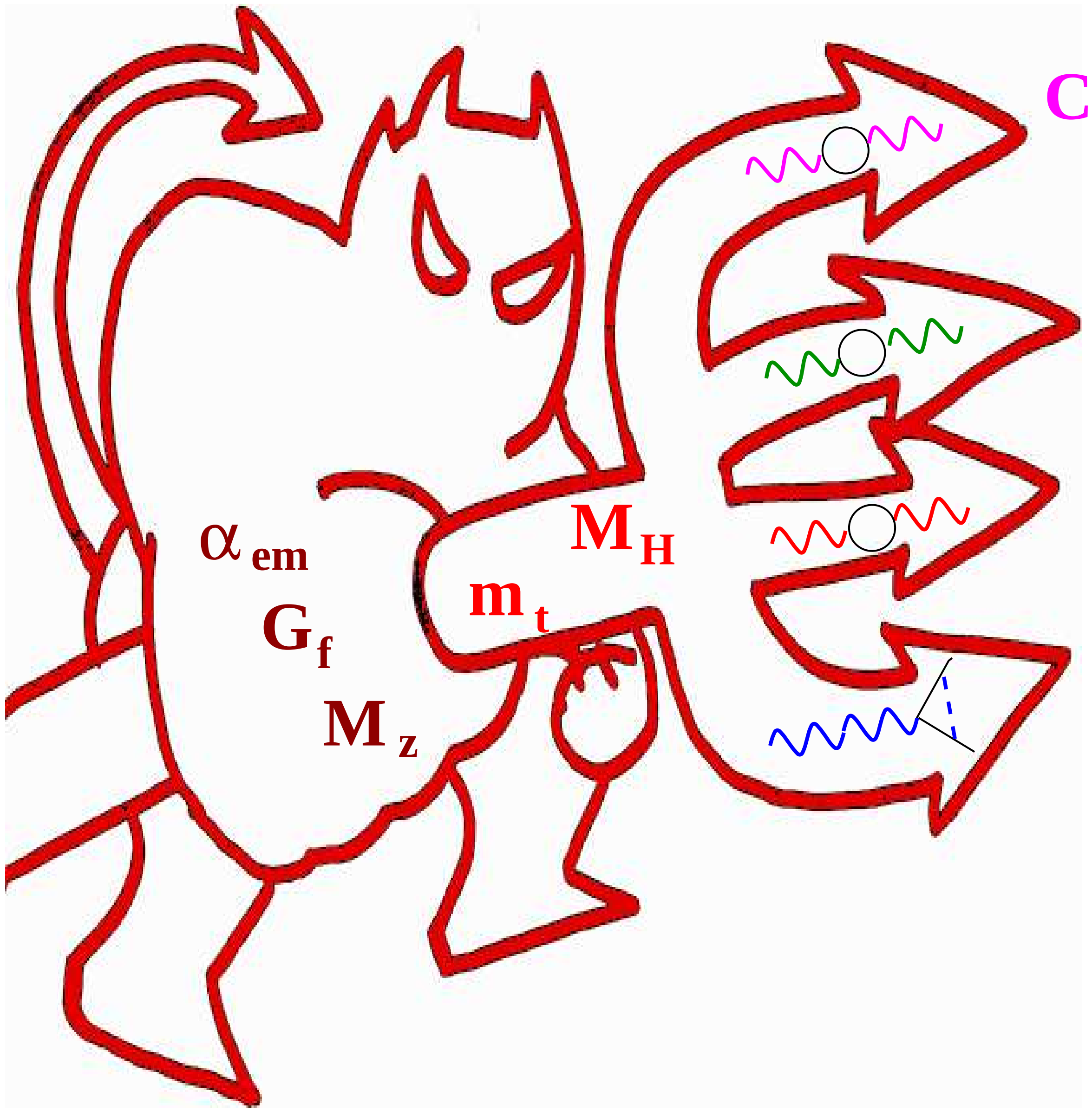


Fit for A_c yields

A_c = 0.643 +- 0.038 (SM value 0.668)

Summary of $Sin^2\theta_W$ from all asymmetries





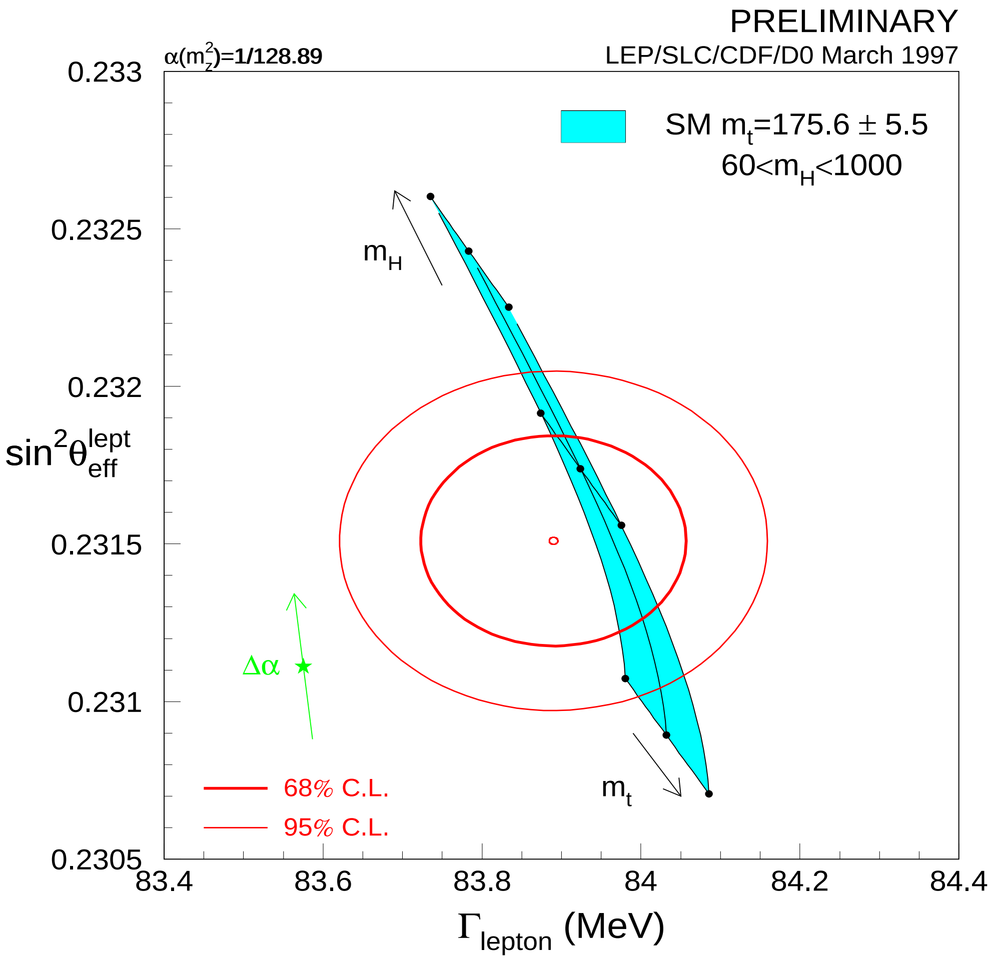
Γ_Z ,
Cross-sections,
Γ_f , $a^2 + v^2$

Asymmetries,
$\sin^2\theta_w$

M_W

R_b

Electro-weak corrections



All quantities Q = { Γ_l , $\sin^2\theta_W$, M_W , ...} depend upon m_t , m_H

through EW corrections:

$$Q = Q(m_t , m_H) \sim Q(C\ m_t^2 - K \log m_H)$$

The C and K are different for each quantity.

Interpretation using m_t and m_H as currency....

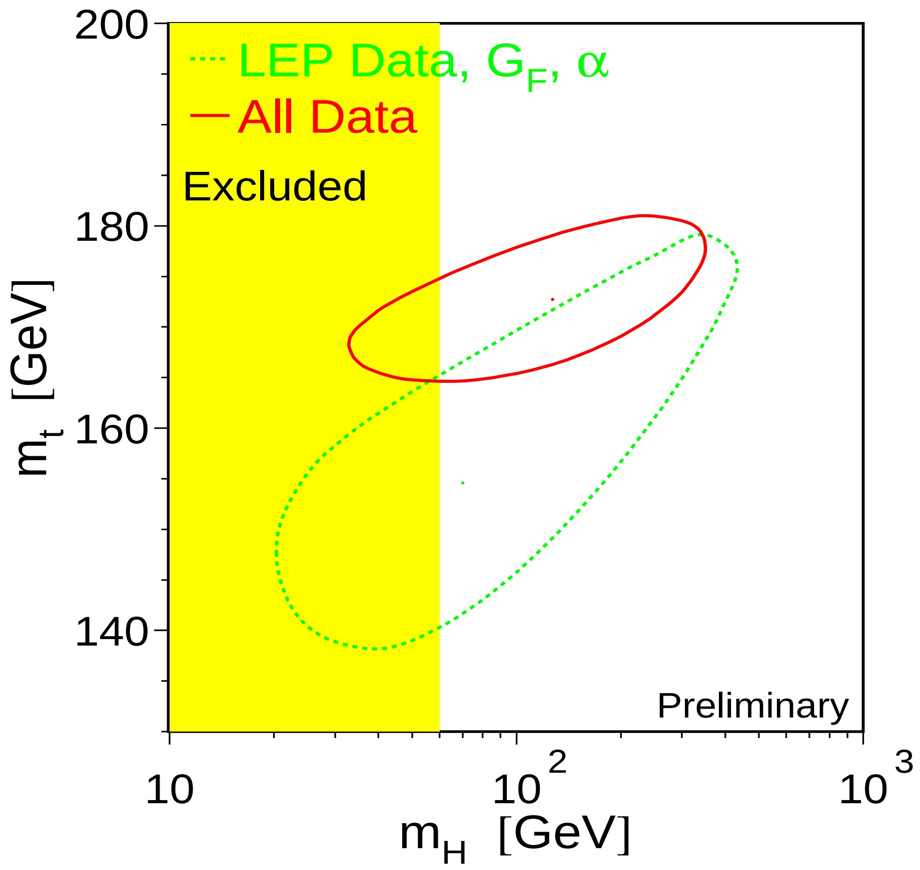
$\Gamma_l\ (m_t\ ,\ m_H\ )$

$\sin^2\theta_W\ (m_t\ ,\ m_H\ )$ *LEP,SLD,νN*

$R_b\,(m_t\,)$

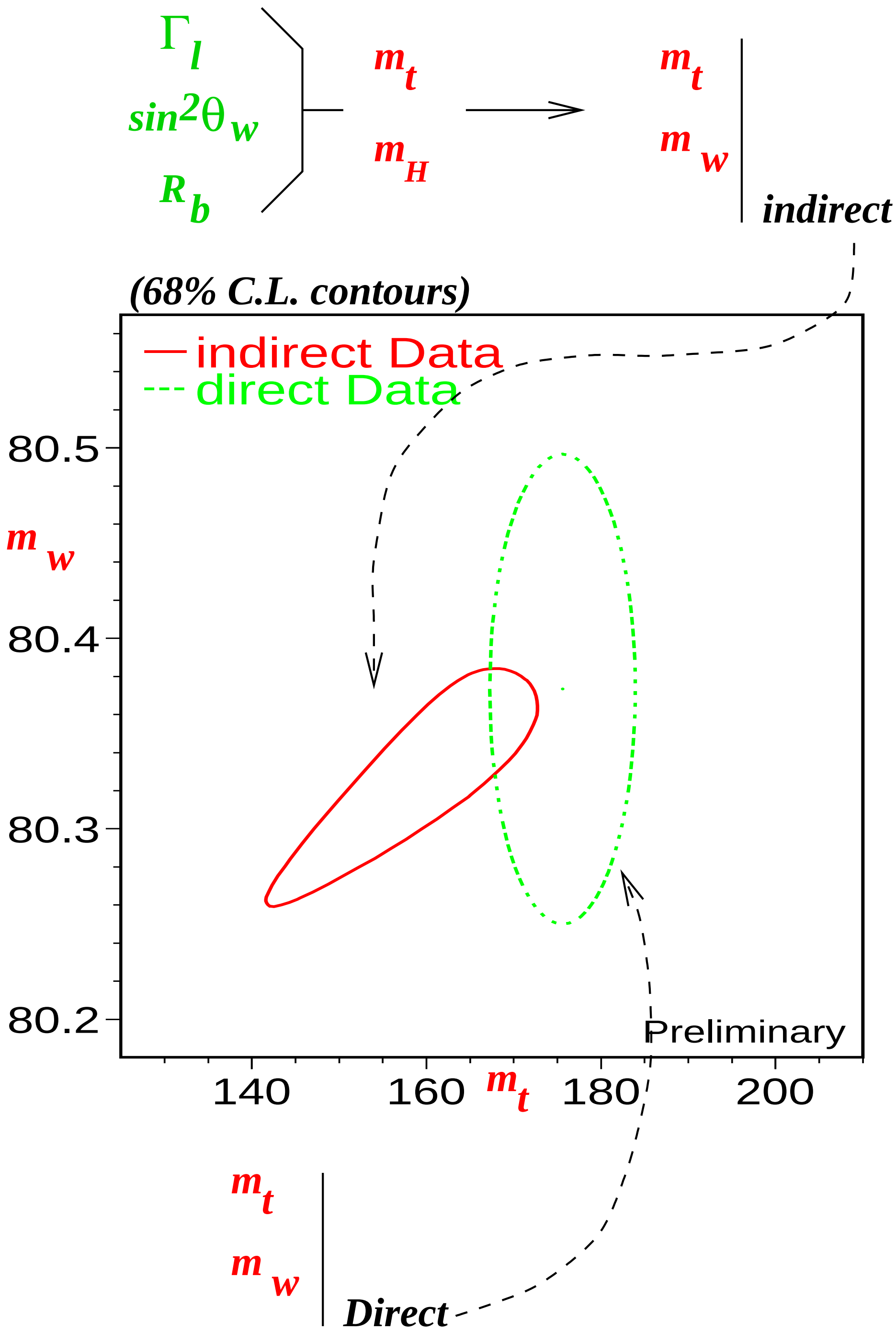
$M_W\ (m_t\ ,\ m_H\ )$ = *80.37 +- 0.10 GeV , CDF,D0*
= *80.38 +- 0.14 GeV , LEP-2*

m_t = *175.6 +- 5.5 GeV , CDF,D0*



(68% C.L. contours)

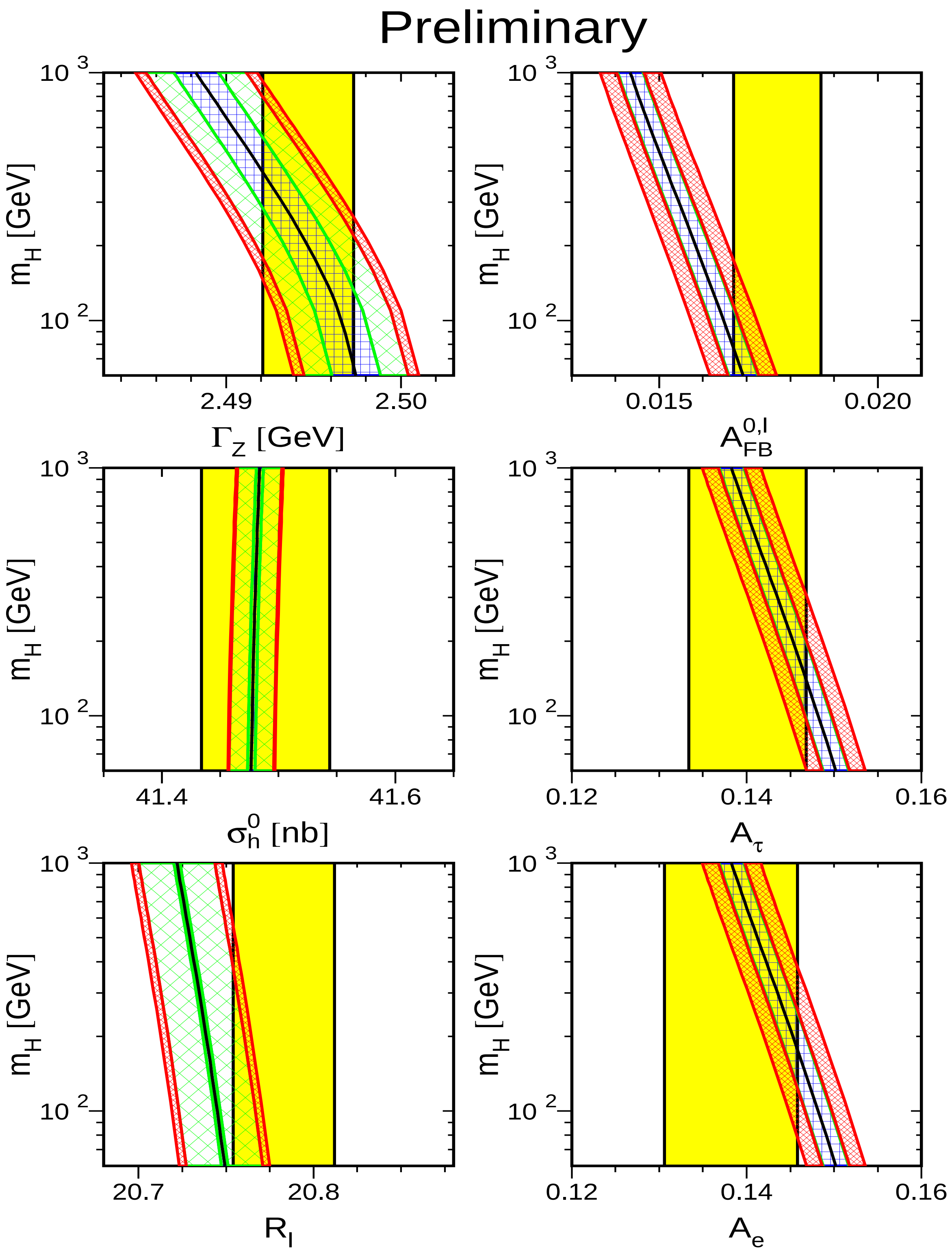
Interpretation using m_t and m_W as currency....

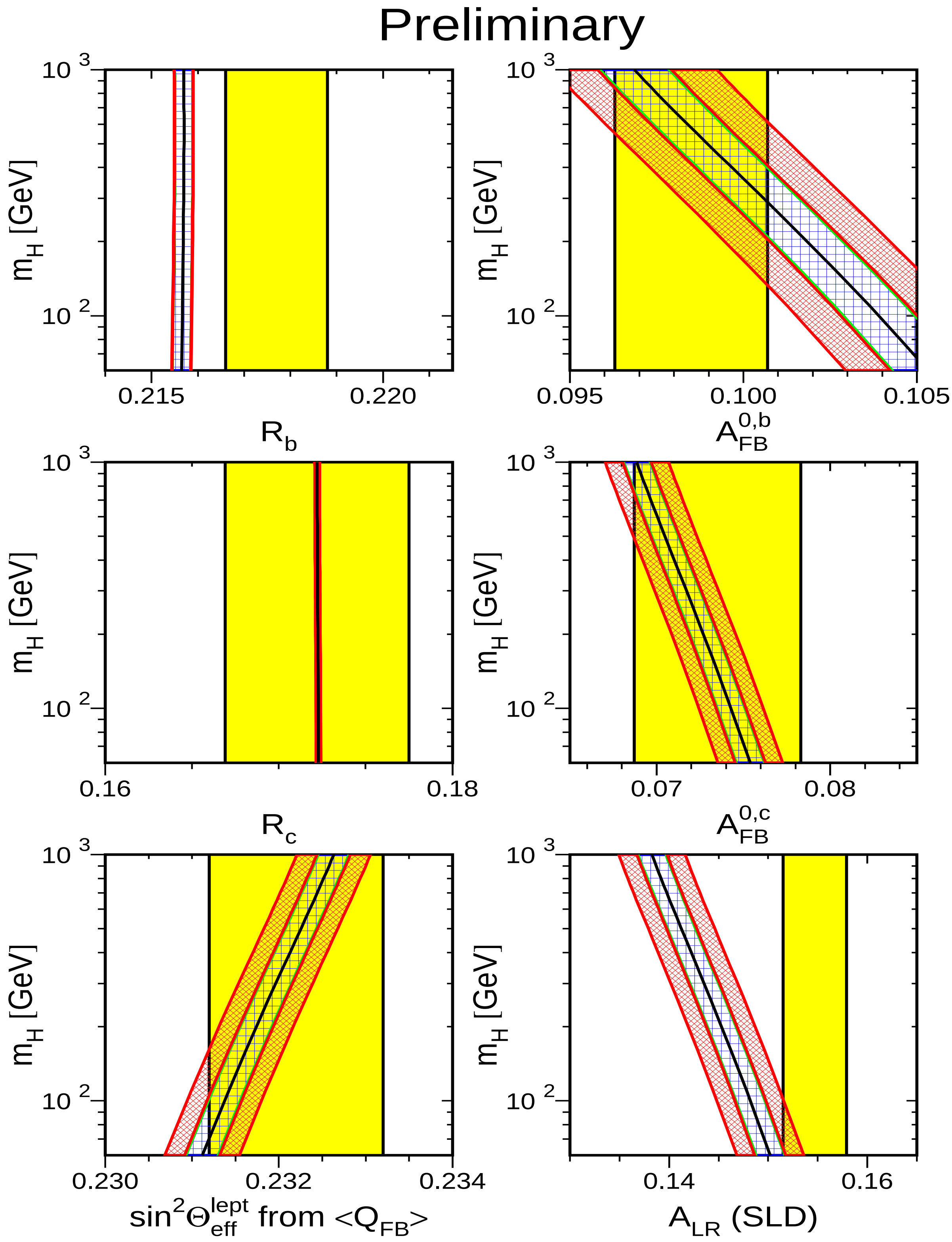


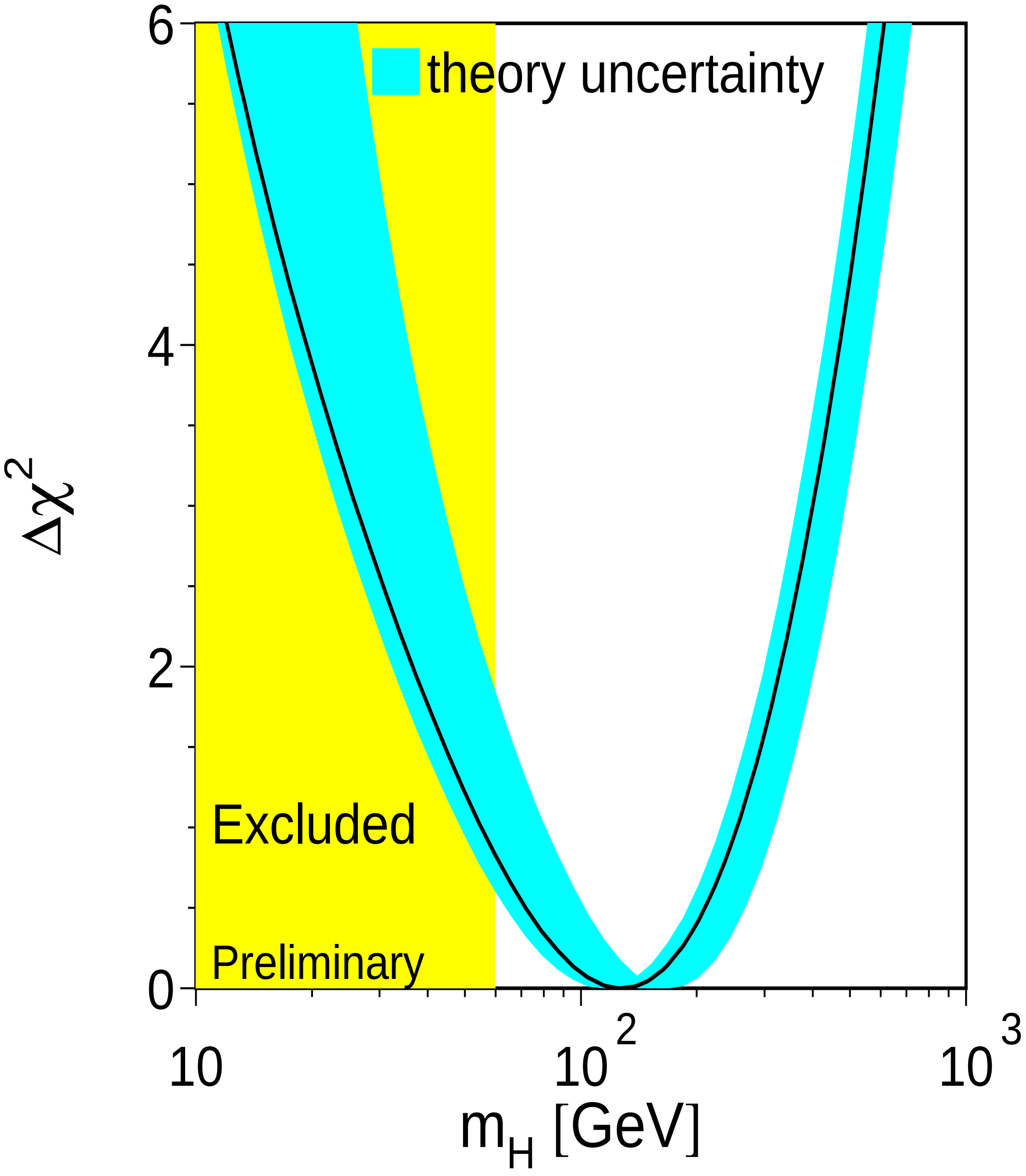
Combined m_w ⇨ 80.366 +- 0.031 GeV

Higgs mass constraints

(with m_t fixed by direct measurement)




Preliminary
m_H [GeV]
10^3
10^2
0.215
0.220
R_b
0.095
0.100
0.105
$A_{FB}^{0,b}$
0.16
0.18
R_c
0.07
0.08
$A_{FB}^{0,c}$
0.230
0.232
0.234
$\sin^2\Theta_{eff}^{lept}$ from <Q_{FB}>
0.14
0.16
A_{LR} (SLD)



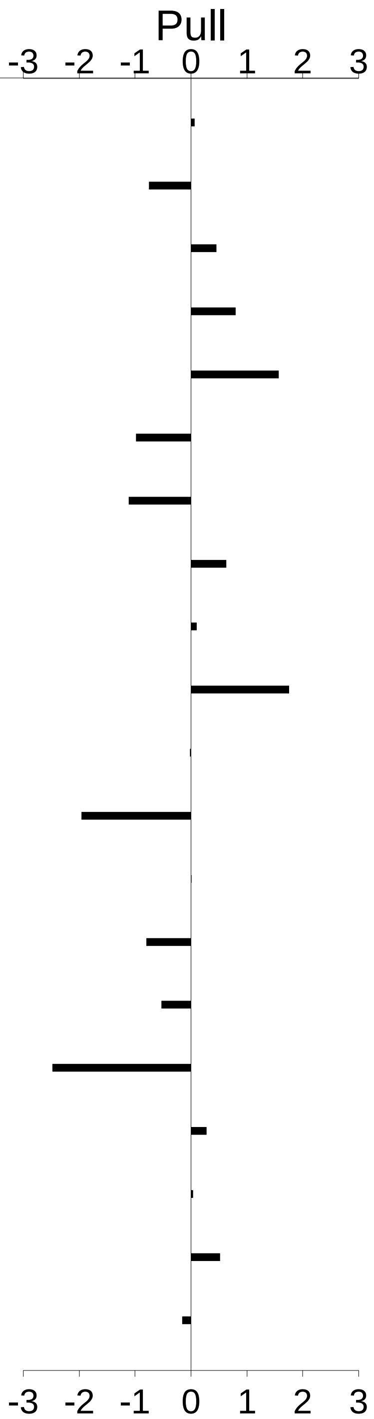
(Theory errors taken from comparison of ZFITTER/TOPAZ0/BHM)

$$m_H = 127^{+127}_{-72} \text{ GeV}$$

$$m_H < 465 \text{ GeV} \quad @ \; 95\% \text{ C.L.}$$

Moriond 1997

	Measurement	Pull
m_Z [GeV]	91.1863 ± 0.0019	.06
Γ_Z [GeV]	2.4947 ± 0.0026	-.75
σ^0_{hadr} [nb]	41.489 ± 0.055	.46
R_l	20.783 ± 0.029	.80
$A^{0,l}_{fb}$	0.0177 ± 0.0010	1.57
A_τ	0.1401 ± 0.0067	-.98
A_e	0.1382 ± 0.0076	-1.11
$\sin^2\theta^{lept}_{eff}$	0.2322 ± 0.0010	.63
m_W [GeV]	80.38 ± 0.14	.10
R_b	0.2177 ± 0.0011	1.75
R_c	0.1722 ± 0.0053	-.01
$A^{0,b}_{fb}$	0.0985 ± 0.0022	-1.96
$A^{0,c}_{fb}$	0.0735 ± 0.0048	.01
A_b	0.897 ± 0.047	-.80
A_c	0.623 ± 0.085	-.53
$\sin^2\theta^{lept}_{eff}$	0.23055 ± 0.00041	-2.48
$1 - m^2_W/m^2_Z$	0.2244 ± 0.0042	.28
m_W [GeV]	80.37 ± 0.10	.04
m_t [GeV]	175.6 ± 5.5	.52
$1/\alpha$	128.894 ± 0.090	-.16



χ^2 = ***21/15***

SUMMARY

The LEP-1 programme has been a great sucess
[and a pleasure to be part of]

It is now in the 'endgame'
- some data yet to be added
- final publications soon

SLD will continue to make important measurements
Particularly Alr and Rb

Heavy quark results have improved with new technology
- still expect improvements
- some data yet to be analysed

Electroweak measurements from LEP/SLD are
'well matched' as tests of quantum corrections
and
in conjunction with the m_t from CDF/D0
provide a constraint upon M_H