Electro-weak Measurements from Z^0 production

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XVII International Conference on Physics in Collision
June 25-27 1997, University of Bristol, UK

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

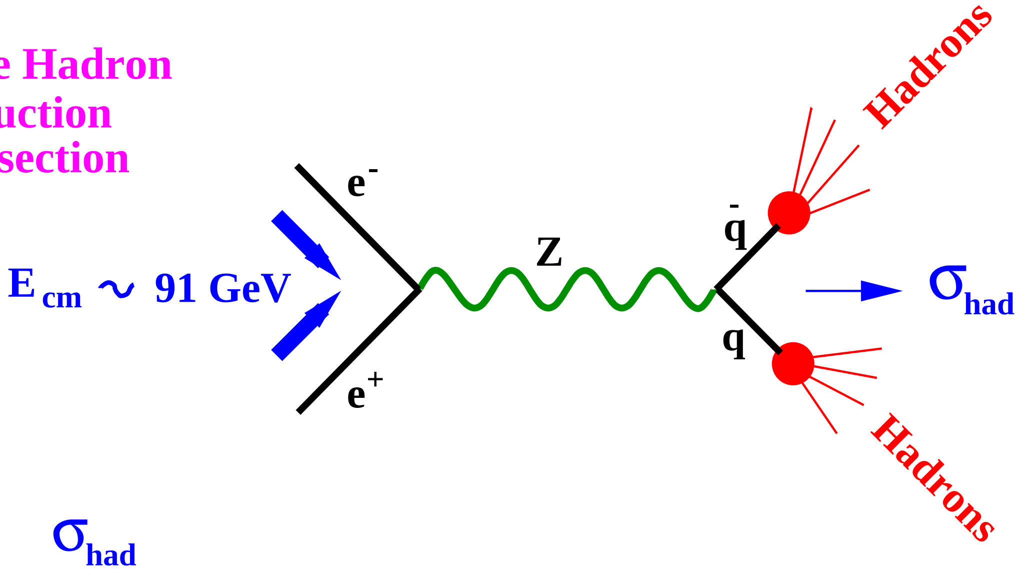
Interpretation
&
constraints upon M_H

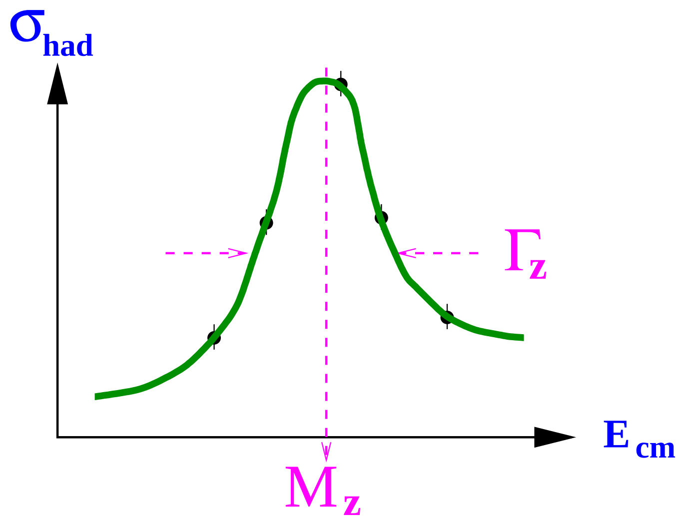
Results from
LEP: ALEPH, DELPHI, L3, OPAL
SLC: SLD
Tevatron: CDF, D0

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

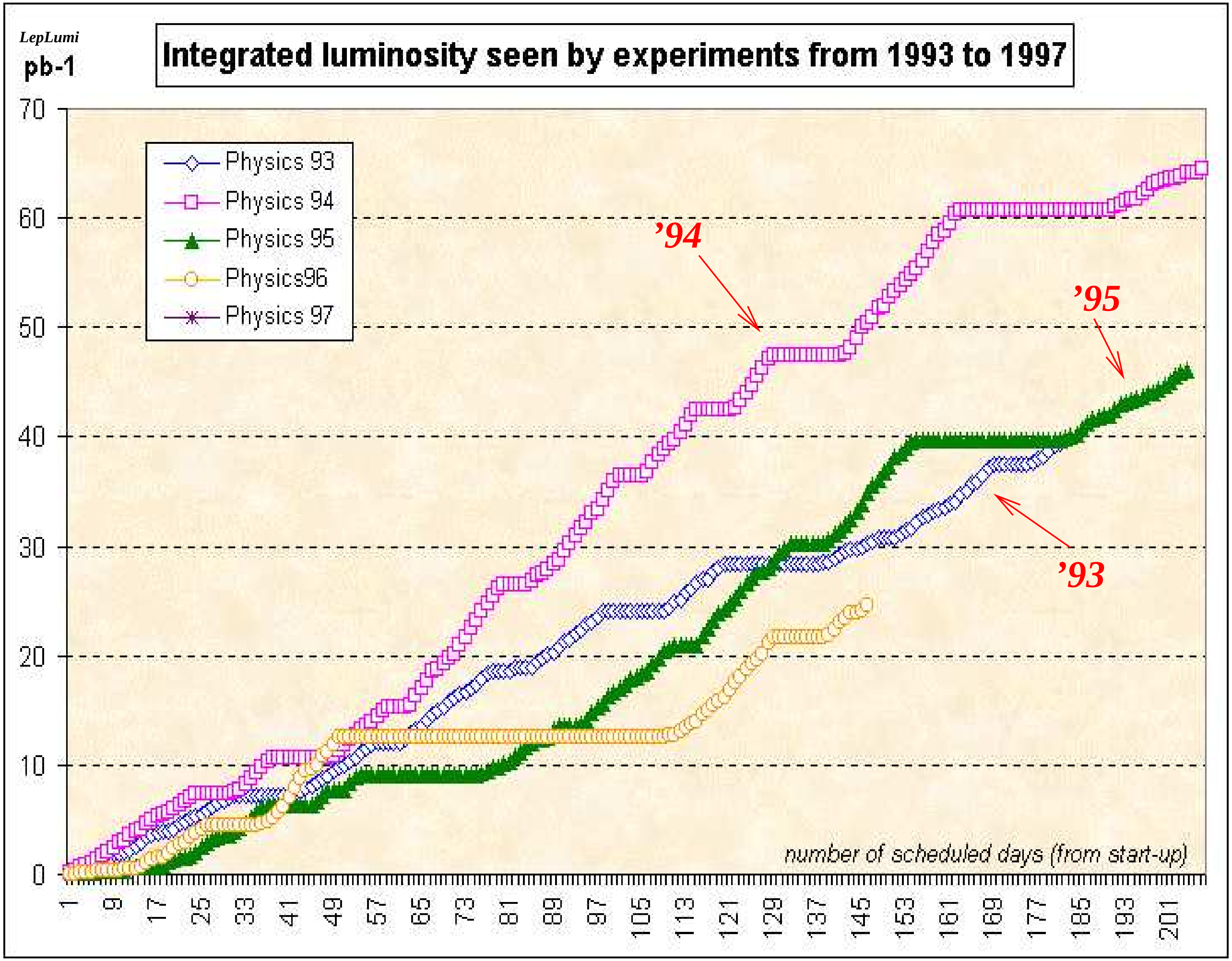
LEP History

Year	Int. Lumi. (pb^{-1}) on-peak	Int. Lumi. (pb^{-1}) off-peak	History
1989	1.3		
1990	6.8		Old energy calibration
1991	8	5	
1992	25	-	Experiments install precision luminometers
1993	16	18	High luminosity "Pretzel"; Resonant depolarisation; Precision scan !
1994	47	-	
1995	9	18	Bunch Trains; New NMR instrumentation; Precision scan !
Total:	100	50	⇨ 4 M hadronic events/exp.

- Experimental statistical precision:

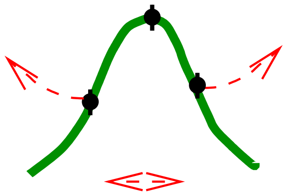
$$\Delta M_Z = 1.2 \text{ MeV}$$

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


LepLumi
pb-1
Integrated luminosity seen by experiments from 1993 to 1997
Physics 93
Physics 94
Physics 95
Physics96
Physics 97
’94
’95
’93
number of scheduled days (from start-up)

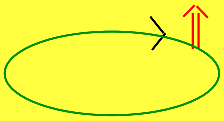
Lep Beam Energy Measurement

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*

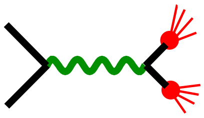
Total
~ 1.5 MeV

- ***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*

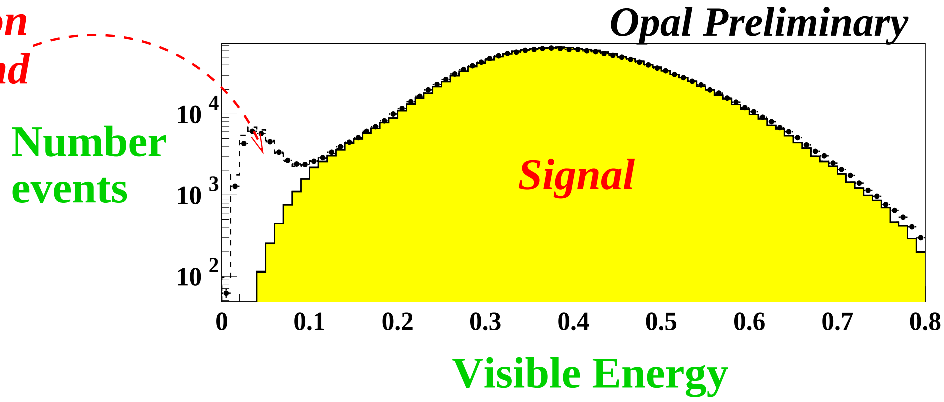
	Aleph	Delphi	L3	Opal
Acceptance (%)	*99.1*	*96*	*99.4*	*99.5*
Syst. error (%)	*0.07*	*0.10*	*0.05*	*0.08*

[Statistical precision 0.05% / exp]

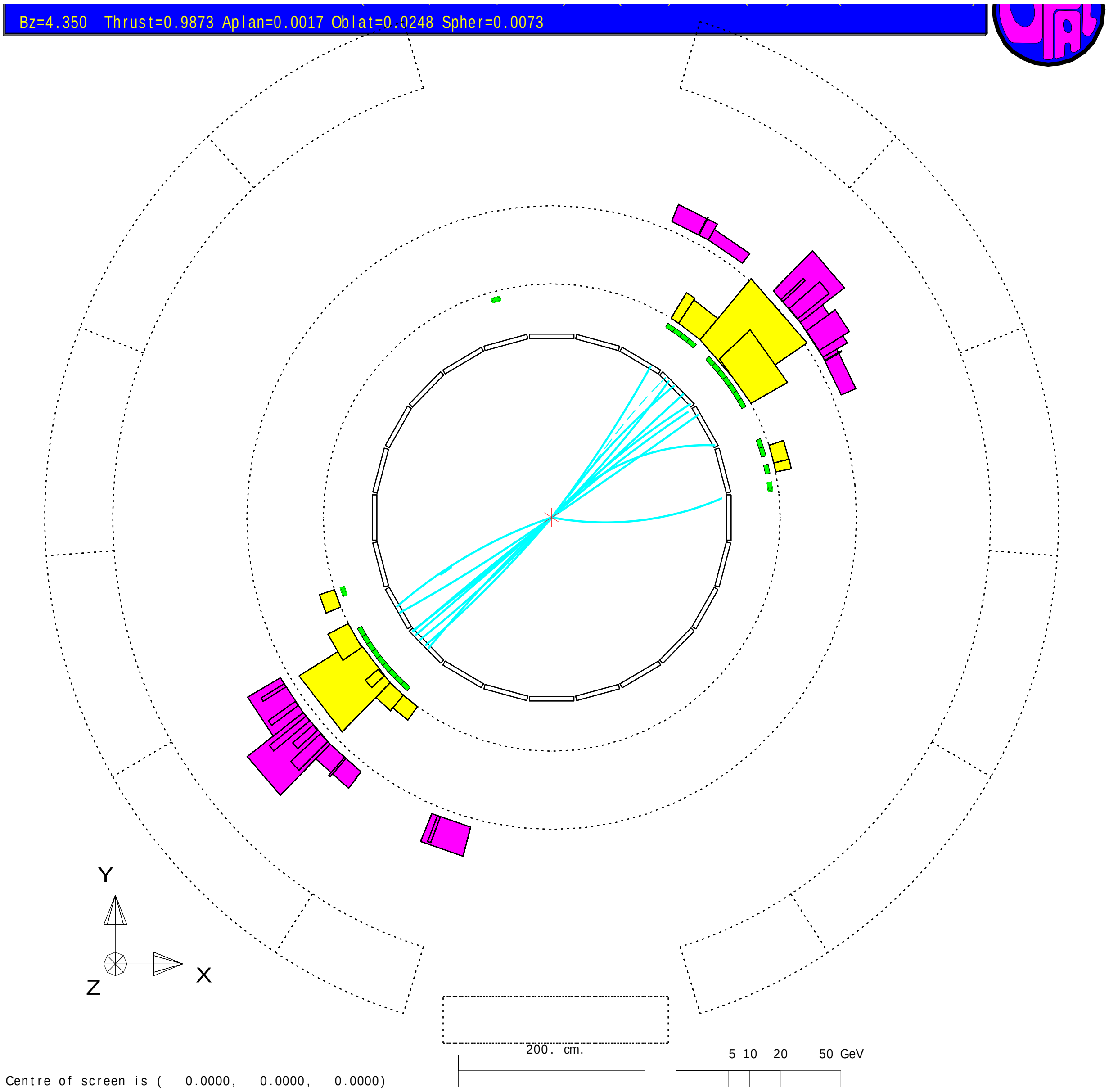
- **Backgrounds:**
  - *non-resonant (two-photon) 0.2%*
  - *ee -> $\tau\tau$ 0.2%*

- **Data quality:**

Two photon background



- **Luminosity measurement:**
  - *- low angle Bhabha scattering*
  - *- precision Silicon position measurement + calorimeters*
  - *-> typical experimental uncertainty 0.08%*
  - *-> theoretical uncertainty in Bhabha cross section 0.11%*

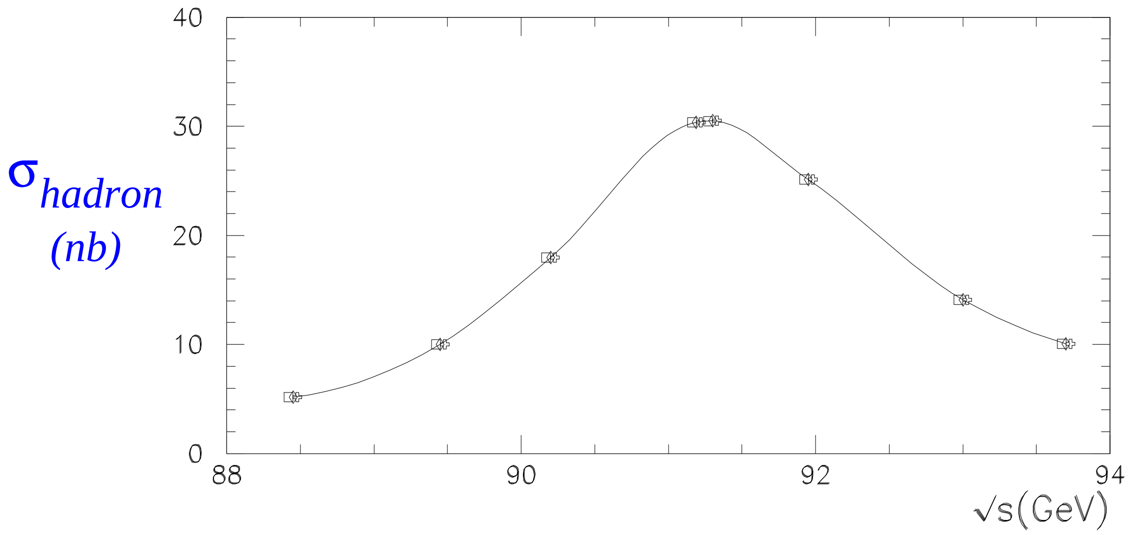

Bz=4.350 Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
Y
X
Z
200. cm.
5 10   20   50 GeV
Centre of screen is (0.0000,   0.0000,   0.0000)

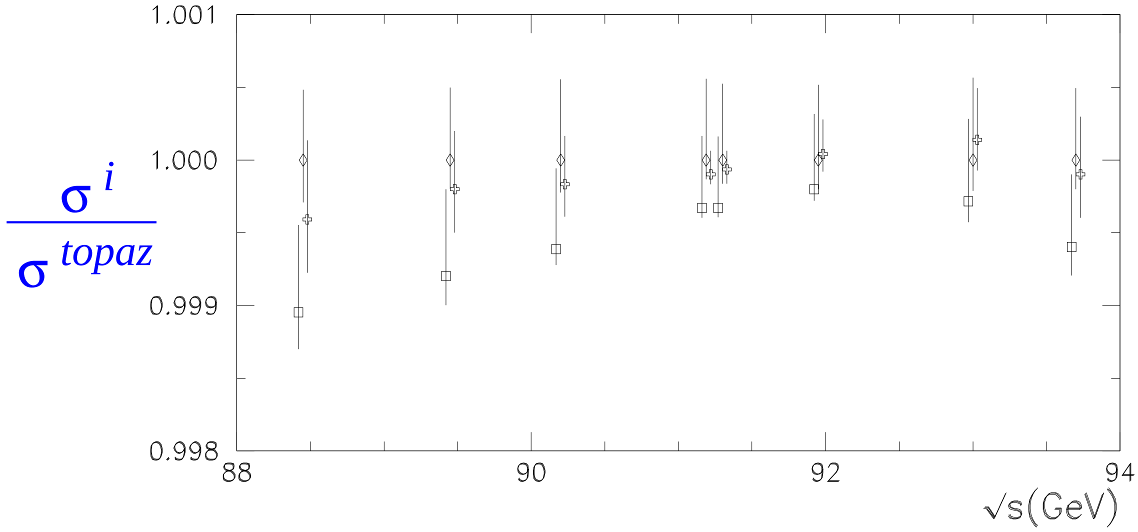
Theoretical Tools

- ***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.)



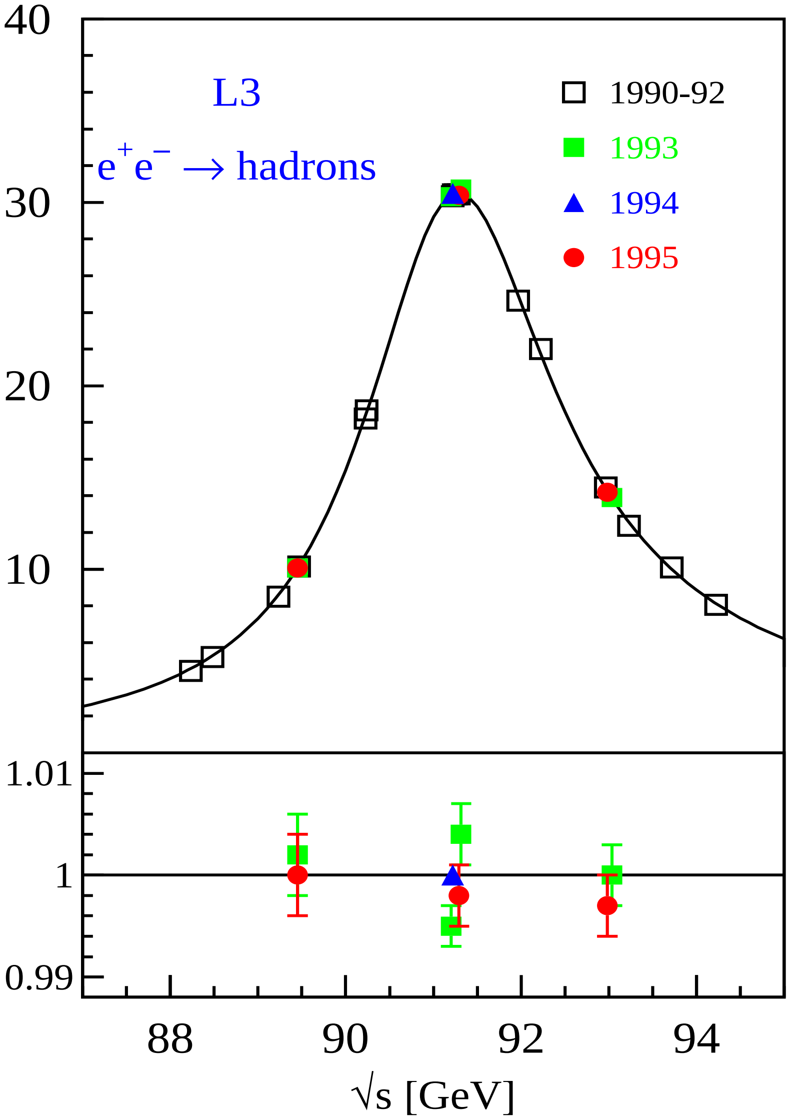


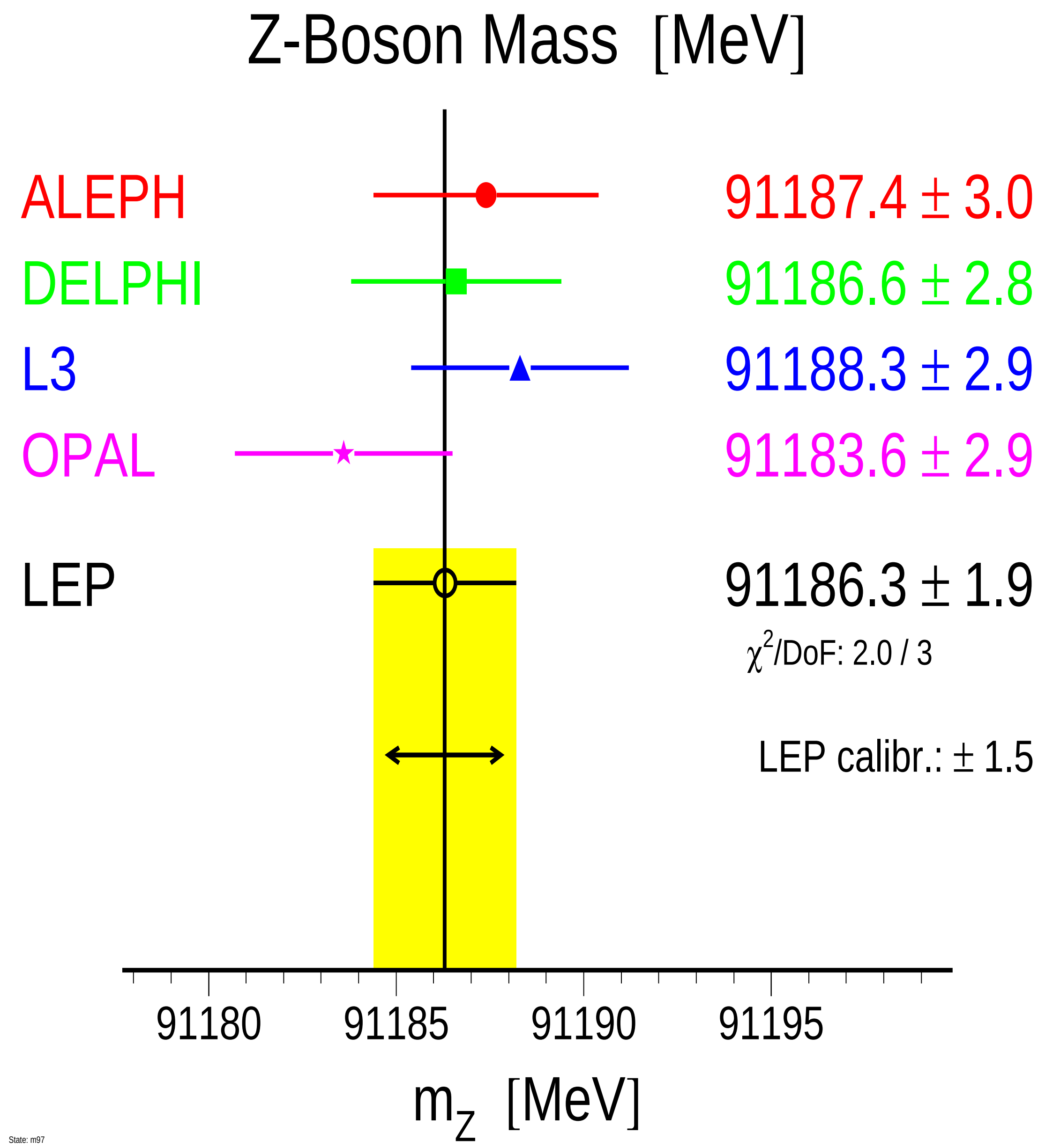
Results

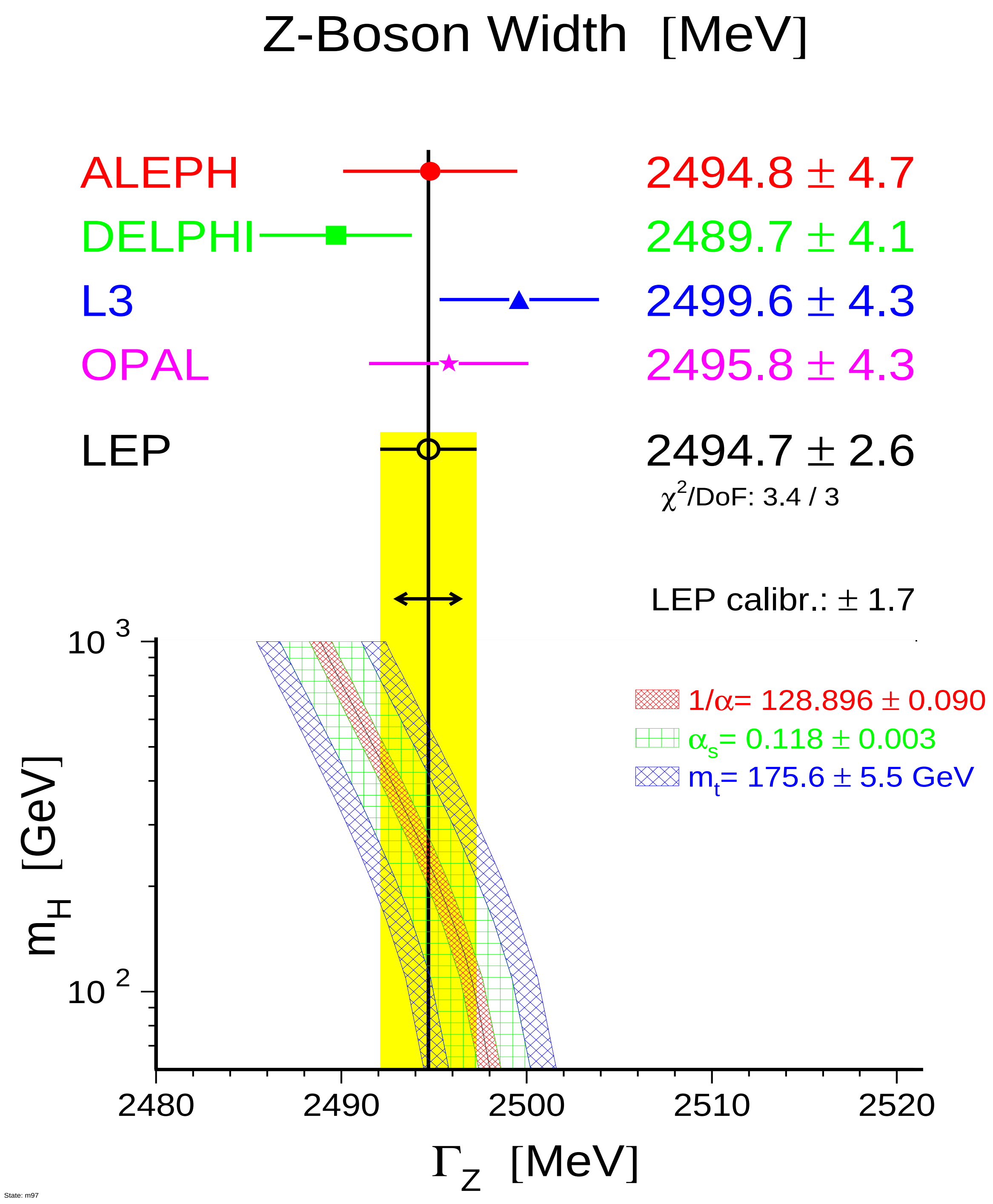
L3 preliminary results

Measured hadron cross-section (nb)

Ratio:




Z-Boson Mass [MeV]
ALEPH
DELPHI
L3
OPAL
LEP
91187.4 ± 3.0
91186.6 ± 2.8
91188.3 ± 2.9
91183.6 ± 2.9
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
DELPHI
L3
OPAL
LEP
2494.8 ± 4.7
2489.7 ± 4.1
2499.6 ± 4.3
2495.8 ± 4.3
2494.7 ± 2.6
χ²/DoF: 3.4 / 3
LEP calibr.: ± 1.7
1/α= 128.896 ± 0.090
α_s= 0.118 ± 0.003
m_t= 175.6 ± 5.5 GeV
10³
10²
m_H [GeV]
2480
2490
2500
2510
2520
Γ_Z [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

$$\Gamma_{had} = 1743.5 \text{ +- } 2.4 \text{ MeV}$$

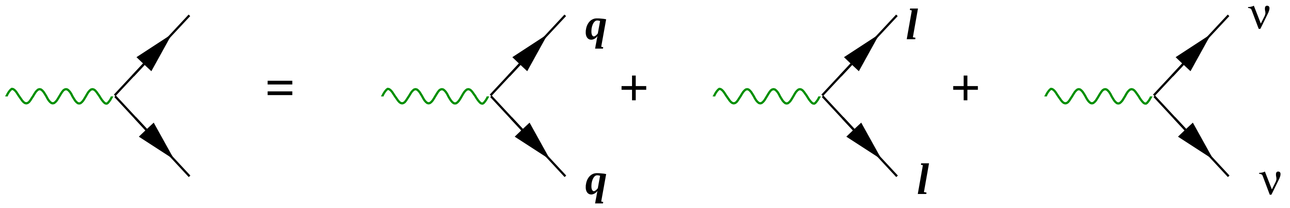
$$\Gamma_e = 83.94 \text{ +- } 0.15 \text{ MeV}$$

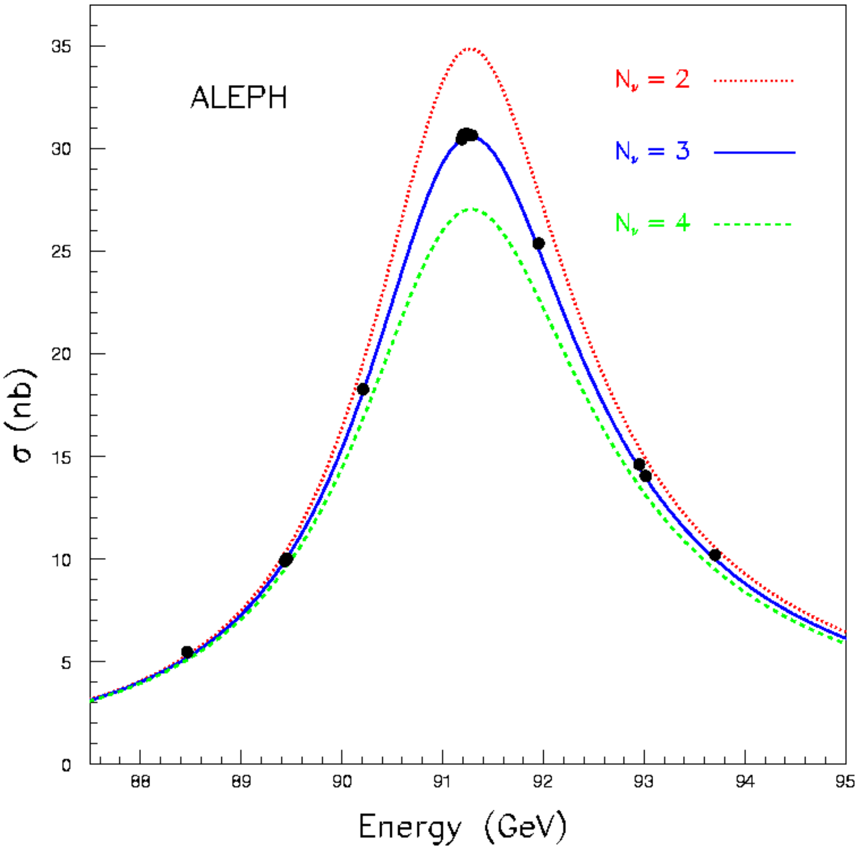
$$\Gamma_\mu = 83.79 \text{ +- } 0.21 \text{ MeV}$$

$$\Gamma_\tau = 83.64 \text{ +- } 0.26 \text{ MeV}$$

Number of light neutrino species

$$\Gamma_z \qquad \Gamma_{had} \qquad \Gamma_{lepton} \qquad \Gamma_{invisible}$$





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

$$\longrightarrow \quad N_{\nu\nu} = 2.992 \ \text{+-}\ 0.011$$

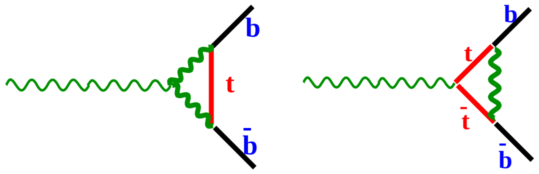
R_b and R_c

- 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*

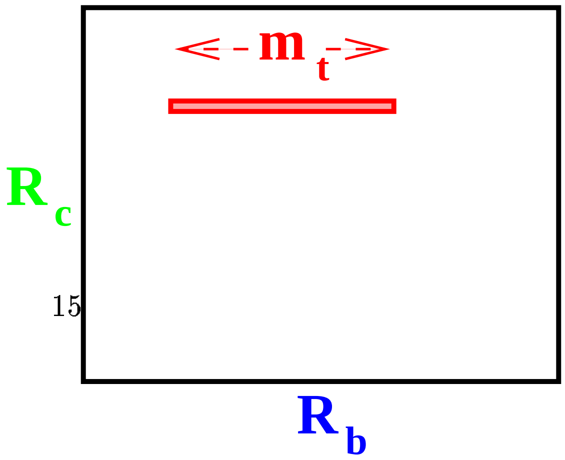
- *Uniquely for b quarks:*



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

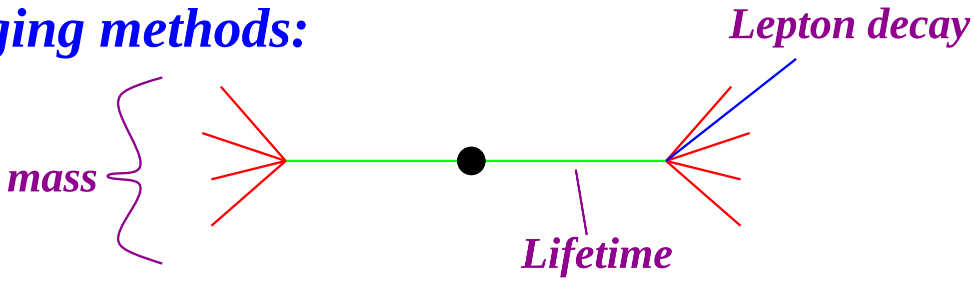
⇨ *Sensitive to extra* m_t *correction*

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

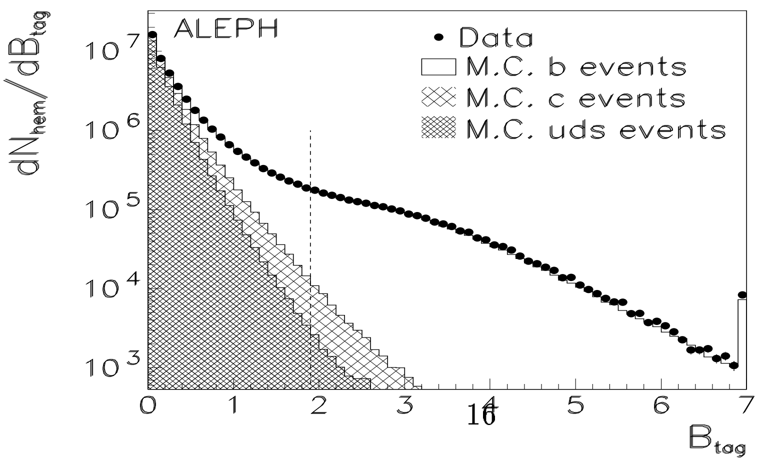
- ***Main systematic errors:***

  - 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%)

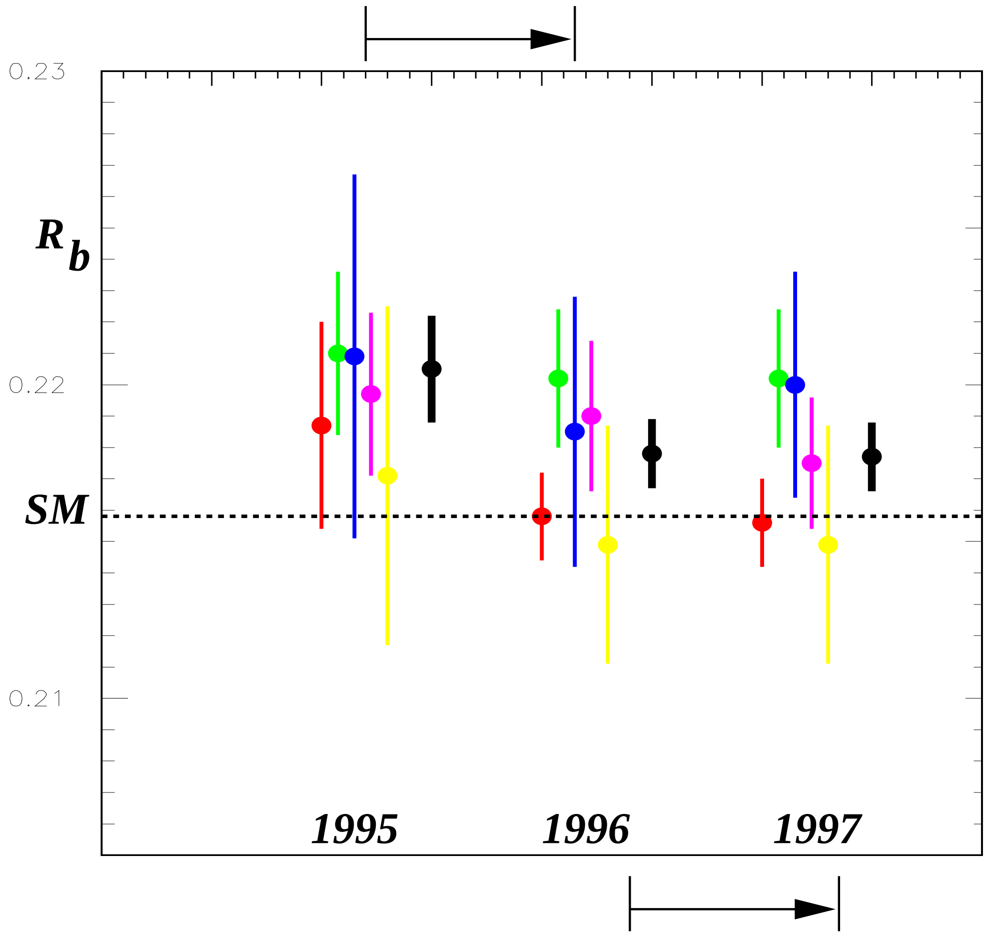


Efficiency -> 25%

Purity -> 98%

History of R_b

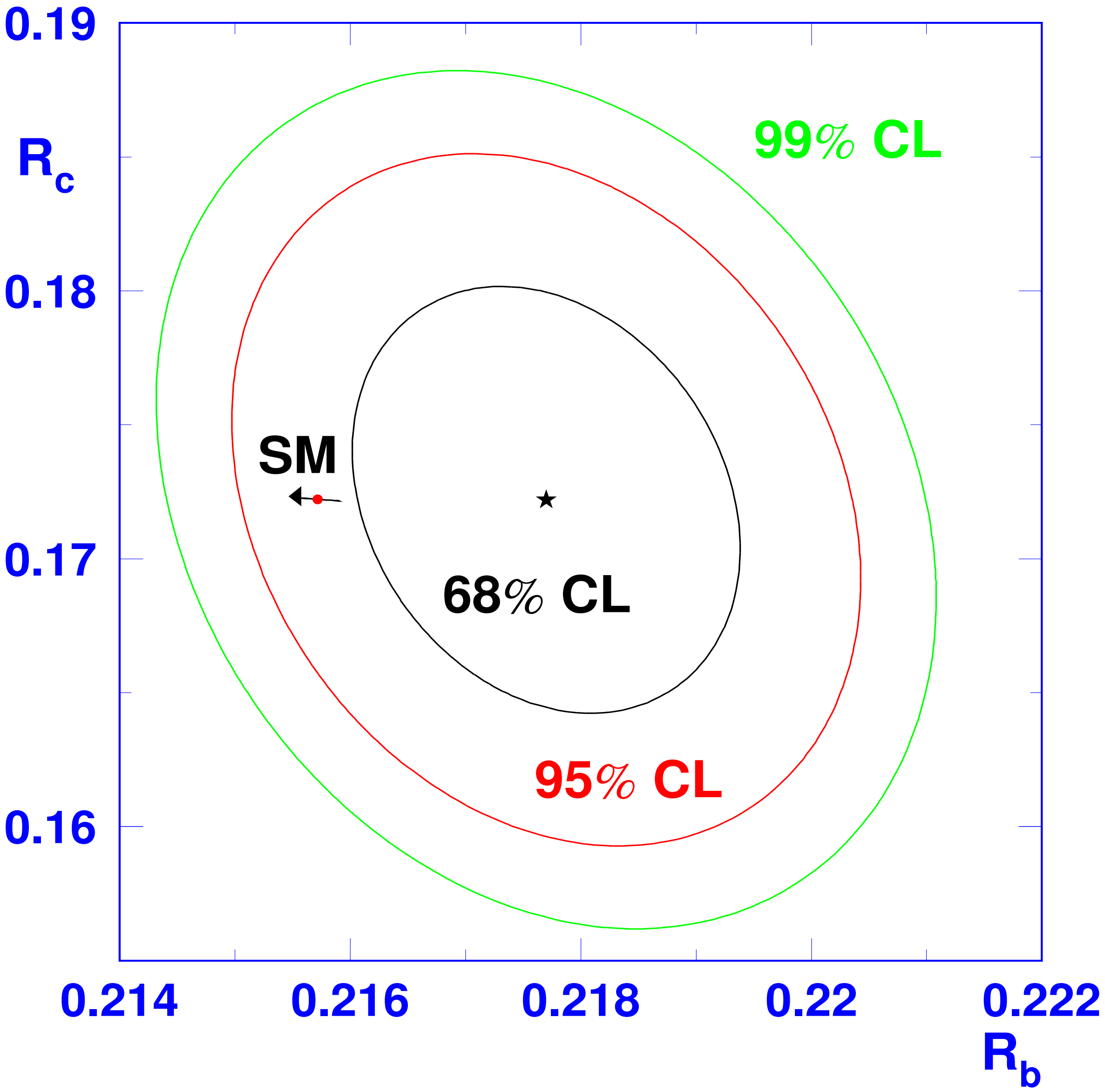
-Aleph introduce pure/multiple method ->1995
-Delphi add 1994 data
-L3 introduce lifetime tag ->1994
-Sld introduce new pure mass tag analysis
-Some changes to related params.
(Rc - 0.0008, gluon splitting -0.0003)



-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:

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

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

Lepton Forward-Backward asymmetry

τ polarisation

Left-Right asymmetry from SLD

All measure A_{lepton}

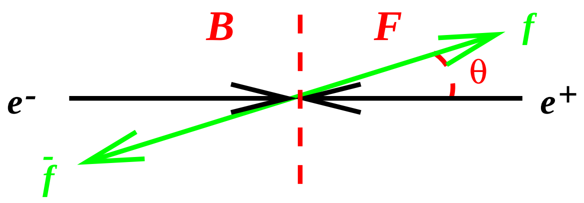
b,c quark Forw.-Back. asymmetry

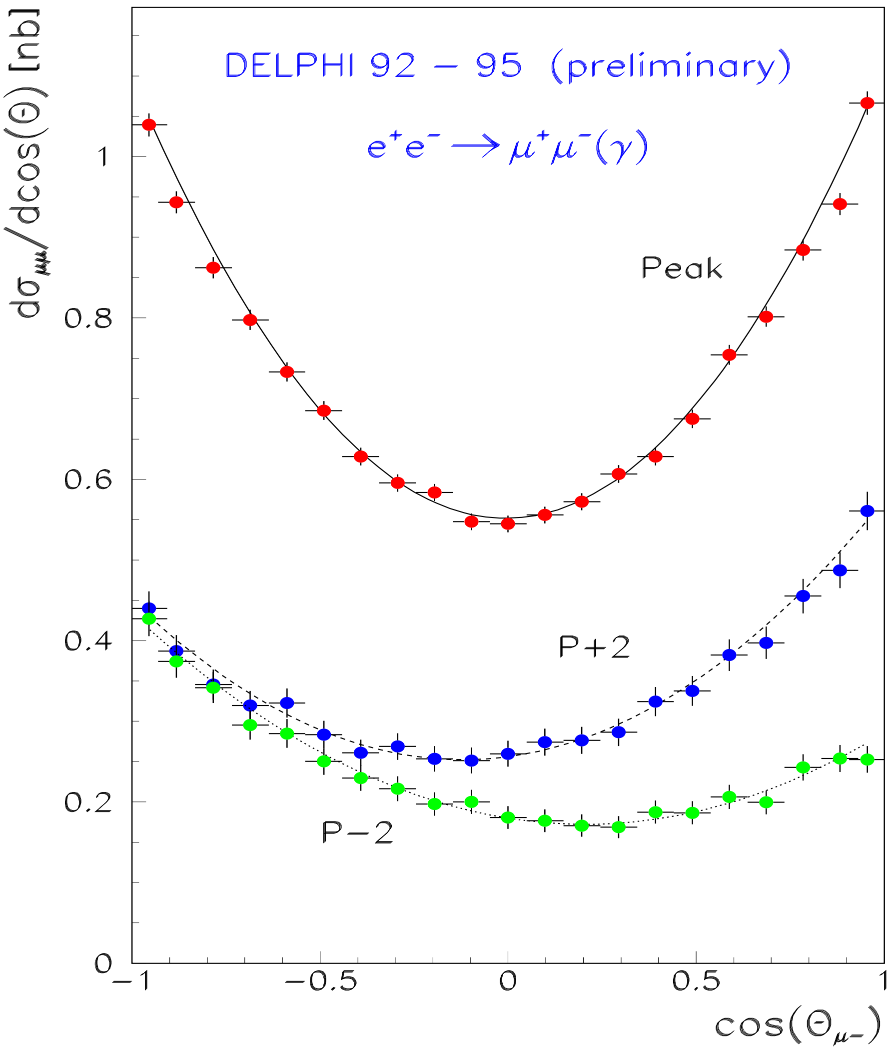
measures $A_{lepton} \cdot A_{b,c}$

b,c quark polarised asymmetries from SLD

measures $A_{b,c}$

Lepton Forward - Backward Asymmetries



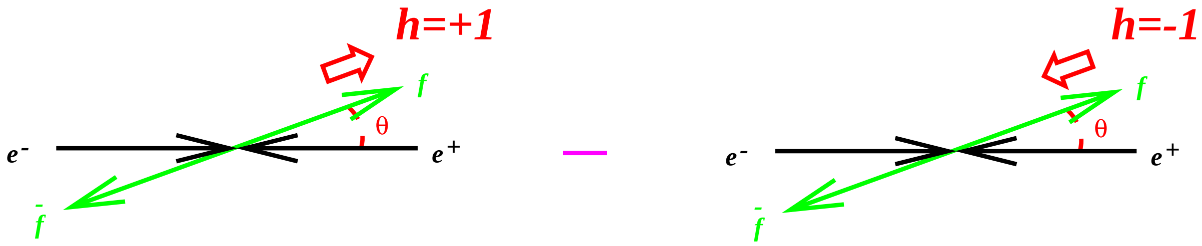


LEP Average

A_l^{fb} = 0.0177 +- 0.0010

→ A_l = 0.1536 +- 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

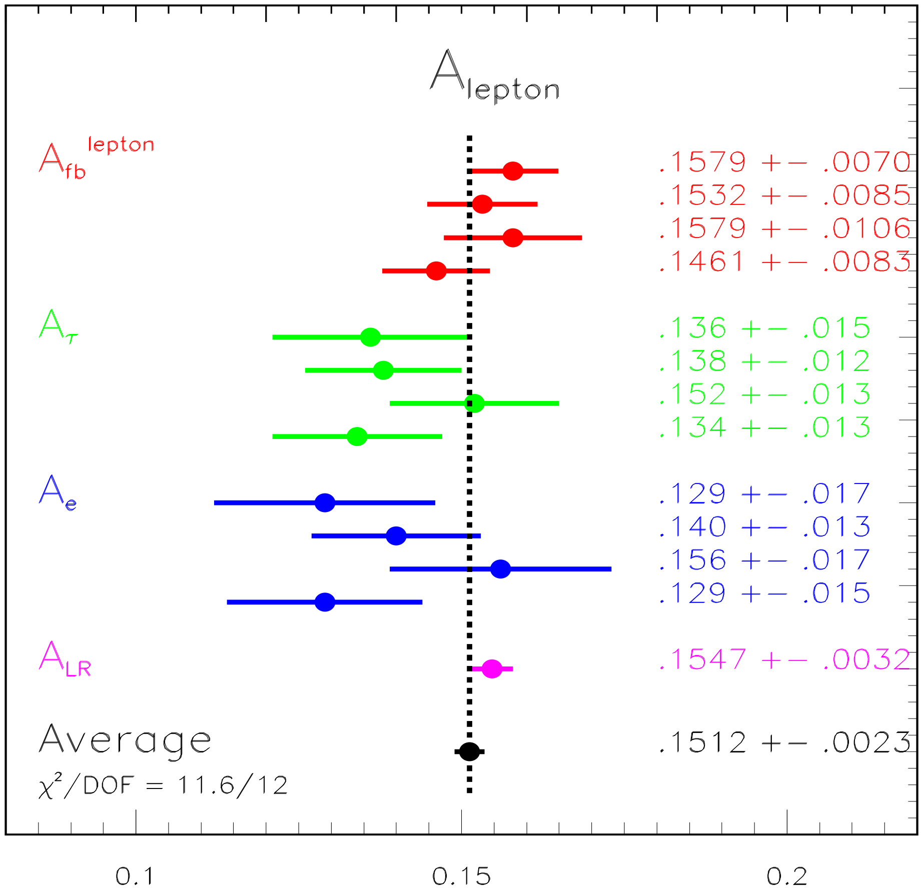
- measures A_e (independent of final state detected)

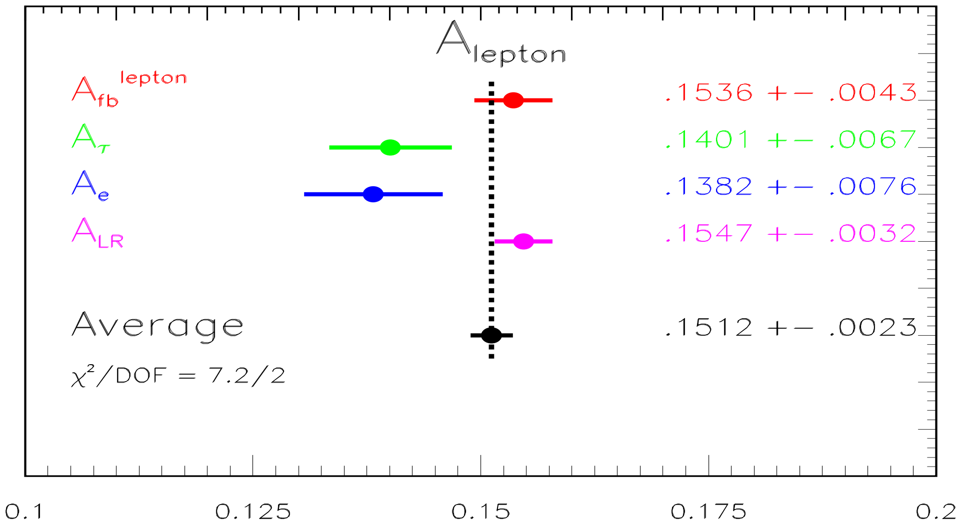
SLD				
A_e	=	0.1547	+-	0.0032

Comparison of measurements of A_l

A
D
L
O

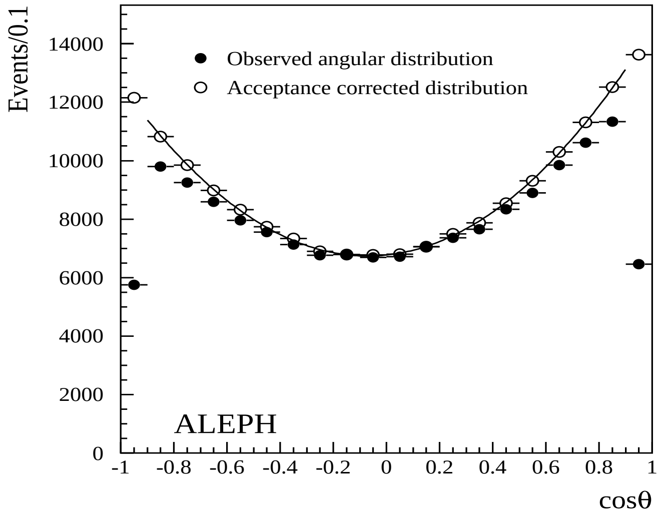
SLD





b quark asymmetries

- ***b quark Forward - Backward asymmetry:***

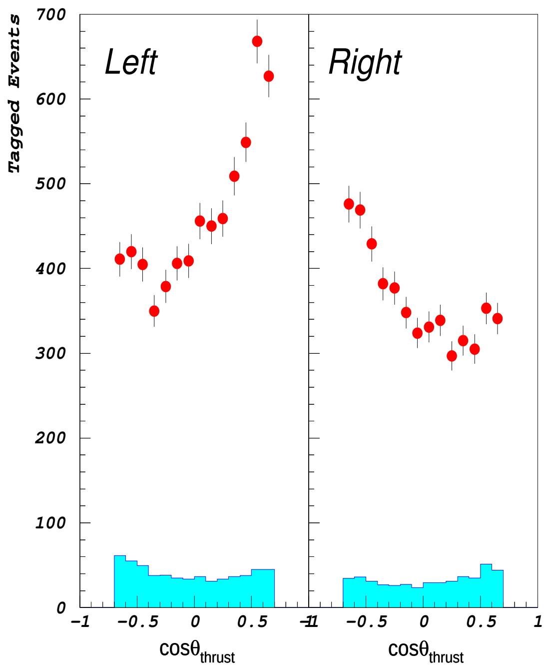


LEP Average

$A^{0,b}_{fb}$ = 0.0985 +- 0.0022

- ***b quark polarised Forward - Backward asymmetry:***

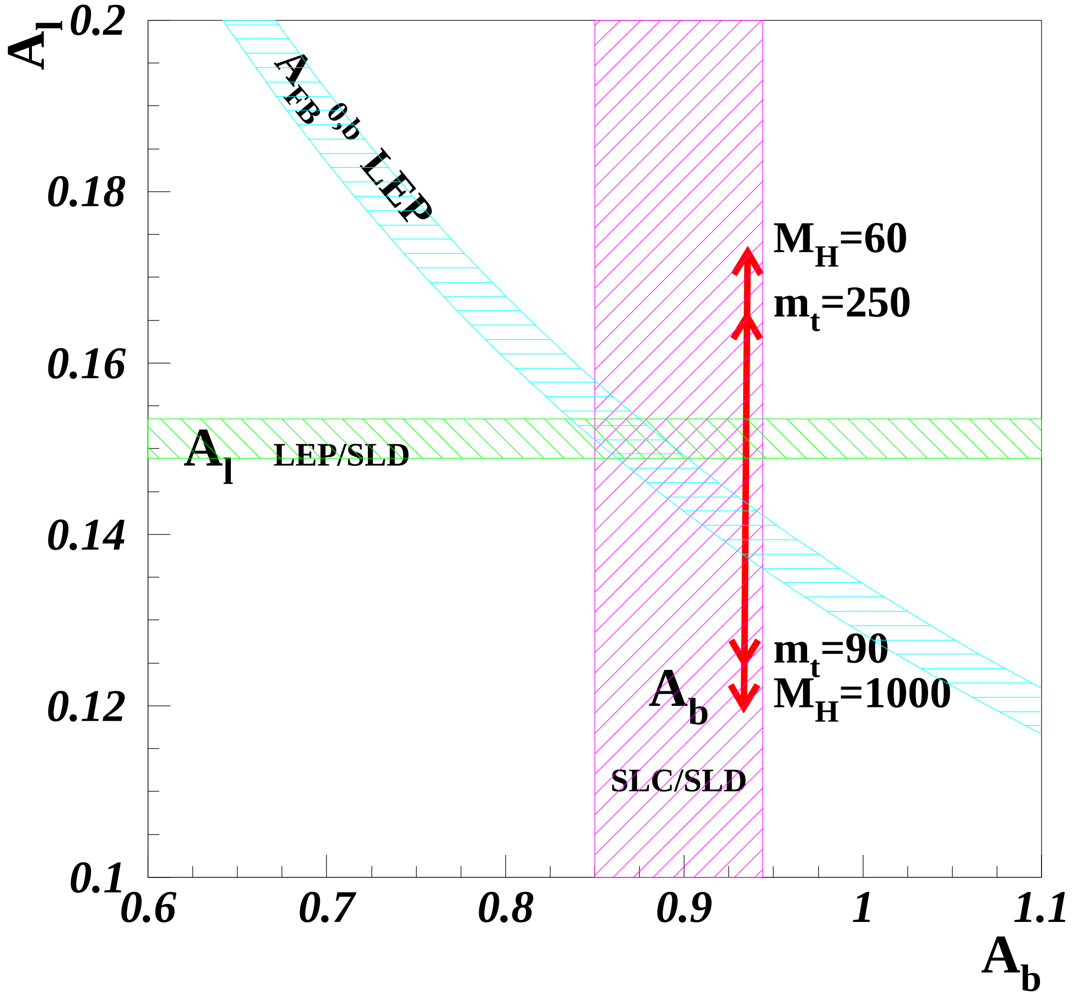
A_b from Jet-Charge, SLD 1993-1995



SLD

A_b = 0.897 +- 0.0038

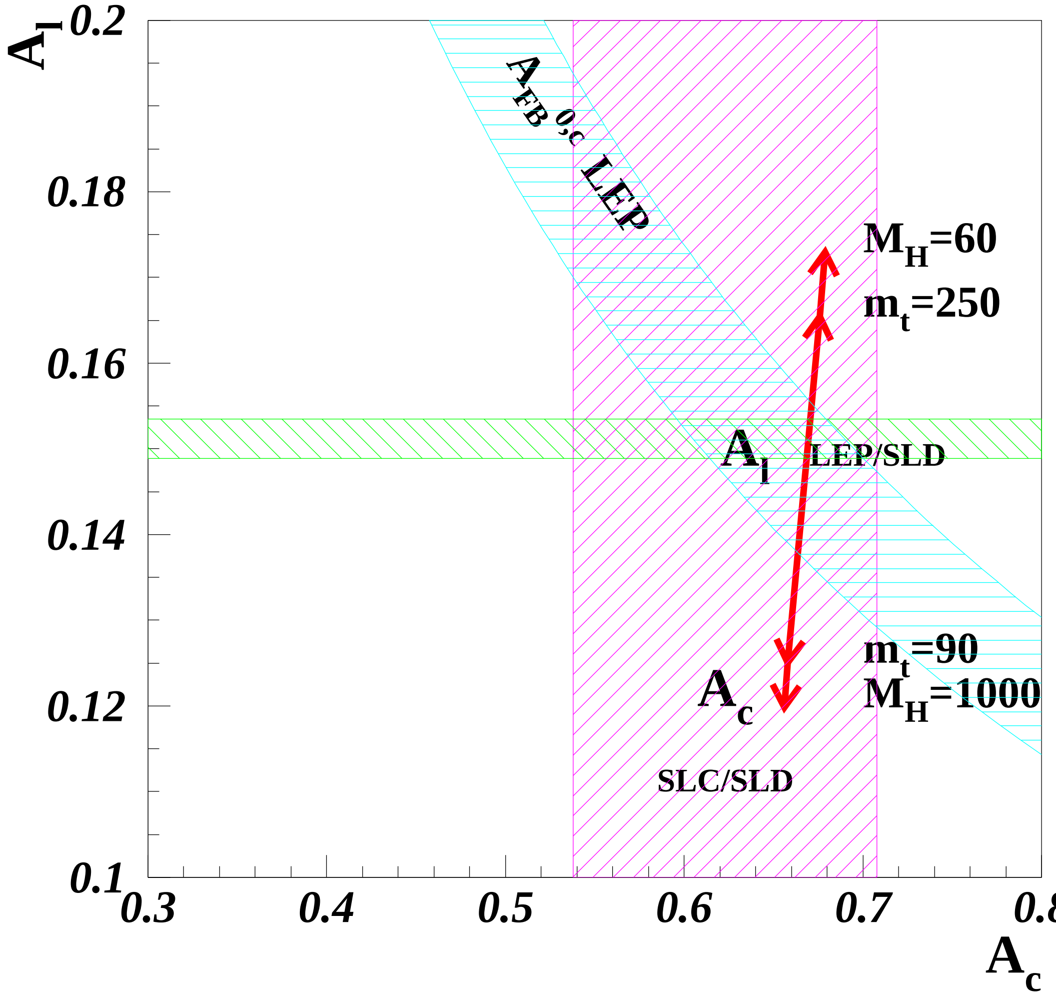
Constraints on A_l and A_b



Fit for A_b yields

A_b = 0.875 +- 0.021 (SM value 0.935)

Constraints on A_l and A_c

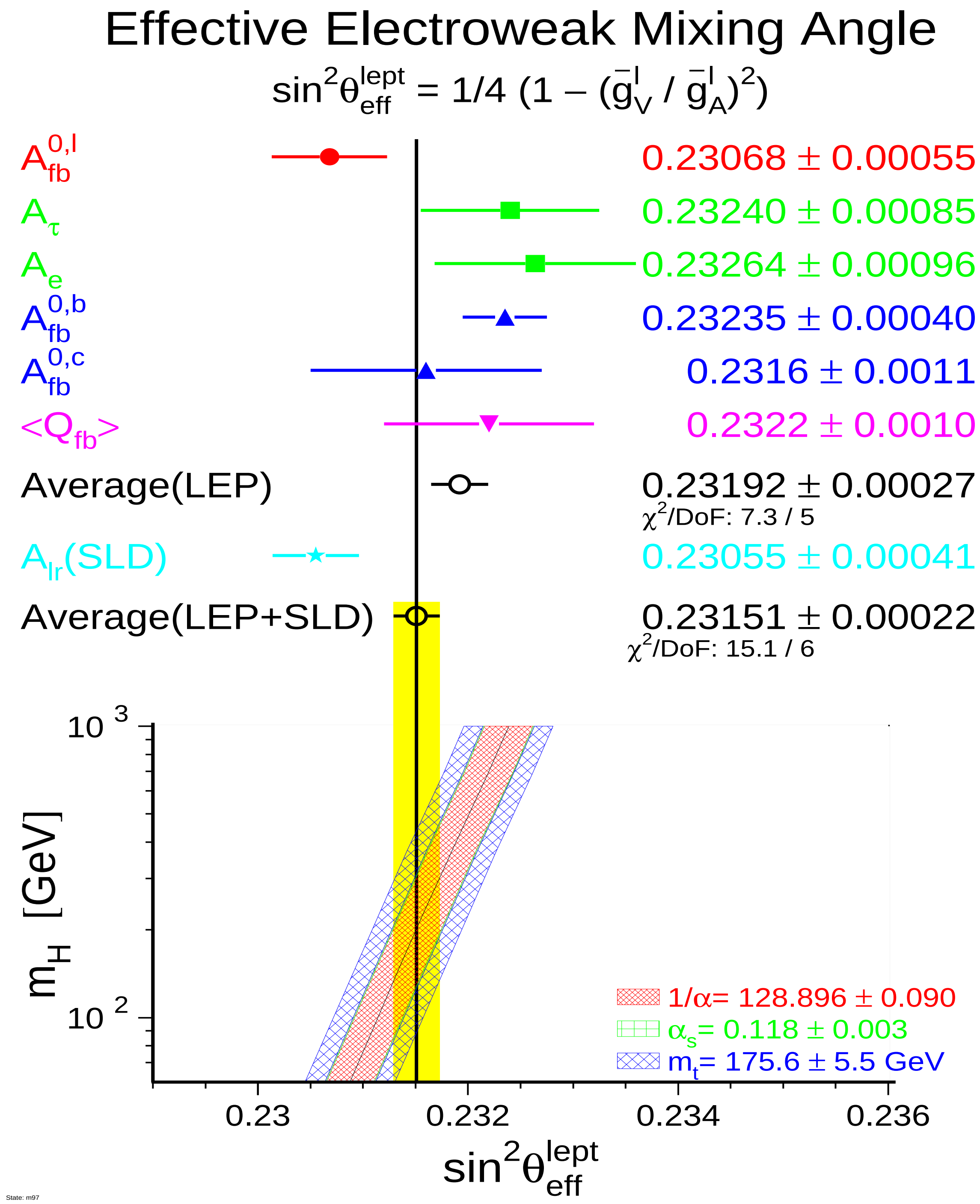


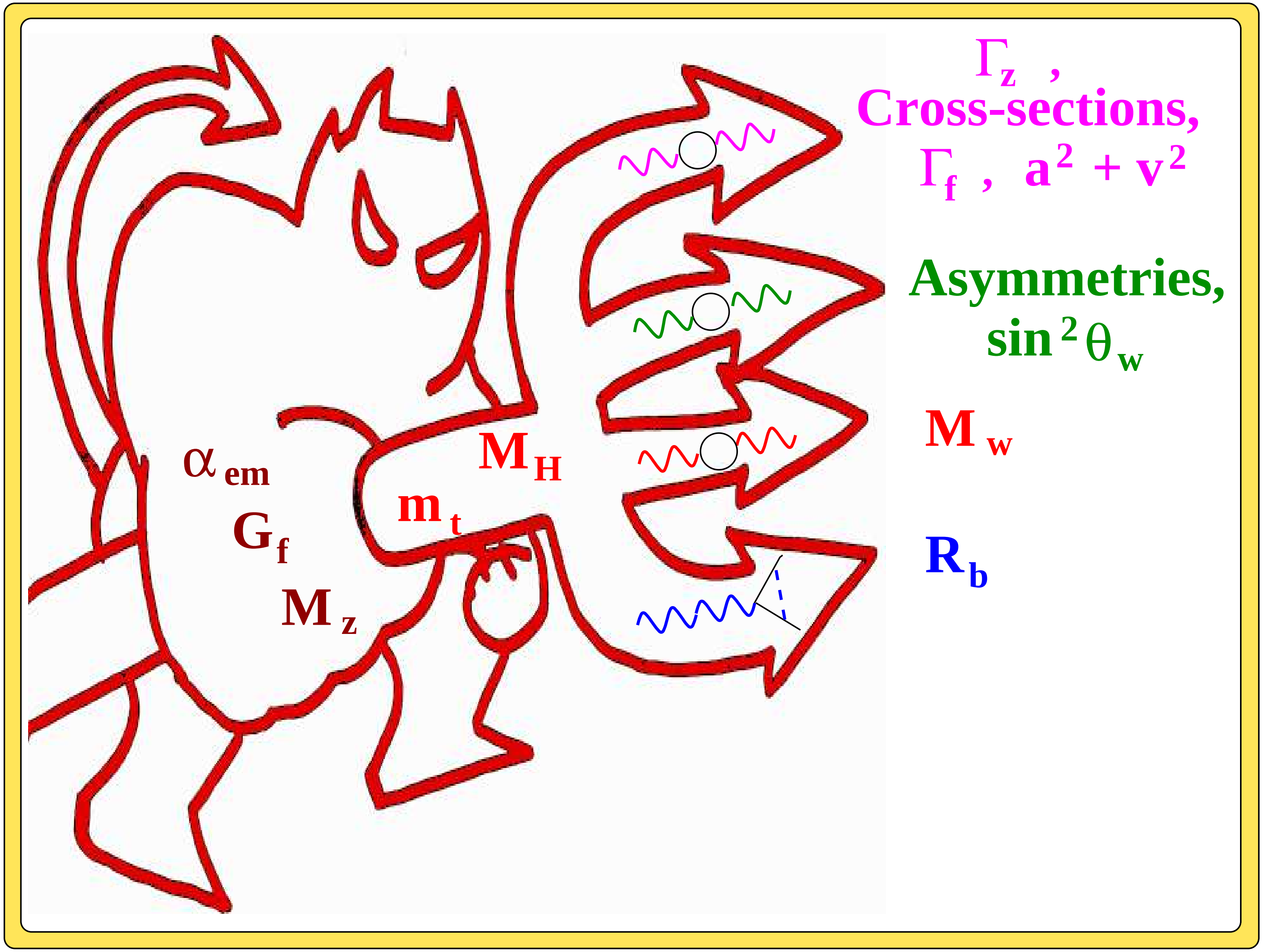
Fit for A_c yields

A_c = 0.643 +- 0.038 (SM value 0.668)

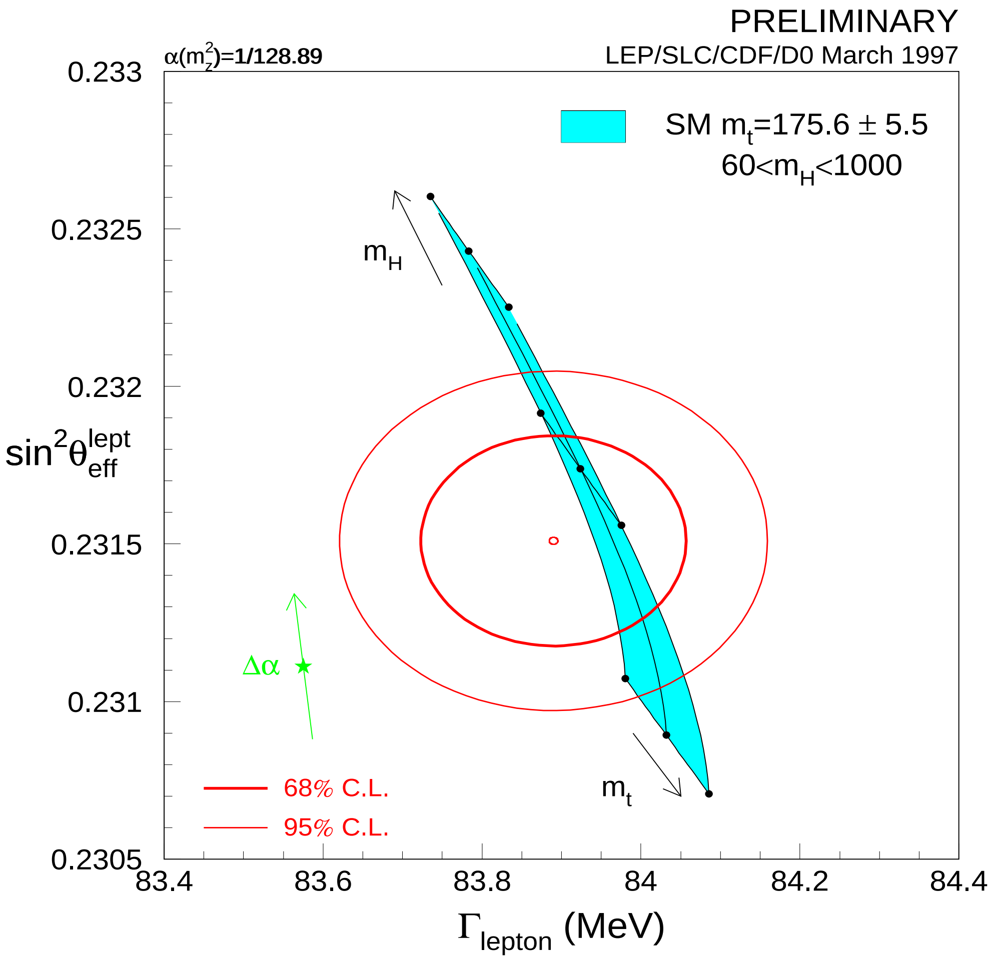
Sin2wAll

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




α_{em}
G_f
M_z
m_t
M_H
Γ_z ,
Cross-sections,
Γ_f , $a^2 + v^2$
Asymmetries,
$\sin^2\theta_w$
M_w
R_b

Electro-weak corrections



All quantities $Q = \{\ \Gamma_l\ ,\ \sin^2\theta_W\ ,\ M_W\ , \ldots\ldots.\}$ ***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....

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

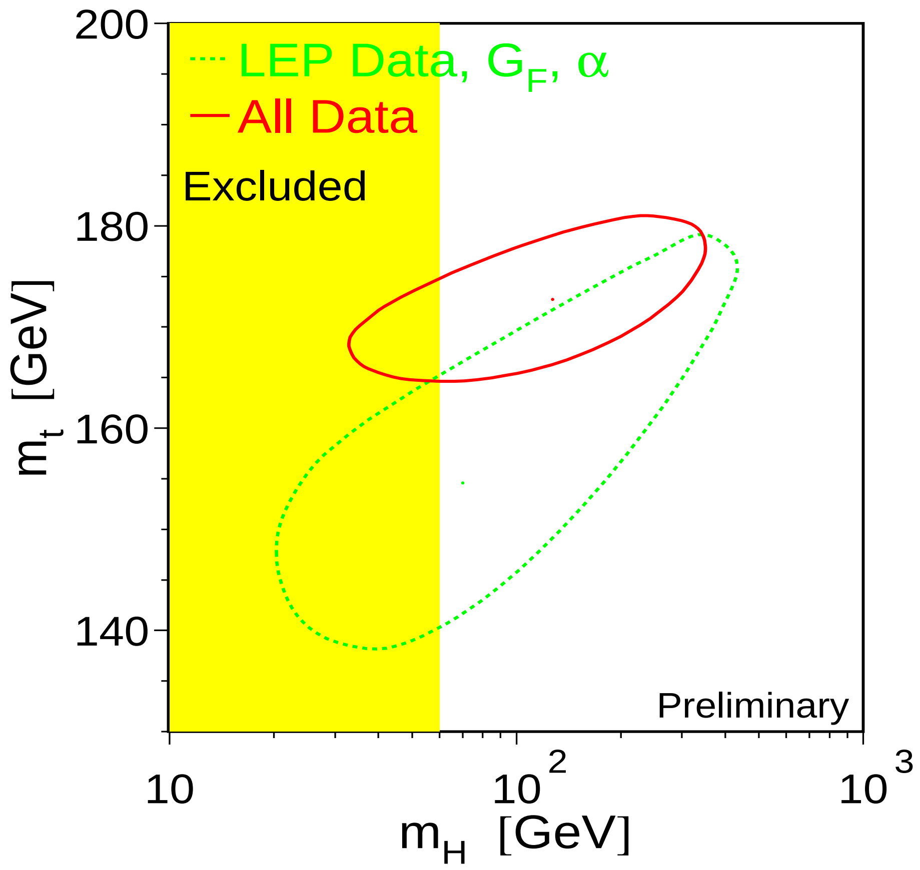
$\sin^2\theta_W\ (m_t\ ,\ m_H\ )$

$R_b\ (m_t\ )$

LEP,SLD,νN

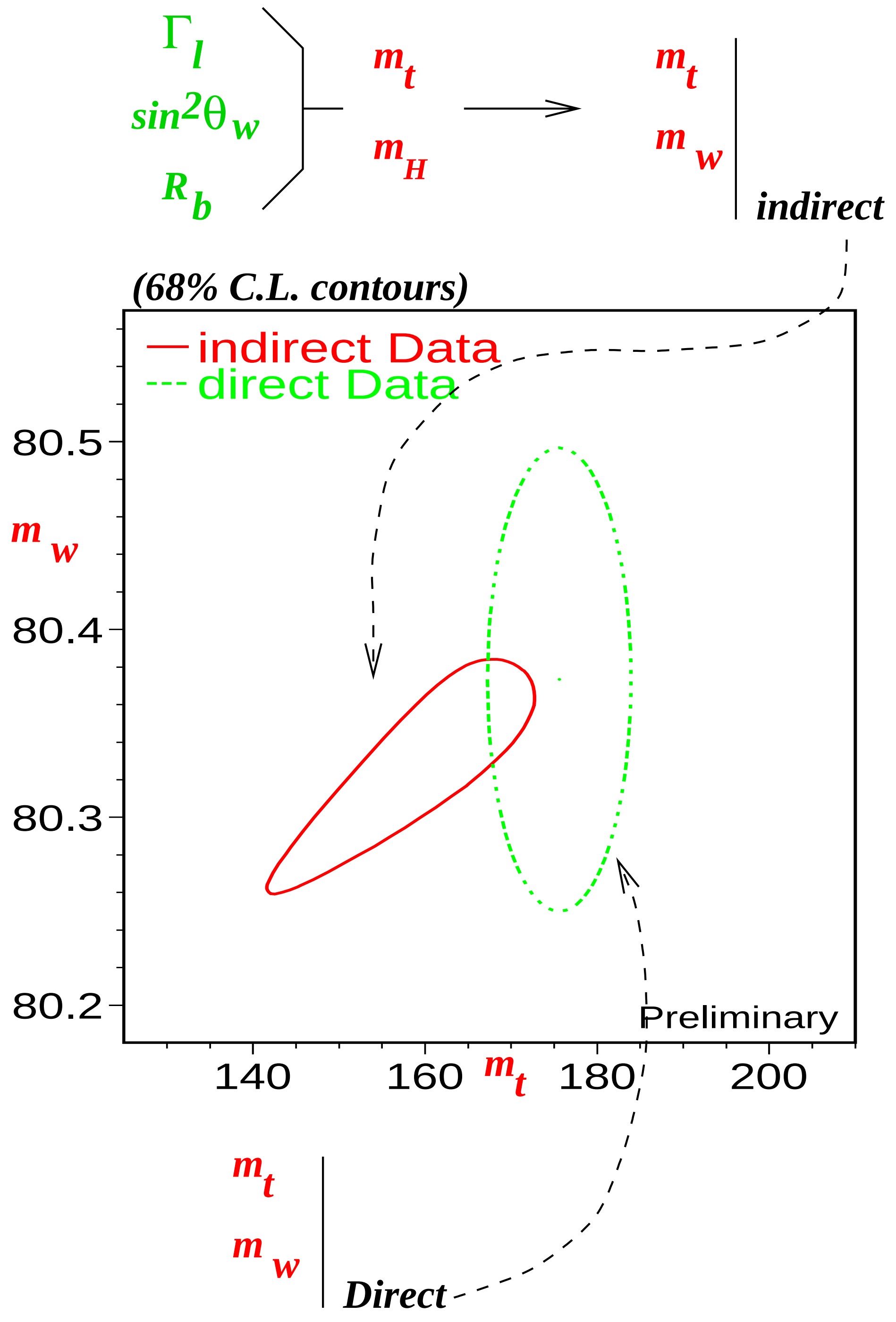
$M_W\ (m_t\ ,\ m_H\ )$ *= 80.37 +- 0.10 GeV, CDF,D0*
= 80.38 +- 0.14 GeV, LEP-2

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



(68% C.L. contours)

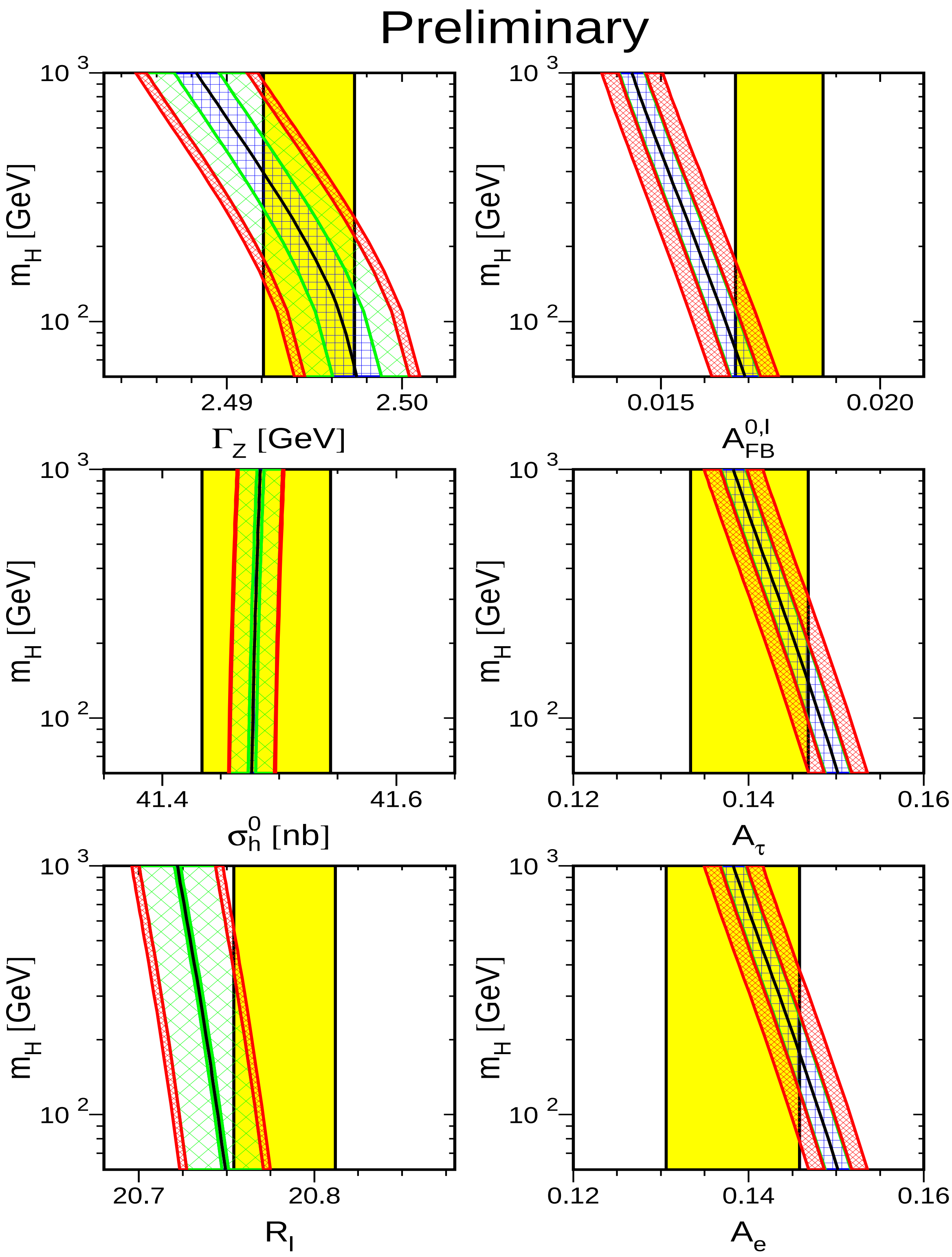
Interpretation using m_t and m_W as currency....

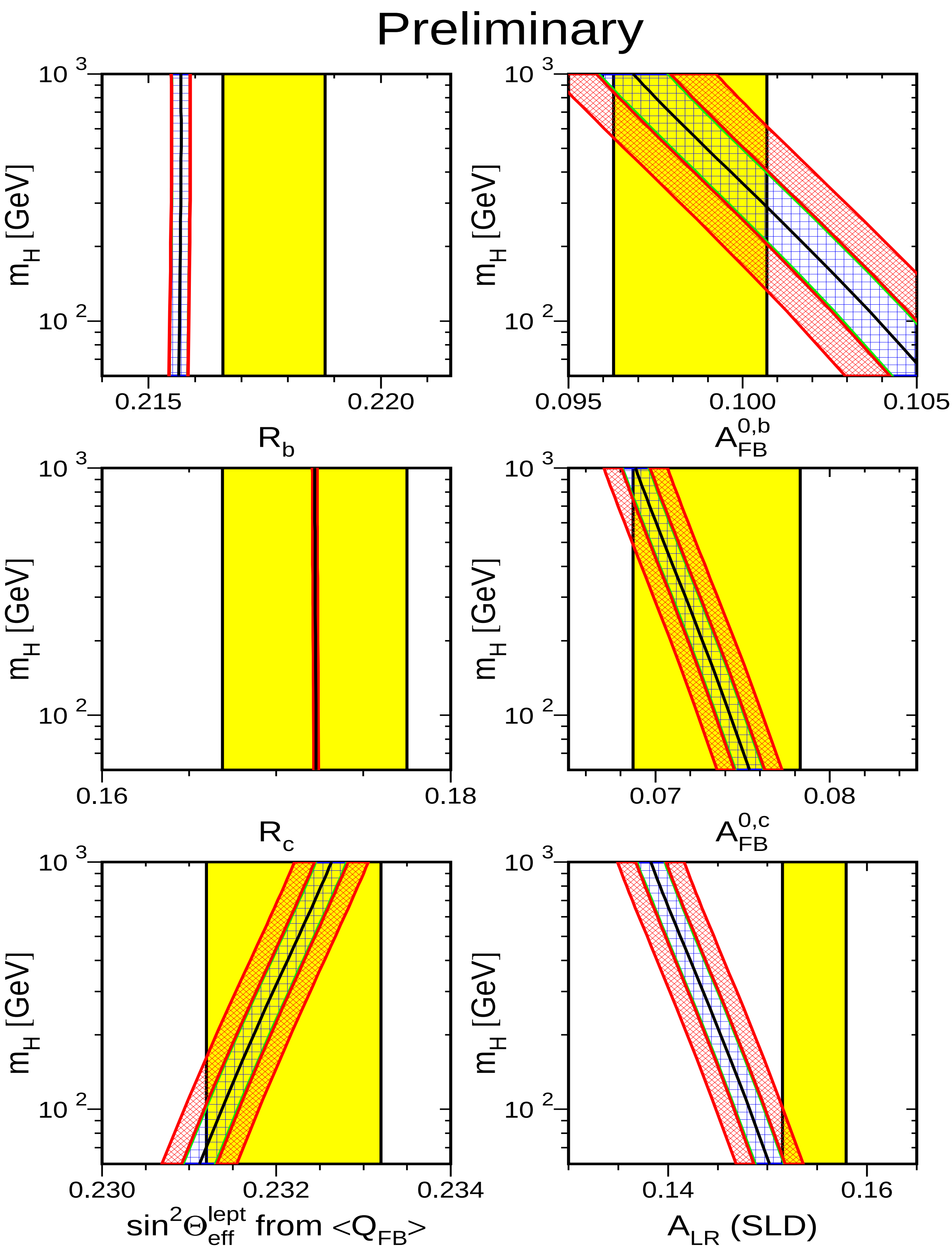


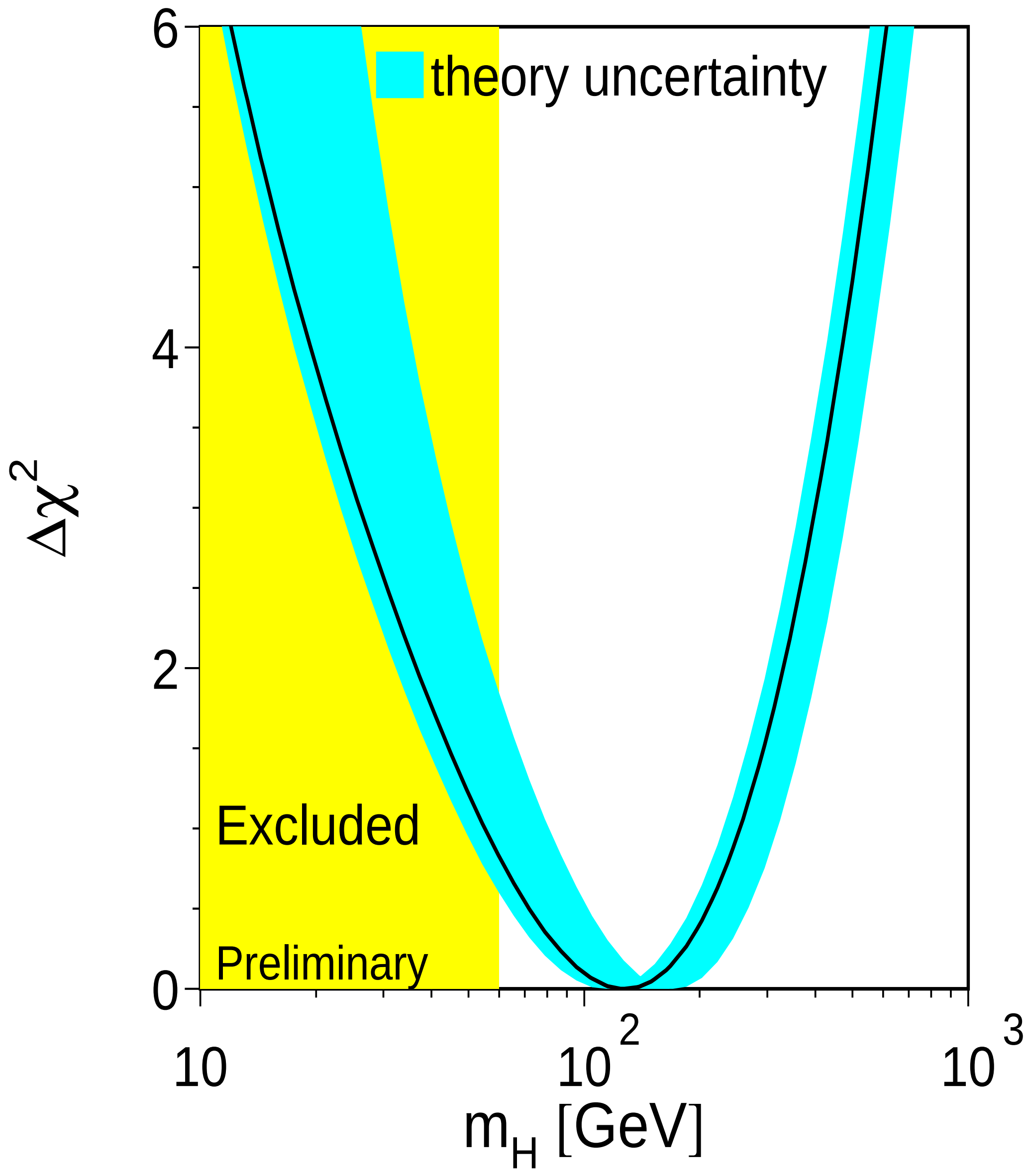
Combined m_W ⇨ 80.366 +- 0.031 GeV

Higgs mass constraints

(with m_t fixed by direct measurement)




Preliminary
10^3
10^2
m_H [GeV]
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)



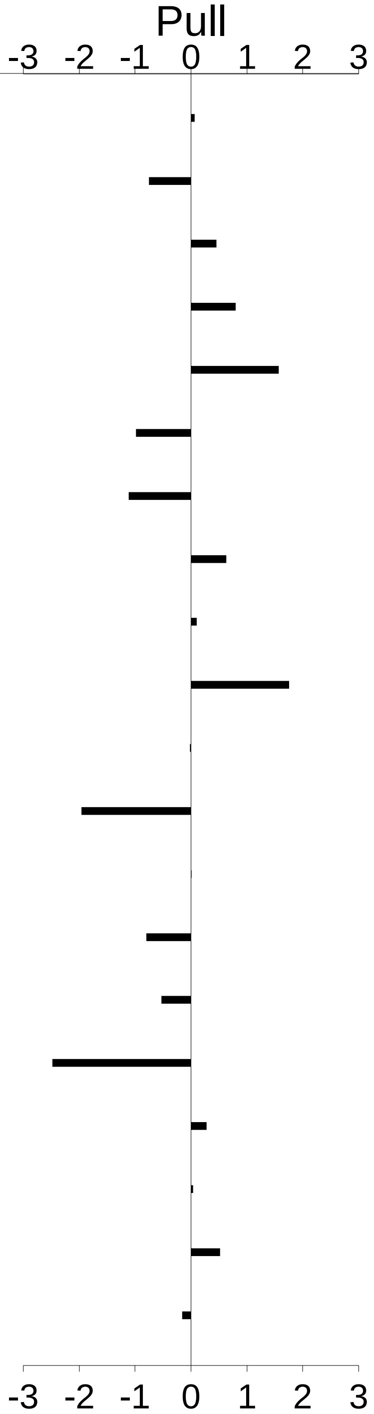
(Theory errors taken from comparison of ZFITTER/TOPAZ0/BHM)

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

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

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