Electroweak Results from LEP

20th Johns Hopkins Workshop

27 June 1996

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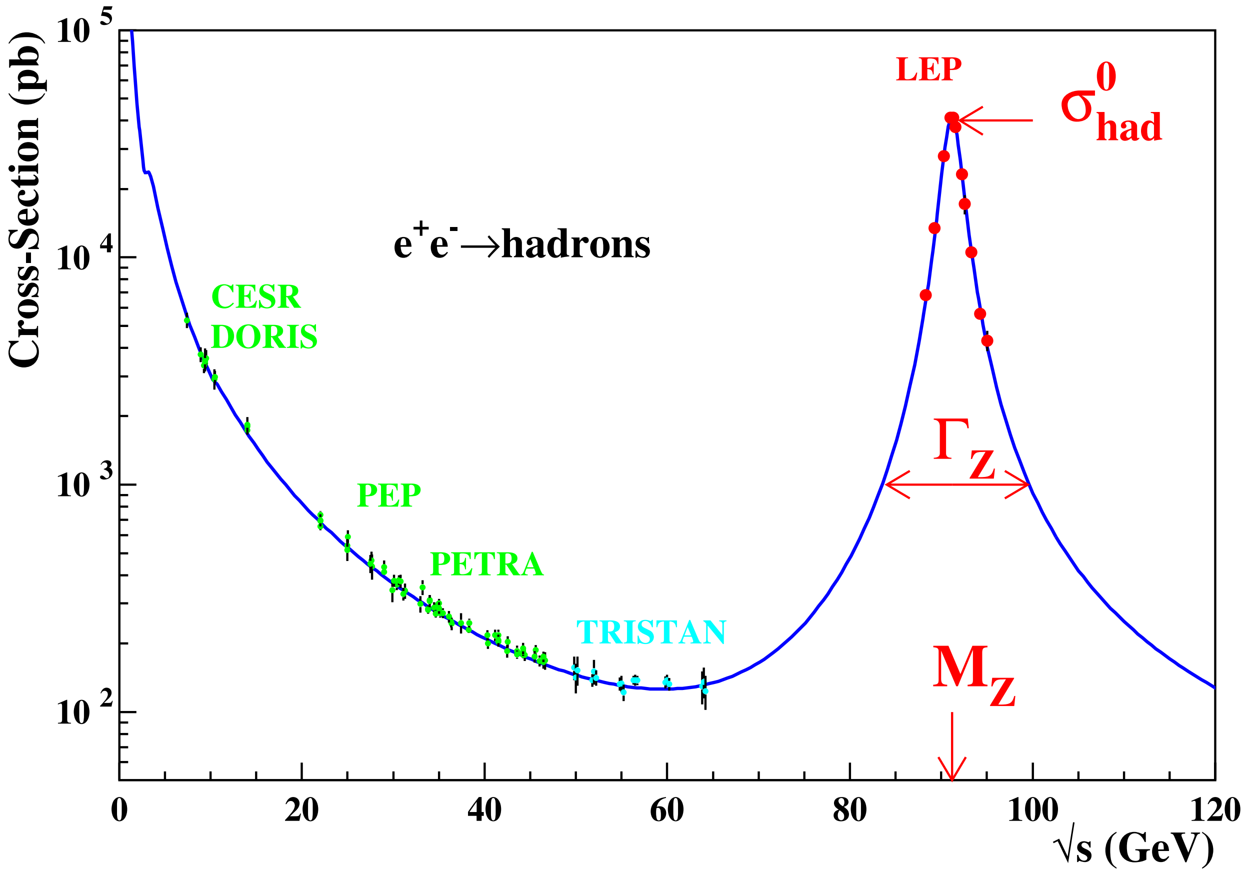
Results from Moriond 96: Updates for Warsaw not quite ready

Outline

- Z^0 mass and width
- Lepton asymmetries
- Heavy quark measurements
  - R_{c} analyses
  - R_{b} analyses
- Combined electroweak fits
- The LEP energy upgrade: “LEP-1.5”
  - Electroweak
  - Not electroweak: 4-jet final state
- Next week’s data?
- Summary

Z Mass and Width

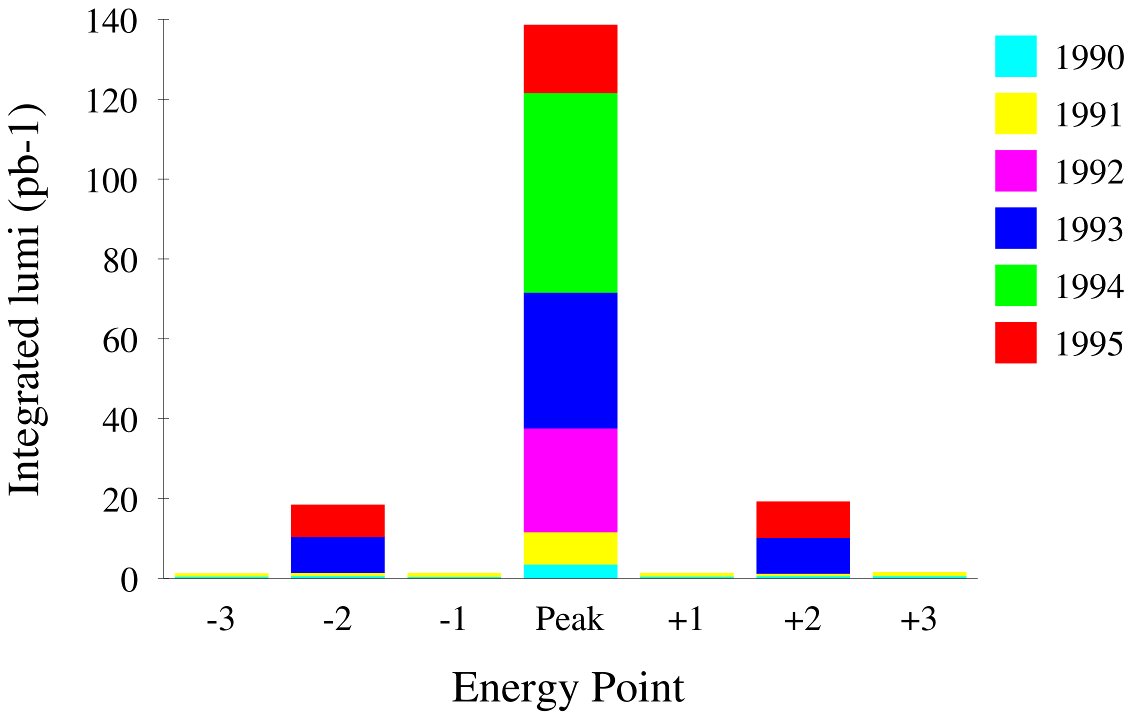


Main (common) uncertainties:

- Absolute LEP energy scale for m_Z
  (1.5 MeV of 2.2 MeV for data up to 1993)
- Relative LEP energy scale and beam energy spread for Γ_Z
  (2.0 MeV of 3.2 MeV for data up to 1993)
- Theoretical uncertainty on luminosity for $\sigma_{\mathrm{had}}^{\mathrm{pole}}$
  (0.16% of 0.19% for data up to 1994)

Decision to scan in 1995 in order to improve statistical precision on Γ_Z

Off-Peak Data



1995 data $\Rightarrow$ off-peak sample almost doubled

Should give close to factor two improvement in Γ_Z

Analysis is currently in progress:

- Energy calibration surprises...
- Experimental analyses approaching systematic limits: require care and time

Results shown do not include 1995 data

Energy Calibration of LEP

Energy Calibration

- LEP energy calibration improved to a few MeV in 1993 by resonant depolarization technique
- Intrinsic precision $<$1 MeV at time of measurement (end of fill) on mean energy in LEP

Difficulties:

- Uncalibrated fills: 60% in 1993, 30% in 1995
- Extrapolation within each fill: uses energy model, includes temperature effects, beam orbit position, tides, etc.
- Check model with calibrated fills: Residual scatter c.6 MeV in 1993, 3 MeV in 1995
- Sawtooth corrections needed to find energy at I.P.s from LEP average: RF model

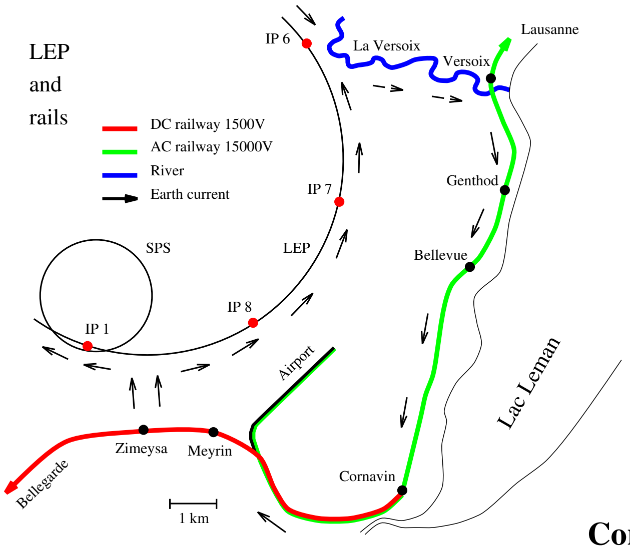
One of the checks made in 1995:

- Variation of energy within a fill, using NMR probes installed in tunnel

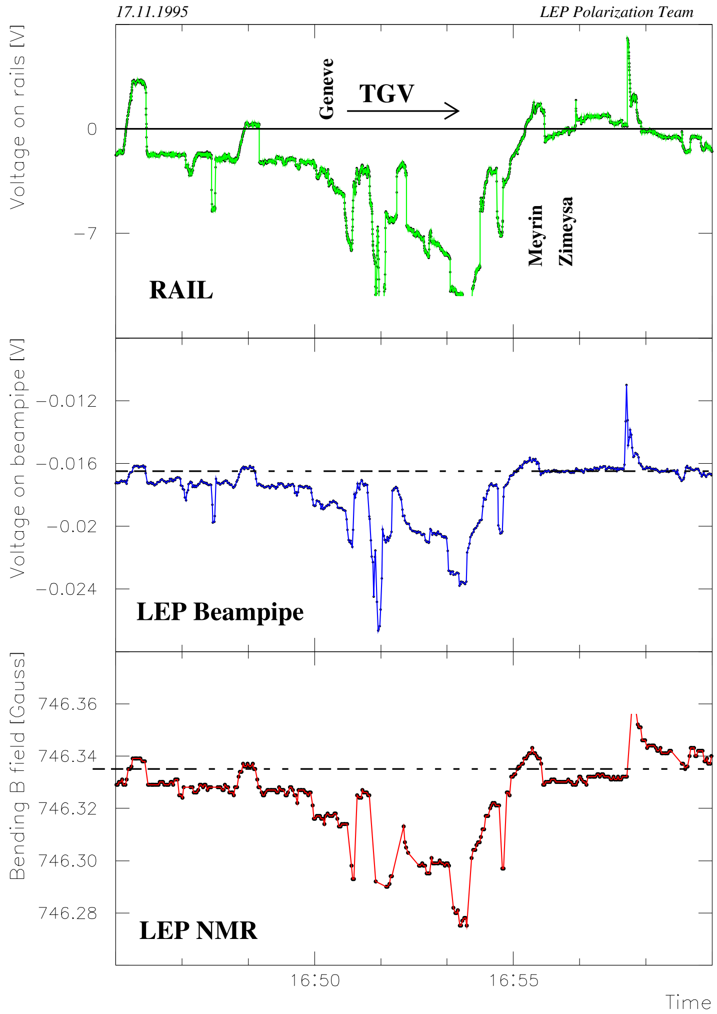
Result: large energy variation during a fill

New effect found to be correlated with the train timetable..!

The TGV Effect



Correlation between trains and LEP



Implication of the TGV Effect

Subject of intense study by the LEP energy calibration working group: effect now largely understood

- Current along beampipe induces slow additional rise in beam energy during a fill
- Effect expected to be same at peak+2 and peak–2
- The measurement of m_Z is significantly affected (shift may be comparable to previously quoted error)
- The measurement of Γ_Z is essentially unaffected
- Updated preliminary results likely for Warsaw

Further tests will be made during 1996 running to improve and check understanding

Cross-Sections and Luminosities

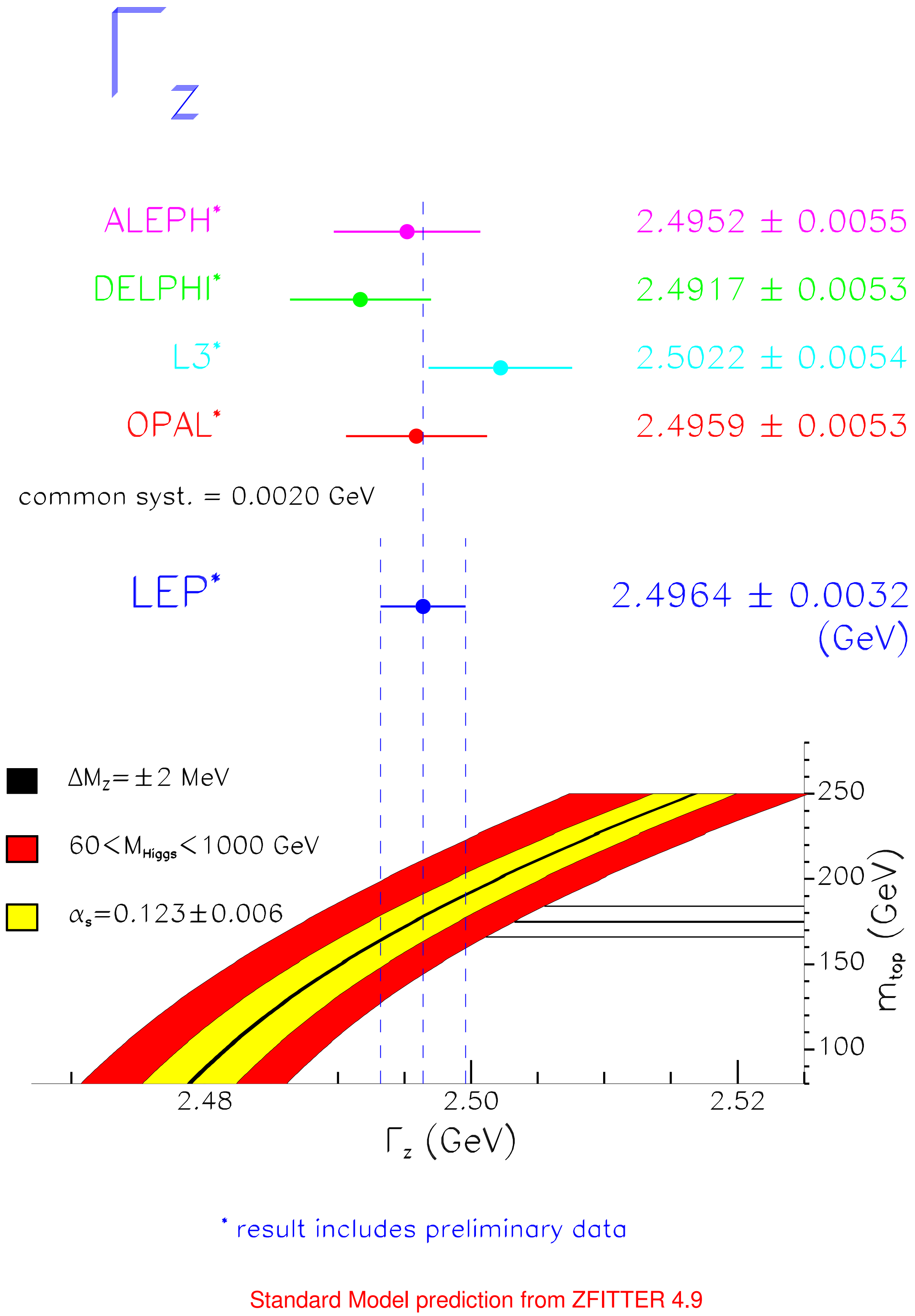
Measure $\sigma(s) = (N_S - N_B)/\epsilon \int \mathcal{L}\mathrm{d}t$

LEP systematic errors (1993-94)

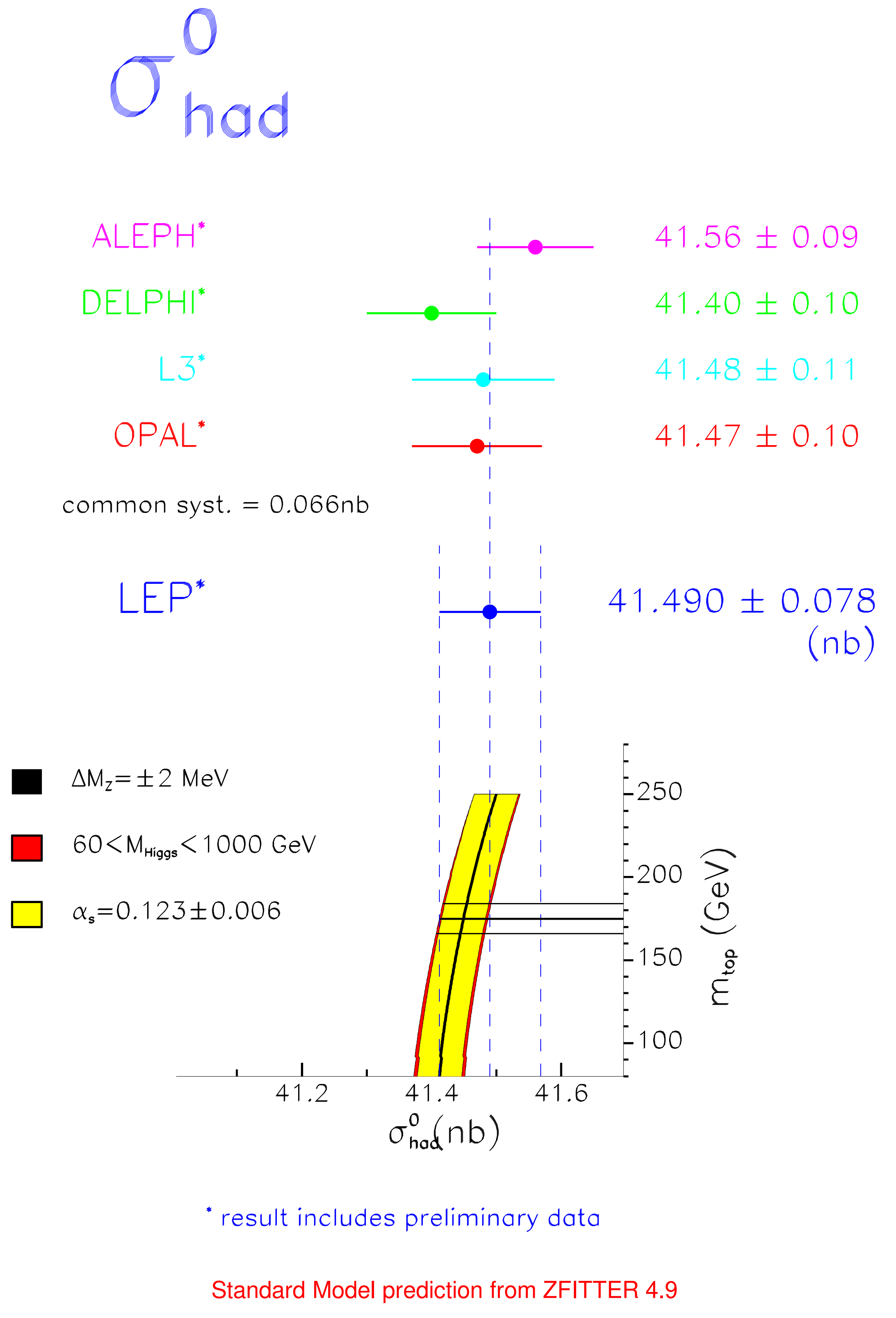
	σ	A_{FB}
had	$0.07 \sim 0.2\%$	–
e	$0.2 \sim 0.5\%$	$0.0016 \sim 0.004$
μ	$0.15 \sim 0.6\%$	$0.001 \sim 0.002$
τ	$0.3 \sim 1.5\%$	$0.002 \sim 0.006$
$\mathcal{L}^{\mathrm{exp.}}$	$0.08 \sim 0.15\%$	–

Luminosity Measurement

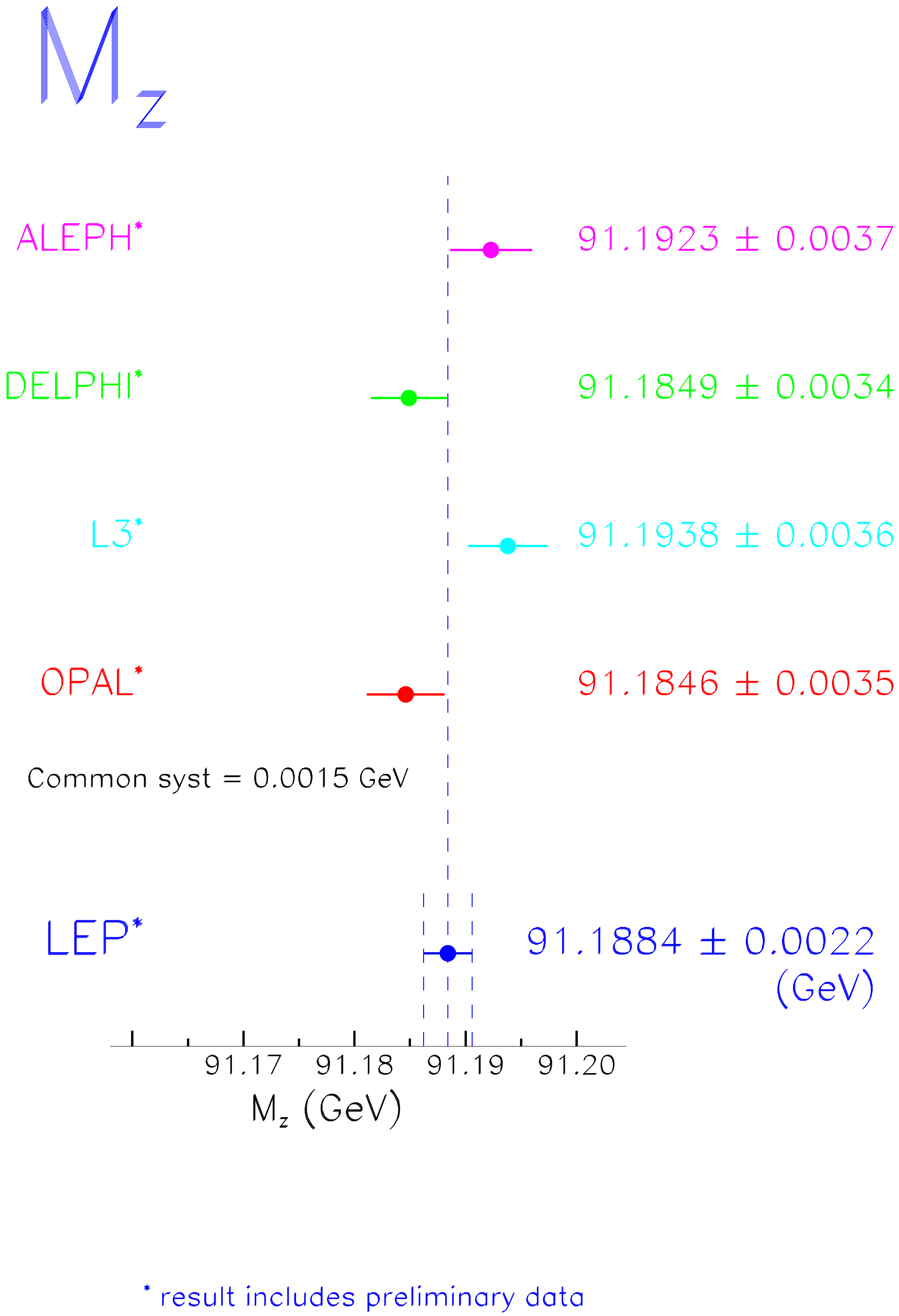
- Luminosity measured with low angle Bhabha events,
  $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{e}^+\mathrm{e}^-$, $\sigma \propto 1/\theta^3$
- All LEP experiments have commissioned new luminometers,
  $\Longrightarrow$ precise determination of acceptance
- Common theory error of 0.16% dominates



Γ_Z
ALEPH*
2.4952 ± 0.0055
DELPHI*
2.4917 ± 0.0053
L3*
2.5022 ± 0.0054
OPAL*
2.4959 ± 0.0053
common syst. = 0.0020 GeV
LEP*
2.4964 ± 0.0032
(GeV)
ΔM_Z=±2 MeV
60<M_Higgs<1000 GeV
α_s=0.123±0.006
250
200
150
100
m_top (GeV)
2.48
2.50
2.52
Γ_Z (GeV)
* result includes preliminary data
Standard Model prediction from ZFITTER 4.9

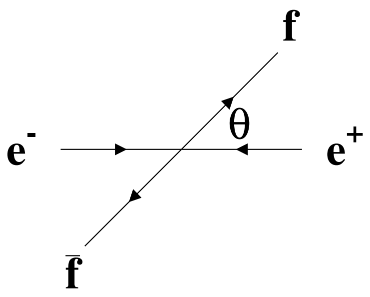


σ^0_{had}
ALEPH* 41.56 ± 0.09
DELPHI* 41.40 ± 0.10
L3* 41.48 ± 0.11
OPAL* 41.47 ± 0.10
common syst. = 0.066nb
LEP* 41.490 ± 0.078 (nb)
$\Delta M_Z = \pm 2$ MeV
$60 < M_{Higgs} < 1000$ GeV
$\alpha_s = 0.123 \pm 0.006$
250
200
150
100
m_{top} (GeV)
41.2
41.4
41.6
σ^0_{had}(nb)
* result includes preliminary data
Standard Model prediction from ZFITTER 4.9



Caveat: LEP energy calibration can shift these values

Lepton Asymmetries



$$\frac{d\sigma}{d\cos\theta} \propto 1+\cos^2\theta+\frac{8}{3}A^f_{\rm FB}\cos\theta$$

$$A^f_{\rm FB} = \frac{\sigma_{\rm F}-\sigma_{\rm B}}{\sigma_{\rm F}+\sigma_{\rm B}}$$

$$A^{0,\,f}_{\rm FB} \equiv \frac{3}{4}\mathcal{A}_{\rm e}\mathcal{A}_{\rm f} \qquad \text{when } \sqrt{s} = m_{\rm Z}$$

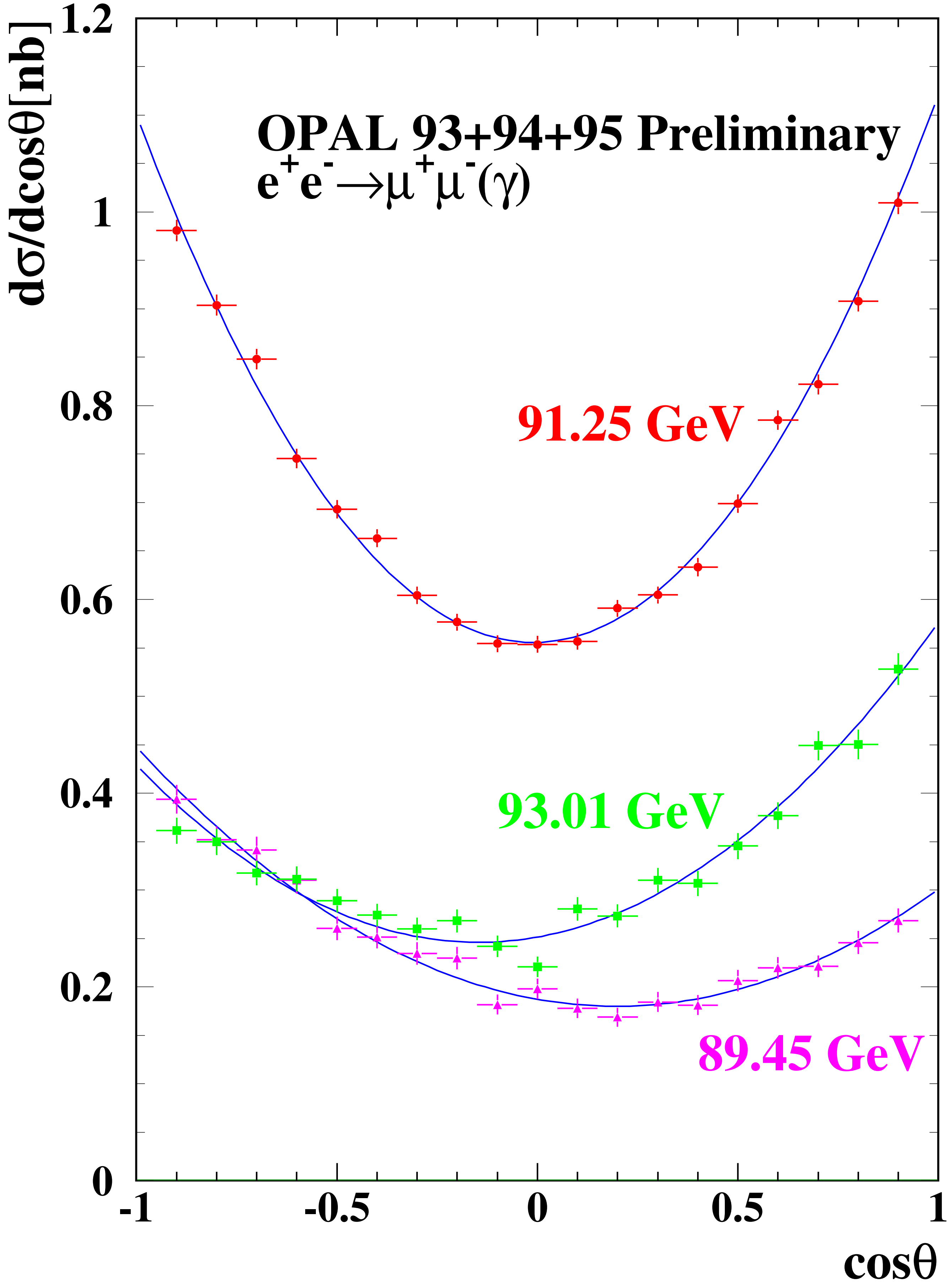
$$\mathcal{A}_f = 2\frac{v_f a_f}{(v_f^2 + a_f^2)}$$

$$\frac{v_f}{a_f} = (1 - 4|Q_f|\sin^2\theta_{\rm W}^{{\rm eff},\,f})$$

Leptons define $\sin^2\theta_{\rm W}^{{\rm eff},\ell}$. Small corrections for quarks.

$$\begin{aligned} \mathcal{A}_{\rm e} &\approx 0.14 \\ \mathcal{A}_{\rm c} &\approx 0.7 \\ \mathcal{A}_{\rm b} &\approx 0.9 \end{aligned}$$

Energy dependence of asymmetries from changing relative sizes of $\rm Z^0$ and γ ($\rm Z^0$-γ) contributions



OPAL 93+94+95 Preliminary
$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
91.25 GeV
93.01 GeV
89.45 GeV
$d\sigma/d\cos\theta$[nb]
$\cos\theta$
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1

Combined Lineshape Results

Combining hadron and lepton cross-sections and lepton asymmetries:

- Choose 9 variables with small correlations:

$$m_{\mathrm{Z}},\, \Gamma_{\mathrm{Z}},\, \sigma^{\mathrm{pole}}_{\mathrm{had}},$$
$$R_{\mathrm{e}} \equiv \Gamma_{\mathrm{had}}/\Gamma_{\mathrm{ee}},\, R_{\mu},\, R_{\tau},$$
$$A^{0,\,\mathrm{e}}_{\mathrm{FB}},\, A^{0,\,\mu}_{\mathrm{FB}},\, A^{0,\,\tau}_{\mathrm{FB}}$$

- Account for common errors (LEP energy, lumi. theory)

- Check for lepton universality $\longrightarrow$ plot

  Reduce to 5 variables

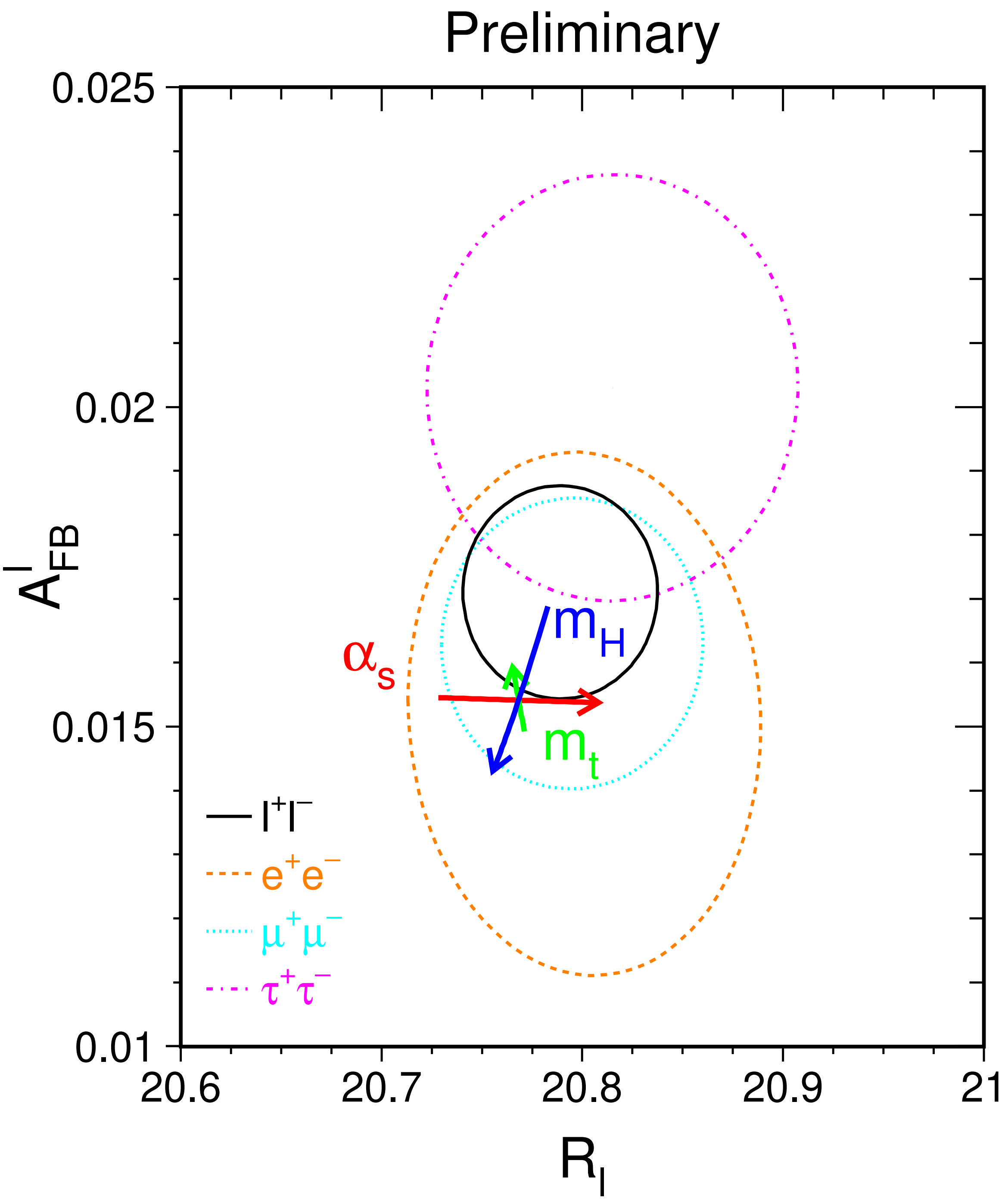
Invisible width:

- Extract $\Gamma_{\mathrm{inv}}/\Gamma_{\ell\ell} = 5.954 \pm 0.031$

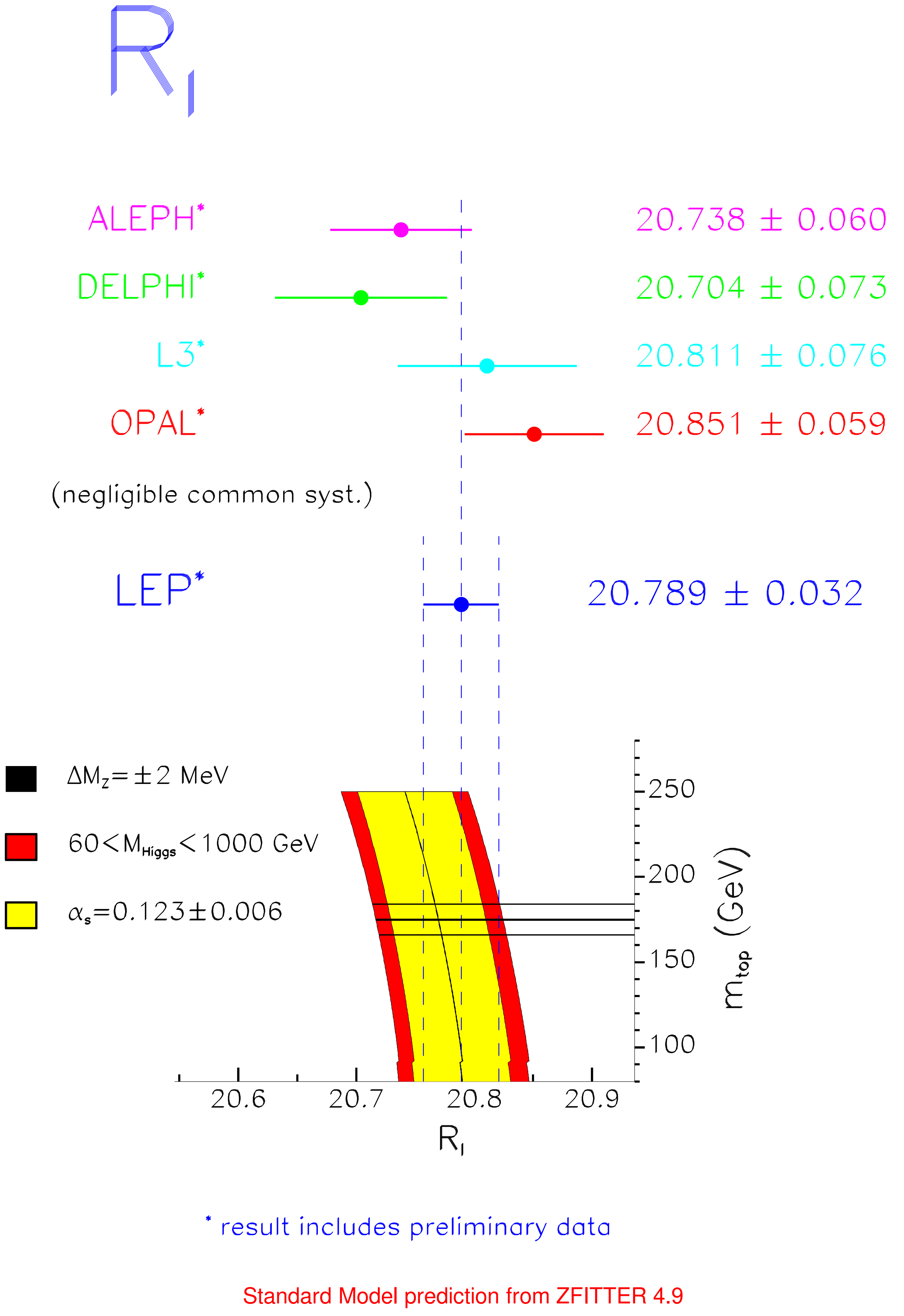
- Taking $(\Gamma_{\nu}/\Gamma_{\ell\ell})_{SM} = 1.991 \pm 0.001$

  $\Longrightarrow N_{\nu} = 2.991 \pm 0.016$

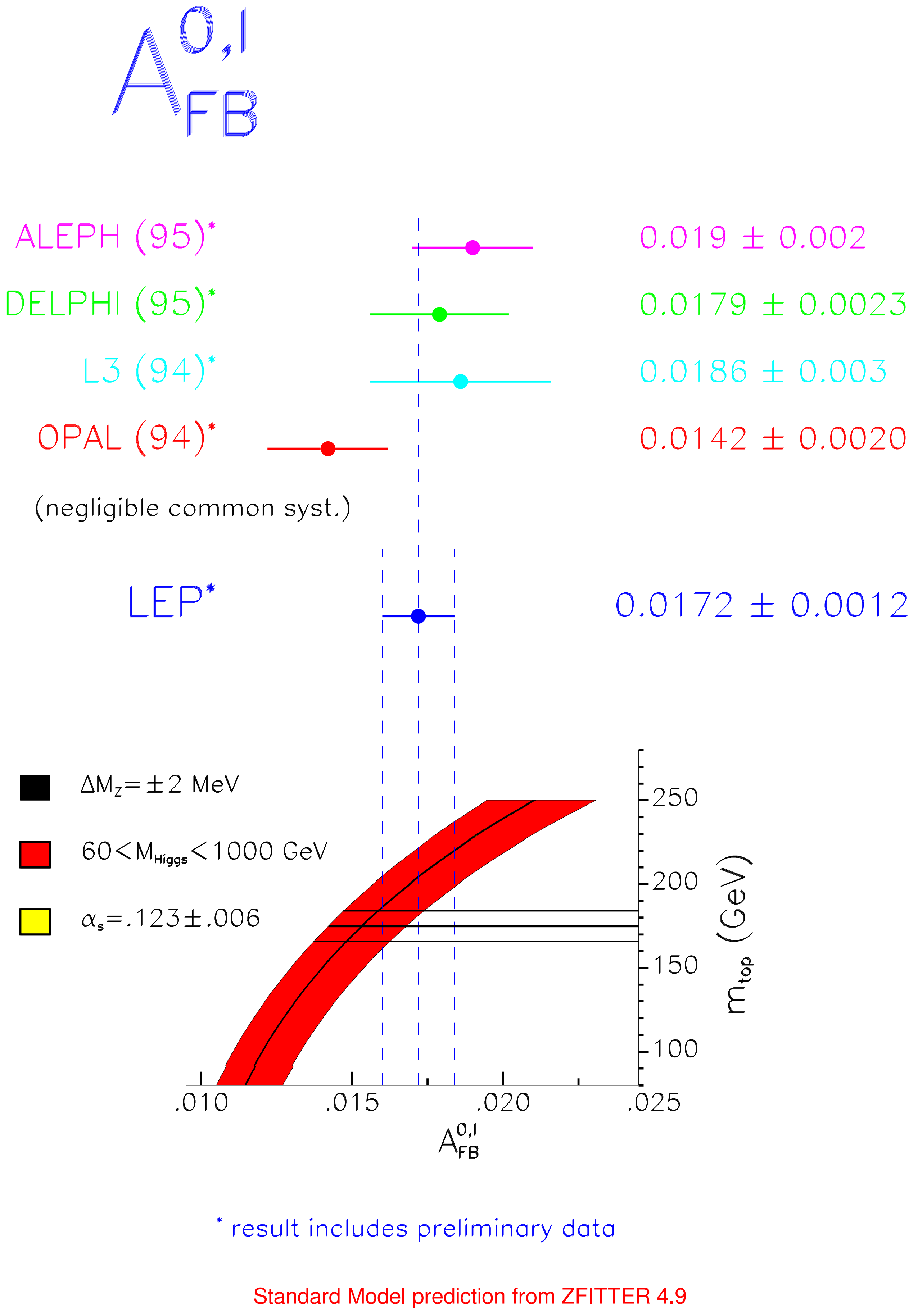
Lepton Universality



68% probability contours



R_l
ALEPH*
20.738 ± 0.060
DELPHI*
20.704 ± 0.073
L3*
20.811 ± 0.076
OPAL*
20.851 ± 0.059
(negligible common syst.)
LEP*
20.789 ± 0.032
$\Delta M_Z = \pm 2$ MeV
$60 < M_{Higgs} < 1000$ GeV
$\alpha_s = 0.123 \pm 0.006$
250
200
150
100
m_{top} (GeV)
20.6
20.7
20.8
20.9
R_l
* result includes preliminary data
Standard Model prediction from ZFITTER 4.9



$A_{FB}^{0,l}$
ALEPH (95)*
DELPHI (95)*
L3 (94)*
OPAL (94)*
0.019 ± 0.002
0.0179 ± 0.0023
0.0186 ± 0.003
0.0142 ± 0.0020
(negligible common syst.)
LEP*
0.0172 ± 0.0012
$\Delta M_Z = \pm 2$ MeV
$60 < M_{Higgs} < 1000$ GeV
$\alpha_s = .123 \pm .006$
250
200
150
100
m_{top} (GeV)
.010
.015
.020
.025
$A_{FB}^{0,l}$
* result includes preliminary data
Standard Model prediction from ZFITTER 4.9

Polarised Asymmetries

At LEP, polarised asymmetries accessible only via $\mathrm{Z}^0 \to \tau^+\tau^-$, but gives both $\mathcal{A}_\mathrm{e}$ and $\mathcal{A}_\tau$:

$$\mathcal{P}_\tau = \frac{\sigma^L - \sigma^R}{\sigma^L + \sigma^R} = -\mathcal{A}_\tau$$

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos\theta^2) + \mathcal{A}_\mathrm{e} 2\cos\theta}{(1+\cos\theta^2) + \mathcal{A}_\tau \mathcal{A}_\mathrm{e} 2\cos\theta}$$

At SLC, initial state e^- polarization is known

define $\sigma^L = \sigma(\mathrm{e}^+\mathrm{e}^-_\mathrm{L} \to \mathrm{Z}^0 \to X)$:

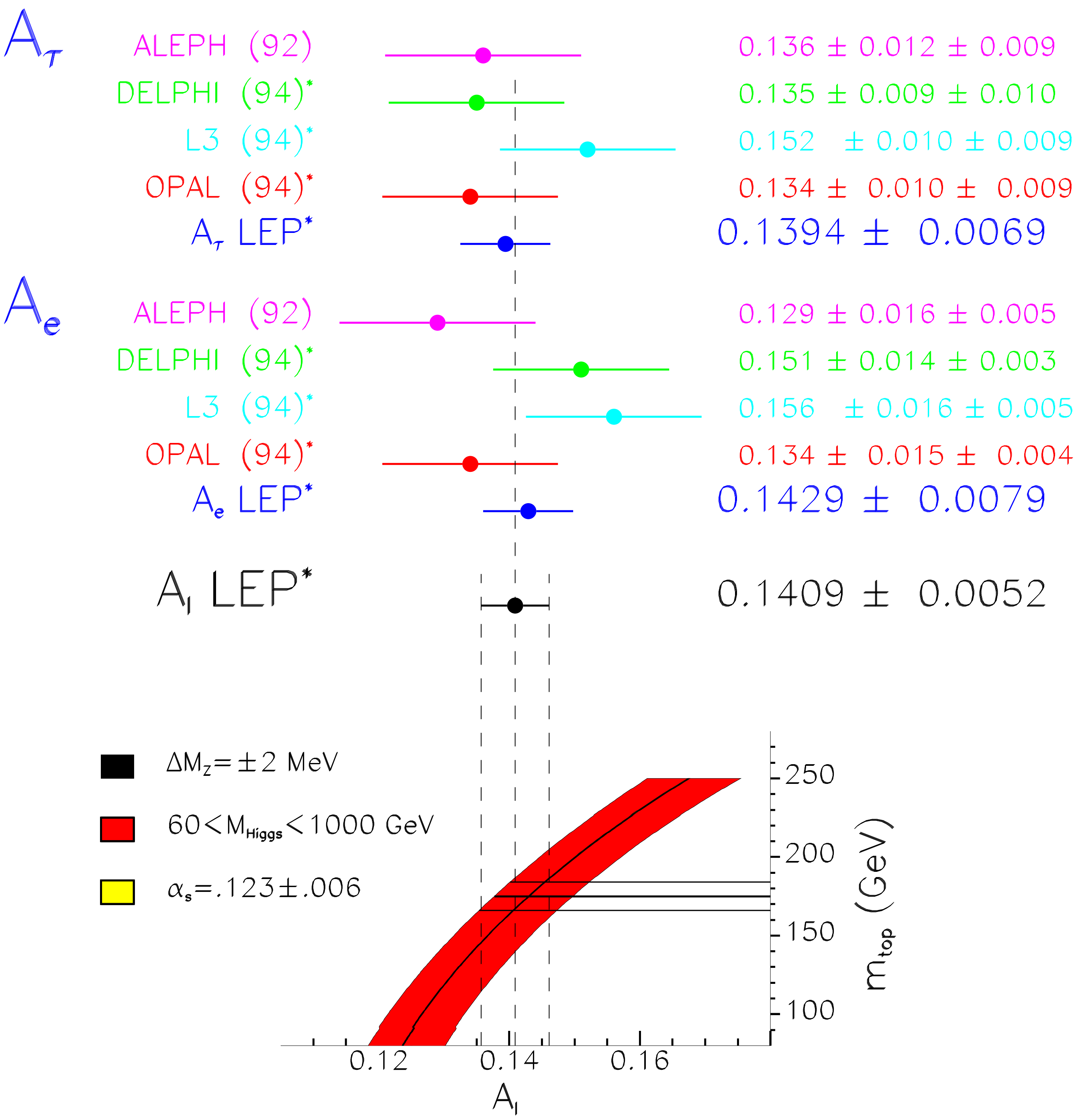
$$A_\mathrm{LR} = \frac{\sigma^L - \sigma^R}{\sigma^L + \sigma^R} = \mathcal{A}_\mathrm{e}$$

Observed $A_\mathrm{LR} = \mathcal{P}_\mathrm{e}\mathcal{A}_\mathrm{e}$

SLD also measure left-right forward-backward asymmetries for heavy quarks:

$$\frac{[\sigma_\mathrm{F}^\mathrm{L} - \sigma_\mathrm{B}^\mathrm{L}] - [\sigma_\mathrm{F}^\mathrm{R} - \sigma_\mathrm{B}^\mathrm{R}]}{[\sigma_\mathrm{F}^\mathrm{L} + \sigma_\mathrm{B}^\mathrm{L}] + [\sigma_\mathrm{F}^\mathrm{R} + \sigma_\mathrm{B}^\mathrm{R}]} = \frac{3}{4}\mathcal{P}_\mathrm{e}\mathcal{A}_\mathrm{q}$$

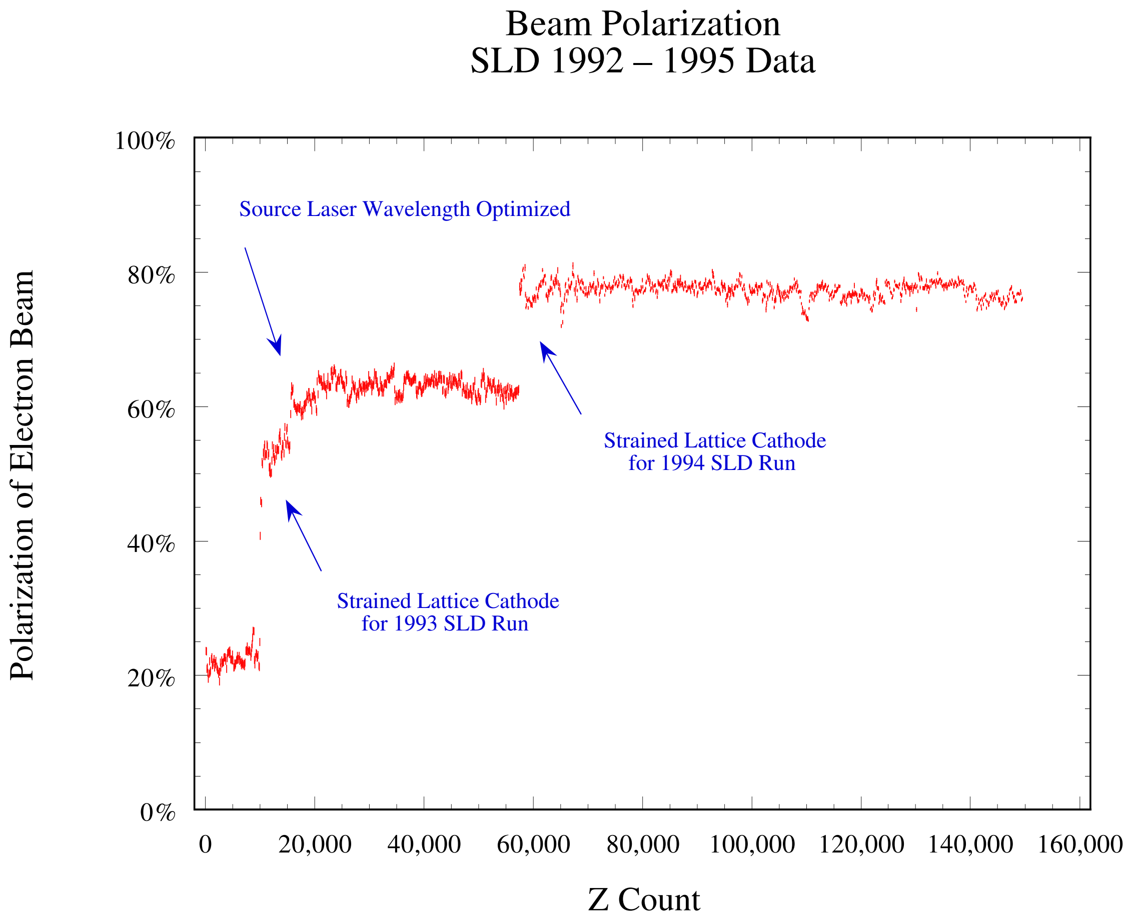
τ polarisation



* result includes preliminary data

(OPAL results have been finalised since, changes minor)

SLD Measurement of A_{LR}



- Can use all visible Z^0 decay modes.
  SLD exclude $\mathrm{e}^+\mathrm{e}^-$ (t-channel)
- Strained GaAs Photocathode $\Longrightarrow$ source of polarized electrons – randomly chosen polarization for each bunch
- Polarization measured by Compton Polarimeter after interaction point
- 1994-95 data: $\langle \mathcal{P}_{\mathrm{e}} \rangle = 77.34 \pm 0.61\%$
- 1992-95 data: $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\ell} = 0.23049 \pm 0.00050$

Heavy Quark Partial Widths

Measure fraction of hadronic Z^0 decays which contain primary $\mathrm{b\overline{b}}$ or $\mathrm{c\overline{c}}$ pairs:

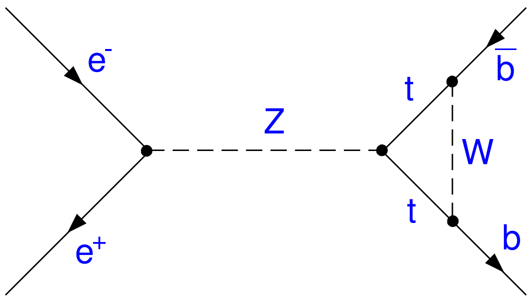
$$R_{\mathrm{Q}} = \frac{\sigma(\mathrm{e^+e^-} \to \mathrm{Q\overline{Q}})}{\sigma(\mathrm{e^+e^-} \to \mathrm{hadrons})} \simeq \frac{\Gamma(\mathrm{Z^0} \to \mathrm{Q\overline{Q}})}{\Gamma(\mathrm{Z^0} \to \mathrm{hadrons})}$$

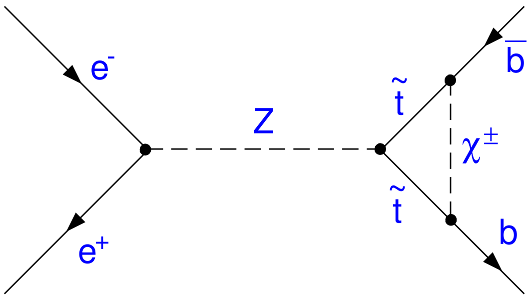
(small corrections for γ and γ-Z^0 interference)

Advantage of R_{Q}:

- Propagator and ISR corrections cancel
- Sensitivity to vertex corrections

R_{b} case: “special” vertex corrections, SM or non-SM:





Experimental Techniques

Measurements of R_{c}:

- D counting
- D^{*+} production rate
- D^{*+} double tag measurements

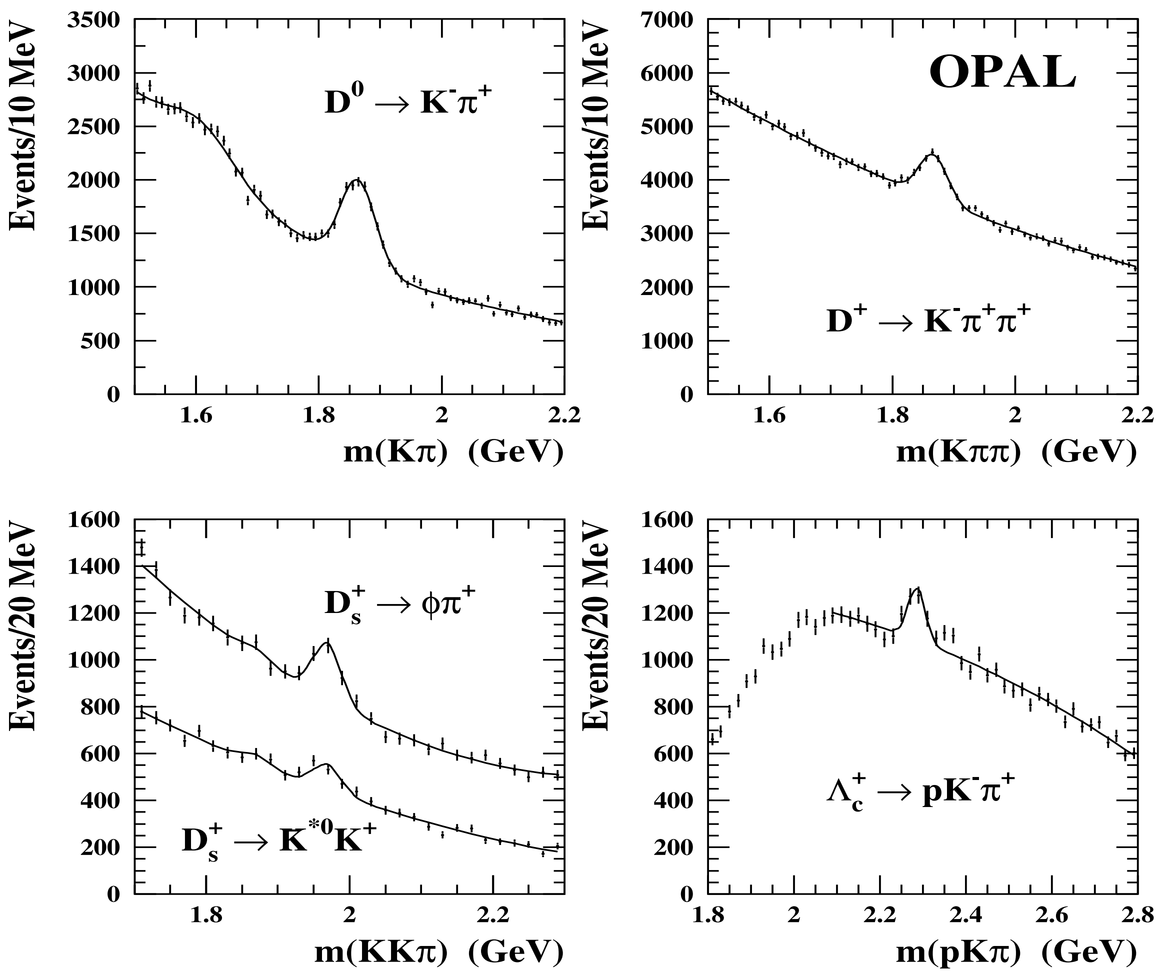
Measurements of R_{b}:

- Double lifetime tagging method
- Improved lifetime tags
- Systematic limitations

R_c from D Counting

All charm quarks end up in weakly decaying hadrons:

$$P_{c\to \mathrm{D}^0} + P_{c\to \mathrm{D}+} + P_{c\to \mathrm{D_s}+} + P_{c\to \Lambda_c} \times (1 + S_{c-\mathrm{baryon}}) = 1$$



Need to separate contributions for b, c events $\Longrightarrow$

R_c from total production rates of D^0,D^+,D_s^+,Λ_c^+ in $\mathrm{Z}^0 \to c\bar{c}$ events

+ "LEP-only" measurement

+ Allows verification of low energy measurements of D production

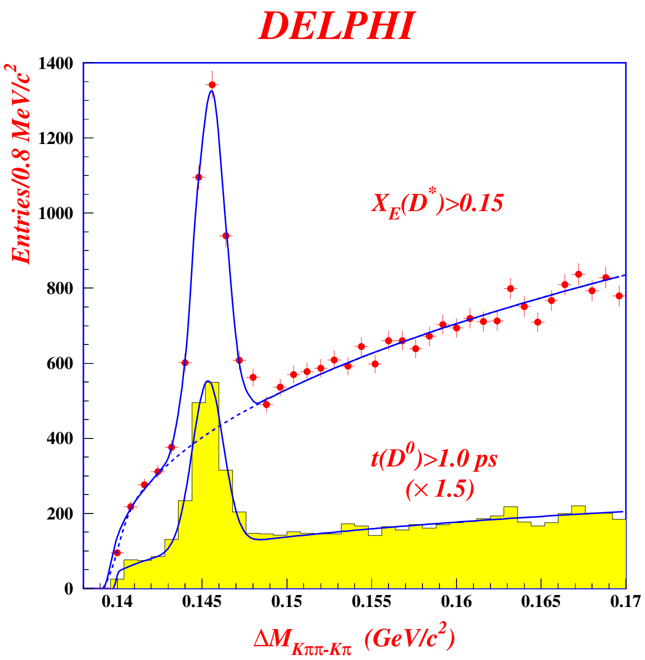
+ Well-established techniques, controllable errors

− Low efficiency + large background $\longrightarrow$ large statistical error

Dominant systematics: c fragmentation, particle-id

R_c from D^* Production

Distinctive kinematic signature: $D^{*+} \to \pi D^0$



For a specific D^0 final state X, this technique measures (after b/c separation)

$$R_c \times P(c \to D^{*+} \to \pi^+ D^0) \times B(D^0 \to X)$$

+ (Relatively) high-purity samples

+ Well-established techniques, controllable errors

+ Can also measure rate for $g \to c\bar{c}$

− External input required to obtain R_c

$$P(c \to D^{*+} \to \pi^+ D^0) \times B(D^0 \to X)$$

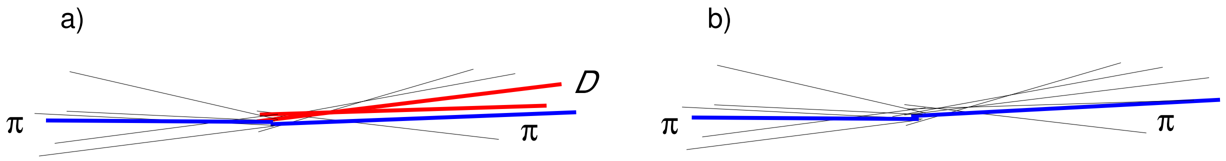
(from lower energy data or from LEP)

Dominant systematics: $P(c \to D^{*+} \to \pi D^0)$, D^0 decay BRs, c fragmentation

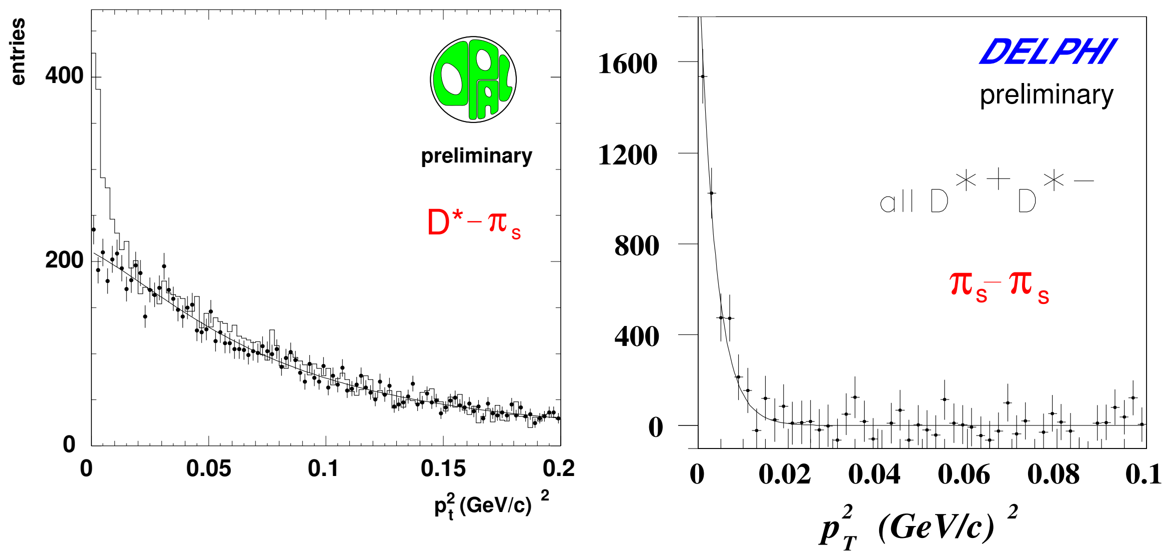
R_c from D^* Double-Tag

The branching fraction $c \to D^{*+} \to \pi D^0$ is sufficiently large ($\sim 20\%$) to consider a D^{*+} *Double Tag* to measure R_c

$\Longrightarrow \pi_s$ has ~ 0 p_T with respect to D^{*+} or jet



Inclusive π_s-Exclusive D^{*+} Inclusive π_s-Inclusive π_s



Neglecting backgrounds for simplicity (and after b/c separation),

$$N_{(\pi \text{or } D)} \propto R_c \cdot P(c \to D^{*+} \to \pi^+ D^0) \cdot \varepsilon_{(\pi \text{ or } D)}$$
$$N_{\pi,(\pi \text{ or } D)} = N_{(\pi \text{ or } D)} \cdot [P(c \to D^{*+} \to \pi^+ D^0) \cdot \varepsilon^c_\pi]$$

R_c and $P(c \to D^{*+} \to \pi^+ D^0)$ can be measured simultaneously

R_c from D^* Double-Tag

+ "LEP-only" measurement

– MC still required for efficiencies ($D^* - \pi_s$ analyses)

– Large backgrounds under π_s signal

Dominant systematics: background subtraction, ε_π, b/c separation

Results for $P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0)$:

OPAL ('92-'94) ($D^{*+} - \pi_s$ Double tag)

$$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0) = 0.162 \pm 0.014(stat) \pm 0.013(syst)$$

DELPHI ('91-'94) ($\pi_s - \pi_s$ Double tag)

$$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0) = 0.166 \pm 0.009(stat) \pm 0.013(syst)$$

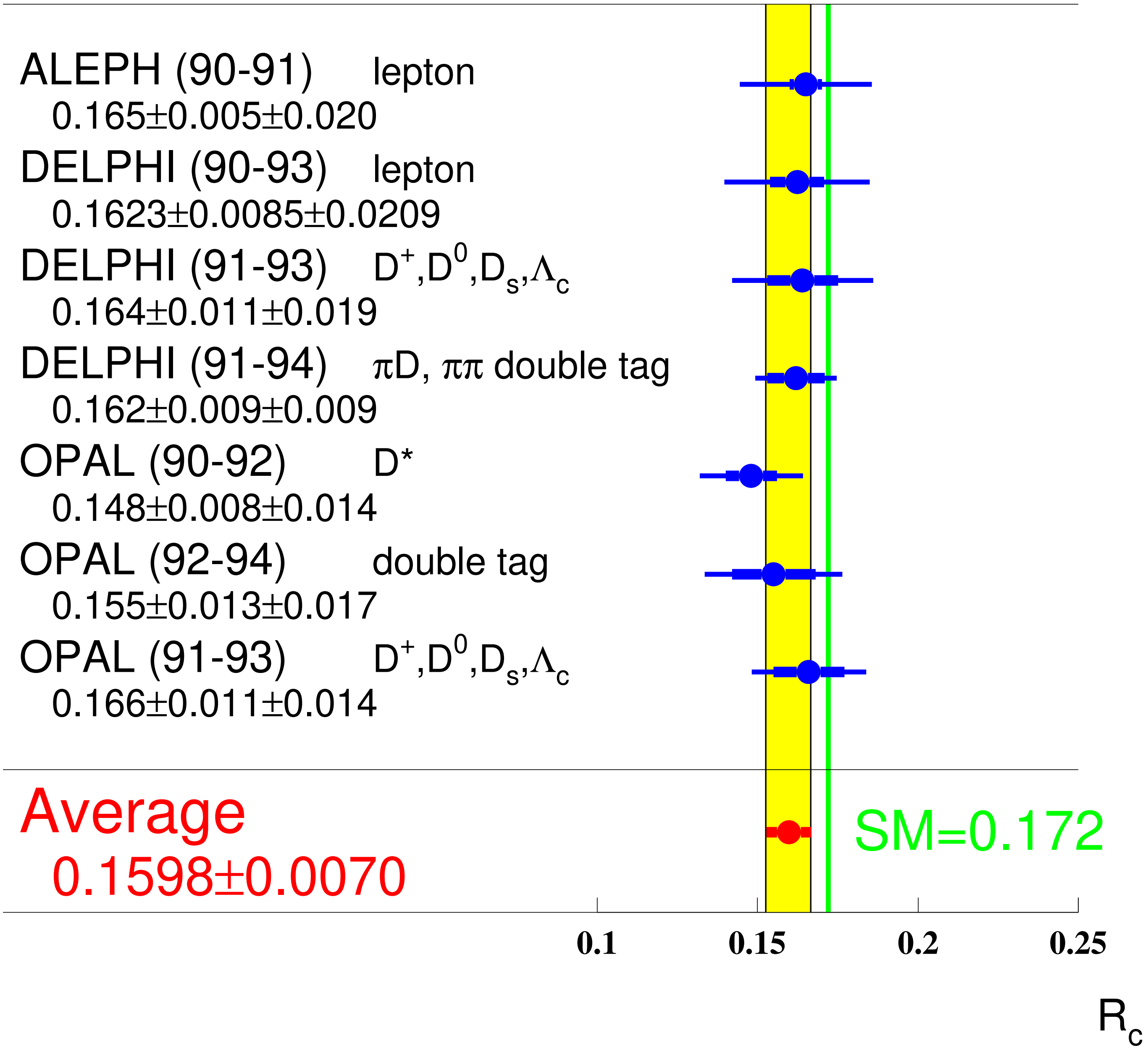
DELPHI ('91-'94) ($D^{*+} - \pi_s$ Double tag)

$$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0) = 0.162 \pm 0.016(stat) \pm 0.009(syst)$$

Compare low-energy average:

$$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0) = 0.178 \pm 0.013$$

R_c Results



$\gamma - Z$ interference correction (-0.0003) applied to average

Results have been corrected to PDG '95 $B(D^0 \rightarrow K\pi)$, low energy

$P(c \rightarrow D^{*+} \rightarrow \pi^+ D^0) = 0.178$ where needed

R_b with Lifetime Tags

b hadrons have high masses and long lifetimes

$\Longrightarrow$ b events can be more easily isolated from all other flavours

$\Longrightarrow$ high purity, high efficiency tags

Measurements based on lifetime tags dominate the precision of R_b

Method:

Apply a b tag to each thrust hemisphere of an event.

Number of tagged hemispheres N_t:

$$\frac{N_t}{2N_{had}} = \varepsilon^b R_b + \varepsilon^c R_c + \varepsilon^{uds}(1 - R_b - R_c)$$

Number of double-tagged events N_{tt}:

$$\frac{N_{tt}}{N_{had}} = C_b(\varepsilon^b)^2 R_b + (\varepsilon^c)^2 R_c + (\varepsilon^{uds})^2(1 - R_b - R_c)$$

- Solve for R_b and ε^b, from N_t, N_{tt}, N_{had}
  $\Longrightarrow$ ε^b measured from data
- Take R_c, C_b, ε^c, ε^{uds} from MC $\Longrightarrow$ high purity tags
- Assume (hemisphere tag correlations)$\times\varepsilon^2$ are small for uds, c
- Statistical error $\propto N_{tt} \propto (\varepsilon^b)^2$ $\Longrightarrow$ high ε^b tags

$+$ Most important quantities (ε^b) derived directly from data

$-$ MC (external values) still required for ε^c and C_b

Dominant systematics: ε^c and C_b

b Tags: Lifetime Probability

ALEPH and DELPHI form a "no-lifetime" probability for tracks with physics signed impact parameter $b > 0$:

$$\mathcal{P}_T = \int_b^\infty \mathcal{R}(x)\mathrm{d}x$$

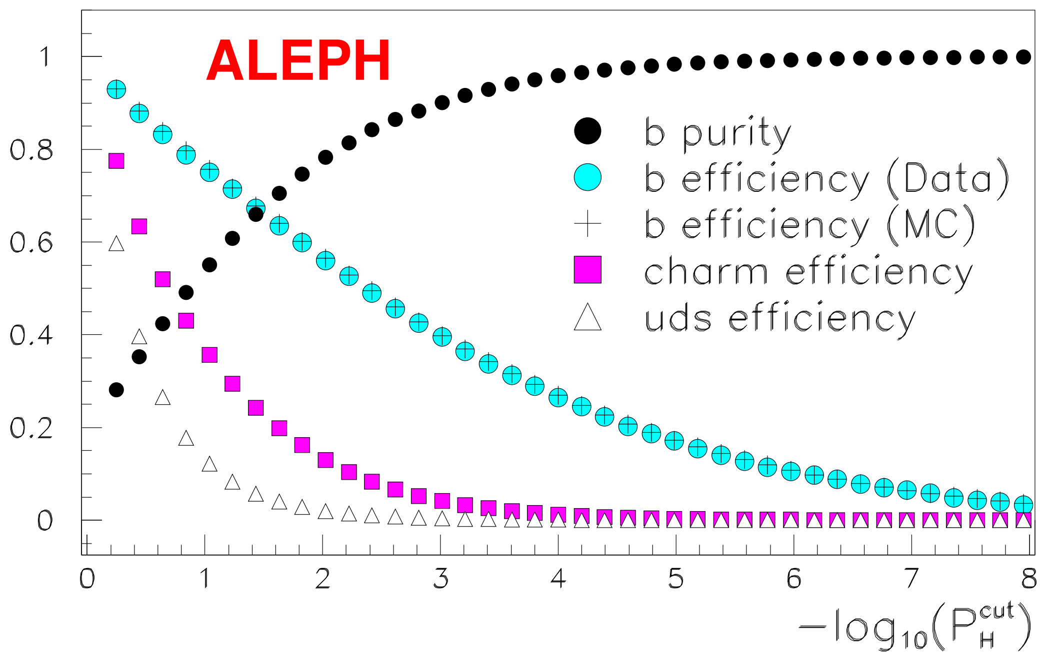
resolution function $\mathcal{R}$ measured from $b < 0$ distribution

The joint probability for "no-lifetime" in the hemisphere is then:

$$\mathcal{P}_N \equiv \Pi \sum_{j=0}^{N-1} \frac{(-\ln \Pi)^j}{j!}$$

where

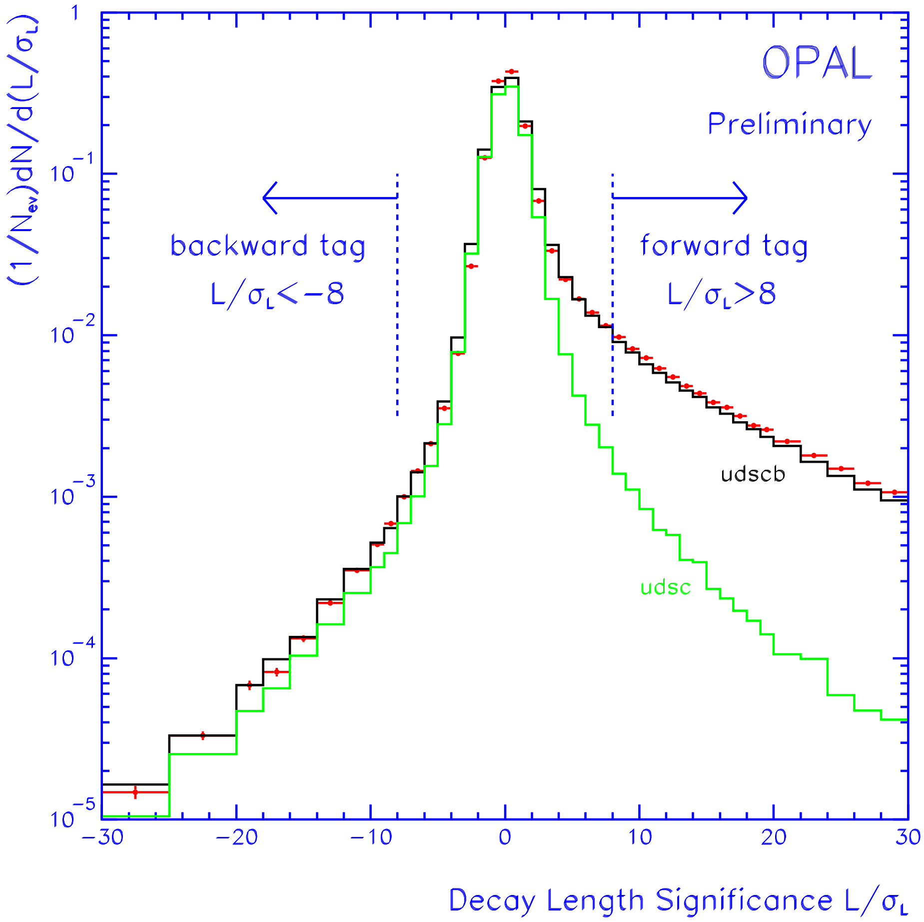
$$\Pi \equiv \prod_{i=1}^{N} (\mathcal{P}_T)_i$$



b Tags: Secondary Vertices

OPAL reconstructs high-multiplicity secondary vertices from tracks in each jet

Construct physics signed decay length significance:



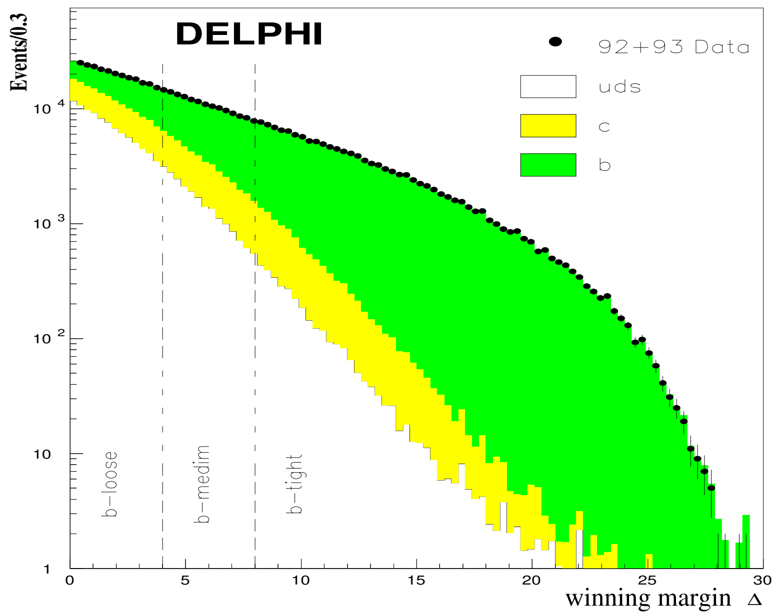
Folded tag: subtract statistically backwards vertices from forwards vertices to reduce resolution uncertainties

R_b with Multivariate Tag (DELPHI)

Multivariate tag attempts to use more of the information in event to discriminate between b and other flavours

- 6 "tags": *uds-tight*, *uds-loose*, *c*, *b-loose*,*b-medium*, *b-tight*,
- based on 13 (mostly vertex-related) variables combined into a joint-probability
- Tag "clarity" for hemisphere is given by the "winning margin"

$$\Delta = \mathcal{L}_{first} - \mathcal{L}_{second} \; (\mathrm{or}, \; \mathcal{L}_b - \mathcal{L}_{other})$$



- Taking $\Delta \to \infty$ and looking at *opposite* hemisphere allows a simultaneous measurement of tag efficiencies, backgrounds, R_b.

+ ALL important quantities (ε^b) derived directly from data

+ Potentially much smaller dependence on MC, external inputs

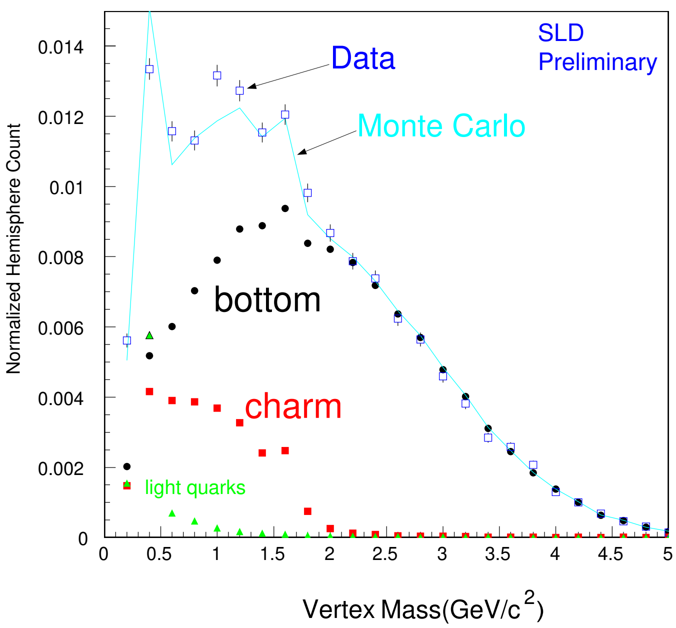
− Complicated, difficult to check directly

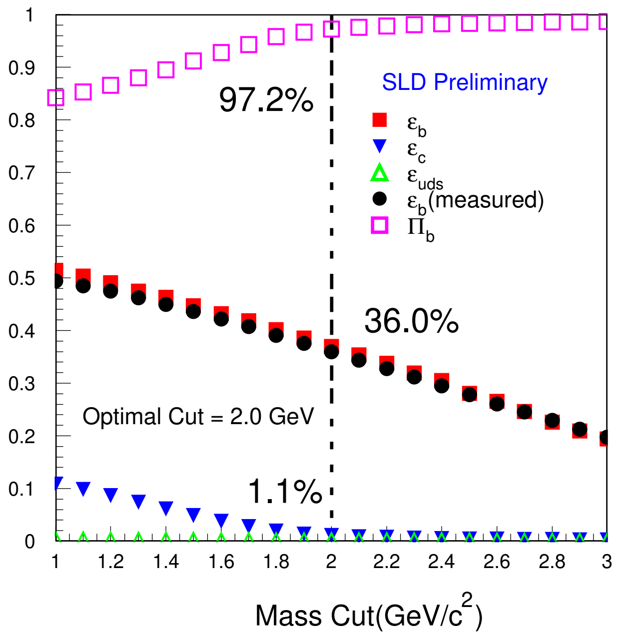
Dominant systematics: MC statistics to determine C_b, fit method

Improved Lifetime Tag (SLD)

SLD has a new method based on a improved vertex detector/beam spot combination...

- Topological vertex reconstruction to assign each track to either the primary event vertex or a secondary decay vertex
- Vertex "mass" is used to separate b from other flavours





+ Charm contamination $\longrightarrow$ zero

+ Potentially much smaller dependence on MC, external inputs

+ Tiny SLC beamspot reduces correlation uncertainty

− None???

Dominant systematics: MC statistics, detector

R_b Systematic Errors

R_b systematic errors dominated by two sources:

- Charm background $\Longrightarrow \varepsilon^c$
- Hemisphere correlations $\Longrightarrow C_b$

Charm background:

- Production fractions of different c-hadron species: lower energy measurements and those at LEP agree well
- Decay multiplicities of c hadrons: Mark-III measurement used; consistent with summation of exclusive BRs, but requires assumptions
- Lifetimes, fragmentation less important

Results shown use “1992” status inputs: latest numbers agree very well (smaller errors!)

Hemisphere correlations:

- Dominated by effects of (hard and soft) gluon radiation
- Detector-related effects mostly well controllable
- Shared primary vertex information needs care

Evolving area, being studied intensively: **but** no major problems found

Hemisphere correlations

Reminder:

$$R_{\mathrm{b}} \approx C_{\mathrm{b}} \frac{N_t^2}{4 N_{\mathrm{tt}} N_{\mathrm{had}}}$$

$$\lambda_{\mathrm{b}} \equiv (C_{\mathrm{b}} - 1)\varepsilon^{\mathrm{b}}/(1 - \varepsilon^{\mathrm{b}})$$

	C_{b}	λ_{b}	ε^{b}	$C_{\mathrm{b}} - 1$
OPAL (92–94)	1.006 ± 0.003		23%	$+0.6 \pm 0.3\%$
ALEPH (92)		$-2.0 \pm 0.3\%$	26%	$-5.7 \pm 0.8\%$
DELPHI (91)		$-0.1 \pm 0.4\%$	24%	$-0.4 \pm 1.3\%$
DELPHI (92)		$-0.3 \pm 0.2\%$	20%	$-1.0 \pm 0.7\%$
DELPHI (93)		$-1.3 \pm 0.2\%$	21%	$-4.8 \pm 0.6\%$
SLD (93–95)		$+0.5 \pm 0.2\%$	36%	$-0.9 \pm 0.4\%$

Size of correlations dominated by effects of gluon radiation

Estimates of error due to C_{b} dominated by statistics (Monte Carlo or data)

$\Longrightarrow$ assume uncertainty not correlated between measurements

Varying assumptions on correlated uncertainty due to C_{b} has a tiny effect on R_{b}

Hemisphere correlations are an area of intense study

Common systematic errors - I

Representative table of significant contributions to total error.

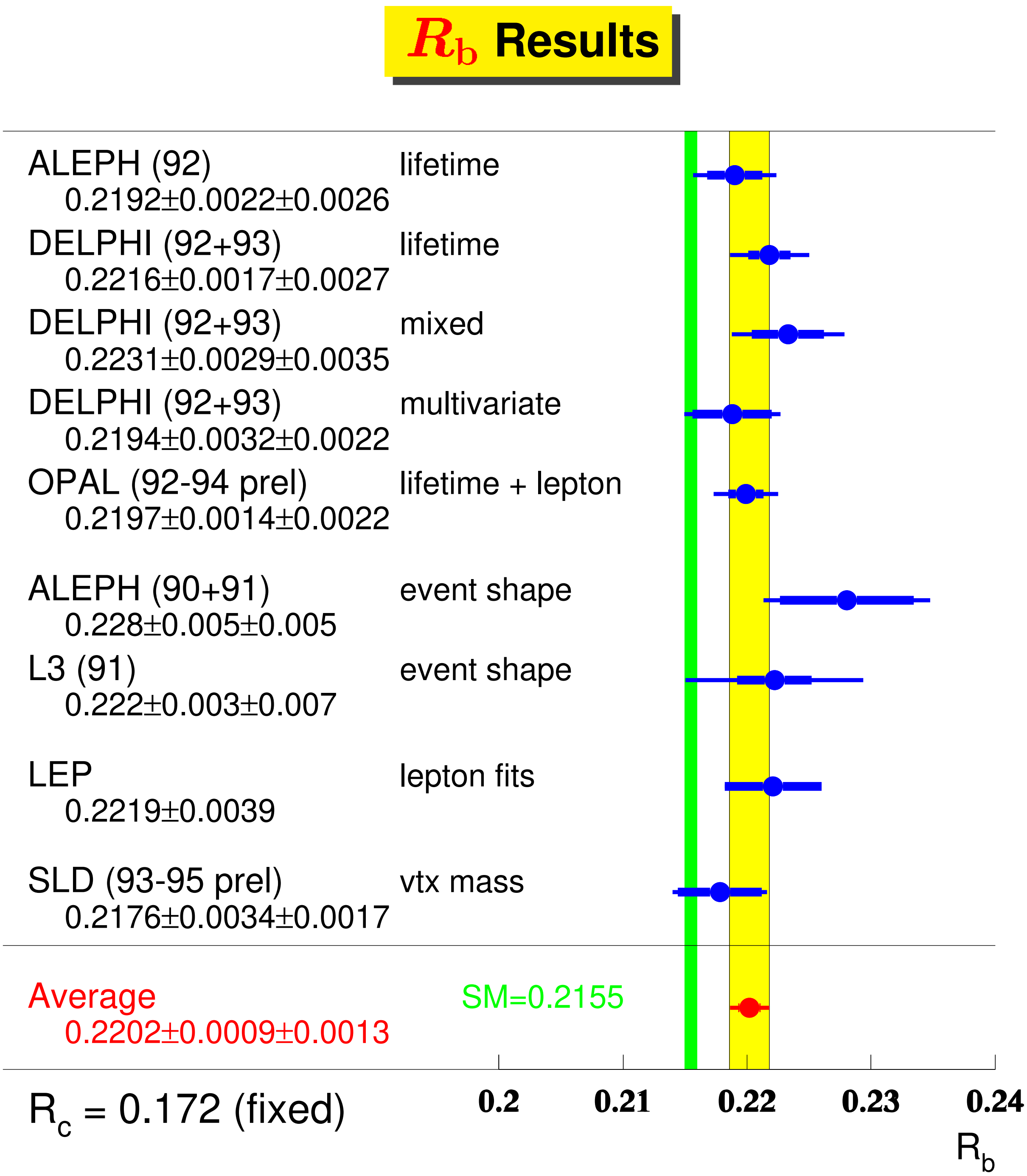
"Value and range" correspond mostly to PDG '92, "New value" is either PDG '96 or unofficial LEP average. "Pull" is (Average – Standard Model) / (Error from this source).

Error source	Value and range	New value	R_b pull	R_c pull
Decay model $\mathrm{b} \to \ell$	ACCMM$^{+\mathrm{ISGW}}_{-\mathrm{ISGW**}}$		–47	–34
Decay model $\mathrm{c} \to \ell$	CL1 $^{+\mathrm{CL2}}_{-\mathrm{CL3}}$		–88	∞
$\mathrm{Br}(\mathrm{c} \to \ell)$	(9.8 ± 0.5)%		+21	+5
$\mathrm{Br}(\mathrm{b} \to \bar{\mathrm{c}} \to \ell^-)$	(1.3 ± 0.5)%		–161	+168
x_E^{b} (if not in fit)	0.70 ± 0.02	0.702 ± 0.008 LEP	–129	+16
x_E^{c} (if not in fit)	0.51 ± 0.02	$0.484 \pm 0.008*$ LEP	–100	+13
b fragmentation model	Peterson, Kartvelishvelli, Collins–Spiller		∞	+67
c fragmentation model	"		–135	–8
$\mathrm{BR}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+)$	(3.84 ± 0.13)% PDG'95	(3.83 ± 0.12)% PDG'96	+61	+9
$\mathrm{BR}(\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+)$	(9.1 ± 0.6)% PDG'95	(9.1 ± 0.6)% PDG'96	+168	+25
$\mathrm{BR}(\mathrm{D_s}^+ \to \phi\pi^+)$	(3.5 ± 0.4)% PDG'95	(3.6 ± 0.9)% PDG'96	+178	+34
$\mathrm{BR}(\Lambda_\mathrm{c} \to \mathrm{pK}^-\pi^+)$	(4.4 ± 0.6)% PDG'95	(4.4 ± 0.6)% PDG'96	+198	+30
c baryon/Λ_c^+	1.15 ± 0.05		∞	–94

($*$ weakly decaying c hadron: correct by $\sim +0.03$ to old definition)

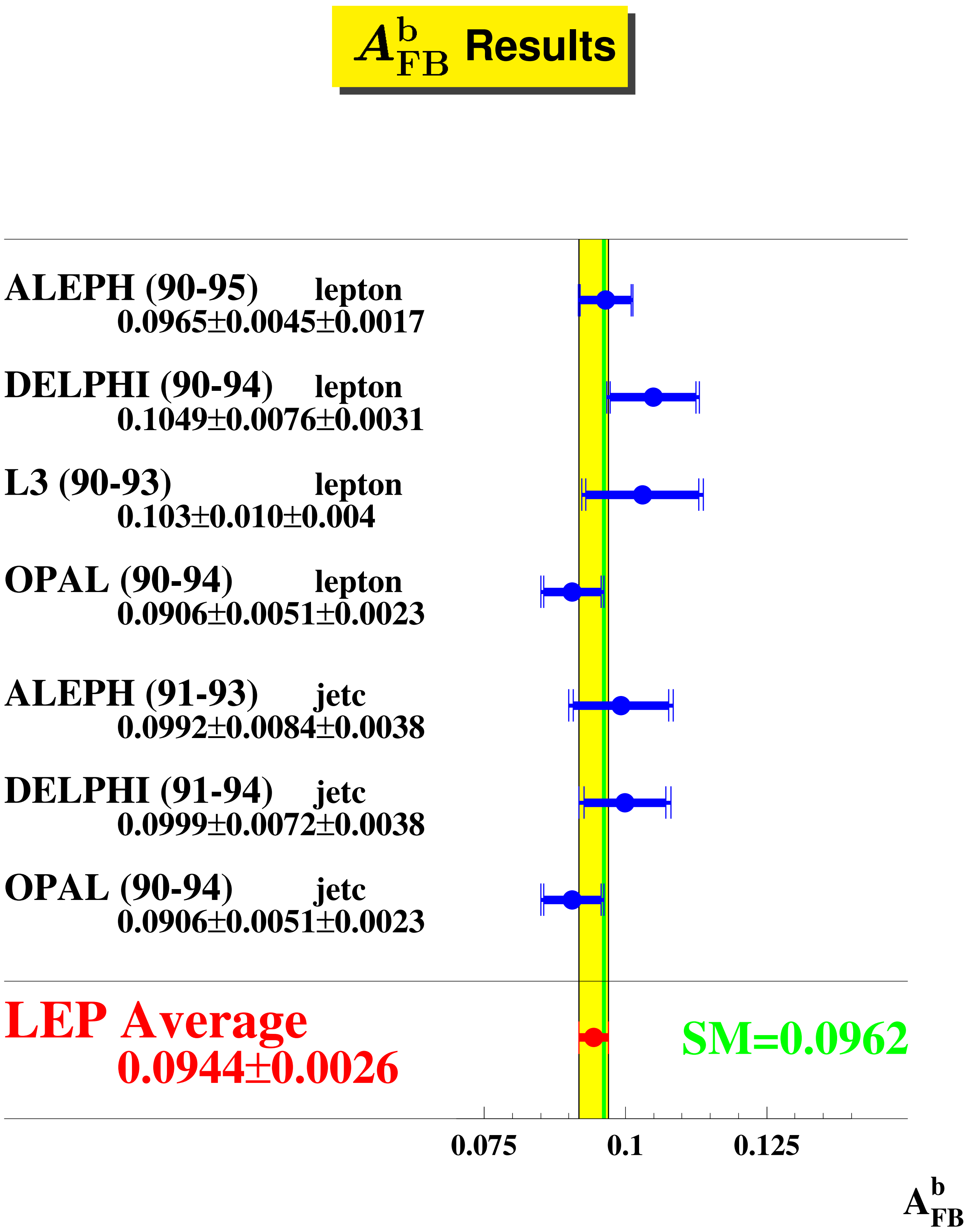
Common systematic errors - II

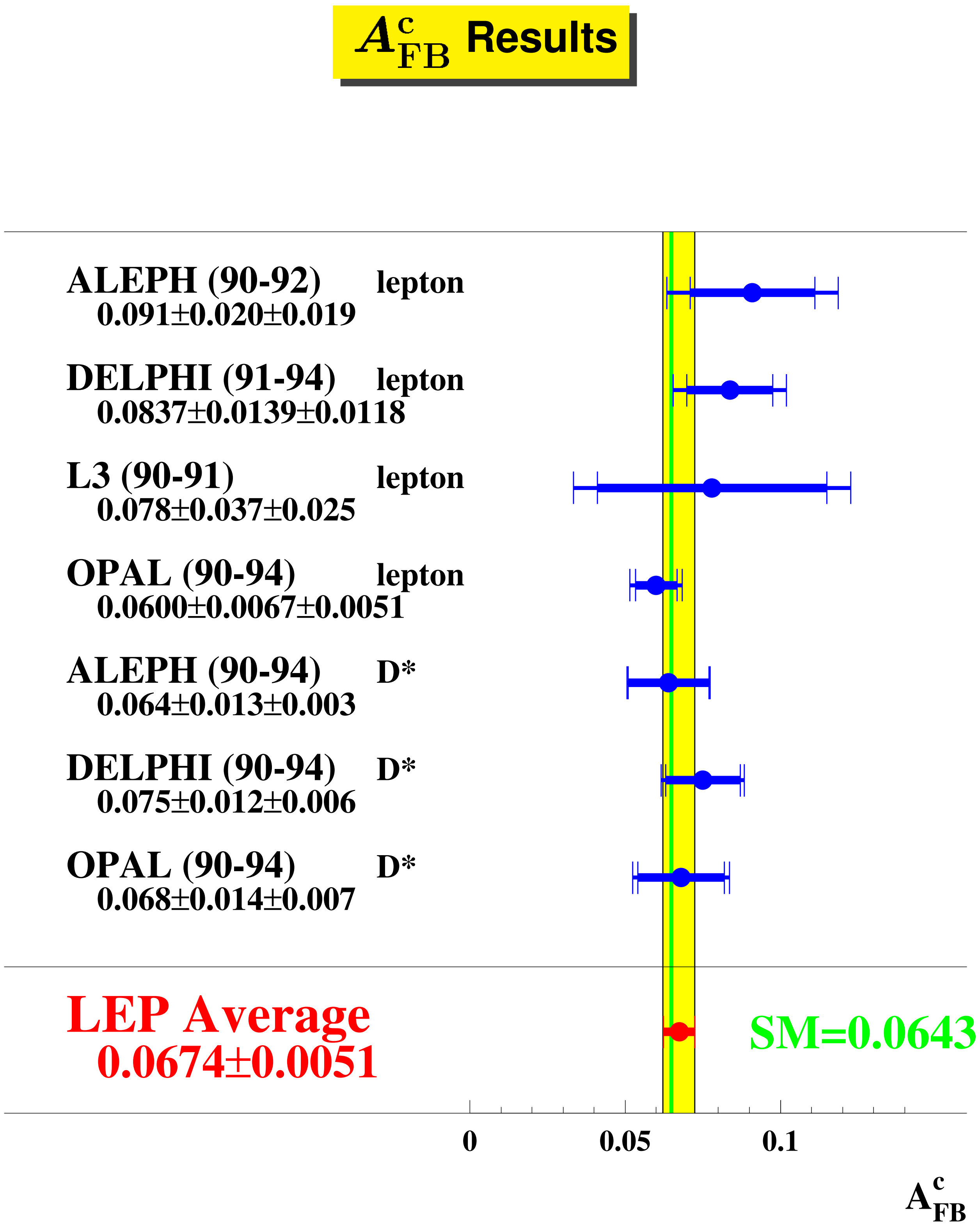
Error source	Value and range	New value	R_b pull	R_c pull
D^0 fraction in $c\bar{c}$ events	0.557 ± 0.053	0.596 ± 0.033 LEP	–132	∞
D^+ fraction	0.248 ± 0.037	0.231 ± 0.026 LEP	–11	+55
$(D^0 + D^+)$ fraction	0.80 ± 0.07		–19	+124
D_s^+ fraction	0.12 ± 0.05	0.110 ± 0.017 LEP	–18	+119
Λ_c^+ fraction	0.08 ± 0.05	0.063 ± 0.029 LEP	–198	∞
D^0 lifetime (ps)	0.420 ± 0.008	0.415 ± 0.004 PDG'96	–35	–76
D^+ lifetime (ps)	1.066 ± 0.023	1.057 ± 0.015 PDG'96	–31	–52
D_s^+ lifetime (ps)	$0.450^{+0.030}_{-0.026}$	0.467 ± 0.017 PDG'96	–44	–96
Λ_c^+ lifetime (ps)	$0.191^{+0.015}_{-0.012}$	0.206 ± 0.012 PDG'96	–323	–30
B decay multiplicity	5.5 ± 0.5 OPAL	5.73 ± 0.35 OPAL, DELPHI	–263	+52
D decay multiplicity	2.53 ± 0.06		–15	+101
$BR(D \to K_S^0 X)$	0.46 ± 0.06		+17	–109
$N(g \to b\bar{b})$	$(0.16 \pm 0.08)\%$		–41	∞
$N(g \to c\bar{c})$	$(1.6 \pm 0.8)\%$ theory	(2.38 ± 0.48)% OPAL	–28	–24
Rate long-lived light h	JETSET$\pm 10\%$		–26	+118
Light quark frag.	JETSET $\pm$ small		+20	–72



Small corrections have been applied to plotted results for consistency with LEP HF EW WG recommendations

Photon correction of +0.0003 already applied to average


A^{b}_{FB} Results
ALEPH (90-95) lepton
0.0965±0.0045±0.0017
DELPHI (90-94) lepton
0.1049±0.0076±0.0031
L3 (90-93) lepton
0.103±0.010±0.004
OPAL (90-94) lepton
0.0906±0.0051±0.0023
ALEPH (91-93) jetc
0.0992±0.0084±0.0038
DELPHI (91-94) jetc
0.0999±0.0072±0.0038
OPAL (90-94) jetc
0.0906±0.0051±0.0023
LEP Average
0.0944±0.0026
SM=0.0962
0.075
0.1
0.125
A^{b}_{FB}



A_{FB}^{c} Results
ALEPH (90-92) lepton
0.091±0.020±0.019
DELPHI (91-94) lepton
0.0837±0.0139±0.0118
L3 (90-91) lepton
0.078±0.037±0.025
OPAL (90-94) lepton
0.0600±0.0067±0.0051
ALEPH (90-94) D*
0.064±0.013±0.003
DELPHI (90-94) D*
0.075±0.012±0.006
OPAL (90-94) D*
0.068±0.014±0.007
LEP Average
0.0674±0.0051
SM=0.0643
0
0.05
0.1
A_{FB}^{c}

LEP HF EW Averaging Procedure

Heavy flavour electroweak analyses often:

- measure several parameters simultaneously (A_{FB}^b, χ, etc.)
- depend on other widths, branching ratios, etc.

The LEP Heavy Flavour group combination procedure handles all correlations and dependences on external inputs (and their errors) consistently.

The results are derived from a 10-parameter overall χ^2 minimization fit using the full covariance matrix between measurements

Checks include:

- Internal consistency with simple one-parameter averages
- Varying the details of correlation assumptions only has a small effect

Combined LEP and SLD Results

$$\begin{aligned}
\boldsymbol{R_{\mathrm{b}}} &= \mathbf{0.2211 \pm 0.0016} \\
\boldsymbol{R_{\mathrm{c}}} &= \mathbf{0.1598 \pm 0.0070} \\
A_{\mathrm{FB}}^{0,\mathrm{b}} &= (10.0 \pm 0.28)\% \\
A_{\mathrm{FB}}^{0,\mathrm{c}} &= (7.59 \pm 0.51)\% \\
\mathcal{A}_{\mathrm{b}} &= 0.842 \pm 0.053 \\
\mathcal{A}_{\mathrm{c}} &= 0.618 \pm 0.090 \\
\mathrm{Br}(\mathrm{b} \to \ell) &= (11.12 \pm 0.23)\% \\
\mathrm{Br}(\mathrm{b} \to \mathrm{c} \to \ell^{+}) &= (7.81 \pm 0.42)\% \\
\overline{\chi} &= 0.1221 \pm 0.0052 \\
P(c \to D^{+*} \to \pi D^{0}) &= 0.168 \pm 0.007
\end{aligned}$$

With a χ^2/dof of $40.8/(76-10)$

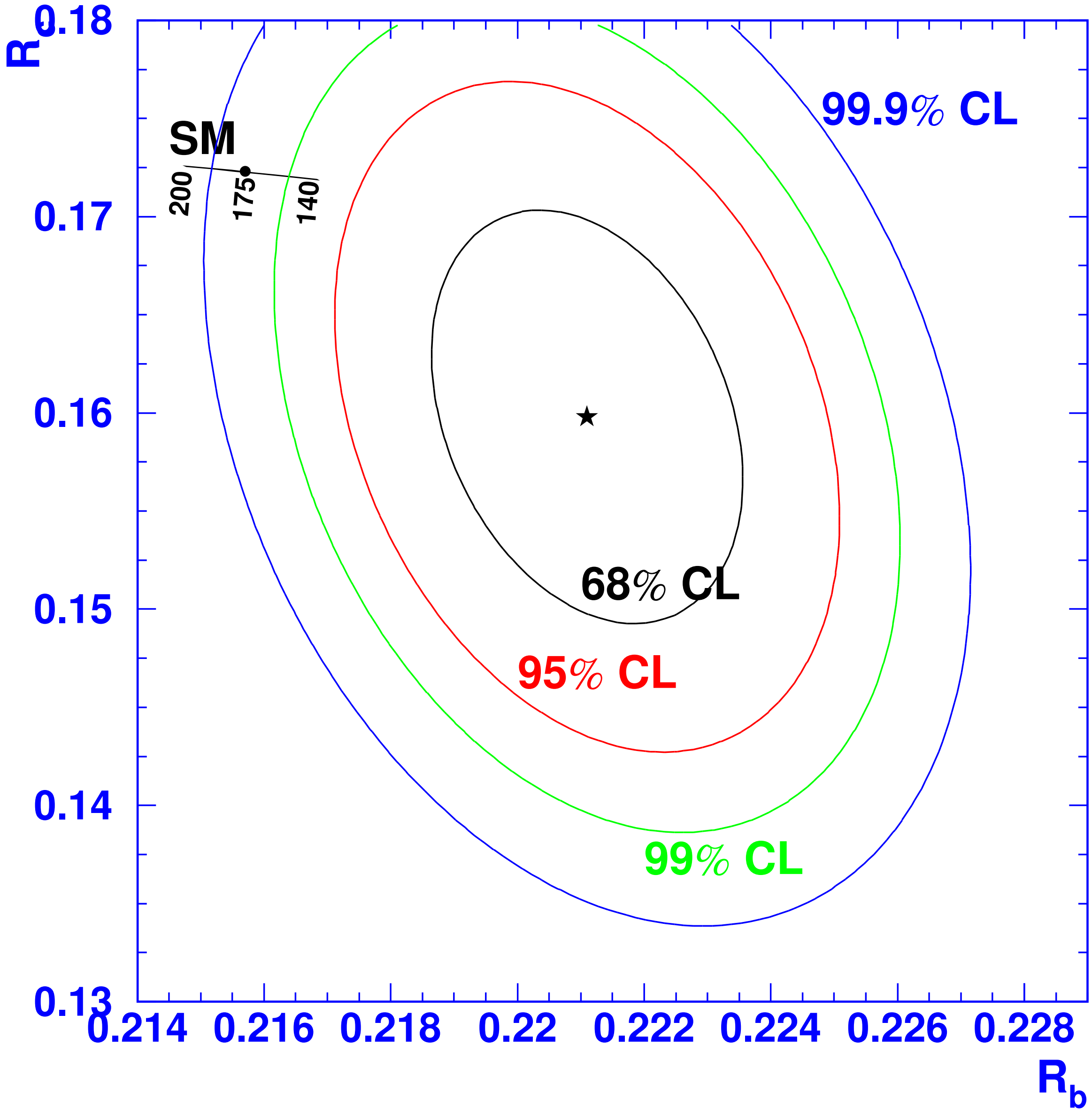
If R_{c} fixed to Standard Model $R_{\mathrm{c}} = 0.172$

$$\boldsymbol{R_{\mathrm{b}}(R_{\mathrm{c}} = 0.172) = 0.2202 \pm 0.0016}$$

Correlation matrix:

$$\begin{array}{l} R_{\mathrm{b}} \\ R_{\mathrm{c}} \\ A_{\mathrm{FB}}^{0,\mathrm{b}} \\ A_{\mathrm{FB}}^{0,\mathrm{c}} \\ \mathcal{A}_{\mathrm{b}} \\ \mathcal{A}_{\mathrm{c}} \\ P_{c\to D^*} \end{array}
\left(\begin{array}{rrrrrrr}
1.00 & -.30 & .00 & .01 & -.05 & .04 & .11 \\
-.30 & 1.00 & .06 & -.01 & .06 & -.06 & -.40 \\
.00 & .06 & 1.00 & .12 & .06 & .02 & -.07 \\
.01 & -.01 & .12 & 1.00 & .00 & .05 & -.04 \\
-.05 & .06 & .06 & .00 & 1.00 & .07 & -.04 \\
.04 & -.06 & .02 & .05 & .07 & 1.00 & .04 \\
.11 & -.40 & -.07 & -.04 & -.04 & .04 & 1.00
\end{array}\right)$$

Standard Model Comparison: R_c vs. R_b



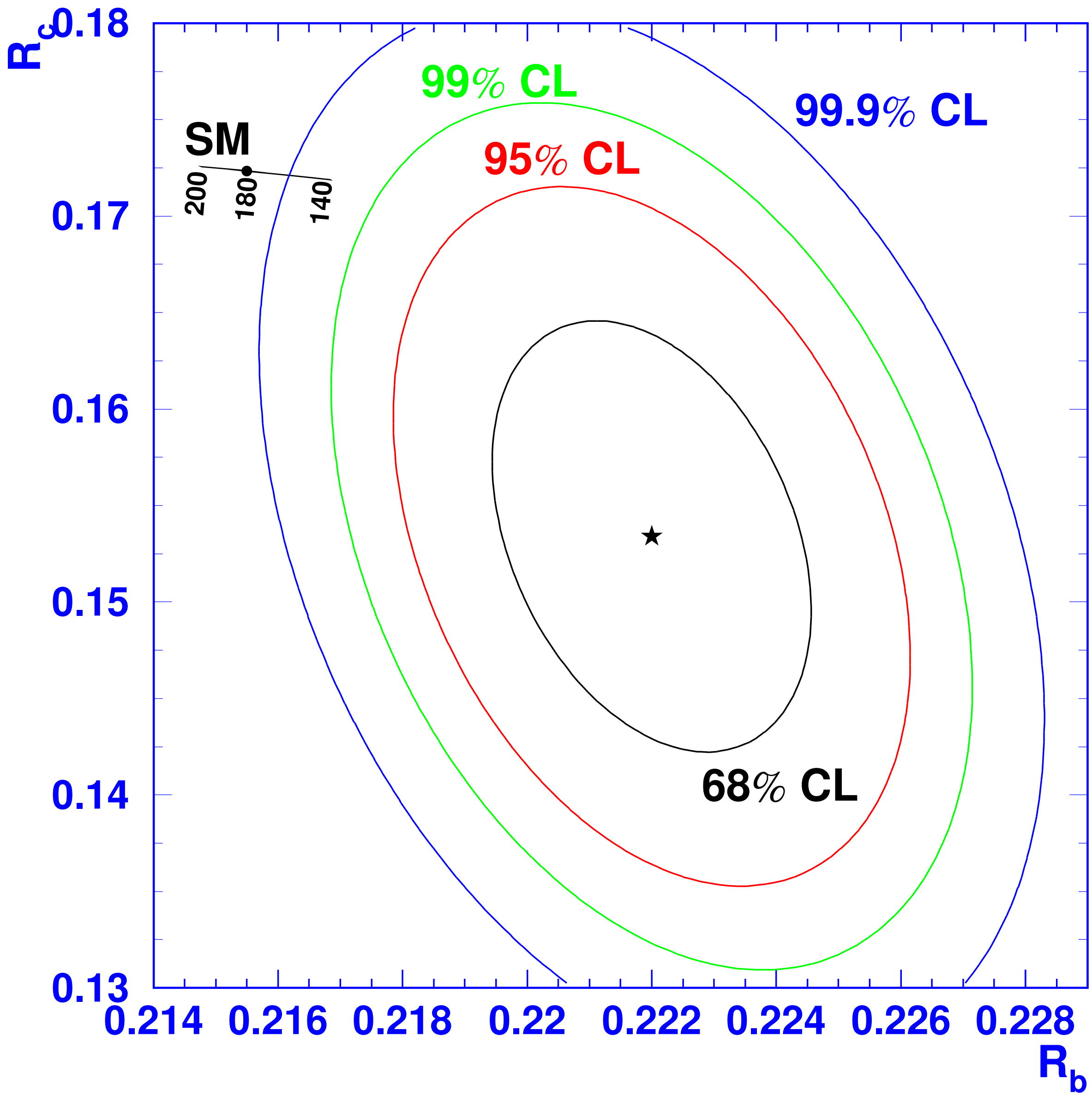
$\Delta\chi^2$ between best fit with Standard Model R_b and R_c

($m_{top} = 175$ GeV, $R_b = 0.2157$, $R_c = 0.172$),

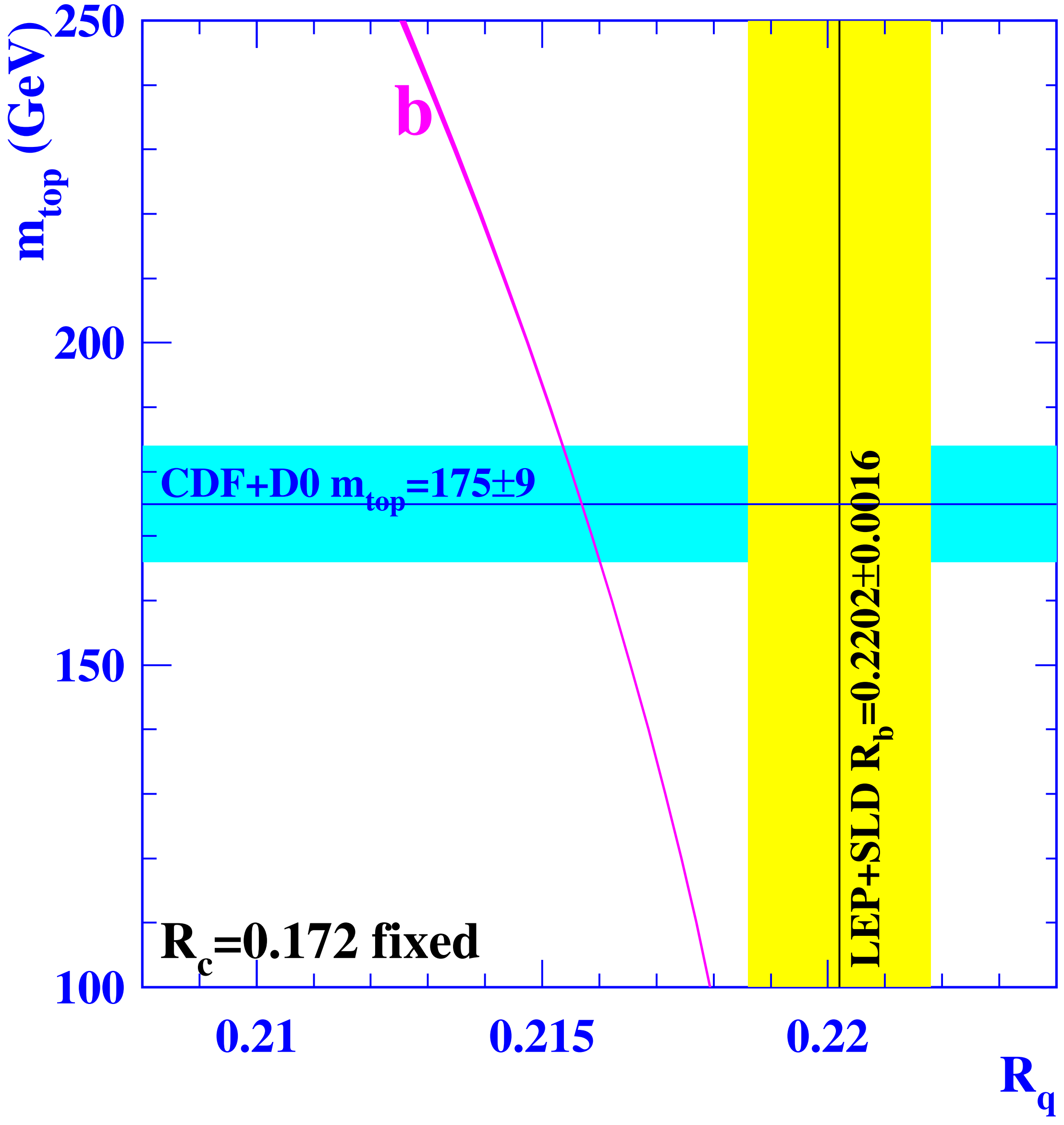
and best overall fit, is 10.3

(was 16.0 in summer 95)

EPS-HEP Brussels 1995: R_c vs. R_b



Comparison with Standard Model: R_c Fixed



Standard Model predictions from ZFITTER 4.9:

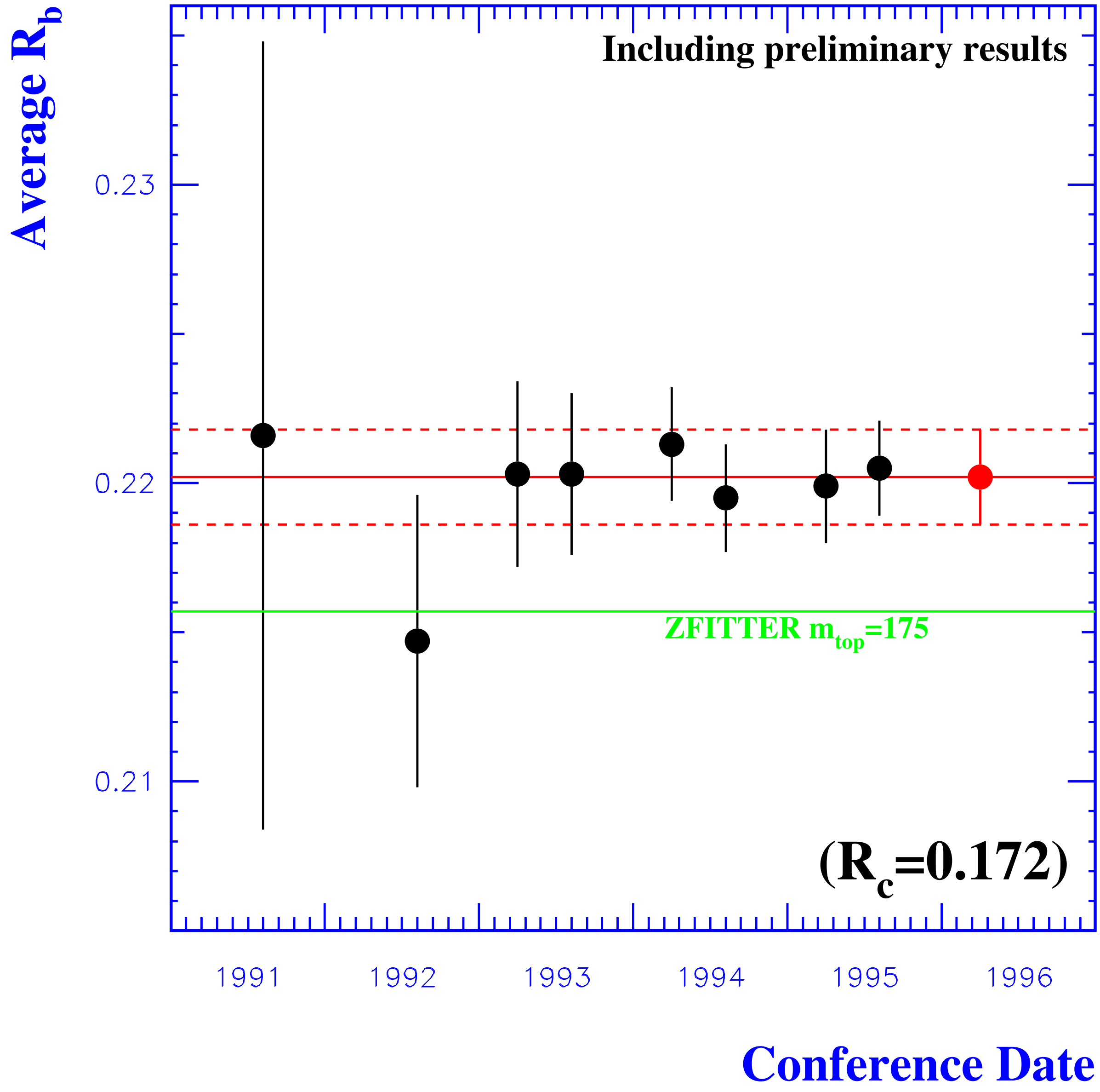
m_Z=91.1888 GeV, 60 GeV $< m_H <$ 1000 GeV,

$\alpha_s(m_Z)$=0.12, $\alpha(m_Z)$=1/128.867

For $m_{top} = 175 \pm 9$ GeV, Standard Model prediction

$R_b = 0.2157 \pm 0.0004$

Time Evolution of World Average R_b



Standard Model Fits

Check validity and consistency of SM

- Infer information on $m_{\rm top}$, $m_{\rm H}$ through loop corrections
- Use directly measured $m_{\rm top}$ $\Longrightarrow m_{\rm H}$ constraints?

Theoretical precision?

Unknown $m_{\rm top}$, $m_{\rm H}$, $\alpha(m_{\rm Z})$, $\alpha_s(m_{\rm Z})$

Take $\alpha(m_{\rm Z}) = 1/(128.896 \pm 0.090)$
$\Longrightarrow \Delta \sin^2\theta_{\rm W}^{{\rm eff},\ell} = 0.00023$, $\Delta m_{\rm top} = 4$ GeV

Effect of missing higher-order corrections and interplay with QCD corrections from:

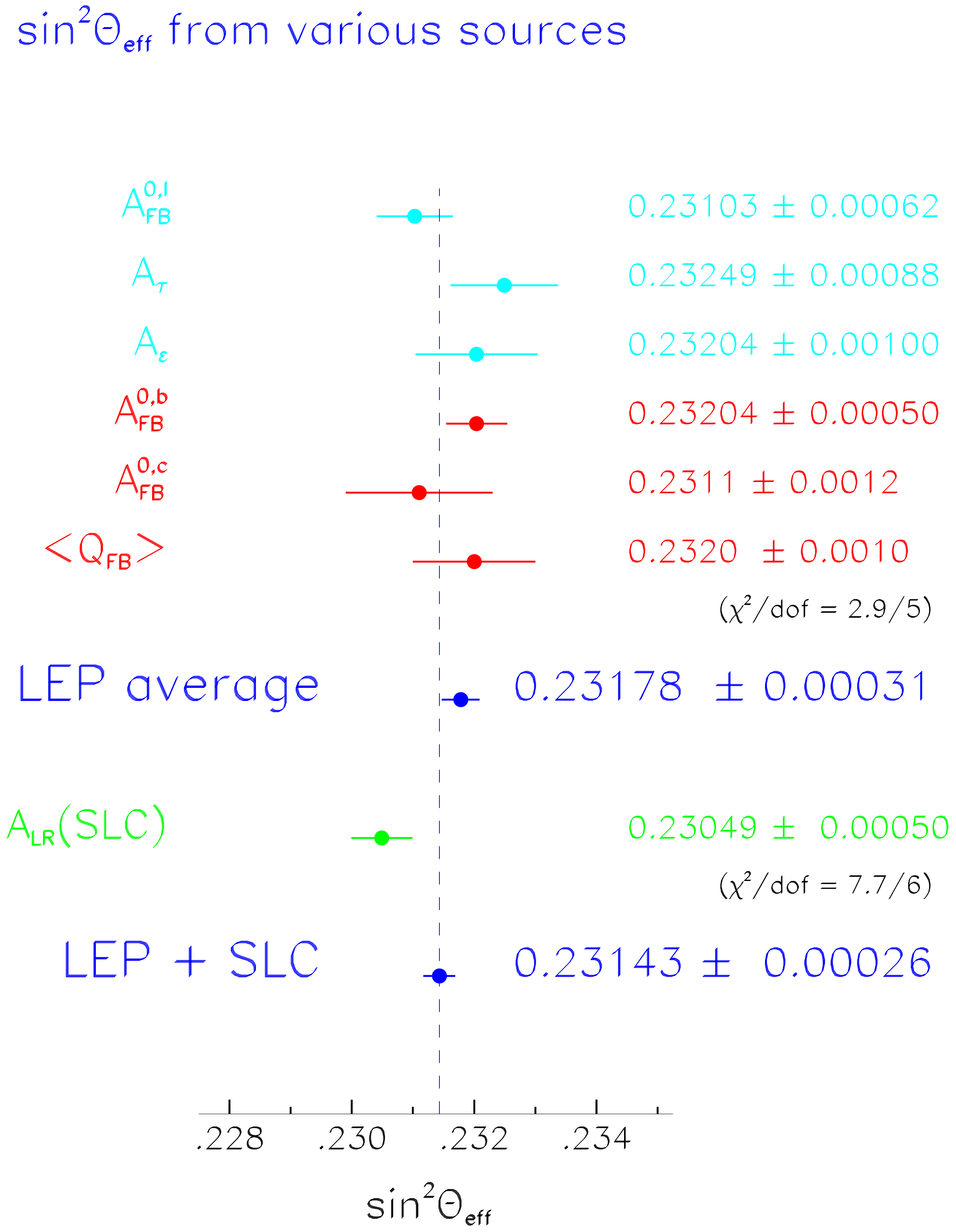
CERN 95-03: “Precision Calculations for the Z Resonance”

(detailed comparisons of codes)

Summary of Measurements

	Measurement	SM Fit	Pull
LEP			
line-shape/lepton asy			
m_Z [GeV]	91.1884 ± 0.0022	91.1869	0.7
Γ_Z [GeV]	2.4964 ± 0.0032	2.4979	-0.5
$\sigma^{\mathrm{pole}}_{\mathrm{had}}$ [nb]	41.490 ± 0.078	41.454	0.5
R_ℓ	20.788 ± 0.032	20.770	0.6
$A^{\mathrm{pole}}_{\mathrm{FB}}$	0.0171 ± 0.0011	0.0159	1.1
τ polarization:			
$\mathcal{A}_\tau$	0.1394 ± 0.0069	0.1455	-0.9
$\mathcal{A}_e$	0.1429 ± 0.0079	0.1455	-0.3
b and c quark results:			
R_b	0.2215 ± 0.0017	0.2155	3.5
R_c	0.1596 ± 0.0070	0.1725	-1.8
$A^{0,b}_{\mathrm{FB}}$	0.1002 ± 0.0028	0.1020	-0.6
$A^{0,c}_{\mathrm{FB}}$	0.0756 ± 0.0051	0.0728	0.5
$q\overline{q}$ charge asymmetry:			
$\sin^2\theta^{\mathrm{eff},\ell}_{\mathrm{W}}$ ($\langle Q_{FB}\rangle$)	0.2320 ± 0.0010	0.23171	0.3
SLD			
$\sin^2\theta^{\mathrm{eff},\ell}_{\mathrm{W}}$ (A_{LR})	0.23049 ± 0.00050	0.23172	-2.4
R_b	0.2176 ± 0.0039	0.2155	0.5
$\mathcal{A}_b$	0.842 ± 0.052	0.934	-1.8
$\mathcal{A}_c$	0.618 ± 0.091	0.667	-0.5
$p\overline{p}$ and νN			
m_W [GeV] ($p\overline{p}$)	80.33 ± 0.15	80.37	-0.2
$\sin^2\theta_W$ (νN)	0.2257 ± 0.0047	0.2232	0.5

Standard Model predictions from fit to all data, $m_H = 300$ GeV.



$\sin^2\Theta_{eff}$ from various sources
$A_{FB}^{0,l}$
A_τ
A_e
$A_{FB}^{0,b}$
$A_{FB}^{0,c}$
<Q_{FB}>
0.23103 ± 0.00062
0.23249 ± 0.00088
0.23204 ± 0.00100
0.23204 ± 0.00050
0.2311 ± 0.0012
0.2320 ± 0.0010
(χ^2/dof = 2.9/5)
LEP average
0.23178 ± 0.00031
A_{LR}(SLC)
0.23049 ± 0.00050
(χ^2/dof = 7.7/6)
LEP + SLC
0.23143 ± 0.00026
.228
.230
.232
.234
$\sin^2\Theta_{eff}$

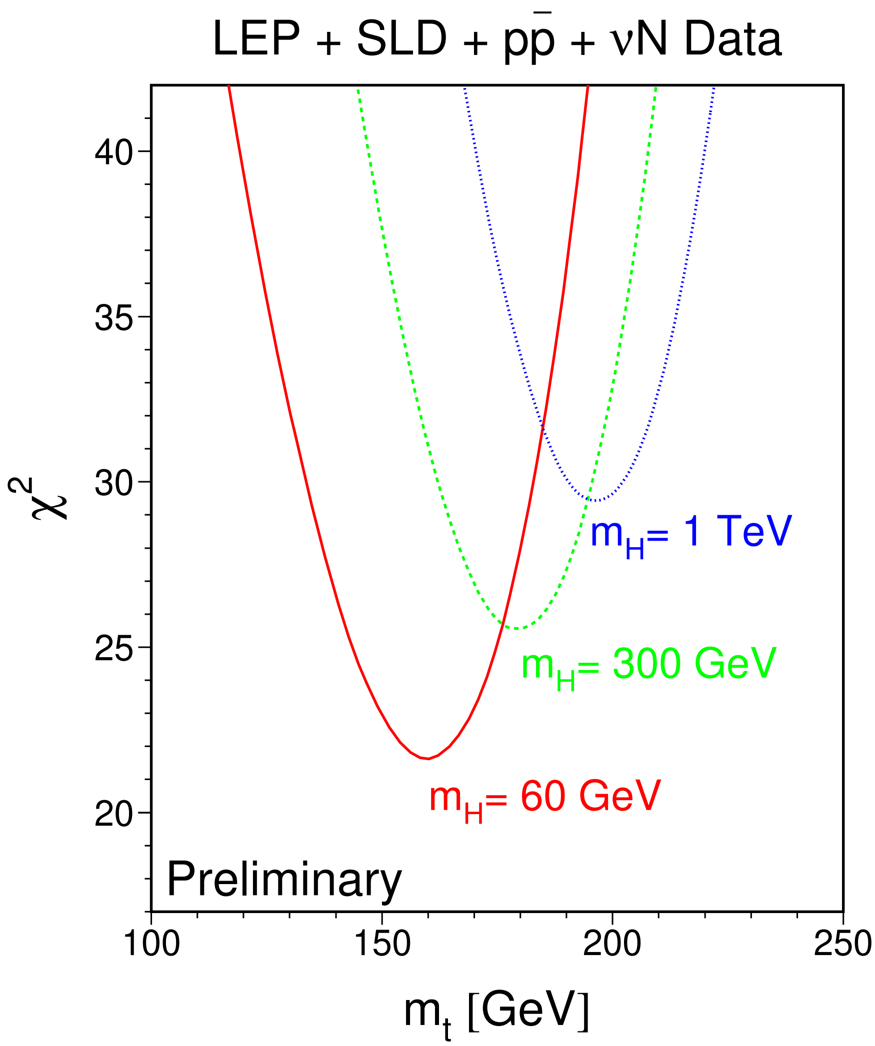
Results of Standard Model Fits

- No external constraint on $\alpha_s(m_Z)$
- Central values and first errors $m_H = 300$ GeV.
- Second errors for varying m_H in the interval $[60, 1000]$
- Constraint $\alpha(m_Z) = 1/(128.896 \pm 0.090)$
- Contribution of about 12 to χ^2 from R_b and R_c
- Compare $\alpha_s(m_Z)$ with value from event shapes of $\alpha_s(m_Z) = 0.123 \pm 0.006$

	LEP	LEP + SLD
m_{top} [GeV]	$172 \ {}^{+9}_{-10} \ {}^{+18}_{-20}$	$180 \ {}^{+8}_{-9} \ {}^{+18}_{-21}$
$\alpha_s(m_Z)$	$0.124 \pm 0.004 \ \pm 0.002$	$0.123 \pm 0.004 \ \pm 0.002$
χ^2/d.o.f.	$15/9$	$24/12$
$\sin^2\theta_W^{eff,\ell}$	$0.23195 \pm 0.00026 \ {}^{+0.00007}_{-0.00014}$	$0.23163 \pm 0.00024 \ {}^{+0.00006}_{-0.00012}$
$\sin^2\theta_W$	$0.2244 \pm 0.0009 \ {}^{+0.0005}_{-0.0003}$	$0.2235 \pm 0.0008 \ {}^{+0.0005}_{-0.0004}$
m_W [GeV]	$80.305 \pm 0.053 \ {}^{+0.016}_{-0.027}$	$80.357 \pm 0.046 \ {}^{+0.017}_{-0.029}$

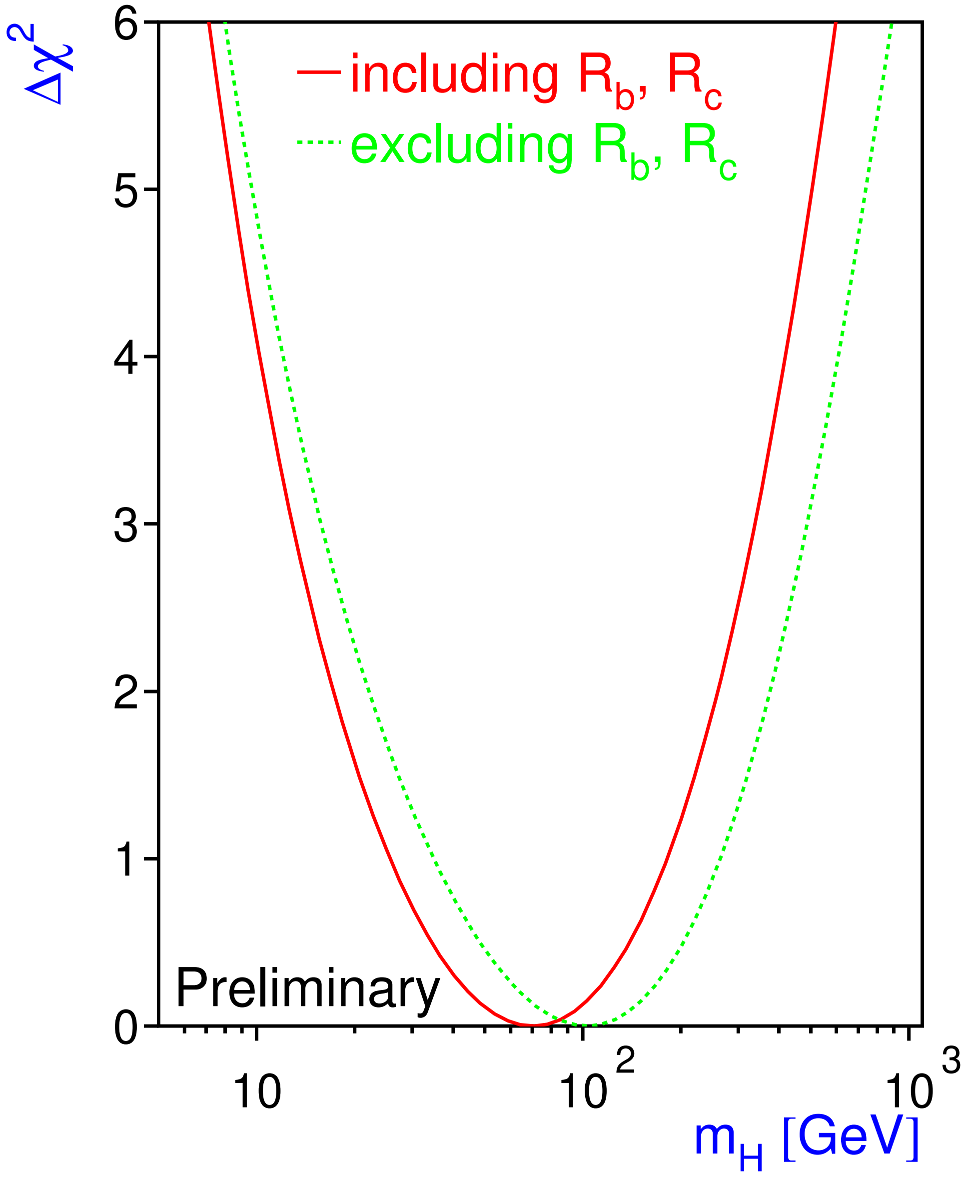
	LEP + SLD + $p\bar{p}$ and νN data
m_{top} [GeV]	$179 \pm 8 \ {}^{+18}_{-20}$
$\alpha_s(m_Z)$	$0.123 \pm 0.004 \ \pm 0.002$
χ^2/d.o.f.	$25/14$
$\sin^2\theta_W^{eff,\ell}$	$0.23164 \pm 0.00022 \ {}^{+0.00007}_{-0.00010}$
$\sin^2\theta_W$	$0.2236 \pm 0.0007 \ {}^{+0.0004}_{-0.0003}$
m_W [GeV]	$80.350 \pm 0.042 \ {}^{+0.016}_{-0.025}$

Constraint on $m_{\rm H}$?



- Add constraint from CDF/DO $m_{\rm top} = 175 \pm 9$ GeV $\Longrightarrow$ information on $m_{\rm H}$
- Most variables have similar $m^2_{\rm top}$ and $\log m_{\rm H}$ dependence
- $R_{\rm b}$ has special $m^2_{\rm top}$ dependence, independent of $\log m_{\rm H}$, prefers low $m_{\rm top}$ $\Longrightarrow$ larger $m_{\rm H}$ preferred if $R_{\rm b}$ excluded
- Omitting $R_{\rm b}$ and $R_{\rm c}$ from SM fits, $m_{\rm top}$ increases by only 4 GeV, $\alpha_s(m_{\rm Z})$ is unchanged $\Longrightarrow$ insensitive

Constraint on m_{H}?



The LEP Energy Upgrade: LEP-1.5

31 Oct – 22 Nov 1995

A first short run at energies well above the Z^0 threshold

Main aim: learn about high-energy operation of superconducting RF

Physics goal: Collect $\geq$5 pb^{-1} at high energy

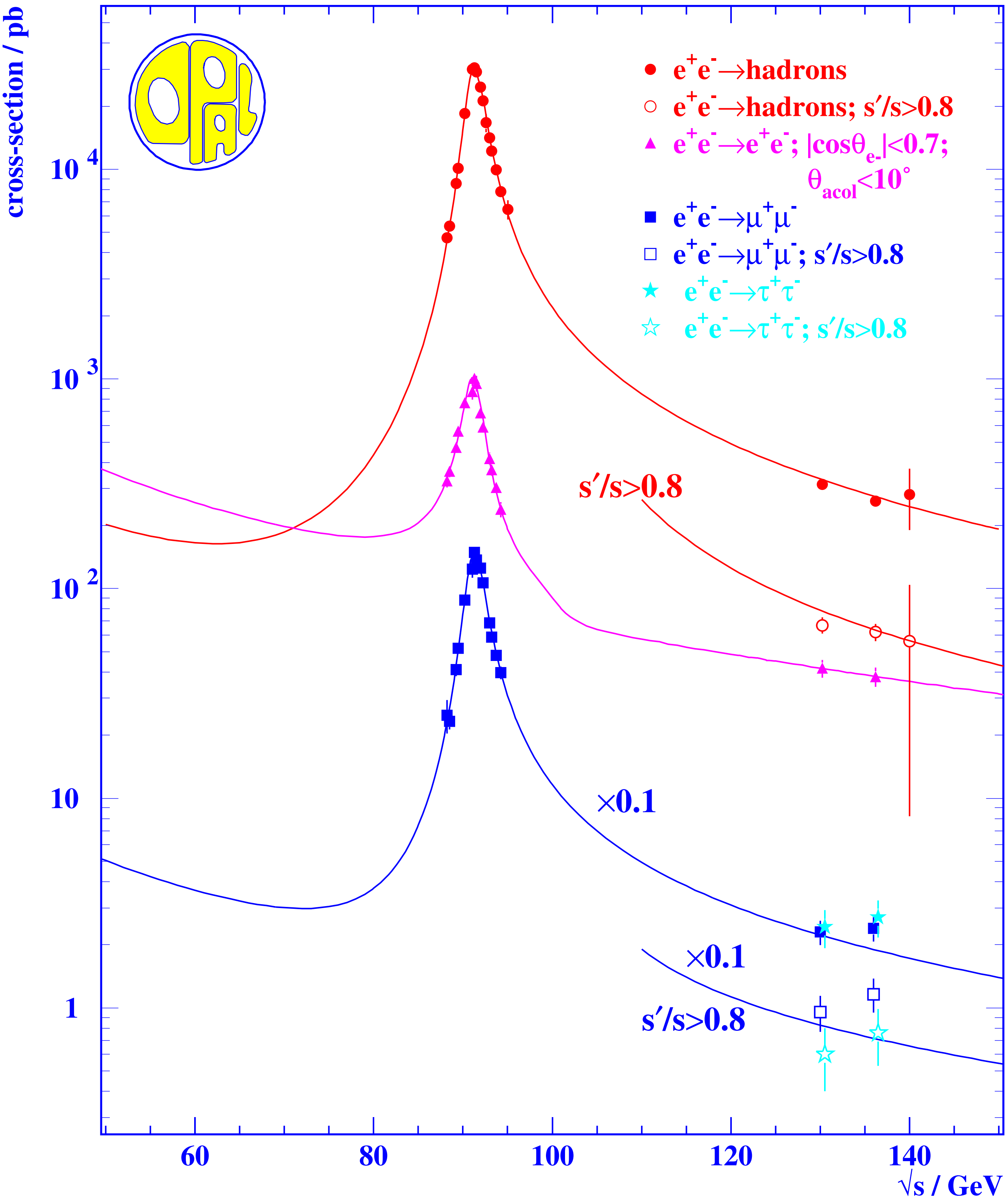
In practice:

- 3 pb^{-1} at 130 GeV
- 3 pb^{-1} at 136 GeV
- 0.05 pb^{-1} at 140 GeV

Main features of fermion pair production:

- Some events with full energy $\longrightarrow$
- "Radiative return" to the Z^0 $\longrightarrow$

Most interest in measuring non-radiative cross-sections and event properties



cross-section / pb
10^4
10^3
10^2
10
1
60
80
100
120
140
$\sqrt{s}$ / GeV
$e^+e^- \rightarrow$ hadrons
$e^+e^- \rightarrow$ hadrons; $s'/s>0.8$
$e^+e^- \rightarrow e^+e^-$; $|\cos\theta_{e-}|<0.7$; $\theta_{acol}<10°$
$e^+e^- \rightarrow \mu^+\mu^-$
$e^+e^- \rightarrow \mu^+\mu^-$; $s'/s>0.8$
$e^+e^- \rightarrow \tau^+\tau^-$
$e^+e^- \rightarrow \tau^+\tau^-$; $s'/s>0.8$
$s'/s>0.8$
$\times 0.1$
$\times 0.1$
$s'/s>0.8$

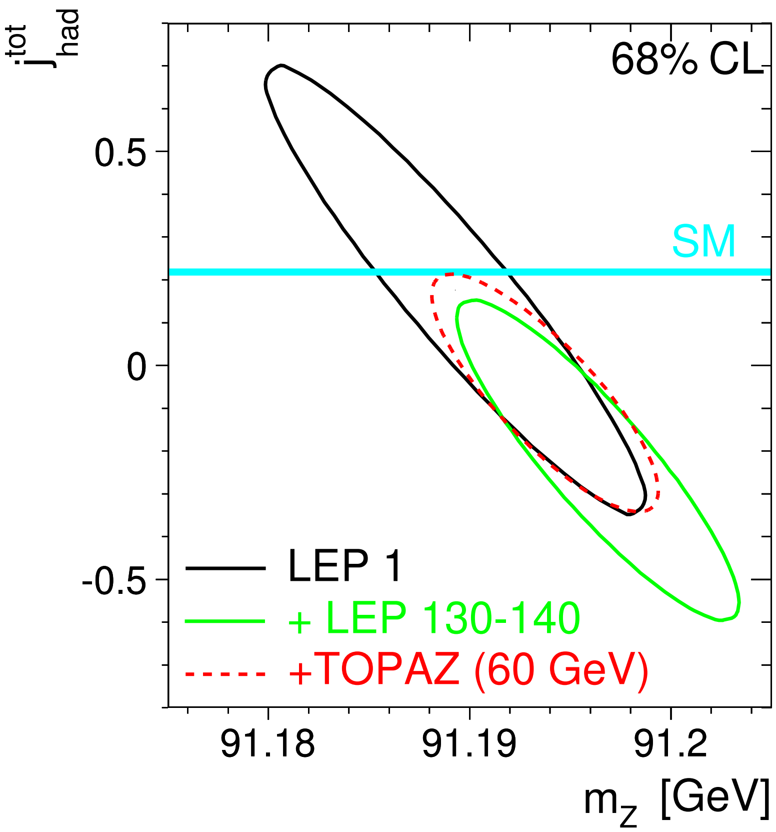
γ-Z^0 Interference

Without radiative corrections:

$$\sigma_{q\bar{q}}(\sqrt{s}) = \frac{A_\gamma}{s} + \frac{A_{\gamma Z}(s - m_Z^2) + A_Z s}{(s - m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

- Standard fit: relative sizes of A_γ, $A_{\gamma Z}$, A_Z fixed $\longrightarrow m_Z, \Gamma_Z$
- "S-Matrix" fit effectively allows $A_{\gamma Z}$ to float $\longrightarrow \mathrm{j_{had}}$
- m_Z precision reduced in this case
- 130 GeV data particularly sensitive to interference term

	δm_Z (MeV)	$\mathrm{j_{had}}$
$\mathrm{j_{had}}$ fixed	2.2	0.22
fit to LEP-1	6.2	0.18 ± 0.34
fit to LEP-1+LEP1.5	4.8	-0.22 ± 0.25
fit to LEP + TOPAZ	3.8	-0.06 ± 0.18

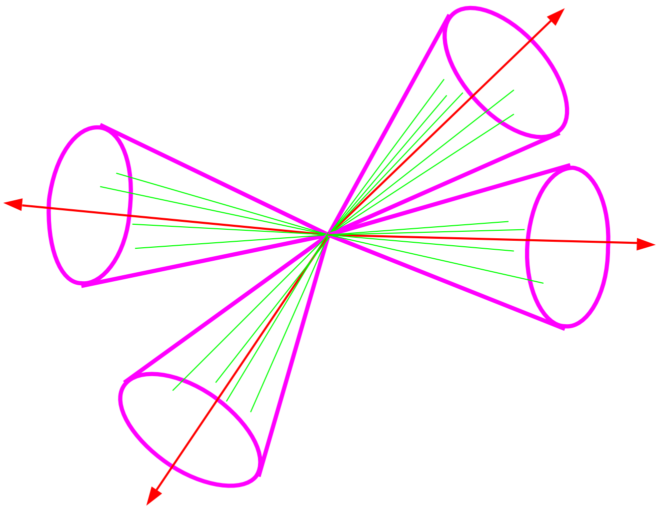


Search in 4-jet channel by ALEPH

CERN PPE/96-052

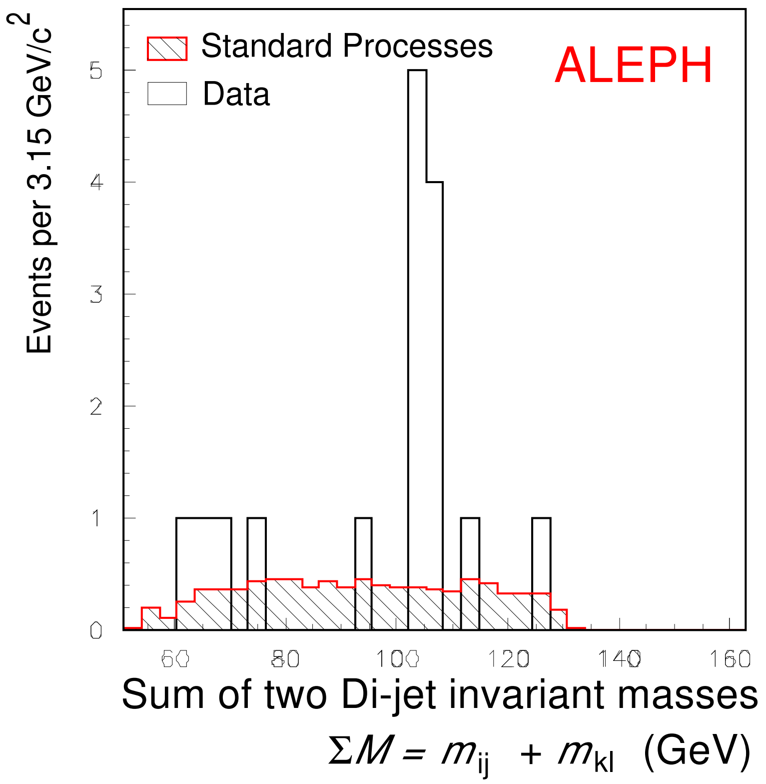
ALEPH reported a search in 4-jet channel, originally for hA

- Select hadronic events with high $\sqrt{s'}$
- Require 4 or 5 jets (Durham jet-finder $y = 0.008$)
- Veto photon-like jets
- Rescale jet energies using jet directions and total centre-of-mass energy, reject any event with $E_{jet} < 0$
- require jet-jet masses above 25 GeV, pairwise sums of jet masses above 10 GeV, high charged multiplicity jets



Leaves 16 four-jet events, expect 8.6±0.6 (PYTHIA + 4-f MC) (1.5% probability)

Look at sum of dijet masses, choose combination with smallest mass difference (prefers equal masses $\Longrightarrow$ pair production hypothesis)



In 105$\pm$6.3 GeV window, 9 events, 0.8 expected (0.01% prob.)

Also second-smallest mass-difference $\Longrightarrow$ 3 more events

Look in more detail at events:

- only one event looks like $\mathrm{b\bar{b}b\bar{b}}$ from lifetime
- no lepton tags

$\Longrightarrow$ no $\mathrm{b\bar{b}}$ excess, as would expect from hA

Also does not match with H^+H^- (rate too high, no $H^- \to \tau\nu$)

Do events look like QCD background: 90% $\mathrm{q\bar{q}gg}$, 10% $\mathrm{q\bar{q}q\bar{q}}$?

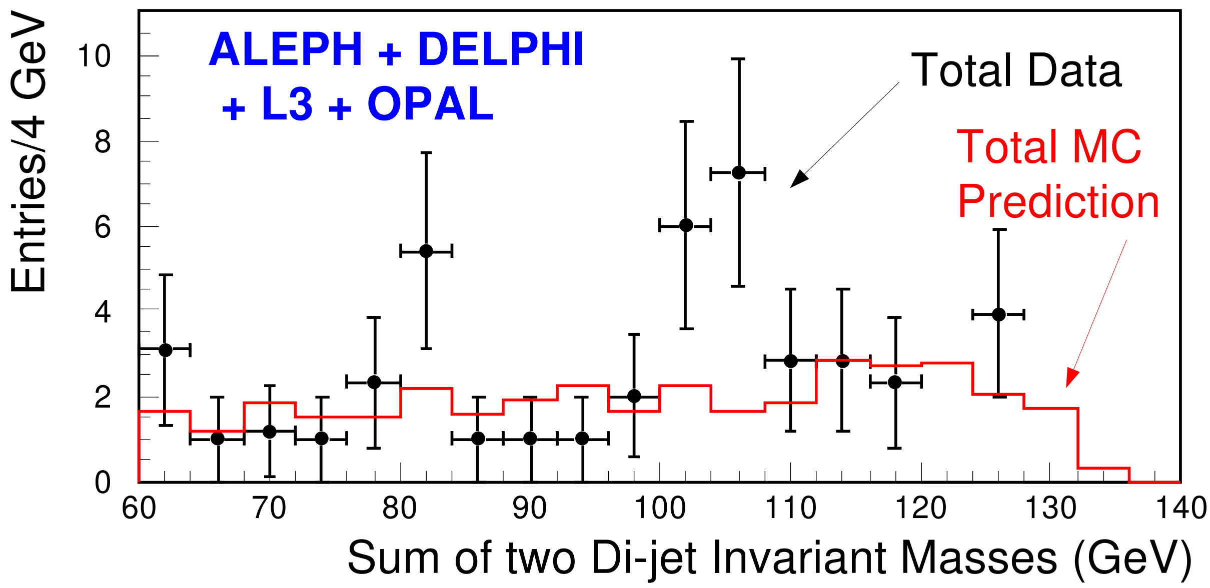
- QCD matrix element squared smaller than expected
- Jet charges larger than expected for gluon jets
- Jet charge separation higher than expected

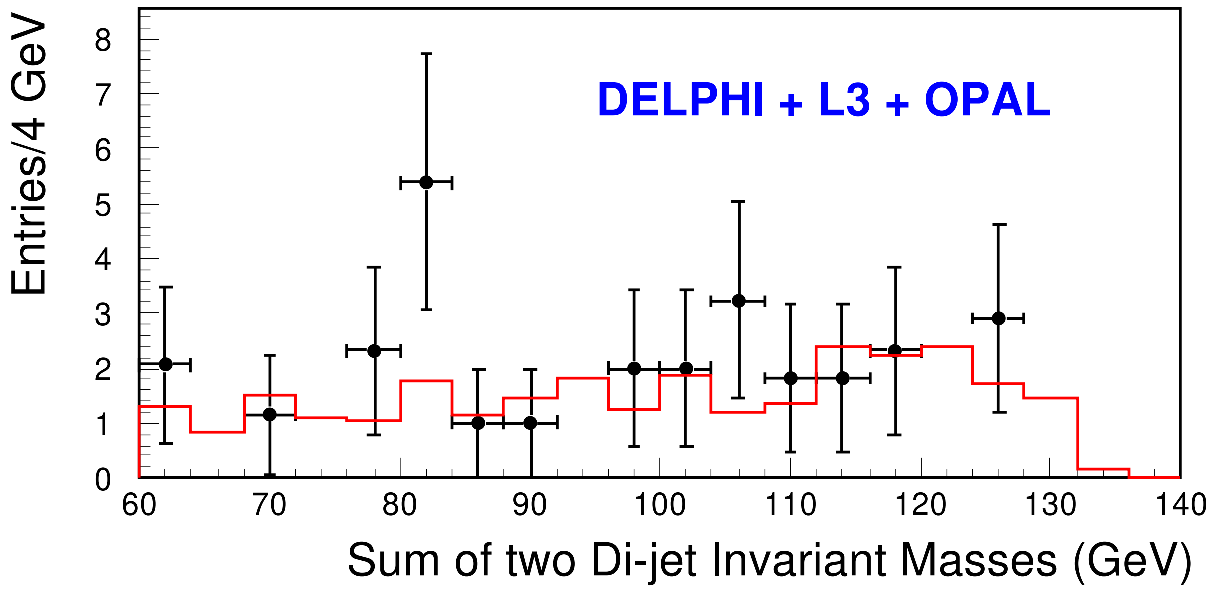
If this were a signal, it would correspond to

$$\sigma = 3.1 \pm 1.7\mathrm{pb}$$

4 Jet Events in DELPHI, L3, OPAL?

Combined mass sum plots from all 4 collaborations:





No support for effect from other experiments, but statistics currently insufficient to exclude it

We need more data!

What Next

LEP-2 is coming REALLY soon now

Date	Max. E_{cm} (GeV)	Max. $\mathcal{L}$ (10^{31} cm^{-2}s^{-1})	
Nov 95	136	3	"LEP-1.5"
Jun 96	161	8	$\mathrm{W}^+\mathrm{W}^-$ threshold
Oct 96	176	9	short run
Jun 97	188	9	main 1997 run
May 98	192	11	"Phase IV"

(adapted from C. Wyss, LEPC May 1996)

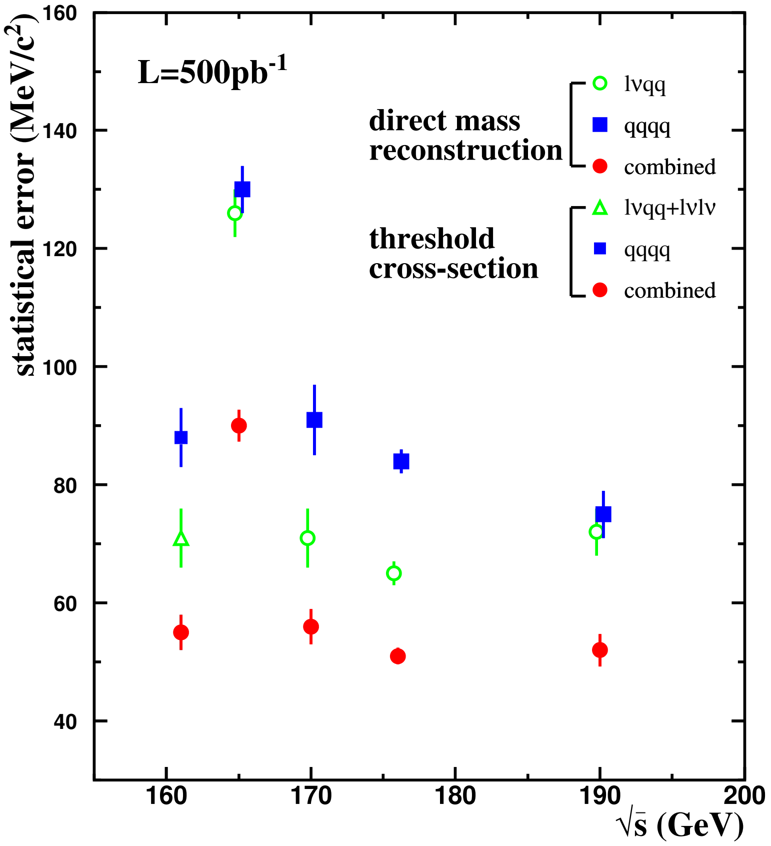
This year, expect

- $\mathcal{O}$(30 pb^{-1}) at $\sqrt{s} = 161$ GeV
- $\mathcal{O}$(15 pb^{-1}) at $\sqrt{s} \simeq 176$ GeV

Measurement of m_W at LEP-II

Two main techniques:

- Threshold cross-section at $\sqrt{s} = 161$ GeV
  - + Uses all visible W decays, only need cross-section
  - − QED corrections (Coulomb) large
  - − Poor for searches, TGC, etc.
- Direct reconstruction of W decay products at $\sqrt{s} > 170$ GeV
  - + Higher statistics WW samples
  - − QCD reconnection effect large $\Longrightarrow$ dilutes $q\bar{q}q\bar{q}$ channel?



Similar statistical precisions per pb^{-1}, systematics quite different (except $E_{\rm beam}$)

m_W Measurements

Current CDF/D0/UA2 result:

$$m_W = 80.33 \pm 0.15 \text{ GeV}$$

Expect from 161 GeV run (4 expts combined):

$$\Delta m_W \simeq 130 \text{ MeV}$$

Expect from whole of LEP-II (500 pb$^{-1} \times$ 4 expts):

$$\Delta m_W \simeq 30 \text{ MeV}$$

Ultimately, CDF/D0 may achieve a similar precision as LEP-II (full run II statistics)

With this precision, m_W measured to same level it is predicted by electroweak SM fits $\Longrightarrow$ test of SM consistency

Summary

- Impressive range of high precision electroweak results from LEP and SLD
- Overall agreement with SM is very good
- Problems:
  - R_{b} deviation from SM: being studied intensively but no major problems found
  - R_{c} deviation from SM: decreasing slowly with time?
- LEP energy upgrade has produced first results
- LEP-II starts next week!

  For m_{W}, reconnection effects should be understood

- Exciting times for LEP during coming years:
  - Final LEP-I results
  - First LEP-II results