Electroweak Results from EPS-HEP 95

CERN Particle Physics Seminar
29 August 1995

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- W mass from CDF and D0
- Top mass and cross-section from CDF and D0
- νN scatterng from CCFR
- Measurements at the $\mathbb{Z}$ from LEP and SLD
  - Lineshape and lepton forward-backward asymmetries (LEP)
  - Tau polarisation asymmetry (LEP)
  - Left-right asymmetry, A_{LR} (SLC)
  - Partial widths and asymmetries with heavy quarks
  - $\langle Q_{FB} \rangle$
- Fits to electroweak data in the Standard Model

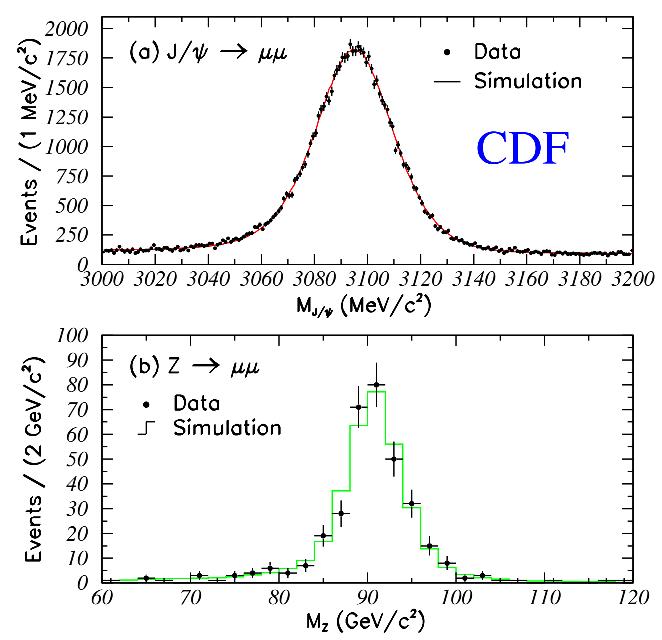
- Many thanks to: Speakers at Brussels and Beijing
  LEP electroweak working group
  LEP and SLD heavy flavour groups

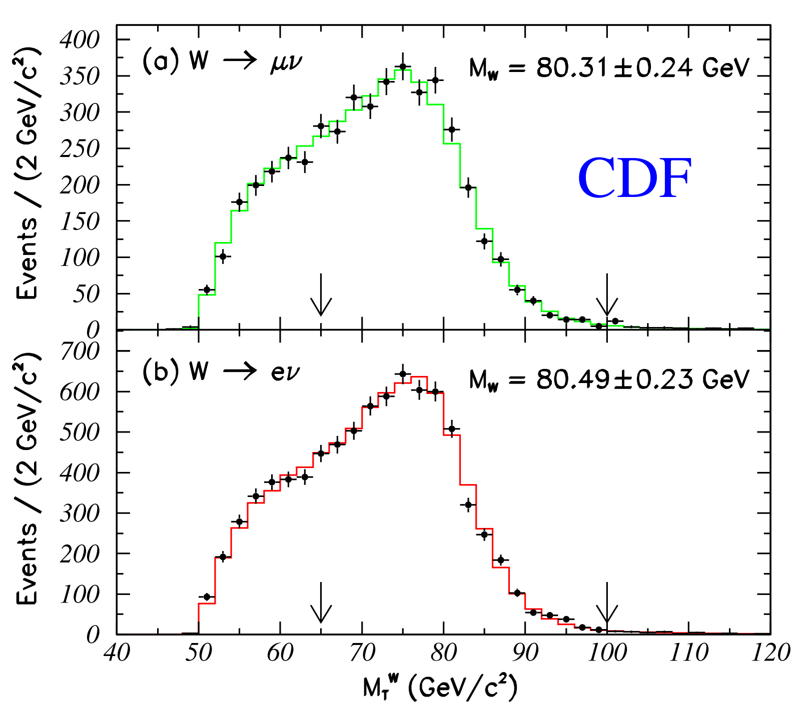
W mass measurements

- CDF 19 pb^{-1} $\mathrm{W} \to \mathrm{e}\nu$ and $\mu\nu$ (published)
- D0 13 pb^{-1} $\mathrm{W} \to \mathrm{e}\nu$ (Glasgow '94)
- Measure M_{W} from fit to transverse mass distribution
- Infer p_T^{ν} from ℓ and recoil energy.

CDF derive p scale from J/ψ. Check with Υ, Z. Electron energy scale from electron sample E/p and p scale.

D0 calibrate from $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$.
(Prel. result 260 MeV scale error)





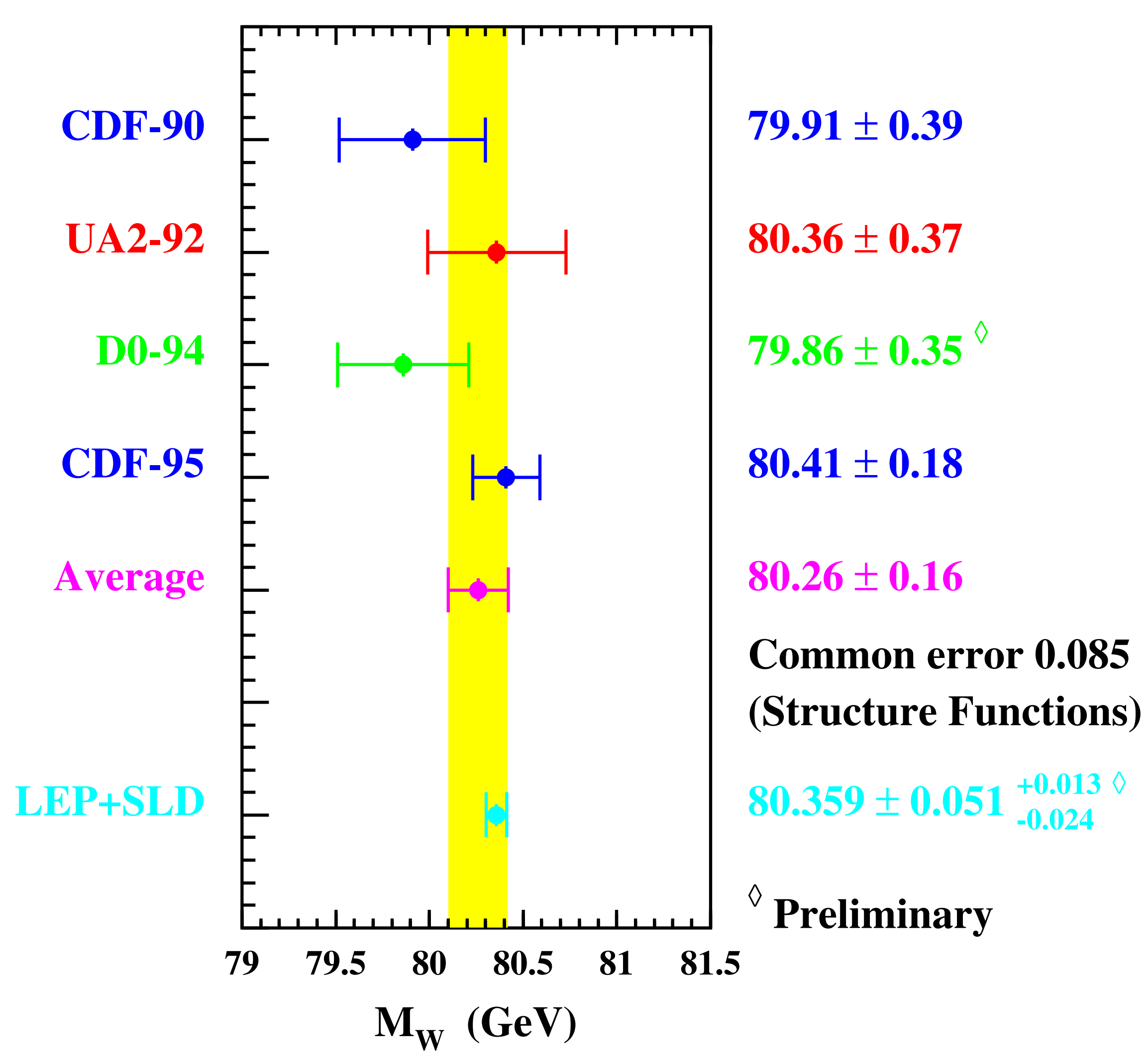
$M_T^2 = (E_T^{\ell}+E_T^{\nu})^2-(p_T^{\ell}+p_T^{\nu})^2$

Typically require

- $E_T^{\ell} > 25$ GeV
- $E_T^{\nu} > 25$ GeV
- $E_T^{\mathrm{recoil}} < 20$ GeV

Calibrate p_T^{W} with Z sample

W mass results



Plus new direct measurement of Γ_{W} from CDF
from high end of M_T spectrum for $\mathrm{W} \rightarrow \mathrm{e}\nu$ events

$\Gamma_{\mathrm{W}} = 2.11 \pm 0.32$ GeV

(SM expectation $\Gamma_{\mathrm{W}} = 2.077 \pm 0.014$ GeV)

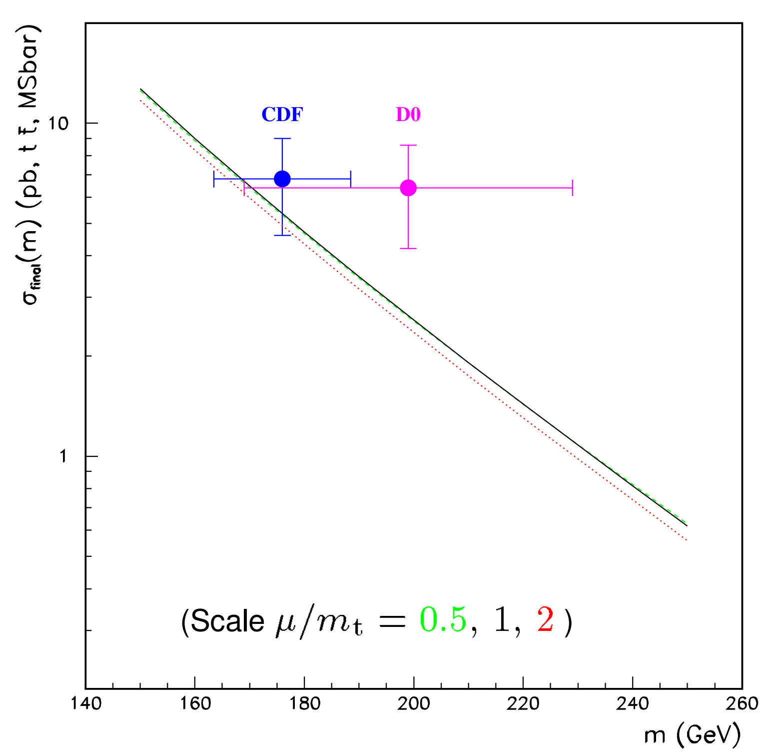
Observation of the top quark

- $\mathrm{t\bar{t}}$ dominates top production in $\mathrm{p\bar{p}}$ collisions at 1.8 TeV
- $\mathrm{t\bar{t}} \longrightarrow \ell\nu j_b \ell\nu j_b$ ($\ell \equiv \mathrm{e}\mu$) (5%)
- $\mathrm{t\bar{t}} \longrightarrow \ell\nu j_b jjj_b$ (30%)
- $\mathrm{t\bar{t}} \longrightarrow jjj_b jjj_b$ (44%)
- Mass from constrained fits to lepton + jets samples
- Cross-section from dilepton, lepton + jets (with b tag)

Published mass and cross-section measurements (Spring 95)

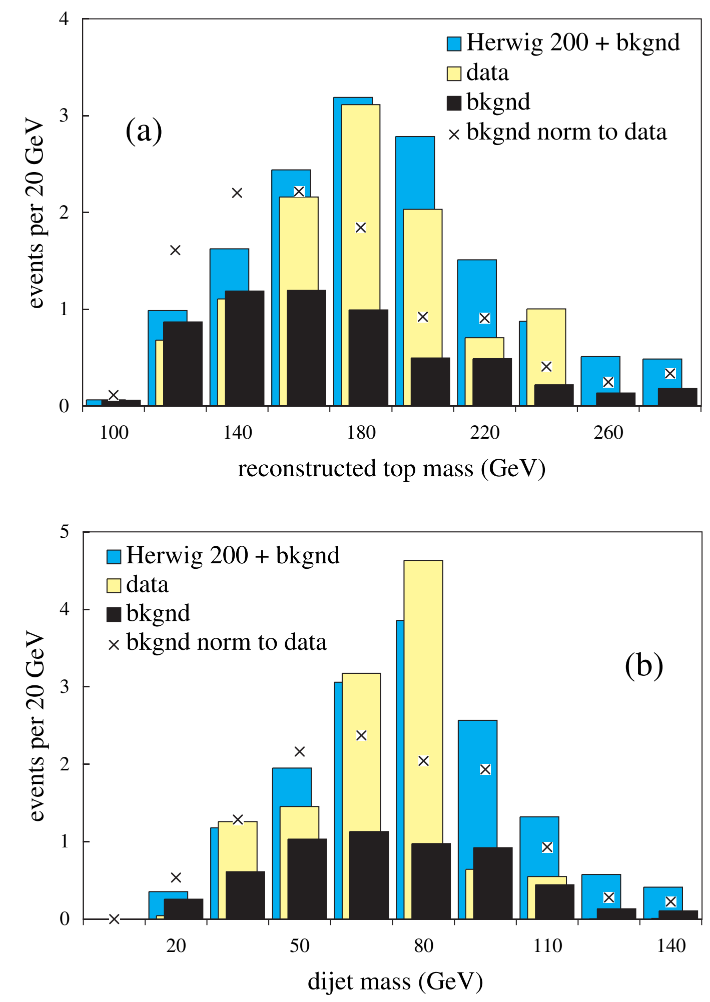
	CDF	D0
m_{t} (GeV)	$176 \pm 8 \pm 10$	$199^{+19\,+14}_{-21\,-21}$
$\sigma(\mathrm{t\bar{t}})$ (pb)	$7.6^{+2.4}_{-2.0}$	6.4 ± 2.2
$\int \mathcal{L}$ (pb^{-1})	$67(50)$	50

New cross-section calculation (Berger and Contopanagos)



Top physics - new results

- D0: $m_{\mathrm{t}} = 145 \pm 25 \pm 20$ GeV (prel. from 5 $\ell\ell$ events)
- CDF+D0: Analysis in progress of $\sim$100 pb^{-1} of data (no new mass value reported – consistent with published value)
- Improved use of kinematic variables to separate W+jets and $\mathrm{t\bar{t}}$
- Attempting to relax constraint on $m_{jj} = M_{\mathrm{W}}$ in fits for m_{t} to $\ell\nu j_b j j j_b$ sample. Examine m_{jj} vs. reconstructed m_{t}:



D0 (a) $M_{jj} > 58$ GeV (b) $m_{\mathrm{t}} > 150$ GeV

- First results on 6 jet channel using b-tag and kinematic variables
  CDF 62 ev, 42.9 bkg $\sigma = 9.7 \pm 3.3$(stat) pb
  D0 4 ev, 3.2 bkg (tight) or 50 ev, 41.7 bkg, $\sigma = 5.5 \pm 4.8$pb

New CCFR Analysis

- Deep inelastic ν scattering
- Measure $R^{\nu} = NC/CC$
- Derive $\sin^2\theta_{\mathrm{W}} = 1 - {M_{\mathrm{W}}}^2/{M_{\mathrm{Z}}}^2$
- Previous analysis used Monte Carlo to predict relationship between observed ratio and $\sin^2\theta_{\mathrm{W}}$
- New analysis uses MC for background subtraction but direct theoretical prediction to relate R^{ν} to $\sin^2\theta_{\mathrm{W}}$
- Published result:
  $\sin^2\theta_{\mathrm{W}} = 0.2218 \pm 0.0025\text{stat} \pm 0.0036\text{syst} \pm 0.0040\text{model}$
- New preliminary result:
  $\sin^2\theta_{\mathrm{W}} = 0.2224 \pm 0.0025\text{stat} \pm 0.0036\text{syst} \pm 0.0040\text{theory}$
- Agrees with previous analysis, with different input assumptions $\Longrightarrow$ cross-check.

Measurements at the Z

Data samples available

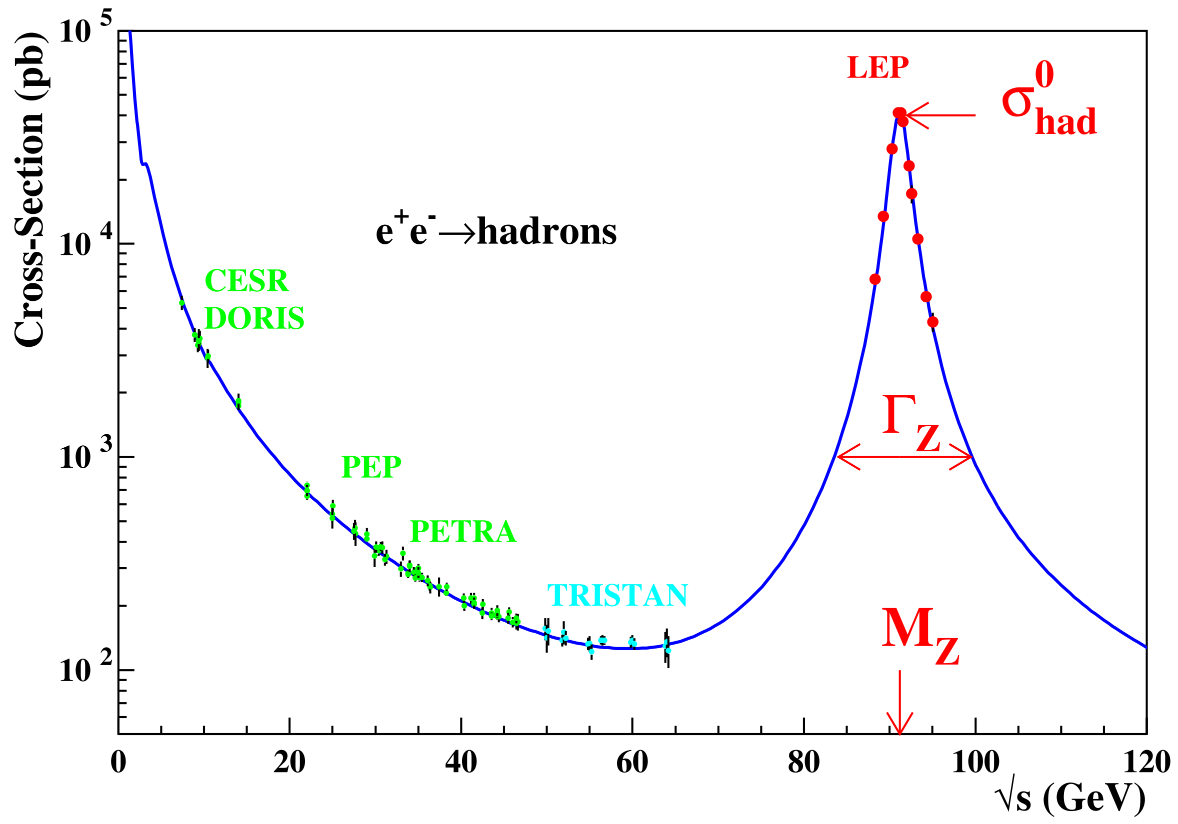
LEP (ALEPH, DELPHI, L3, OPAL)

- 1989-94: $12.4 \cdot 10^6\ \mathrm{q\overline{q}}$ and $1.3 \cdot 10^6\ \ell^+\ell^-$
- 1993: 3 point energy scan (peak, ± 2 GeV) $\sim 650 \cdot 10^3\ \mathrm{q\overline{q}}/$expt.
- 1994: on peak, $(1.1 \sim 1.5) \cdot 10^6\ \mathrm{q\overline{q}}/$expt.

SLC (SLD)

- 1992-95: $150 \cdot 10^3$ visible Z.
- 1994-95: $92 \cdot 10^3\ \mathrm{Z}$ with 80% polarization of electron beam.

Z Lineshape



$$\sigma_f(s) = \sigma_f^0 \frac{s{\Gamma_{\mathrm{Z}}}^2}{(s - {M_{\mathrm{Z}}}^2)^2 + s^2{\Gamma_{\mathrm{Z}}}^2/{M_{\mathrm{Z}}}^2} + [\gamma] + [\gamma/\mathrm{Z}]$$

$$\sigma_f^0 = 12\pi\Gamma_{\mathrm{e}}\Gamma_f/{M_{\mathrm{Z}}}^2{\Gamma_{\mathrm{Z}}}^2$$

- Radiative corrections important especially for peak cross-section
- Photon and interference terms small

$$\Gamma_f = \frac{G_\mu {M_{\mathrm{Z}}}^3}{6\pi\sqrt{2}}(v_f^2 + a_f^2)N_{\mathrm{col}}$$

$$\Gamma_{\mathrm{Z}} = \Gamma_{\mathrm{had}} + 3\Gamma_{\ell\ell} + \Gamma_{\mathrm{inv}} = \sum \Gamma_{\mathrm{q\bar{q}}} + 3\Gamma_{\ell\ell} + 3\Gamma_{\nu\nu}$$

Cross-section measurements

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	$0.3 \sim 1.5\%$	$0.002 \sim 0.006$
$\mathcal{L}^{\mathrm{exp.}}$	$0.08 \sim 0.21\%$	–

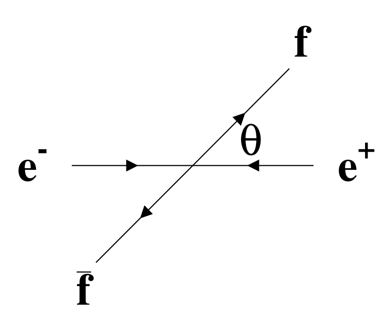
Luminosity Measurement

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

Energy Calibration

- LEP energy calibration improved to a few MeV in 1993 by Resonant Depolarization technique
- Intrinsic precision $<$1 MeV at time of measurement
- Energy variation with Earth tides, magnet temperature...
- Extrapolate using beam orbit position. Residual scatter 6.9 (2.8) MeV at peak–2 (peak+2)

Forward-Backward Asymmetries



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1+\cos^2\theta+\frac{8}{3}A_{\mathrm{FB}}^{f}\;\cos\theta$$

$$A_{\mathrm{FB}}^{f} = \frac{\sigma_{\mathrm{F}}\;-\sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}}\;+\sigma_{\mathrm{B}}}$$

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

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

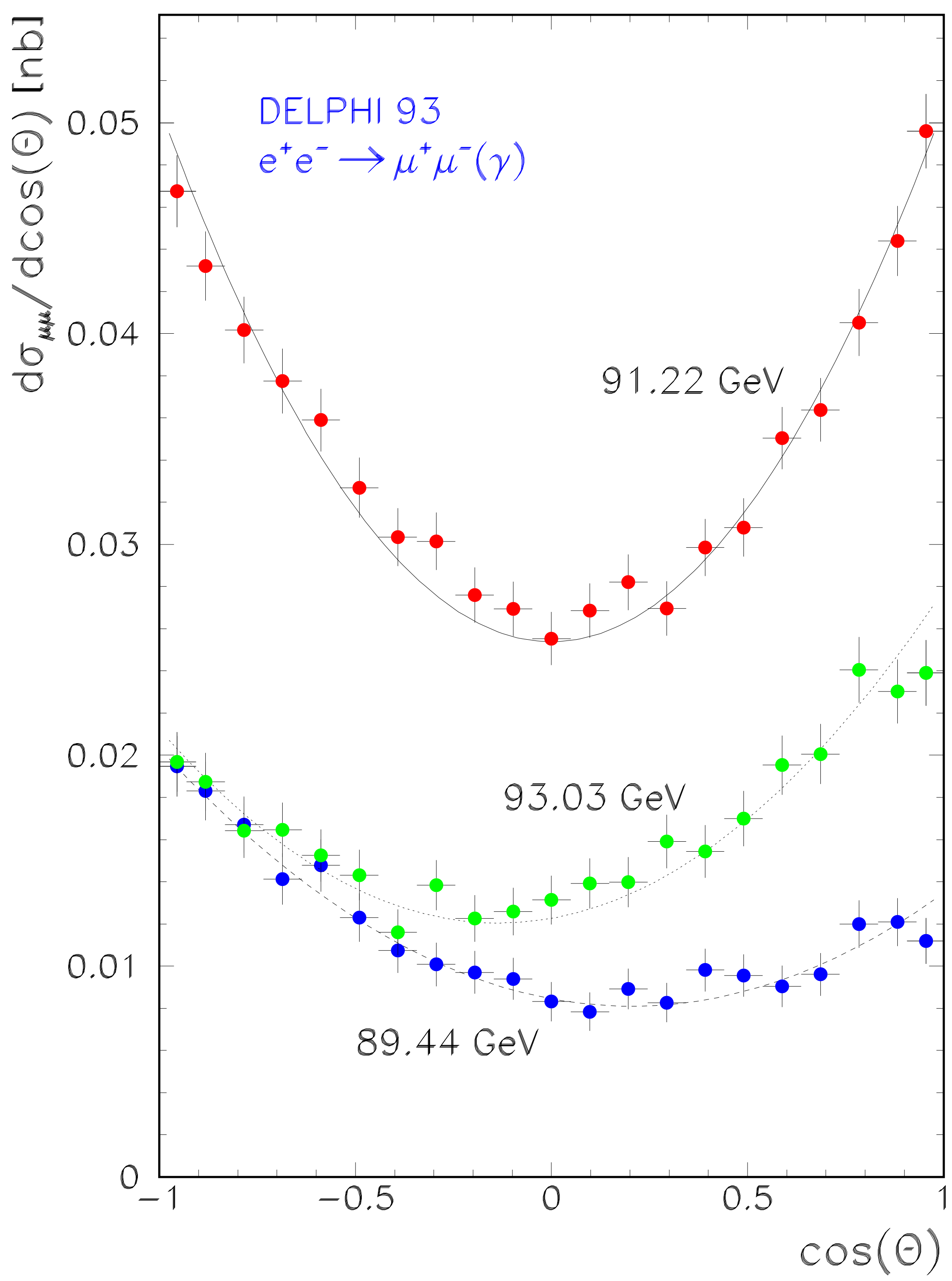
$$\frac{v_f}{a_f} = (1 - 4|Q_f|\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\,f})$$

Leptons define $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$. Small corrections for quarks.

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

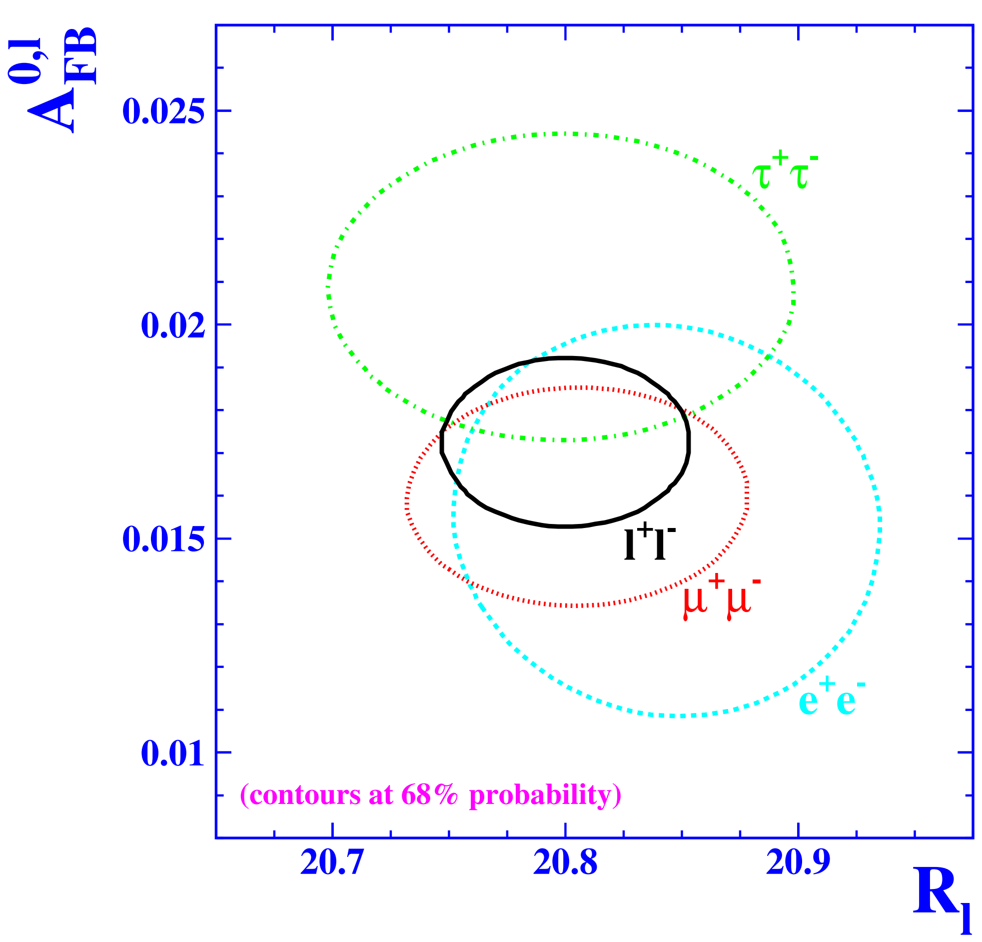
($\Longrightarrow A_{\mathrm{FB}}^{\mathrm{b}}$ sensitive to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$)

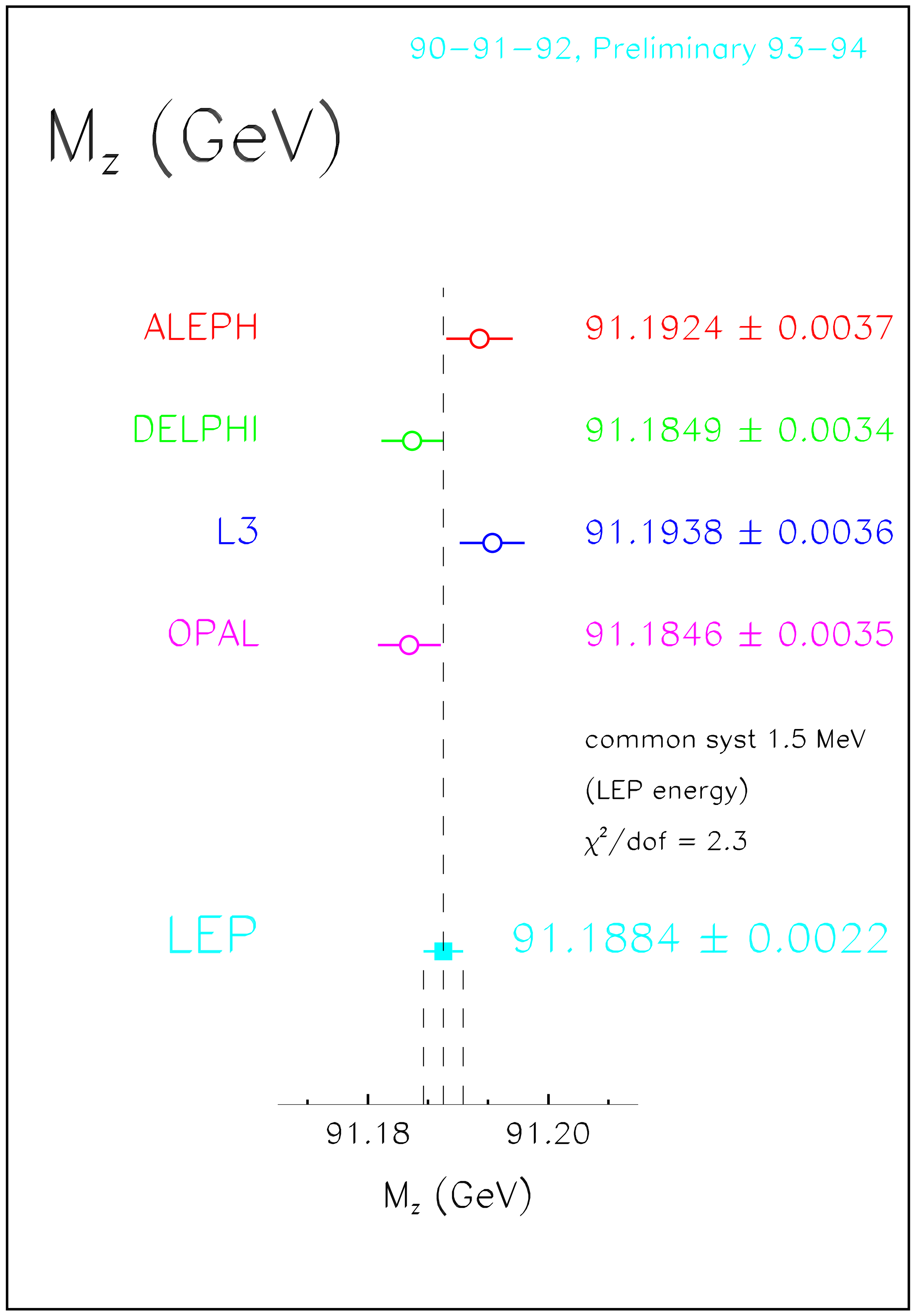
Lepton Forward-Backward Asymmetry



Combined lineshape results

- Choose 9 variables with small correlations to combine cross-sections and lepton $A_{\rm FB}$:
  $M_{\rm Z}$, $\Gamma_{\rm Z}$, $\sigma^{\rm pole}_{\rm had}$,
  $R_{\rm e} \equiv \Gamma_{\rm had}/\Gamma_{\rm ee}$, R_μ, R_τ,
  $A^{0,\,{\rm e}}_{\rm FB}$, $A^{0,\,\mu}_{\rm FB}$, $A^{0,\,\tau}_{\rm FB}$
- Account for common errors (LEP energy, Lumi. theory)
- Check for lepton universality. Reduce to 5 variables.
- Also extract $\Gamma_{\rm inv}/\Gamma_{\ell\ell} = 5.956 \pm 0.031$
  Taking $(\Gamma_\nu/\Gamma_{\ell\ell})_{\rm SM} = 1.991 \pm 0.001$
  $\Longrightarrow N_\nu = 2.991 \pm 0.016$

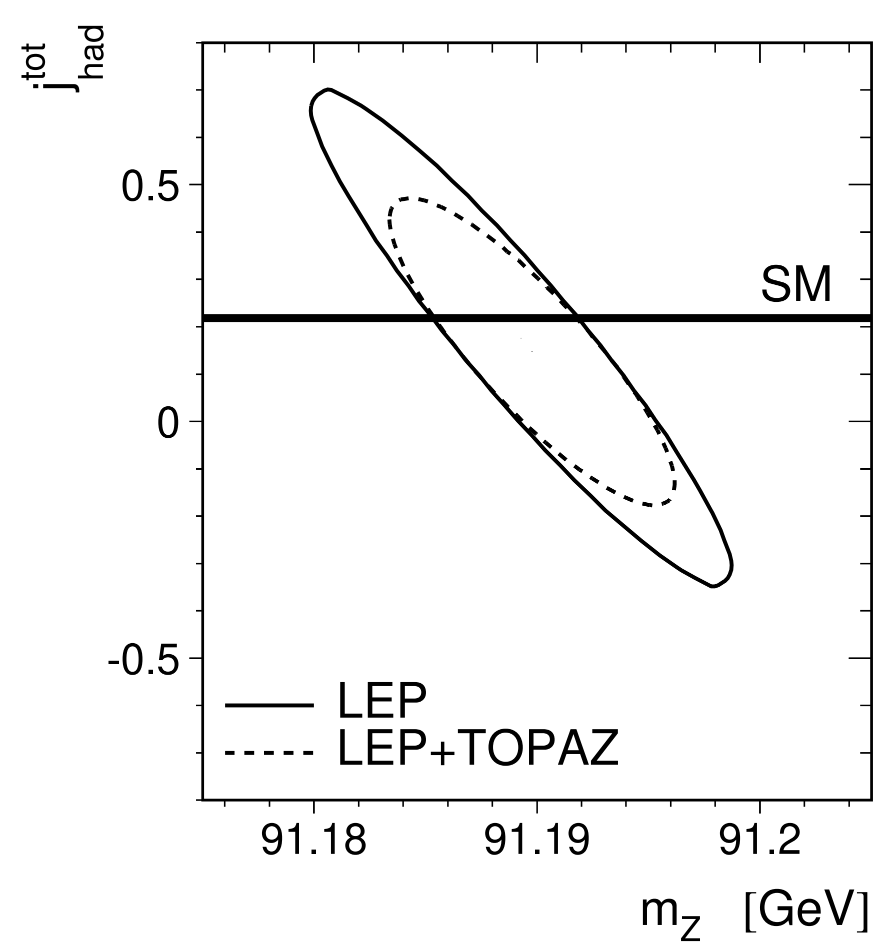


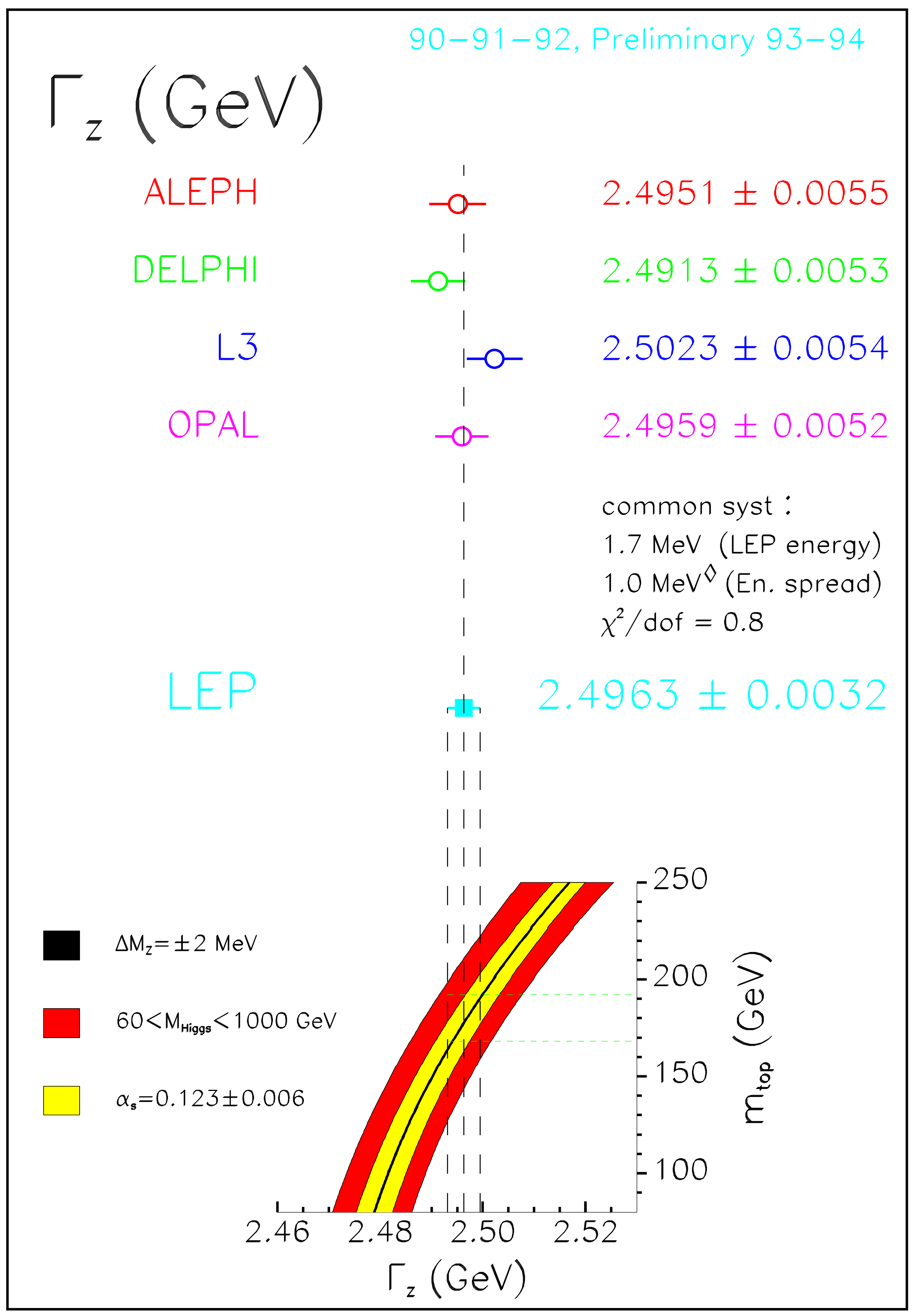

90−91−92, Preliminary 93−94
M_z (GeV)
ALEPH
91.1924 ± 0.0037
DELPHI
91.1849 ± 0.0034
L3
91.1938 ± 0.0036
OPAL
91.1846 ± 0.0035
common syst 1.5 MeV
(LEP energy)
χ²/dof = 2.3
LEP
91.1884 ± 0.0022
91.18
91.20
M_z (GeV)

$\gamma - \mathrm{Z}$ Interference

$\gamma - \mathrm{Z}$ interference term $\mathrm{j_{had}}$ fixed to SM value in standard fits – predicted $\mathrm{j_{had}} = 0.22 \pm 0.03$.

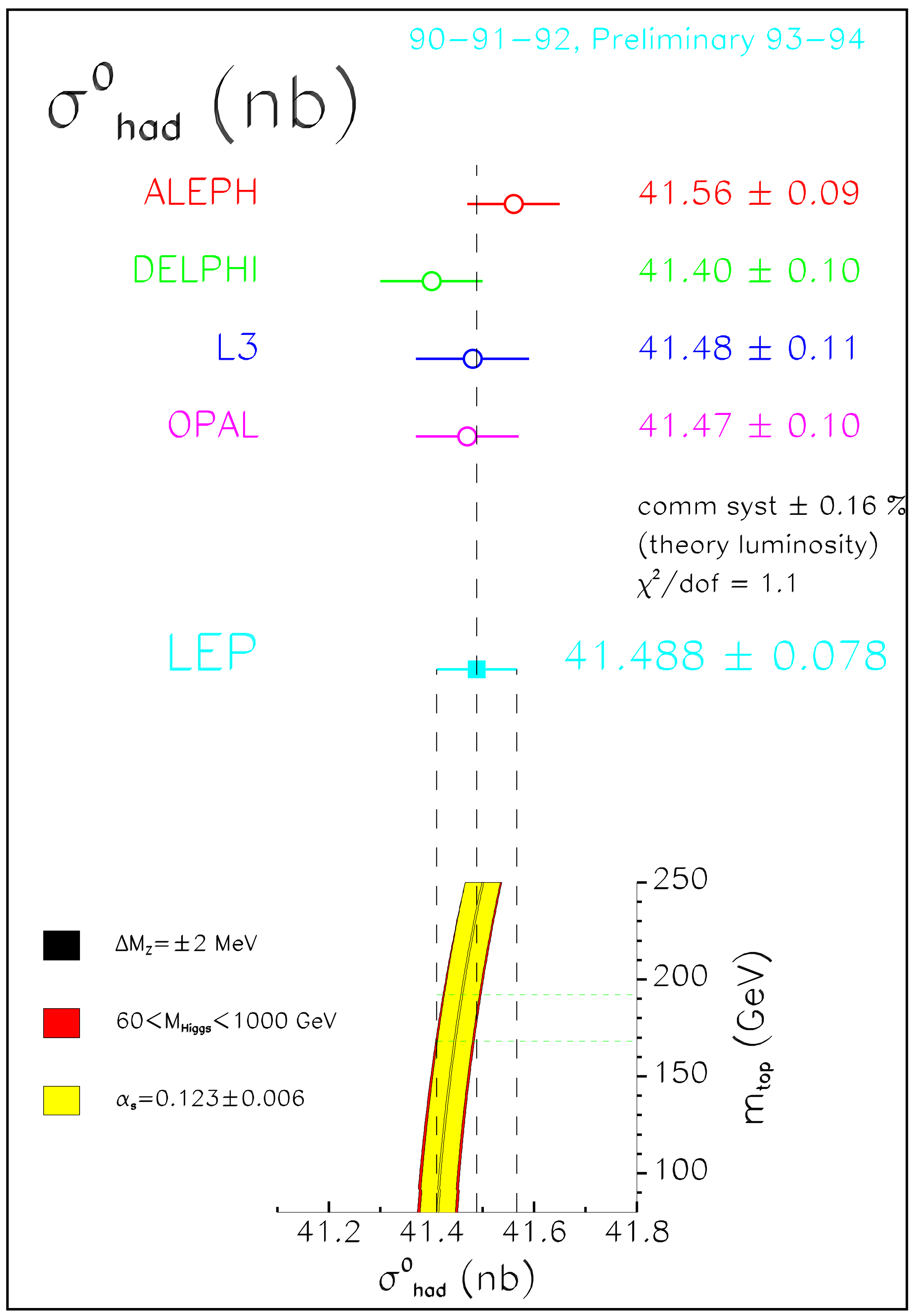
	δM_Z (MeV)	$\mathrm{j_{had}}$
$\mathrm{j_{had}}$ fixed	2.2	0.22
fit to LEP	6.2	0.18 ± 0.34
fit to LEP + TOPAZ	4.2	0.15 ± 0.21

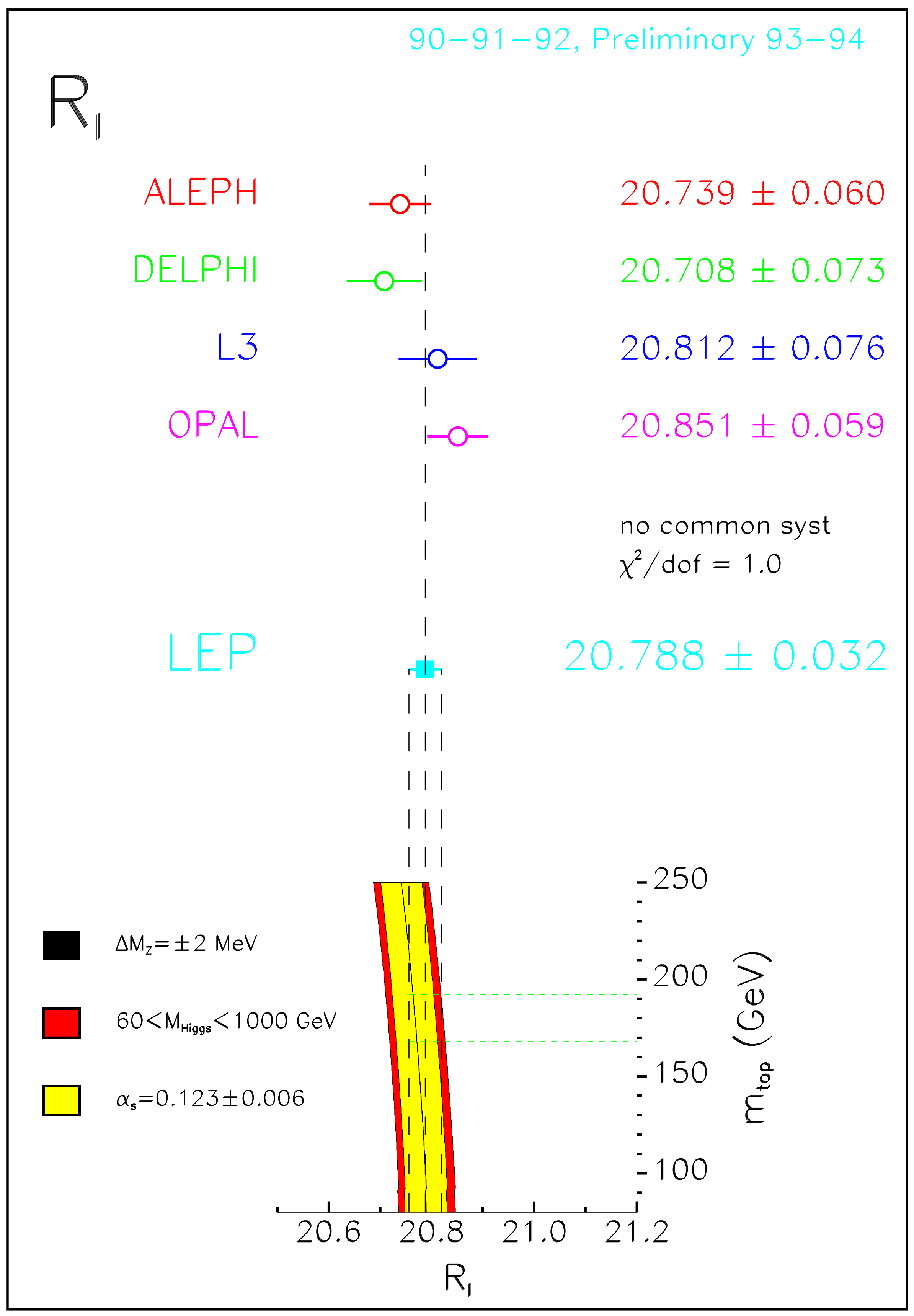




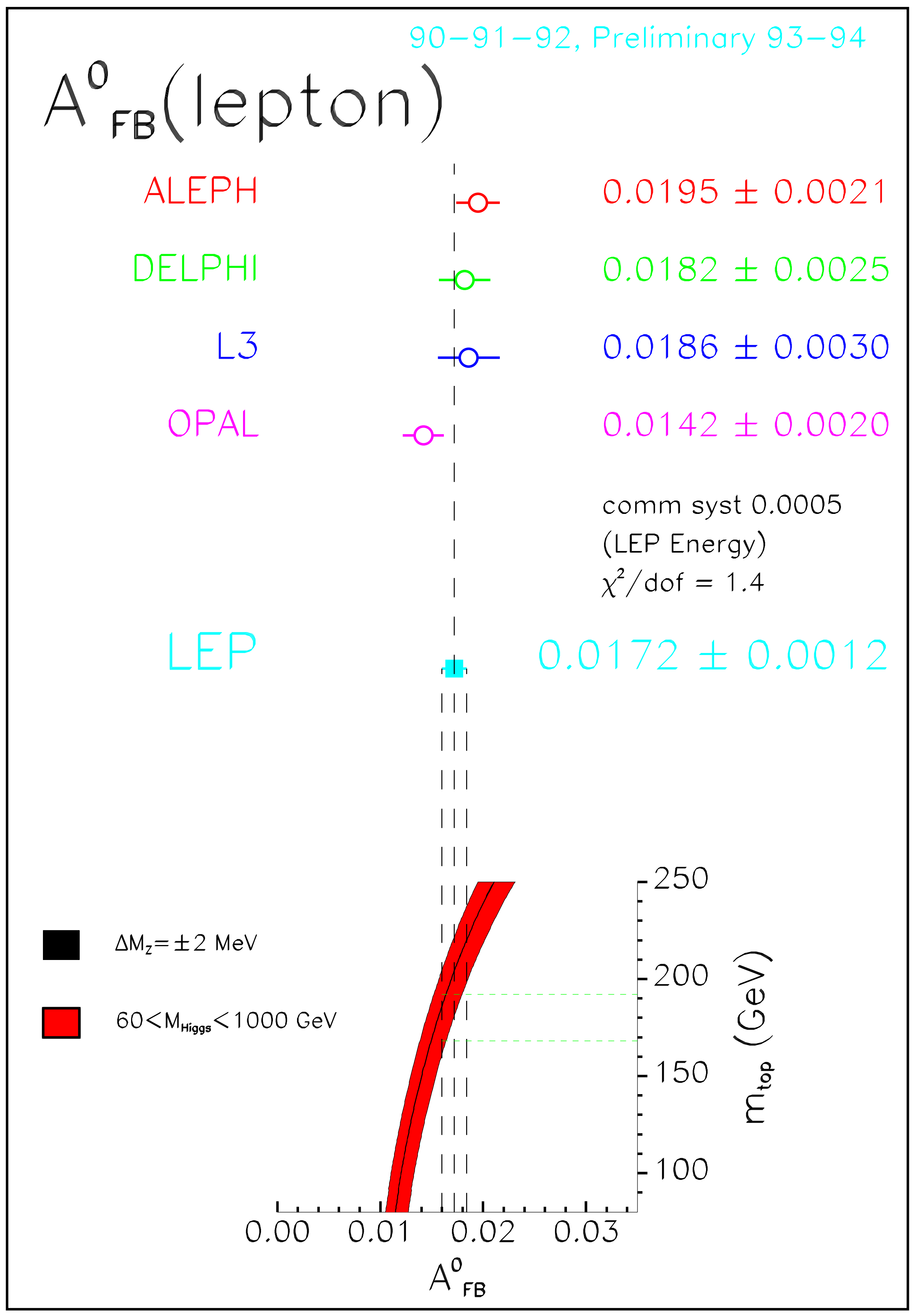
◊ not included in the error of each experiment

Standard Model prediction from ZFITTER 4.9


90−91−92, Preliminary 93−94
σ^0_{had} (nb)
ALEPH
41.56 ± 0.09
DELPHI
41.40 ± 0.10
L3
41.48 ± 0.11
OPAL
41.47 ± 0.10
comm syst ± 0.16 %
(theory luminosity)
χ^2/dof = 1.1
LEP
41.488 ± 0.078
ΔM_Z=±2 MeV
60<M_{Higgs}<1000 GeV
α_s=0.123±0.006
250
200
150
100
m_{top} (GeV)
41.2
41.4
41.6
41.8
σ^0_{had} (nb)



90−91−92, Preliminary 93−94
R_l
ALEPH
20.739 ± 0.060
DELPHI
20.708 ± 0.073
L3
20.812 ± 0.076
OPAL
20.851 ± 0.059
no common syst
χ²/dof = 1.0
LEP
20.788 ± 0.032
ΔM_Z=±2 MeV
60<M_Higgs<1000 GeV
α_s=0.123±0.006
250
200
150
100
m_top (GeV)
20.6
20.8
21.0
21.2
R_l



90−91−92, Preliminary 93−94
A0FB(lepton)
ALEPH
0.0195 ± 0.0021
DELPHI
0.0182 ± 0.0025
L3
0.0186 ± 0.0030
OPAL
0.0142 ± 0.0020
comm syst 0.0005
(LEP Energy)
χ²/dof = 1.4
LEP
0.0172 ± 0.0012
ΔMZ=±2 MeV
60<MHiggs<1000 GeV
250
200
150
100
mtop (GeV)
0.00
0.01
0.02
0.03
A0FB

Polarised Asymmetries

If initial state polarization is known (SLC electron beam) define $\sigma_{\rm L} = \sigma(\mathrm{e^+e^-_L} \to \mathrm{Z} \to X)$:

$$A_{\rm LR} = \frac{\sigma_{\rm L} - \sigma_{\rm R}}{\sigma_{\rm L} + \sigma_{\rm R}} = \mathcal{A}_{\rm e}$$

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

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

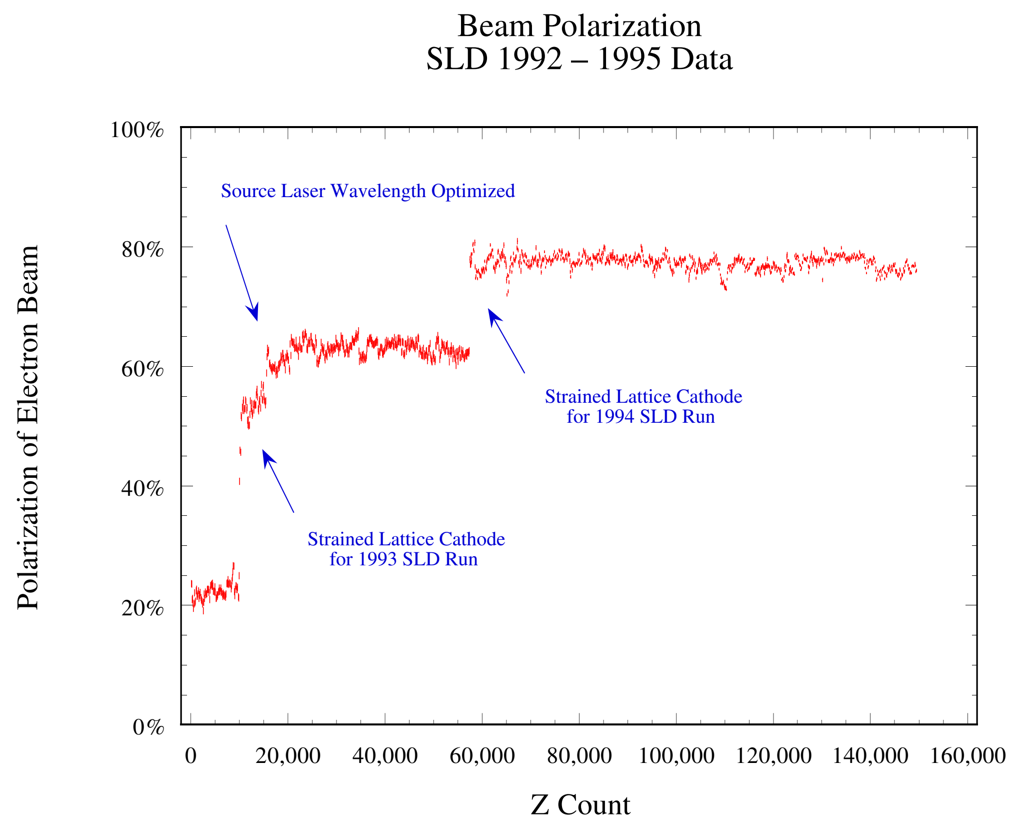
$$\frac{[\sigma_{\rm L}(\mathrm{F}) - \sigma_{\rm L}(\mathrm{B})] - [\sigma_{\rm R}(\mathrm{F}) - \sigma_{\rm R}(\mathrm{B})]}{\sigma_{\rm L}(\mathrm{F}) + \sigma_{\rm L}(\mathrm{B}) + [\sigma_{\rm R}(\mathrm{F}) + \sigma_{\rm R}(\mathrm{B})]} = \frac{3}{4}\mathcal{P}_{\rm e}\mathcal{A}_{\rm q}$$

Analysing final-state polarization of $\tau^+\tau^-$at LEP allows both $\mathcal{A}_{\rm e}$ and $\mathcal{A}_\tau$ to be measured:

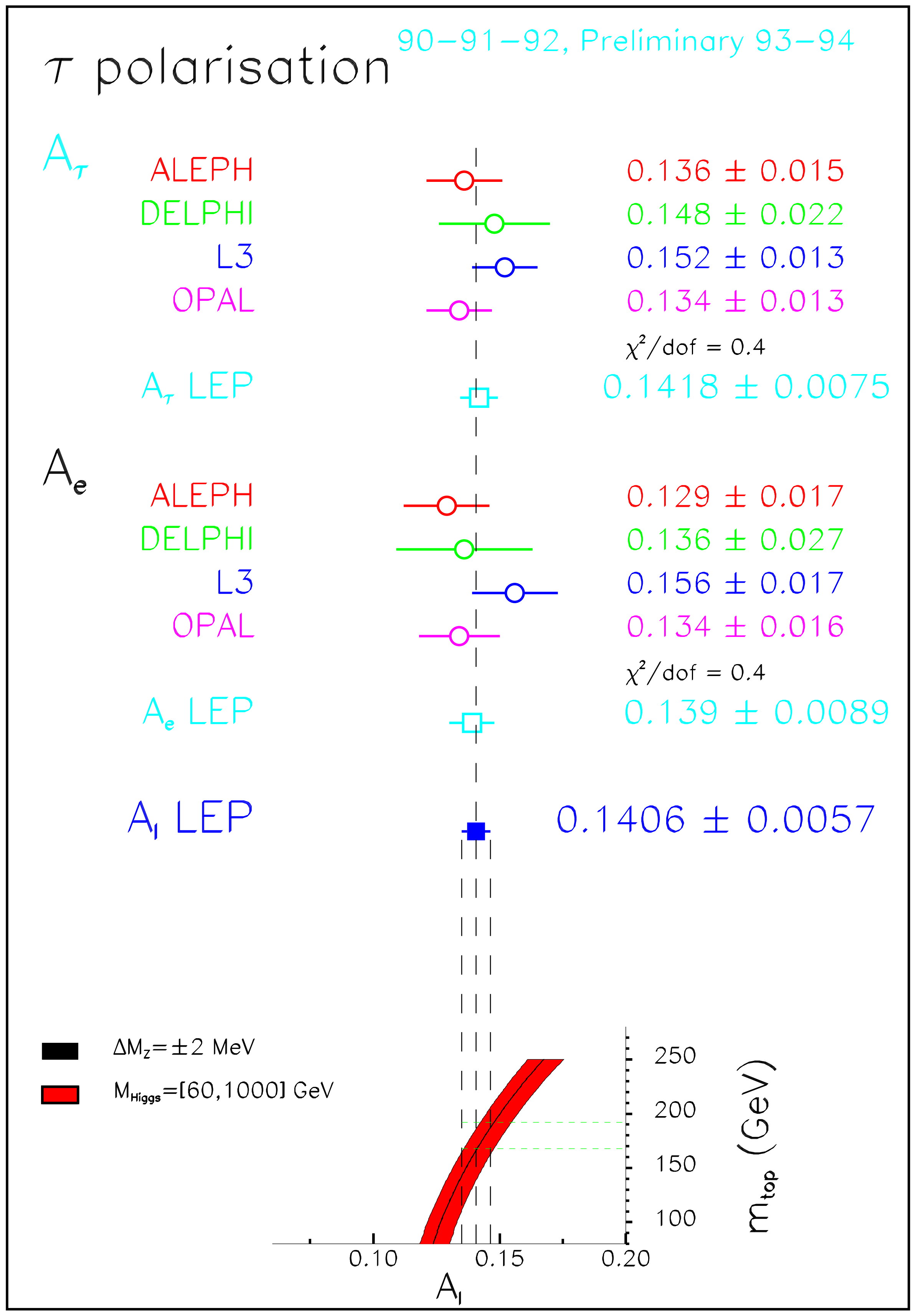
$$\mathcal{P}_\tau = \frac{\sigma_{\rm L} - \sigma_{\rm R}}{\sigma_{\rm L} + \sigma_{\rm R}}$$

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

SLD Measurement of A_{LR}



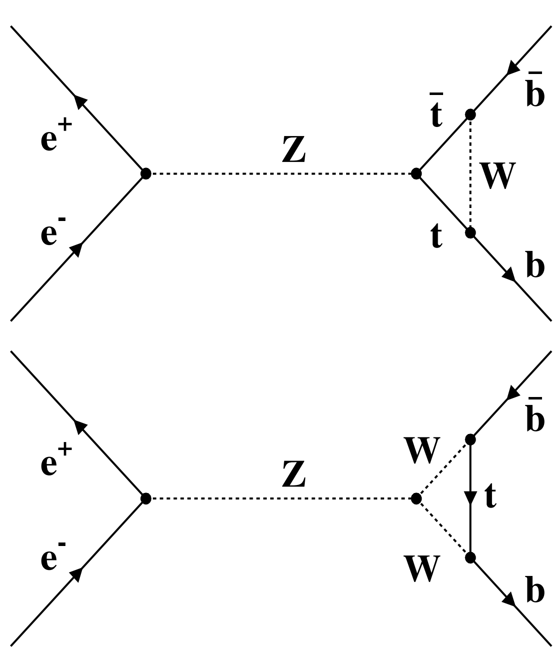
- Can use all visible Z decay modes.
  SLD exclude $\mathrm{e^+e^-}$ (t-channel)
- Strained GaAs Photocathode $\Longrightarrow$ source of polarized electrons - randomly chosen polarization for each bunch
- Polarization measured by Compton Polarimeter after interaction point
- 1994-95 data: $\langle \mathcal{P}_{\mathrm{e}}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

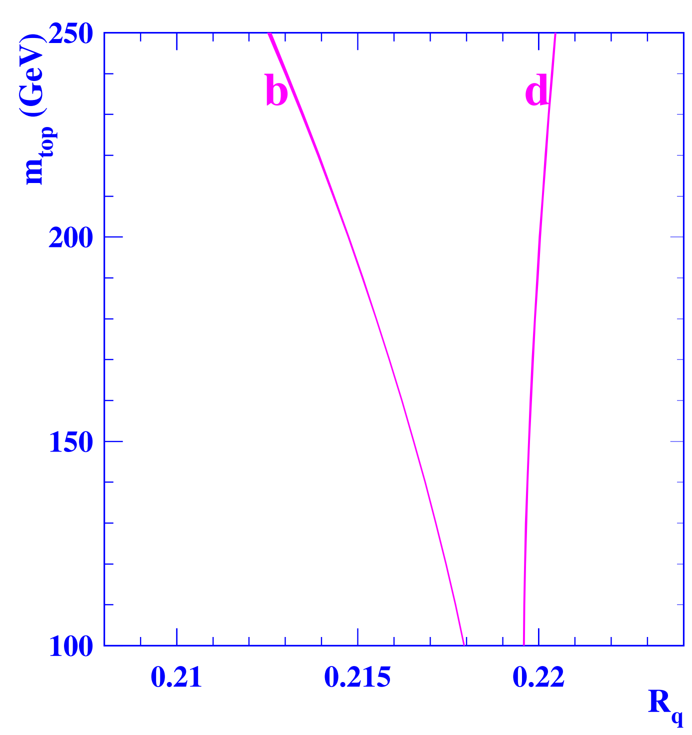


τ polarisation
90-91-92, Preliminary 93-94
A_τ
ALEPH 0.136 ± 0.015
DELPHI 0.148 ± 0.022
L3 0.152 ± 0.013
OPAL 0.134 ± 0.013
χ^2/dof = 0.4
A_τ LEP 0.1418 ± 0.0075
A_e
ALEPH 0.129 ± 0.017
DELPHI 0.136 ± 0.027
L3 0.156 ± 0.017
OPAL 0.134 ± 0.016
χ^2/dof = 0.4
A_e LEP 0.139 ± 0.0089
A_l LEP 0.1406 ± 0.0057
ΔM_Z=±2 MeV
M_{Higgs}=[60,1000] GeV
0.10
0.15
0.20
A_l
250
200
150
100
m_{top} (GeV)

Results with heavy quarks

- Try to separate quark flavours to measure partial widths and asymmetries
- b and c tagged by lifetime, semileptonic decays, high mass (fragmentation, p_{T}, event shapes)
- A_{FB} needs quark charge and direction (thrust axis).
- Higgs and top mass dependence from propagator corrections cancel in $R_{\mathrm{Q}} \equiv \Gamma_{\mathrm{Q\bar{Q}}}/\Gamma_{\mathrm{had}}$.
- $\mathrm{Zb\overline{b}}$ vertex gives top mass dependence of R_{b}.
- New physics in $\mathrm{Zb\overline{b}}$ vertex (coupling to mass) ??





Double-Tagging Method for R_b

- b and $\overline{\mathrm{b}}$ typically back-to-back.
- Look for b tag in each thrust hemisphere.
- Count tagged hemispheres N_t
  and double-tagged events N_tt

$$\frac{N_\mathrm{t}}{2N_\mathrm{had}} = \varepsilon^\mathrm{b} R_\mathrm{b} + \varepsilon^\mathrm{c} R_\mathrm{c} + \varepsilon^\mathrm{uds}(1 - R_\mathrm{b} - R_\mathrm{c})$$
$$\frac{N_\mathrm{tt}}{N_\mathrm{had}} = \mathcal{C}_\mathrm{b}(\varepsilon^\mathrm{b})^2 R_\mathrm{b} + (\varepsilon^\mathrm{c})^2 R_\mathrm{c} + (\varepsilon^\mathrm{uds})^2(1 - R_\mathrm{b} - R_\mathrm{c})$$

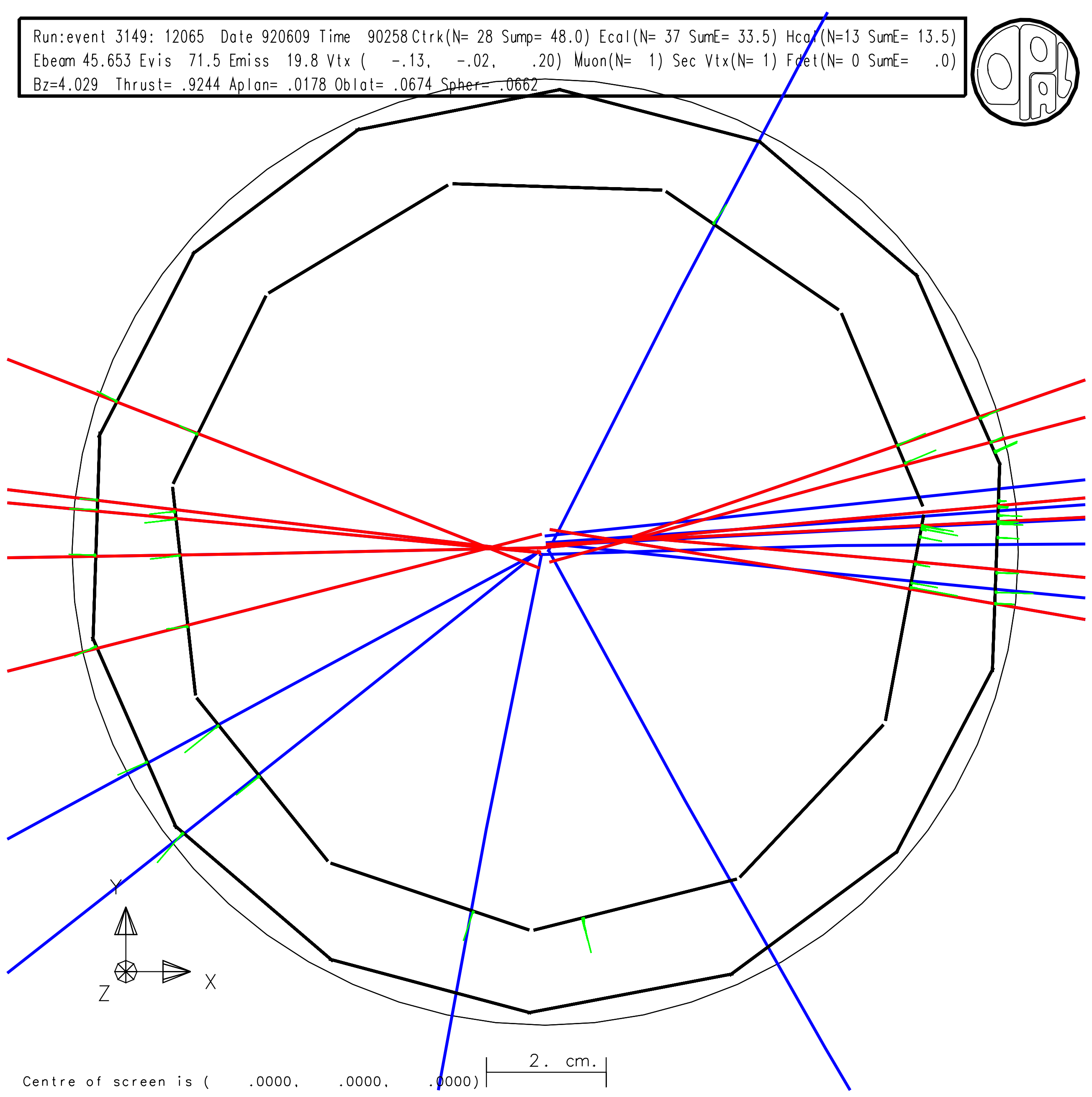
- Solve for R_b and ε^b $\Longrightarrow$ ε^b measured from data
- Input R_c, $\mathcal{C}_\mathrm{b}$, ε^c, ε^uds
- Statistical error dominated by N_tt
- Systematic error dominated by ε^c, $\mathcal{C}_\mathrm{b}$
- R_c dependence handled in averaging procedure
- Lifetime tags dominate (Si micro-vertex detectors)

	ε^b	b purity
ALEPH	26%	96%
DELPHI	21%	92%
OPAL*	23%	94%
SLD	31%	94%

(* includes high-p_T lepton tag)

Lifetime Tag

	B	D^+	D^0
Lifetime (ps)	1.6	1.0	0.4
$\langle x_E \rangle$	0.7	0.5	0.5
Charged multiplicity	5.5	2.2	2.2

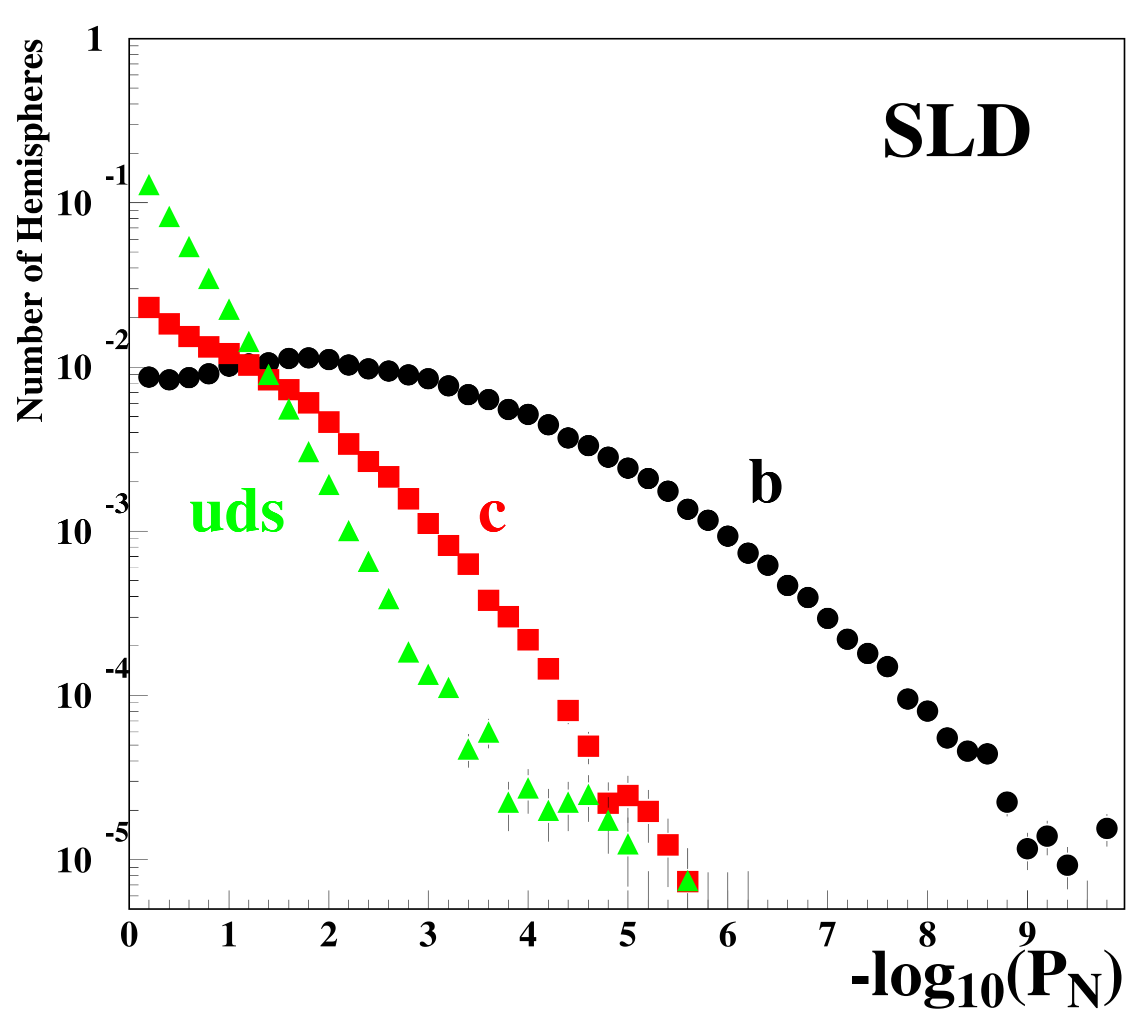


Impact Parameter Probability b Tag

Used by ALEPH, DELPHI, SLD for R_b

- Construct "no-lifetime" probability for each track from impact parameter w.r.t. primary vertex
- Use resolution function measured from data from tracks with negative impact parameter
- Construct joint probability for "no-lifetime" from all tracks in hemisphere with positive impact parameter

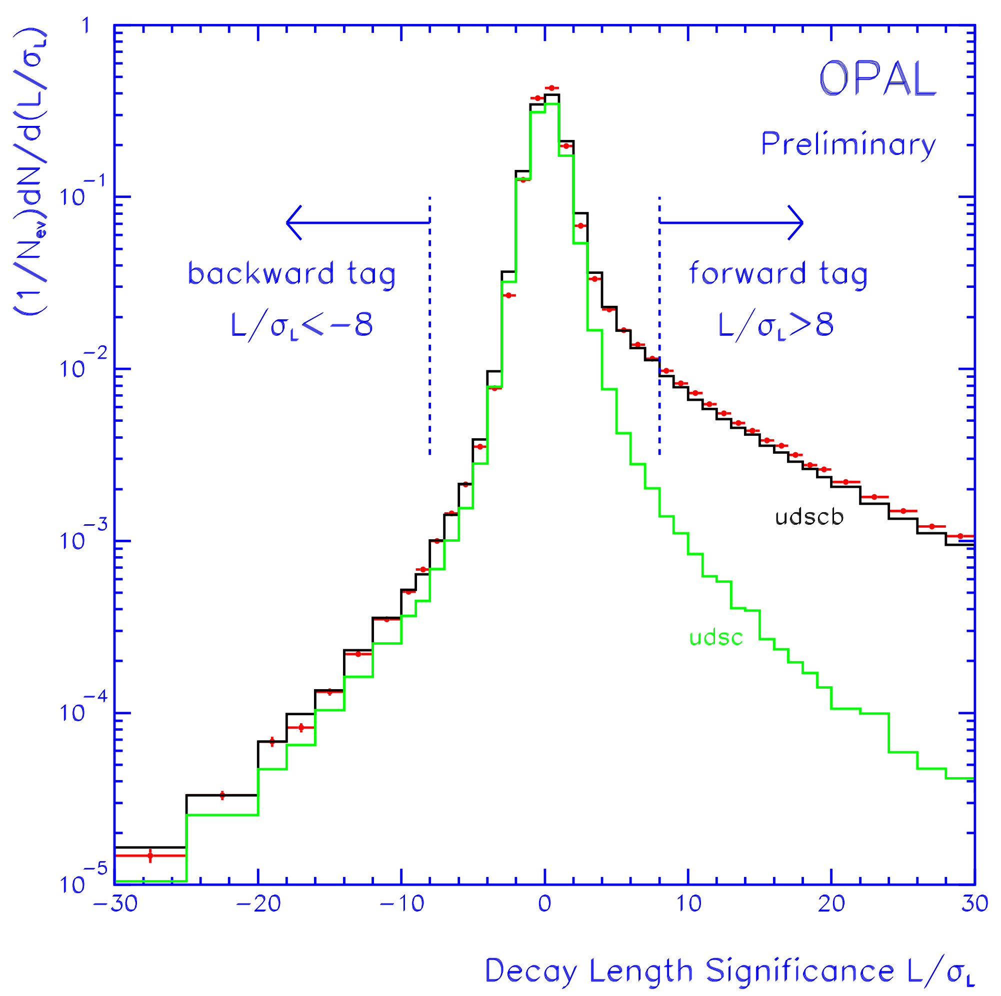
⇐ No-lifetime   Lifetime ⇒



Secondary Vertex b Tag

Used by OPAL for R_{b}

- Reconstruct secondary vertices from tracks in jet
- Construct physics-signed decay length significance: (distance primary to secondary vertex) / error



- Folded tag: subtract statistically backwards vertices from forwards vertices $\Longrightarrow$ reduced resolution uncertainties

Double-tag systematic uncertainties

Hemisphere correlations

- Evaluated from combination of MC and data
- Gluon radiation $\Longrightarrow p(\mathrm{b})$ and $p(\overline{\mathrm{b}})$ correlated.
  Hard gluon $\Longrightarrow \mathrm{b}$ and $\overline{\mathrm{b}}$ in same hemisphere
- Geometry: detector non-uniformity, primary vertex effects

Charm properties

- Up to factor 4 difference in lifetimes $\Longrightarrow$ relative fractions of different species important (Taken from CLEO and ARGUS measurements - new LEP measurements of fractions consistent and competitive)
- MARK III measurements for charged decay multiplicity of D^0,D^+,D_s^+, and for $B(\mathrm{D} \to \mathrm{K}^0(\mathrm{or}\ \overline{\mathrm{K}}^0)X)$
- Error of $\pm$0.5 about JETSET prediction for Λ_c^+ decay multiplicity

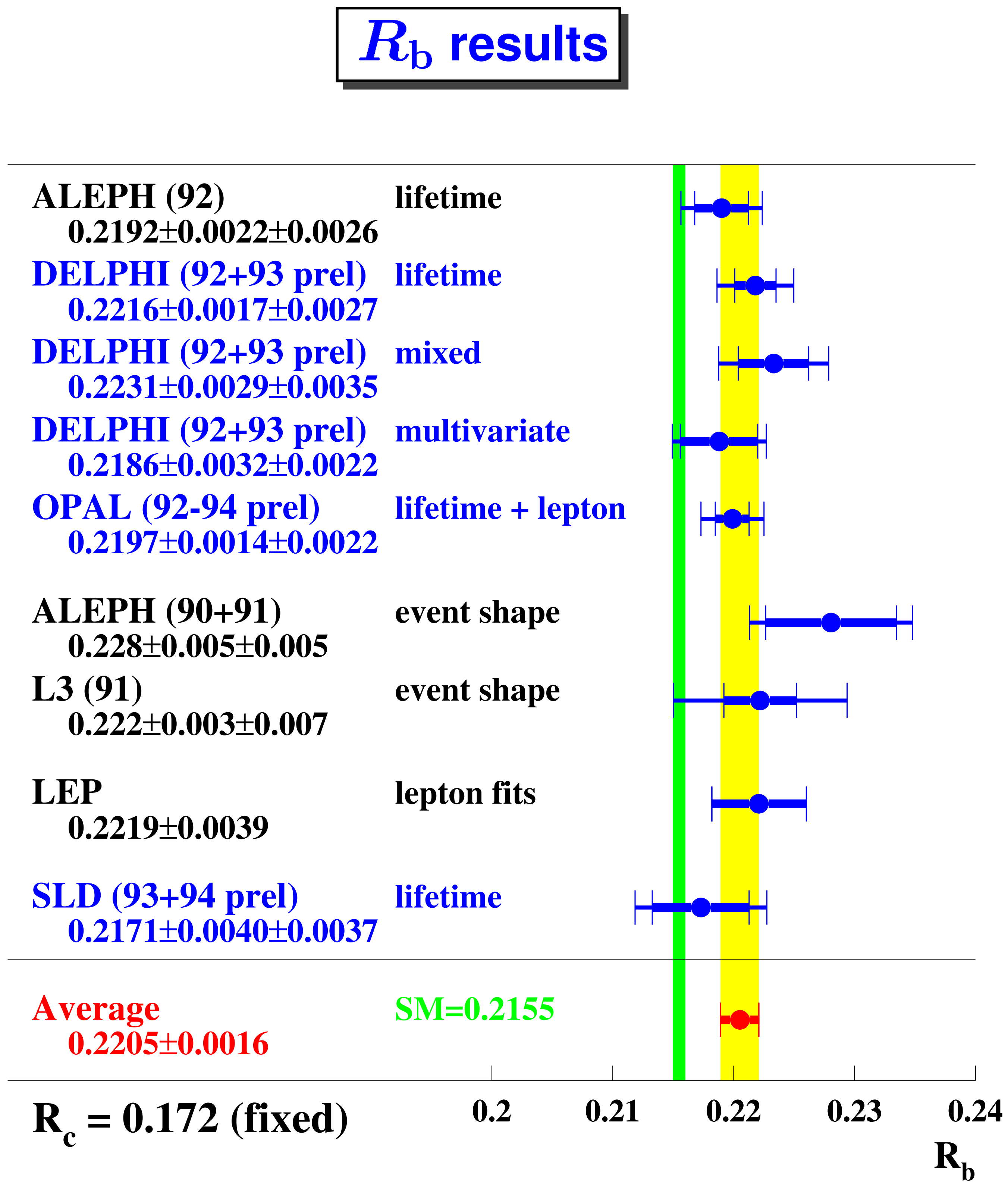
Gluon Splitting ($n_{\mathrm{g}\to\mathrm{c}\overline{\mathrm{c}}}$, $n_{\mathrm{g}\to\mathrm{b}\overline{\mathrm{b}}}$ per hadronic Z^0 decay)

- Theoretical prediction: $n_{\mathrm{g}\to\mathrm{c}\overline{\mathrm{c}}} = (1.3 \pm 0.4)\%$
  $n_{\mathrm{g}\to\mathrm{b}\overline{\mathrm{b}}} = (0.18 \pm 0.05)\%$
- Measured by OPAL: $n_{\mathrm{g}\to\mathrm{c}\overline{\mathrm{c}}} = (2.38 \pm 0.48)\%$
- Used for R_b, JETSET $\pm$50%: $n_{\mathrm{g}\to\mathrm{c}\overline{\mathrm{c}}} \simeq 1.6\%$
  $n_{\mathrm{g}\to\mathrm{b}\overline{\mathrm{b}}} \simeq 0.16\%$

R_b from Double-Tag Total Errors

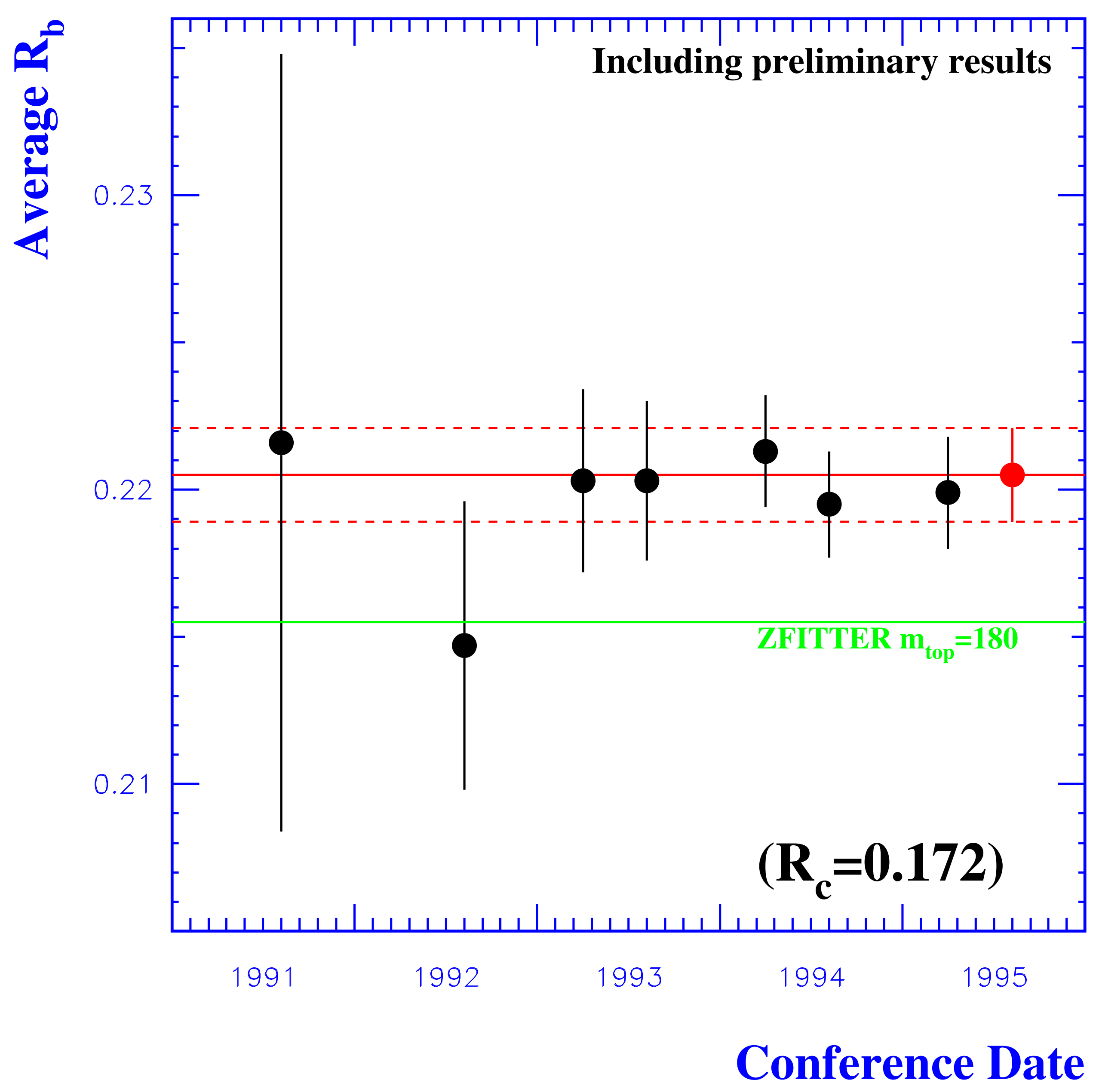
- Tune tagging algorithm to minimise total error:
  Systematic error (charm contamination ε^c, $\mathcal{C}_b$)
  Statistical error (N_{tt})

	ALEPH	DELPHI	OPAL	SLD
efficiency correlation	0.0016	0.0011	0.0007	0.0010
c production fractions	0.0009	0.0016	0.0009	0.0013
c decay multiplicity	0.0006	0.0010	0.0010	0.0018
c lifetimes	0.0005	0.0006	0.0004	0.0003
c fragmentation	0.0001	0.0005	0.0008	0.0012
gluon splitting	0.0003	0.0003	0.0005	0.0004
detector/MC statistics	0.0015	0.0009	0.0012	0.0025
light quark bkgd	0.0002	0.0006	0.0003	0.0001
total systematic	0.0026	0.0027	0.0022	0.0037
statistical	0.0022	0.0017	0.0014	0.0040



R_b results
ALEPH (92) lifetime
0.2192±0.0022±0.0026
DELPHI (92+93 prel) lifetime
0.2216±0.0017±0.0027
DELPHI (92+93 prel) mixed
0.2231±0.0029±0.0035
DELPHI (92+93 prel) multivariate
0.2186±0.0032±0.0022
OPAL (92-94 prel) lifetime + lepton
0.2197±0.0014±0.0022
ALEPH (90+91) event shape
0.228±0.005±0.005
L3 (91) event shape
0.222±0.003±0.007
LEP lepton fits
0.2219±0.0039
SLD (93+94 prel) lifetime
0.2171±0.0040±0.0037
Average
0.2205±0.0016
SM=0.2155
R_c = 0.172 (fixed)
0.2
0.21
0.22
0.23
0.24
R_b

Evolution of R_b Measurement

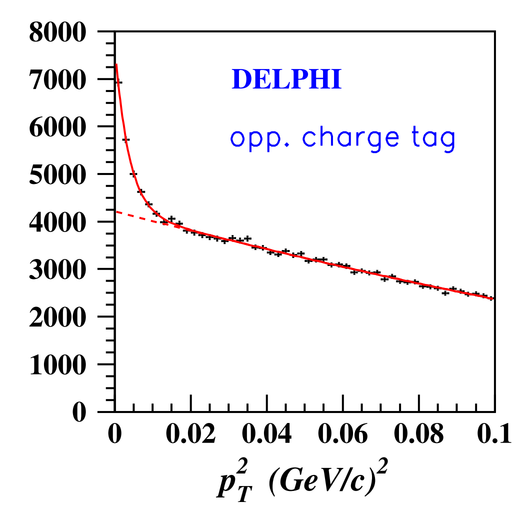


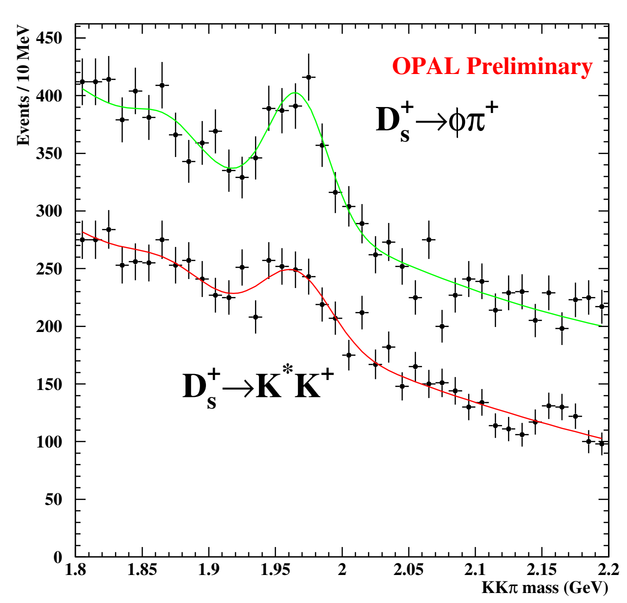
Charm partial width

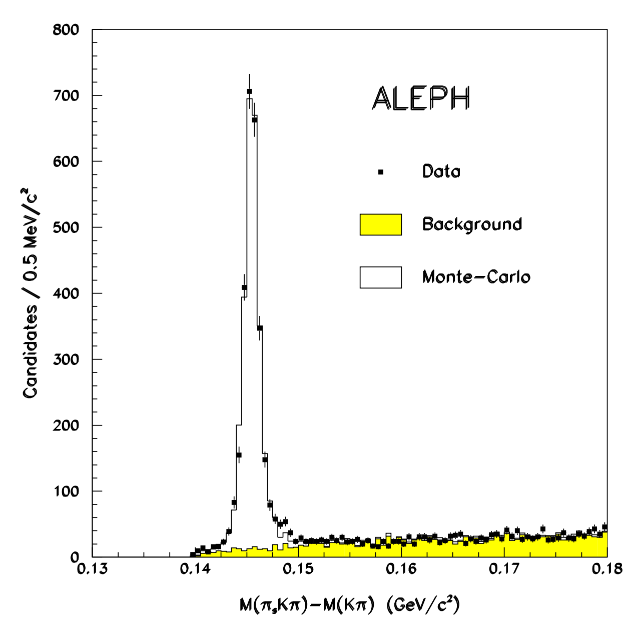
- Charm from $\mathrm{Z} \longrightarrow \mathrm{c\overline{c}}$, $\mathrm{Z} \longrightarrow \mathrm{b\overline{b}}$, $\mathrm{g} \longrightarrow \mathrm{c\overline{c}(b\overline{b})}$.
- Statistical separation by lifetime, $\langle x_E \rangle$, event shapes...

Charm tags:

- Slow π from $\mathrm{D}^\star \longrightarrow \mathrm{D}^0 \pi_s$
- (Partially-) reconstructed D, $\mathrm{D}^\star$ mesons
- ℓ tag (high p low p_T)

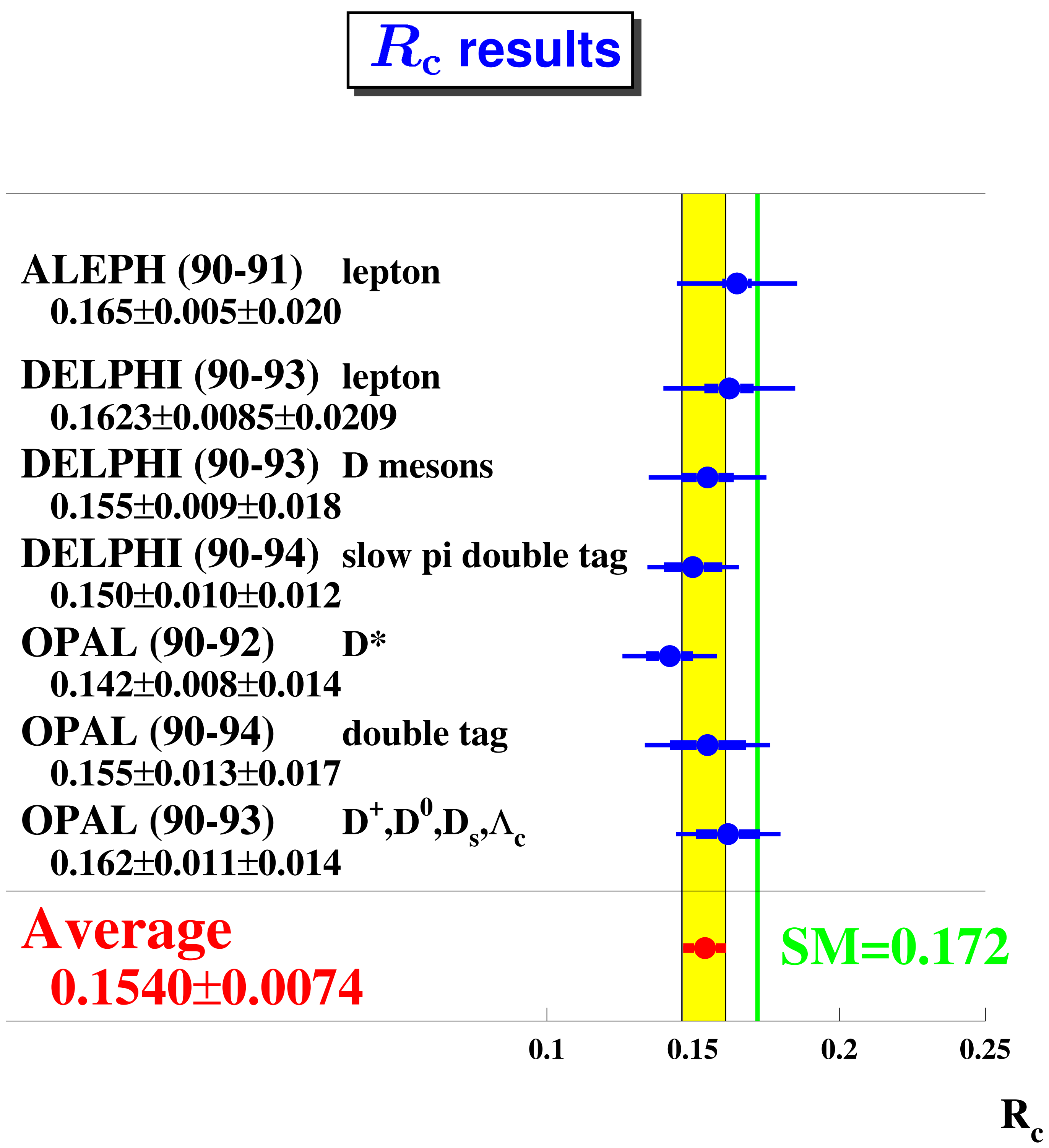






Measuring R_c:

- Single-tag - systematic errors from BR's (low energy data)
- Double-tag - either two π_s or $\mathrm{D}^\star$ opposite π_s
- Total rate of D^0, D^+, $\mathrm{D_s}$ and Λ_c saturates $\mathrm{Z} \longrightarrow \mathrm{c\overline{c}}$
- Syst errors from b/c separation, BR's, π_s efficiency.



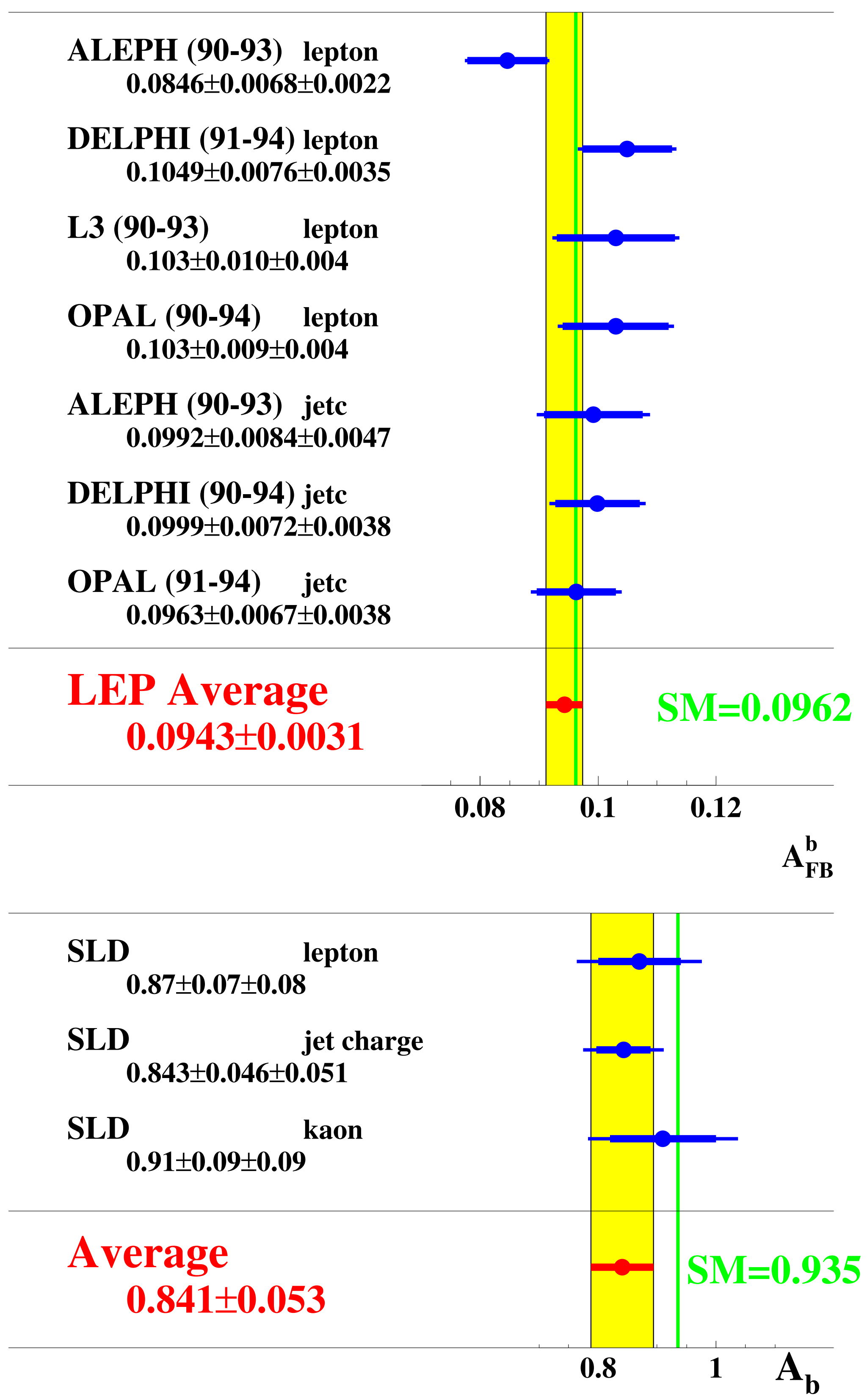
R_c results
ALEPH (90-91) lepton
0.165±0.005±0.020
DELPHI (90-93) lepton
0.1623±0.0085±0.0209
DELPHI (90-93) D mesons
0.155±0.009±0.018
DELPHI (90-94) slow pi double tag
0.150±0.010±0.012
OPAL (90-92) D*
0.142±0.008±0.014
OPAL (90-94) double tag
0.155±0.013±0.017
OPAL (90-93) D^+,D^0,D_s,Λ_c
0.162±0.011±0.014
Average
0.1540±0.0074
SM=0.172
0.1
0.15
0.2
0.25
R_c

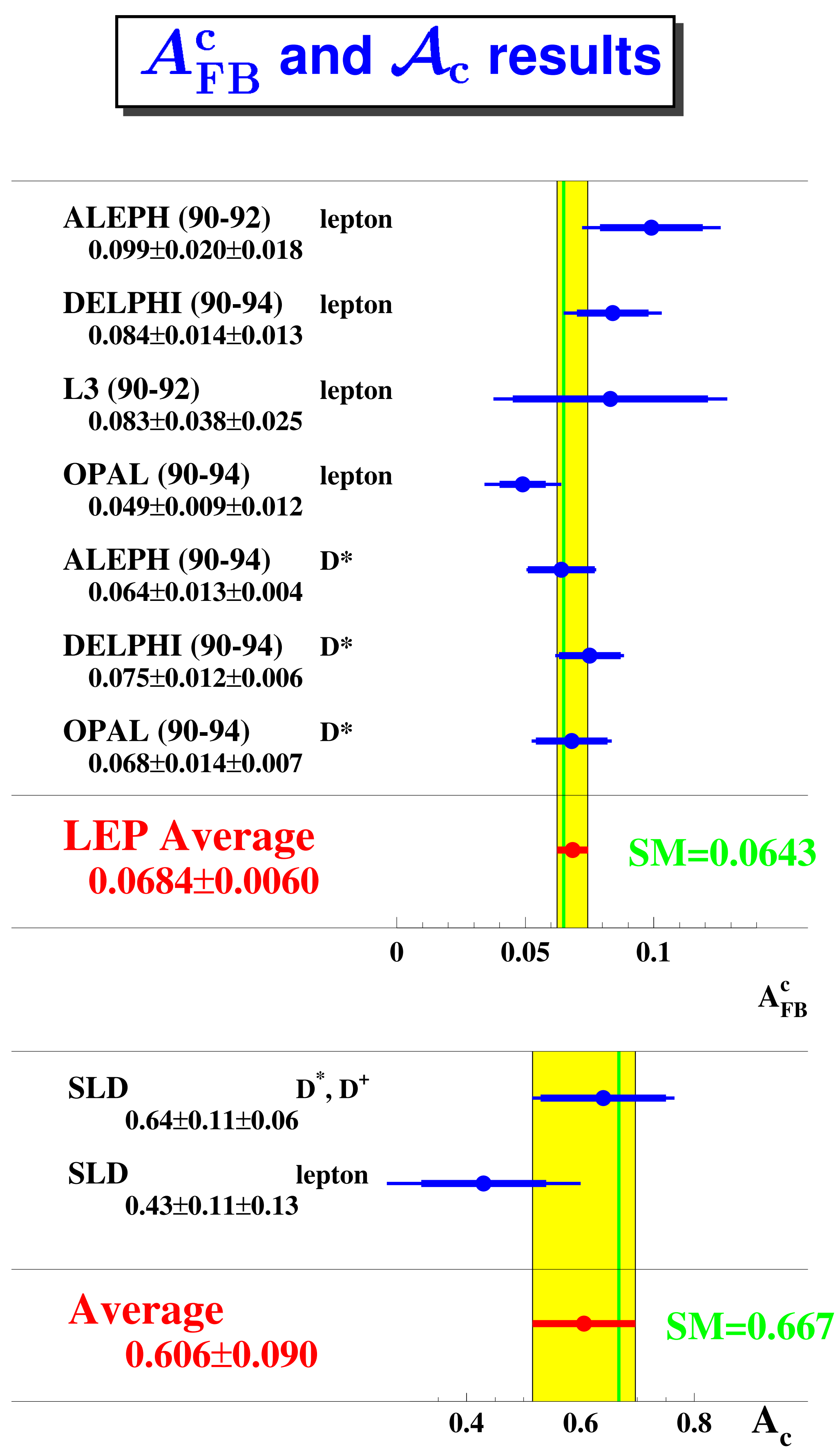
Quark asymmetry measurements

- LEP measure $A_{\mathrm{FB}}^{\mathrm{b}}, A_{\mathrm{FB}}^{\mathrm{c}}$ from F-B asymmetry
- SLD measure $\mathcal{A}_{\mathrm{b}}, \mathcal{A}_{\mathrm{c}}$ from L-R F-B asymmetry
- ℓ, D, D*, K all indicate quark charge
- Momentum weighted sum of track charges, jet-charge, gives quark charge for lifetime-tags
  Calibrate jet-charge from data $\Longrightarrow$ control systematic uncertainty
- BB mixing $\Longrightarrow A_{\mathrm{FB}}^{\mathrm{b}}(\text{obs}) = (1-2\overline{\chi})A_{\mathrm{FB}}^{\mathrm{b}}$
- $\langle \mathrm{Q_{FB}} \rangle$: measure charge-flow for all flavours. Use heavy flavour tagged samples where possible.
  Compare determinations of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

Exp.		$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
ALEPH	90-93 prel.	$0.2323 \pm 0.0010 \pm 0.0010$
DELPHI	90-91	$0.2345 \pm 0.0030 \pm 0.0027$
OPAL	91-94 prel.	$0.2326 \pm 0.0012 \pm 0.0013$
Average		0.2325 ± 0.0013

A_{FB}^{b} and $\mathcal{A}_{b}$ results





A_{FB}^{c} and $\mathcal{A}_c$ results
ALEPH (90-92) lepton
0.099±0.020±0.018
DELPHI (90-94) lepton
0.084±0.014±0.013
L3 (90-92) lepton
0.083±0.038±0.025
OPAL (90-94) lepton
0.049±0.009±0.012
ALEPH (90-94) D*
0.064±0.013±0.004
DELPHI (90-94) D*
0.075±0.012±0.006
OPAL (90-94) D*
0.068±0.014±0.007
LEP Average
0.0684±0.0060
SM=0.0643
0
0.05
0.1
A_{FB}^{c}
SLD D^*, D^+
0.64±0.11±0.06
SLD lepton
0.43±0.11±0.13
Average
0.606±0.090
SM=0.667
0.4
0.6
0.8
A_c

$\mathcal{A}_{\rm b}$ and $\mathcal{A}_{\rm c}$

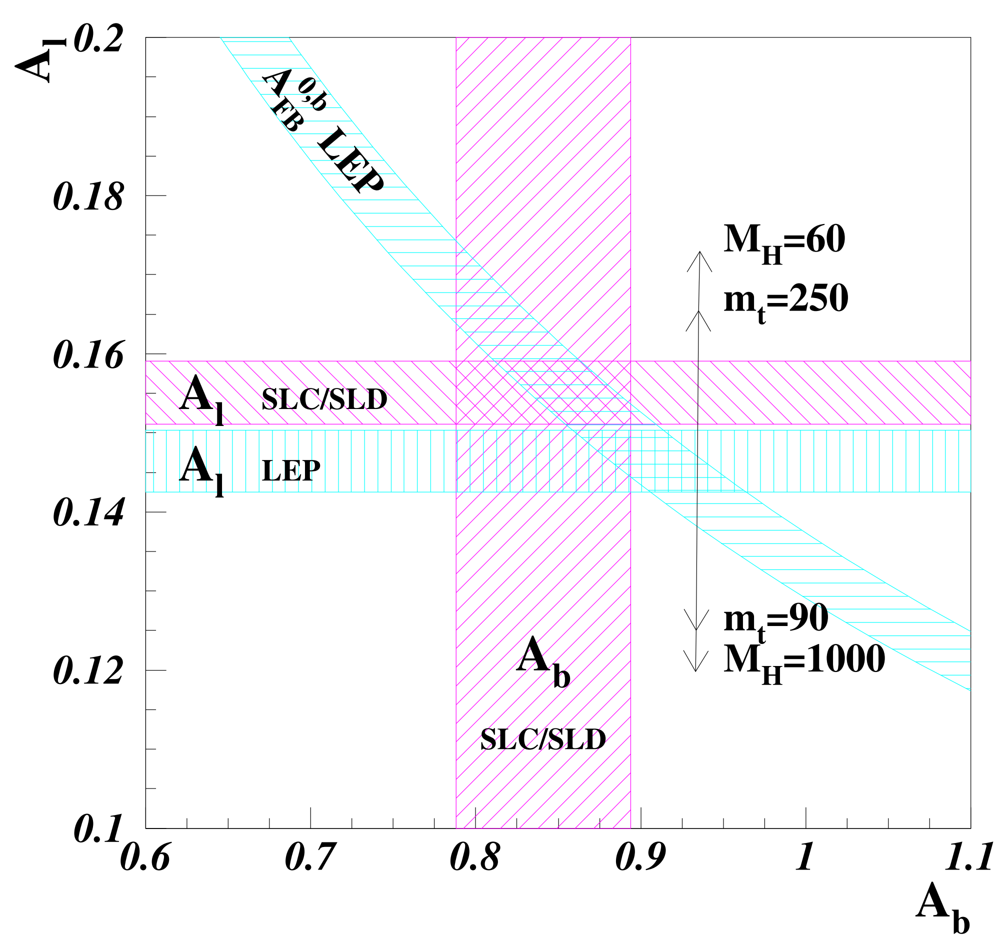
Recall: $A_{\rm FB}^{0,f} \equiv \frac{3}{4}\mathcal{A}_{\rm e}\mathcal{A}_{\rm f}$

	$\mathcal{A}_{\rm b}$	$\mathcal{A}_{\rm c}$
SLD Average	0.841 ± 0.053	0.606 ± 0.090
LEP (a)	0.910 ± 0.037	0.660 ± 0.056
Combined (b)	0.871 ± 0.027	0.635 ± 0.046
SM (c)	0.935	0.667

(a) Using $\mathcal{A}_\ell = 0.1464 \pm 0.0039$ from $A_{\rm FB}^{0,\ell}$ and τ pol

(b) Using $A_{\rm LR}$ in addition

(c) $m_{\rm Z} = 91.1884$ GeV, $m_{\rm t} = 180$ GeV, $m_{\rm H} = 300$ GeV



Combining Heavy Quark Results

Heavy quark analyses may:

- Measure several parameters simultaneously (e.g. asymmetries)
- Depend on external inputs (e.g. lifetimes, branching ratios) and possibly other heavy quark electroweak parameters (e.g. R_{b} depends on R_{c})

$\Longrightarrow$ Combination procedure (heavy flavour group):

- Provides standard ranges for external inputs which lead to systematic errors
- Takes into account correlated errors and interdependencies of electroweak parameters
- Overall χ^2 minimization using full covariance matrix between measurements

Cross-checks:

- Consistency with simple one-parameter averages

Asymmetry measurements:

- Combined at 3 energy points
- Small corrections applied to derive $A_{\mathrm{FB}}^{0,\,\mathrm{b}}$, $A_{\mathrm{FB}}^{0,\,\mathrm{c}}$

Combined LEP and SLD Results

R_{b}	$=$	0.2219 ± 0.0017
R_{c}	$=$	0.1540 ± 0.0074
$A_{\mathrm{FB}}^{\mathrm{b},0}$	$=$	$(9.97 \pm 0.31)\%$
$A_{\mathrm{FB}}^{\mathrm{c},0}$	$=$	$(7.29 \pm 0.58)\%$
$\mathcal{A}_{\mathrm{b}}$	$=$	0.841 ± 0.053
$\mathcal{A}_{\mathrm{c}}$	$=$	0.606 ± 0.090
$\mathrm{BR}(\mathrm{b} \to \ell)$	$=$	$(11.12 \pm 0.23)\%$
$\mathrm{BR}(\mathrm{b} \to \mathrm{c} \to \ell^{+})$	$=$	$(7.76 \pm 0.36)\%$
$\overline{\chi}$	$=$	0.1145 ± 0.0061

χ^2/dof of $55.1/(74-9)$, χ^2 probability 80%

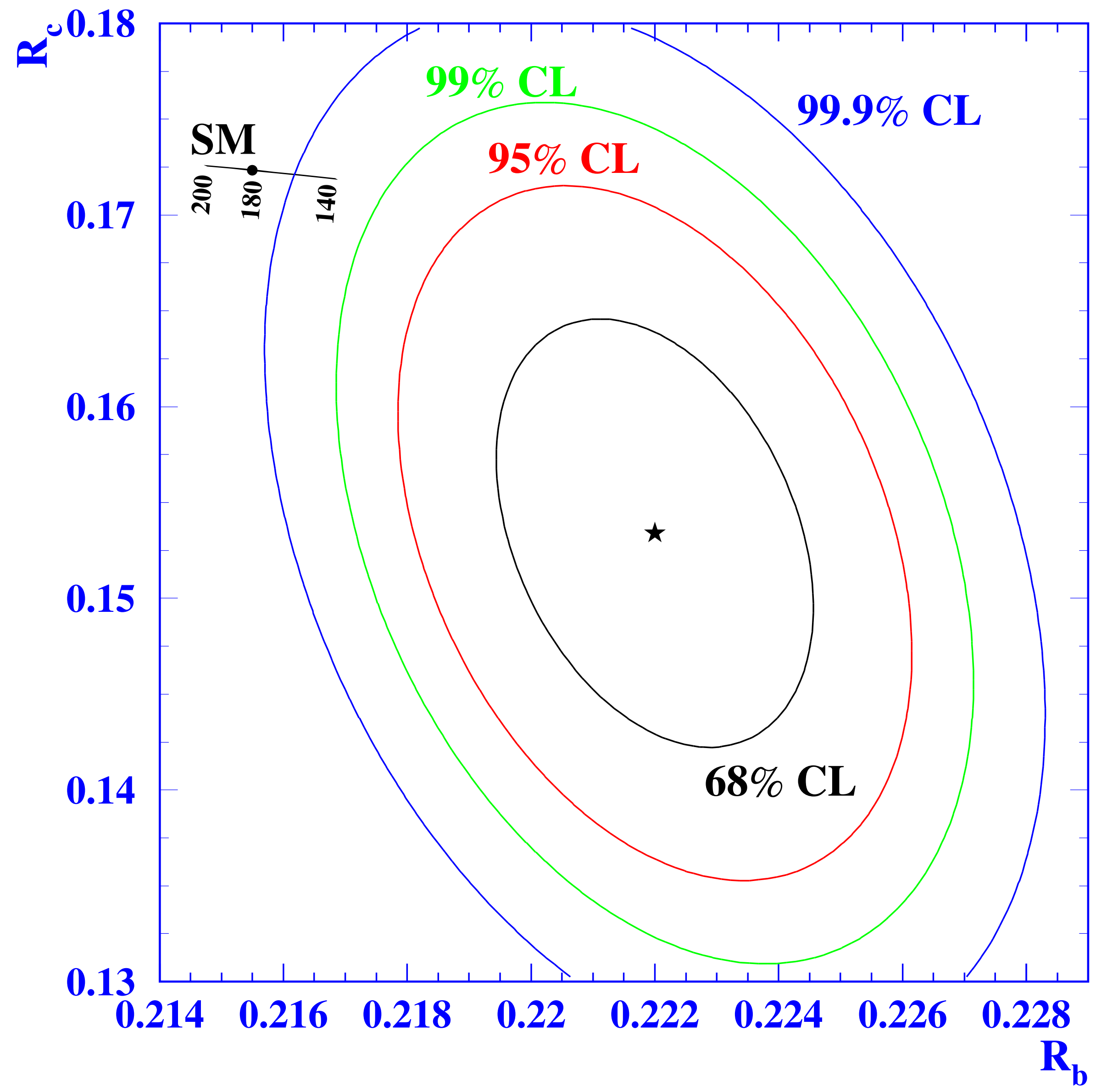
Correlation matrix:

	R_{b}	R_{c}	$A_{\mathrm{FB}}^{\mathrm{b},0}$	$A_{\mathrm{FB}}^{\mathrm{c},0}$	$\mathcal{A}_{\mathrm{b}}$	$\mathcal{A}_{\mathrm{c}}$
R_{b}	1.00	–0.35	0.01	0.06	–0.07	0.05
R_{c}	–0.35	1.00	0.08	–0.06	0.07	–0.06
$A_{\mathrm{FB}}^{\mathrm{b},0}$	0.01	0.08	1.00	0.11	0.06	–0.03
$A_{\mathrm{FB}}^{\mathrm{c},0}$	0.06	–0.06	0.11	1.00	–0.02	0.07
$\mathcal{A}_{\mathrm{b}}$	–0.07	0.07	0.06	–0.02	1.00	0.07
$\mathcal{A}_{\mathrm{c}}$	0.05	–0.06	–0.03	0.07	0.07	1.00

If R_{c} fixed to Standard Model,

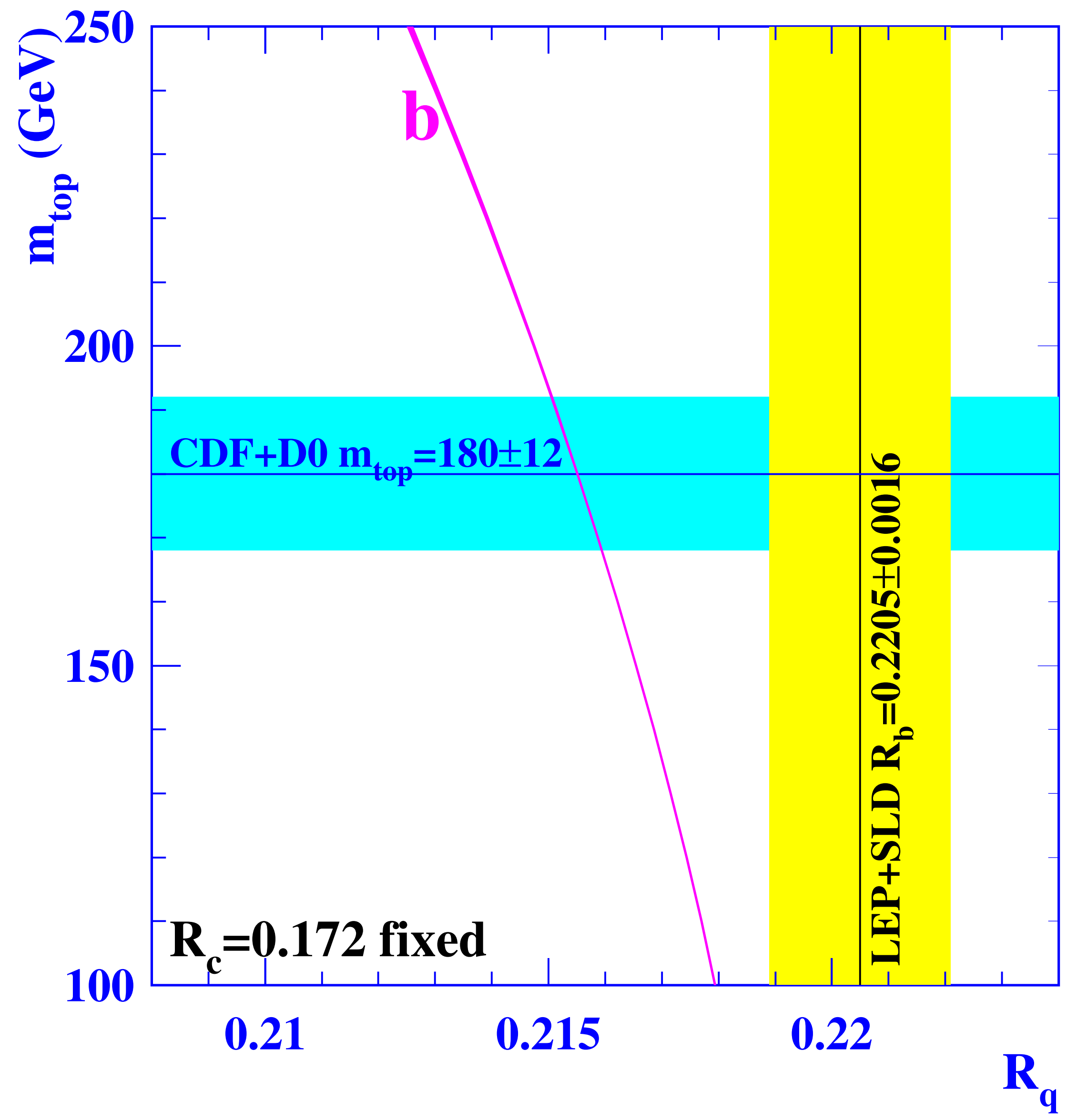
$$\boxed{R_{\mathrm{b}}(R_{\mathrm{c}} = 0.172) \quad = \quad 0.2205 \pm 0.0016}$$

Comparison with SM: R_c vs. R_b



$\Delta\chi^2$ between best fit with Standard Model R_b and R_c
($m_{top} = 180$ GeV, $R_b = 0.2155$, $R_c = 0.172$),
and best overall fit, is 16.0

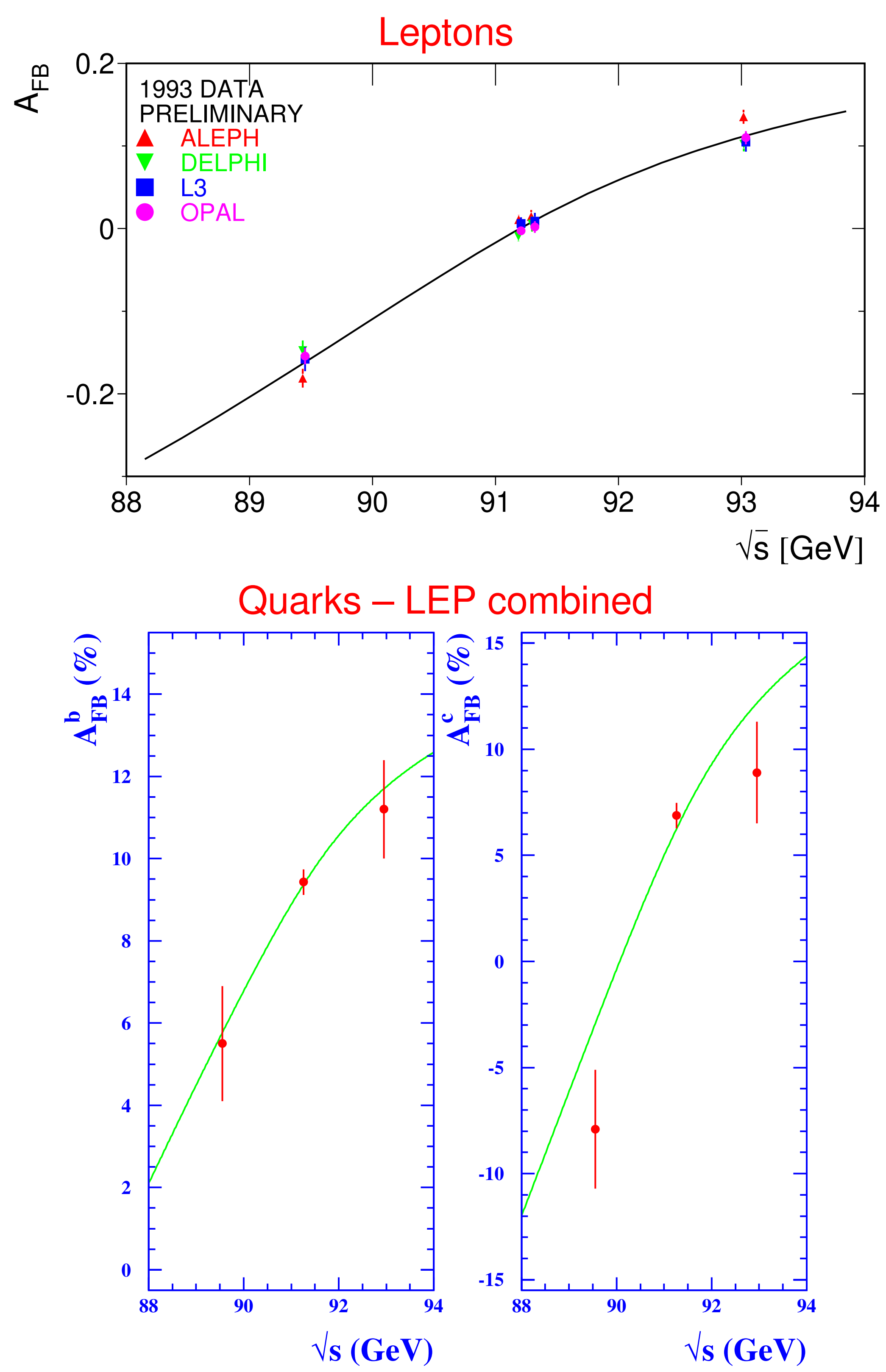
Comparison with SM: R_{b} (R_{c} Fixed)



Standard Model predictions from ZFITTER 4.9:
m_{Z^0}=91.1888 GeV, 60 GeV < m_{H} < 1000 GeV,
$\alpha_s(m_{\mathrm{Z}})$=0.12, $\alpha(m_{\mathrm{Z}})$=1/128.9

For $m_{\mathrm{top}} = 180 \pm 12$ GeV, Standard Model prediction
$R_{\mathrm{b}} = 0.2155 \pm 0.0005$

Energy dependence of asymmetries



Fits to the Standard Model

Check validity and consistency of SM

Infer information on m_{t} and m_{H} through loop corrections

Compare CDF/D0 $m_{\mathrm{t}} = 180 \pm 12$ GeV, constrain m_{H}?

Theoretical precision? Unknown m_{t}, m_{H}, $\alpha(m_{\mathrm{Z}})$, $\alpha_s(m_{\mathrm{Z}})$

Calculations based on integration of $R_{\mathrm{had}}(s) \Longrightarrow$

$\alpha^{-1}(M_{\mathrm{Z}})$ =	128.90(09)	Eidelman, Jergerlehner (1995)
	128.89(09)	Burkhardt, Pietrzyk (1995)
	128.96(06)	Swartz (1995 update, prel.)

$\alpha^{-1}(M_{\mathrm{Z}})$ = 128.89(09) $\Longrightarrow \delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ 0.00023, δm_{t} 4 GeV

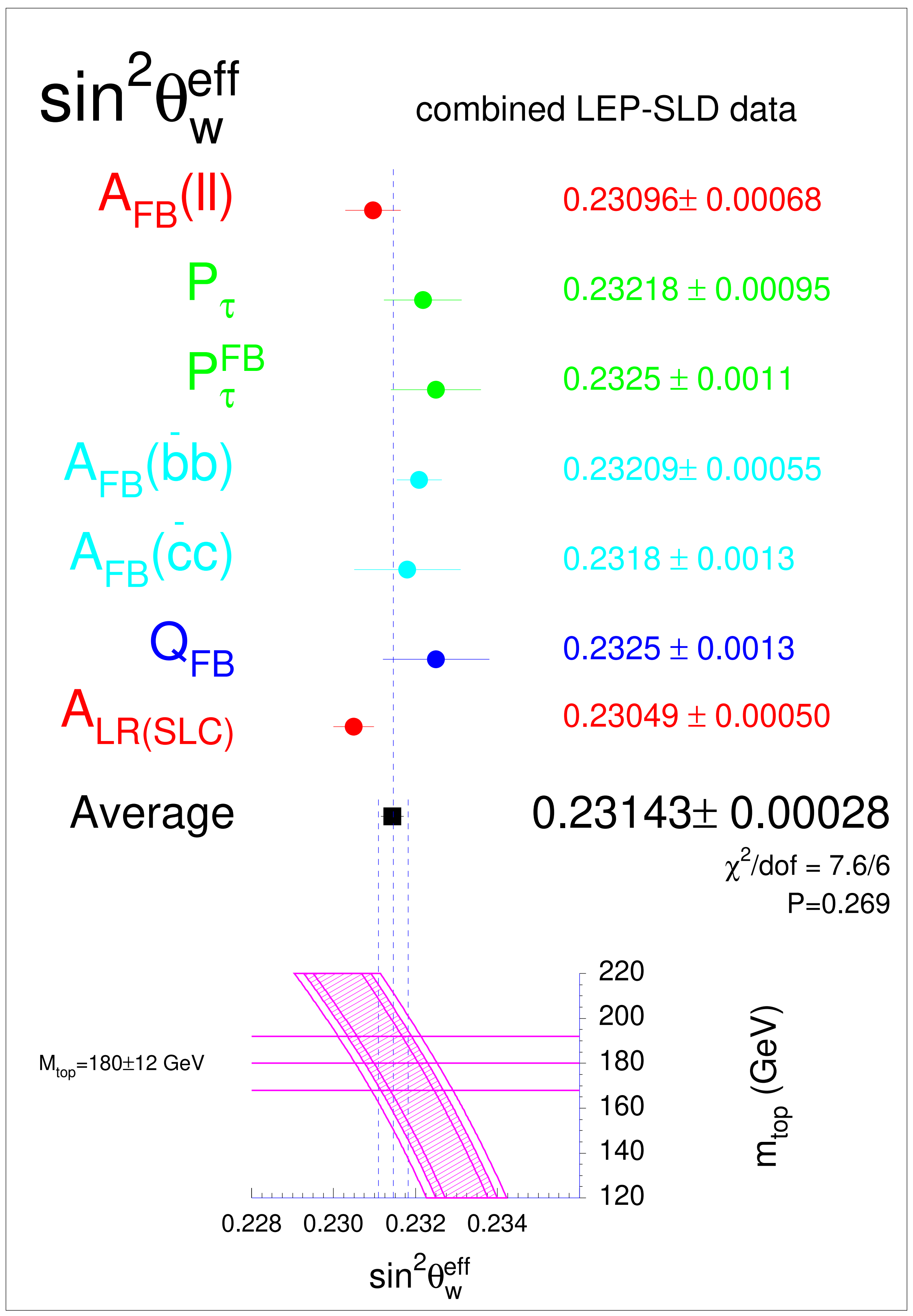
Comparison of codes for $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ and R_{b} vs. m_{t}

CERN 95-03 Working group on Precision Calculations for the Z Resonance

Summary of Measurements

	Measurement	SM Fit	Pull
LEP			
line-shape/lepton asy			
m_Z [GeV]	91.1884 ± 0.0022	91.1882	0.1
Γ_Z [GeV]	2.4963 ± 0.0032	2.4973	-0.3
$\sigma^{\mathrm{pole}}_{\mathrm{had}}$ [nb]	41.488 ± 0.078	41.450	0.5
R_ℓ	20.788 ± 0.032	20.773	0.5
$A^{0,\ell}_{\mathrm{FB}}$	0.0172 ± 0.0012	0.0159	1.1
τ polarization:			
$\mathcal{A}_\tau$	0.1418 ± 0.0075	0.1455	-0.5
$\mathcal{A}_{\mathrm{e}}$	0.1390 ± 0.0089	0.1455	-0.7
b and c quark results:			
$R_{\mathrm{b}}{}^{(a)}$	0.2219 ± 0.0017	0.2156	3.7
$R_{\mathrm{c}}{}^{(a)}$	0.1543 ± 0.0074	0.1724	-2.5
$A^{0,\mathrm{b}(a)}_{\mathrm{FB}}$	0.0999 ± 0.0031	0.1020	-0.7
$A^{0,\mathrm{c}(a)}_{\mathrm{FB}}$	0.0725 ± 0.0058	0.0728	0.0
$\mathrm{q}\overline{\mathrm{q}}$ charge asymmetry:			
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ ($\langle Q_{\mathrm{FB}}\rangle$)	0.2325 ± 0.0013	0.23172	0.6
SLC			
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ (A_{LR})	0.23049 ± 0.00050	0.23172	-2.5
R_{b}	0.2171 ± 0.0054	0.2156	0.3
$\mathcal{A}_{\mathrm{b}}$	0.841 ± 0.053	0.935	-1.8
$\mathcal{A}_{\mathrm{c}}$	0.606 ± 0.090	0.667	-0.7
$\mathrm{p}\overline{\mathrm{p}}$ and νN			
m_{W} [GeV] ($\mathrm{p}\overline{\mathrm{p}}$)	80.26 ± 0.16	80.35	-0.5
$1-\frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2}$ (νN)	0.2257 ± 0.0047	0.2237	0.4

Standard Model predictions from fit to all data, $m_{\mathrm{H}} = 300$ GeV.



sin²θ_w^eff
combined LEP-SLD data
A_FB(ll)
0.23096± 0.00068
P_τ
0.23218 ± 0.00095
P_τ^FB
0.2325 ± 0.0011
A_FB(bb̄)
0.23209± 0.00055
A_FB(cc̄)
0.2318 ± 0.0013
Q_FB
0.2325 ± 0.0013
A_LR(SLC)
0.23049 ± 0.00050
Average
0.23143± 0.00028
χ²/dof = 7.6/6
P=0.269
M_top=180±12 GeV
220
200
180
160
140
120
m_top (GeV)
0.228
0.230
0.232
0.234
sin²θ_w^eff

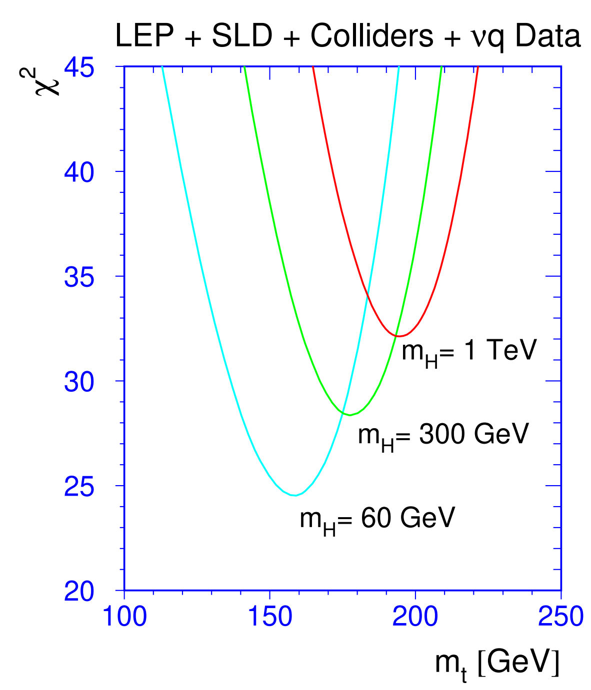
Results of Standard Model Fits

- 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 $\alpha^{-1}(M_Z) = 128.896 \pm 0.090$
- Contribution of about 15 to χ^2 from R_b and R_c

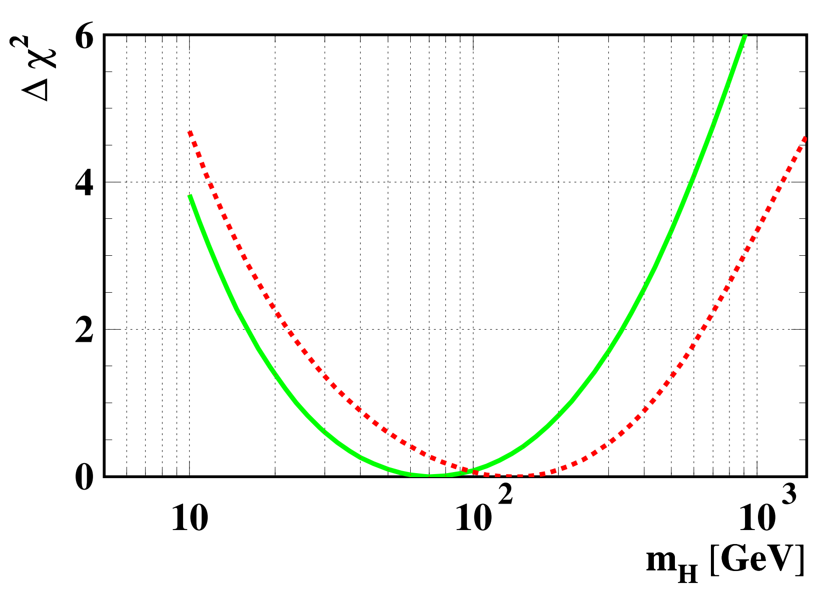
	LEP	LEP + SLD
m_t (GeV)	$170 \pm 10\ ^{+17}_{-19}$	$180\ ^{+8}_{-9}\ ^{+17}_{-20}$
$\alpha_s(m_Z)$	$0.125 \pm 0.004\ \pm 0.002$	$0.123 \pm 0.004\ \pm 0.002$
χ^2/d.o.f.	$18/9$	$28/12$
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$0.23206 \pm 0.00028\ ^{+0.00008}_{-0.00017}$	$0.23166 \pm 0.00025\ ^{+0.00006}_{-0.00013}$
$1 - \frac{m_W^2}{m_Z^2}$	$0.2247 \pm 0.0010\ ^{+0.0004}_{-0.0002}$	$0.2234 \pm 0.0009\ ^{+0.0005}_{-0.0002}$
m_W (GeV)	$80.295 \pm 0.057\ ^{+0.011}_{-0.019}$	$80.359 \pm 0.051\ ^{+0.013}_{-0.024}$

	LEP + SLD + $p\overline{p}$ and νN data
m_t (GeV)	$178 \pm 8\ ^{+17}_{-20}$
$\alpha_s(m_Z)$	$0.123 \pm 0.004\ \pm 0.002$
χ^2/d.o.f.	$28/14$
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$0.23172 \pm 0.00024\ ^{+0.00007}_{-0.00014}$
$1 - \frac{m_W^2}{m_Z^2}$	$0.2237 \pm 0.0009\ ^{+0.0004}_{-0.0002}$
m_W (GeV)	$80.346 \pm 0.046\ ^{+0.012}_{-0.021}$

Constraint on $m_{\rm H}$?



- Add constraint from CDF/DO $m_{\rm top} = 180 \pm 12$ 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



Comments on R_b, R_c, $\alpha_s(m_Z)$

- Omitting R_b and R_c from SM fits, m_t increases by 4 GeV, $\alpha_s(m_\mathrm{Z})$ is unchanged $\Longrightarrow$ insensitive
- Fitted $\alpha_s(m_\mathrm{Z})$ depends on R_ℓ, Γ_Z, $\sigma^{\mathrm{pole}}_{\mathrm{had}}$. Agrees with value determined from event shapes of

$$\alpha_s(m_\mathrm{Z}) = 0.123 \pm 0.006$$

- Allowing $\Gamma_{\mathrm{b\bar{b}}} = \Gamma_{\mathrm{b\bar{b}}}(\mathrm{SM}) + X_\mathrm{b}$ $\Longrightarrow$

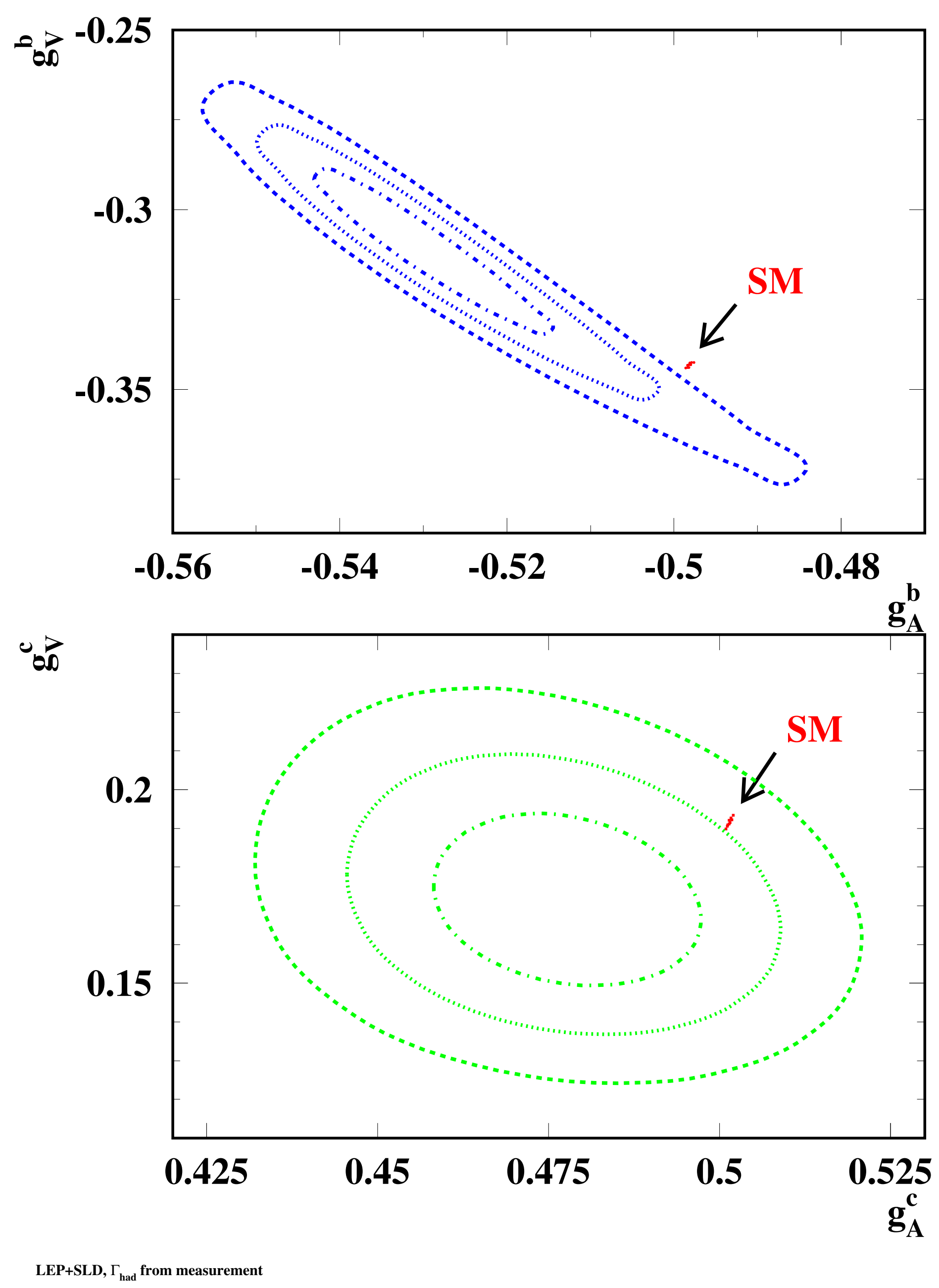
$$\begin{aligned} X_\mathrm{b} &= 11.7 \pm 3.8 \pm 1.4 \text{ MeV} \\ \alpha_s(m_\mathrm{Z}) &= 0.102 \pm 0.008 \\ m_\mathrm{t} &= 181 \pm 8^{+17}_{-19} \text{ GeV} \\ \chi^2/\text{d.o.f.} &= 18/13 \end{aligned}$$

- Allowing $\Gamma_{\mathrm{b\bar{b}}} = \Gamma_{\mathrm{b\bar{b}}}(\mathrm{SM}) + X_\mathrm{b}$ and $\Gamma_{\mathrm{c\bar{c}}} = \Gamma_{\mathrm{c\bar{c}}}(\mathrm{SM}) + X_\mathrm{c}$ $\Longrightarrow$

$$\alpha_s(m_\mathrm{Z}) = 0.18 \pm 0.04$$

Heavy quark couplings

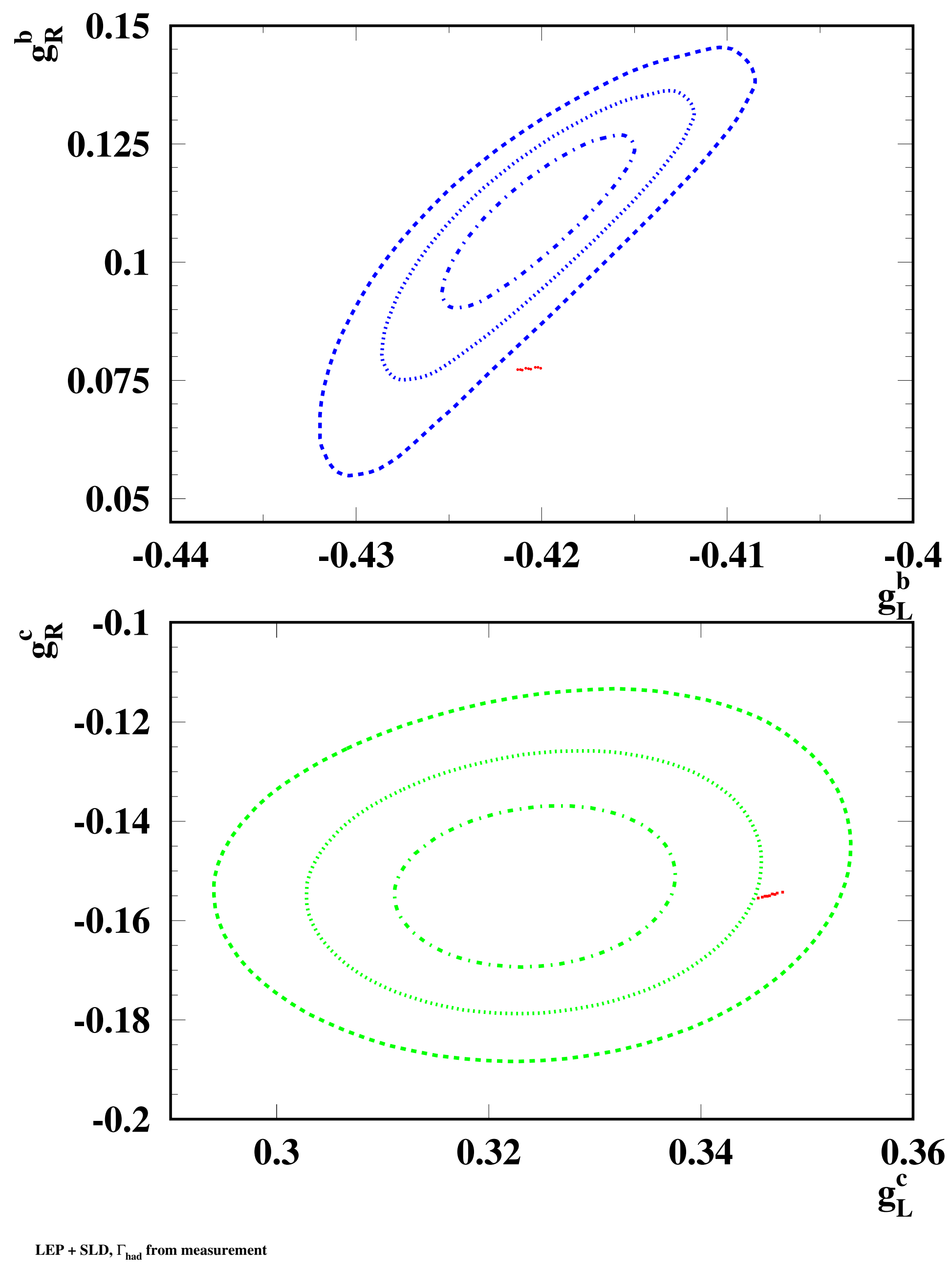
- $\Gamma_f \propto v_f^2 + a_f^2$, (take $\Gamma_{\rm had}$ from measurement)
- $\mathcal{A}_{\rm f} \implies v_f/a_f$



- Contours are 68%, 95% and 99.7%.
- $\alpha_s(m_{\rm Z}) = 0.123 \pm 0.006$

SM

Heavy quark couplings



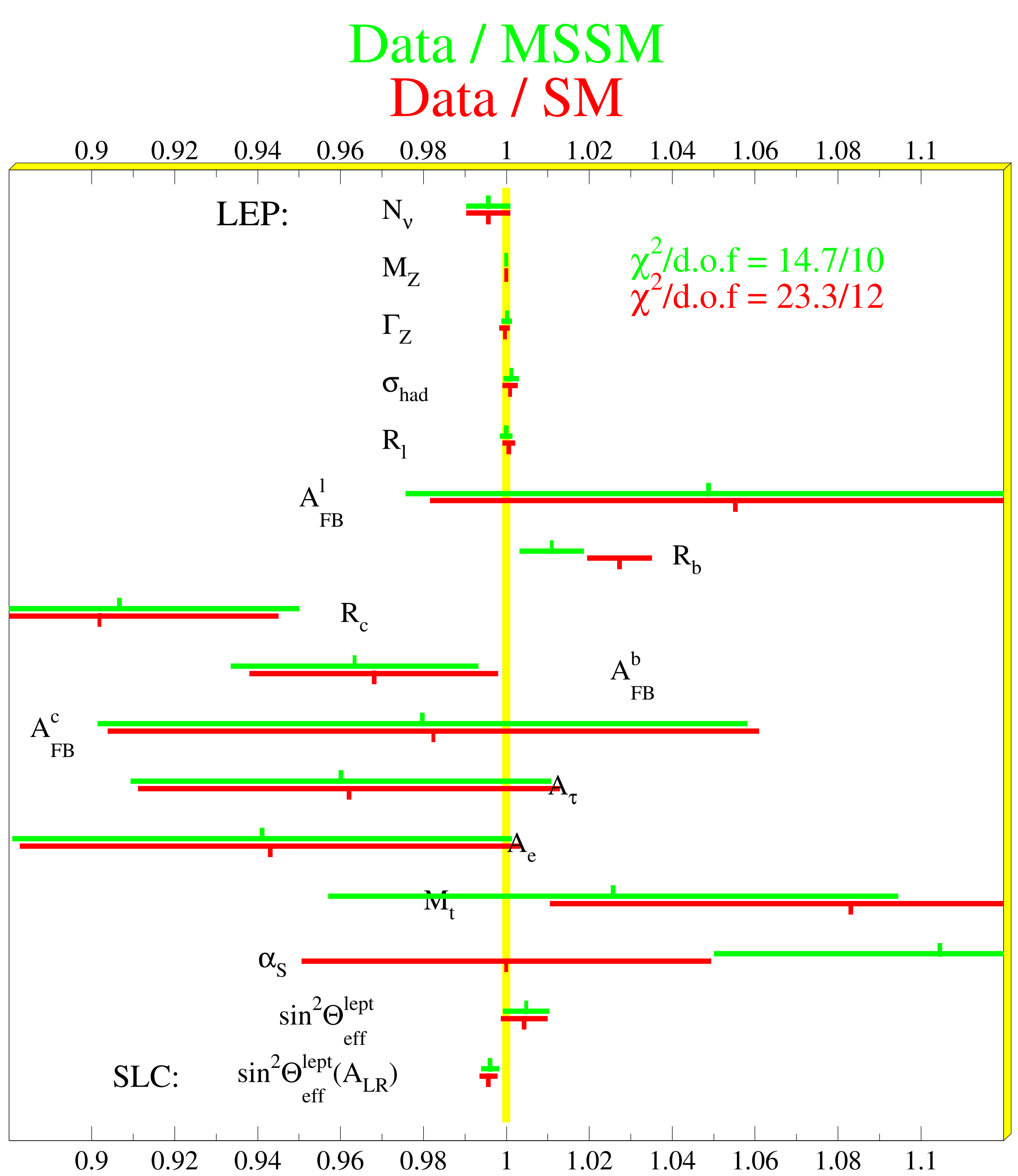
- Contours are 68%, 95% and 99.7%.

SM

Epsilon analyses

Comparison with MSSM

de Boer et. al.



Outlook

- Precision electroweak measurements are in general in excellent agreement with the Standard Model
- However, R_{b} and R_{c} are together only consistent with the Standard Model at the 0.1% level
- More data to be analysed/delivered from LEP1 (scan 95), SLC $\Longrightarrow$ improved Z parameters, in particular Γ_{Z} and A_{LR}
- Top physics at the Tevatron
- LEP2 and Tevatron will bring $\delta M_{\mathrm{W}} < 50$MeV
- Look forward to yet more stringent tests of electroweak theory
- First hint of new physics from precision measurements?