LEP Results on $\alpha_{\mathrm{s}}(M_{\mathrm{Z}})$

from R_{had} and Event Shapes

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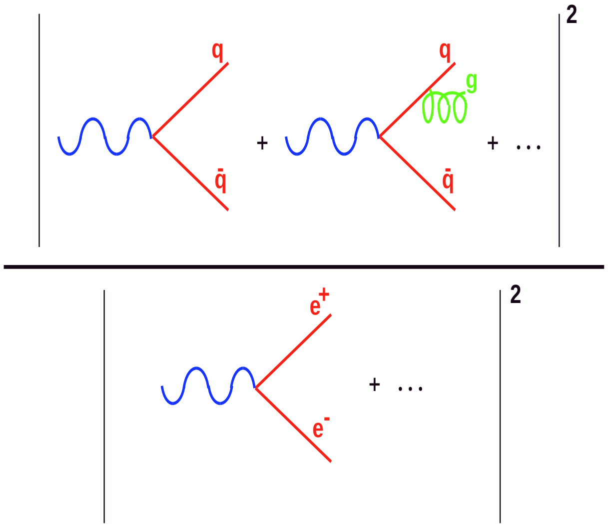
XXXth Rencontres de Moriond
Les Arcs. March 19-26, 1995

α_s determination from R_{had}

R_{had} definition and α_{s}

$$R_{\text{had}} = \frac{\Gamma\left(\text{Z} \longrightarrow \text{hadrons}\right)}{\Gamma\left(\text{Z} \longrightarrow \text{electrons}\right)} =$$

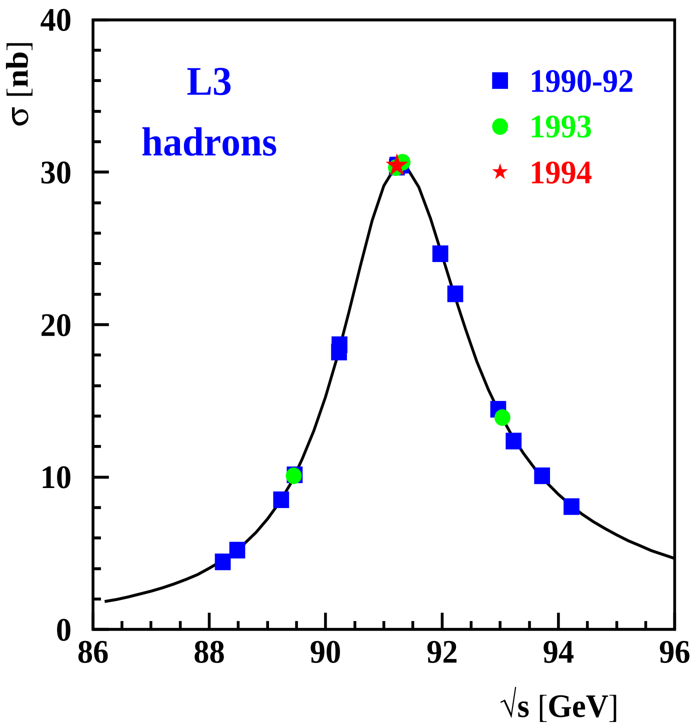


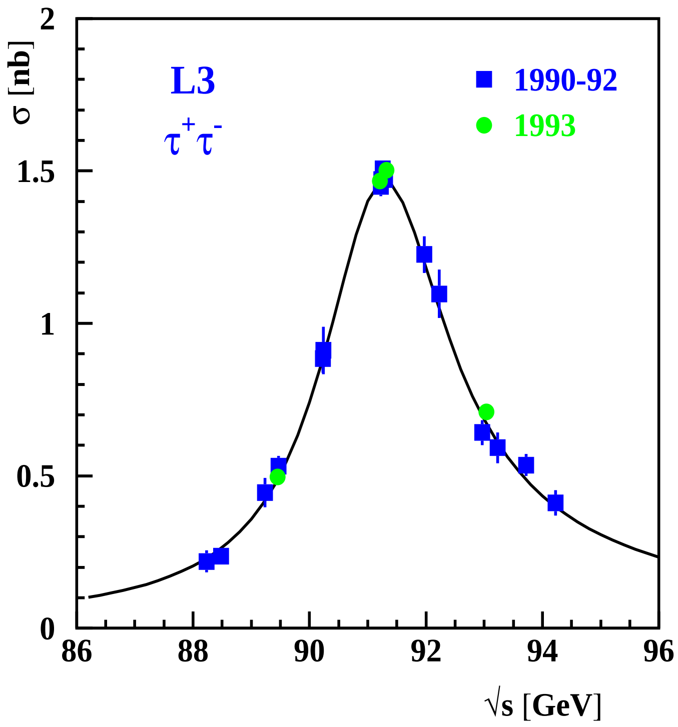
- Fully inclusive measurement of α_{s}
- Non-perturbative effects are negligible: $O\left(\Lambda/\text{M}_{\text{Z}}\right)^2$
- QCD corrections known up to $O(\alpha_{\text{s}}^3)$
- EW and QCD corrections do not exactly factorize.
  An effective formula can be used

$$\boxed{R_{\text{had}} = 19.943 \cdot \left(1 + 1.060\frac{\alpha_{\text{s}}}{\pi} + 0.85\left(\frac{\alpha_{\text{s}}}{\pi}\right)^2 - 15\left(\frac{\alpha_{\text{s}}}{\pi}\right)^3\right)}$$

L3 collected events during 1990-1994 ('93 and '94 preliminary)

	90-92	93	94	total
$q\bar{q}$	1094 K	658 K	1362 K	3114 K
e^+e^-	38 K	26 K	47 K	111 K
$\mu^+\mu^-$	35 K	21 K	41 K	97 K
$\tau^+\tau^-$	25 K	15 K	-	40 K
Luminosity	41 pb^{-1}	32 pb^{-1}	45 pb^{-1}	118 pb^{-1}





SM Fit and Results

Fit of the Standard Model parameters from the measured cross sections and asymmetries (lepton universality is assumed)

Parameters	fitted values
M_Z (MeV)	91193.5$\pm$3.7
Γ_Z (MeV)	2504.0 $\pm$5.3
σ^o_{had} (nb)	41.41 $\pm$0.11
R_{had}	20.836$\pm$0.080
A^o_{FB} (M_Z)	0.0183$\pm$0.0032
χ^2/d.o.f. =	117/139

Correlation coefficients from the fit

Γ_Z	σ^o_{had}	R_{had}	A^o_{FB}	
.055	-.063	-.010	.078	M_Z
	-.254	.011	.001	Γ_Z
		.186	.006	σ^o_{had}
			-.010	R_{had}

Systematic errors on cross sections (%)

	σ_{had}	σ_e	σ_μ	σ_τ
90-92	0.15	0.3	0.5	0.7
93	0.11-0.14	0.30-0.34	0.29-0.34	0.63-1.37
94	0.2	0.4	-	-

From the L3 preliminary result

$$\boxed{R_{\rm had} \;=\; 20.836 \;\pm\; 0.080\,(\rm exp)}$$

Assuming $m_{\rm top} = 179$ GeV and $m_{\rm Higgs} = 300$ GeV, we obtain

$$\boxed{\alpha_{\rm s}(M_{\rm Z}) \;=\; 0.132 \;\pm\; 0.012\,(\rm exp) \;\pm\; 0.004\,(\rm theor)}$$

Theoretical uncertainties

- EW corrections
  Factorization vs. non factorization of QED and QCD corrections $\Rightarrow \Delta(\alpha_s) = \pm 0.001$
  Hadronic contribution to $\alpha_{\rm em}$ $\Rightarrow \Delta(\alpha_s) = \pm 0.001$
- QCD corrections
  variation of renormalization scale μ between $M_{\rm Z}/4$ and $M_{\rm Z}$ $\Rightarrow \Delta(\alpha_s) = \pm 0.002$
- $m_{\rm top}, m_{\rm Higgs}$
  $m_{\rm top} = 179 \pm 12$ GeV (CDF+D0) $\Rightarrow \Delta(\alpha_s) = \pm 0.0005$
  $m_{\rm Higgs}$ variation: $60 - 1000$ GeV $\Rightarrow \Delta(\alpha_s) = \pm 0.002$

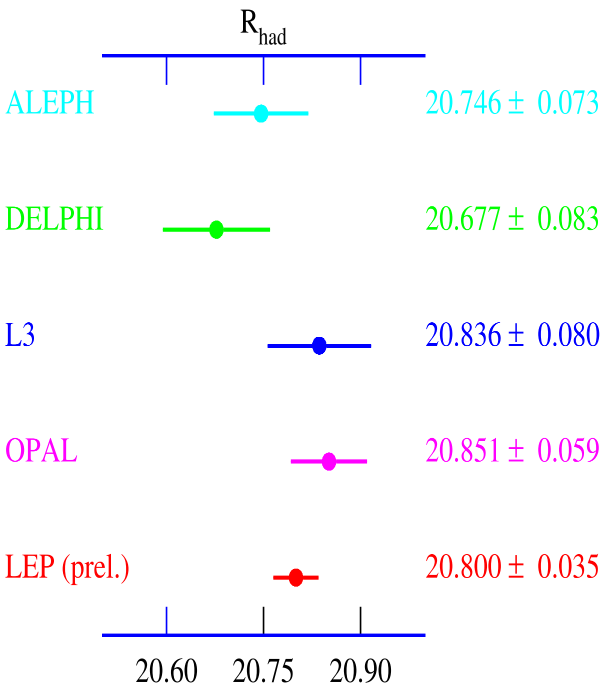
LEP combined Results

- Line shape and asymmetry fits from the four LEP experiments
  '93 and '94 data still preliminary

	ALEPH	DELPHI	L3	OPAL
M_Z (GeV)	91.1918$\pm$ 0.0039	91.1862$\pm$ 0.0034	91.1936$\pm$ 0.0037	91.1846$\pm$ 0.0035
Γ_Z (GeV)	2.4929$\pm$ 0.0058	2.4942$\pm$ 0.0055	2.5040$\pm$ 0.0053	2.4959$\pm$ 0.0052
σ^o_{had} (nb)	41.62 $\pm$ 0.10	41.27$\pm$ 0.17	41.42 $\pm$ 0.11	41.47$\pm$ 0.10
R_{had}	20.746$\pm$ 0.073	20.677$\pm$ 0.083	20.836$\pm$ 0.080	20.851$\pm$ 0.059
$A^o_{FB}(M_Z)$	0.0206$\pm$ 0.0026	0.0182$\pm$ 0.0025	0.0183$\pm$ 0.0032	0.0142$\pm$ 0.0020
χ^2/d.o.f. =	180/182	157/137	117/139	15/10

- Results of the LEP combined fit

Parameter	Average Value
M_Z (GeV)	91.1887 $\pm$ 0.0022
Γ_Z (GeV)	2.4971 $\pm$ 0.0033
σ^o_{had} (nb)	41.492 $\pm$ 0.081
R_{had}	20.800 $\pm$ 0.035
$A^o_{FB}(M_Z)$	0.0172 $\pm$ 0.0013
χ^2/d.o.f. =	22.0/15



LEP combined Results

- Common systematic errors used for the LEP average
  - Theoretical uncertainty in the luminosity normalization

$$\Delta\sigma^{\mathrm{o}}_{\mathrm{had}}/\sigma^{\mathrm{o}}_{\mathrm{had}} = 0.16\%$$

  - LEP energy calibration

$$\Delta M_{\mathrm{Z}} = 1.5\mathrm{MeV} \qquad \Delta\Gamma_{\mathrm{Z}} = 1.5\mathrm{MeV} \qquad \Delta \mathrm{A}^{\mathrm{o}}_{\mathrm{FB}} = 0.0005$$

  - Beam energy spread

$$\Delta\Gamma_{\mathrm{Z}} = 1\mathrm{MeV}$$

- From the LEP combined preliminary result

$$\boxed{R_{\mathrm{had}} \; = \; 20.800 \; \pm \; 0.035\,(\mathrm{exp})}$$

we obtain

$$\boxed{\alpha_{\mathrm{s}}(M_{\mathrm{Z}}) \; = \; 0.127 \; \pm \; 0.005\,(\mathrm{exp}) \; \pm \; 0.004\,(\mathrm{theor})}$$

α_s from Event Shapes

- AIM: Define observables sensitive to multijet events

$$N_{3-\mathrm{jet}}/N_{2-\mathrm{jet}} \sim \alpha_s$$

- REQUIREMENT: Infrared and Collinear safe

- EVENT SHAPE VARIABLES USED IN L3 ANALYSIS

  – THRUST:

$$T = \max \frac{\Sigma|\vec{p}_i \cdot \vec{n}_T|}{\Sigma|\vec{p}_i|}$$

  The perpendicular plane to the thrust axis divides the event in two hemispheres (+ and -)

  – HEAVY JET MASS:

$$M_H = \max\left[M_+(\vec{n}_T), M_-(\vec{n}_T)\right] \quad ; \quad \rho = M_H^2/E_{vis}^2$$

  where $M_\pm$ are the invariant masses of the two hemispheres

  – JET BROADENING VARIABLES:

$$B_\pm = \frac{\Sigma_\pm|\vec{p}_i \times \vec{n}_T|}{2\Sigma|\vec{p}_i|}$$

  TOTAL JET BROADENING: $B_T = B_+ + B_-$

  WIDE JET BROADENING: $B_W = \max(B_+, B_-)$

Event Shape variable definition

– ENERGY-ENERGY CORRELATION:

$$\mathrm{EEC}(\chi_{\mathrm{bin}}) = \frac{1}{\Delta_{\mathrm{bin}} \cdot \mathrm{N}} \sum_{\mathrm{events}}^{\mathrm{N}} \sum_{\mathrm{i,j}} \frac{\mathrm{E_i} \cdot \mathrm{E_j}}{\mathrm{E_{vis}^2}} \delta_{\mathrm{bin}}(\chi_{\mathrm{bin}} - \chi_{\mathrm{i,j}})$$

$$\mathrm{AEEC}(\chi_{\mathrm{bin}}) = \mathrm{EEC}(\chi_{\mathrm{bin}}) - \mathrm{EEC}(\pi - \chi_{\mathrm{bin}})$$

– JET MULTIPLICITY:

Jade and Durham clustering algorithms:

JADE $\qquad y_{ij} = \frac{2\,\mathrm{E_i} \cdot \mathrm{E_j}}{\mathrm{E_{vis}^2}} \cdot (1 - \cos\theta_{i,j})$

DURHAM $\qquad y_{ij} = \frac{2\min(\mathrm{E_i^2}, \mathrm{E_j^2})}{\mathrm{E_{vis}^2}} \cdot (1 - \cos\theta_{i,j})$

We measure the 3-jet and the average jet multiplicities

$$\mathrm{R}_3 = \frac{\mathrm{N_{3-jet}}}{\mathrm{N}} \qquad\qquad < \mathrm{n_{jet}} > = \frac{1}{\mathrm{N}} \sum_{\mathrm{events}}^{\mathrm{N}} \mathrm{n_{jet}}$$

for fixed y_{cut} (R_3) or as a function of y_{cut} $(< \mathrm{n_{jet}} >)$

$O(\alpha_s^2)$ and resummed predictions

- Event shape variable y $\quad$ ($y \to 0$ on 2-jet events)

  $\Rightarrow$ $\quad$ (1-T) , ρ , B_T , B_W , $(1+\cos\chi)/2$ for EEC , y_{cut} for jet rates

- Define cummulative cross section

$$R(y) = \int_0^y dz \, \frac{1}{\sigma} \frac{d\sigma}{dz}$$

- The perturbative expansion of $\ln R$ leads to the following terms

	LL	NLL	subleading			
1st order	$\alpha_s L^2$	$\alpha_s L$	α_s	$\alpha_s O\left(\frac{1}{L}\right)$		
2nd order	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	$\alpha_s^2 O\left(\frac{1}{L}\right)$	
3rd order	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$\alpha_s^3 L^2$	$\alpha_s^3 L$	α_s^3	$\alpha_s^3 O\left(\frac{1}{L}\right)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

where $L = \ln\left(\frac{1}{y}\right)$

  – $O(\alpha_s^2)$ known from ERT-matrix elements
  – LL+NLL terms have been resummed for some Event Shape variables

- Several prescriptions relate fixed order and resummed predictions

Data Selection

We select $e^+e^- \rightarrow$ hadrons recorded by the L3 detector during 1991 using two independent methods

- Calorimeter based selection
  - $N_{clus} > 12$
  - $0.6 < E_{vis}/\sqrt{s} < 1.4$
  - $|E_{\parallel}/E_{vis}| < 0.4$ $\qquad E_{\perp}/E_{vis} < 0.4$

  $\Rightarrow$ 240,000 hadronic events (98.5% efficency)

- Charged track based selection
  - $N_{track} > 5$
  - $E^T_{vis}/\sqrt{s} > .15$
  - $|E^T_{\parallel}/E^T_{vis}| < 0.75$ $\qquad E^T_{\perp}/E^T_{vis} < 0.75$
  - $\phi_2 < 170^o$
  - $|\cos\theta_{thrust}| < 0.7$

  $\Rightarrow$ 160,000 hadronic events (66.7% efficency)

We measure the Event Shape distributions on both samples separately

Event Shape variables measurement

- Histograms containing the measured distributions

  $\Rightarrow$ bin width > 1.5 experimental resolution

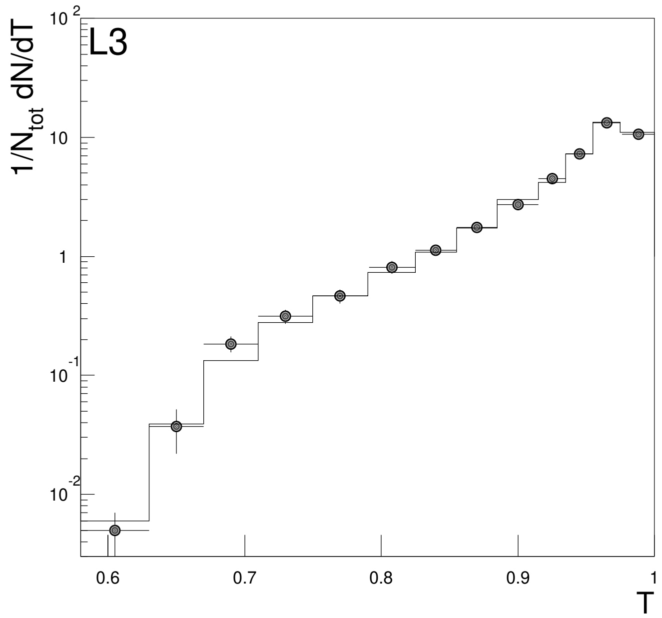
- Detector unfolding

  $\Rightarrow$ JETSET 7.3 PS , HERWIG 5.6

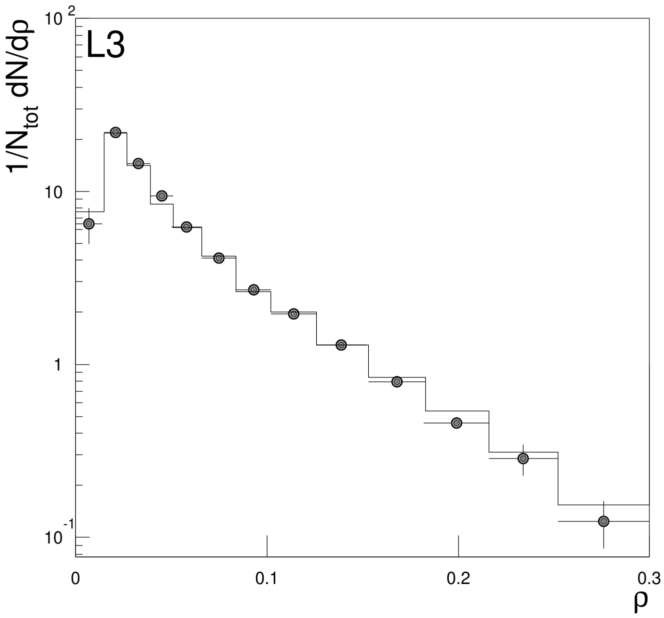
  – Regularized unfolding for T, ρ, B_T, B_W
  – Bin-by-bin correction for EEC
  – Matrix unfolding for jet fractions

- Unfolded distributions

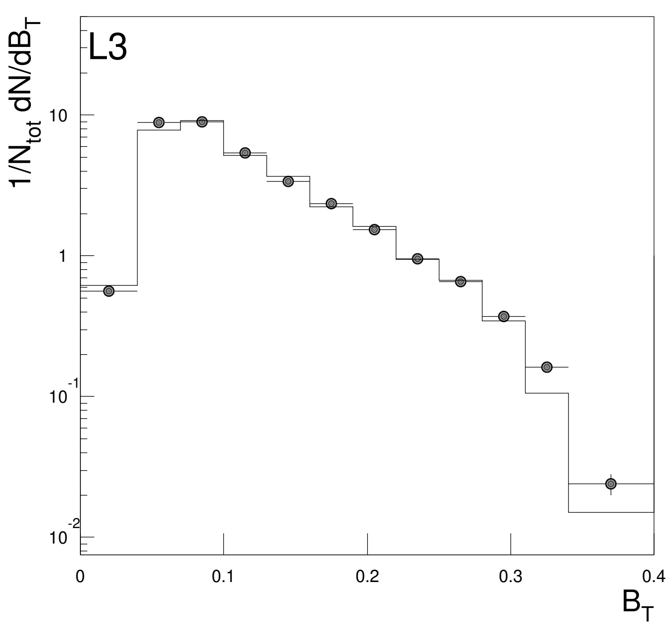
THRUST



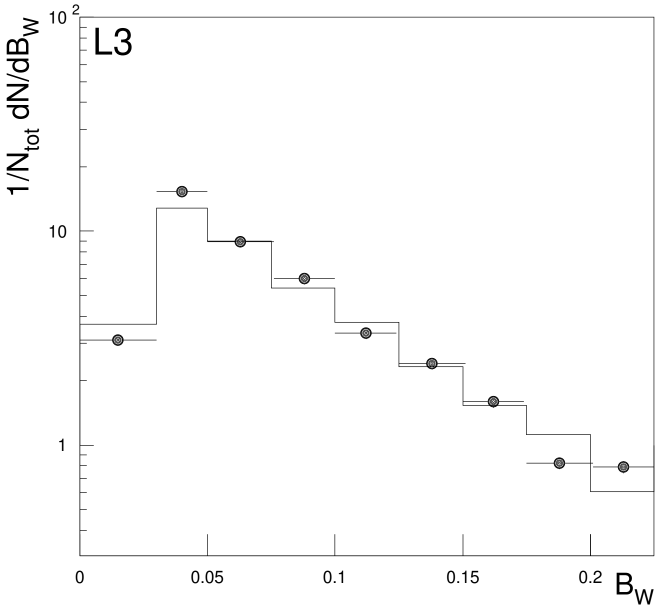
ρ parameter



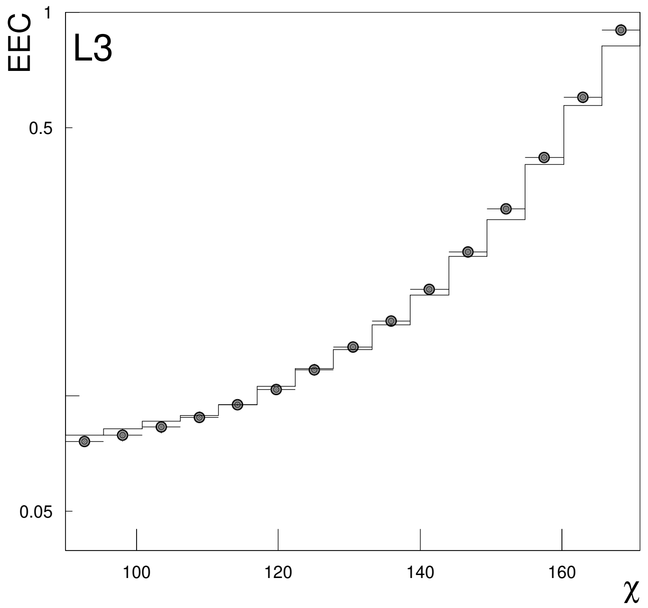
TOTAL JET BROADENING



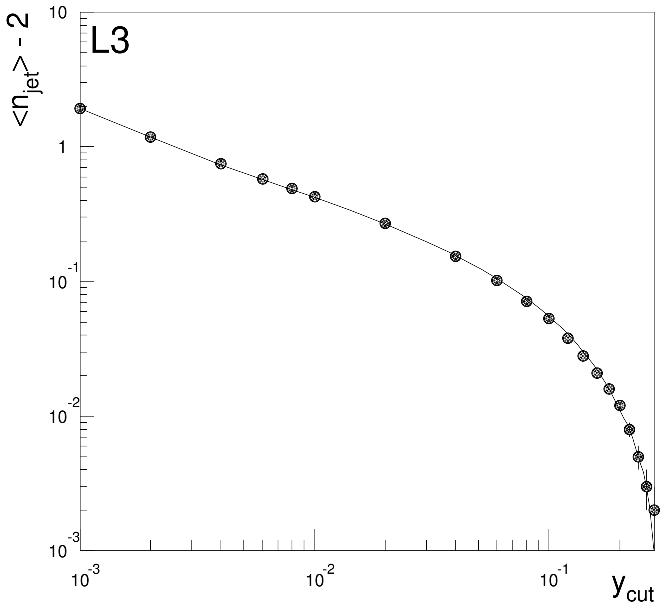
WIDE JET BROADENING



EEC



$< n_{jet} >$



Event Shape variables measurement

- Hadronization corrections

  $\Rightarrow$ JETSET 7.3 PS , HERWIG 5.6 , ARIADNE 3.3 , NLLJET 2.0

  – Convolution integral for $\mathrm{T}, \rho, \mathrm{B_T}, \mathrm{B_W}$

  – Bin-by-bin correction for EEC and $\mathrm{n_{jet}}$

- Fit range

  – Reliable theoretical calculation

  – Detector and hadronization corrections small ($< 10\%$)

theory	variable	fit range
α_s^2+LL+NLL	$1 - \mathrm{T}$	$0.065 - 0.290$
α_s^2+LL+NLL	ρ	$0.039 - 0.216$
α_s^2+LL+NLL	$\mathrm{B_T}$	$0.070 - 0.250$
α_s^2+LL+NLL	$\mathrm{B_W}$	$0.050 - 0.175$
α_s^2+LL+NLL	EEC : χ	$90^o - 160.2^o$
α_s^2+LL+NLL	$< \mathrm{n_{jet}} >$: $\mathrm{y_{cut}}$	0.002, 0.02, 0.10
α_s^2	EEC : χ	$57.6^o - 138.6^0$
α_s^2	AEEC : χ	$36.0^o - 90.0^o$
α_s^2	$\mathrm{R_3}$: $\mathrm{y_{cut}}$	0.08

Results

theory	variable	$\alpha_s(M_Z)$	$\Delta(\alpha_s)$(exp)	$\Delta(\alpha_s)$(theor)
α_s^2+LL+NLL	$1-\mathrm{T}$	0.123	0.003	0.008
α_s^2+LL+NLL	ρ	0.123	0.001	0.005
α_s^2+LL+NLL	$\mathrm{B_T}$	0.126	0.002	0.008
α_s^2+LL+NLL	$\mathrm{B_W}$	0.117	0.002	0.006
α_s^2+LL+NLL	EEC	0.133	0.001	0.006
α_s^2+LL+NLL	$<\mathrm{n_{jet}}>$	0.132	0.002	0.005
α_s^2	EEC	0.121	0.004	0.010
α_s^2	AEEC	0.115	0.004	0.007
α_s^2	$\mathrm{R_3}$	0.115	0.005	0.011

- Experimental uncertainties
  - $\Rightarrow$ variation of energy response of calorimeters
  - $\Rightarrow$ JETSET vs HERWIG
  - $\Rightarrow$ compare calorimetric and track distributions
- Theoretical uncertainties
  - Hadronization uncertainties
    - $\Rightarrow$ compare different hadronization models
    - $\Rightarrow$ variation of fragmentation parameters
  - Scale uncertainties
    - $\Rightarrow$ repeat the fit for different values of μ
  - Matching uncertainties (Resummed)
    - $\Rightarrow$ change the matching scheme.

Results

We average separately the results using α_s^2 or α_s^2+LL+NLL predictions

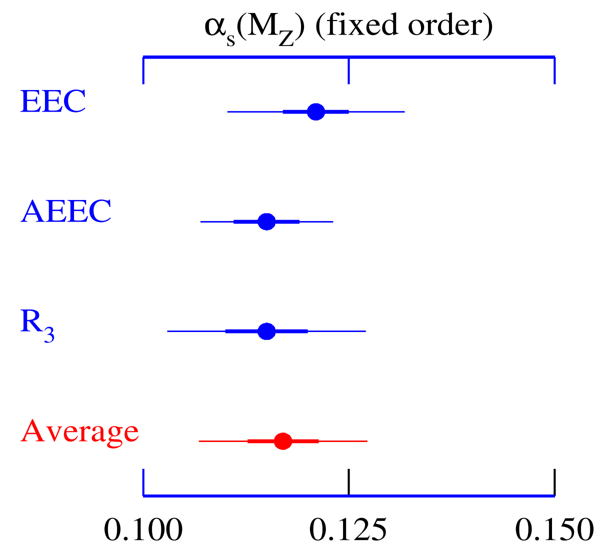
from fixed order theory we obtain

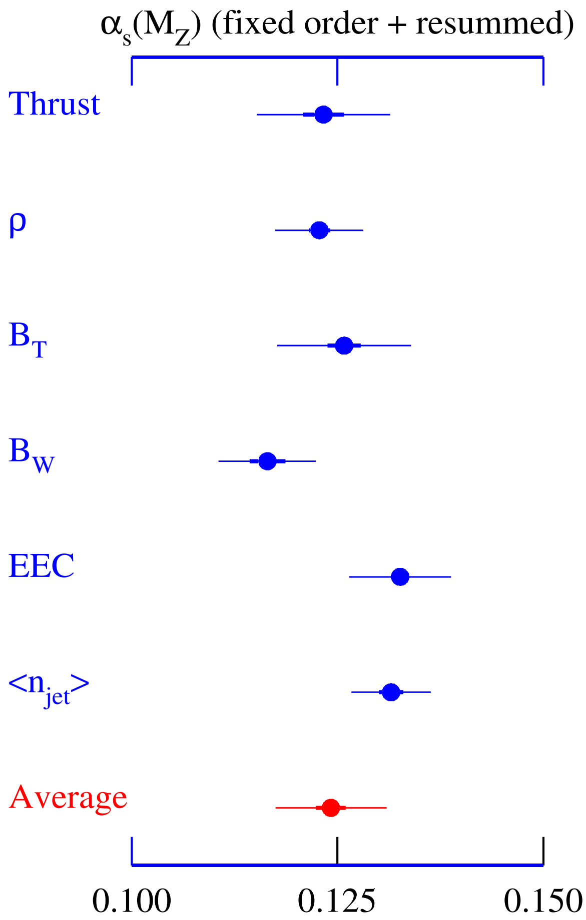
$$\boxed{\alpha_s(M_Z) = 0.117 \pm 0.004\,(\mathrm{exp}) \pm 0.009\,(\mathrm{theor})}$$

from fixed order and resummed theory we obtain

$$\boxed{\alpha_s(M_Z) = 0.124 \pm 0.002\,(\mathrm{exp}) \pm 0.007\,(\mathrm{theor})}$$

($<\mathrm{n_{jet}}>$ not included in the average)





Similar analyses have been performed by the other LEP collaborations

	$O(\alpha_s^2)$
ALEPH	0.117 ± 0.010
DELPHI	0.113 ± 0.007
L3	0.117 ± 0.010
OPAL	0.122 ± 0.006

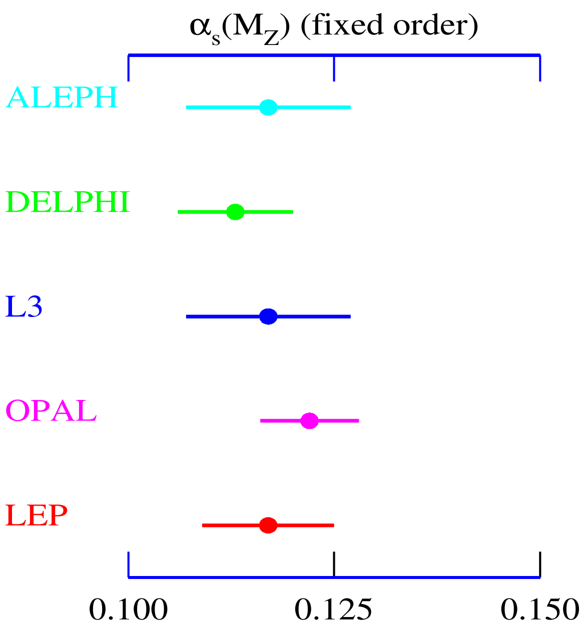
	$O(\alpha_s^2)$+Res.
ALEPH	0.125 ± 0.005
DELPHI	0.123 ± 0.006
L3	0.124 ± 0.007
OPAL	0.120 ± 0.006

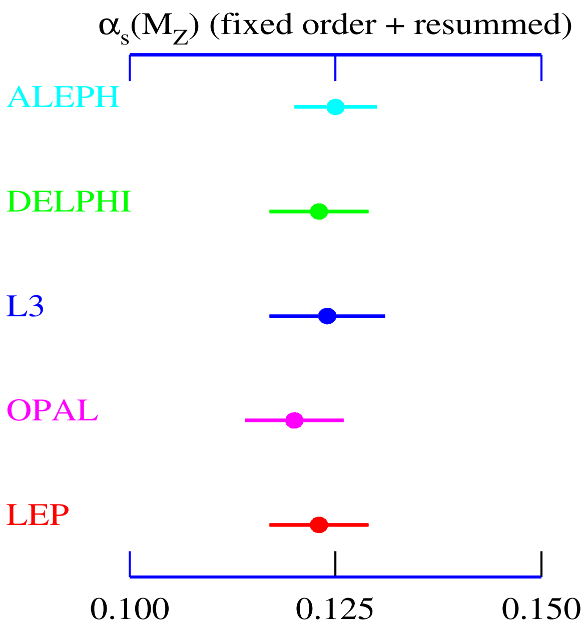
The errors are dominated by the theoretical uncertainties.

The LEP combined result for α_s from Event Shape variables is

	$O(\alpha_s^2)$
LEP	0.117 ± 0.008

	$O(\alpha_s^2)$+Res.
LEP	0.123 ± 0.006





Conclusions

Conclusions

- The $\alpha_s(M_Z)$ determination from R_{had} and Event Shapes has been presented
- LEP combined results
  - From the Z^o line shape fits we obtain

    $$R_{\mathrm{had}} = 20.800 \pm 0.035\,(\mathrm{exp})$$

    which corresponds to

    $$\boxed{\alpha_{\mathrm{S}}(M_Z) = 0.127 \pm 0.006}$$

  - From the measurement of Event Shape variables we obtain

    $$\boxed{\alpha_{\mathrm{S}}(M_Z) = 0.123 \pm 0.006}$$

- Both measurements agree within the errors
- Error in $\alpha_s(M_Z)$ determination from Event Shape distributions is dominated by theoretical uncertainties