Experimental Status of α_s Measurements

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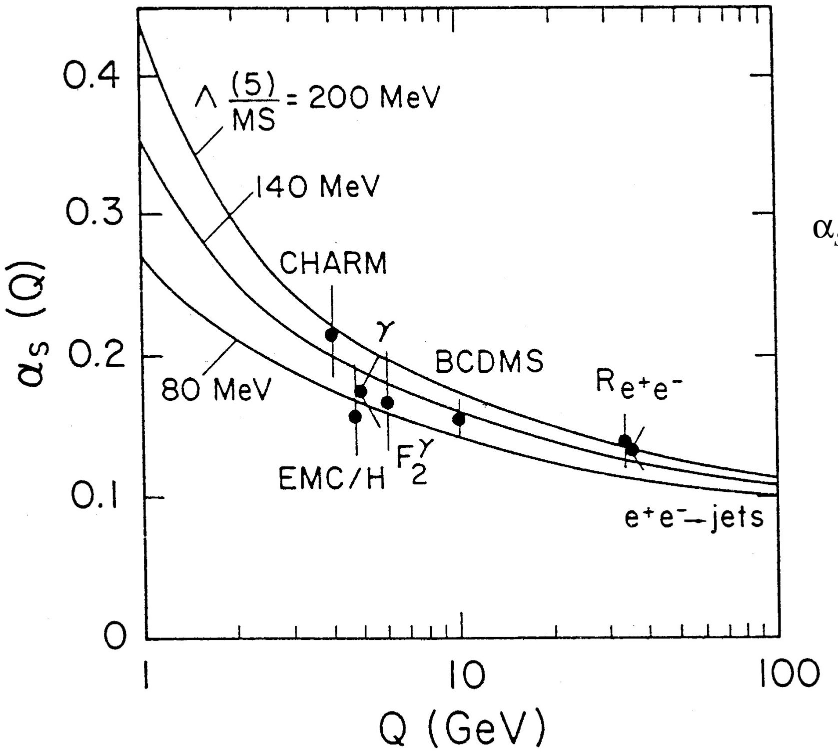
- α_s is the fundamental parameter of QCD, and thus a fundamental parameter of the SM.
- Measurement in many different processes and at different energies is a fundamental test of QCD (and of our ability to calculate it).
- α_s less precisely known than electroweak couplings, but an essential input in consideration of further unification.
- Will try to show how LEP/SLC has furthered our understanding of α_s and our confidence in QCD.
- Collaboration between experimentalists and theorists has been crucial.

History

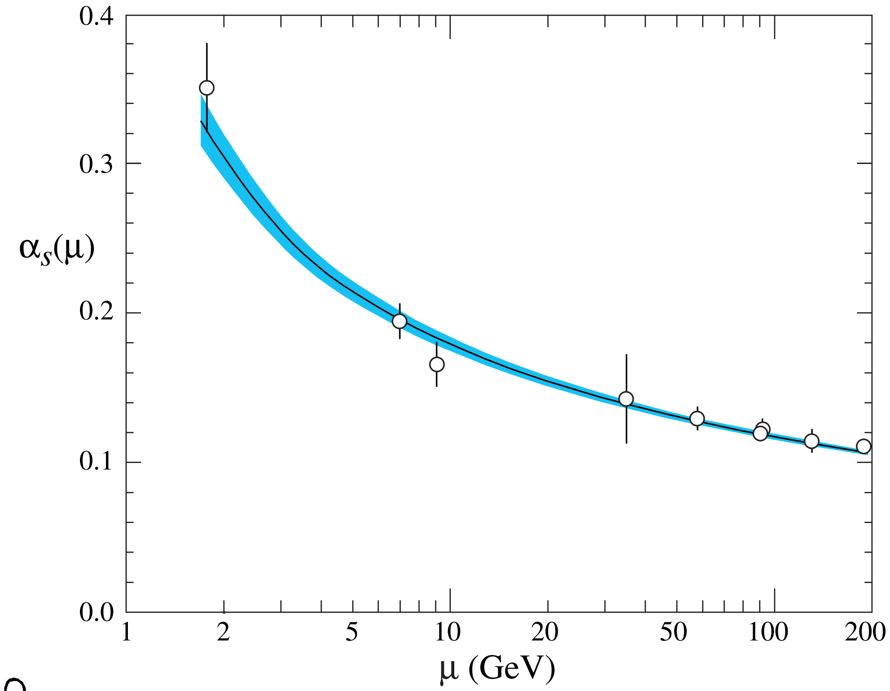
1989



$\alpha_s(M_Z) = 0.11 \pm 0.01$

Physics at LEPI (after Altarelli)

2000



$\alpha_s(M_Z) = 0.118 \pm 0.002$

Particle Data Group 2000

α_s from the Z^0 lineshape

- QCD radiation affects the Z^0 hadronic width, multiplying it by

$$R_{\rm QCD} = 1 + \frac{\alpha_s}{\pi} + 1.409\left(\frac{\alpha_s}{\pi}\right)^2 - 12.805\left(\frac{\alpha_s}{\pi}\right)^3 + \mathcal{O}({\alpha_s}^4)$$

(for massless quarks).

- Reliable prediction – inclusive $\Rightarrow$ negligible hadronization uncertainties; higher order terms small.

- Several of the lineshape observables are sensitive to α_s. $\Rightarrow$

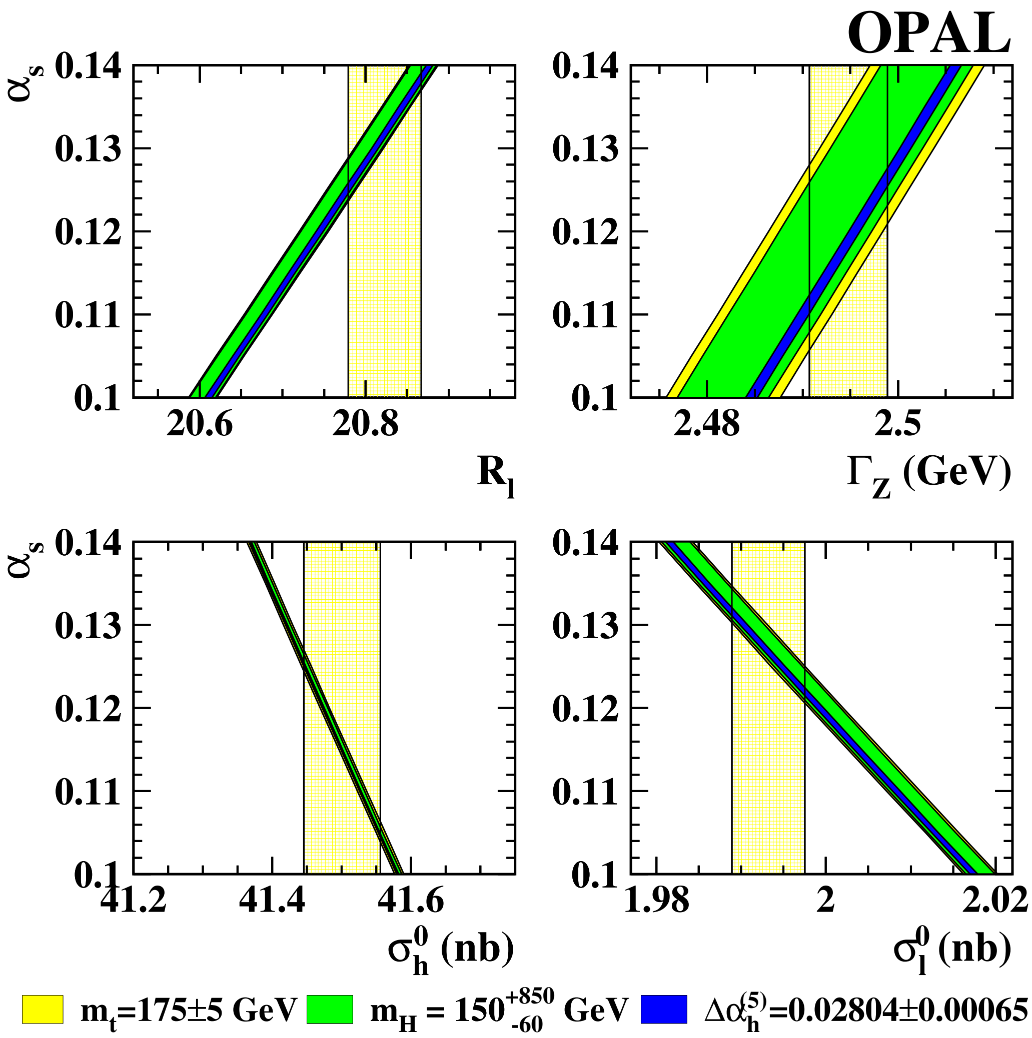
- Hence best determination comes from global fit to all electroweak data, which constrains m_t, m_H etc. from other observables. Quark mass effects etc. are taken into account.

LEP1+SLD	$\alpha_s(M_Z) = 0.119 \pm 0.003$
LEP1+LEP2	$\alpha_s(M_Z) = 0.120 \pm 0.003$
All inputs	$\alpha_s(M_Z) = \mathbf{0.1183^{+0.0026}_{-0.0027}}$

Excluding theoretical error. Various estimates of theoretical error – generally reckoned to be $\mathcal{O}(0.002)$.

α_s from the Z^0 lineshape

- Observables which are sensitive to α_s.



- Of the standard Z^0 lineshape measurements, $R_\ell = \Gamma_{had}/\Gamma_\ell$, Γ_Z and σ_h^0 are all sensitive to α_s. e.g. from R_ℓ alone, $\alpha_s(M_Z) = 0.123 \pm 0.004$. But a combined fit gives better precision.

- σ_ℓ^0 is a derived quantity, which is actually more sensitive to α_s.

α_s from τ-lepton decays

- Analogously to the Z^0, QCD radiation affects the τ-lepton hadronic width, multiplying it by

$$R_{\mathrm{QCD}} = 1 + \frac{\alpha_s}{\pi} + 5.2\left(\frac{\alpha_s}{\pi}\right)^2 + 26.6\left(\frac{\alpha_s}{\pi}\right)^3 + \mathcal{O}({\alpha_s}^4)$$

- Hence, α_s can be extracted from measurements of the τ branching ratio $B(\tau^- \to e^- \nu_\tau \overline{\nu}_e)$ (measured directly, or from the τ lifetime).

- However, at such a low energy, non-perturbative effects likely to be a concern. Estimated using OPE method. Turn out to be a small contribution to R_{QCD}, $\sim -0.014 \pm 0.005$ (Braaten, Narison, Pich).

- Can constrain the NP terms using measurements of spectral moments (i.e. moments of the mass spectrum in hadronic τ decays). These are predicted in terms of the same NP coefficients.

Typical results:

	$\alpha_s(m_\tau)$	$\alpha_s(M_Z)$
ALEPH	0.334 ± 0.022	0.1202 ± 0.0027
OPAL	0.348 ± 0.021	0.1219 ± 0.0022
PDG	0.35 ± 0.03	0.121 ± 0.003

(n.b. the PDG result uses $B(\tau^- \to e^- \nu_\tau \overline{\nu}_e)$ only.)

α_s from jet rates / event shapes

Determination of α_s from 3-jet rate, or other related "event shape" variables is one of the most intuitive techniques.

Observables must be stable under collinear and soft gluon emission, where QCD predictions diverge. More than 20 different observables have been used, e.g.

- 3-jet rate (or resolution parameter y_{23} at which an event changes from 2- to 3-jet). Many schemes available; Durham or k_T scheme most important.
- Thrust
$$T = \max_{\hat{\mathbf{n}}} \left(\frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}|}{\sum_i |\mathbf{p}_i|} \right)$$
- Heavy jet mass M_H^2/s; hemispheres defined by normal to Thrust axis.
- Jet Broadenings B_T, B_W; scaled transverse momenta w.r.t. Thrust axis.

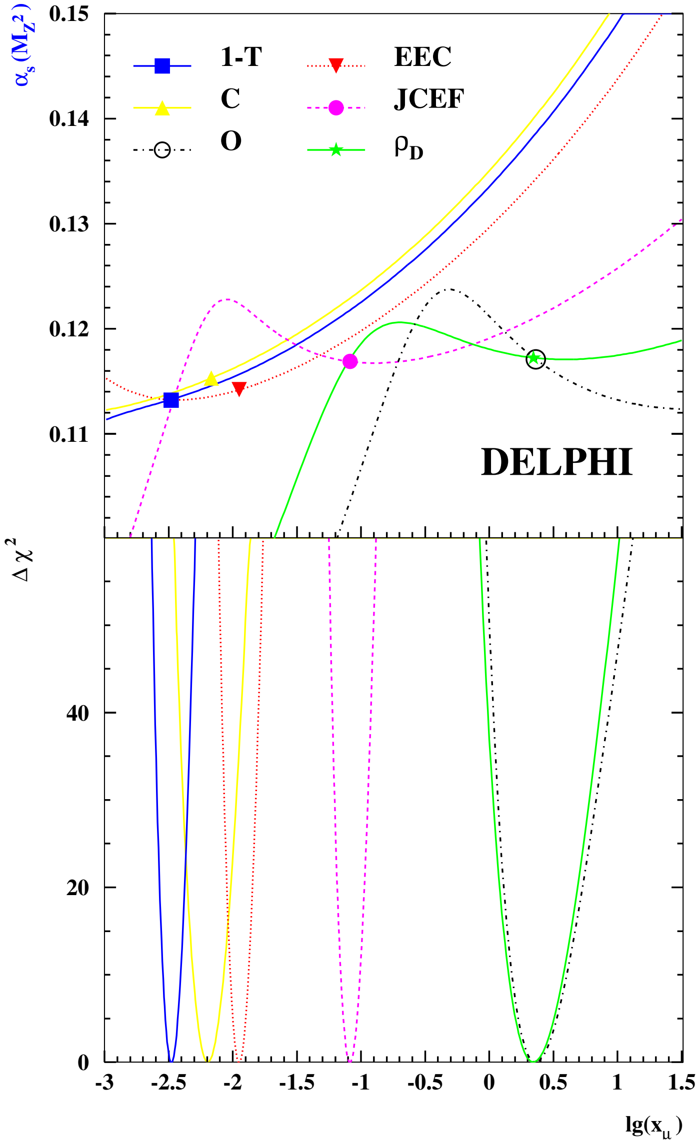
At LEP startup, QCD matrix elements to $\mathcal{O}(\alpha_s^2)$ were known Ellis, Ross, Terrano, $\Rightarrow$ predict distribution of variable y of the form:

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{\alpha_s(\mu)}{2\pi}A(y) + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 \left[A(y)\tfrac{1}{2}\beta_0 \ln({x_\mu}^2) + B(y)\right]$$

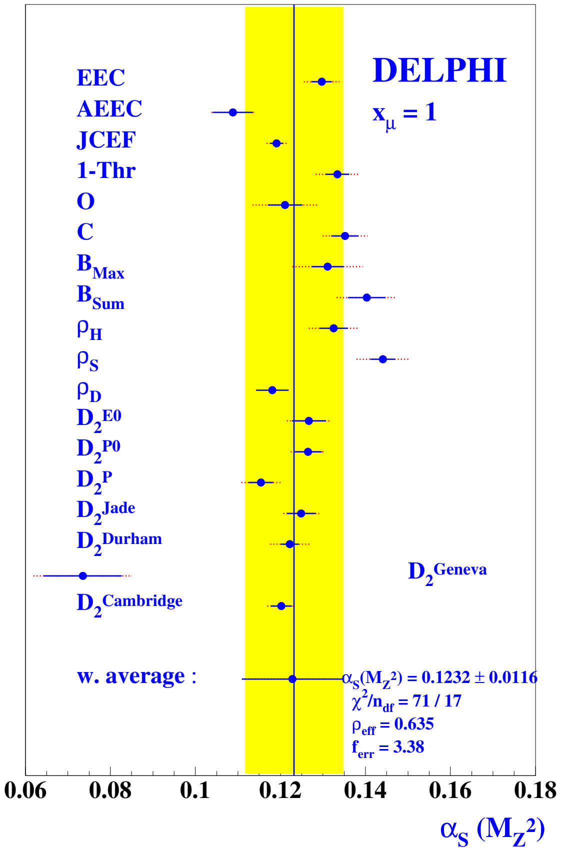
where μ is the renormalization scale, and $x_\mu = \mu/\sqrt{s}$.

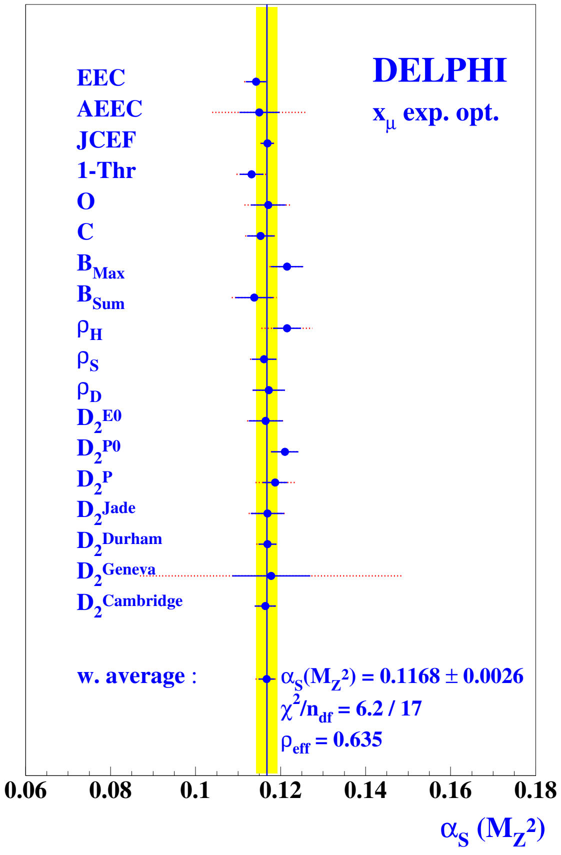
α_s from event shapes: $\mathcal{O}(\alpha_s^2)$

- Leading order coefficient $A(y)$ may be computed analytically; $B(y)$ by numerical integration (EVENT Kunszt+Nason EVENT2 Catani+Seymour).
- All orders calculation would be independent of choice of renormalization scale μ, but fixed-order predictions depend on x_μ.
- Natural to expect $\mu \sim \sqrt{s}$, or $x_\mu \sim 1$. However, data generally favour a value $x_\mu \ll 1$. Indication of importance of higher orders $\rightarrow$ systematic error.
- The other important systematic is hadronization (need to correct hadron$\rightarrow$parton-level before fitting QCD predictions).



α_s from event shapes: $\mathcal{O}(\alpha_s^2)$





Similar results on the Z^0 from all experiments, various observables, differences in treatment of scale uncertainties.

ALEPH	0.121 ± 0.008
DELPHI	0.117 ± 0.003
L3	0.118 ± 0.007
OPAL	0.122 ± 0.006
SLD	0.123 ± 0.011

My average would be

$$\alpha_s(M_Z) = 0.120 \pm 0.005$$

n.b. greater consistency of results when optimized scale is used.

α_s from event shapes : resummation

- $\mathcal{O}(\alpha_s^2)$ QCD predictions diverge in the two-jet region. Specifically, leading order prediction for observable y behaves, as $y \to 0$, like

$$R(y) = \int_0^y (1/\sigma)(\mathrm{d}\sigma/\mathrm{d}y')\mathrm{d}y' \propto \alpha_s L^2$$

where $L = \ln(1/y)$.

- In general, leading term at $\mathcal{O}(\alpha_s^n)$ is of the form $(\alpha_s L^2)^n$. At small y, $\alpha_s L^2$ is not small, so predictions not reliable unless summed to all orders.

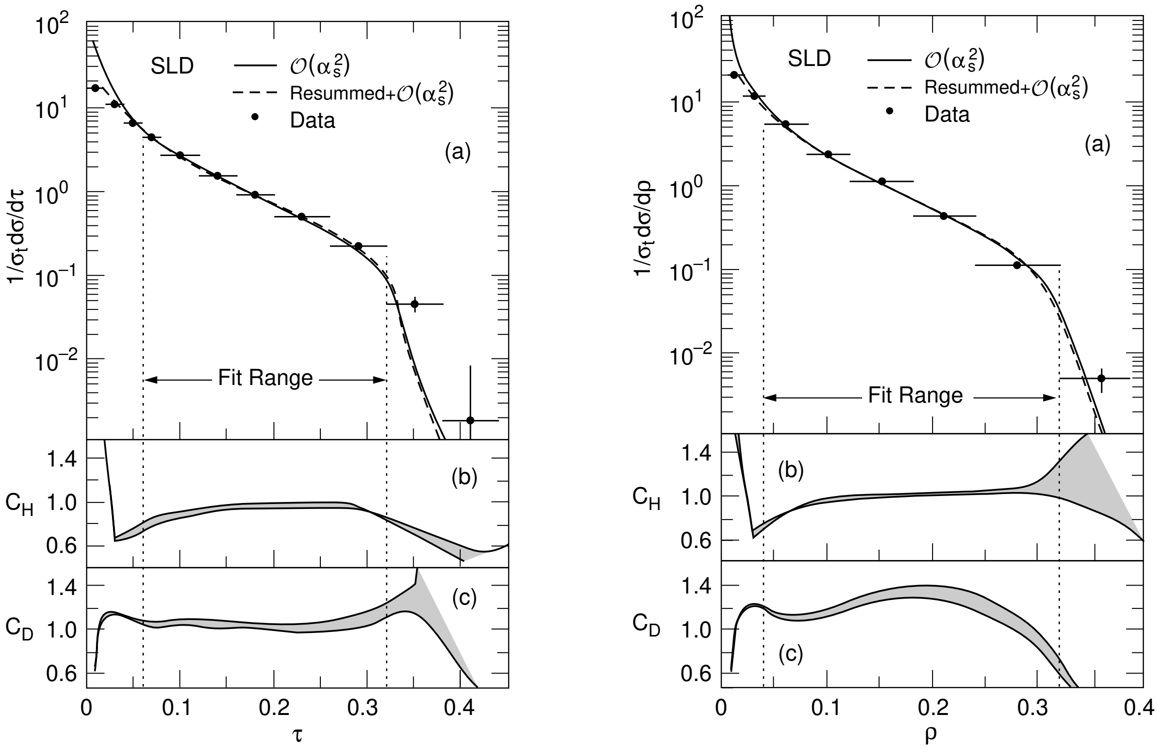
- Such "resummation" of leading and next-to-leading logarithms has proved possible for a few event shape variables (NLLA).(Catani, Webber, Turnock, Trentadue, Dokshitzer, Olsson ...) giving a prediction of the form:

$$R_{NLLA}(y) = (1+C_1\alpha_s+C_2\alpha_s^2)\exp[Lg_1(\alpha_s L)+g_2(\alpha_s L)] \quad .$$

- By careful use of a "matching scheme", $\mathcal{O}(\alpha_s^2)$ and NLLA calculations can be combined without double counting common terms. These are the state-of-the-art calculations for $\mathrm{e}^+\mathrm{e}^-$ event shapes at present, and have largely superseded the $\mathcal{O}(\alpha_s^2)$ approach.

α_s from event shapes : $\mathcal{O}(\alpha_s^2)$+NLLA

- Example of fits to $\mathcal{O}(\alpha_s^2)$+NLLA QCD calculations. Note improved description of data in low y region.

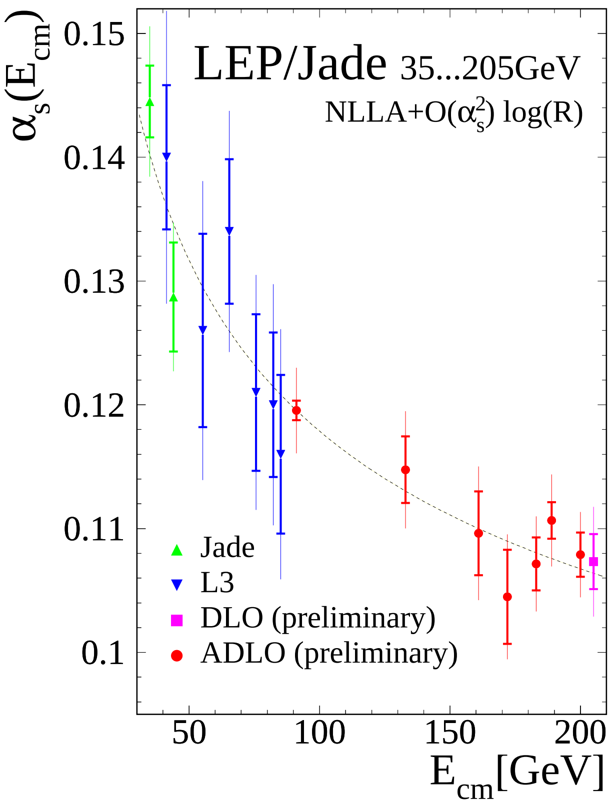


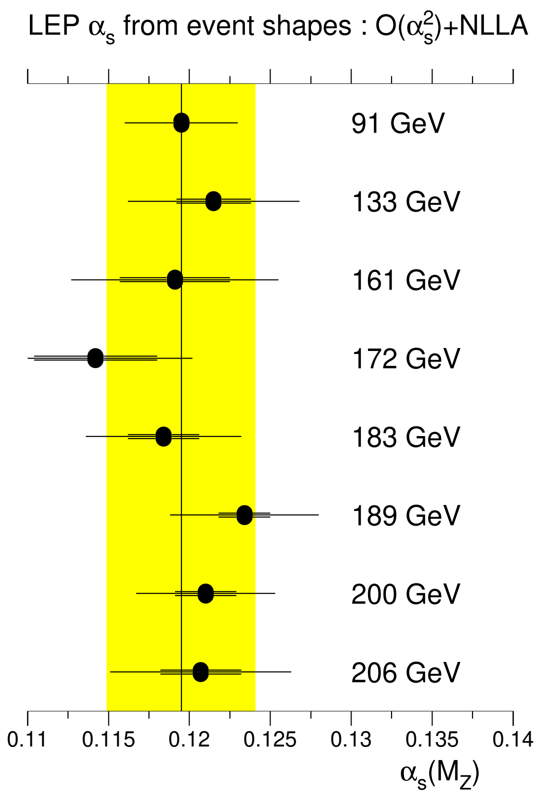
- Sensitivity to renormalization scale reduced – data can be fitted with $x_\mu = 1$, though dependence on x_μ still the largest systematic error.
- Results from LEP1 using $\mathcal{O}(\alpha_s^2)$+NLLA QCD calculations (various combinations of observables):

ALEPH	0.120 ± 0.004
DELPHI	0.125 ± 0.007
L3	0.122 ± 0.007
OPAL	0.120 ± 0.006
SLD	0.118 ± 0.006

α_s at LEP2

- All LEP experiments have produced measurements of α_s at many energies at LEP2. Based on $\mathcal{O}(\alpha_s^2)$+NLLA QCD calculations.
- Main interest – running of α_s. Hadronization errors much smaller than at LEP1, but statistical (and some experimental systematic) errors sizeable because of small data samples.
- LEP QCD Working Group has been combining α_s measurements from ADLO. Results from October 2000:





Combined fit $\Rightarrow$

$$\alpha_s(M_Z) = 0.1195 \pm 0.0007\text{(expt.)}\pm 0.0046\text{(theo.)}$$

(LEP1+LEP2).

α_s at LEP2

LEP QCD Working Group working actively to improve the combination of LEP results:

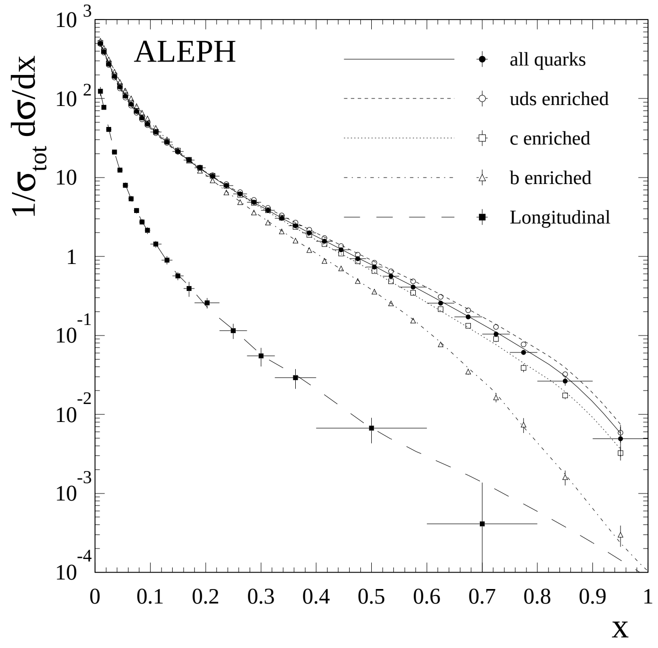
- Detailed checks and comparisons of theoretical calculations used. $\Rightarrow$ Minor bugs fixed.
- Improved calculations for B_T, B_W, y_{23}, C became available since LEP1 era $\rightarrow$ apply retrospectively.
- More complete coverage of observables/energies.
- Consistent use of $\log(R)$ matching scheme, with treatment of kinematic constraints for NLLA calculations.
- Harmonize treatment of systematic errors. Theoretical errors covered; hadronization still to be done.

Work nearly complete; appears that net changes will be small compared to total errors.

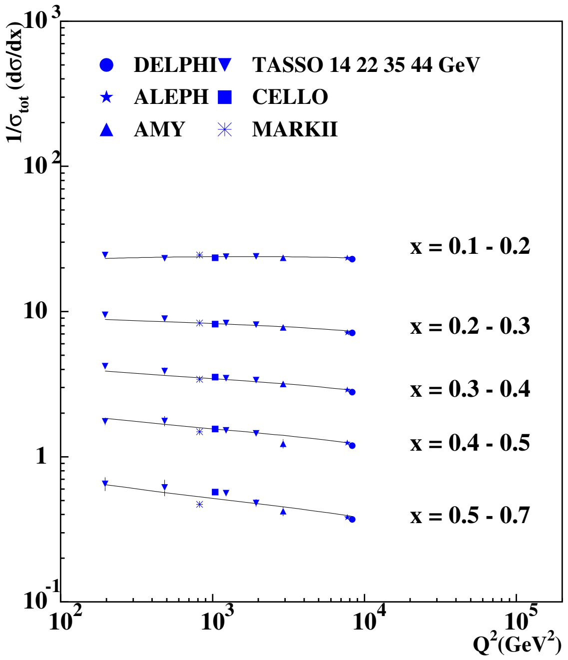
α_s from scaling violations

- Scaling violations in fragmentation functions permit determination of α_s (c.f. scaling violations in DIS).
- Needs data at different energy scales $\Rightarrow$ different flavour mix. Thus need measurements of *flavour-dependent* fragmentation functions (exploiting b- and c-tagging).
- Also need information on gluon fragmentation (using 3-jet events or longitudinal fragmentation function).

Fragmentation functions



Scaling violations



Results using LEP1 +PETRA/PEP data:

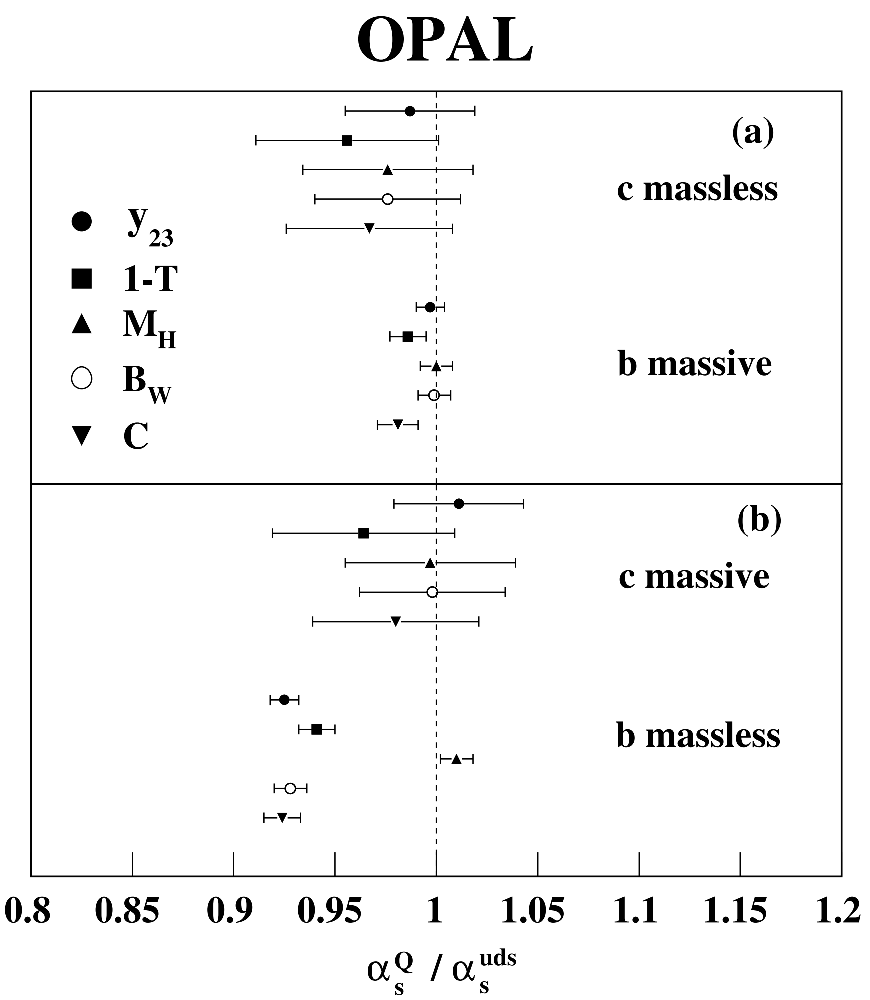
ALEPH $\quad \alpha_s(M_Z) = 0.126 \pm 0.009$

DELPHI $\quad \alpha_s(M_Z) = 0.124 \pm 0.011$

No published results using LEP2 yet.

Flavour dependence of α_s

- QCD requires flavour independence of α_s.
- Flavour tagging developed for LEP electroweak measurements can also be used to test flavour dependence of α_s. Measurement can then be made using usual observables.
- Quark mass effects suppress gluon radiation from heavy quarks. Necessary to take these into account.



Most precise published results (from SLD/OPAL) validate flavour independence of α_s to $\sim 1.5\%$ for b-quarks and to $\sim 5\%$ for c-quarks.

Power corrections and α_s

- Standard approach is to use MC models (JETSET, HERWIG etc.) to account for hadronisation, i.e. for non-perturbative contributions at scales where α_s diverges.

- On general grounds, non-perturbative effects expected to be suppressed by powers of the energy scale $Q(=\sqrt{s})$. In this case $\propto \frac{1}{Q}$ (or $\propto \frac{1}{Q^2}$ in the case of y_{23}).

- Approach due to Dokshitzer, Marchesini, Webber introduces non-perturbative parameter

$$\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} \alpha_s(q)\mathrm{d}q$$

  to parametrise the low energy behaviour of α_s, where $\mu_I = 2$ GeV.

- Predictions for event shape observables y take the form:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{\mathrm{d}\sigma_{\mathrm{Pert}}}{\mathrm{d}y}(y - \mathcal{P}D_y)$$

  where $\mathcal{P}$ is a universal factor, $\propto \frac{1}{Q}$, and D_y depends on the observable, i.e. a simple shift of the distribution.

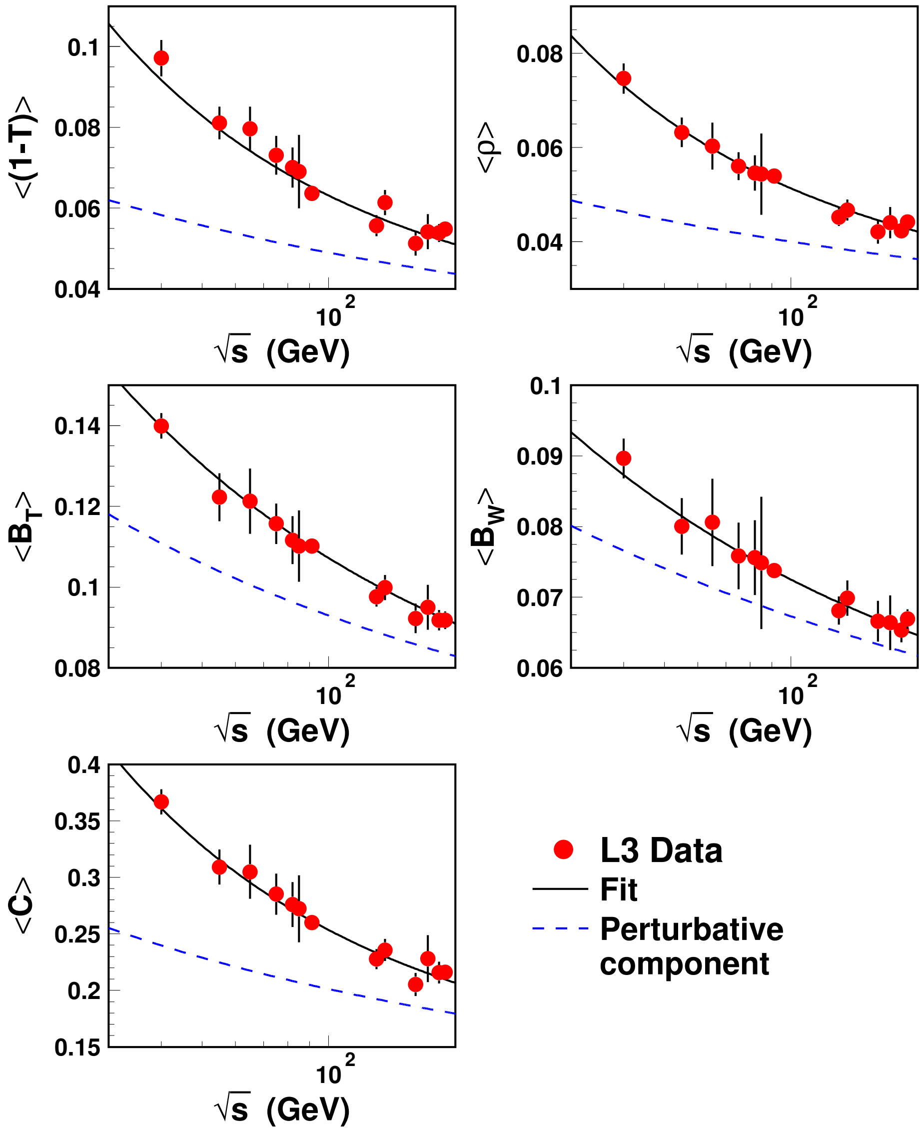
- Can fit data – either distributions, or moments such as $\langle(1-T)\rangle$ – to determine α_s and $\alpha_0(\mu_I)$.

Power corrections and α_s

- Example of power correction fits to moments, using L3 data.
- L3 obtain data below 91 GeV by using Z^0 events with high energy radiated photons. Could also use data from PETRA etc.
- Recent comprehensive analysis using all available data, fitting both moments and distributions, quotes:

$$\alpha_s(M_Z) = 0.1171^{+0.0032}_{-0.0020}$$

- See S. Kluth's talk for more about power corrections.

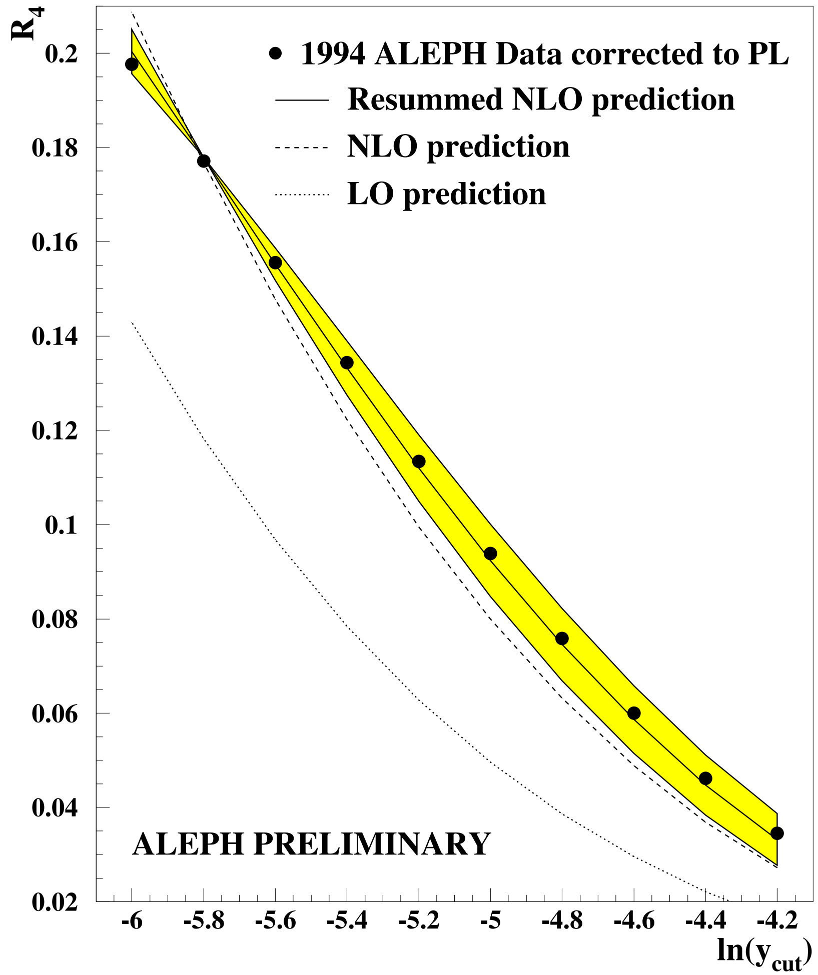


α_s from 4-jet events

- NLO (i.e. $\mathcal{O}(\alpha_s^3)$) corrections to 4-parton final states have been computed Dixon, Signer, Glover, Nagy, Trócsanyí, though $\mathcal{O}(\alpha_s^3)$ contributions to 2- and 3-jet observables not yet known.
- Provides new possibilities for α_s measurement using 4-jet rates, or other observables.
- Preliminary results:

ALEPH	0.117 ± 0.004
DELPHI	0.118 ± 0.002

in good agreement with 3-jet observables. Errors small because optimised scale employed.



α_s from 4-jet events

- All measurements of α_s mentioned so far assume SU(3) group structure of QCD.
- Measurements of QCD colour factors based on 4-jet events using $\mathcal{O}(\alpha_s^2)$ matrix elements are independent of α_s.
- Can now use NLO 4-parton calculations and simultaneously determine α_s and colour factors.
- First such measurements appeared recently:

OPAL	$0.120 \pm 0.011 \pm 0.020$
ALEPH (prelim.)	$0.119 \pm 0.006 \pm 0.022$

  yielding results for α_s (and colour factors) consistent with other measurements, but with large theoretical errors.

See talks of K. Hamacher and S. Kluth for more discussion of colour factors.

Summary

- High precision of LEP data, together with substantial theoretical developments, have allowed great progress in the precision of α_s measurements.
- Excellent agreement among methods, and with world average (which includes LEP data) $\alpha_s = 0.118 \pm 0.002$ (PDG 2000).