Event shape studies at LEP

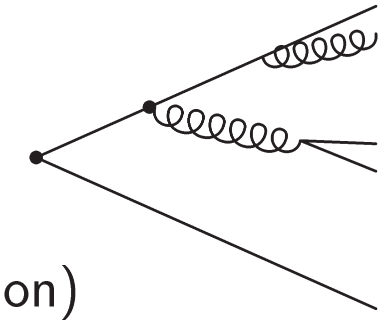
Daniel Wicke
(CERN)

Outline

- Introduction
- Measurements
- Interpretation (α_s, structure constants, power corrections, RGI)
- Combined results (running and coupling)
- Summary

Introduction (1): Observables

Event shapes are directly connected to fundamental properties of QCD.



Sensitive to α_s, but insensitive to non-perturbative effects:

- Infrared safe (i.e. invariant under emission of a no energy gluon)
- Collinear safe (i.e. splitting a parton into two parallel)

Example: Thrust:

$$T := \max_{|\vec{n}|=1} \sum_{i=1}^{n} |\vec{p_i} \cdot \vec{n}| \Big/ \sum_{i=1}^{n} |\vec{p_i}|$$

No connection to production rate.

$$\langle 1 - T \rangle \qquad \mathcal{D}_T(T) = \frac{1}{\sigma_{\mathrm{tot}}} \frac{\mathrm{d}\sigma(T)}{\mathrm{d}T}$$

Such observables are calculable from QCD, not relying on the electro-weak part:

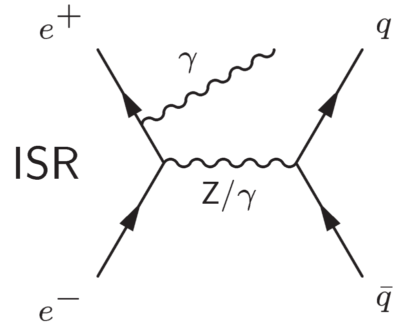
E.g. second order: $\mathcal{D}_y(y) = A(y)\alpha_s(\mu) + B(y,\mu)\alpha_s^2(\mu)$

Introduction (2): Experimental

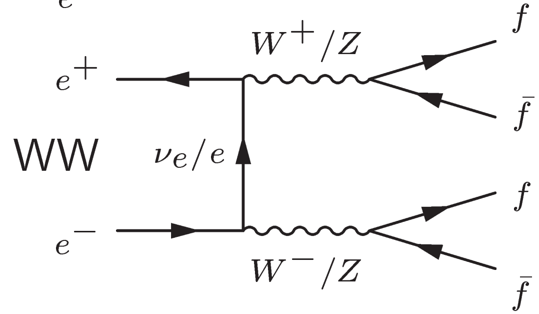
(1) Track and cluster selection (obviously detector dependent)

(2) Event selection: suppression of backgrounds:

- Bhabha, $\tau^+\tau^-$, $\gamma\gamma$



- Initial state radiation (“Z-returns”)
- W-pair production

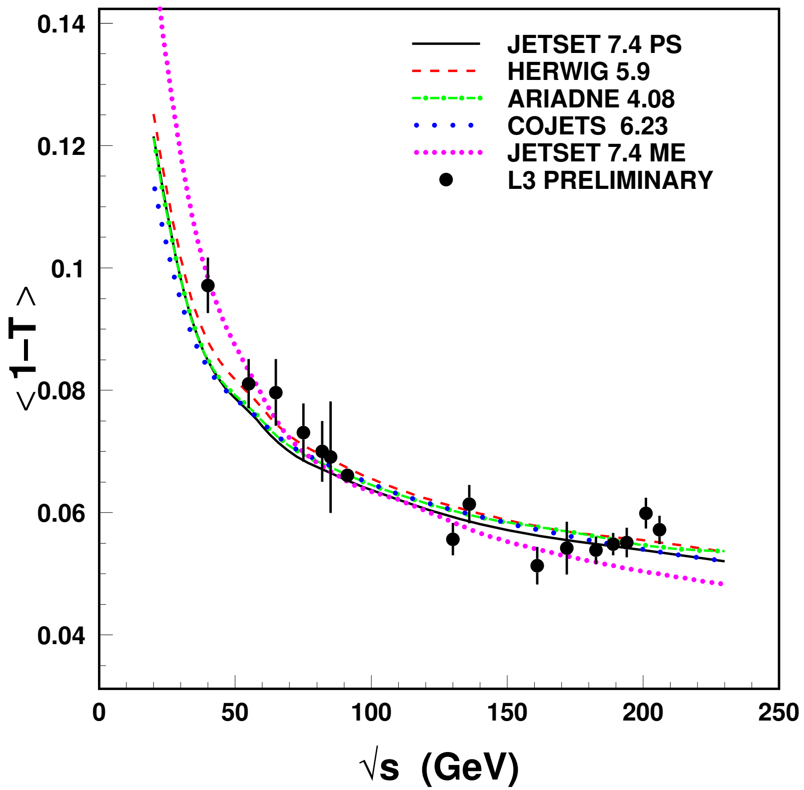


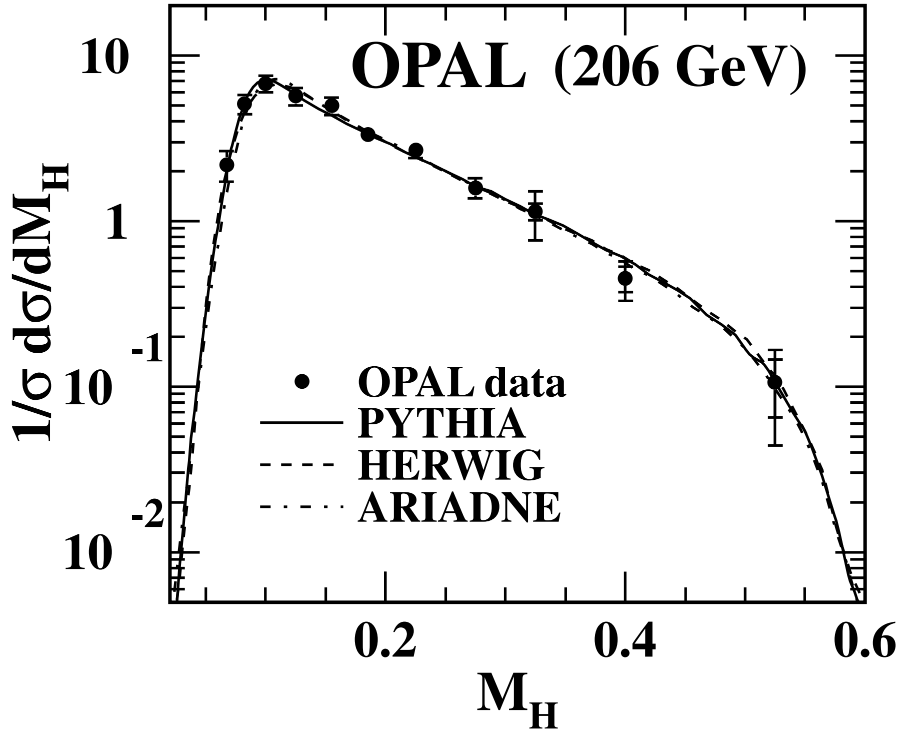
(3) Correct the measured quantities for detector effects to be comparable.

Attention: this is ambiguous.
Stable particles with or without neutrinos and charged only are in use at LEP.

Event shape results compared to MC models

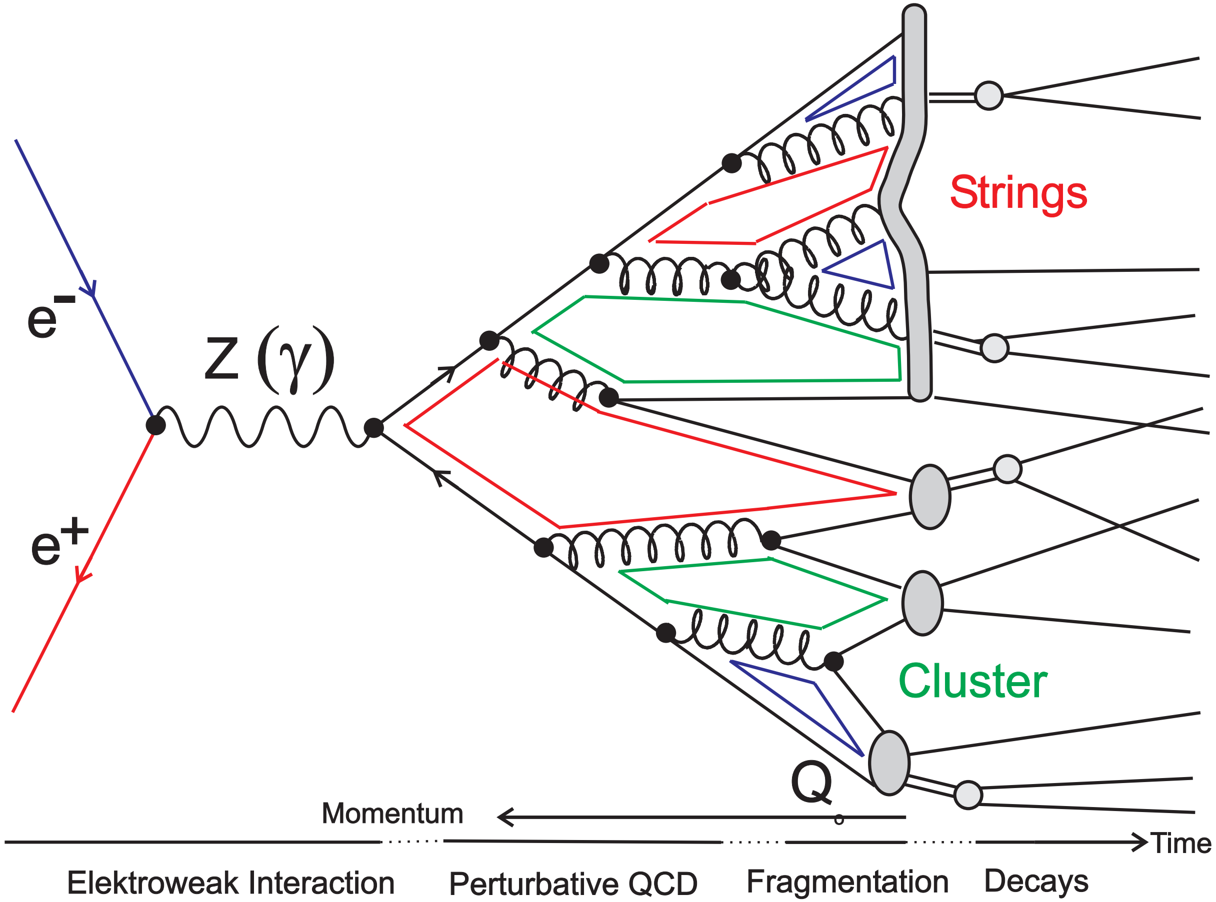
OPAL #205, L3 #510





- Good agreement between data and (tuned) MC.
- ME has deficits in describing the energy evolution.

Introduction (3): Matching theory with data



$\mathcal{O}(\alpha_s^2)$, NLLA, combined $\mathcal{O}(\alpha_s^2)$+NLLA

$\mathcal{O}(\alpha_s^3)$

Monte Carlo Generators

Power Corrections

Measurements of the strong coupling

Results for the strong coupling at $E_{\mathrm{cm}} = 206$ GeV

OPAL #205, DELPHI #313, L3 #510

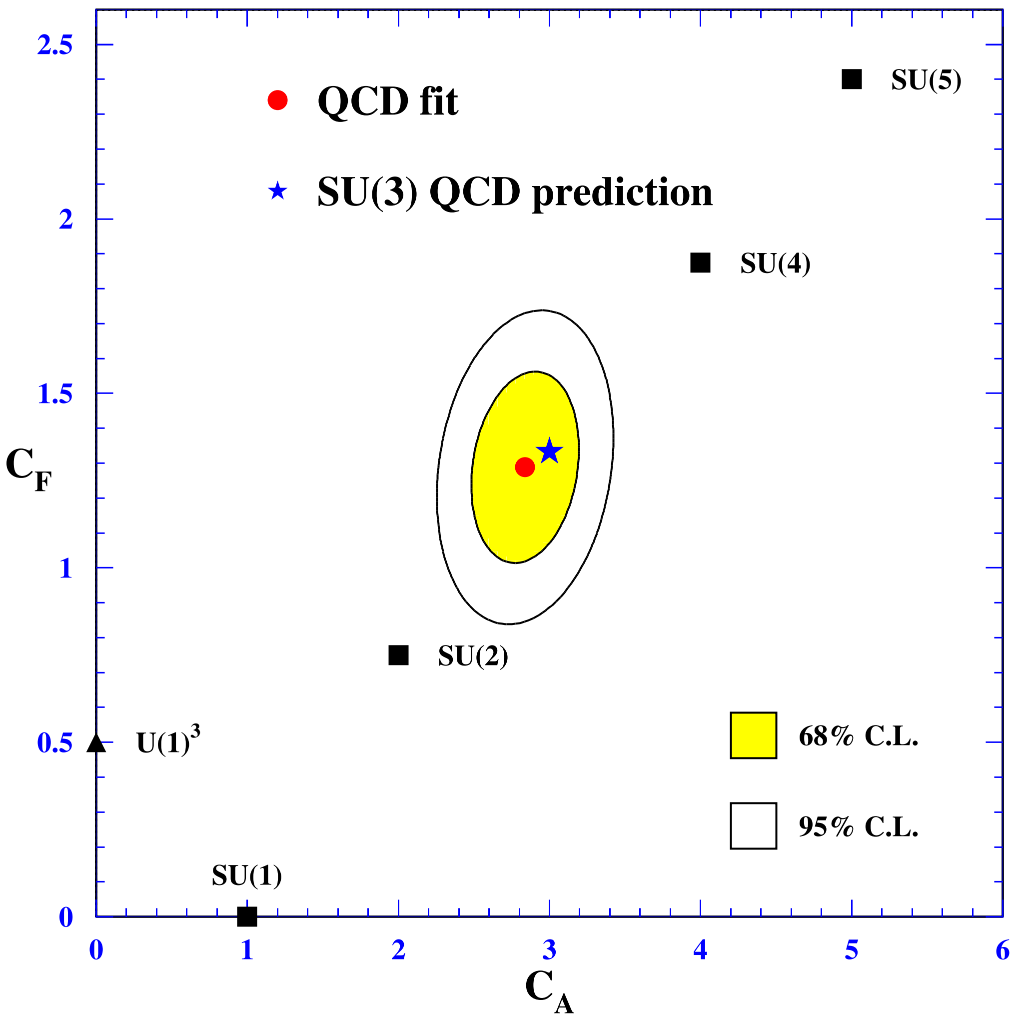
- $\mathcal{O}(\alpha_s^2)$+NLLA $\log R$-scheme with MC based hadronisation corrections.
- DELPHI and L3 used $1-T$, ρ_h, C, B_t and B_w.
- OPAL used in addition y_{23}.
- The results are in good agreement with each other. Combination yields:

$$\alpha_s(206\,\text{GeV}) = 0.1080 \pm 0.0014 \pm 0.0043$$

- OPAL and L3 use still outdated predictions for the broadenings.

DELPHI used also pure $\mathcal{O}(\alpha_s^2)$ with optimised scales and pure NLLA and found agreement within the large theoretical uncertainties.

Measurement of structure constants (S. Kluth *et al.*) #271



- Treat the structure constants C_F, C_A and n_f in the predictions as free parameters.
- $\mathcal{O}(\alpha_s^2)$+NLLA $\log R$ together with power corrections are applied.
- Event shape distributions from 14 to 189 GeV.
- Combined results obtained with fixed α_0.

Power Corrections

#269, #275, #310

Mean values get increased

$\langle y \rangle = \langle y_{\text{pert}} \rangle + c_y \mathcal{P}$

Distributions are shifted

$\mathcal{D}_y(y) = \mathcal{D}_{\text{pert}}(y - c_y \mathcal{P})$

by a term that falls off like $1/E_{\text{cm}}$:

$$\mathcal{P} = \frac{4C_F}{\pi^2} \mathcal{M} \frac{\mu_I}{E_{\text{cm}}} \left[\alpha_0(\mu_I) - \alpha_s(\mu) - \left(b_0 \cdot \log \frac{\mu^2}{\mu_I^2} + \frac{K}{2\pi} + 2b_0 \right) \alpha_s^2(\mu) \right]$$

(Dokshitzer and Webber, 94)
(Dokshitzer, Lucenti, Marchesini and Salam, 97)

Here $\alpha_0(\mu_I)$ is a (universal) non-perturbative parameter accounting for contributions from below the infrared matching scale μ_I.

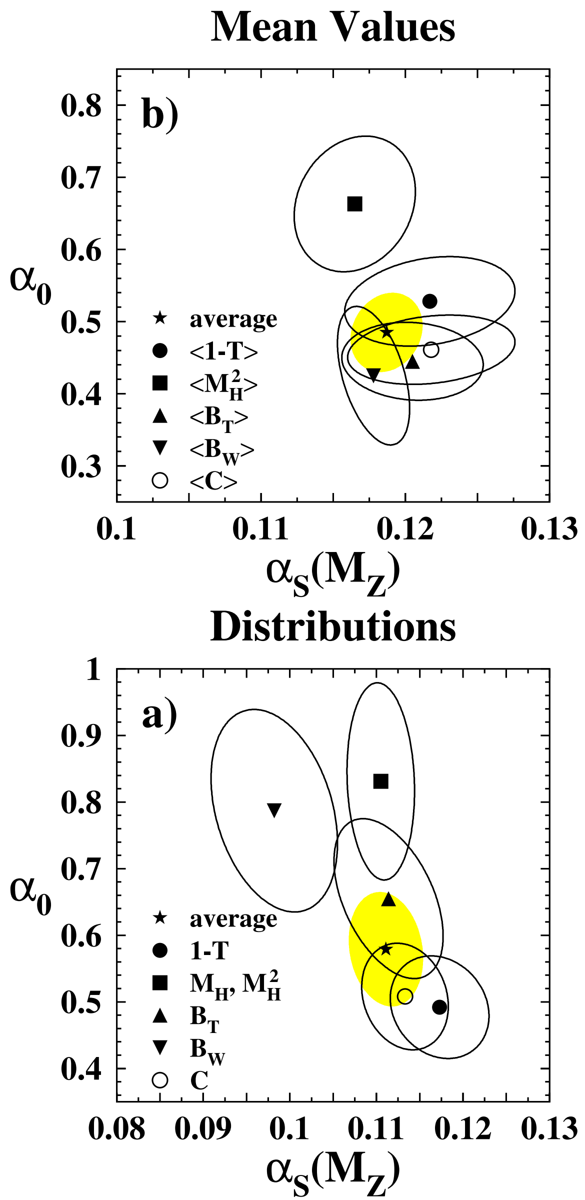
$$\alpha_0(\mu_I) = \frac{1}{\mu_I} \int_0^{\mu_I} \mathrm{d}k \, \alpha_s(k)$$

Observable specific properties are absorbed in c_y:

$$c_{1-T} = 2 \qquad c_{M_{\text{h}}^2/E_{\text{vis}}^2} = 1 \qquad c_{B_{\max}} \sim \frac{1}{\sqrt{\alpha_s(E_{\text{cm}})}}$$

Determination of α_s from power corrections

Movilla Fernández *et al.* #269



- Two parameter fits of $\alpha_s(M_Z)$ and α_0 to data with $E_{\mathrm{cm}} = 14$ to $189\,\mathrm{GeV}$:

- Means:
  $\alpha_s(M_Z) = 0.1187 \pm 0.0014 \pm 0.0001^{+0.0028}_{-0.0015}$
  $\alpha_0(2\,\mathrm{GeV}) = 0.485 \pm 0.013_{\mathrm{fit}} \pm 0.001_{\mathrm{sys}}{}^{+0.065}_{-0.043}{}_{\mathrm{th}}$

- Distributions:
  $\alpha_s(M_Z) = 0.1111 \pm 0.0004 \pm 0.0020^{+0.0044}_{-0.0031}$
  $\alpha_0(2\,\mathrm{GeV}) = 0.579 \pm 0.005_{\mathrm{fit}} \pm 0.011_{\mathrm{sys}}{}^{+0.099}_{-0.081}{}_{\mathrm{th}}$

- The heavy jet mass (in both cases) and the wide jet broadening (in distributions) yield high α_0 results.

Mass effects in power corrections

(G.P. Salam & D.W.) #275

- All used calculations were done for massless particles

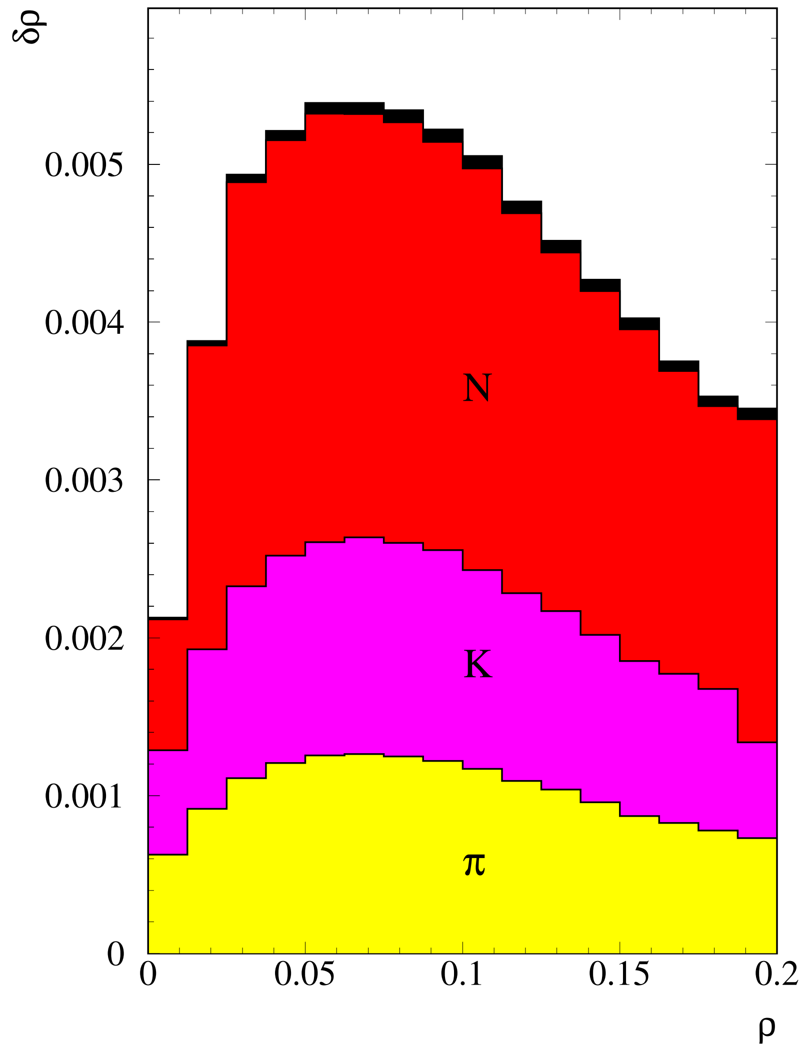
- In the massless case observables calculated with

  $$p = (\vec{p}, E) \quad \longrightarrow \quad (\vec{p}, |\vec{p}|) \quad (p\text{-scheme})$$
  $$p = (\vec{p}, E) \quad \longrightarrow \quad (\hat{p}E, E) \quad (E\text{-scheme})$$

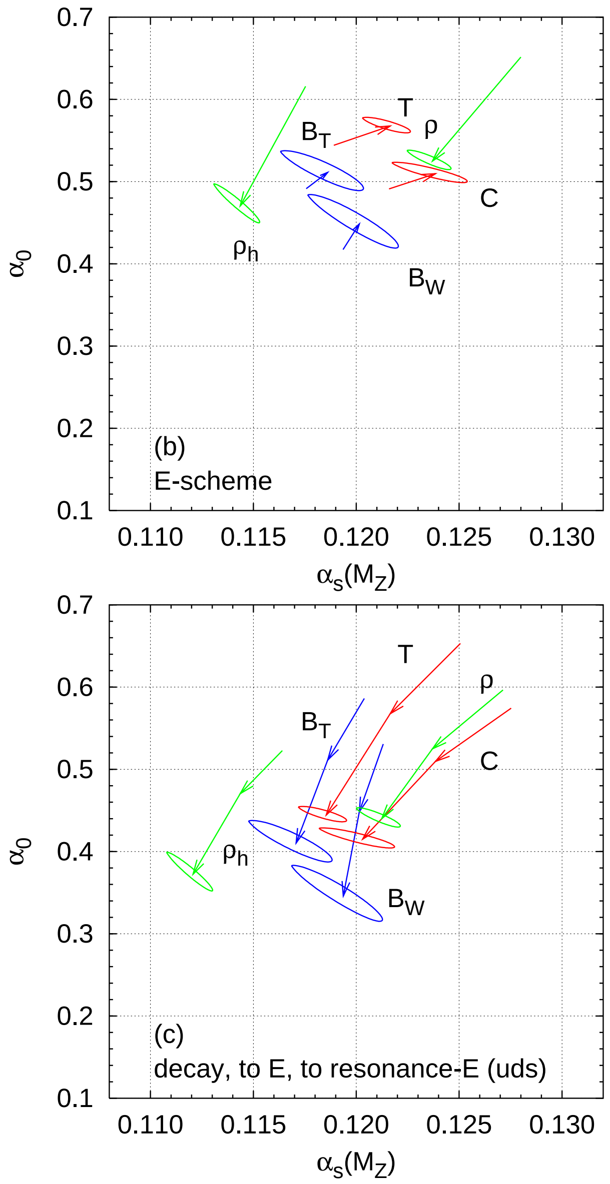
  are equivalent to the standard observ.

- Their differences in the case of massive hadrons behave like a observable dependent power correction.

- E-scheme has no non-universal power correction.



Mass effects in power corrections (2)



- Correcting existing data to the E-scheme using Ariadne allows to check the effect.
- Mean jet mass shows improved consistency.
- For the heavy jet mass it overshoots.
- It may be a hint that the two lowest results on α_0 stem from single hemisphere observables.

- The "hadron level" is ambiguous
- The most extreme levels are
  Resonance — build directly from the string
  Decay — artifically decay also stable particles
- They differ by 0.007 in $\alpha_s(M_Z)$.

Renormalisation group invariant perturbation theory

DELPHI #310

Use the observable itself as expansion parameter

$\longrightarrow$ No dependence on renormalisation scale.

For a mean event shape $R = \langle f \rangle / A_f$

$$Q\frac{\mathrm{d}R}{\mathrm{d}Q} = -\frac{1}{2}\beta_0 R^2 \left(1 + \frac{\beta_1}{2\beta_0}R + \rho_2 R^2 + \ldots\right)$$

$\longrightarrow$ Does allow to measure β_0 directly from a mean event shape, e.g. $\langle 1 - T \rangle$;

This equation can be solved in the same way as the RGE with an integration constant Λ_R which can be connected to $\Lambda^{\mathrm{QCD}}_{\overline{\mathrm{MS}}}$.

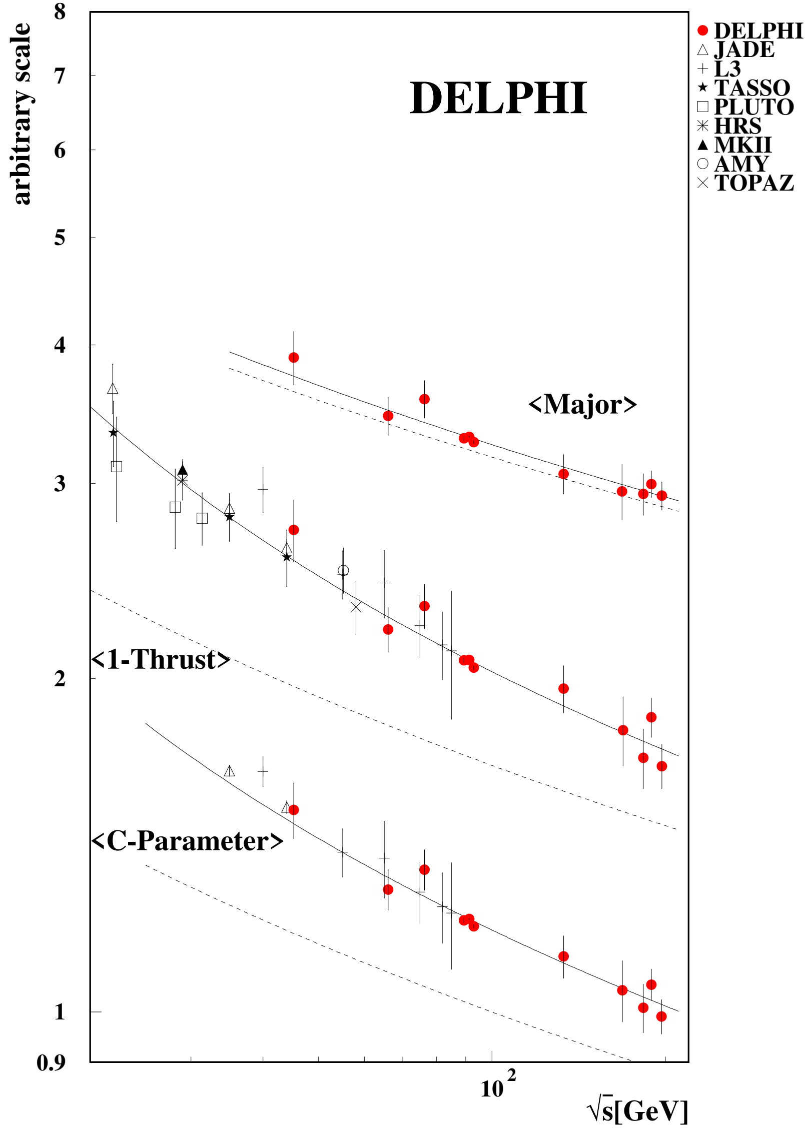
$\longrightarrow$ Does allow to measure $\Lambda^{\mathrm{QCD}}_{\overline{\mathrm{MS}}}$.

RGI with power corrections

- Gives good description of the data with a small spread from 7 observables (requires to use E-scheme def. of jet masses)
- $\alpha_s(m_Z) = 0.1172$ with a spread of 0.0040
- Power terms are compatible with zero.

Comparing pure RGI to data

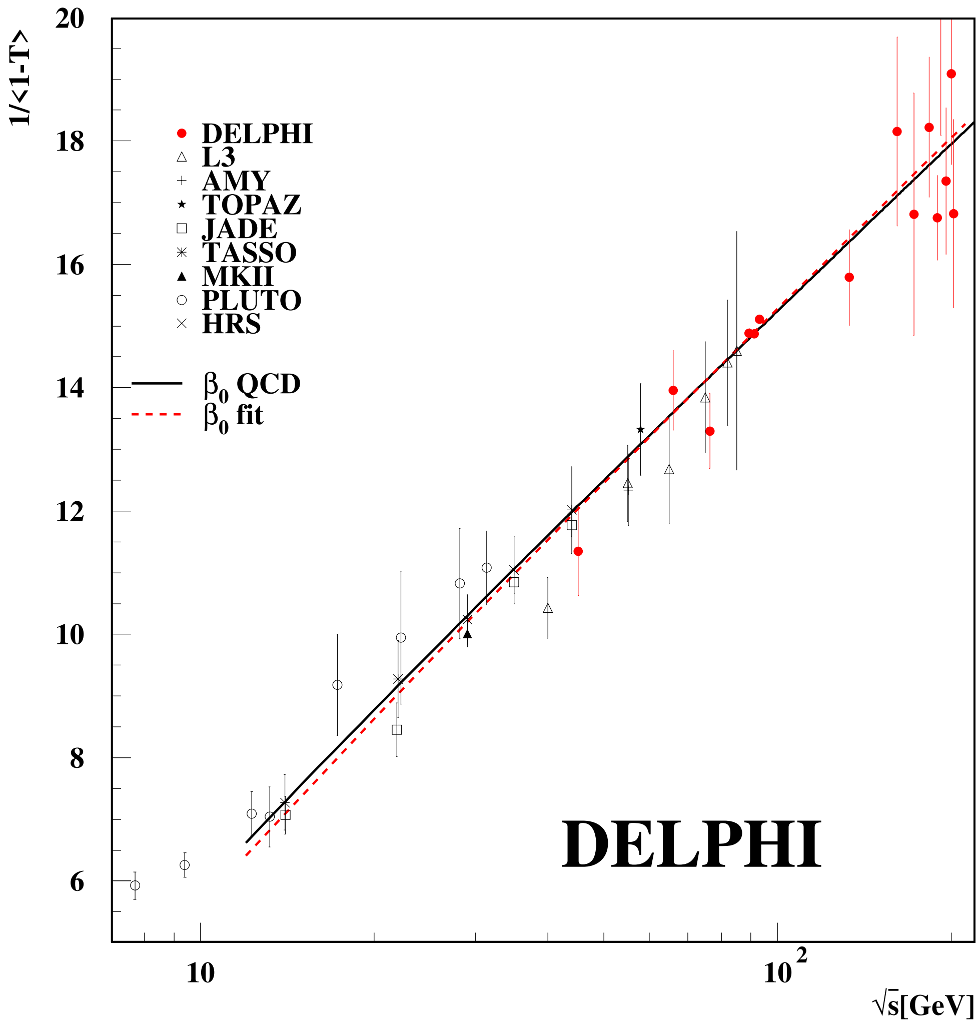
- Gives still a good description of the data with a even smaller spread from 7 observables.
- $\alpha_s(m_Z) = 0.1195$ with a spread of 0.0020
- Mean values can be described without hadronisation correction at 2% level, using a theory that has no renormalisation scale freedom.



Are power corrections to a large part perturbative?

Measuring the β-function with RGI

As a 2% difference does not influence the slope, one can use pure RGI to determine the β-function:



From DELPHI data:

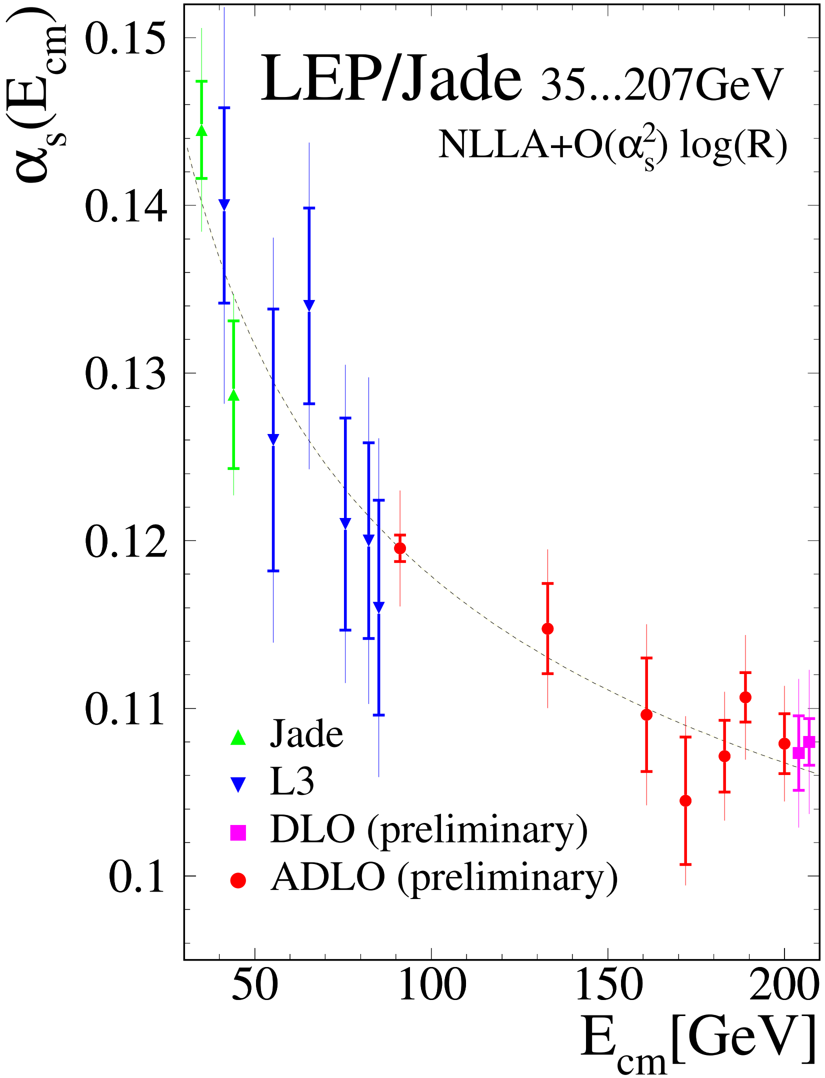
$$\frac{\beta_0}{2\pi} = 1.23 \pm 0.16 \qquad n_{\mathrm{f}} = 4.7 \pm 0.7$$

Including low energy data points:

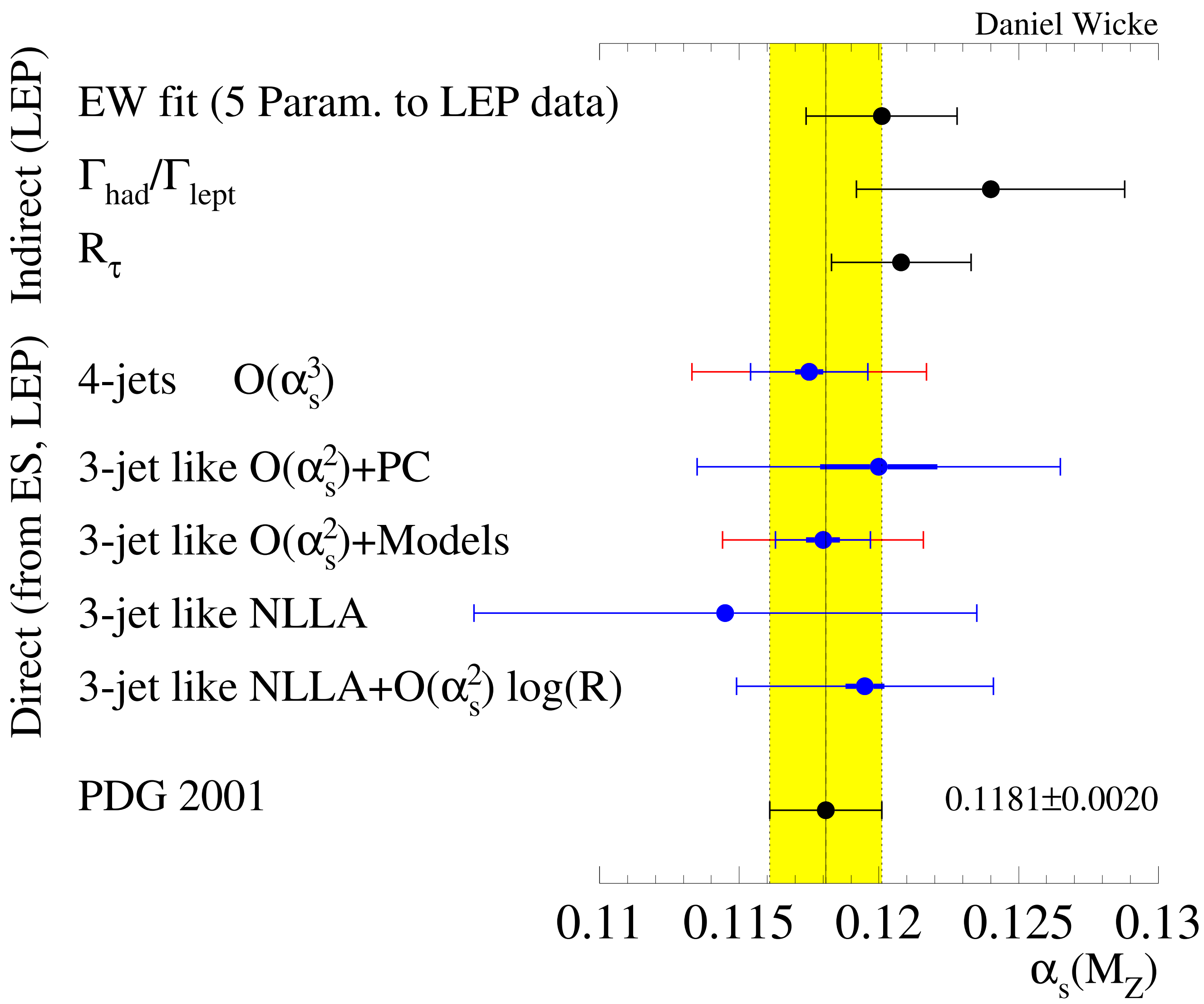
$$\frac{\beta_0}{2\pi} = 1.25 \pm 0.05 \quad n_{\mathrm{f}} = 4.75 \pm 0.44$$

The running of the strong coupling

- The LEP QCD WG has combined the results from energies between 41 and 205 GeV
- Inputs were given by the experiments seperating stat, exp. syst, hadronisation and scale uncertainty.
- Correlations between experiments and between different energies were taken into account.
- An overall $\mathcal{O}(\alpha_s^3)$-fit yields $\alpha_s(M_Z) = 0.1195 \pm 0.0007 \pm 0.0048$ with $\chi^2/\mathrm{ndf} = 31.3/36$.



Comparison of α_s results from LEP



Summary

- Infrared and collinear safe event shapes are a direct probe to hard QCD

- There are still many different options,
  both on the perturbative and on the non-perturbative side.
  – Experimentalists and theorists are interacting to improve the understanding.
  – RGI gives an incredible precise description of mean event shapes.

- Direct measurements of α_s from $E_{\mathrm{cm}} = 41$ to $205\,\mathrm{GeV}$ combined by the LEP QCD WG yield

  $$\alpha_s(M_Z) = 0.1195 \pm 0.0007 \pm 0.0048$$

  confirming the expected running and
  consistent results with more indirect methods.

- The theoretical uncertainty dominates in most areas.