Thomas Hebbeker 1

QCD studies at LEP

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and
Europhysics Conference on High Energy Physics

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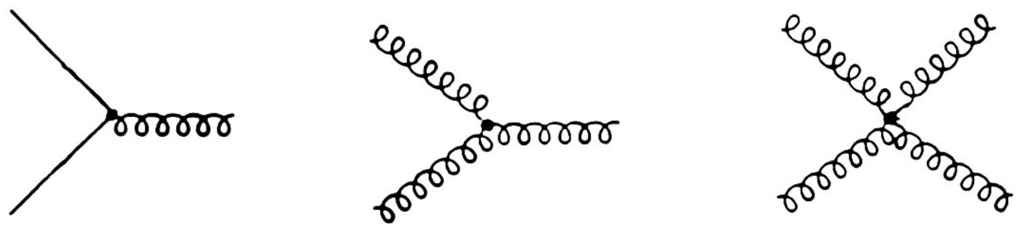
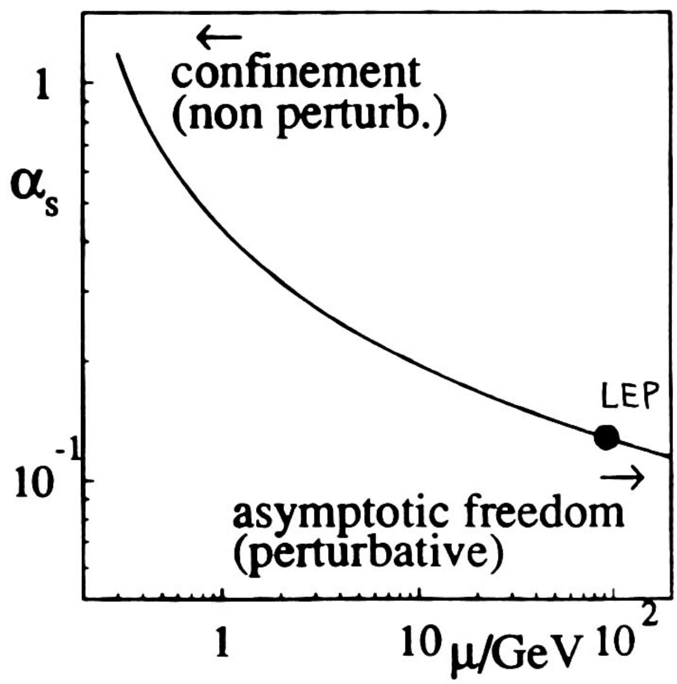
QCD

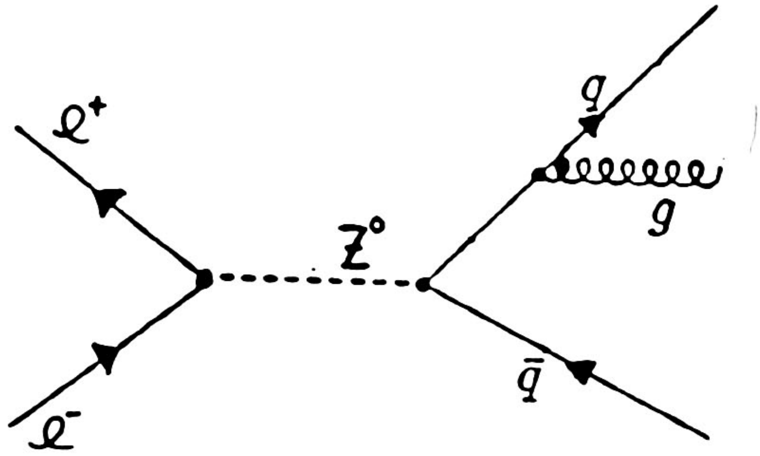
- Interaction of colored quarks and gluons (spin 1)
- Nonabelian gauge theory → gluon self coupling:

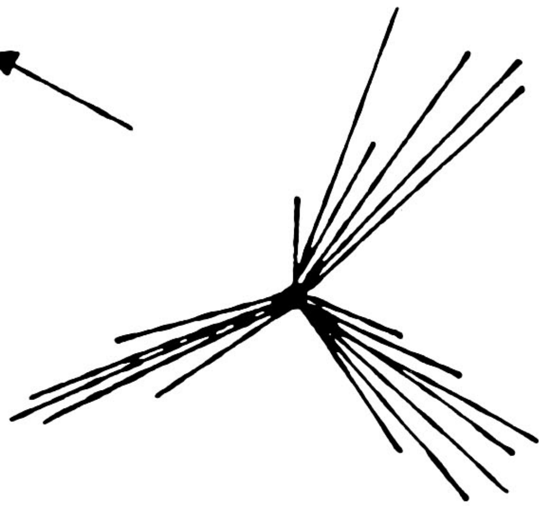


- *One* free parameter: coupling constant α_s
- Decrease of α_s with increasing energy



LEP: $e^+e^- \to Z^0 \to$ jets



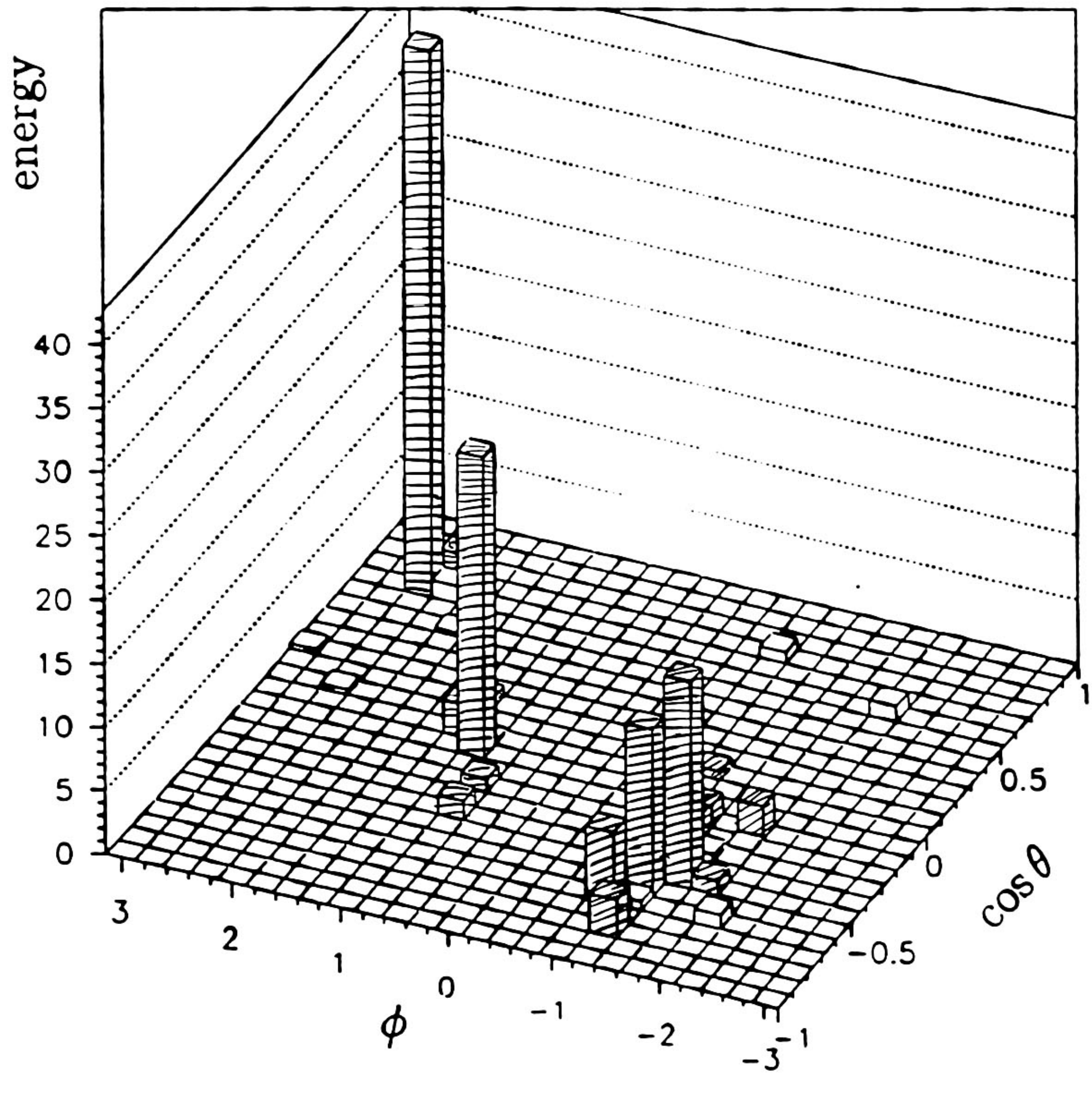


QCD at the Z^0 resonance

- high $\sqrt{s}$ *(new)*
- fragmentation effects small *(precision)*
- cross section large *(precision)*
  - absolute: high statistics
  - relative: low background
- hard initial state radiation suppressed *(precision)*

3-jet event

L3



OUTLINE

- Introduction
- Comparison to models
- Strong coupling constant α_s
  - Measurements at LEP
  - Dependence on flavor, energy
- Test of QCD matrix element
  - 3-jet events: gluon spin
  - 4-jet events: gluon self coupling
- 'Soft' hadron physics
  - Multiplicity
  - Particle spectra
  - String effect
  - Quark-jets versus gluon-jets
  - Intermittency
  - Bose-Einstein correlations
- Future QCD tests at LEP
- Summary

QCD studies at the Z^0 Resonance

More than 1 million hadronic Z^0 decays observed

About 40

Publications, preprints, contributed papers

on QCD studies at the Z^0 resonance

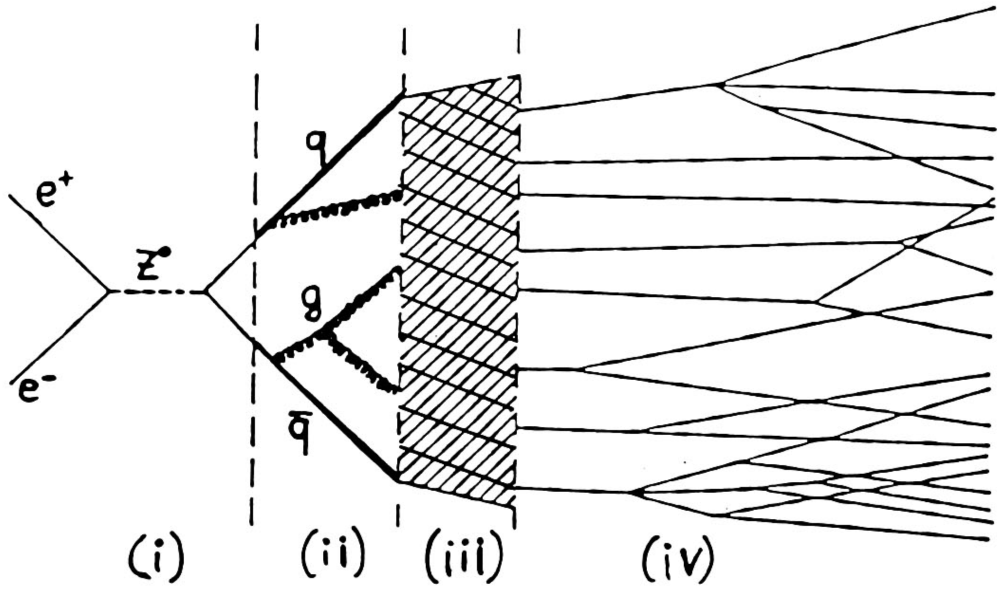
Talks in parallel sessions:

- 'Tests of Perturbative QCD and Jet Fragmentation'
  - David Salmon (ALEPH) — 'Three Gluon Vertex'
  - Elisabetta Gallo (L3) — '$\alpha_s(b)$ and Gluon-Spin'
  - Miriam Turner (OPAL) — 'Quark-Gluon Differences'
- 'Soft Hadron Phenomena'
  - Alessandro De Angelis (DELPHI) — 'Intermittency'
  - Bengt Loerstad (DELPHI) — 'Multiplicity Distributions'
  - Dominique Boutigny (L3) — 'Particle Spectra'
  - Stefano Marcellini (OPAL) — 'Bose-Einstein Correlations'

G. Martinelli
Status of QCD

P. Roudeau:
Heavy Flavour Physics at LEP

$e^+e^- \rightarrow$ hadrons and QCD

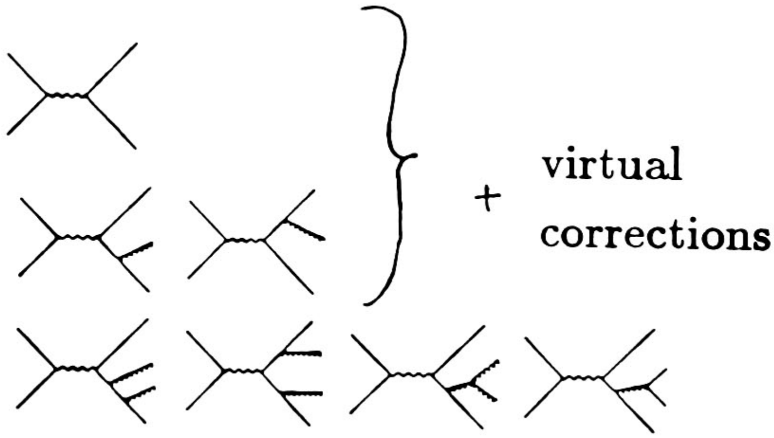


- (i) 10^{-17}cm: electroweak
- (ii) 10^{-15}cm: perturbative QCD
  - matrix elements
  - parton shower evolution
- (iii) 10^{-13}cm: hadronization (models)
  - strings
  - clusters
- (iv) decays (experimental input)

→ Monte Carlo programs

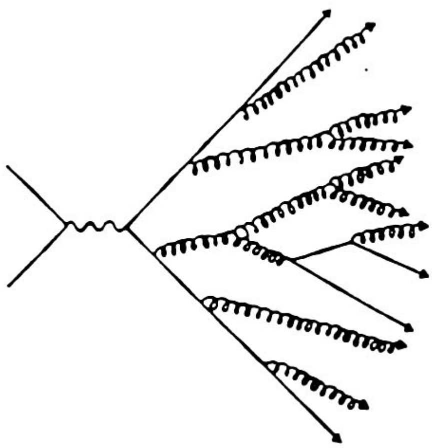
$e^+e^- \rightarrow$ hadrons and QCD

Matrix Elements:



- $O(\alpha_s^2)$ exact
- max. 4 partons
- needed to extract α_s

Parton Showers:



- Leading log approximation
- cutoff at $\approx$ 1 GeV, on average 9 partons
- better description of data

Comparison to Models

= Monte Carlo generators for events $e^+e^- \rightarrow$ hadrons

Needed:

- hadronization and decays

Procedure:

- Model parameters from a fit to selected distributions
- Comparison data $\leftrightarrow$ Monte Carlo for many variables

Most popular generators:

- JETSET (Sjöstrand)
  - Parton Shower or Matrix Element
  - String Fragmentation

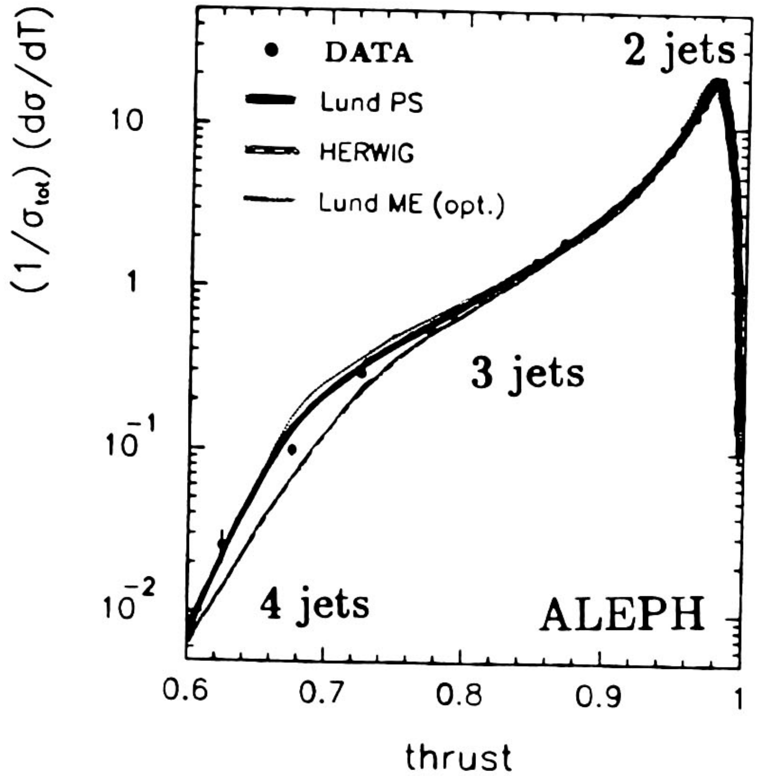
- HERWIG (Marchesini, Webber)
  - Parton Shower
  - Cluster Fragmentation

Comparison to Models

ALEPH, DELPHI, L3, OPAL, MK II

Example: Thrust

$$T = \max \frac{\Sigma\ \vec{E}_i\, \vec{n}_{\text{Thrust}}}{\Sigma\ |\vec{E}_i|}$$



→ **All models describe data well**

Strong coupling constant α_s

- <u>Measurements at LEP</u>
  - α_s from hadronic width
  - α_s from event topology
  - Comparison and combination of LEP results

- <u>Testing QCD</u>
  - Comparison to measurements for other processes
  - Flavour dependence
  - Running of α_s

Measuring α_s from $e^+e^- \to Z \to$ hadrons

(1) QCD correction to total hadronic width

$\sim 1 + \frac{\alpha_s}{\pi} + \ldots \approx 1 + 4\%$
calculated to order $O(\alpha_s^3)$

→ *Event counting*

- (2) Event topology: Jets, Energy correlations, ...

probability for hard gluon radiation $\sim \alpha_s$
calculated to order $O(\alpha_s^2)$

→ *Jet counting, ...*

- Precision of α_s measurements:

method	theoretical error		experim.	total
	higher O	fragm.	error	uncert.
(1) hadr. width	2%	-	10-15%	10-15%
(2) topology	5-10 %	3%	3%	5-10%

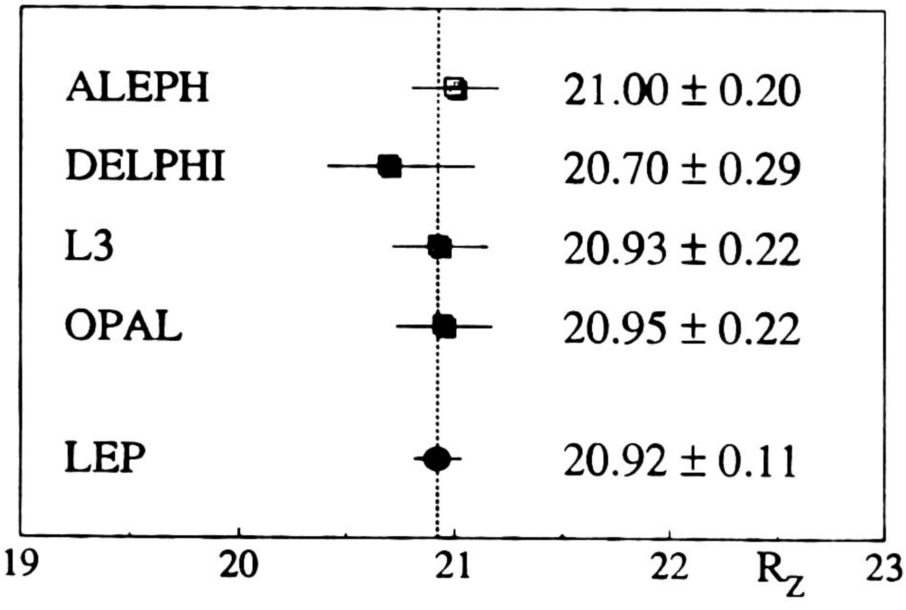
α_s from hadronic Z^0 width

$$R_Z \equiv \Gamma_{\text{had}}/\Gamma_{\text{lep}} = 19.97 \cdot (1 + \delta_{\text{QCD}})$$
$$R \equiv \sigma_{\text{had}}^{\text{peak}}/\sigma_{\text{lep}}^{\text{peak}} = 19.77 \cdot (1 + \delta_{\text{QCD}})$$

↑ depends little on top and higgs mass: ± 0.03

(Surguladze, Samuel)
(Gorishny, Kataev, Larin)

$$\delta_{\text{QCD}} = 1.05 \cdot \frac{\alpha_s}{\pi} + 0.9 \cdot \left(\frac{\alpha_s}{\pi}\right)^2 - 13 \cdot \left(\frac{\alpha_s}{\pi}\right)^3$$



$$\boxed{\alpha_s(M_Z) = 0.141 \pm 0.017}$$

(in second order: $\alpha_s(M_Z) = 0.137$)

Jets

JADE jet algorithm as function of y_{cut}:

- measure energy and direction of all particles
- calculate

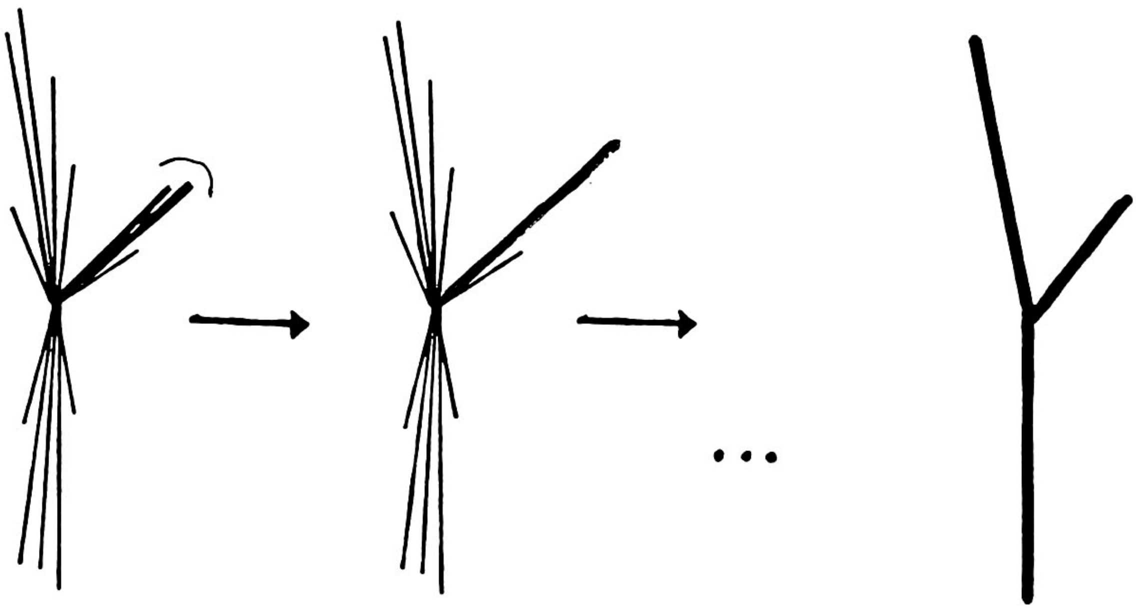
$$\boxed{y_{ij} = 2E_iE_j/E_{\text{vis}}^2 \cdot (1 - \cos\theta_{ij})}$$

for all particles i and j

- find particle i and j for which y_{ij} is smallest
- recombine those into a new 'particle' k:

$$\boxed{p_k = p_i + p_j}$$

- loop until all y_{ij} exceed invariant mass cutoff y_{cut}
- call the remaining 'particles' **jets**



α_s from jet multiplicities

ALEPH, DELPHI, [L3], OPAL, MK II

3-jet fraction at $y_{cut} = 0.08$ (26 GeV)
(corrected for detector effects and photon radiation)

$$\sigma_{3-jets}/\sigma_{tot} = 18.4\ \% \pm 0.9\ \%$$

Comparison to analytical 2nd order QCD calculation
(+ hadronization correction)

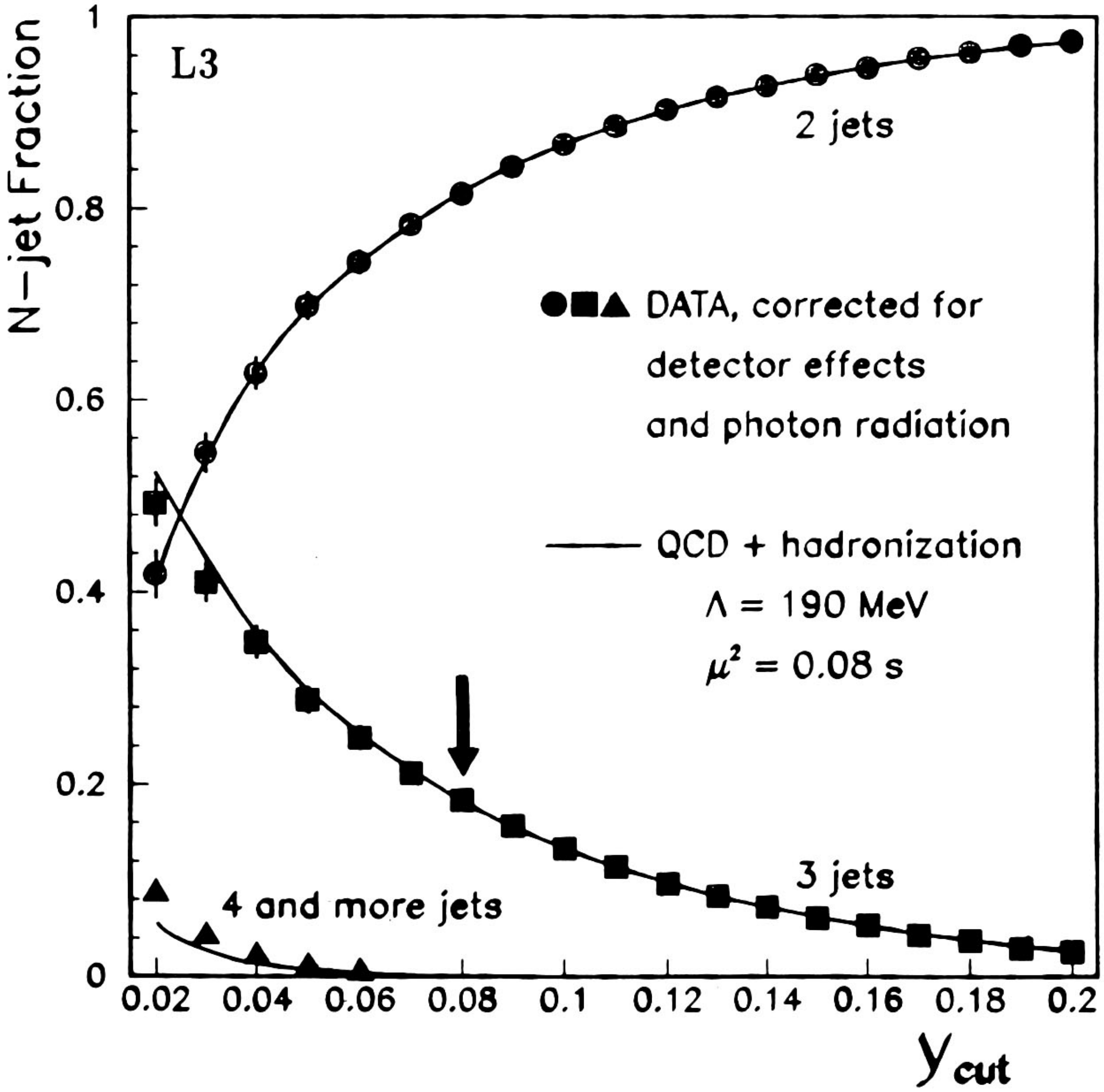
$$\boxed{\alpha_s\,(\sqrt{s} = M_Z) = 0.115 \pm 0.005\,(\text{exp.})\,^{+0.012}_{-0.010}\,(\text{theor.})}$$

Theoretical error dominated by unknown higher order corrections, estimated by a variation of the renormalization scale μ in the range 3 – 91 GeV.

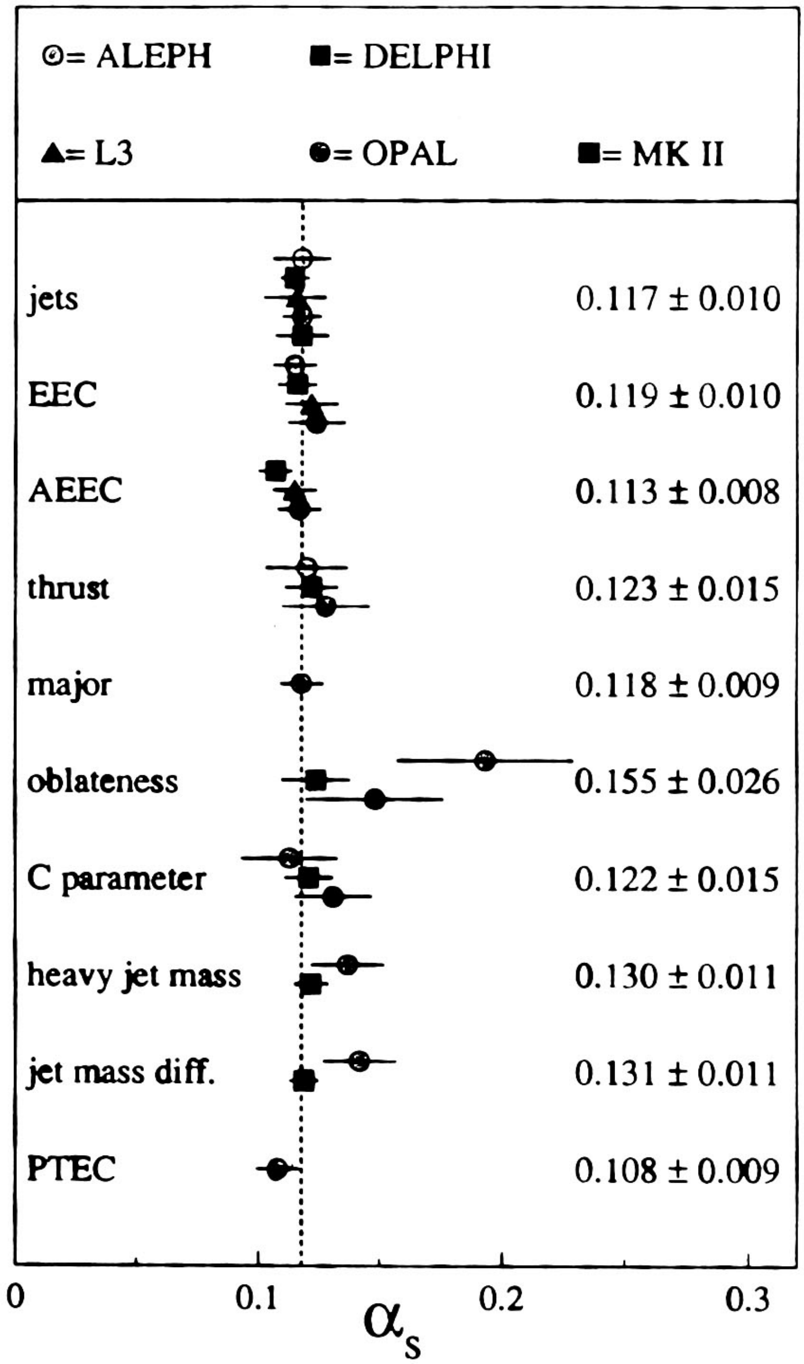
Jet rate becomes independent of the scale μ when calculated to all orders. Therefore the variation of α_s with μ is an estimate of uncalculated higher order corrections.

α_S from jet multiplicities

ALEPH, DELPHI, [L3] , OPAL, MK II



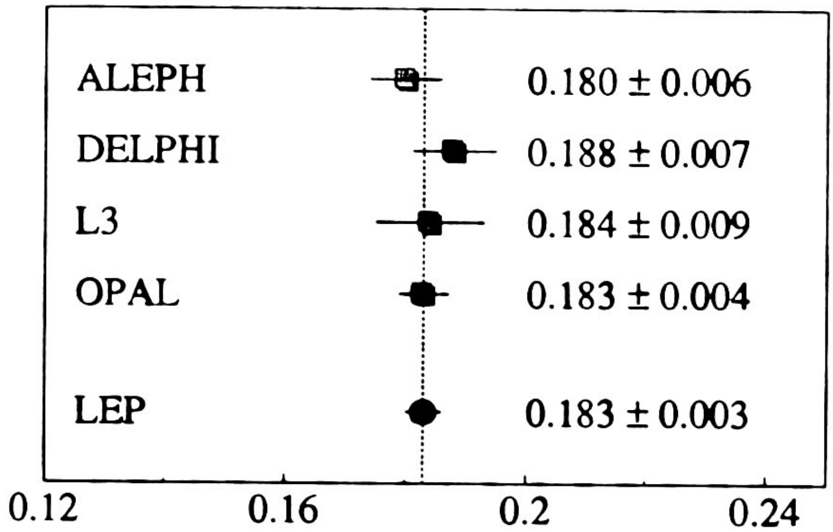
α_s from event topology (at Z^0)



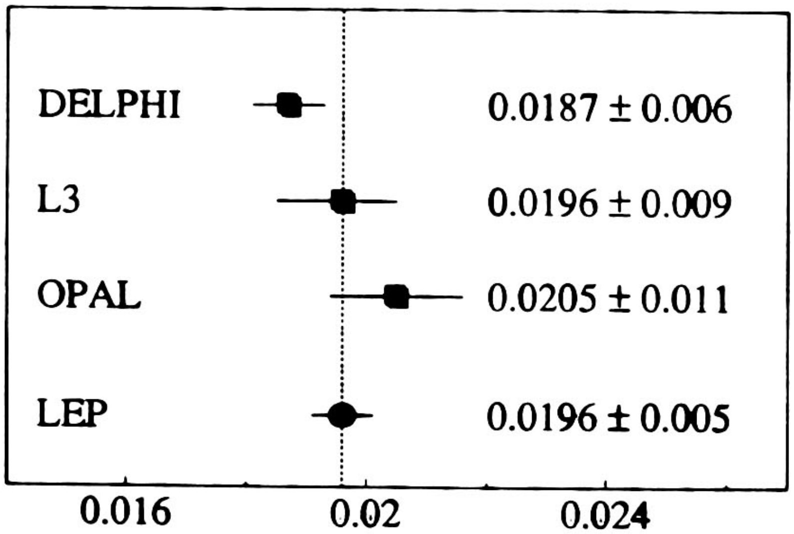
How to combine ?

Comparison of experimental results

3-jet fraction , $y_{\text{cut}} = 0.08$



Asymmetry of energy energy correlations , integral between 36° and 90°



Uncertainties for α_S from event topology

Experimental (all exp. combined)

published experimental errors

spread of results from four LEP experiments

→ about 3%

Hadronization

variation of fragmentation parameters

change of model

→ typically 3%

Missing higher order (> 2) corrections

renormalization scale dependence

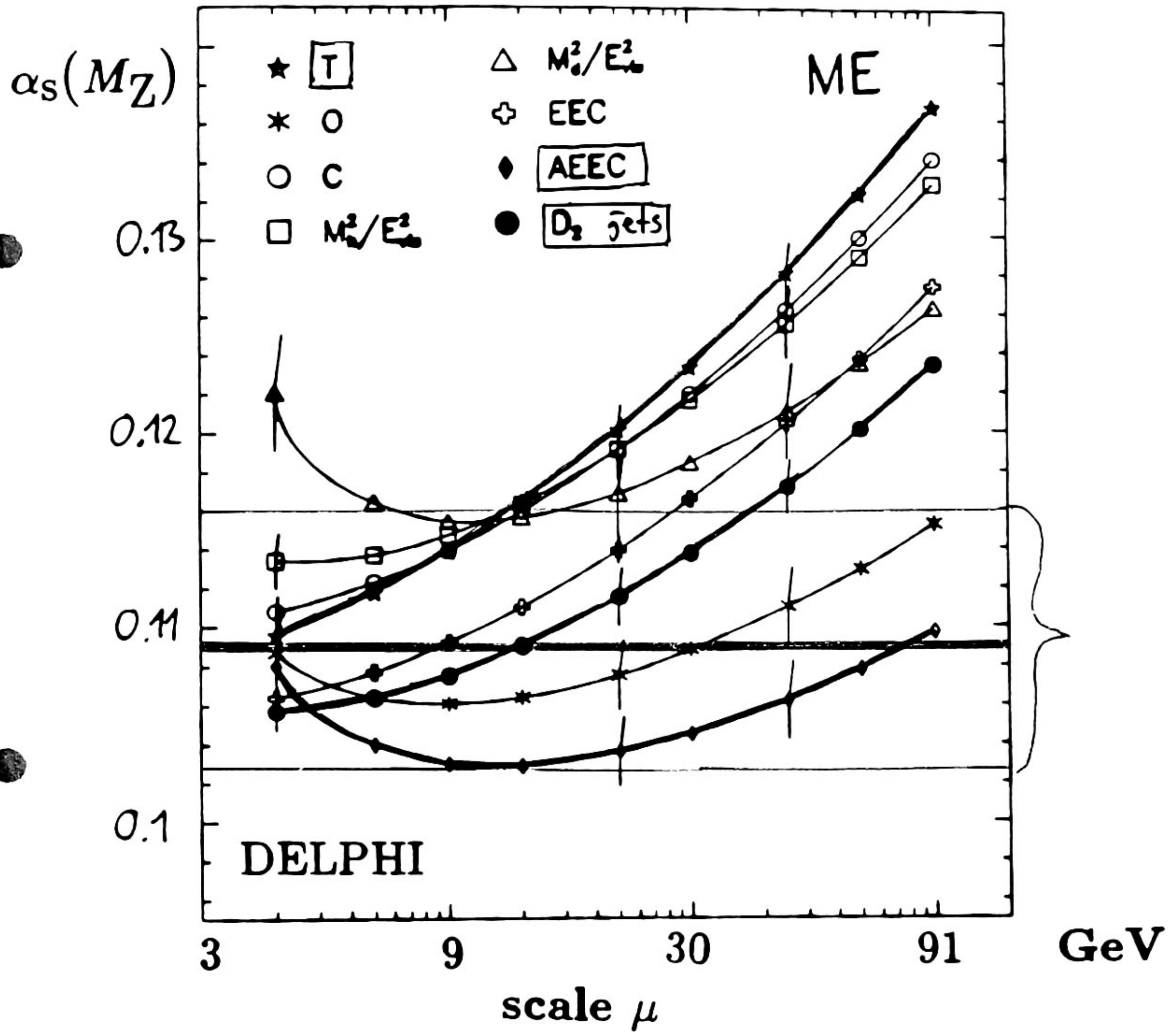
spread of α_s values for different variables

effects of higher orders in parton shower

→ about 5% – 10%

α_s from event topology

ALEPH, DELPHI, L3, OPAL, MK II



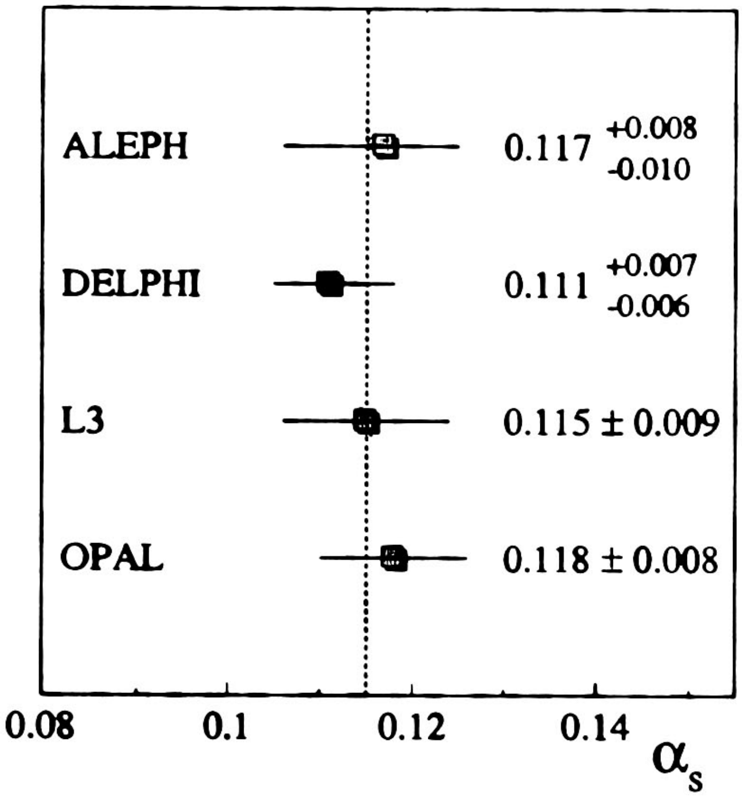
Average for two methods of hadronization correction:

$$\alpha_s(M_Z) = 0.111^{+0.007}_{-0.006}$$

α_s from event topology

(jets, energy correlations, thrust, ...)

'Average' or 'best' values for α_s:

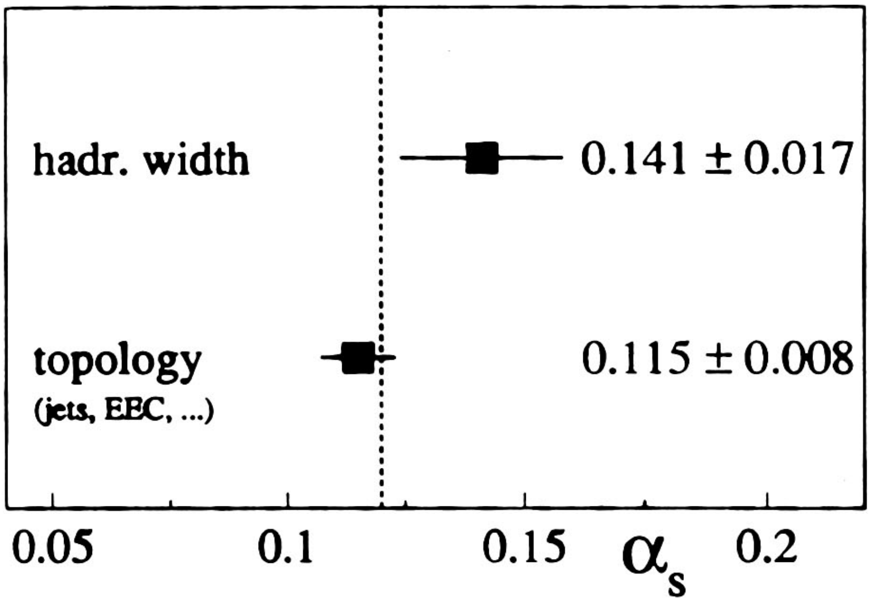


Errors dominated by theoretical uncertainties due to higher order corrections

Unweighted mean (for central value and error):

$$\boxed{\alpha_s(M_Z) = 0.115 \pm 0.008}$$

α_s from LEP



$$\boxed{\alpha_s(M_Z) = 0.120 \pm 0.007}$$

$$\Lambda^{(5)}_{\overline{\mathrm{MS}}} = 250^{+110}_{-\ 80}\ \mathrm{MeV}$$

Errors for α_s from hadronic width dominated by

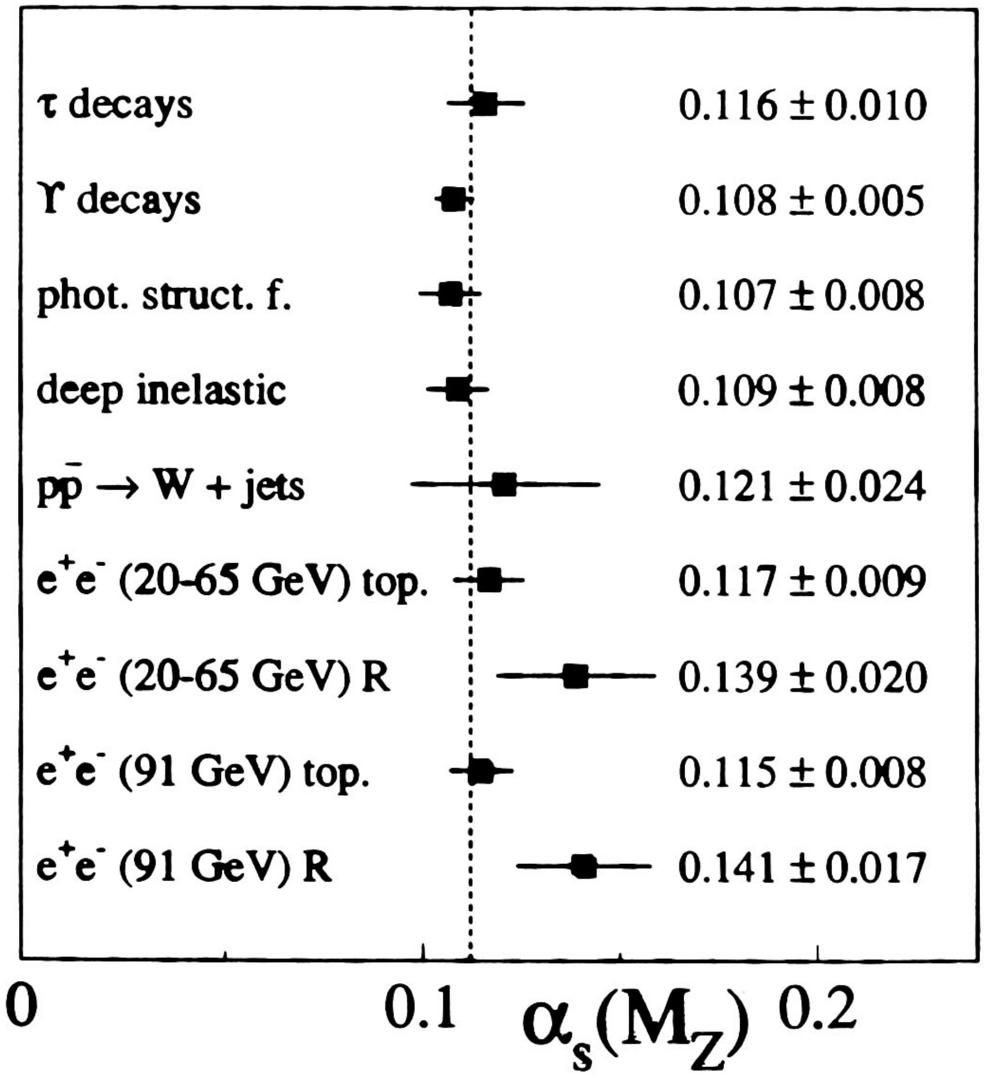
- experimental uncertainties

Errors for α_s from event topology dominated by

- theoretical uncertainties (missing higher orders)

Comparison of α_S measurements

All values extrapolated to $\mu = M_Z$



Testing flavor independence of α_S

α_s for bottom quarks

L3

Method:

- Measure α_s from 3-jet fraction f_3
- Tagging of b quarks via decays $b \to \mu, e + X$

	sample	events	bottom
had	all hadrons	110,000	22%
lep	incl. μ, e events	2,900	87%

Ratio of 3-jet rates f_3 with $y_{cut} = 0.05$:

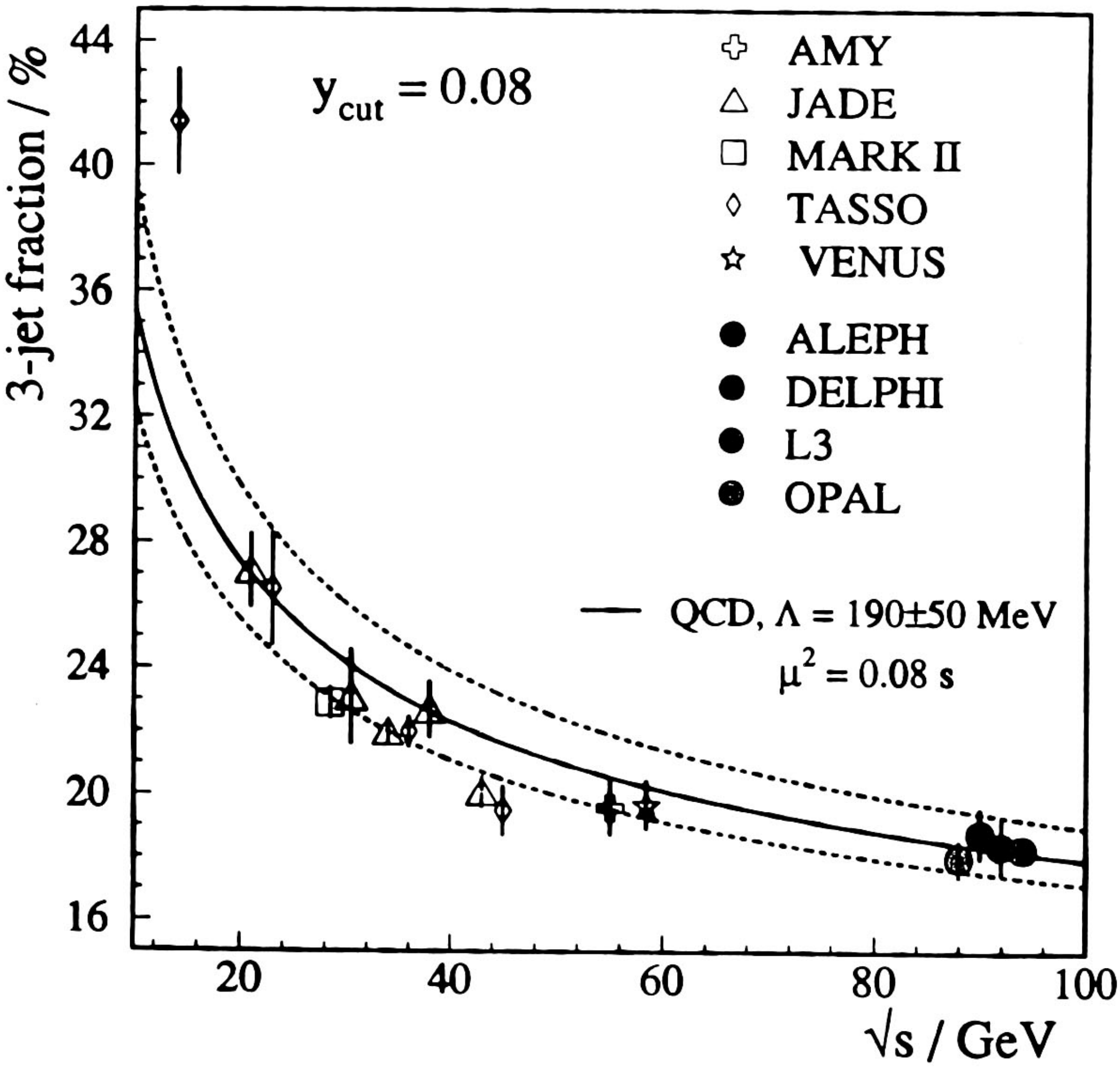
$$\frac{f_3^{lep}}{f_3^{had}} = 1.00 \pm 0.03\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst})$$

Ratio of α_s values for bottom and light quarks:

$$\boxed{\alpha_S^b / \alpha_S^{udsc} = 1.00 \pm 0.08}$$

Running of α_s

$$\text{3-jet rate} \sim \alpha_s \propto \frac{1}{\ln \mu^2/\Lambda^2}$$



→ **'running' of α_s**

→ **indirect evidence for gluon self coupling**

Strong coupling constant α_s

Summary

- Measurements

a) from hadronic Z width

b) from event topology

$$\alpha_s(M_Z) = 0.120 \pm 0.007$$

- Flavor independence √

- **Running** √

Test of QCD matrix element

- **3-jet events**

  → gluon spin

- **4-jet events**

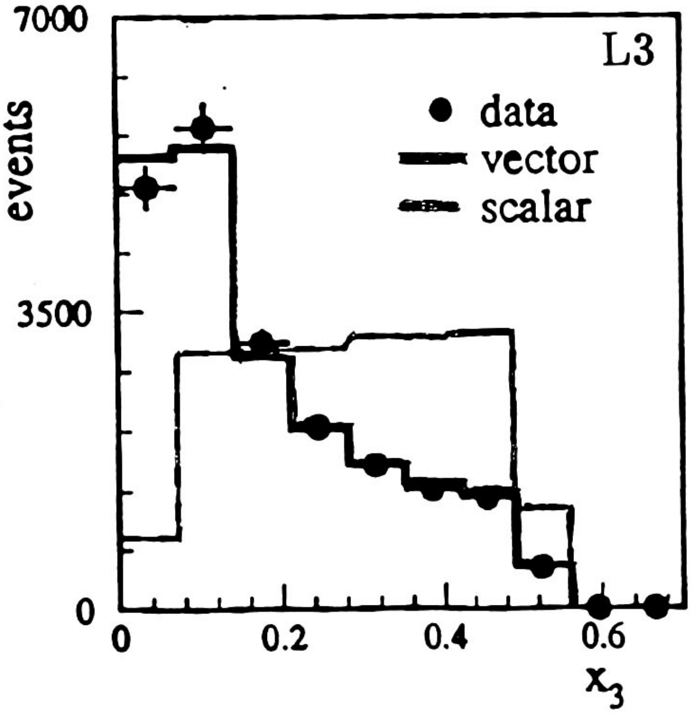
  → gluon self coupling

3-Jet Events: Jet Energies

L3, OPAL

3-jet events selected with $y_{\text{cut}} = 0.02$:

Scaled energy
$x_3 = E_3/E_{\text{beam}}$
of least energetic jet.



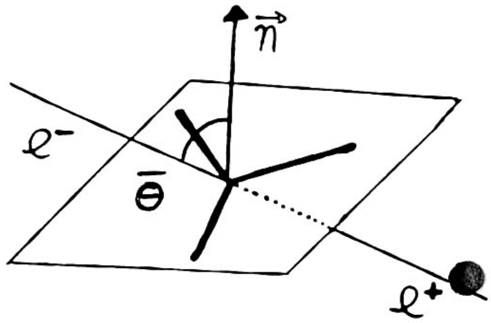
- QCD to second order in α_s (gluon spin = 1) reproduces measurements
- gluon spin = 0 excluded

At $\sqrt{s} = 35$ GeV differences much smaller

3-Jet Events: Jet plane orientation

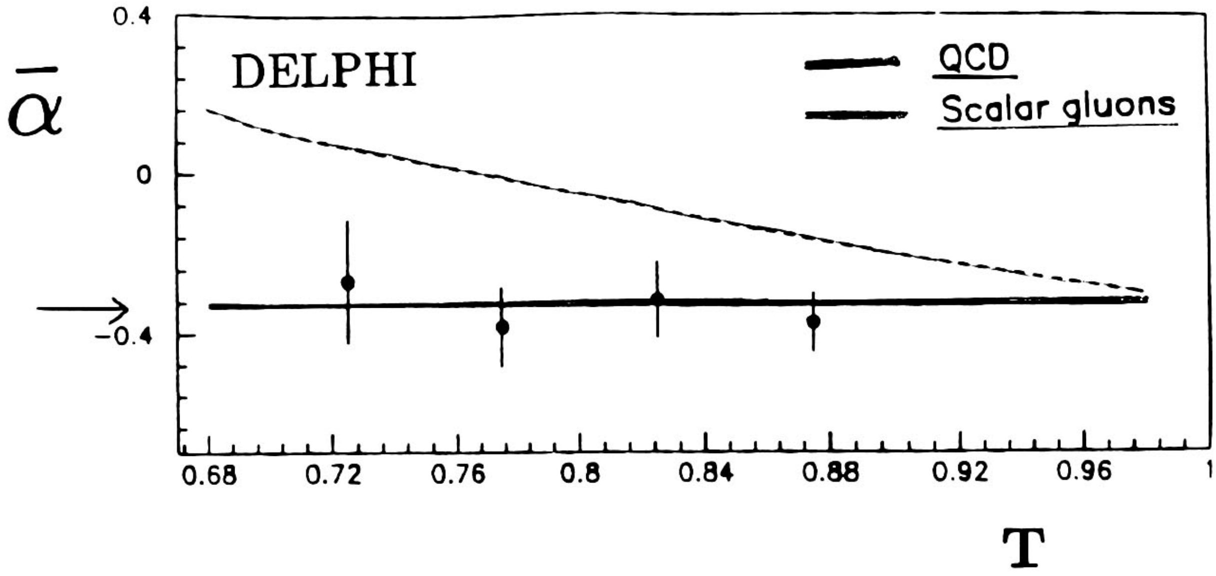
DELPHI , L3

Distribution of the polar polar angle $\bar{\theta}$ of the normal to the three jet plane depends on thrust T:



$$\frac{d\,\sigma}{d\,\cos\bar{\theta}} \propto 1 + \bar{\alpha}(T) \cdot \cos^2\bar{\theta}$$

QCD: $\bar{\alpha} = -1/3$



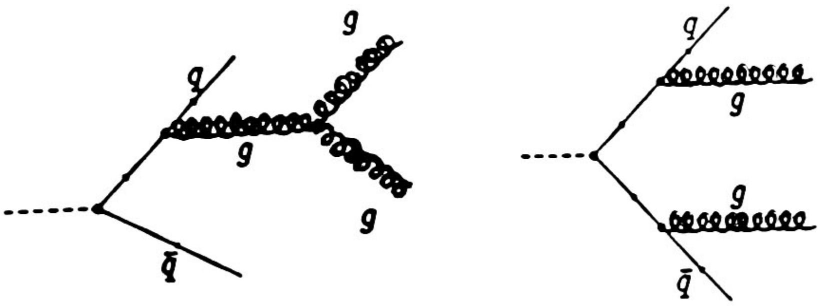
- **Only QCD (gluon spin = 1) describes data**

Test of gluon self coupling

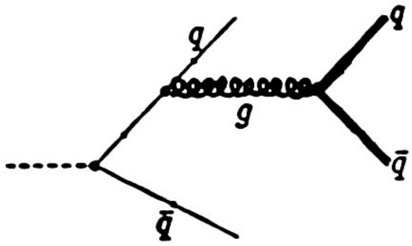
QCD is nonabelian $\rightarrow$ gluon self coupling

$e^+e^- \rightarrow$ 4 jets:

$e^+e^- \rightarrow q\bar{q}gg$



$e^+e^- \rightarrow q\bar{q}q\bar{q}$



To demonstrate the sensitivity of measurements for 4-jet events one can compare to an alternative **abelian model**. Here only double Bremsstrahlung diagrams contribute to $e^+e^- \rightarrow q\bar{q}gg$.

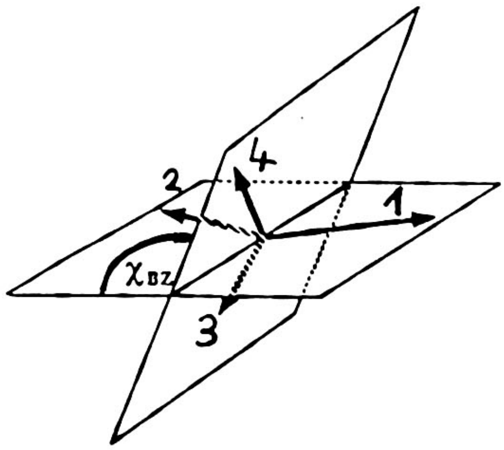
Angular correlations in 4-jet events are different for QCD and the abelian model and allow to distinguish between them.

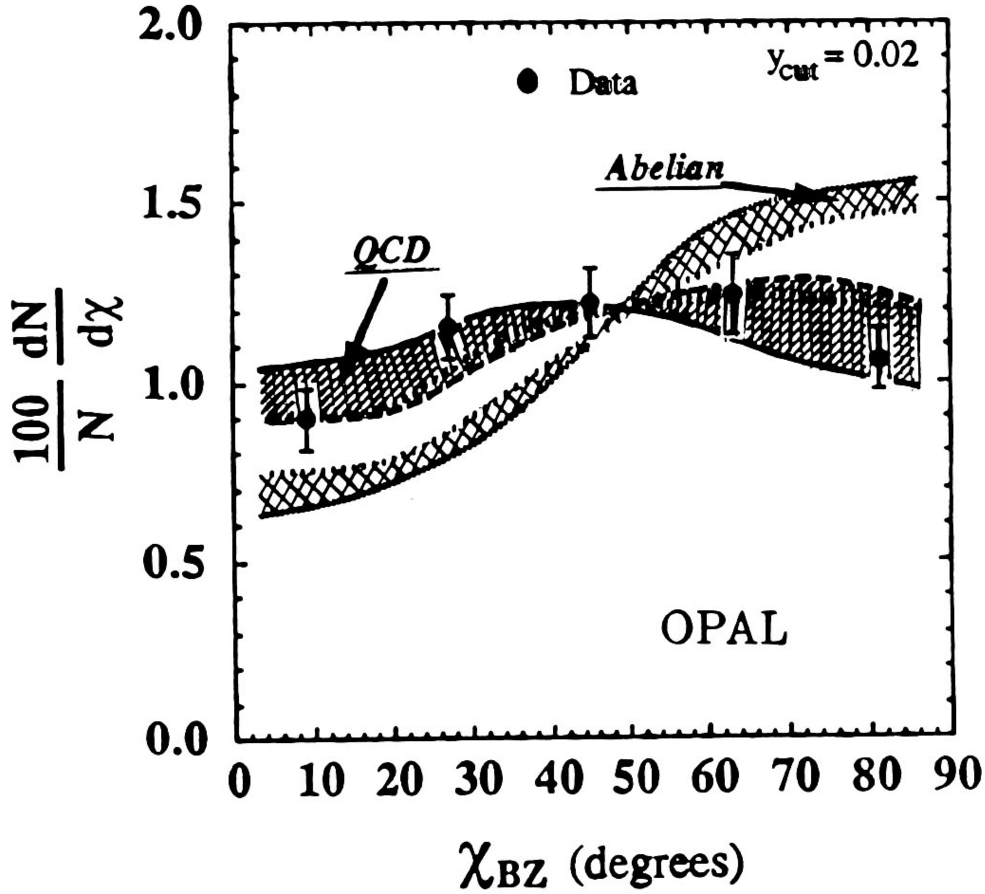
QCD versus Abelian Model

L3, OPAL

Bengtsson-Zerwas angle

χ_{BZ} is the angle between the plane containing jets 1,2 and the plane containing jets 3,4.



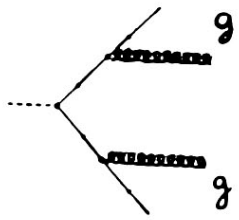


- **abelian model ruled out !**

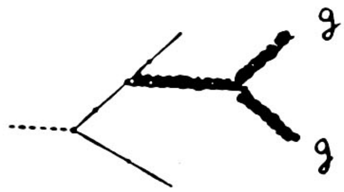
Test of gluon self coupling

4-jet cross section = sum of gauge invariant terms:

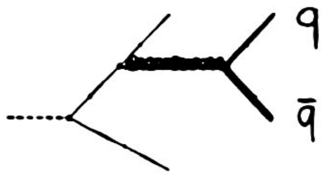
$$\sigma \sim \underline{C_F} \cdot \sigma_{\mathrm{A}} + (C_F - N_C/2) \cdot \sigma_{\mathrm{B}}$$



$$+\underline{N_C} \cdot \sigma_C$$



$$+\underline{T_F} \cdot N_f \cdot \sigma_{\mathrm{D}} + (C_F - N_C/2) \cdot \sigma_{\mathrm{E}}$$



'Color Factors':

	C_F	N_C	T_F
QCD	4/3	3	1/2
abelian	1	0	3

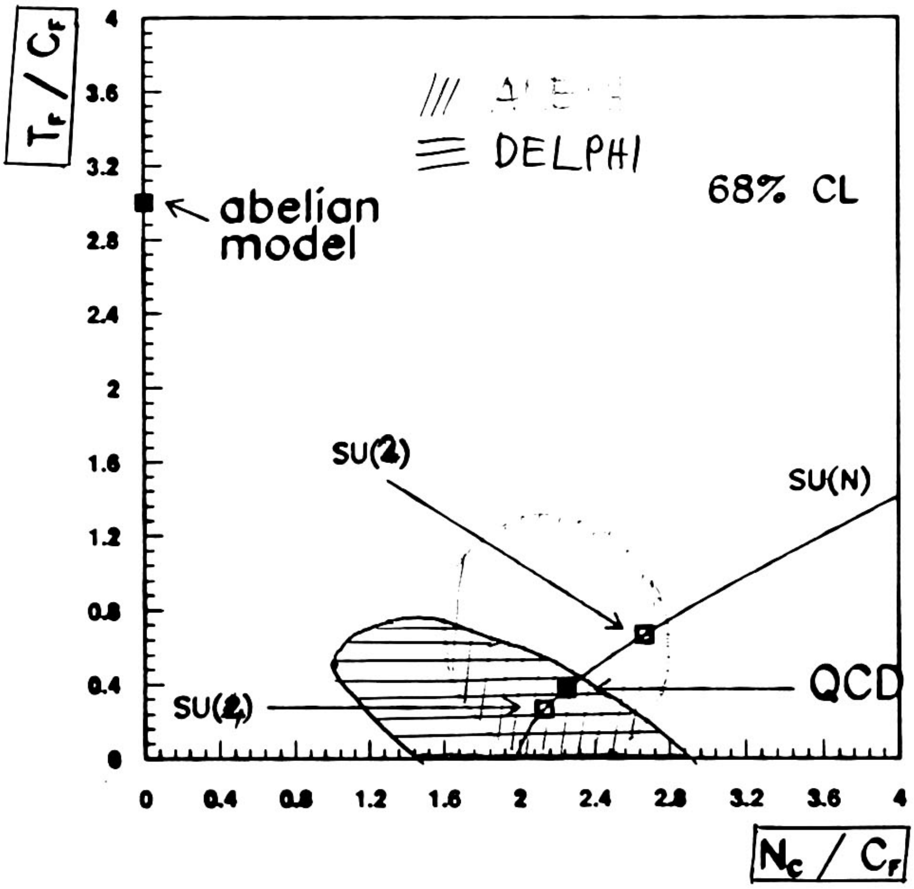
From a fit to the measured differential 4-jet cross sections one can determine N_C/C_F and T_F/C_F:

ALEPH: 5-dimensional, invariant masses y_{ij}

DELPHI: 2-dimensional, two angles between jets

$g \to gg$ and $g \to q\bar{q}$ couplings

ALEPH, DELPHI



Color Factors:

	N_C/C_F $g \to gg$	T_F/C_F $g \to q\bar{q}$
LEP	**2.0 ± 0.3**	**0.3 ± 0.2**
QCD	**2.25**	**0.375**
abelian	**0**	**3**

Test of QCD matrix element

Summary

- The second order QCD matrix element has been tested precisely for
  - 3-jet events
  - 4-jet events

- LEP has provided experimental evidence for

  gluon self coupling

'Soft' hadron physics

For many 'soft' phenomena QCD predictions exist:

- Analytical (next to) Leading Log Calculations
- Parton Shower Monte Carlo Generators

Importance of hadronization and particle decays increased with respect to jet level !

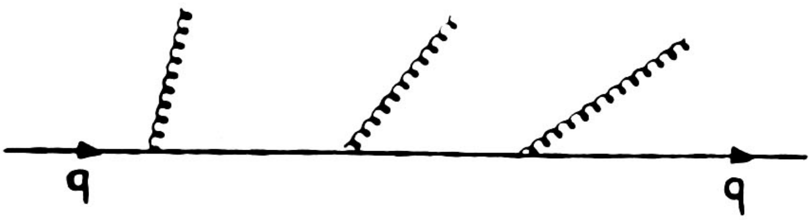
- QCD: Soft Gluon Coherence
- Charged Particle Multiplicity
- Particle Identification (light flavors)
- Particle Spectra
- String Effect
- Quark-Jets versus Gluon-Jets
- Intermittency
- Bose-Einstein Correlations

QCD: Soft gluon coherence

Interference effects of soft gluons lead to:

- INTRA-jet effects:

  In subsequent parton branchings the emission angles decrease: 'Angular ordering'



  → Reduction of available phase space for soft gluons (multiplicities, spectra)

- INTER-jet effects:

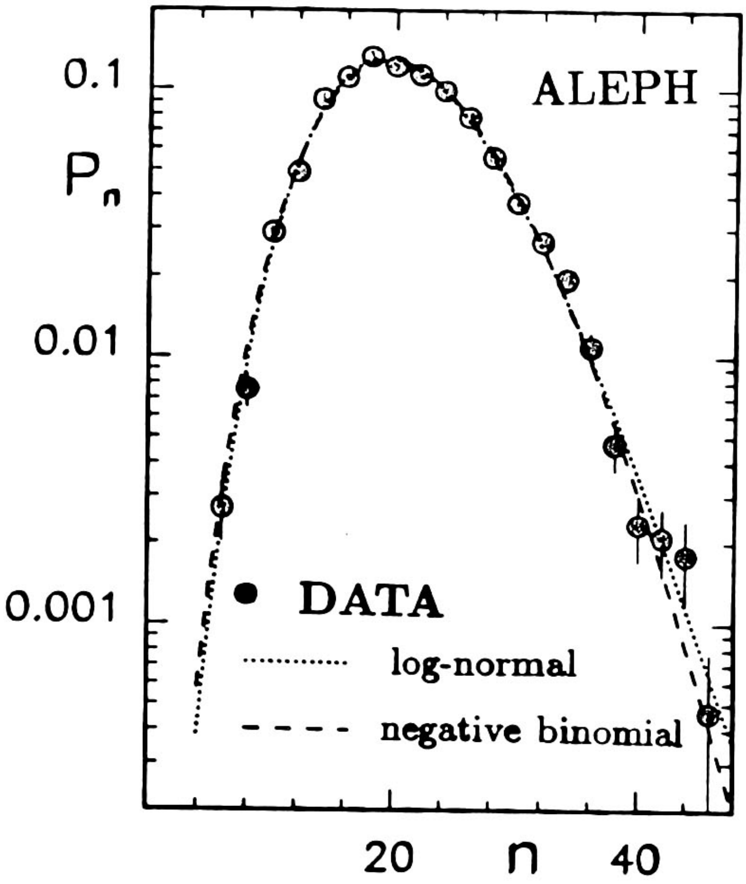
  → Suppression of particles between q and $\bar{q}$ jets in $q\bar{q}g$ events ('string effect')

Experimental tests:

Hypothesis of 'Local Parton Hadron Duality' (LPHD):
The effects on partons are observable by measuring hadrons

Charged Particle Multiplicity

ALEPH, DELPHI, L3, OPAL, MK II

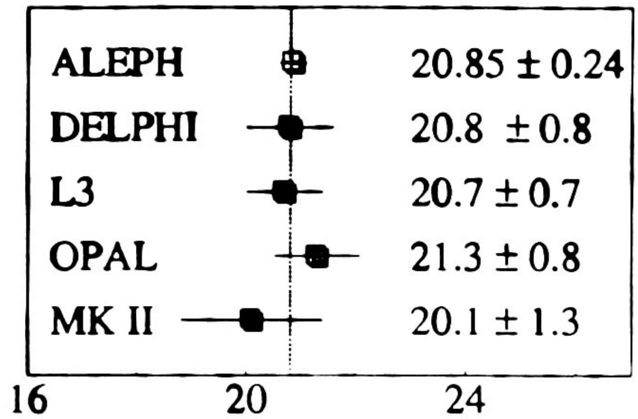


Measured distribution described by

- parton shower Monte Carlo programs
- phenomenological models

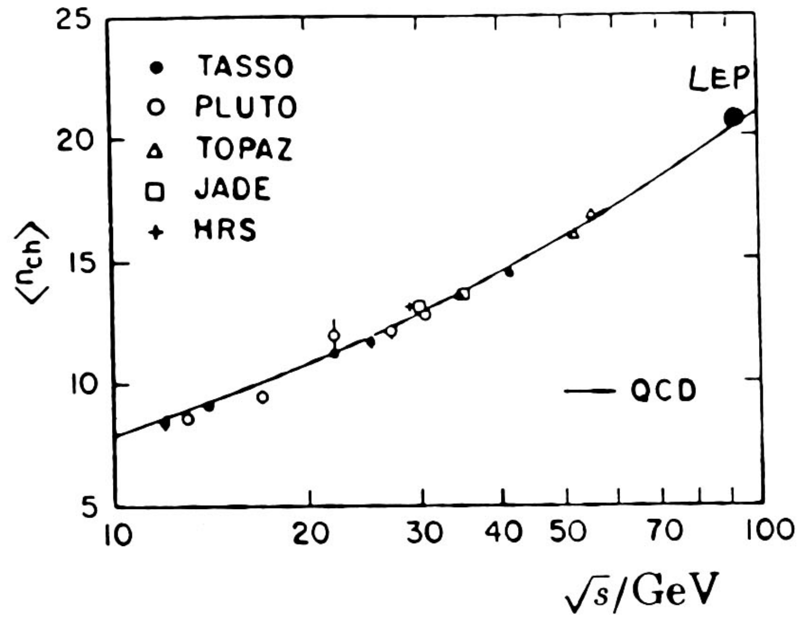
Detailed studies by DELPHI: Dependence on rapidity, jet-configuration, transverse momenta, . . .

Mean Charged Multiplicity



LEP/SLC: $\langle N_{\rm ch} \rangle = 20.8 \pm 0.2$

Center of mass energy dependence:



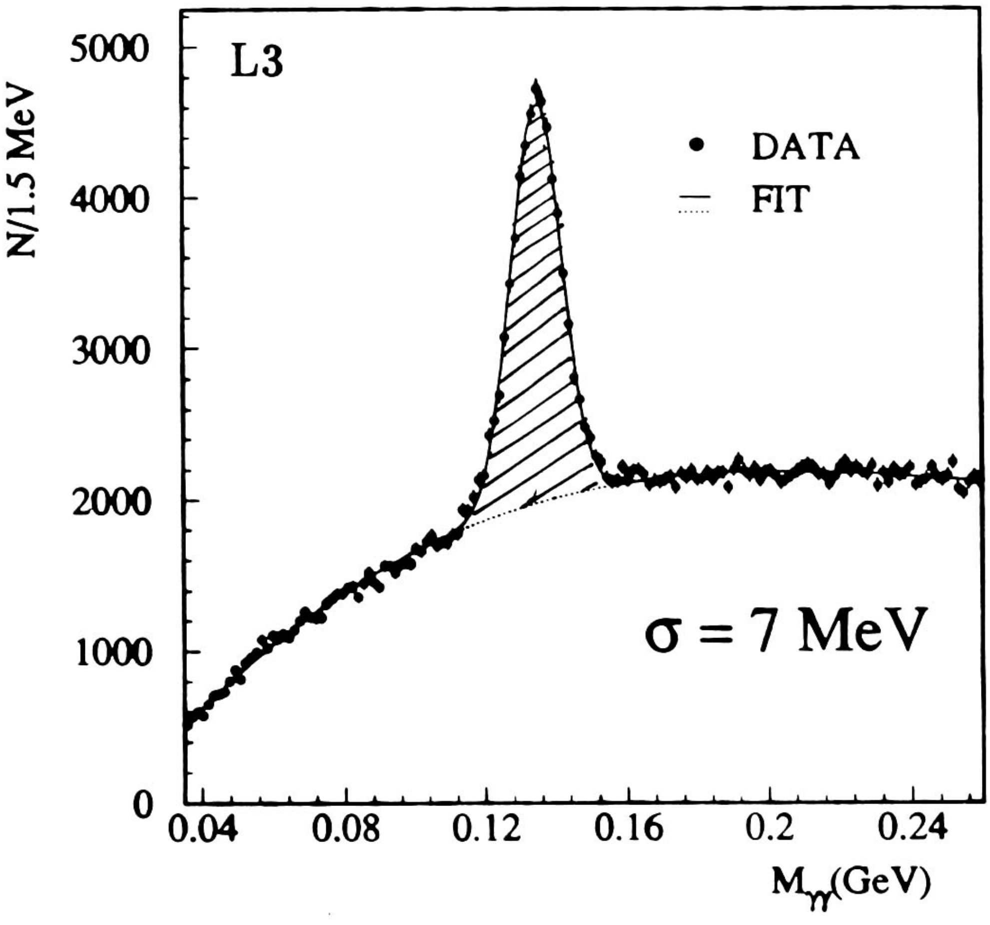
$$\text{QCD}: \quad \langle n \rangle = N_{\rm Norm} \cdot (\alpha_s(s))^b \cdot \exp(c/\sqrt{\alpha_s(s)})$$

Particle Identification
Neutral Pions

L3

Neutral Pions (135 MeV) are reconstructed from photon pairs:

$$\pi^0 \rightarrow \gamma\gamma$$



Number of π^0's per hadron event:

$$\langle n_{\pi^0} \rangle = \underline{\mathbf{9.8 \pm 0.7}}$$

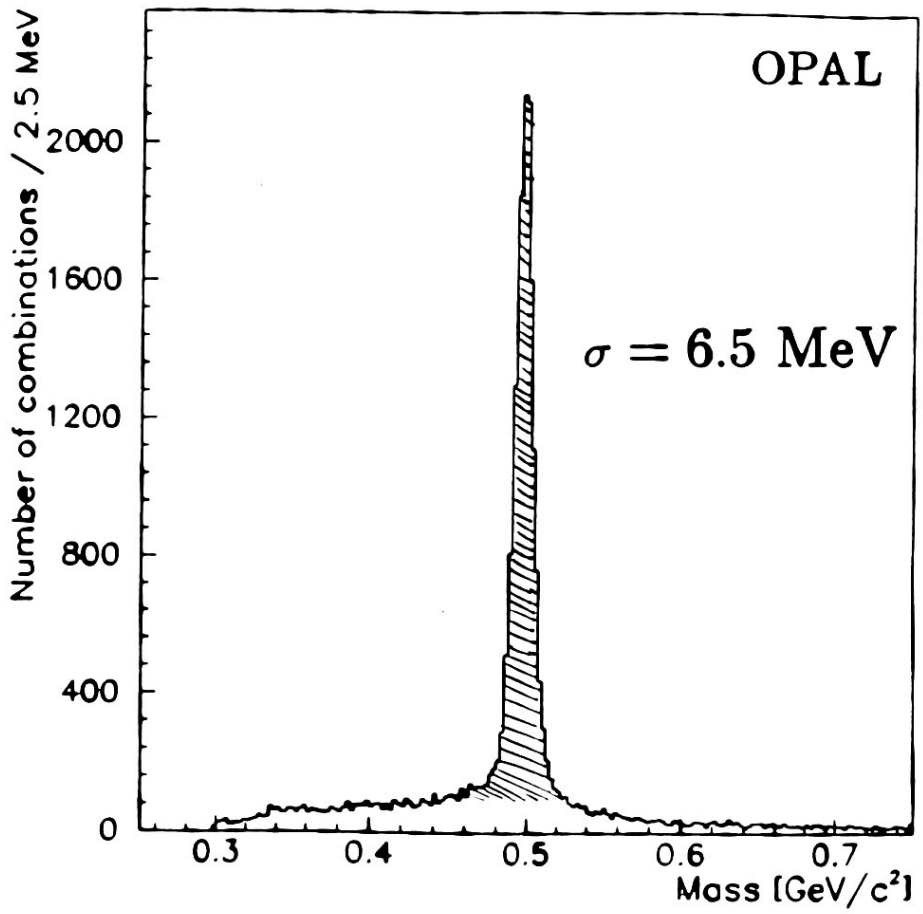
4'

Particle Identification
Neutral Kaons

(ALEPH), DELPHI, OPAL

K_s^0 mesons (498 MeV) are reconstructed from $\pi^+\pi^-$ pairs originating from a secondary vertex ($c\tau = 2.7$cm):

$$K_s^0 \rightarrow \pi^+\pi^-$$



Number of $K^0 + \bar{K}^0$'s per hadron event (DELPHI+OPAL)

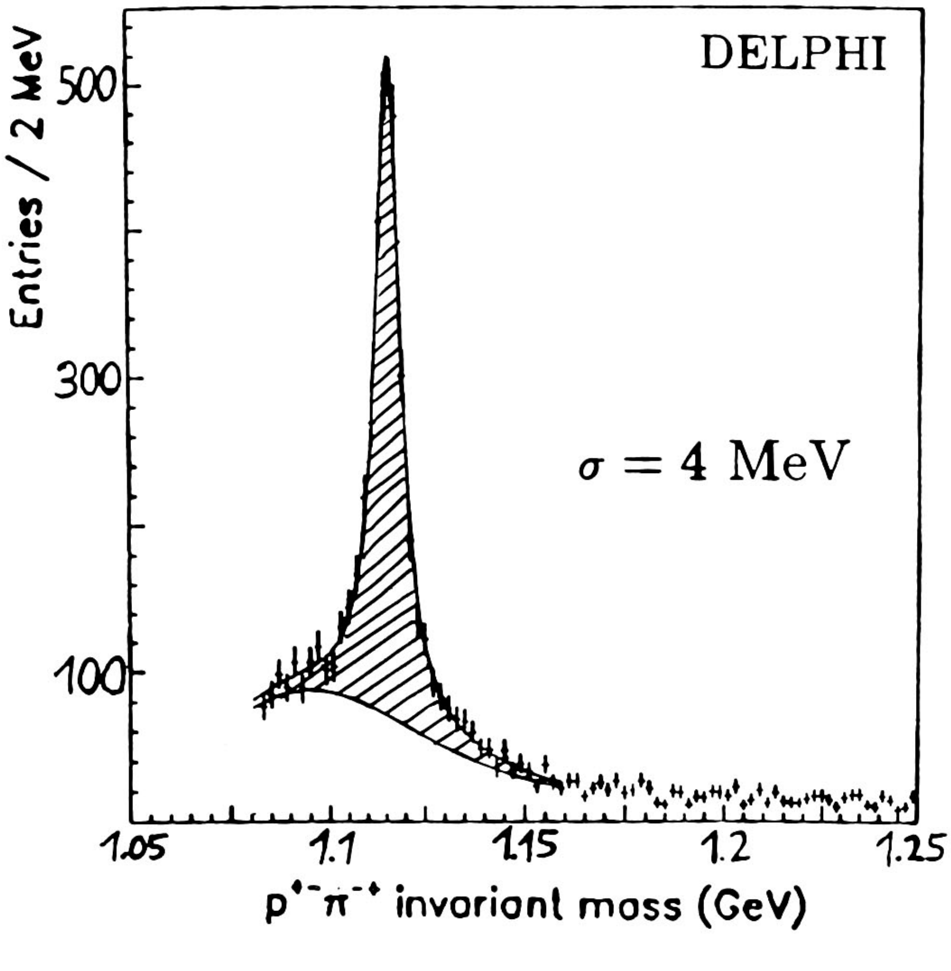
$$\langle n_{K^0} \rangle = \underline{2.04 \pm 0.10}$$

Particle Identification
Lambdas

(ALEPH), DELPHI

Λ baryons (1116 MeV) are reconstructed from $p\pi^-$ pairs originating from a secondary vertex ($c\tau = 7.9$cm):

$$\Lambda \to p + \pi^-$$



Number of $\Lambda + \bar{\Lambda}$'s per hadron event:

$$\langle n_\Lambda \rangle = \underline{0.245 \pm 0.032}$$

Particle Spectra

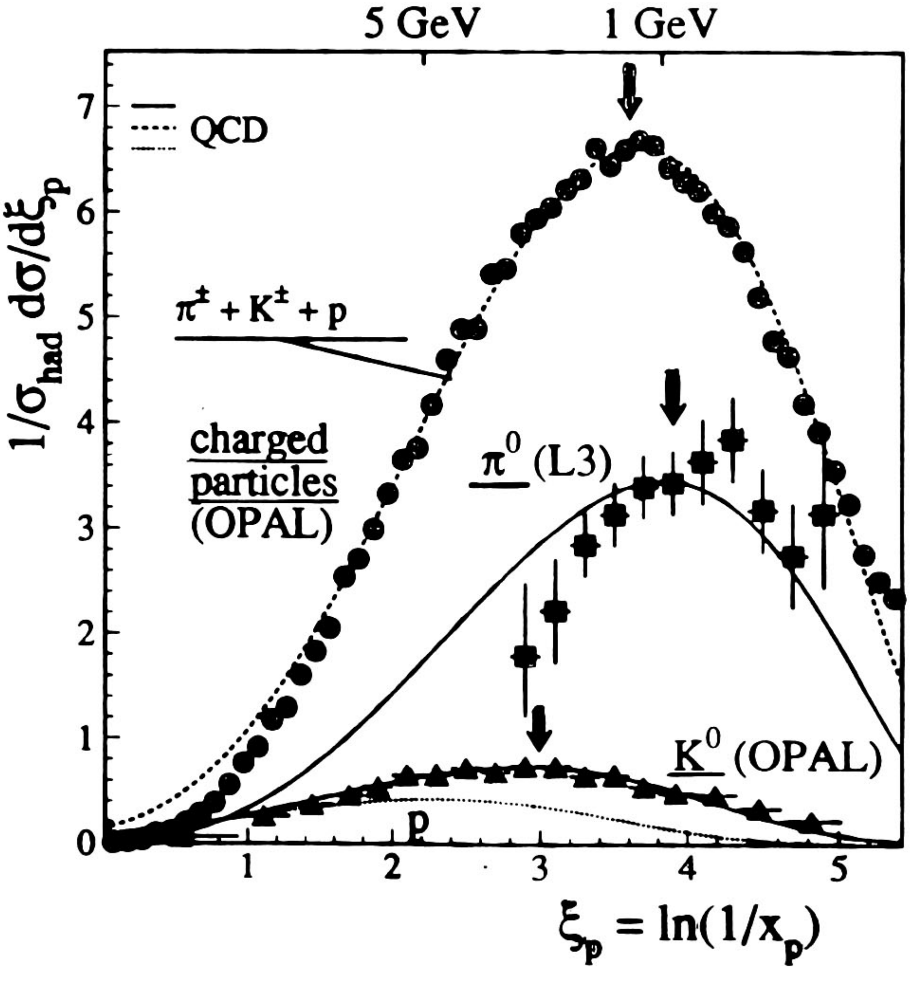
$\xi_p = \ln(1/x_p)$ $\quad$ $x_p =$ particle mom. / beam energy

ALEPH, DELPHI, L3, OPAL

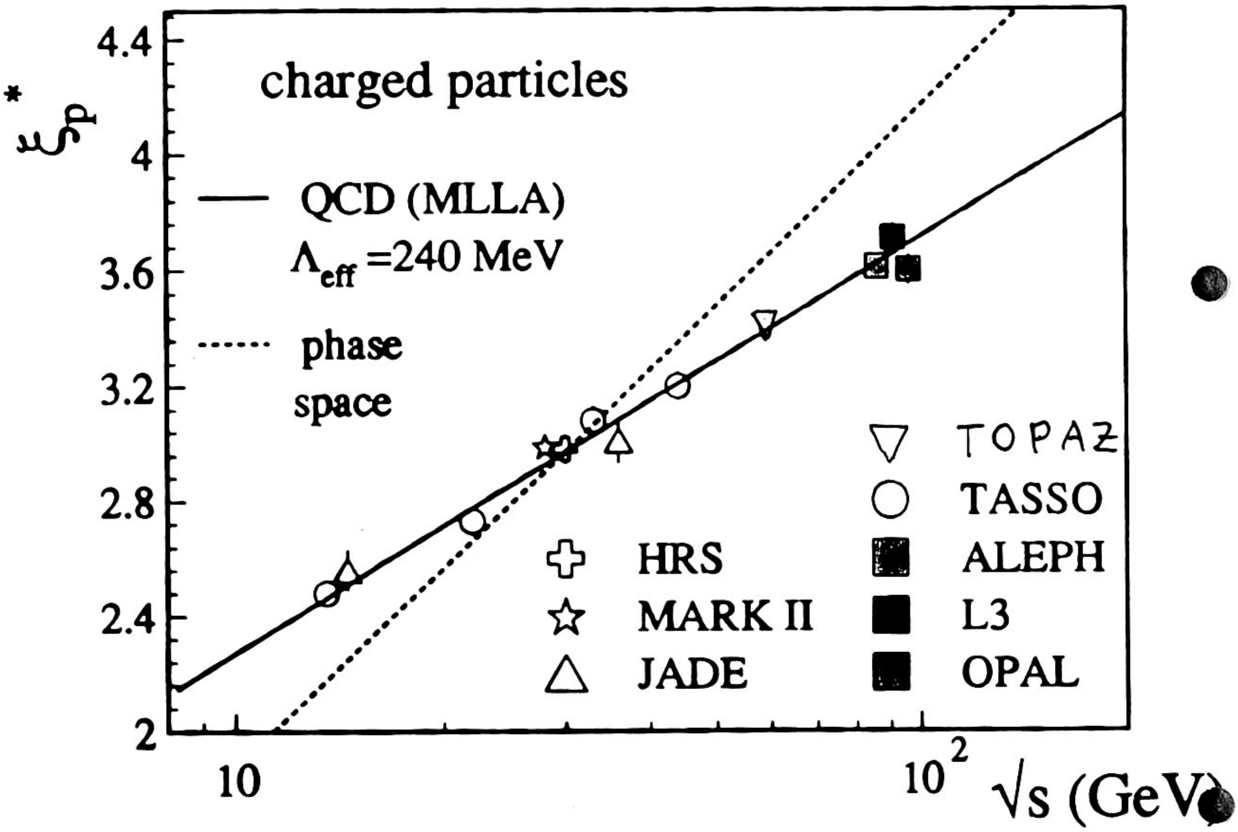
QCD = analytical calculation + LPHD :

(Dokshitzer, Khoze, Troyan)

- Spectra have 'humpbacked' shape
- Peak position ξ_p^* depends on particle mass and $\sqrt{s}$



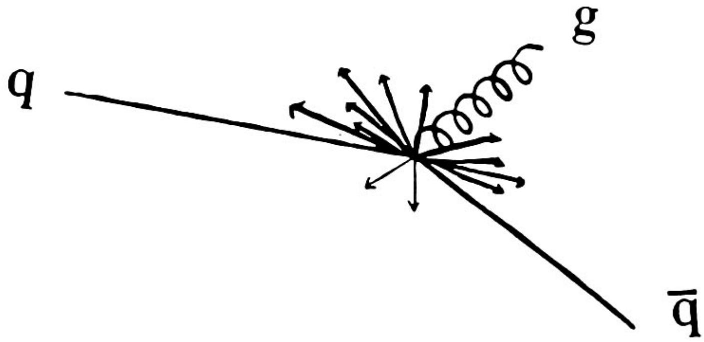
Energy dep. of peak position ξ_p^*



Analytical QCD calculations including soft gluon interference effects together with Local Parton Hadron Duality hypothesis describe data well

'String Effect'

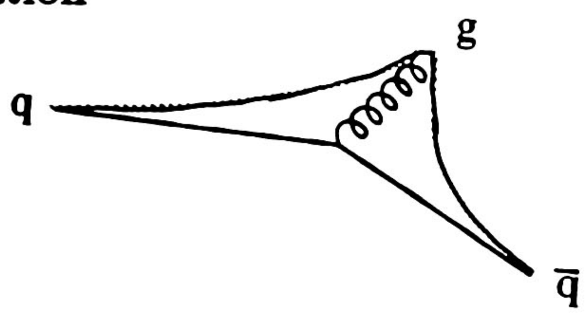
measures interjet interference effects



Less particles in between q and $\bar{q}$ jet in comparison with the other two inter-jet regions

Possible explanations:

- string fragmentation



- leading log QCD calculations: destructive interference !

Can NOT be explained by

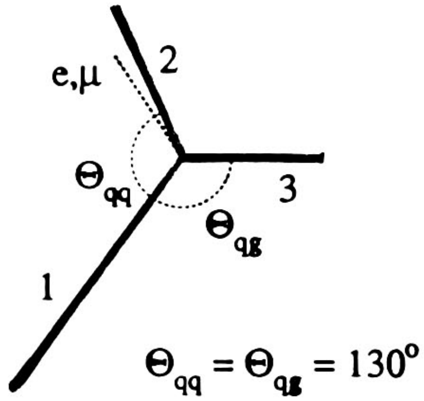
- Incoherent parton shower + 'independent jet fragmentation'

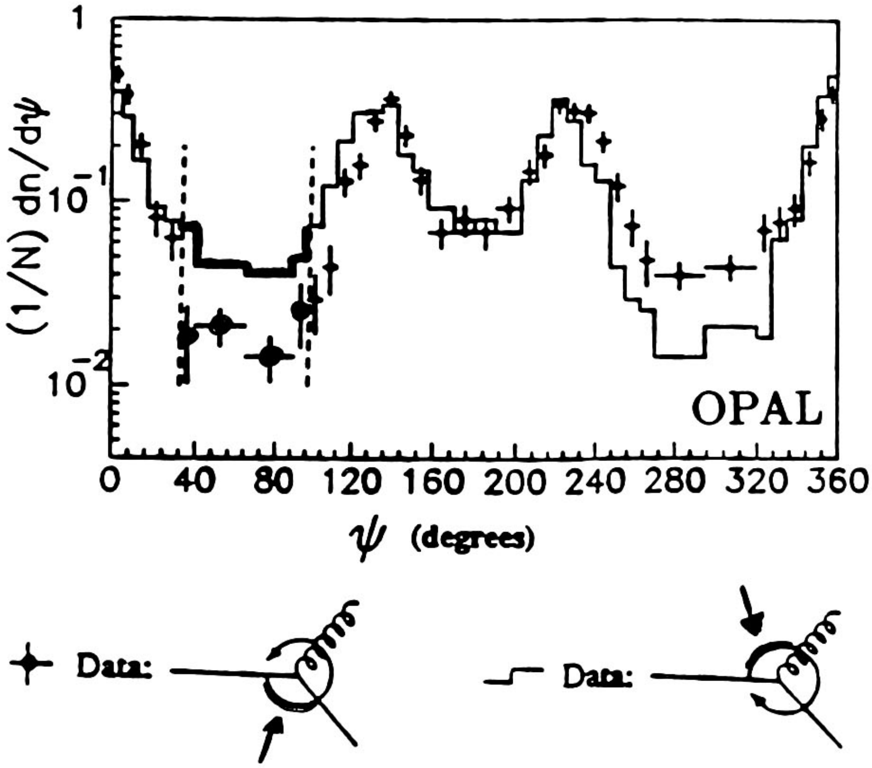
‘String Effect’

DELPHI, OPAL

via quark tagging

- 1^{st} jet: highest energy
  $\rightarrow$ <u>quark jet</u>
- 2^{nd} jet: contains lepton
  $\rightarrow$ <u>quark jet</u>
- 3^{rd} jet
  $\rightarrow$ <u>gluon jet</u> (prob. $\approx$ 70%)



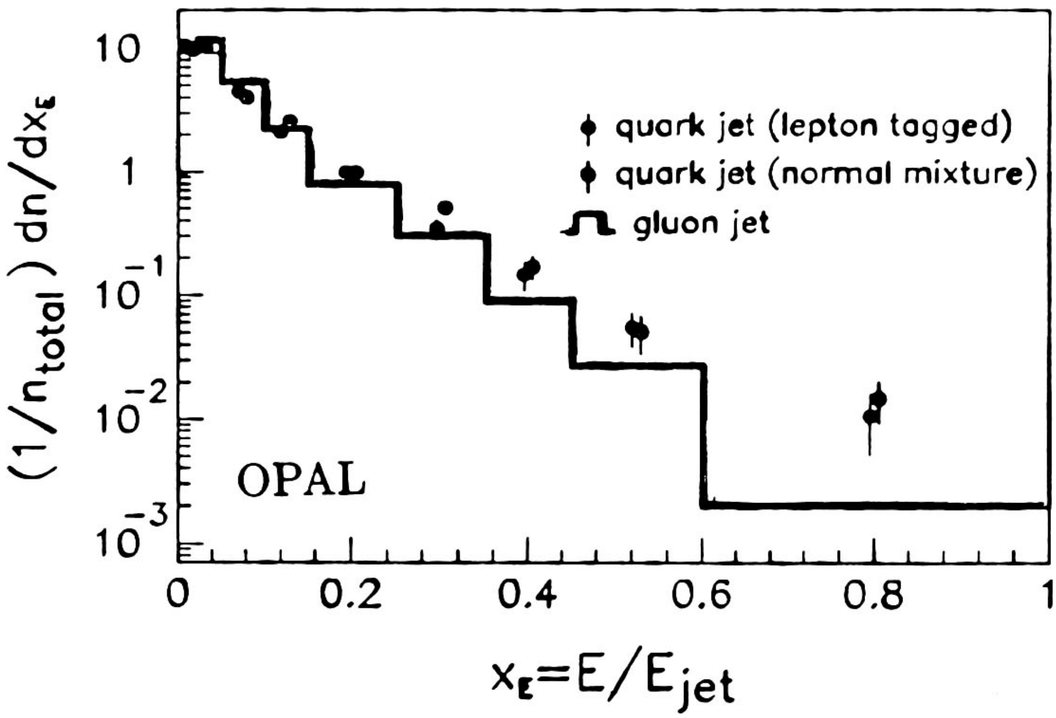


Model-independent confirmation of string effect!
No distinction between different possible interpretations!

Quark-jets versus Gluon-jets'

DELPHI, OPAL

via quark tagging



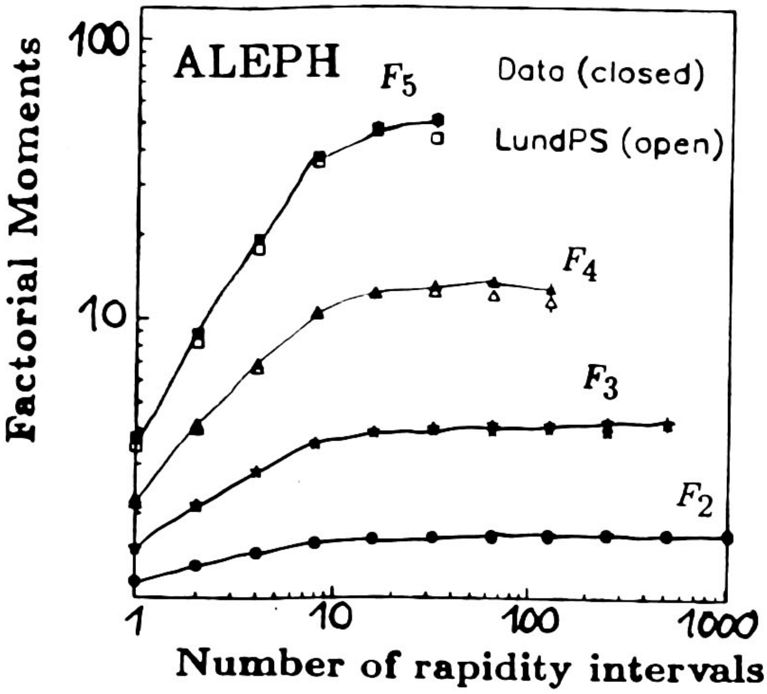
- hadrons in gluon jet core are softer than in quark jets
- gluon jets are broader than quark jets
- charged multiplicities are similar: DELPHI + OPAL:

$$\langle n_{\mathrm{gluon}}\rangle / \langle n_{\mathrm{quark}}\rangle = 1.06 \pm 0.05$$

Intermittency

local particle density fluctuations

ALEPH, DELPHI, OPAL



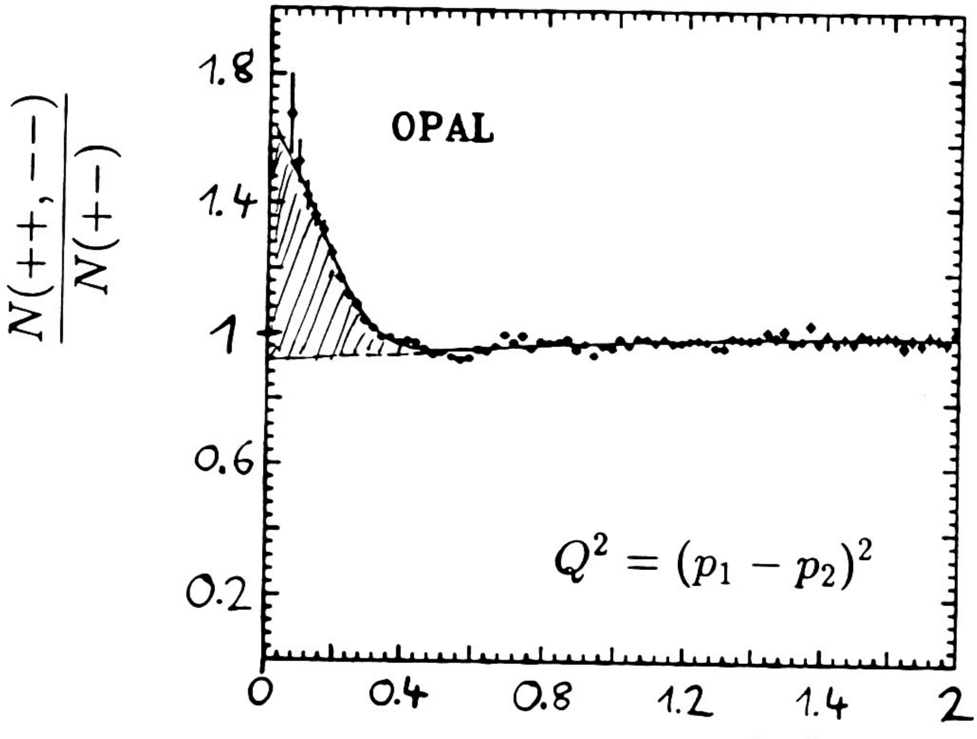
- Factorial moments do rise with increasing rapidity resolution
  → there are local density fluctuations
- Measurements well described by JETSET Monte Carlo program
  → explained by known physics (hard gluon emission ...)

Similar results for different variables and also for analyses in more than one dimension

Bose-Einstein Correlations

ALEPH, DELPHI, OPAL

Identical Bosons (like sign charged pions) prefer to occupy the same quantum state:



Model:
Enhancement at low Q

$$R(Q) = 1 + \lambda \exp(-Q^2 \cdot r^2)$$

LEP:

Strength $\lambda = 0.5 \pm 0.2$
Source size $r = 0.8 \pm 0.1$ **fm**

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‘Soft’ hadron physics

Summary

- A large number of distributions has been measured

- All of them can be reproduced by standard Monte Carlo programs based on QCD parton showers

- Analytical QCD calculations, together with LPHD, give a good description of
  - charged multiplicity ($\sqrt{s}$)
  - particle spectra (form and $\sqrt{s}$ dependence)

Particle yields per hadronic Z^0 decay:

charged particles	20.8 ± 0.2
π^0	9.8 ± 0.7
K^0	2.04 ± 0.10
$K^{*\pm}$	0.93 ± 0.25
Λ	0.25 ± 0.03

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Future QCD studies at the Z^0 resonance

Experimental improvements:

- $\Delta\alpha_s = 0.005$ from R_Z
- QCD tests with identified quark and gluon jets
- more detailed studies of 'soft' phenomena

Theoretical improvements:

- higher order corrections to jet rates etc.
  → reduction of $\Delta\alpha_s$ from jet fraction

Summary and Conclusions

- Strong coupling constant
  - $\boxed{\alpha_S = 0.120 \pm 0.007}$
  - **'running'** $\surd$
- Precise tests of $O(\alpha_s^2)$ QCD matrix element
  - **gluon self interaction** $\surd$
- soft hadron physics
  - **all distributions reproduced by QCD Monte Carlo programs or analytical calculations**

LEP has increased our confidence in QCD significantly