QCD in e^+e^- Collisions at High Energies

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Many thanks to my colleagues in the L3, Aleph, Opal and Delphi analysis groups

Visit L3 at http://hpl3sn02.cern.ch/

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Abstract

In 1996 the LEP center-of-mass energy has reached the up to now highest value of 172 GeV in e^+e^-**collisions. This allows to continue to test the theory of strong interactions (QCD) over the range of data available at LEP - starting at**$\sqrt{s}$**= 91 GeV - with the same experimental facilities consisting of the four detectors L3, Aleph, Opal and Delphi. This allows a precise determination of the strong coupling constant** α_s **at** $\sqrt{s}$**= 172 GeV and enables a comparison of its relative change with energy to the QCD prediction. The variation with energy of the charge multiplicity and of the mean value of several global event shape variables of hadronic final states is compared to QCD models over the energy range from** $\sqrt{s}$**= 10 to 172 GeV.**
The comparison of particle production from quark fragmentation and from gluon fragmentation is of interest for the hadronization process. The total production rates of K^0_s **and** Λ **on the basis of 3.1 million events collected with the L3 detector allow the comparison of their production in preferentially enriched quark and gluon jets and is well described with QCD using string fragmentation Monte Carlo calculations.**

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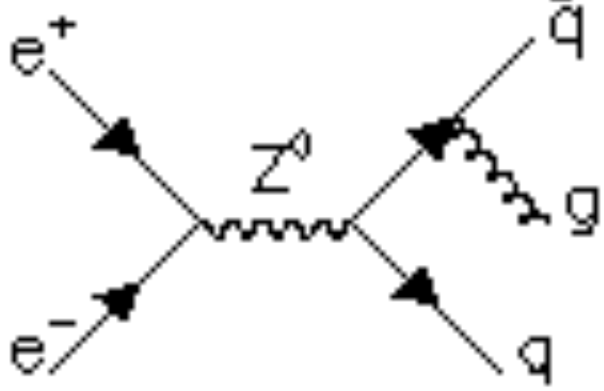
Introduction

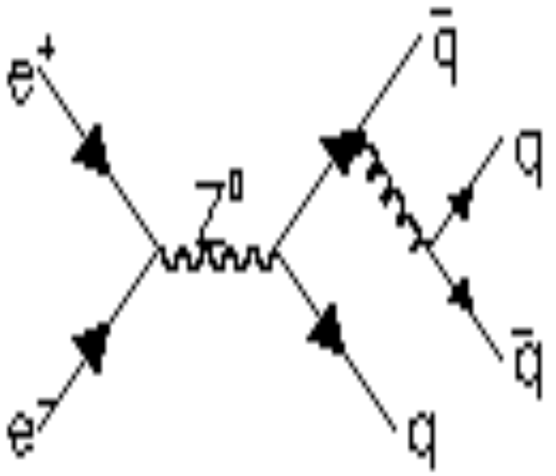
QCD Tests with LEP

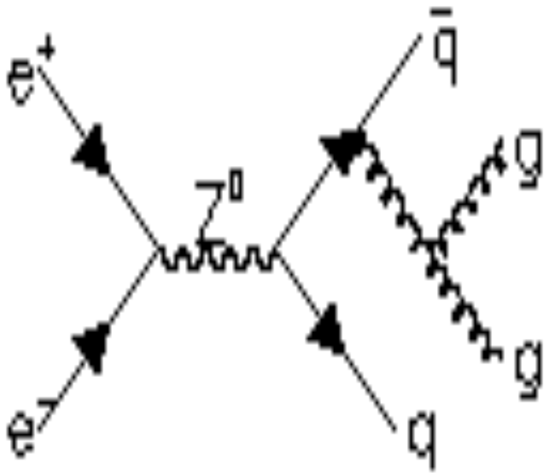
LEP allows testing the strong interaction sector of the standard model, QCD (Quantum Chromo Dynamics) via - among other processes - of Z^0boson and $\mathrm{W}^+\mathrm{W}^-$ boson decays to quarks, which in turn form jets of hadrons.
The strong interaction between quarks is mediated by gluons, and sometimes one of the quarks emits an energetic gluon.



In this case an event containing three jets of hadrons can be seen. By studying such events one can test QCD.

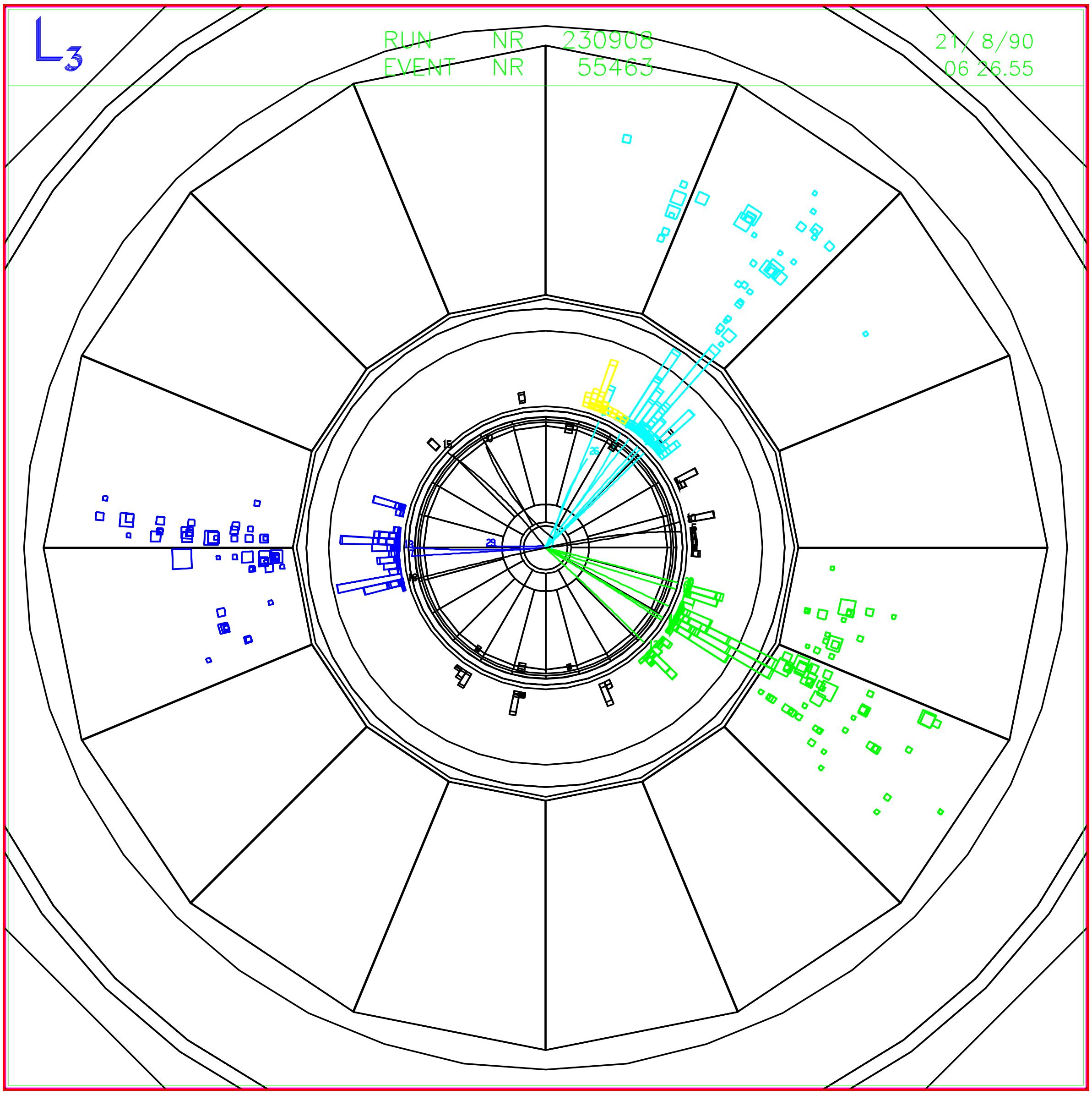
When higher orders in QCD are considered, more complicated processes can take place in which, for example, a gluon can split into a quark-antiquark pair, or into two gluons.





The fundamental parameter α_s , the quark-gluon coupling constant and among others the relative probabilities of quark and gluon jets as well as event shape observables are fully predicted by QCD and depend on the nature of the underlying symmetry group SU(3).

3 Jet Event from Z^0Decay



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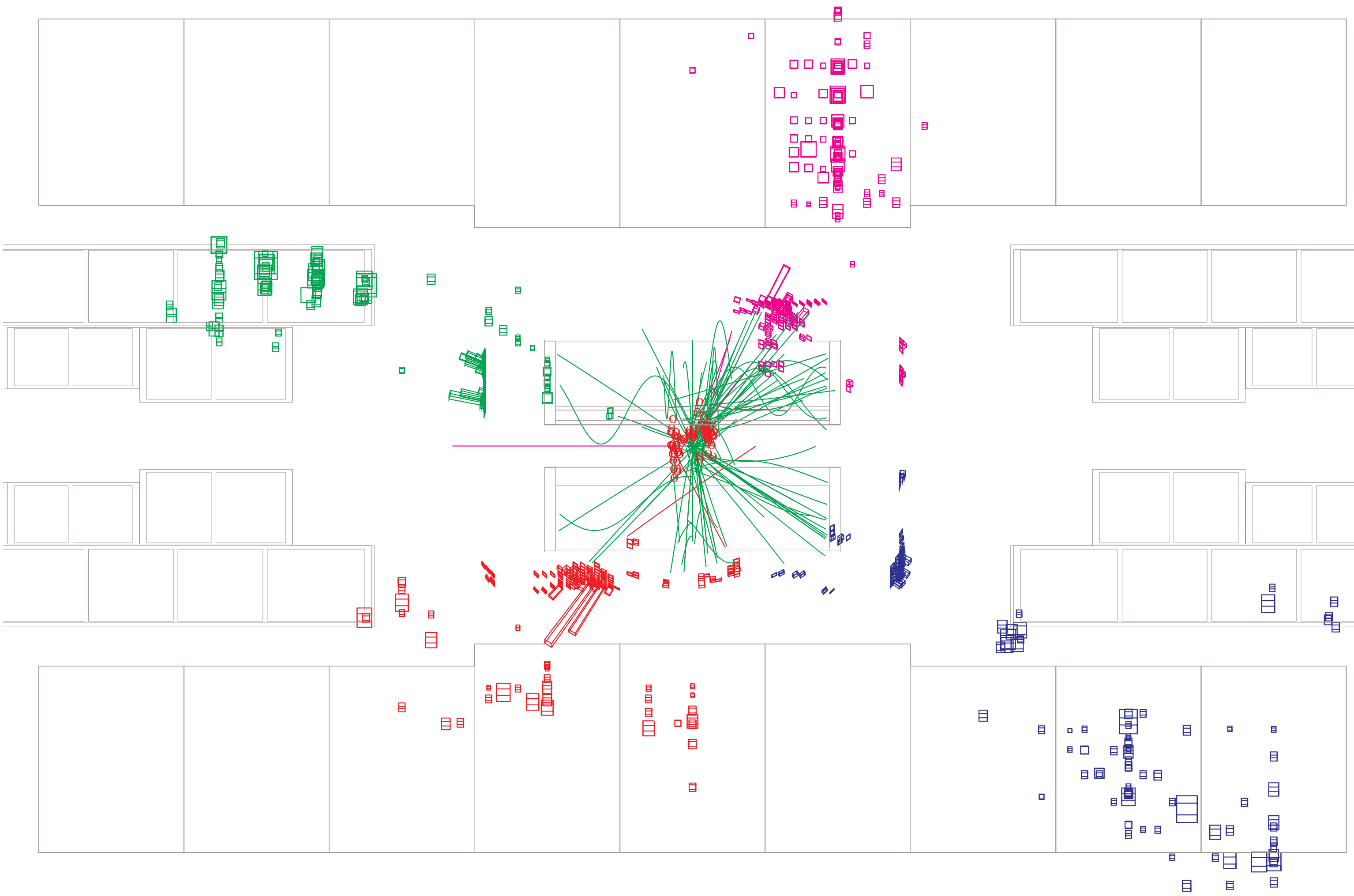
4 Jet Event from W^+W^- Decay



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Introduction

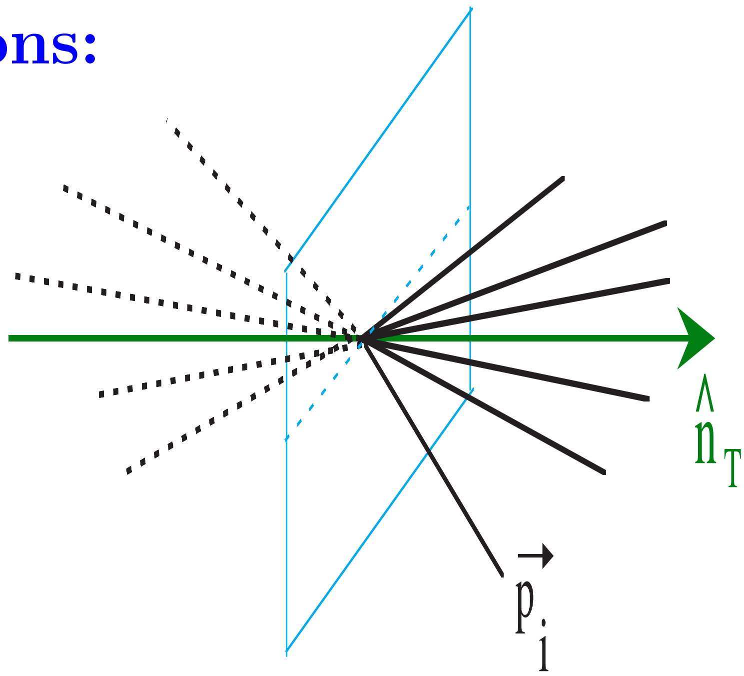
QCD Monte Carlo Programs

To compare the observables to the QCD predictions following QCD Monte Carlo Programs are most commonly used.

- **JETSET**
  parton shower option
  or
  full $O(\alpha_s{}^2)$ matrix element treatment of perturbative QCD
  string fragmentation
- **HERWIG**
  parton shower simulation
  simulation of QCD interference phenomena
  cluster fragmentation
- **ARIADNE**
  parton shower based program
  string fragmentation
- **NLLJET**
  parton shower based program
  based on the next-to-leading logarithmic approximation
- **COJETS**
  multiple gluon radiation simulation
  independent fragmentation

Event Shape Variables

Definitions:



- **Thrust**
  The global event shape variable thrust, T is defined as:

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

where $\vec{p}_i$ is the momentum vector of the particle i. The thrust axis $\vec{n}_T$ is the unit vector which maximises the above expression. The value of the thrust can vary between 0.5 and 1.

- **Heavy jet mass**

$$M_H = \max[M_+(\vec{n}_T), M_-(\vec{n}_T)] ,$$

where $M_\pm$ are the invariant masses in the two hemispheres, $S_\pm$:

$$M_\pm^2 = \left(\sum_{i\in S_\pm} p_i\right)^2$$

The scaled heavy jet mass ρ is defined as:

$$\rho = M_H^2/s .$$

- **Jet broadening variables**

$$B_\pm = \frac{\Sigma_{i\in S_\pm} |\vec{p}_i \times \vec{n}_T|}{2\,\Sigma_i\,|\vec{p}_i|} \,.$$

$$B_T = B_+ + B_- \qquad B_W = \max(B_+, B_-)$$

'total jet broadening' and 'wide jet broadening'

- **jet multiplicity rates**
  Jets are reconstructed using the JADE and the Durham algorithms
  For Durham algorithm, the expression for y_{ij} is:

$$y_{ij} = \frac{2min(E_i^2, E_j^2)}{s} \cdot (1 - \cos\theta_{ij})$$

In the JADE case for each pair of particles i and j the expression:

$$y_{ij} = \frac{2E_iE_j}{s} \cdot (1 - \cos\theta_{ij})$$

is evaluated. E_i and E_j are their energies and θ_{ij} is the angle between them. The pair for which y_{ij} is smallest is replaced by a pseudoparticle l with four-momentum

$$p_l = p_i + p_j \,.$$

This procedure is repeated until all y_{ij} exceed the jet resolution parameter . The remaining pseudoparticles are called jets.

- **Charge multiplicity**
  We define charge multiplicity, n_{ch}, as the number of charged particles per event.

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α_s Data before 1996

K.McFarland's table presents a critical discussion of the different experimental methods.
The following plot (from Langacker) summarizes the world's α_s data.

α_s Measurements - Strengths and Weaknesses

Measurement	$\alpha_s(\mathrm{M}_\mathrm{Z}^2)$	Strength	Weakness
CCFR GLS Sum Rule	$0.108^{+0.007}_{-0.009}$		large higher twist contrib
CCFR xF_3 Evolution	0.111 ± 0.006	no gluon dependence	scale uncertainty
R$_\tau$ $CLEO$	0.114$\pm$0.003	NNLO	non-pertub-ative error
R$_\tau$ LEP	0.121$\pm$0.0024	small error	estimate?
Lattice QCD	0.115$\pm$0.002	small error	Lattice QCD errors
LEP global EW Fit	0.122$\pm$0.004	perfect SM	$\mathrm{R_b}, \mathrm{R_c}$
LEP Event Shapes	0.122$\pm$0.006	statistics	scale ?
SLD Event Event Shapes	0.120$\pm$0.008		statistics?
World Average	0.117$\pm$0.005		

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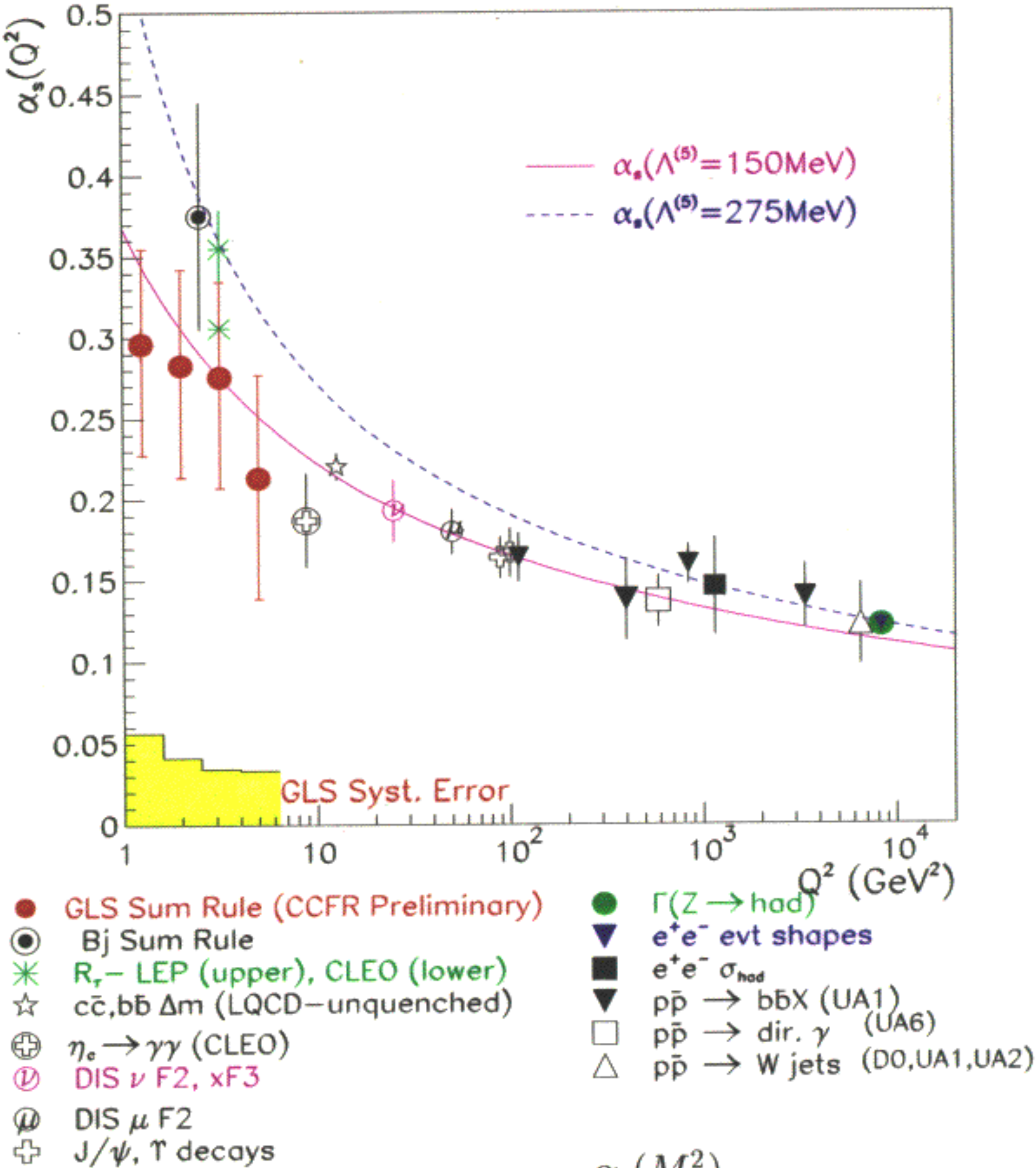
The World's α_s Data



	$\alpha_s(M_Z^2)$
CCFR Non-Singlet Evolution	$0.111 \pm 0.004 \pm 0.004$
CCFR GLS Sum Rule	$0.108 \; ^{+0.005}_{-0.005} \; ^{+0.004}_{-0.006}$
LEP Electroweak Fit	$0.122 \pm 0.004 \pm 0.002$
LEP Event Shapes	$0.122 \pm 0.001 \pm 0.006$

$\rightarrowtail 2.2\sigma$

Note that LEP 1 data from the Z^0peak are already included.

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LEP-2 Data

What is LEP-1.5 and LEP-2

LEP-2 runs at an energy allowing the direct production of W^+W^- pairs, i.e. above 161 GeV c.m. energy.

During fall 1995 LEP operated at an intermediate energy range of 130 and 136 GeV (LEP 1.5) in order to tune and prepare the storage ring and the experiments for the 100 % E_{cm}energy increase. L3 collected an integrated luminosity of $\approx$ 5 pb^{-1} at that energy.

Recent LEP runs:

- **July 9, 1996 LEP2 reaches 161 GeV**
  The L3 Detector recorded $\approx$ 11 pb^{-1}
- **October 19, 1996 LEP goes to 172 GeV**
  The L3 Detector recorded $\approx$ 11 pb^{-1}
  1.00 pb^{-1} at 170.3 GeV
  9.25 pb^{-1} at 172.3 GeV
- **the other three LEP experiments collected similar amounts of data**

The following results are based on the

- **LEP-2 data run**
- **all LEP data runs sofar**

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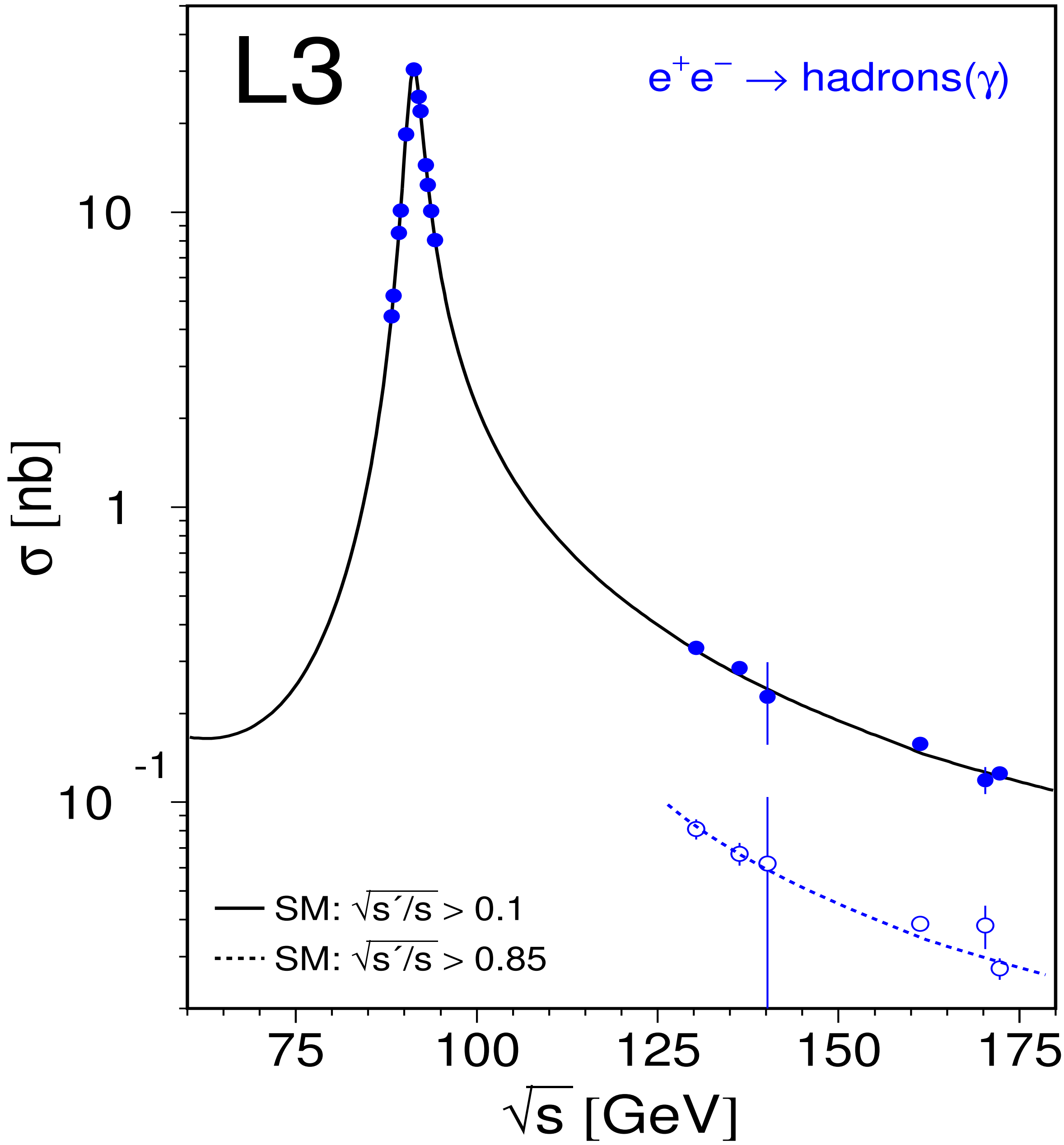
LEP Data

- Total data sample of 4 experiments
  14.4 M hadronic events;
  1.6 M leptonic events.
- First Z^0events: August 13, 1989
- Energy scans around Z^0peak: 1993, 1995.



Total accumulated L3 hadron final states

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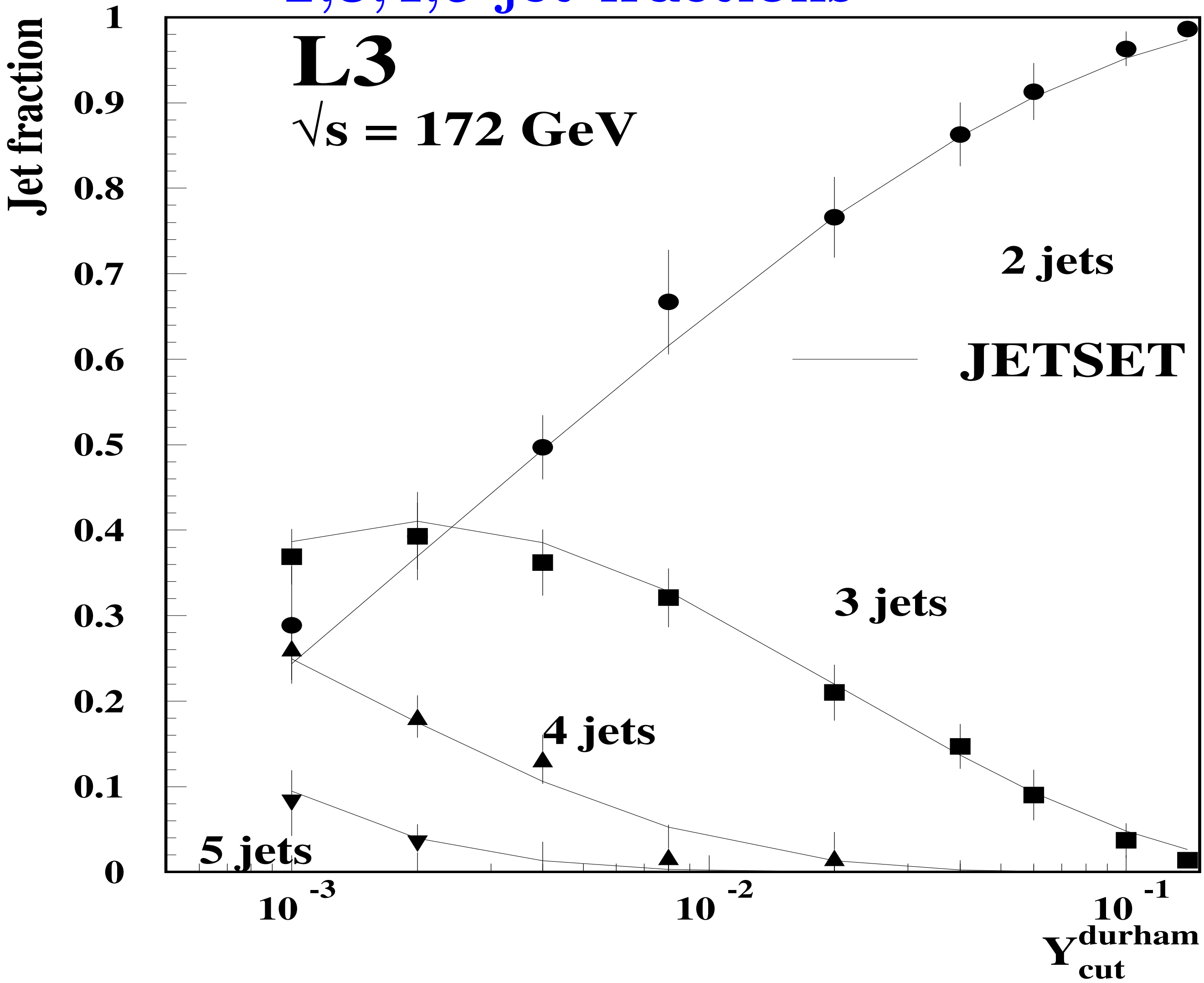
α_s Data at 172 GeV

α_s obtained by average jet multiplicity

2,3,4,5 jet fractions



- Jet fractions obtained with Durham algorithm
- Very good agreement with QCD predictions

Mean charge multiplicity $<n_{ch}>$

$$26.61 \pm 0.47(stat) \pm 0.30(syst)$$

Mean Thrust value $< \mathrm{T} >$

$$0.9493 \pm 0.0031(stat) \pm 0.0019(syst)$$

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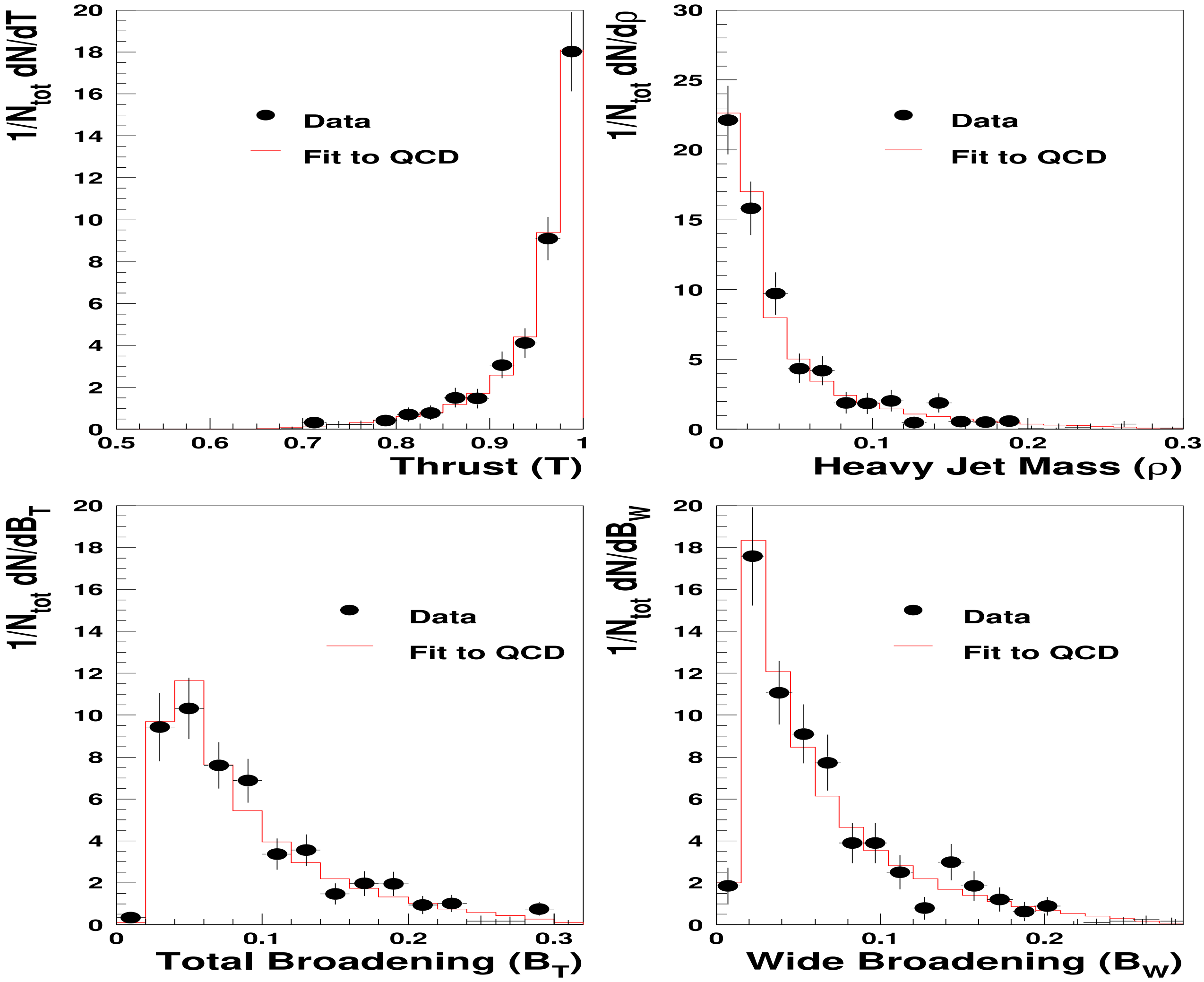
α_s Data at 172 GeV

α_s obtained by event shape variables QCD fit for L3 data at 172 GeV comprising

- thrust T
- scaled heavy jet mass ρ
- total jet broadening B_T
- wide jet broadening B_W

results in

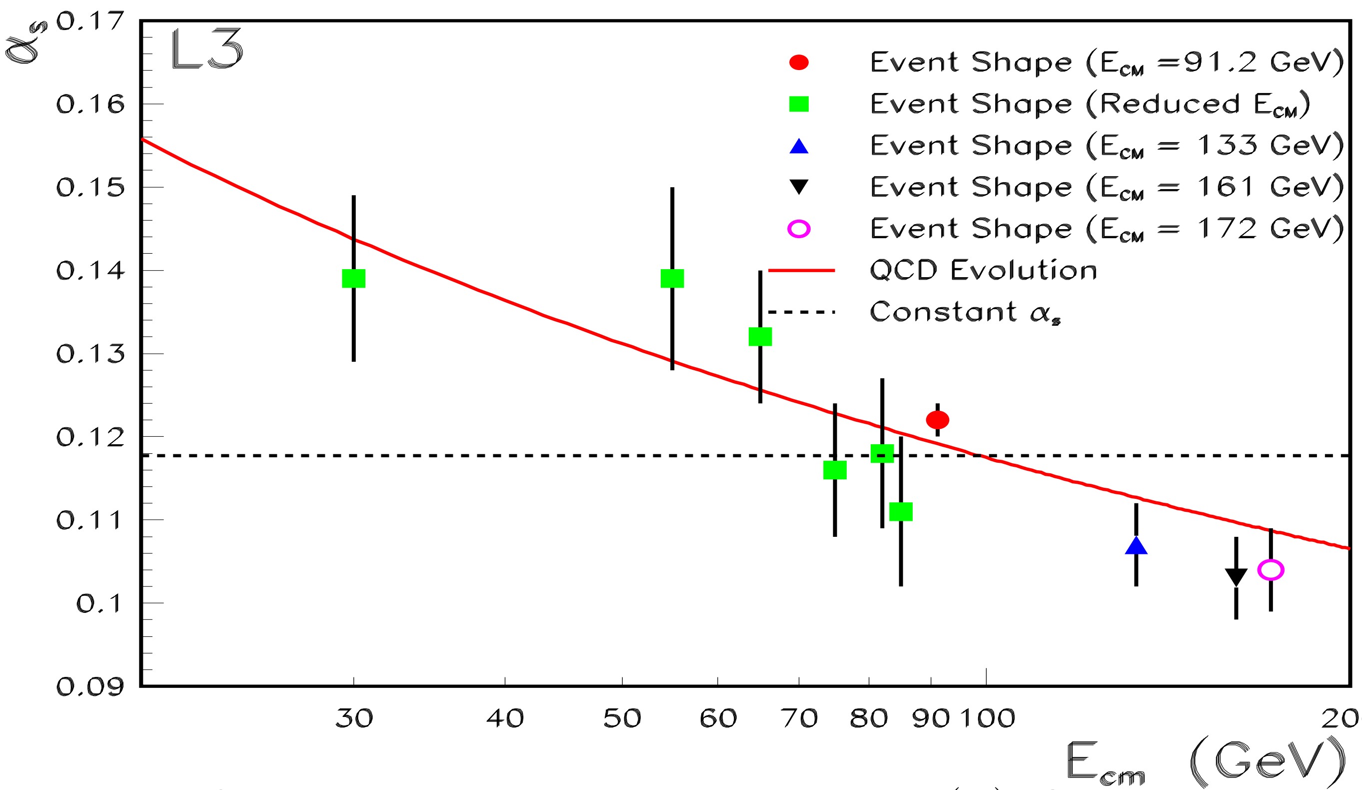
$$\alpha_s\ \mathbf{(172GeV)} = 0.104 \pm 0.006(exp) \pm 0.005(theo)$$



α_s Data

α_s values are obtained from fits to the QCD predictions of event shape variables

- **Fit with α_s (E) as predicted by QCD**
  α_s **(91.2 GeV)** $= 0.119 \pm 0.002(exp)$
  χ^2 **/ d.o.f = 10.6/9 (prob=0.30)**
- **Fit with constant α_s**
  $\alpha_s = 0.118 \pm 0.002(exp)$
  χ^2 **/ d.o.f = 35.3/9 (prob=0.00053)**



α_s data from the L3 experiment; $qq(\gamma)$ final states

The final state photon energy measurement allows to extend the energy range to lower values than the LEP energy.

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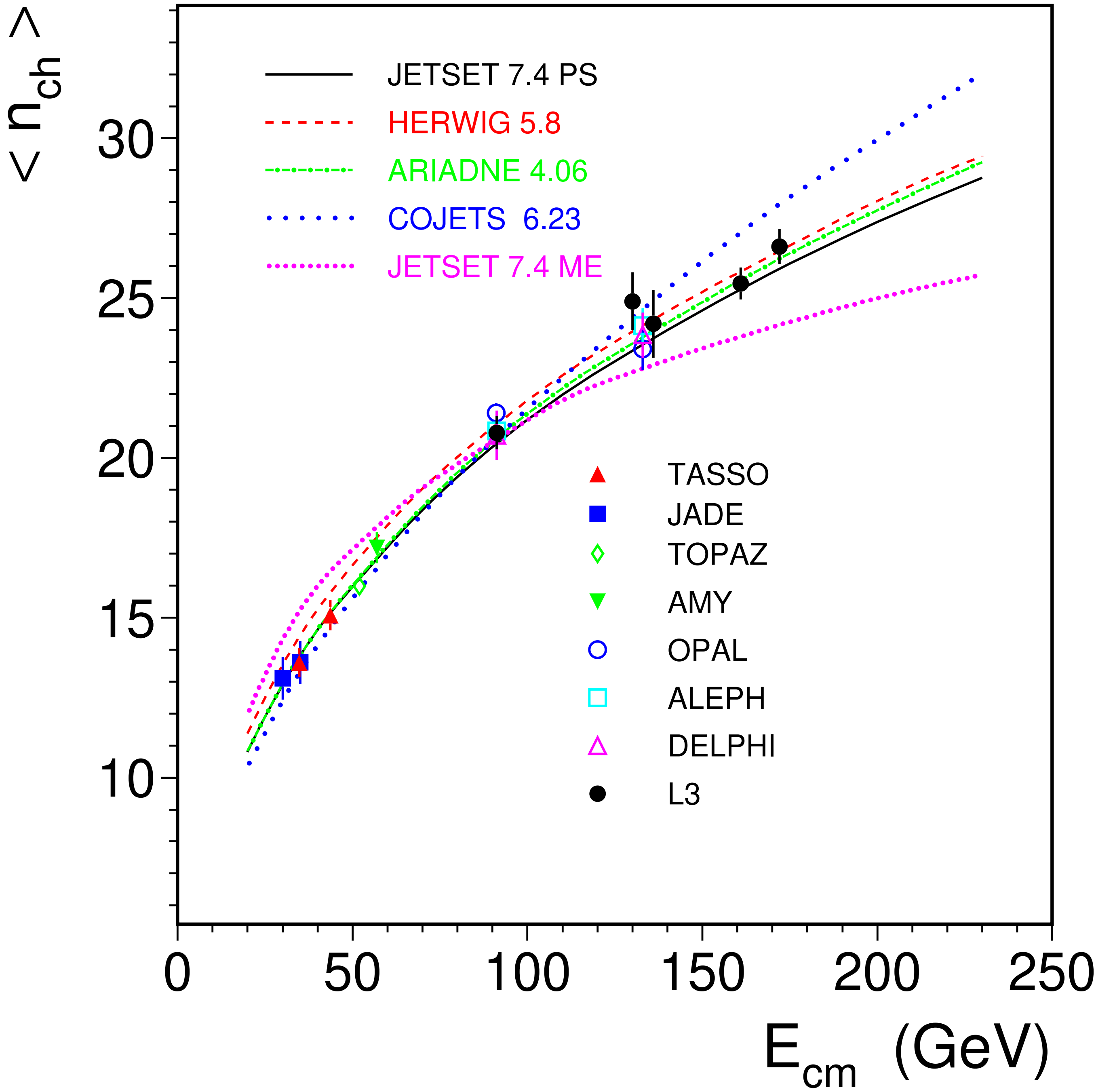
α_s Data
α_s obtained by charge multiplicity
mean charge multiplicity $<n_{ch}>$ vs E_{cm}



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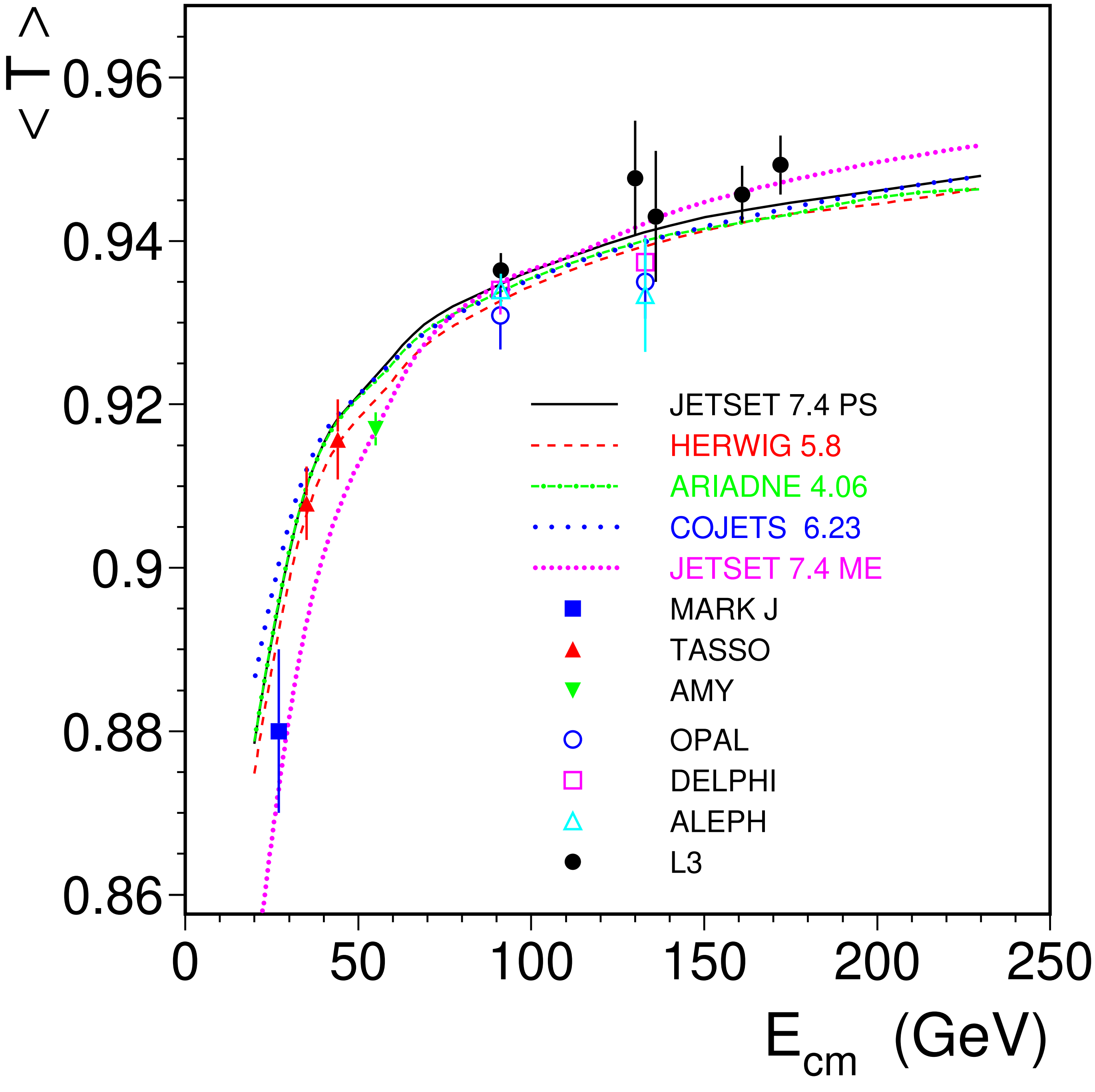
α_s Data
α_s obtained by event shape variables
thrust T vs E_{cm}



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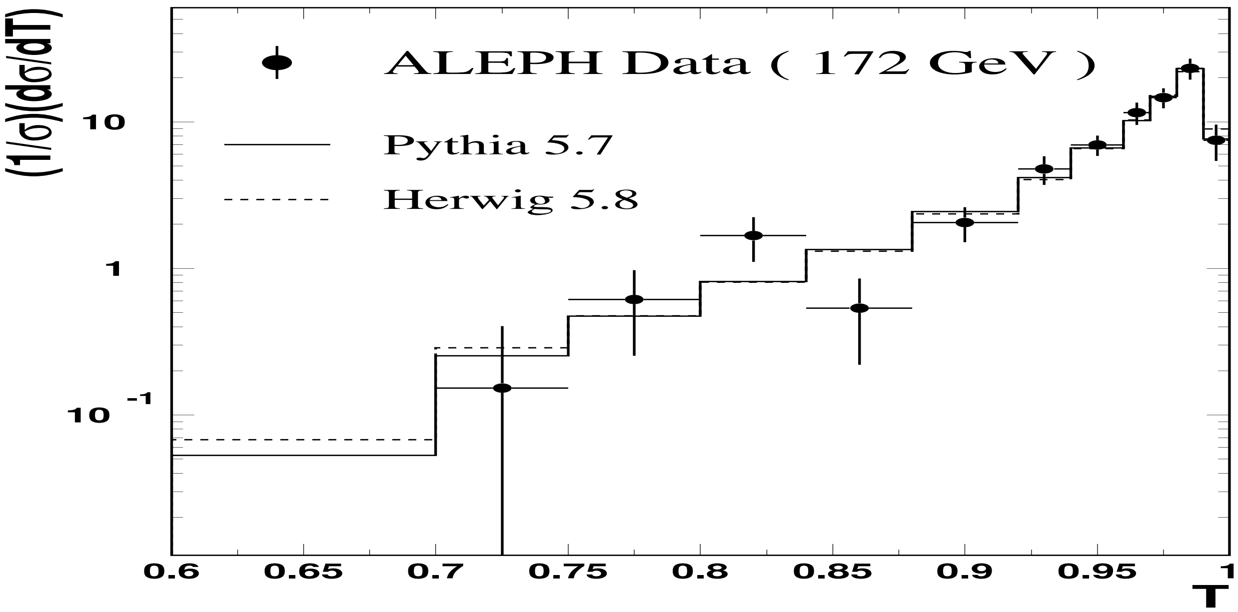
ALEPH Experiment at LEP
QCD data at 172 GeV



Preliminary ALEPH QCD values – 10.3.97

For questions please contact Glen Cowan, glen.cowan@cern.ch or Yuanning Gao, Y.Gao@rhbnc.ac.uk

*** $< Nch >$ from integral of rapidity distribution,**

$$< Nch > (161GeV) = 26.53 \pm 0.41(stat) \pm 0.38(syst)$$

$$< Nch > (172GeV) = 26.33 \pm 0.44(stat) \pm 0.41(syst)$$

*** Thrust**

$$< 1 - T > (161GeV) = 0.0610 \pm 0.0039(stat) \pm 0.0029(syst)$$

$$< 1 - T > (172GeV) = 0.0532 \pm 0.0043(stat) \pm 0.0039(syst)$$

*** α_s from y3 distribution,**

fit range 1.2 $\leq -lny3 \leq 7.6$

$$\alpha_s \ \mathbf{(161GeV) = 0.1085}$$

$$\pm 0.0045(stat) \pm 0.0020(syst) \pm 0.0004(hadr) \pm 0.0047(theo)$$

$$\alpha_s \ \mathbf{(172GeV) = 0.108}$$

$$\pm 0.0050(stat) \pm 0.0024(syst) \pm 0.0004(hadr) \pm 0.0045(theo)$$

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OPAL Experiment at LEP

QCD data at 172 GeV

Preliminary OPAL QCD values – 28.2.97

*** $< Nch >$ from direct measurement,**

$$< Nch > (172GeV) = 25.92 \pm 0.56(stat) \pm 0.81(syst)$$

$$D(172GeV) = 8.05 \pm 0.55(stat) \pm 0.77(syst)$$

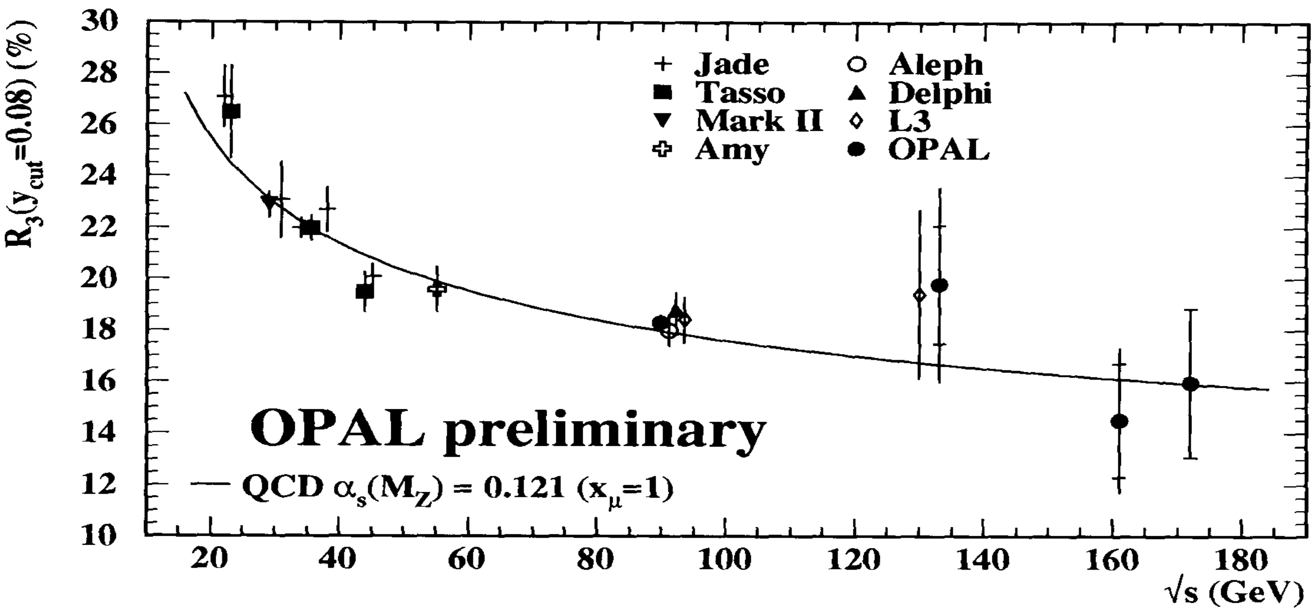
D is the dispersion

*** determination of α_s based on fits to**

$1-T$	M_H	B_T	B_W	D_2

$$\alpha_s \ \mathbf{(172GeV) = 0.093}$$

$$\pm 0.005(stat) \pm 0.006(syst)$$



- three jet rate R_3 between $22GeV \leq \sqrt{s} \leq 172GeV$

- solid line is a QCD prediction fit

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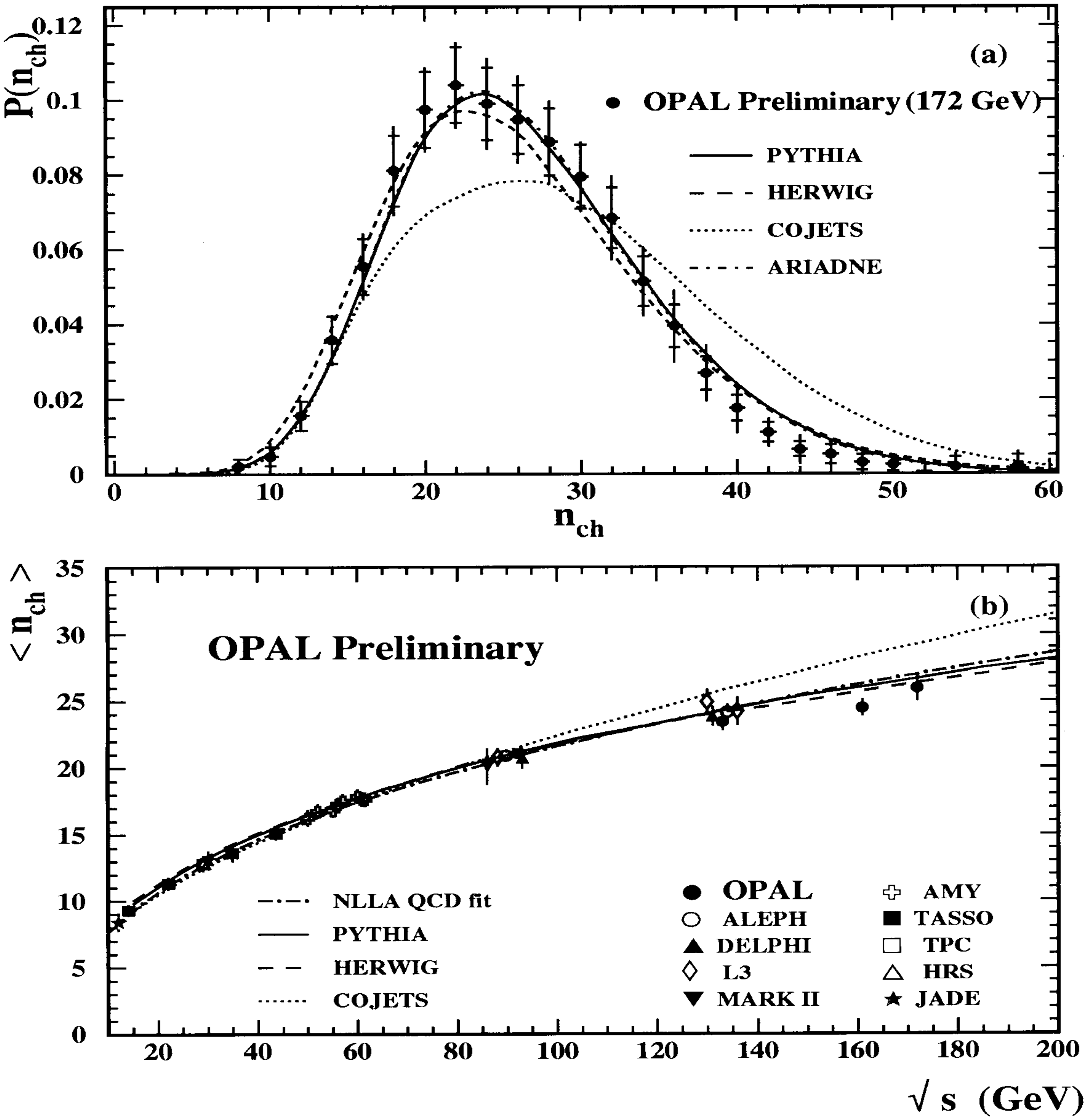
OPAL Experiment at LEP

n_{ch} data at 172 GeV



- n_{ch} **at** $\sqrt{s}$**= 172 GeV**
- $< n_{ch} >$ **between** $22 GeV \leq \sqrt{s} \leq 172 GeV$

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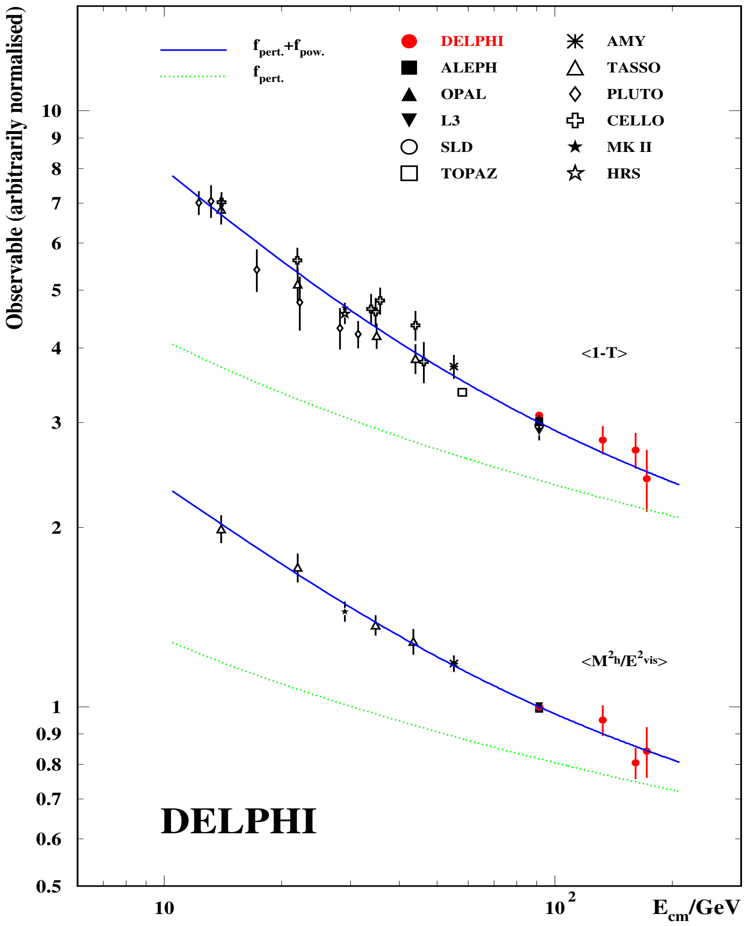
Delphi Experiment

Fragmentation Model Independent α_s Determination

$$\langle f \rangle = \frac{1}{\sigma_{tot}} \int f \frac{d\sigma}{df} df = \langle f_{pert} \rangle + \langle f_{pow} \rangle$$

$$\langle f_{pow} \rangle = a_f \cdot \frac{\mu_I}{E_{cm}} \left[\bar{\alpha}_0(\mu_I) - \alpha_s(\mu) - \left(b_0 \cdot \log \frac{\mu^2}{\mu_I^2} + \frac{K}{2\pi} + 2b_0 \right) \cdot \alpha_s^2(\mu) \right]$$



$$\alpha_s(133 \text{ GeV}) = 0.116 \pm 0.007_{exp} {}^{+0.005}_{-0.004}{}_{theo}$$

$$\alpha_s(161 \text{ GeV}) = 0.107 \pm 0.008_{exp} {}^{+0.005}_{-0.004}{}_{theo} \qquad \text{(preliminary)}$$

$$\alpha_s(172 \text{ GeV}) = 0.104 \pm 0.013_{exp} {}^{+0.005}_{-0.004}{}_{theo} \qquad \text{(preliminary)}$$

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Hadronization

Study the process of how hadronization occurs in particle production

- **the Z^0 decays into quarks**
- **quark fragmentation**
- **(radiative) gluon fragmentation**

$*$ **Selection of enriched quark or gluon jets**

$*$ **Compare K_S^0 and Λ total production rates**

Via JETSET program reconstruction the probability is

$\geq$ **70%** **that the less energetic jet originates from gluon fragmentation**

$\geq$ **90%** **that the most energetic jet originates from one of the primary quark fragmentations**

$\geq$ **70%** **that the two most energetic jets originate from one of the primary quark fragmentations**

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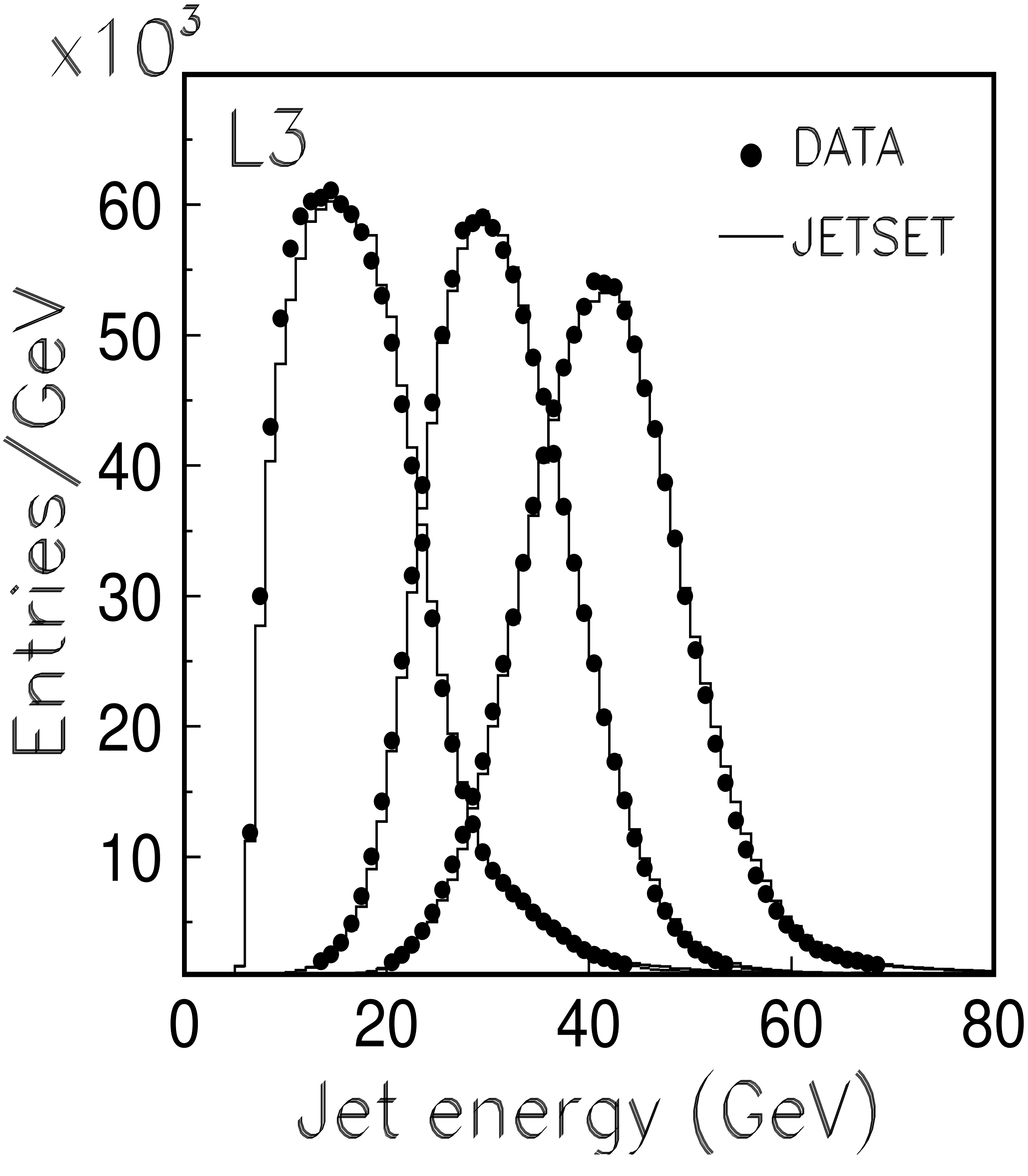
Gluon and Quark Jet Selection

The reconstructed jet energy distributions for the three categories of jets in three jet events.



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K_s^0 and Λ production

The most recent K_s^0 and Λ total production rates as measured by the different experiments at LEP and their comparison with Monte Carlo expectation.

	$\langle K_s^0 \rangle$/event	$\langle \Lambda \rangle$/event
L3 [5]	1.02±0.01±0.07	0.37±0.01±0.04
ALEPH [6]	1.03±0.024	0.386±0.016
DELPHI [7]	0.981±0.011±0.028	0.357±0.003±0.017
OPAL [8]	0.995±0.005±0.020	0.374±0.010
Tuned JETSET	1.02	0.35
This study	1.01±0.003±0.021	0.36±0.004±0.017

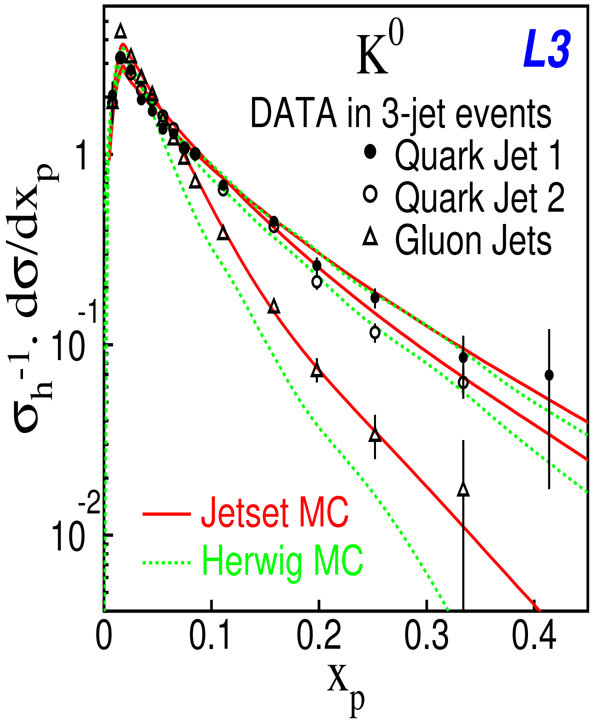
The global rates and shapes are in agreement with both JETSET and HERWIG MC predictions.

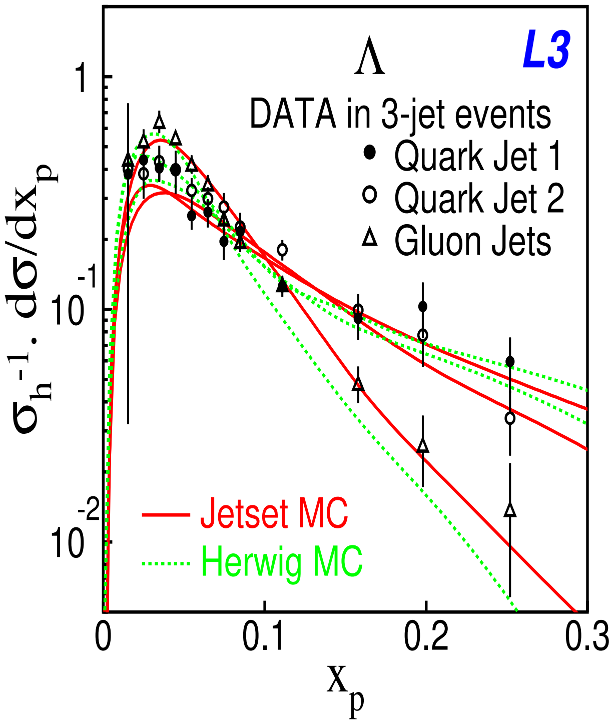
We define the relative K_s^0 and Λ rates as

. $$\mathrm{R}(\mathrm{K}_s^0) = \frac{\frac{\langle \mathrm{K}_s^0 \rangle_{perjet}}{\langle N_{ch} \rangle_{perjet}}}{\frac{\langle K_s^0 \rangle_{total}}{\langle N_{ch} \rangle_{total}}} \quad \text{and} \quad \mathrm{R}(\Lambda) = \frac{\frac{\langle \Lambda \rangle_{perjet}}{\langle N_{ch} \rangle_{perjet}}}{\frac{\langle \Lambda \rangle_{total}}{\langle N_{ch} \rangle_{total}}}$$

Gluon and Quark Jet Results

Comparison of the relative production rates, R(K_s^0) and R(Λ), observed in the different categories of jets with the Monte Carlo expectation.





Only JETSET reproduces correctly the gluon jet behavior in K_s^0 and Λ data.

- **least energetic jet**
  reduced available energy during the fragmentation
  production rate for the K_s^0 unchanged
  production rate for the Λ baryon enhanced
- **most energetic jet**
  quark production increase with E_{cm} favours baryon production
  Λ baryon production rate enhanced
  production rate for the K_s^0 unchanged

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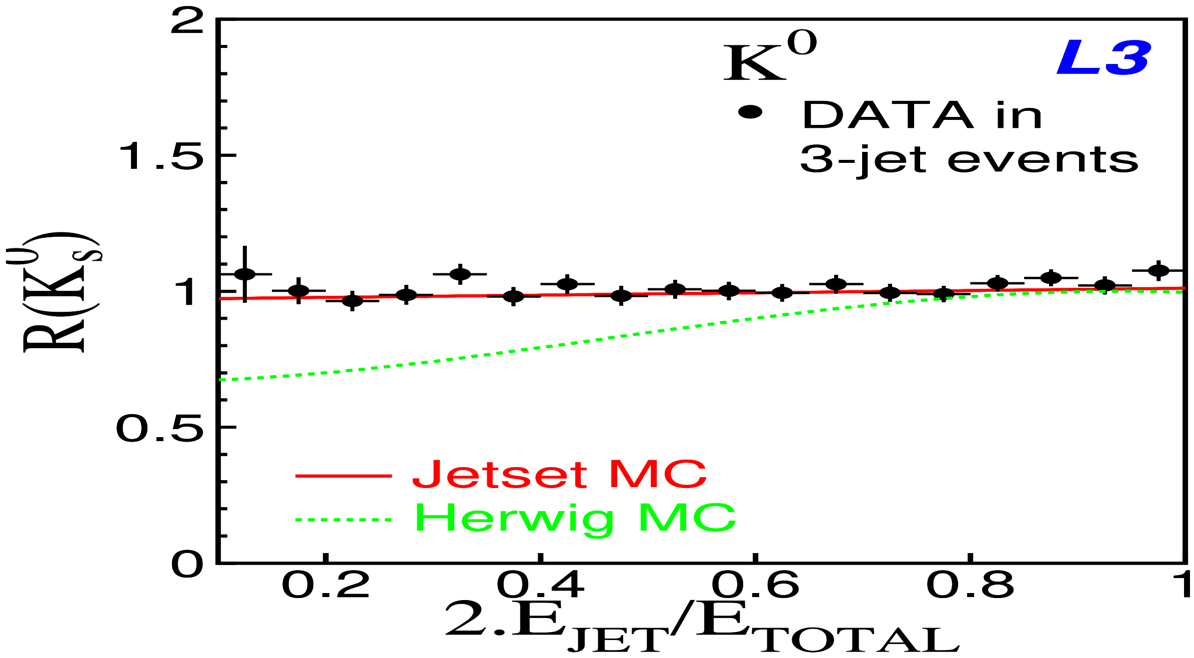
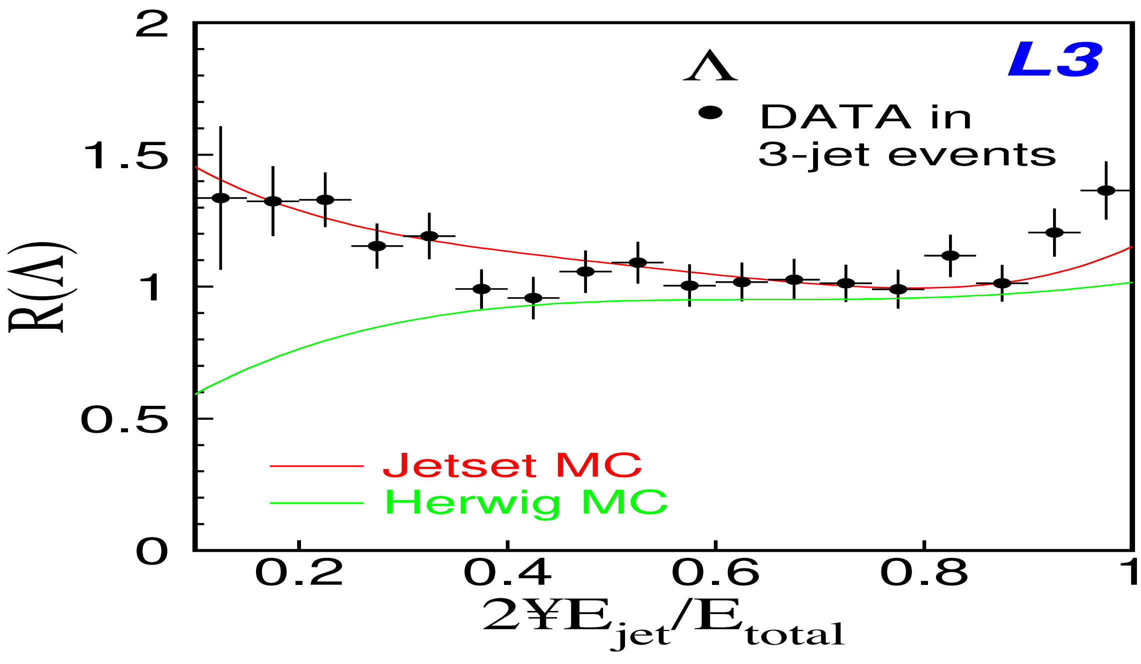
Gluon and Quark Jet Results

- relative rate $R(K_s^0)$ of K_s^0 meson
- relative rate $R(\Lambda)$ of Λ baryon
- good agreement with JETSET Monte Carlo
- poor agreement with HERWIG Monte Carlo





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