Study of Event Shape Variables at LEP

- Introduction
- Event Selection
- Event Shape Variables
- Comparison with QCD Predictions
- Power Law Description of Fragmentation
- Studies at Reduced CM Energies using LEP I data
- Summary

Subir Sarkar
TIFR - Bombay & CERN

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Introduction

Experiments at LEP

- Detectors cover 99% of 4π
- Hadronic events identified with small systematic errors
- Energy and direction of jets precisely measured

New theoretical calculations

- Complete calculations to $\mathcal{O}({\alpha_s}^2)$
- Leading and next-to-leading terms calculated to all orders
- Calculations exist for several event shape variables

$\Rightarrow$ QCD studies can be performed with

small experimental and theoretical uncertainties

Event Selection : $e^+e^- \rightarrow q\bar{q}$

Hadronic events characterised by

- Large visible energy
- Large number of particles in the final state

High Energy LEP Data

$\sqrt{s}$ (GeV)	$\int \mathcal{L}(pb^{-1})$/Expt	Events/Expt
130–140	5.5	$\sim$ 300
161	11.0	$\sim$ 300
172	10.5	$\sim$ 250

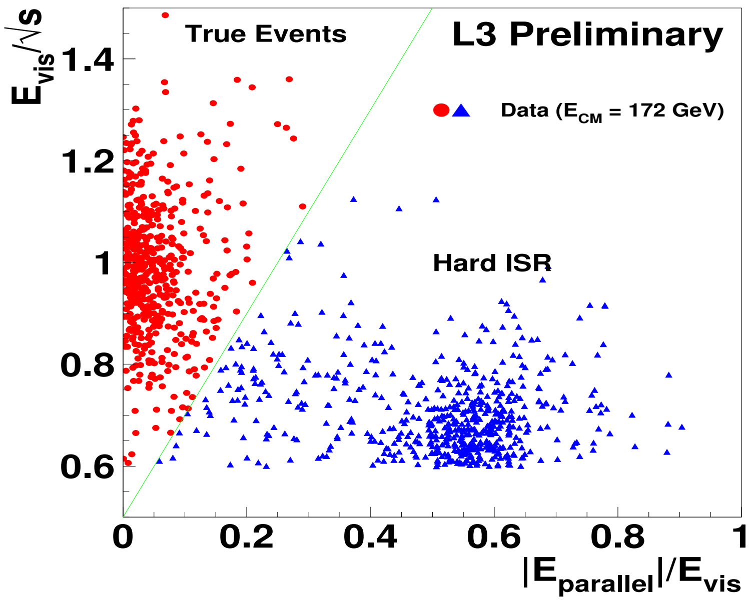
Large contribution from radiative return to Z

Reject this background demanding

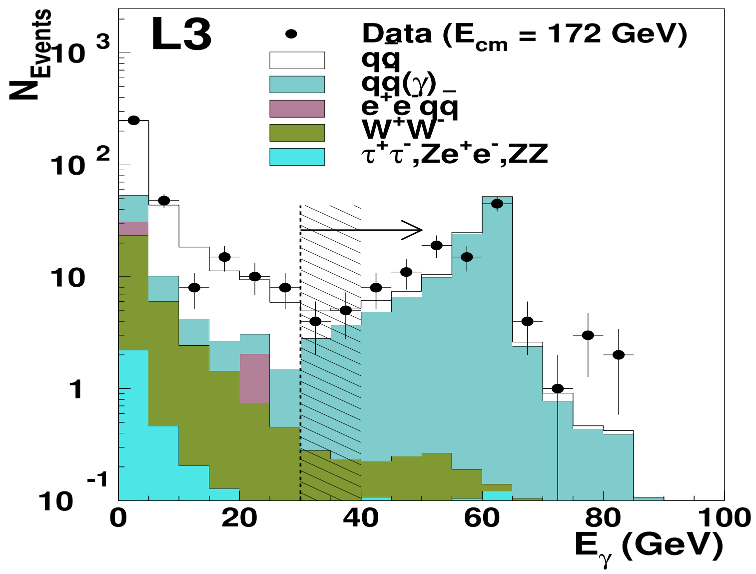
- Low longitudinal energy imbalance
- No energetic photon seen in the detector

Event Selection : $e^+e^- \rightarrow q\bar{q}$

L3



$$(E_{vis}/\sqrt{s}) > 2.0\,(\mid E_{parallel} \mid /E_{vis}) + 0.5$$



$$E_\gamma < 30 \text{ GeV}$$

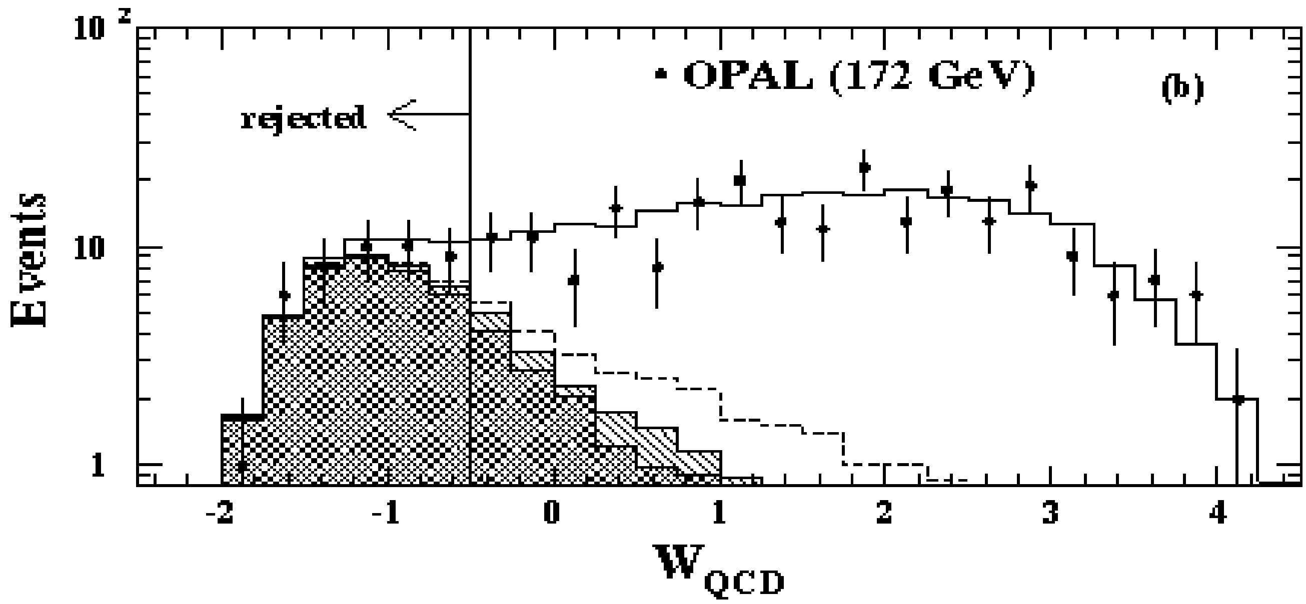
Large contribution from WW events at 172 GeV

OPAL

$$W_{QCD} = \max_{\{p_1,p_2,p_3,p_4\}} \log\left(|\,\mathcal{M}(p_1,p_2,p_3,p_4)\,|^2\right)$$

from $\mathcal{O}(\alpha_s{}^2)$ matrix element calculations of $e^+e^- \to q\bar{q}q\bar{q}, q\bar{q}gg$

- Force events into four jet configuration
- Compute W_{QCD} from 4-momenta of the four jets



$W_{QCD} \geq -0.5$

Event Shape Variables

- Thrust

$$T = \max \frac{\sum_a |\vec{p_a} \cdot \vec{n_T}|}{\sum_a |\vec{p_a}|}$$

- Scaled Heavy Jet Mass

$$\begin{aligned} M_\pm^2 &= \left(\sum_{a \in S_\pm} p_a\right)^2 \\ M_H &= \max[M_+(\vec{n_T}), M_-(\vec{n_T})] \\ \rho &= M_H^2/s \end{aligned}$$

- Jet Broadening Variables

$$B_\pm = \frac{\sum_{a \in S_\pm} |\vec{p_a} \times \vec{n_T}|}{2 \sum_a |\vec{p_a}|}$$

  - Total Jet Broadening $\quad B_T = B_+ + B_-$
  - Wide Jet Broadening $\quad B_W = \max(B_+, B_-)$

- Reconstruct jets using k_T algorithm. Define

  Average jet multiplicity

$$\langle n_{jet} \rangle = \frac{1}{N} \sum_{i=1}^{N} n_{jet}^i$$

  Differential two jet rate

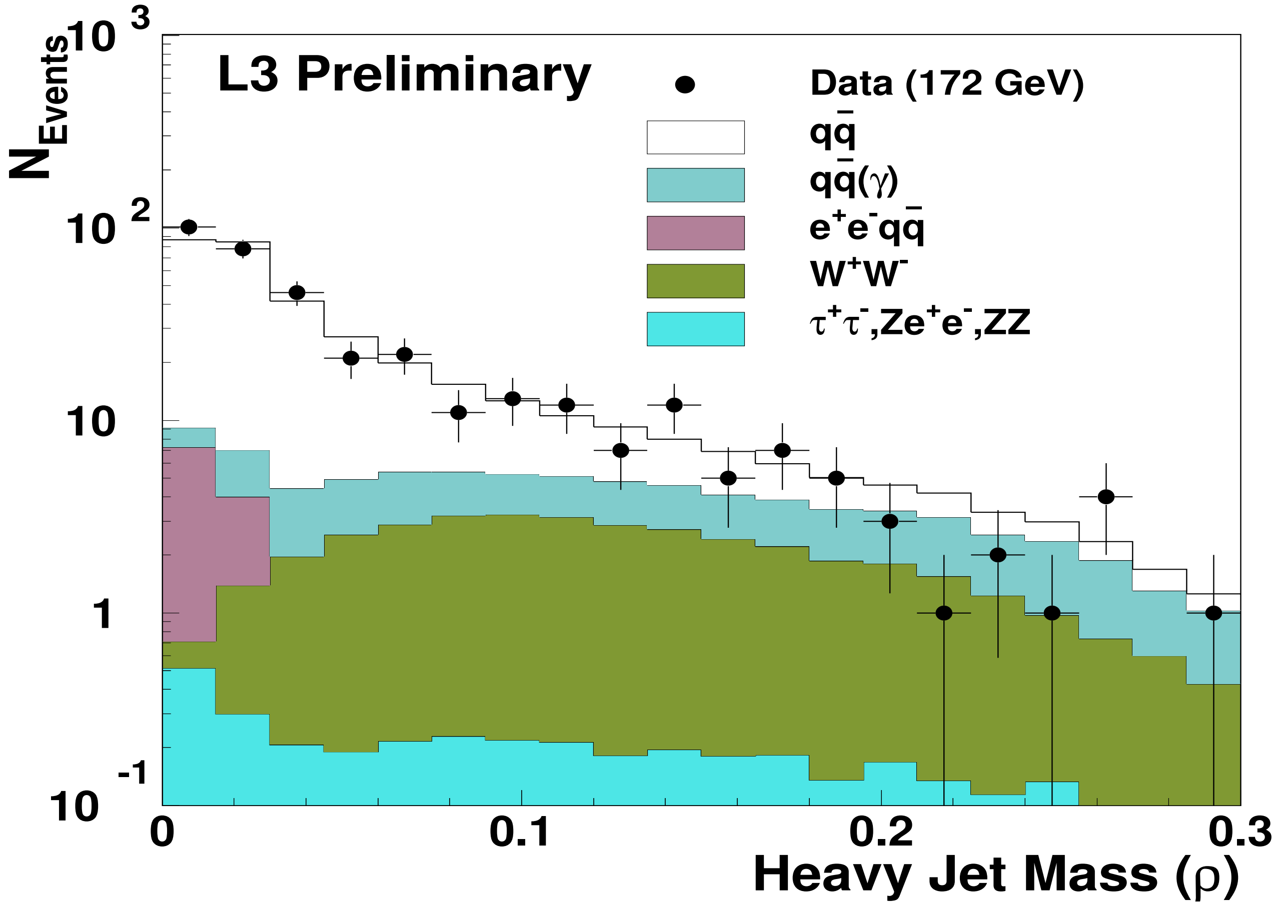
$$D_2 = \frac{1}{\sigma} \frac{d\sigma}{dy_{23}^D}$$

and

$$L = -\ln(y_3)$$

where y_3 is the values of y_{cut} for which a three-jet configuration is retained.

L3 Data at 172 GeV (Detector Level)

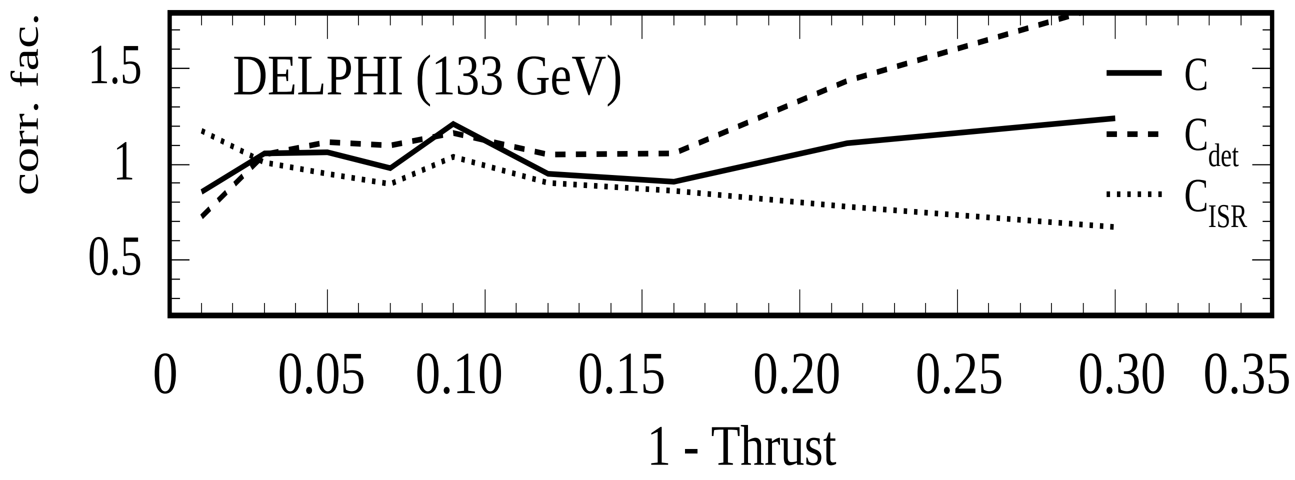


Event Shape Variable

Detector level distributions corrected bin-by-bin for

- Remaining background
- Finite detector resolution
- Acceptance
- Initial and final state radiation

Charge multiplicity corrected using matrix unfolding method



- Correction factors typically between 0.5 and 1.5
- Detector and ISR corrections compensate each other

Comparison with QCD Predictions

QCD Models

QCD Model	Shower Development	Fragmentation
JETSET	Parton Shower	String
HERWIG	Parton Shower	Cluster
ARIADNE	Color Dipole	String
COJETS	Incoherent Parton Shower	Independent

All models tuned using LEP I data

Analytical Calculations

- Complete Calculations to $\mathcal{O}({\alpha_s}^2)$

$$\begin{aligned} R(\alpha_s, y) &\equiv \int_0^y \frac{1}{\sigma}\frac{d\sigma}{dy} \\ &= \overline{\alpha}_s A(y) + {\overline{\alpha}_s}^2 \left[B(y) + 2\pi\beta_\circ \ln(\mu^2/s)A(y)\right] \end{aligned}$$

  – Describe data well in the multi-jet region

  – But fail in the two jet region (small y)

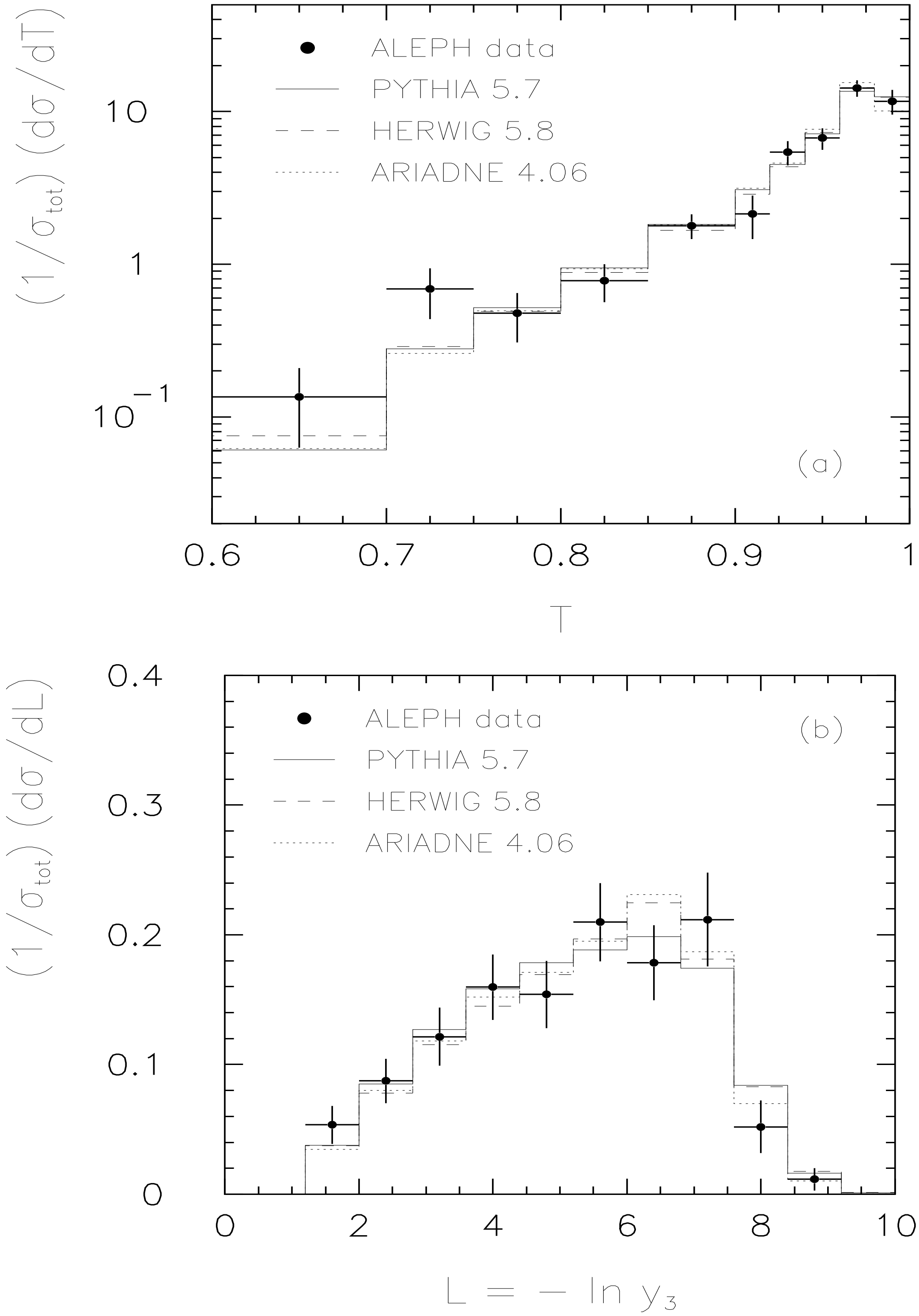
- Resummation of

Leading-Log	$\Sigma(\alpha_s L^2)^n$	$(L = \ln(1/y))$
Next-to-Leading-Log	$\frac{1}{L}\Sigma(\alpha_s L^2)^n$	terms

Combine these two $\Rightarrow$ Describe data over wide range

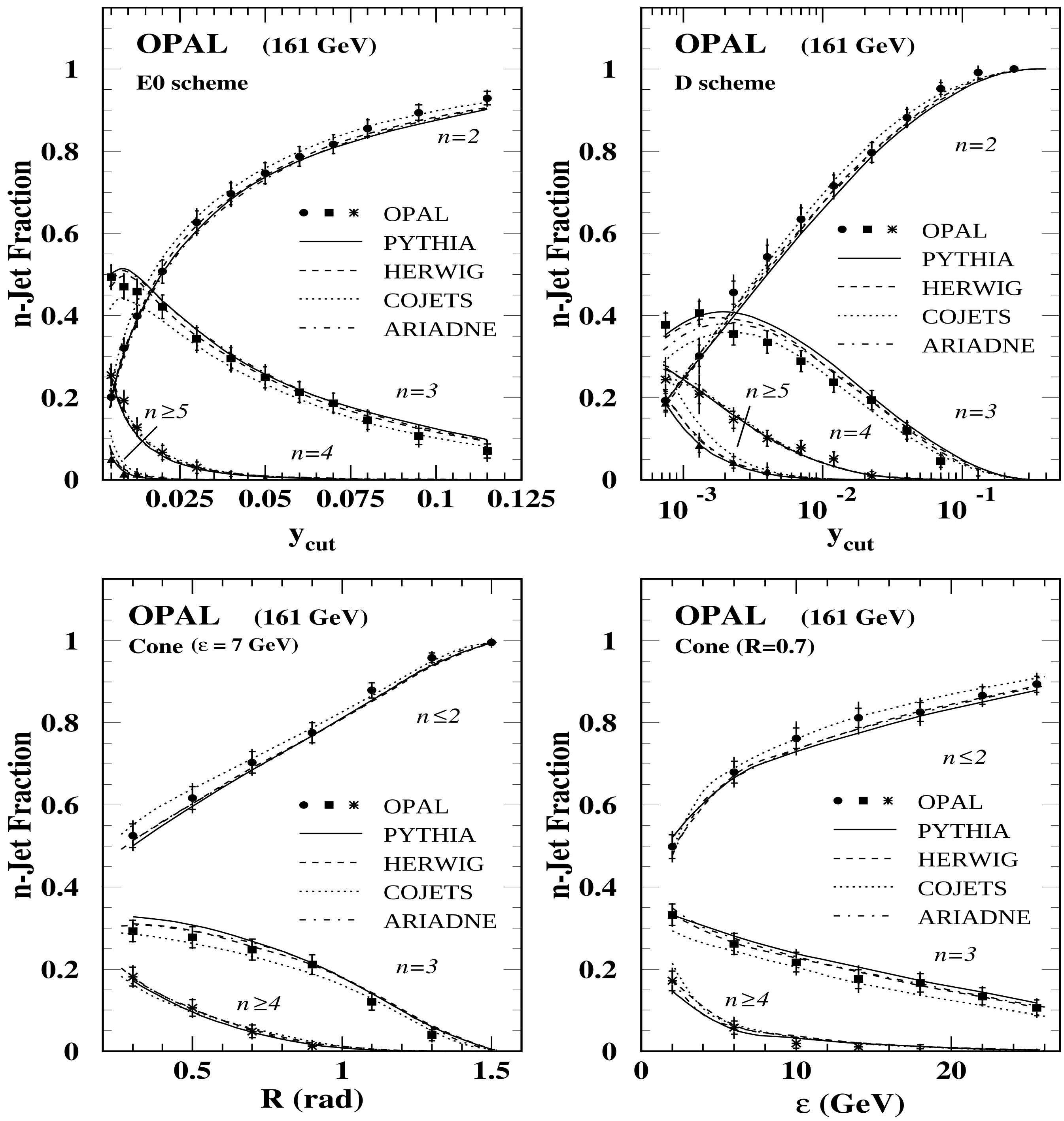
Hadronisation effect folded in using PS Monte Carlo

ALEPH Data at 133 GeV

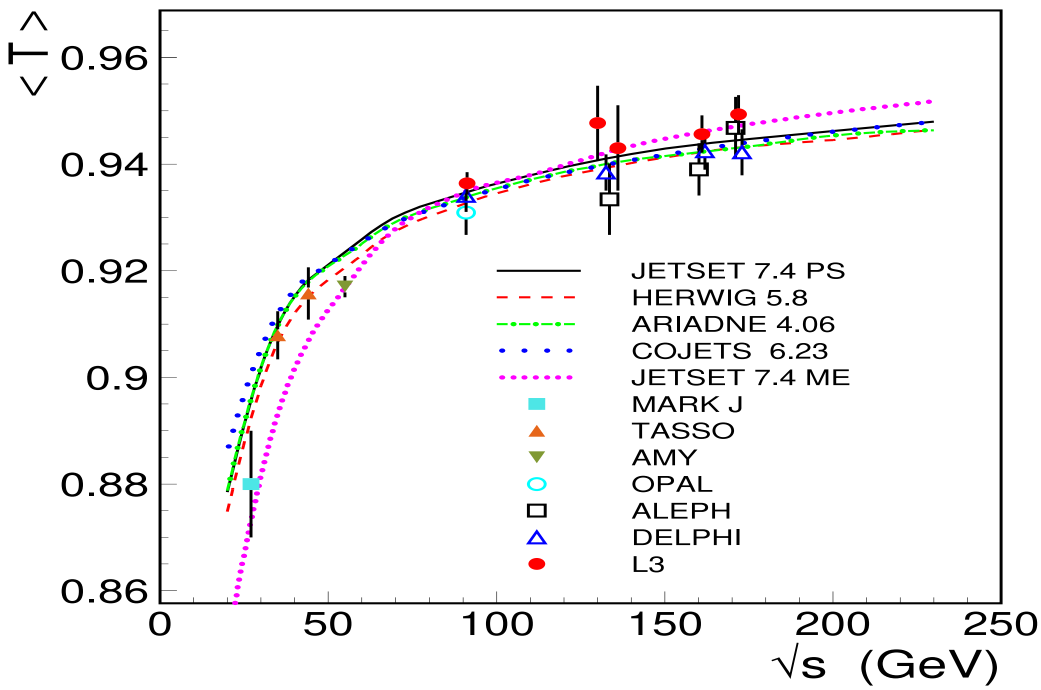


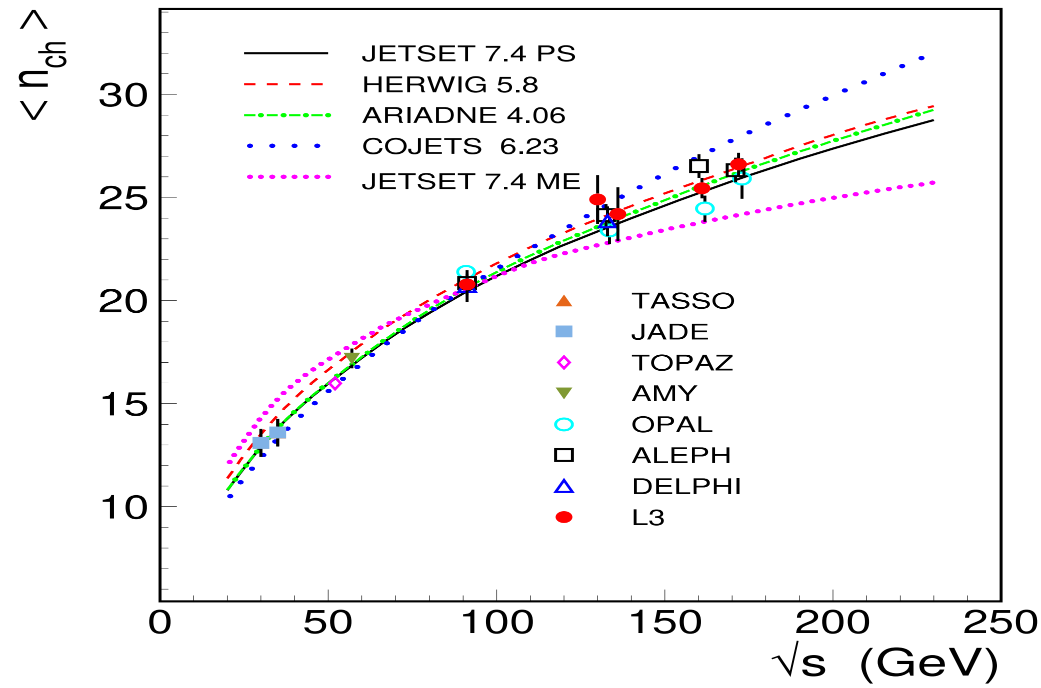
Comparison with QCD Predictions

OPAL Data at 161 GeV



Comparison with QCD Predictions

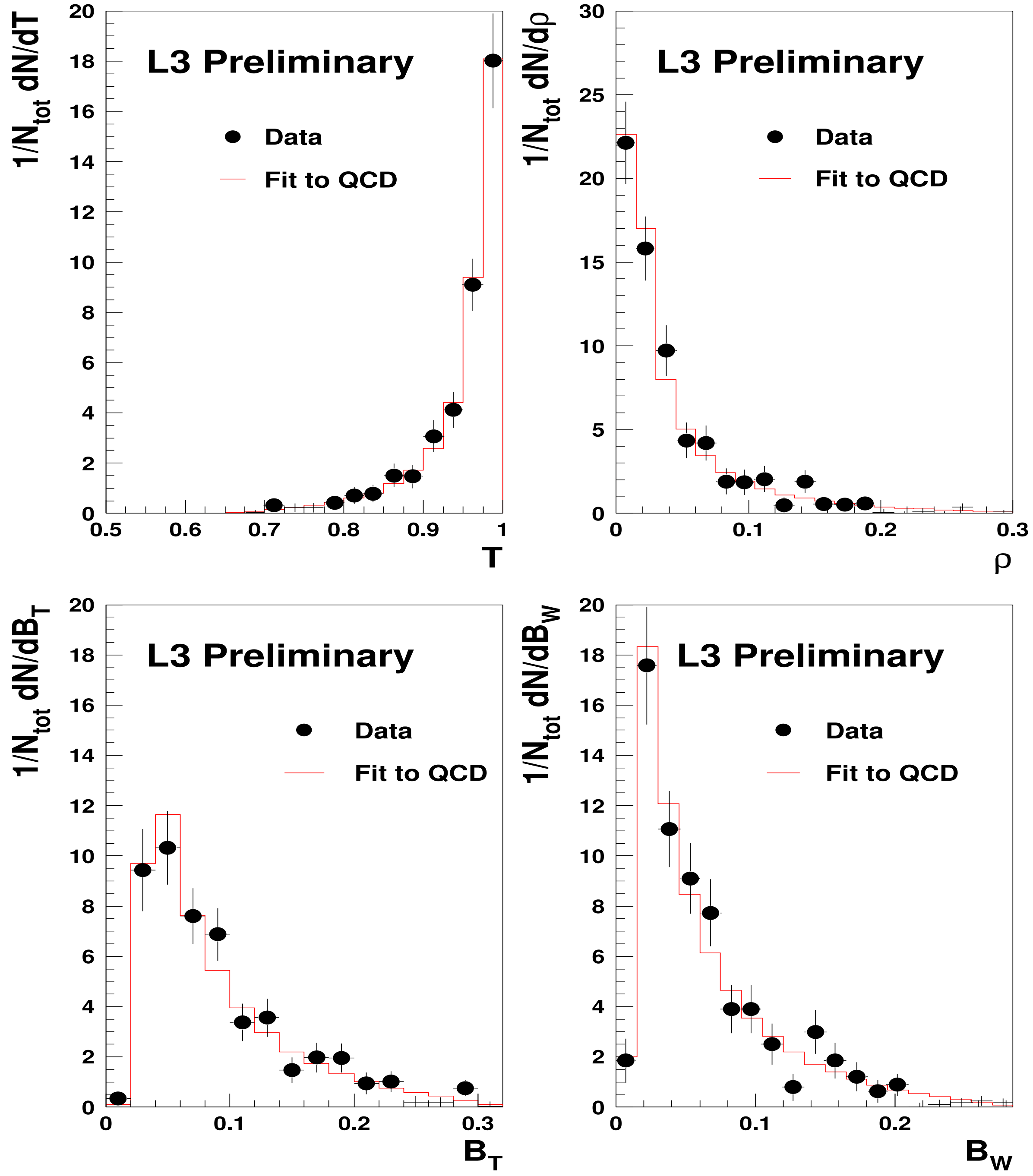




⇒ Most of the models describe data well

Comparison with QCD Predictions

L3 Data at 172 GeV



Power Law Description of Fragmentation

Dependence of event shape variables on CM energy $\Rightarrow$

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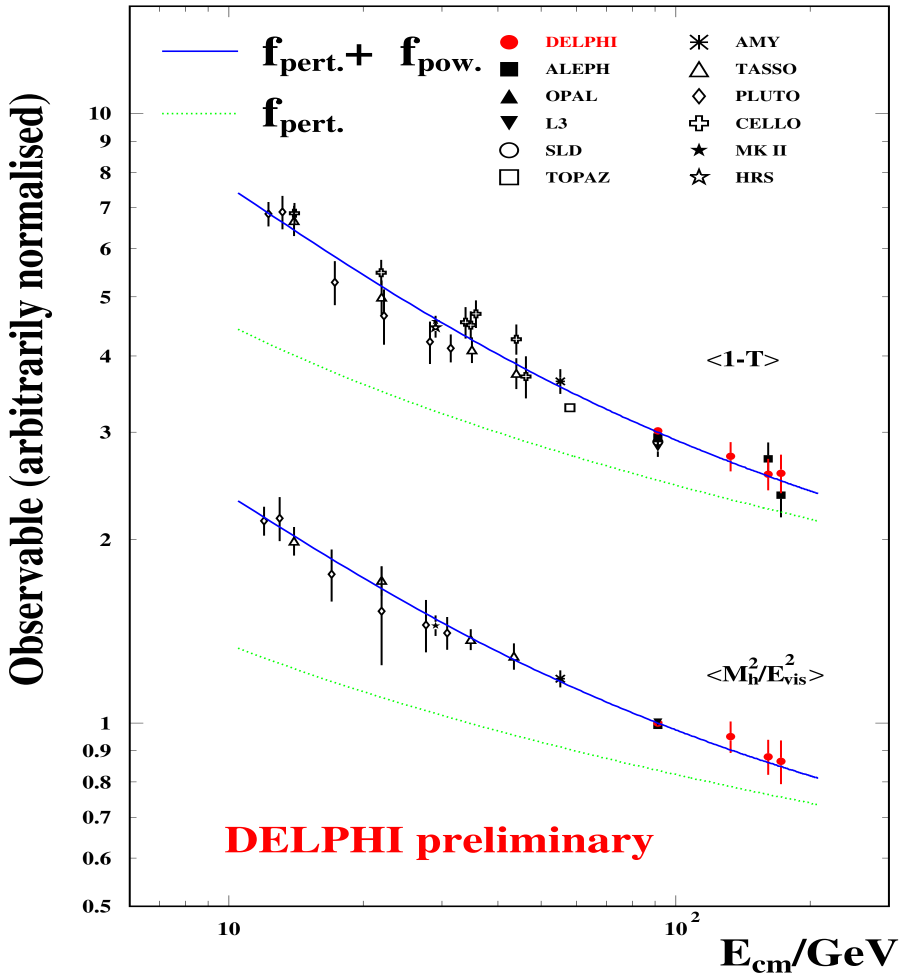
- Logarithmic dependence of α_s on energy
- Fragmentation $\propto 1/E_{CM}$

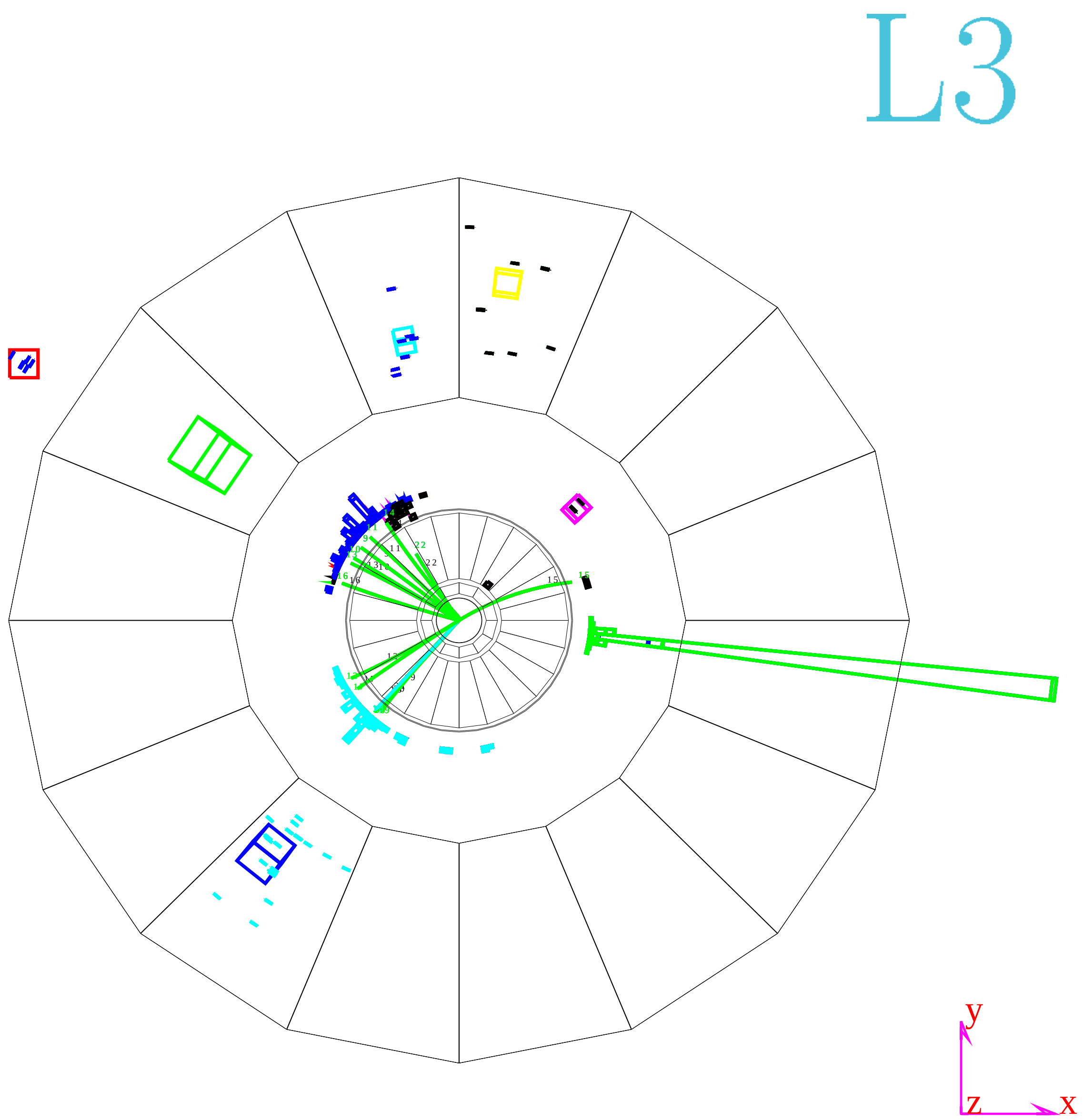
Study effect of fragmentation

$$\langle f \rangle = \frac{1}{\sigma_{tot}} \int f \frac{d\sigma}{df} df = \langle f_{pert} \rangle + \langle f_{power} \rangle \quad , \quad f_{power} = \frac{C_1}{E_{CM}} + \frac{C_2}{E_{CM}^2}$$

$\langle f_{pert} \rangle$ is the $\mathcal{O}({\alpha_s}^2)$ expression , C_1,C_2 free parameters, estimated from fit



$$e^+e^- \to \gamma^*/Z \to \textit{hadrons} + \gamma$$

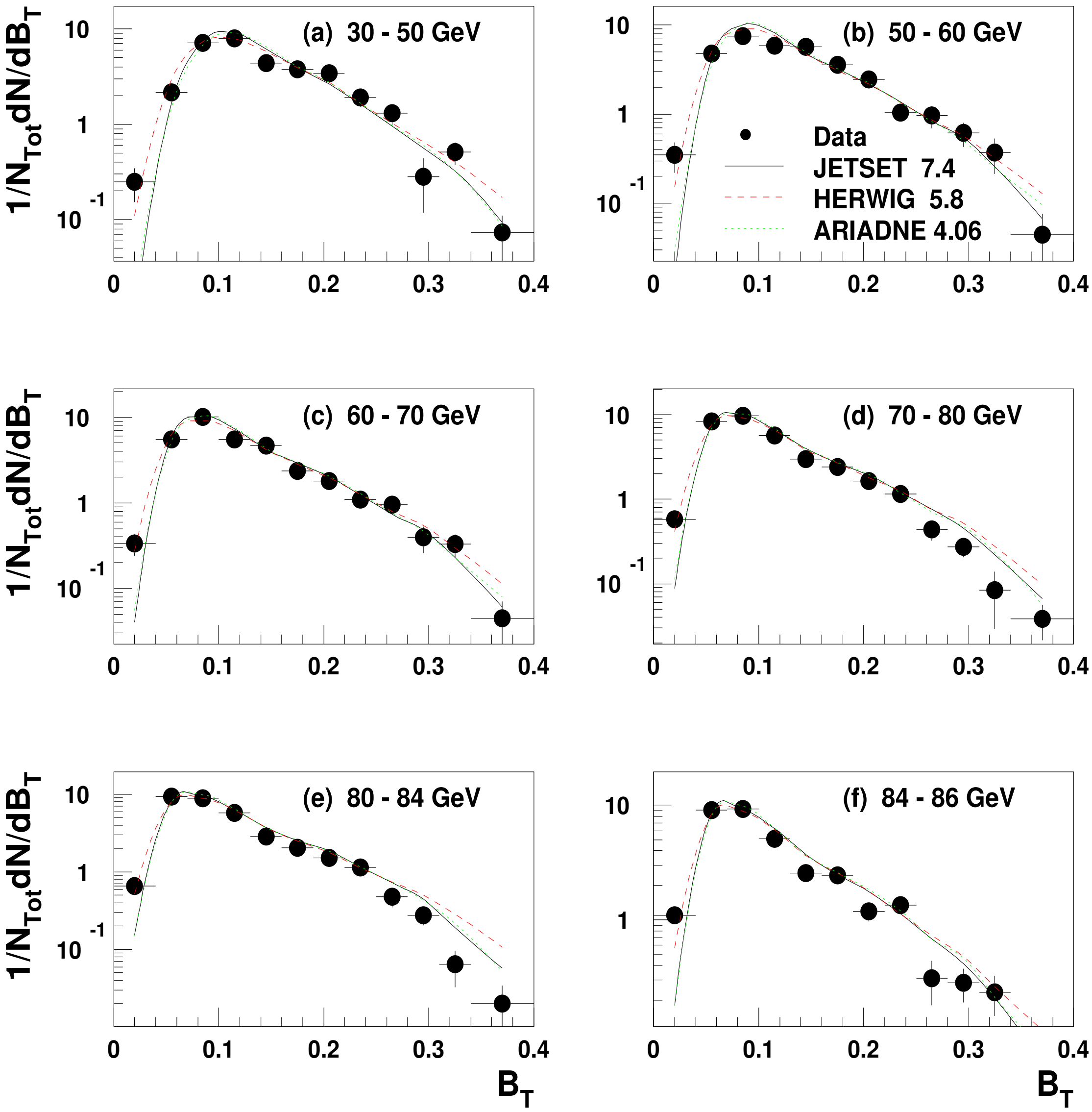


- Select isolated energetic photons in hadronic events
- Remove γ from the event

$$\sqrt{s'} = \sqrt{s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)}$$

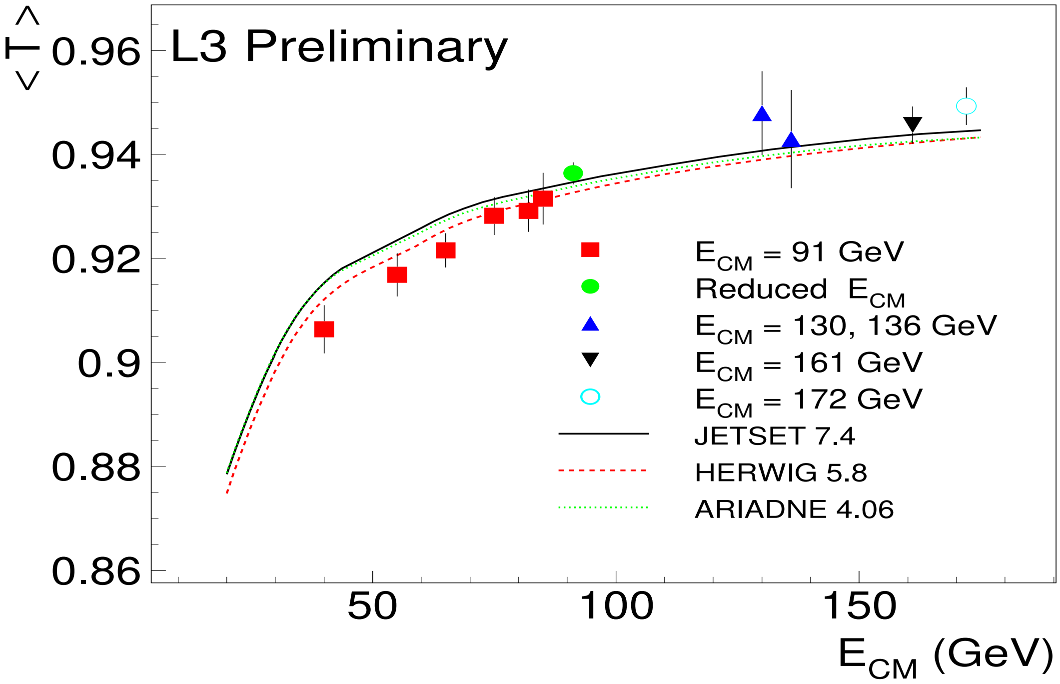
- Boost the event in the CM of the remaining subsystem
- Study event shape variables

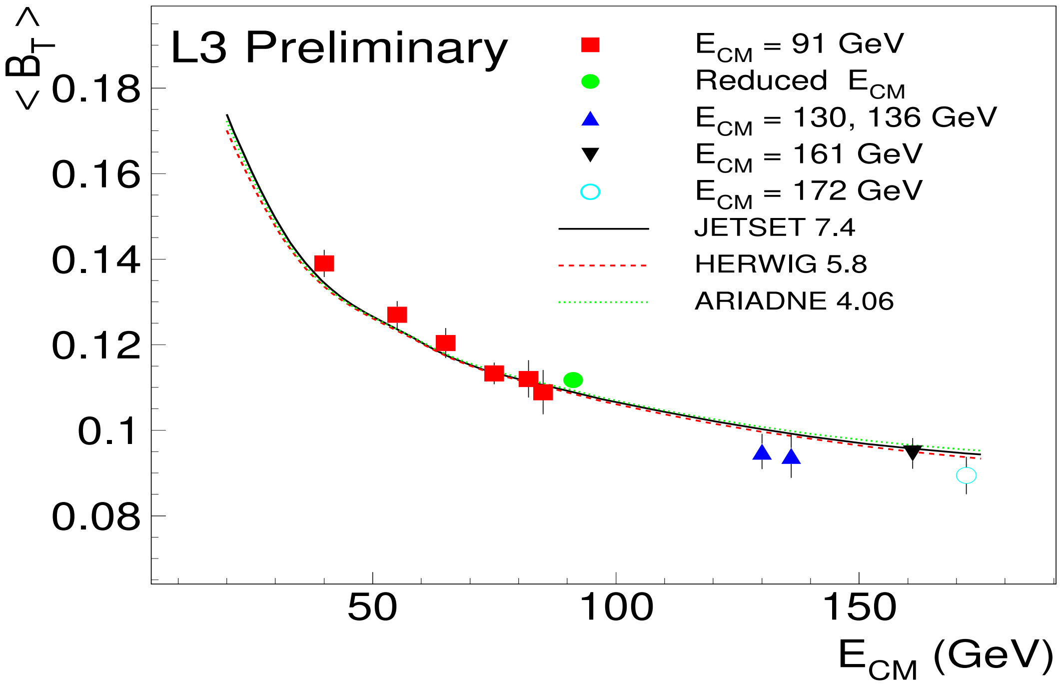
L3



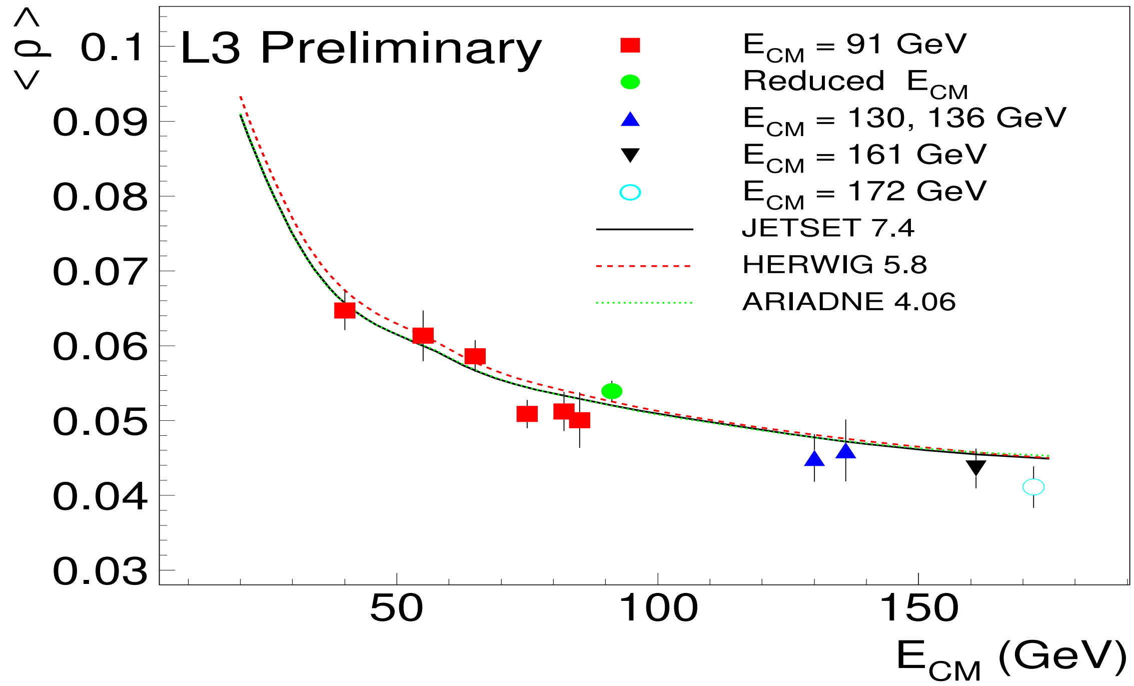
- Events generated at reduced energies without ISR and FSR

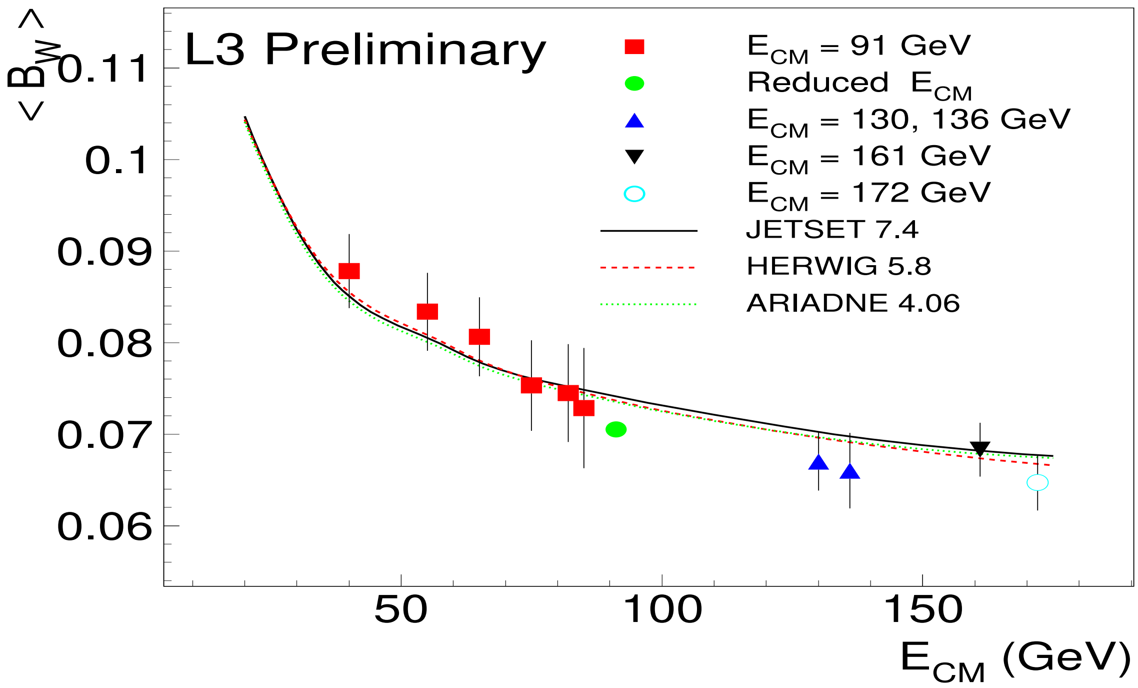
Studies at Reduced E_{CM} Using LEP I Data





$\Rightarrow$ QCD models predict the evolution reasonably well


L3 Preliminary
$< \rho >$
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
50
100
150
E_{CM} (GeV)
E_{CM} = 91 GeV
Reduced E_{CM}
E_{CM} = 130, 136 GeV
E_{CM} = 161 GeV
E_{CM} = 172 GeV
JETSET 7.4
HERWIG 5.8
ARIADNE 4.06


L3 Preliminary
$< B_W >$
0.11
0.1
0.09
0.08
0.07
0.06
50
100
150
E_{CM} (GeV)
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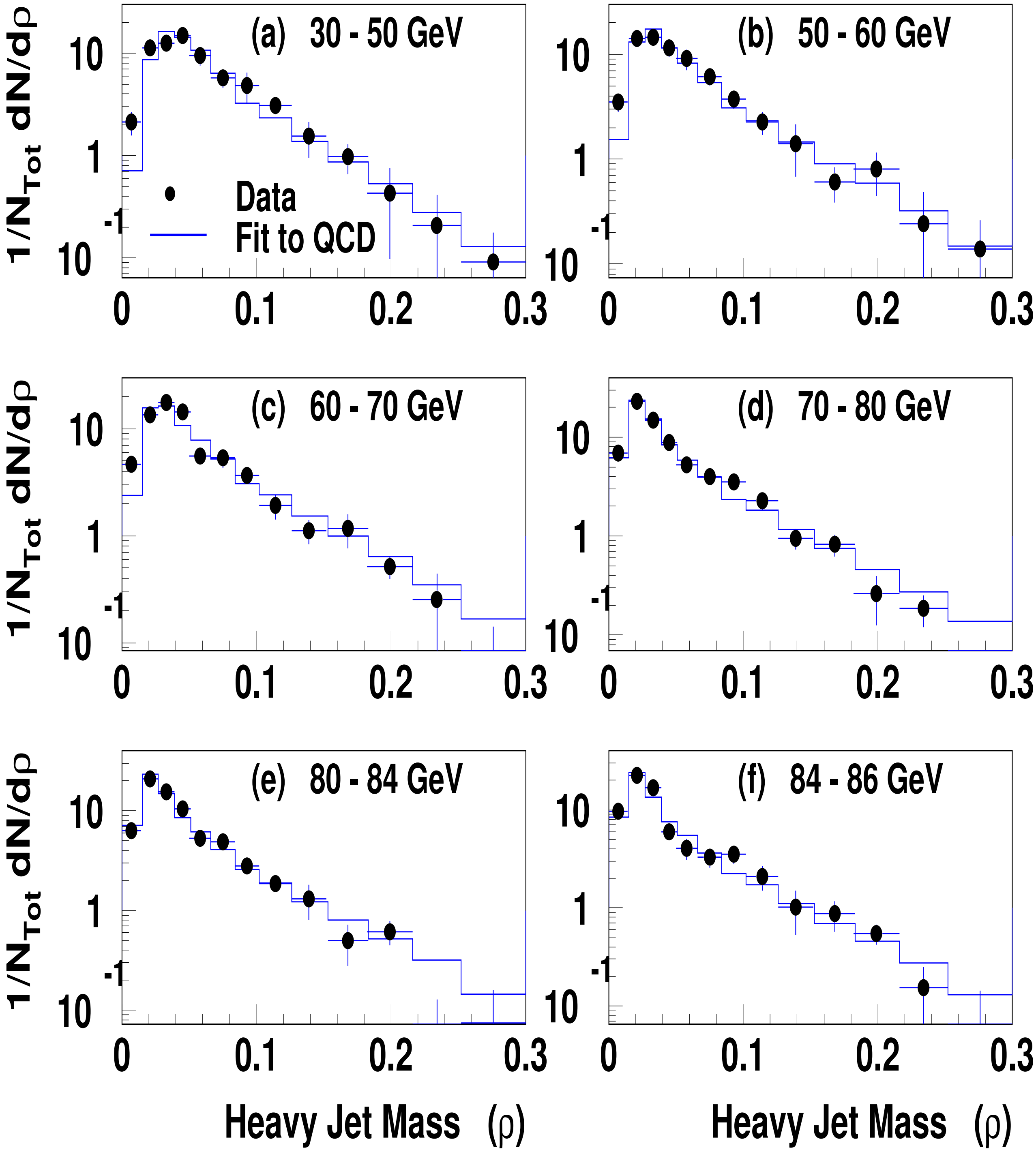
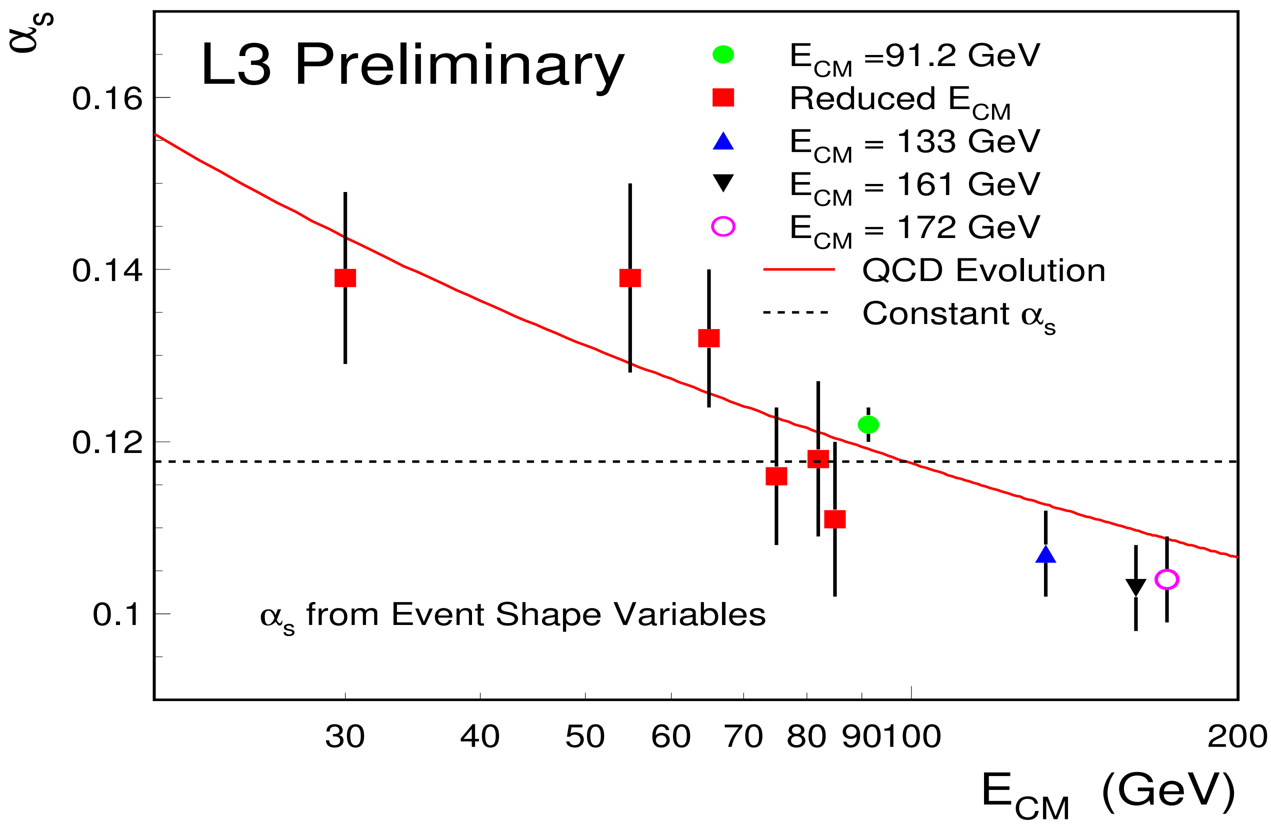


1/N_Tot dN/dρ
(a) 30 - 50 GeV
(b) 50 - 60 GeV
(c) 60 - 70 GeV
(d) 70 - 80 GeV
(e) 80 - 84 GeV
(f) 84 - 86 GeV
Data
Fit to QCD
10
1
10^-1
0
0.1
0.2
0.3
Heavy Jet Mass (ρ)

L3



	$\alpha_s(m_Z)$	χ^2/dof	Probability
QCD Evolution	0.1191 ± 0.0015	10.6/9	0.30
Constant	0.1177 ± 0.0015	38.4/9	1.5×10^{-5}

$\Rightarrow$ Supports QCD evolution

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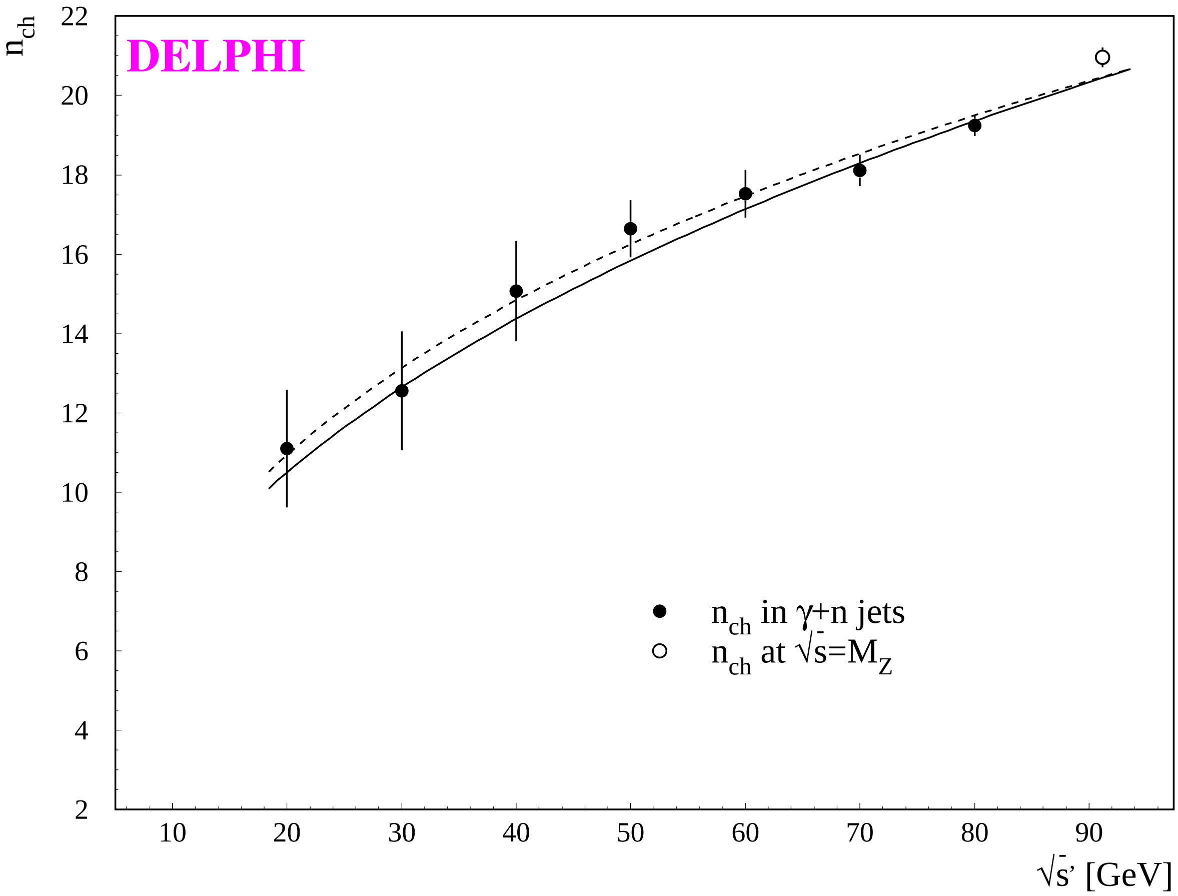
QCD prediction for $n_{ch}(\sqrt{s})$ including LLA + NLLA corrections

$$n_{ch}(\sqrt{s}) \;=\; a \cdot \alpha_s(\sqrt{s})^b \cdot e^{c/\sqrt{\alpha_s(\sqrt{s})}} \left[1 + d \cdot \sqrt{\alpha_s(\sqrt{s})}\right]$$

Use $q\bar{q}\gamma$ events to obtain multiplicity at many energy points



$$\alpha_s(m_Z) = 0.114 \pm 0.005\ (\text{stat}) \pm 0.008\ (\text{syst:a}) \pm 0.005\ (\text{syst:d})$$

Summary

- QCD studies : $20\ \mathrm{GeV} \leq \sqrt{s} \leq 172\ \mathrm{GeV}$ at LEP
- Good agreement between data and QCD models for all the experiments
- Improved analytical calculations yield better agreement
- Studies at higher energies limited by low statistics till now