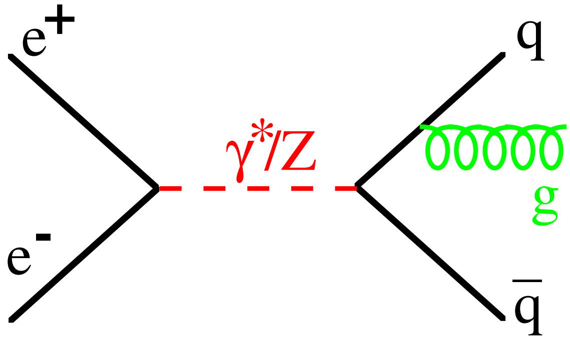
Experimental aspects of QCD in e^+e^-collisions

D. Duchesneau
LAPP, Annecy

- Introduction
- Experimental procedure
- α_s from event shapes
- QCD tests from jet dynamics
- Fragmentation studies
- Quark and gluon jet differences
- Particle production and correlations
- Summary

Introduction:

$e^+ e^- \longrightarrow$ hadrons

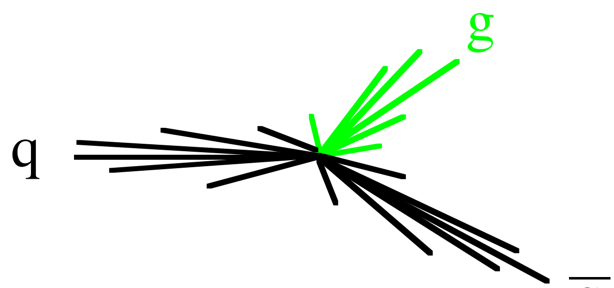


Well defined initial state:

-Hadronic activity limited to final state.
-$E_{CM} = 2 * E_{BEAM}$ (symmetric collider, no ISR)

$\Longrightarrow$ Clean tests of QCD

At high energy:



Hard partons $\Longrightarrow$ collimated jets

- Study of parton dynamics (hard processes):
  - → Strong coupling: α_s
  - → gauge structure of the theory
- Jet structure: fragmentation process (soft QCD)
  - → transition between perturbative and non-perturbative phases

Clean environment in e^+e^- $\Longrightarrow$ best laboratory to study hadronization phase

Theoretical side:

Main theoretical calculations to describe hadronic event structure in e^+e^- annihilation:

- $\mathcal{O}(\alpha_s{}^2)$ QCD calculations available for the global event shape variables.
  - progress in calculations including event orientation
    - S.Catani and M.Seymour Nucl. Phys. B485 (1997) 291
  - NEW: complete calculations for massive quark
    - G.Rodrigo et al., PRL79 (1997) 193
    - W.Bernreuther et al., PRL79 (1997) 189
    - P.Nason and C.Oleari, PL B407 (1997) 57
- NEW $\mathcal{O}(\alpha_s{}^3)$ predictions (1-loop) for 4-jet rates
  - A.Signer and l.Dixon PRL78 (1997) 811
- resummed calculations for several event shape variables.
- Analytic calculations based on several Leading Log Approximations (LLA)

Several models based on basic QCD principles exist. They include:

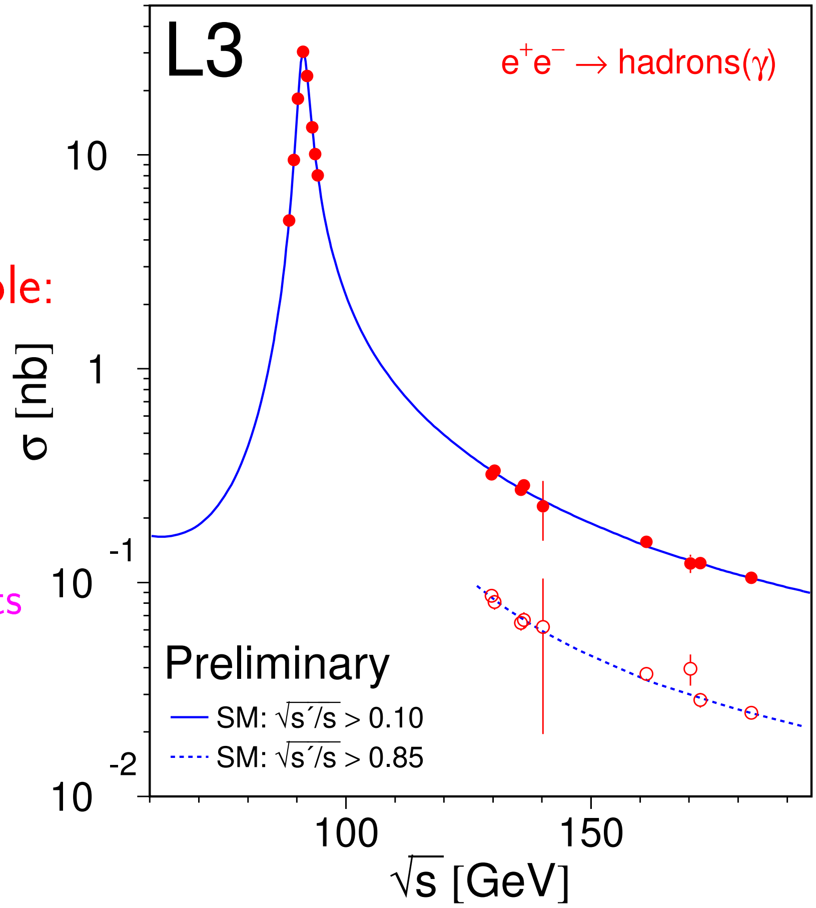
- parton shower phase based on improved LLA (coherence effects)
- fragmentation process based on phenomenological models ("string" or "cluster")

Highest energy e^+e^- colliders:

	$\sqrt{s}$ (GeV)	$\int \mathcal{L}(pb^{-1})/expt$	# of $q\bar{q}$ /expt	dates
PETRA/PEP	14-46	200	40K	1978→1990
TRISTAN	50-64	300	40K	1987→1995
SLC	91.2	15	500K	1993→1998
LEP1	91.2	125	4000K	1989→1995
LEP2	130-189	125	3K	1995→1998

LEP2:

$\sqrt{s}$ (GeV)	130−140	161	172	183	189
$\int \mathcal{L}(pb^{-1})$	12.0	11.0	11	55	35
# of events	600	400	300	1500	1000



QCD studies on the Z pole:

Advantages:

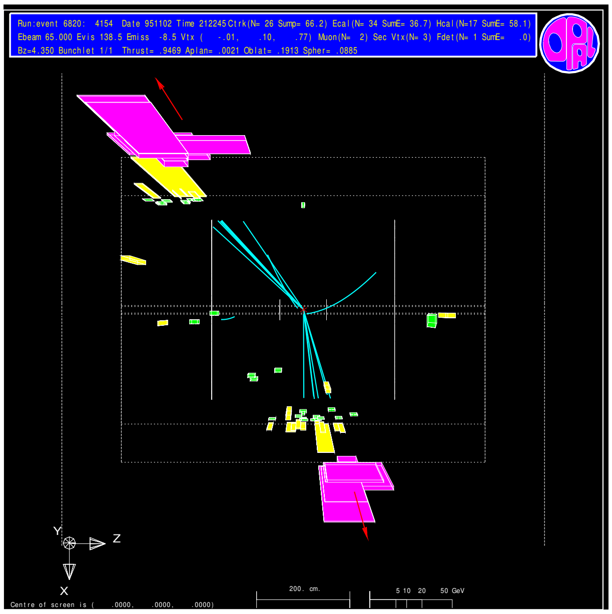
- large Xsection
- negligible background
- Small hadronization effects
- ISR suppressed

→ Very detailed studies of the hadronic event structure and precise QCD tests.

QCD studies above the Z resonance

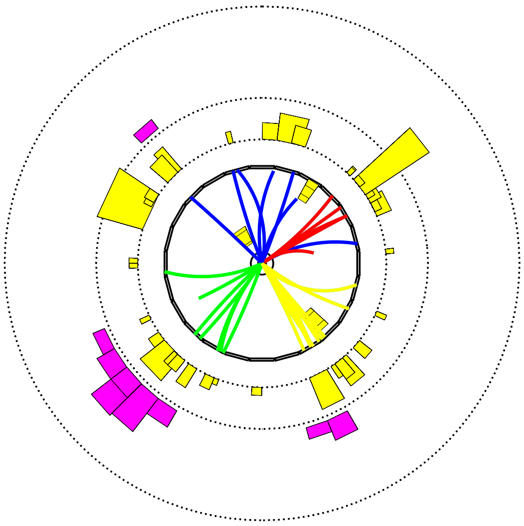
Compared to LEP1 difficult to select events produced at $\sqrt{s}=2*E_{BEAM}$

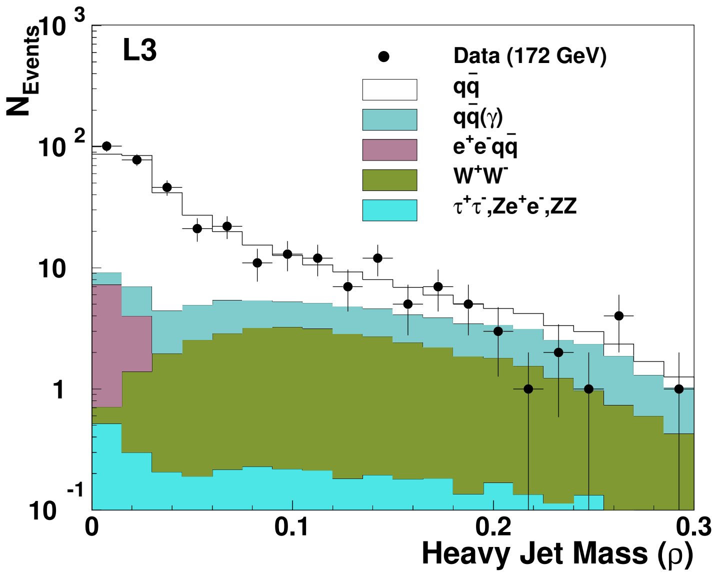
- Large contamination from radiative return to the Z (ISR)



$\rightarrow$ cut on reconstructed CM energy of hadronic system

- Important background from WW events: $e^+e^- \rightarrow q\bar{q}q\bar{q}$

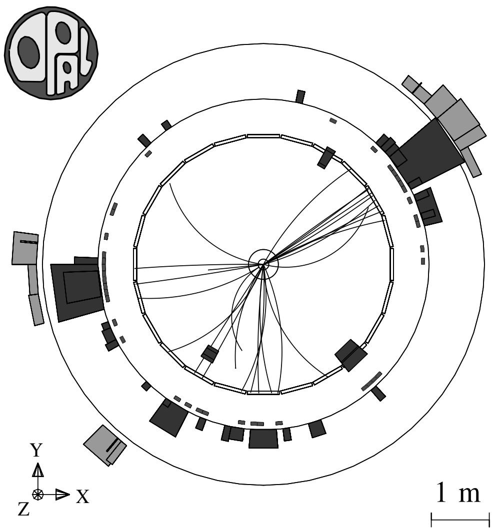


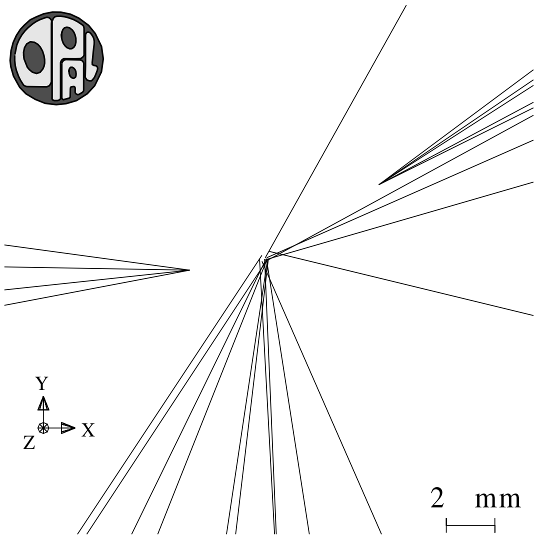


But: may be used to do further tests of QCD
- Colour reconnection
- Bose-Einstein correlations

Flavour tagging at LEP and SLC

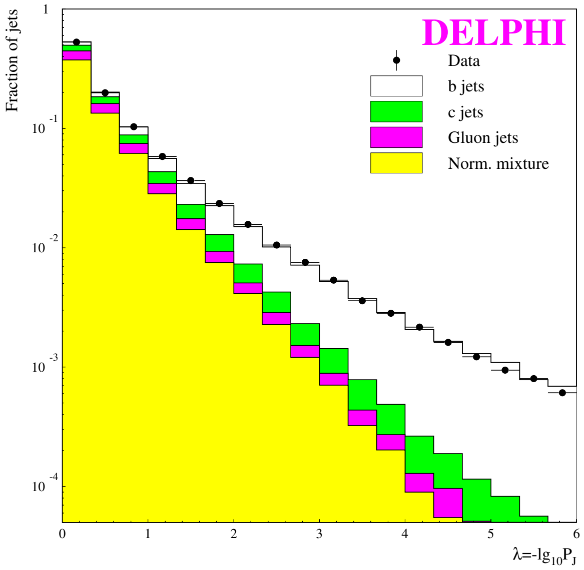
Very precise μvertex detector $\rightarrow$ Flavour dependent studies

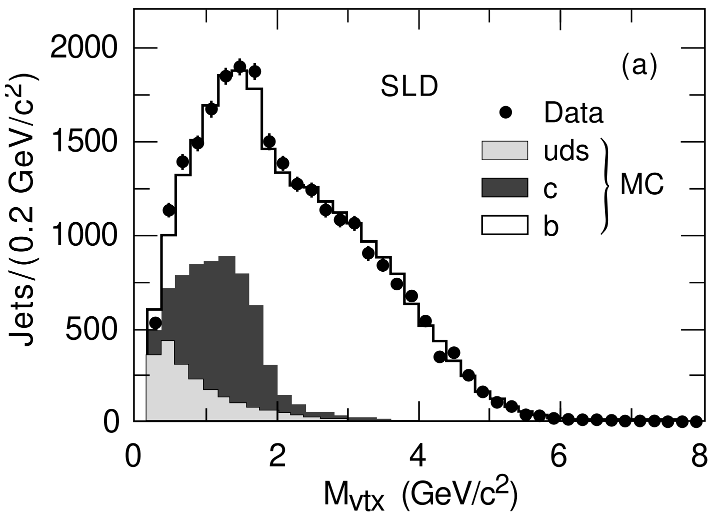




Quark flavour tagging:

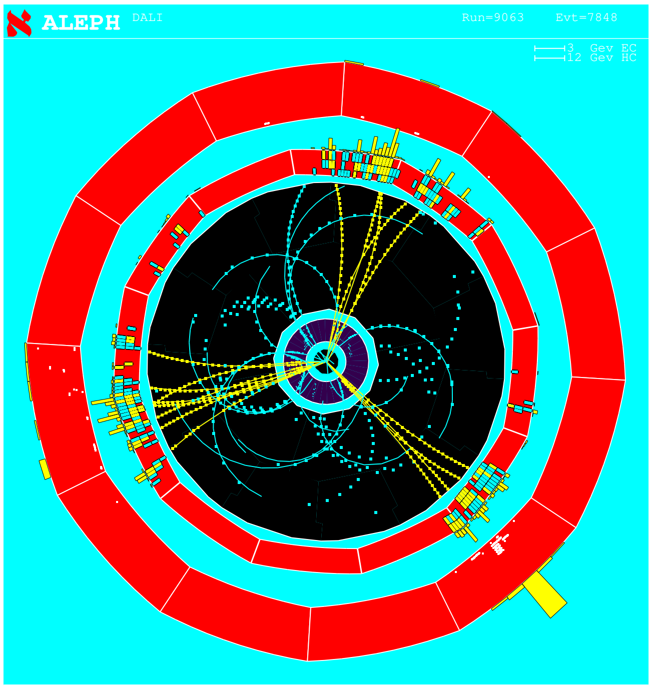
- b quark: B hadron properties = displaced secondary vertices (SV).
- c quark: D^{*+-} reconstruction (OPAL) or SV (SLD).
- uds quarks: anti-tag heavy flavours.





- Very high purity samples: 80% to 98% for b and uds quarks and 55-64% for c-quarks.
- Clean method to tag gluon initiated jet in 3-jet events with a purity up to 94%.

From detector to theory.



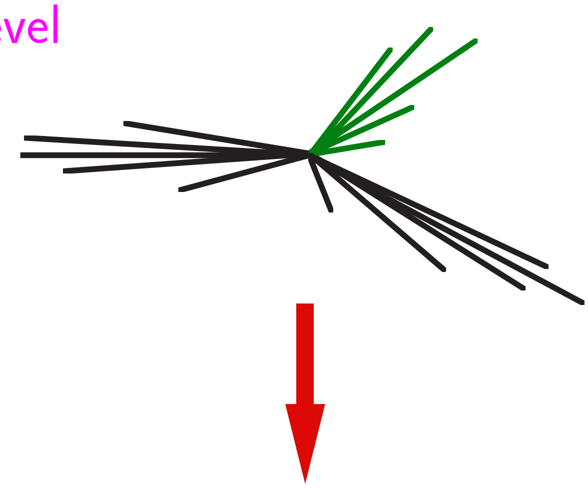
Detector level:

Tracks and clusters

$\rightarrow$ should correct for:

- limited acceptance
- finite resolution
- remaining ISR

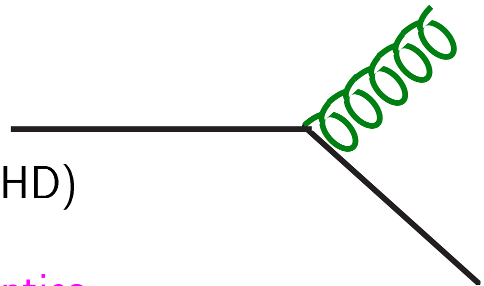
$\rightarrow$ measurement at particle level



Hadron distributions ("all orders"):

$\rightarrow$ should relate to theoretical predictions ("finite order") using:

- Hadronization models
- Power law corrections
- Perturbative QCD assuming Local Parton Hadron Duality (LPHD)



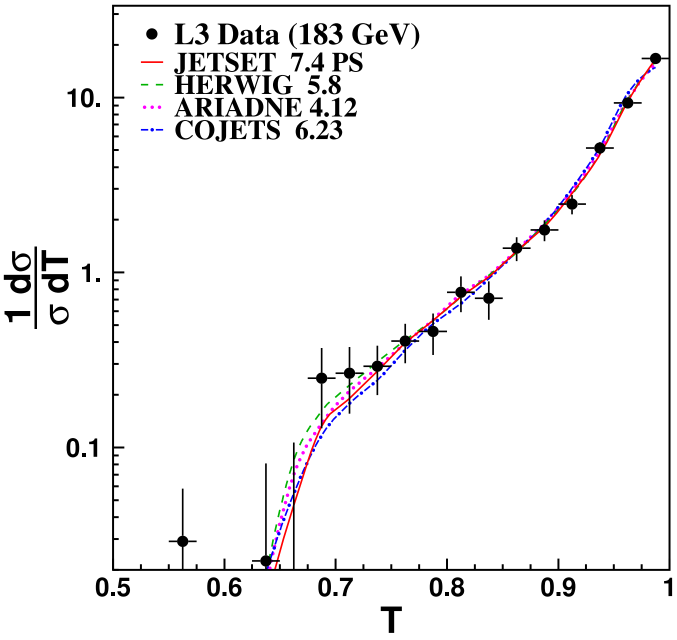
$\rightarrow$ Errors from hadronization uncertainties

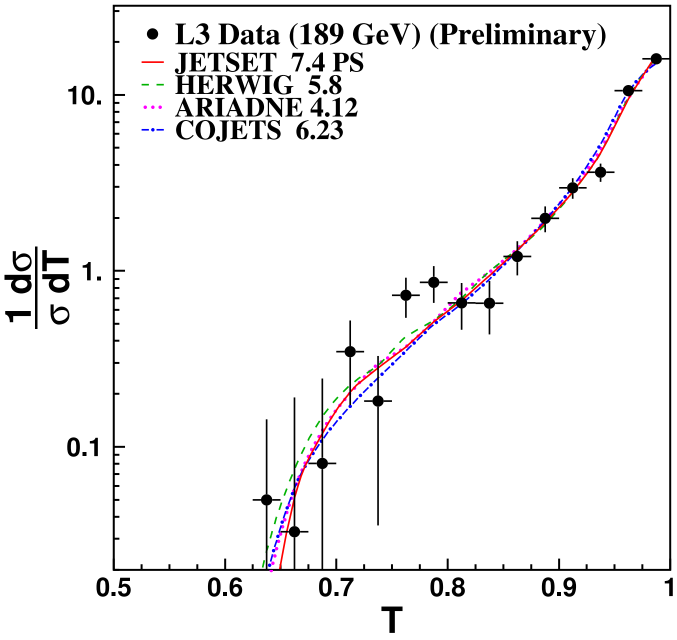
and missing terms in perturbative expansion.

Tests of QCD models

Essential to have reliable models working at various energies

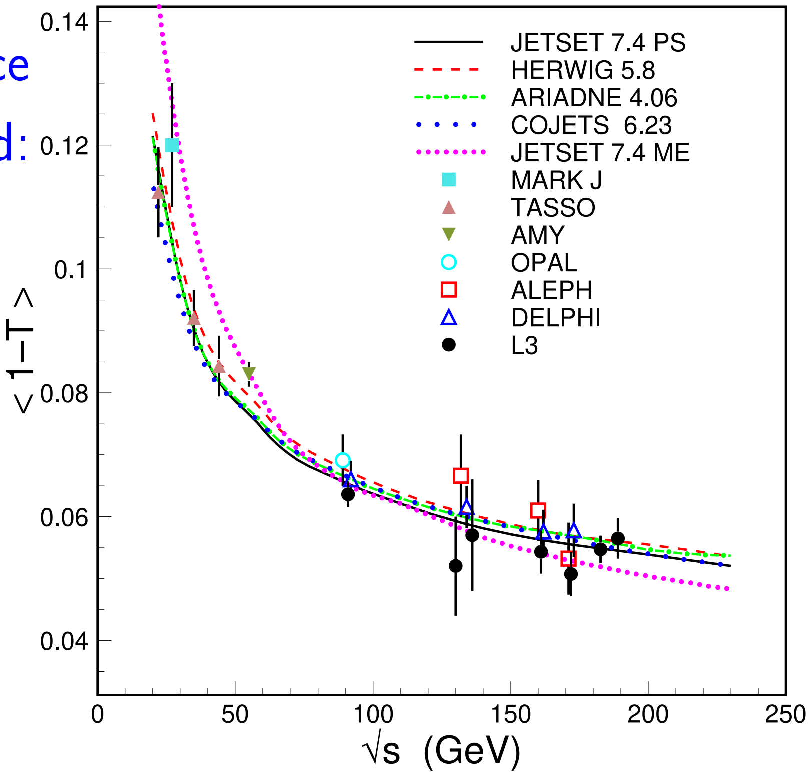
- parameters tuned and models tested in great details on the Z pole
- LEP2: good place to check consistency of QCD predictions.
- Global event shape variables: ex: Thrust





Some energy dependence of mean values expected:

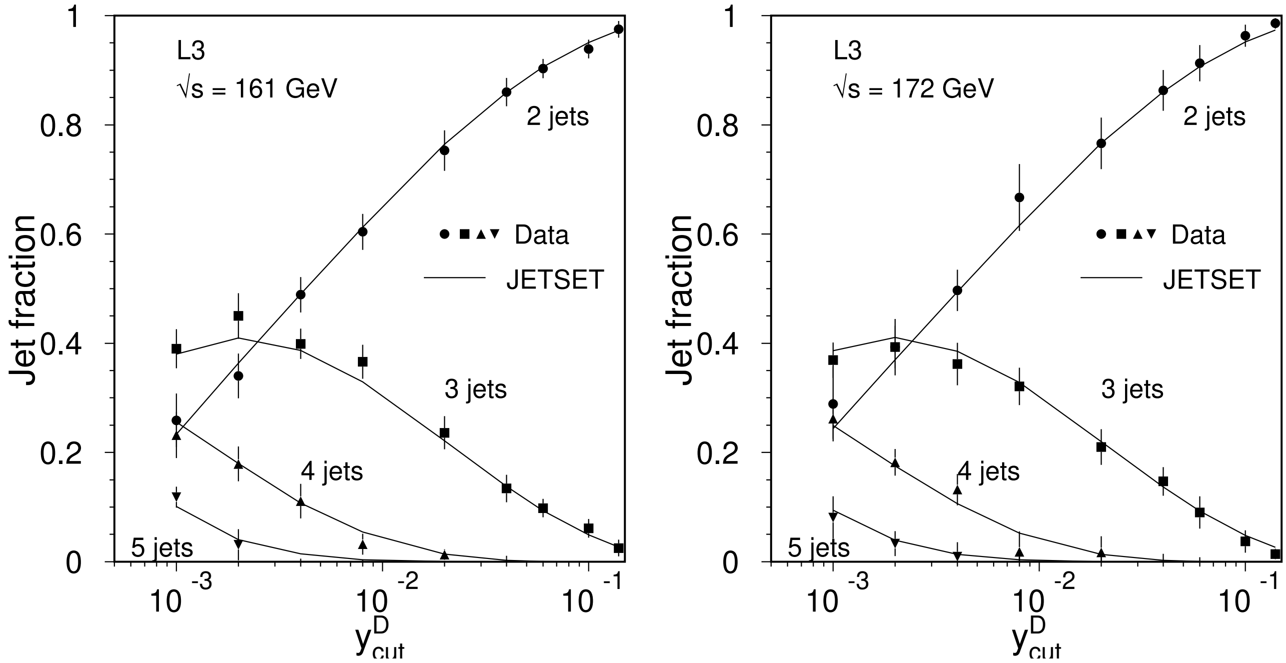
- logarithmic dependence of α_s
- hadronization process: $1/Q$



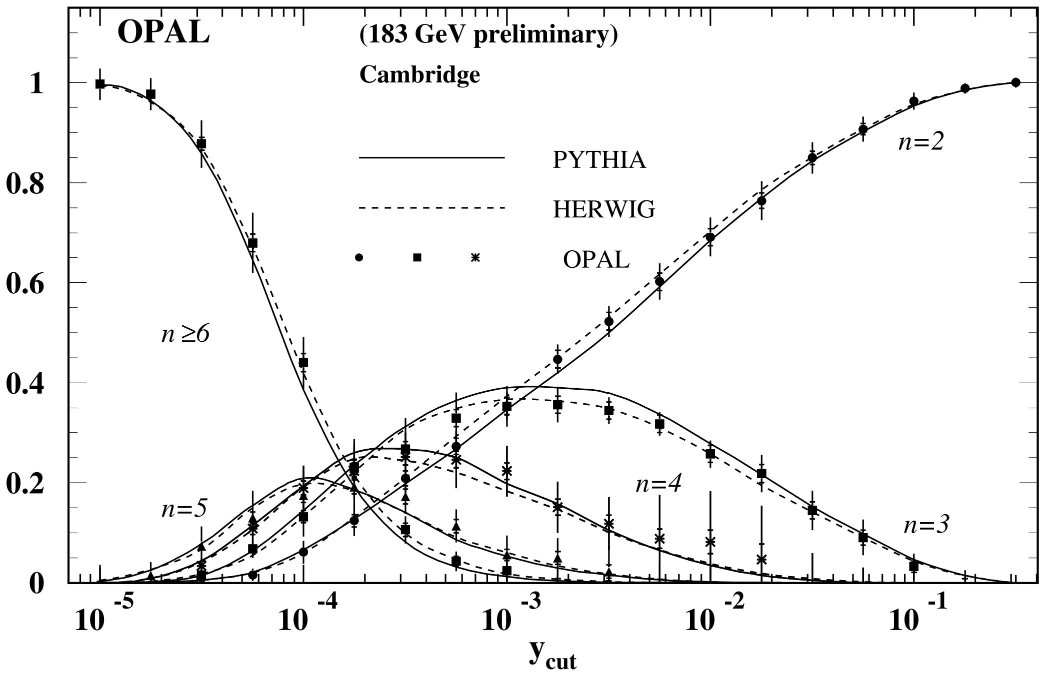
QCD models give a good description of the energy dependence!

Jet multiplicities

Several jet algorithms available: differ in the combination scheme and object pairing



New jet algorithm: CAMBRIDGE (Dokshitzer et al. (JHEP 08 (1997) 1) designed to minimize "finding" spurious jets (not related to partons)



QCD models with parton showers provide good description of the measured jet rates for any number of jets

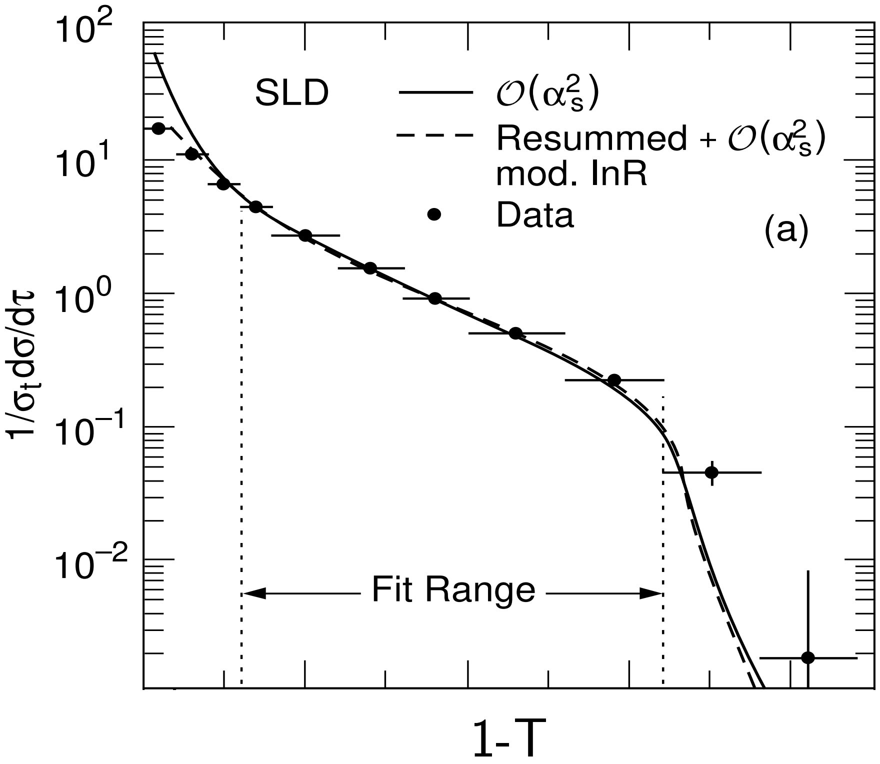
$\boldsymbol{\alpha_s}$ from event shape variables

Basic idea: measure the relative proportion of hard gluon radiation using the event topology

Need variables sensitive to event jet structure

Thrust distribution:

$$T = \max \frac{\Sigma \mid \vec{p_a} \cdot \vec{n_T} \mid}{\Sigma \mid \vec{p_a} \mid}$$



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

$$\int_0^y \frac{1}{\sigma}\frac{d\sigma}{dy} = \frac{\alpha_s(\mu)}{2\pi}A(y) + \frac{\alpha_s(\mu)}{2\pi}^2\left[B(y) + 2\pi\beta_\circ \ln(\mu^2/s)A(y)\right]$$

  - series truncation$\rightarrow$ renormalisation scale and scheme dependence

- $\mathcal{O}({\alpha_s}^2)$ + NLLA calculations: for certain event shape variables:

LL and NLL terms of infrared origin resummed to all orders (NLLA). Combined with $\mathcal{O}({\alpha_s}^2)$:

  - smaller renormalization uncertainties

$\boldsymbol{\alpha_s}$ from event shape variables at LEP1

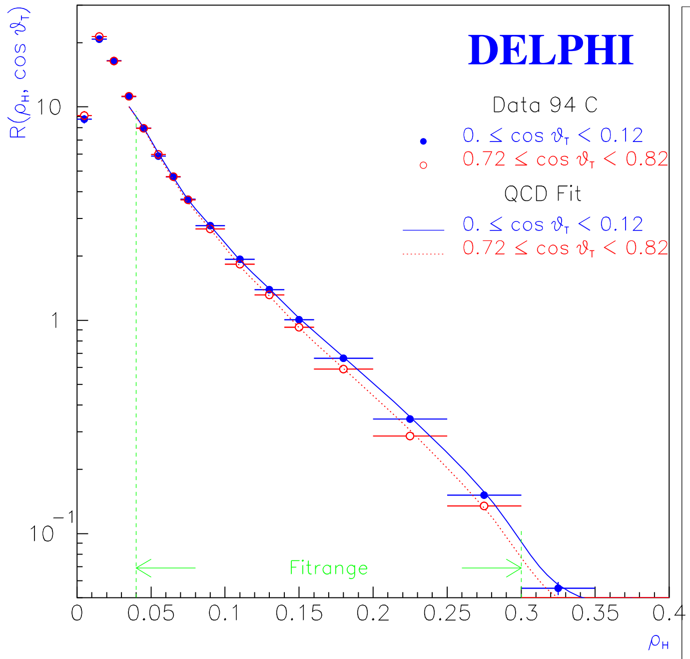
DELPHI: $\mathcal{O}({\alpha_s}^2)$ calculation including event orientation

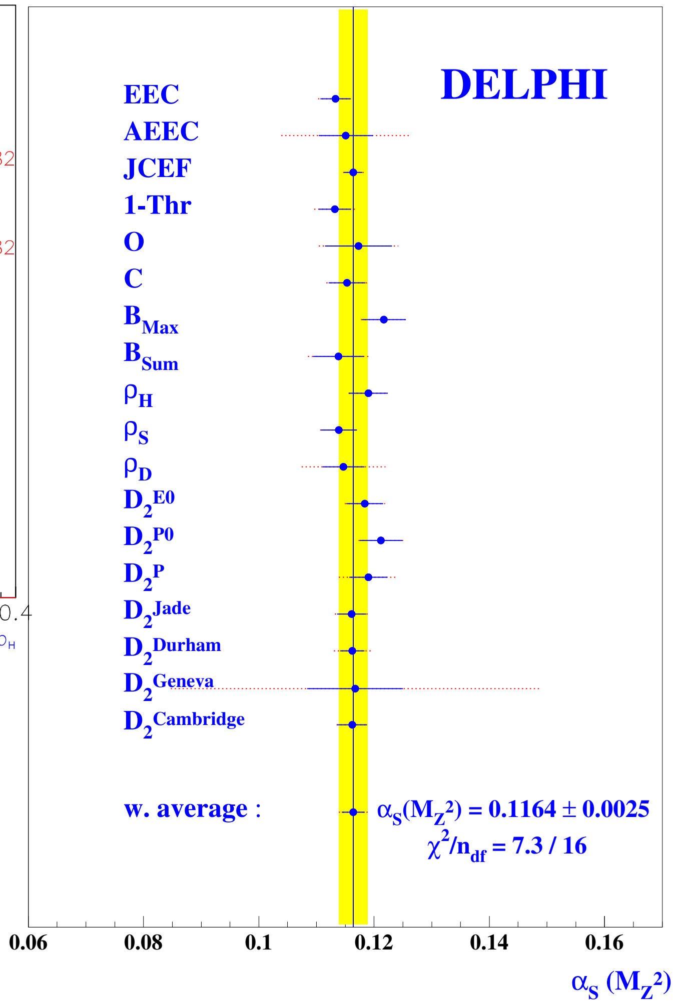
$$\frac{1}{\sigma}\frac{d\sigma(y,\cos(\theta_T))}{dy d\cos(\theta_T)} = \frac{\alpha_s(\mu)}{2\pi}A(y,\theta_T) + \frac{\alpha_s(\mu)}{2\pi}^2\left[B(y,\theta_T) + 2\pi\beta_\circ\ln(\frac{\mu^2}{s})A(y,\theta_T)\right]$$

- measure 18 variables in bins of θ_{Thrust}

To treat the $\mathcal{O}({\alpha_s}^2)$ renormalisation scale ambiguity:

- fit μ and α_s together $\to$ experimentally optimized scales!





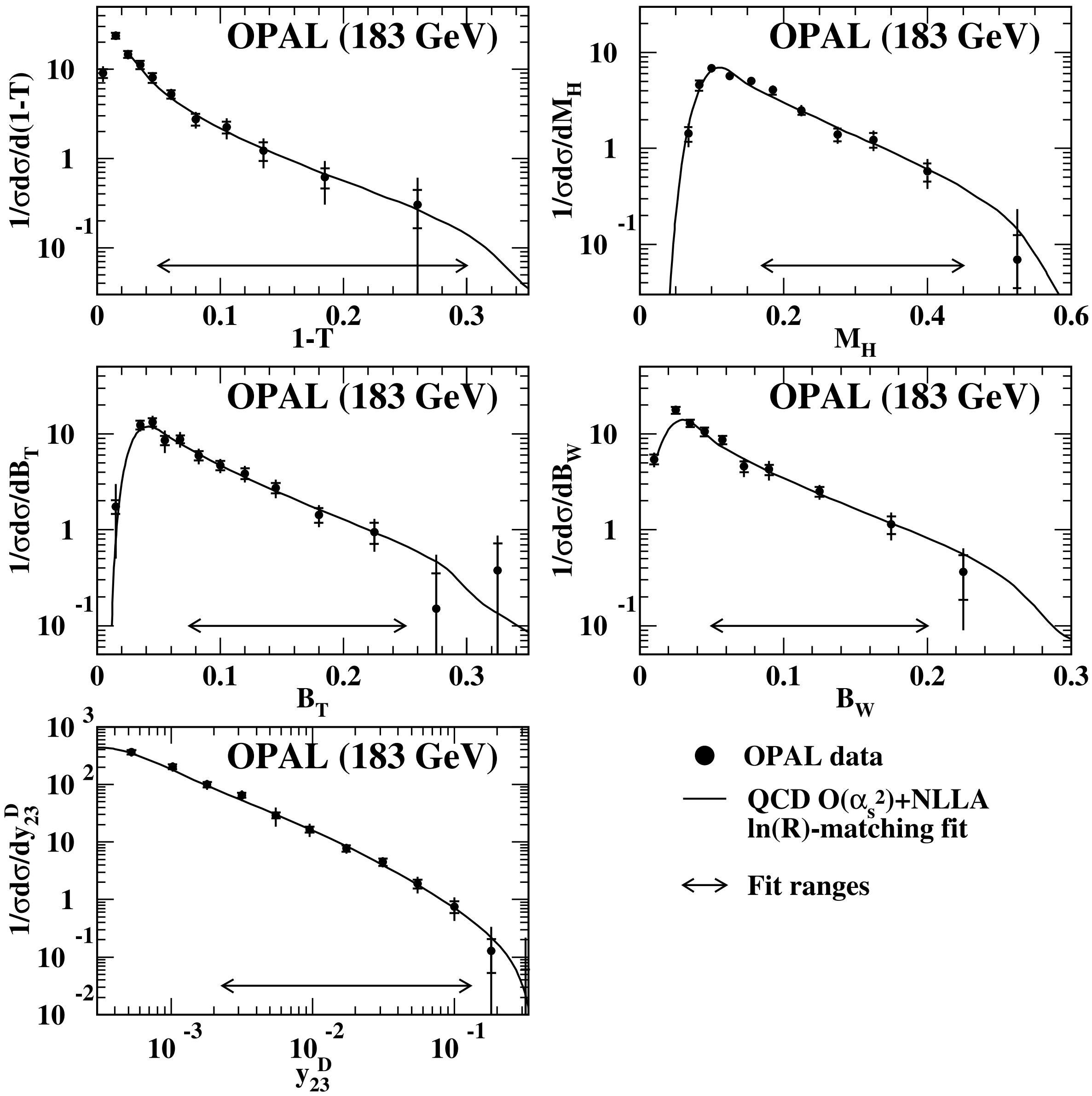
$\alpha_s(m_Z) = 0.1164 \pm 0.0025$

- Very consistent values of α_s with this experimental optimization method
- theoretical "optimized" scales: consistent results for the average α_s (but larger spread).

$\boldsymbol{\alpha_s}$ at LEP2

Use resummed NLLA + O(α_s^2) calculations

- hadronization effects from MC models



	α_s(183 GeV)					fit variable
ALEPH	0.1093	$\pm$	0.0020(stat)	$\pm$	0.0036(syst)	T,ρ,B_w,C,$-lny_3$
DELPHI	0.1127	$\pm$	0.0059(exp)	$\pm$	0.0048(th)	T,ρ
L3	0.1086	$\pm$	0.0026(exp)	$\pm$	0.0054(th)	T,ρ,B_w, B_t
OPAL	0.104	$\pm$	0.003(stat)	$\pm$	0.005(syst)	T,M_H,B_w, B_t, D_2

Different fit ranges + variables + averaging method!

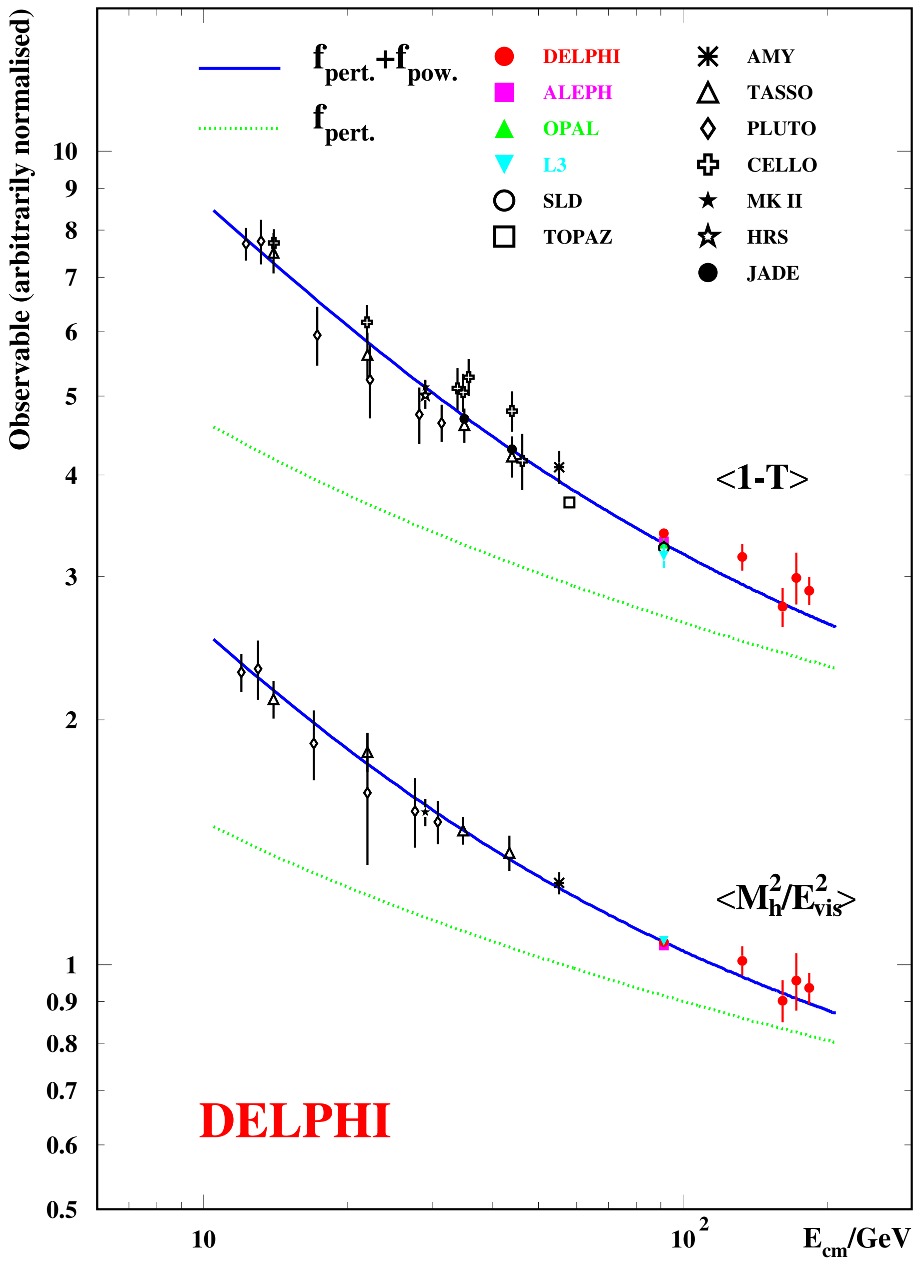
Very consistent results!

$\boldsymbol{\alpha_s}$ using power corrections

DELPHI: instead of using hadronization corrections from models
$\rightarrow$ apply non-pert. term to the $\mathcal{O}({\alpha_s}^2)$ prediction.

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

$$\langle f_{pow} \rangle = a_f \frac{4C_F}{\pi^2} M \frac{\mu_I}{E_{cm}} \left[\alpha_0(\mu_I) - \alpha_s(\mu) - \left(b_0 \log \frac{\mu^2}{\mu_I^2} + \frac{K}{2\pi} + 2b_0 \right) \alpha_s^2(\mu) \right]$$



$\alpha_0 = 0.494$
$\pm 0.008 \pm 0.003$

$\alpha_0 = 0.558$
$\pm 0.022 \pm 0.012$

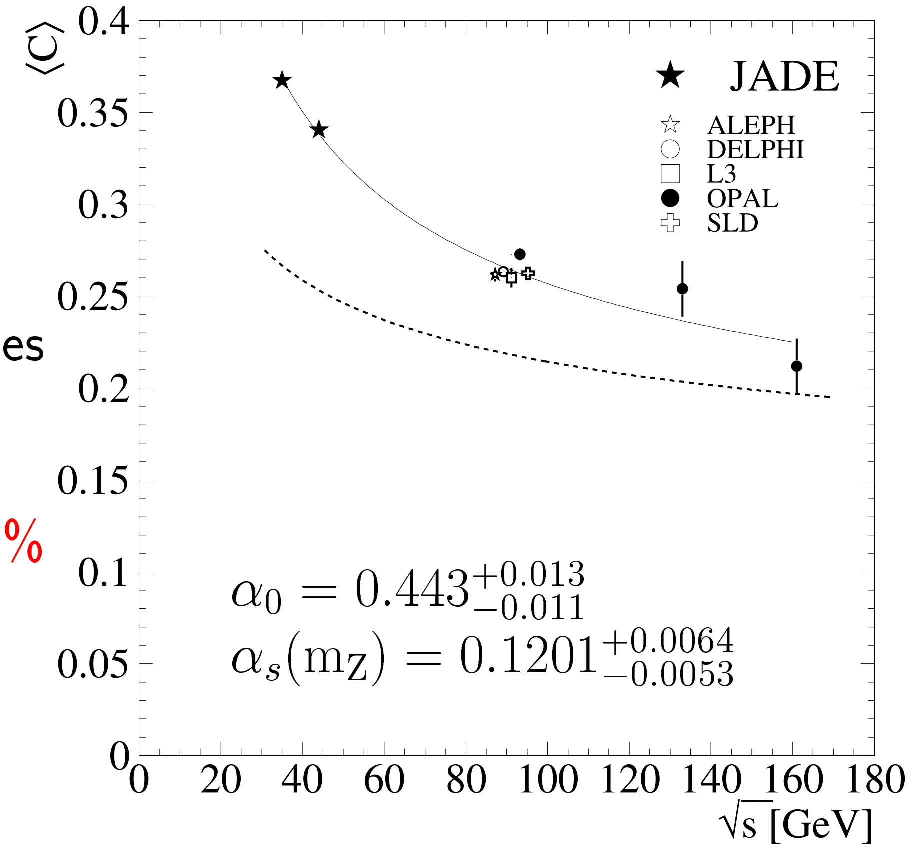
$\alpha_s(183\ \mathrm{GeV}) = 0.1125 \pm 0.0056$ (exp) ± 0.0035 (scale)

$\boldsymbol{\alpha_s}$ using power corrections

Power corrections calculated also for B_T, B_W and C

JADE: reanalysis of data at 35 and 44 GeV

- consistent α_s values for the 5 variables
- Universality of α_0 only at a level of 30%



ALEPH:

Use power law corrections with O(α_s^2)+NLLA on T and C distributions

Fit 2 variables at all LEP energies simultaneously

- 1-T: α_0(2 GeV) $= 0.449 \pm 0.003$ (stat) $\pm\ 0.082$ (syst)
- C: α_0(2 GeV) $= 0.462 \pm 0.003$ (stat) $\pm\ 0.060$ (syst)

Universality of α_0 verified for T and C (ρ in lnR scheme)

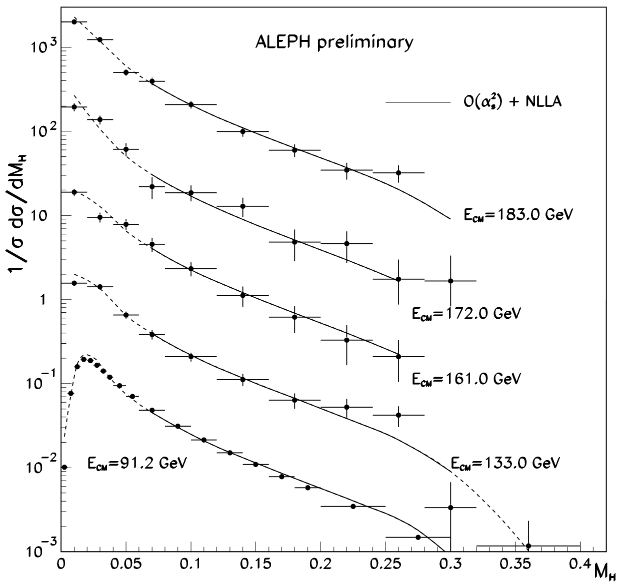
$$\alpha_s(\mathrm{m_Z}) = 0.1168 \pm 0.0003 \text{ (stat)} \pm 0.0048 \text{ (syst)}$$
$$\alpha_0(2 \text{ GeV}) = 0.451 \pm 0.003 \text{ (stat)} \pm 0.065 \text{ (syst)}$$

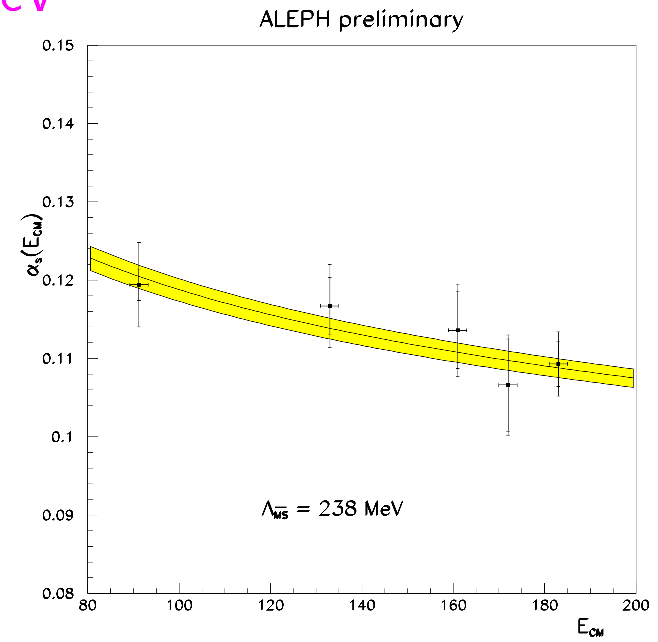
running of α_s at LEP

For the various CM energies use identical procedure

$\rightarrow$ running seen by each LEP experiments

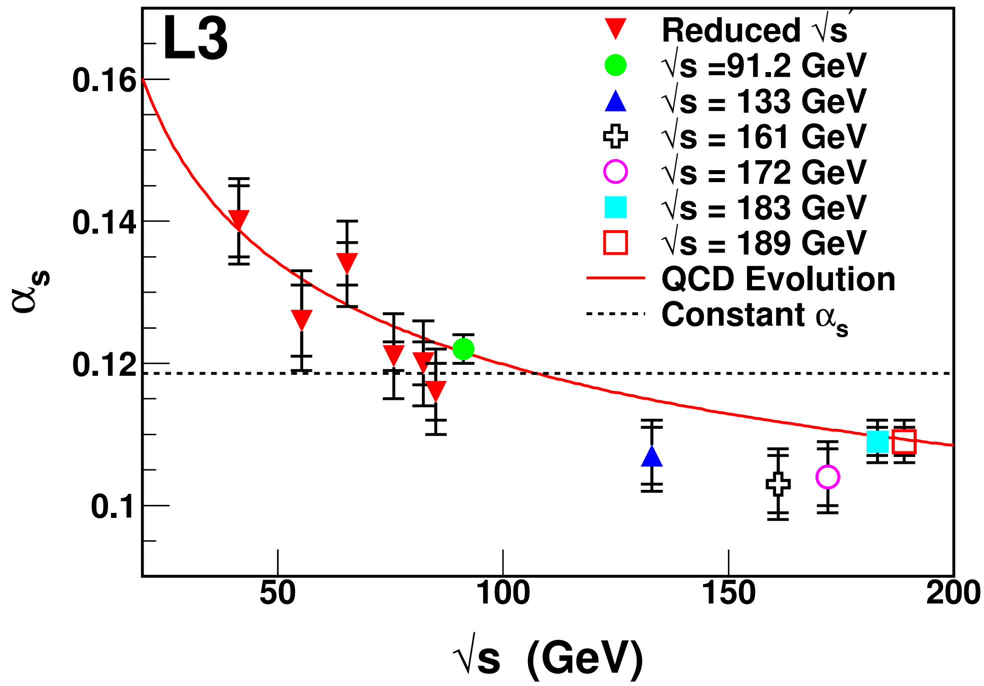
ALEPH: 91 GeV $< \sqrt{s} <$ 183 GeV





Simultaneous fit of 5 observables at 4 different energies assuming the QCD running $\alpha_s(m_Z) = 0.1217 \pm 0.0017$ (stat) ± 0.0044 (syst)

L3: 30 GeV $< \sqrt{s} <$ 189 GeV



$\alpha_s(m_Z) = 0.1216 \pm 0.0017$ (exp) ± 0.0058 (th)

Flavour independence of $\boldsymbol{\alpha_s}$

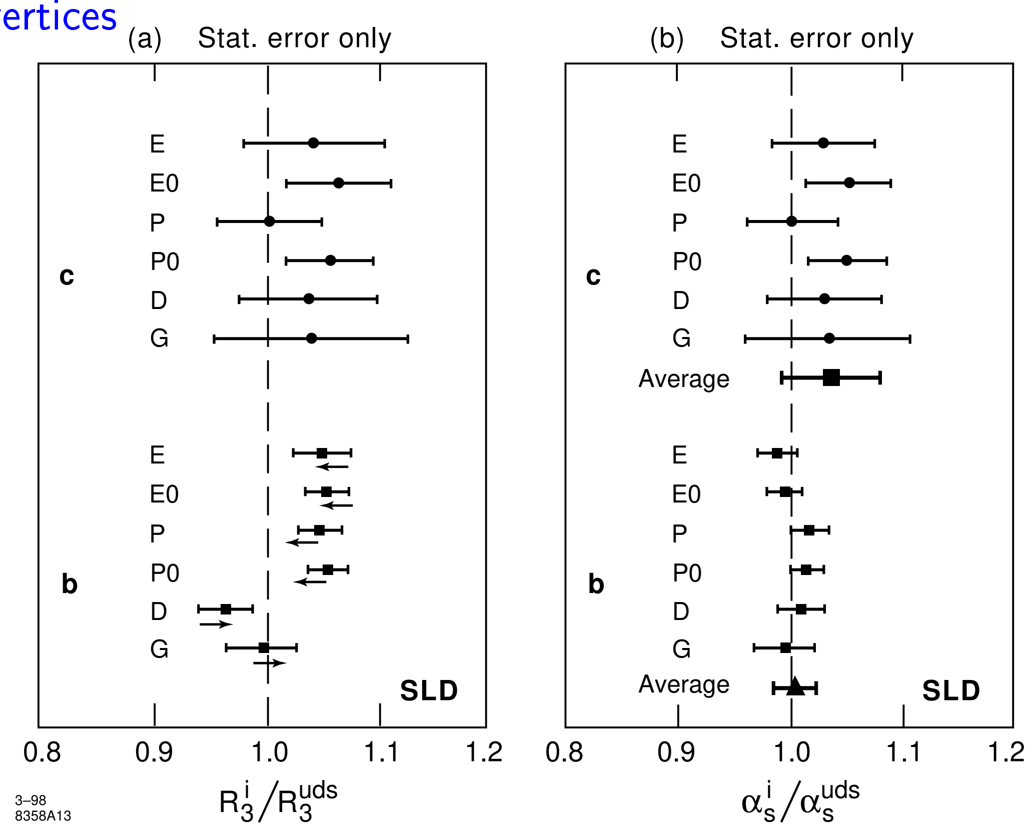
Important test of QCD: any deviation $\rightarrow$ new physics

- measure α_s for different flavour tagged samples
- b mass effects not negligible compared to experimental precision for 3-jet observables

Recently: complete NLO calculations including mass effects.

SLD: New flavour tagging technique based on invariant mass of reconstructed secondary vertices

- high purity uds, b and c samples
- measure 3-jet rates with 6 jet algorithms



- NLO prediction including b mass effect: $\frac{R_3^b}{R_3^{uds}} = f\left(\alpha_s{}^b, \alpha_s{}^{uds}, m_b\right)$

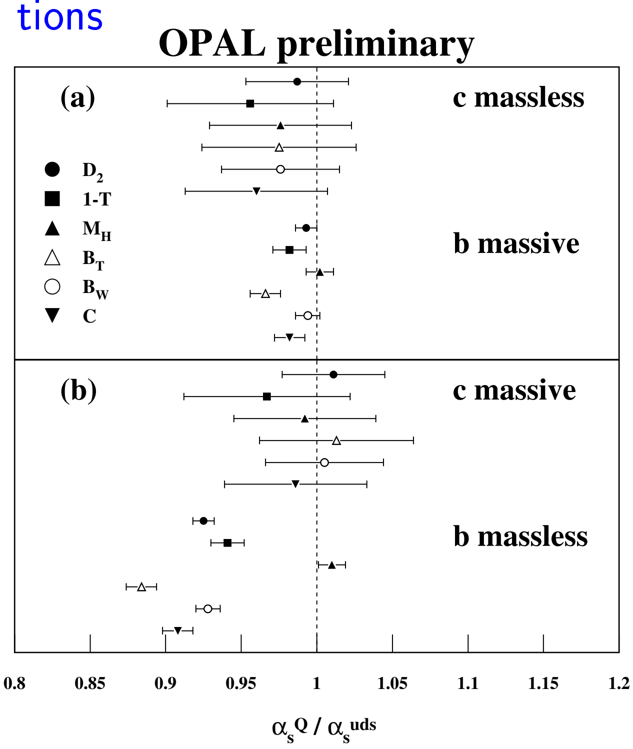
$$\frac{\alpha_s{}^c}{\alpha_s{}^{uds}} = 1.036 \pm 0.043\,(stat)^{+0.041}_{-0.045}\,(syst)^{+0.020}_{-0.018}\,(th)$$

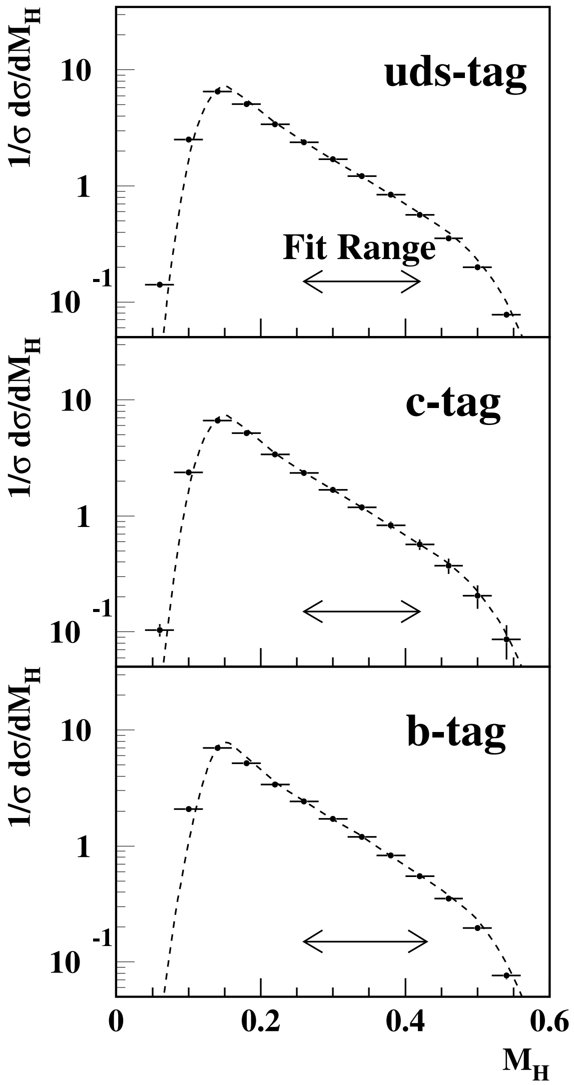
$$\frac{\alpha_s{}^b}{\alpha_s{}^{uds}} = 1.004 \pm 0.018\,(stat)^{+0.026}_{-0.031}\,(syst)^{+0.018}_{-0.029}\,(th)$$

Flavour independence of α_s

OPAL: Different flavour tagging technique: reconstructed $D^{*\pm}$ for c sample

- Measure for each tagged sample T,ρ,B_T,B_W,D_2 and C parameter
- fit with NLO predictions including mass effects for c and b contributions





$$\frac{\alpha_s{}^{c}}{\alpha_s{}^{uds}} = 1.002 \pm 0.017\,(stat) \pm 0.025\,(syst) \pm 0.009\,(th)$$

$$\frac{\alpha_s{}^{b}}{\alpha_s{}^{uds}} = 0.988 \pm 0.005\,(stat) \pm 0.004\,(syst) \pm 0.011\,(th)$$

- b mass effects clearly seen at a level of 5-8%
- All results consistent with flavour independence of α_s

m_b effects on 3 jet rates

- m_b defined in the $\overline{MS}$ scheme $\rightarrow$ renormalization scale dependence
- Assuming flavour independence of α_s $\rightarrow$ study m_b effects
- need NLO QCD corrections to 3 jet production for heavy quarks

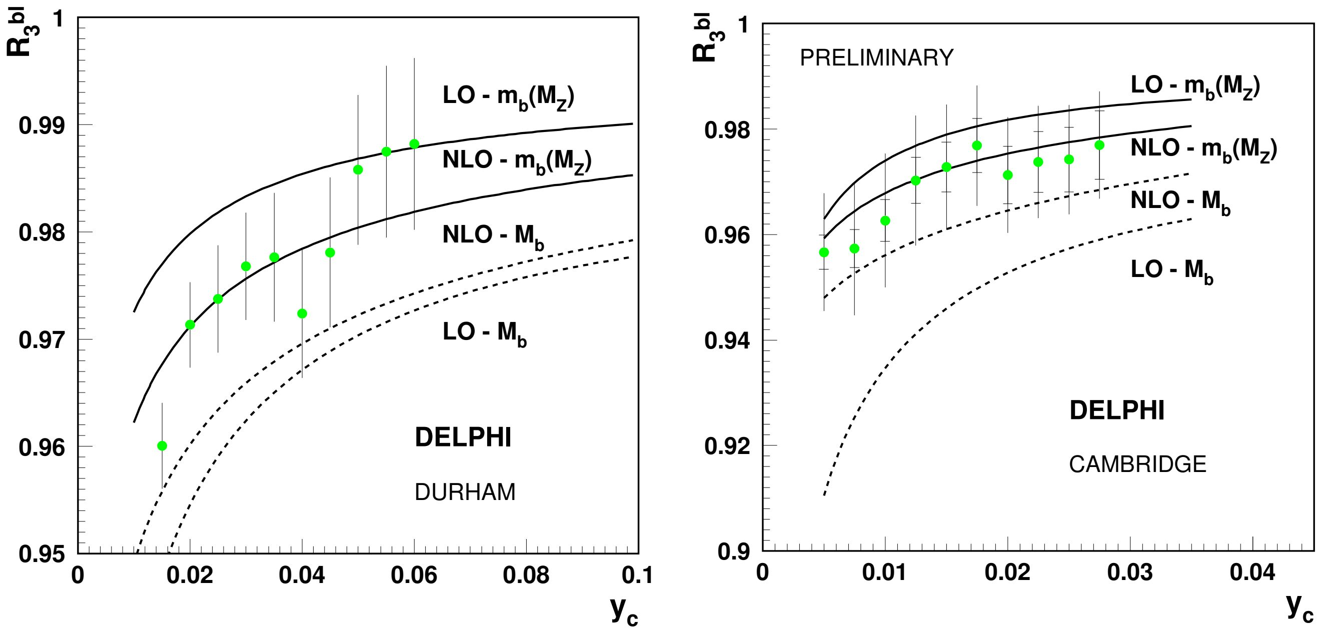
DELPHI: measure 3 jet rate for b and light quarks:

$$R_3^{bl}(y_c) = \frac{\Gamma_{3j}^{Z\to b\bar{b}g}/\Gamma_{tot}^{Z\to b\bar{b}}}{\Gamma_{3j}^{Z\to l\bar{l}g}/\Gamma_{tot}^{Z\to l\bar{l}}}$$

Hadronization error: $\approx 1\%$

NLO calculations including quark mass effects: for new Cambridge jet algorithm

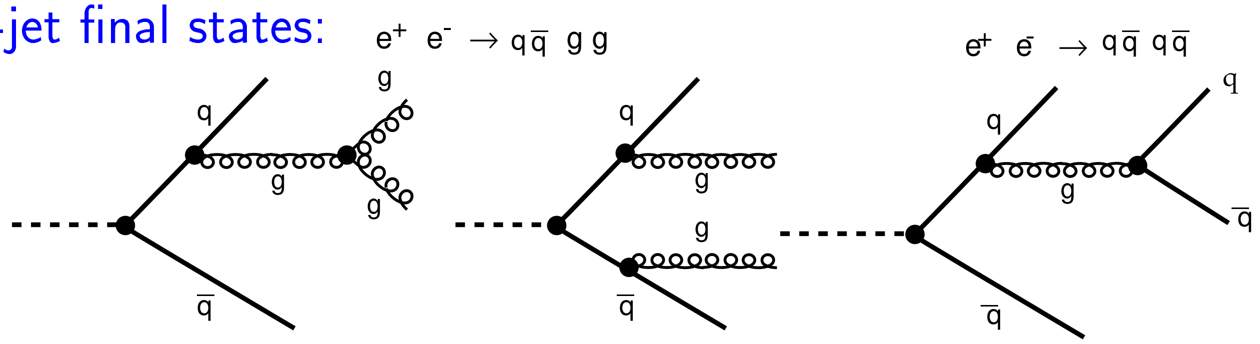
$$R_3^{bl}(y_c) = 1 + r_b(\mu)\left(b_1(y_c, r_b(\mu)) + \frac{\alpha_s(\mu)}{\pi} b_2(y_c, r_b(\mu))\right)$$



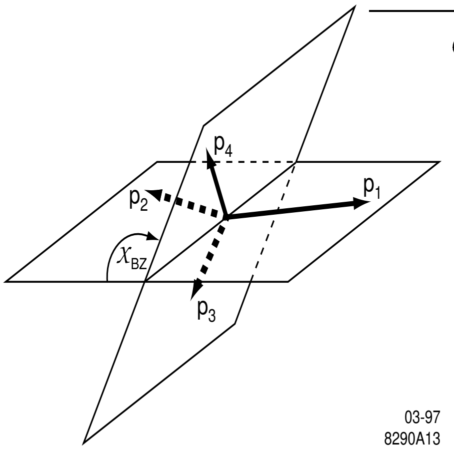
For both algorithms: running mass hypothesis is preferred!

- LO description only acceptable for running m_b
- NLO description: reasonable agreement also with pole mass

4-jet final states:



OPAL: Compare angular correlation variable χ_{BZ} in 4-jet events with $\mathcal{O}({\alpha_s}^2)$ calculation (difference in shape sensitive to $\mathrm{q\bar{q}q\bar{q}}$):



$$\frac{d\sigma\left(x\right)_{4-jets}}{dx} = f_q D_{\mathrm{q\bar{q}q\bar{q}}}\left(x\right) + \left(1-f_q\right) D_{\mathrm{q\bar{q}gg}}\left(x\right)$$

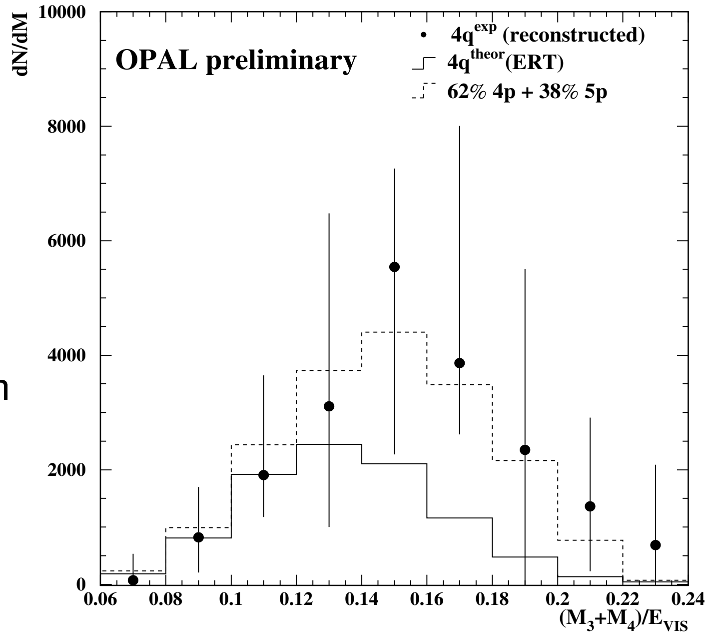
fit f_q: fraction of 4 quark events

$$R_{4q} = \frac{f_q^{expt.}}{f_q^{theor.}} = 2.00^{+0.32}_{-0.40}$$

→ apparent $\mathrm{q\bar{q}q\bar{q}}$ excess

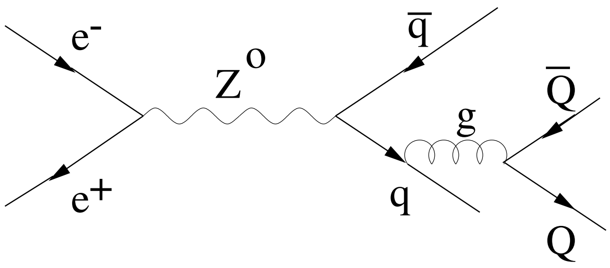
Also consistent with QCD fractions if add:
$(38^{+16}_{-20})\%$ of unresolved 5-partons

- Same χ_{BZ} shape as $\mathrm{q\bar{q}q\bar{q}}$
- different $M_3 + M_4$ distribution



Necessary to use $\mathcal{O}({\alpha_s}^3)$ calculations to study 4-jet production.

gluon splitting into heavy quarks



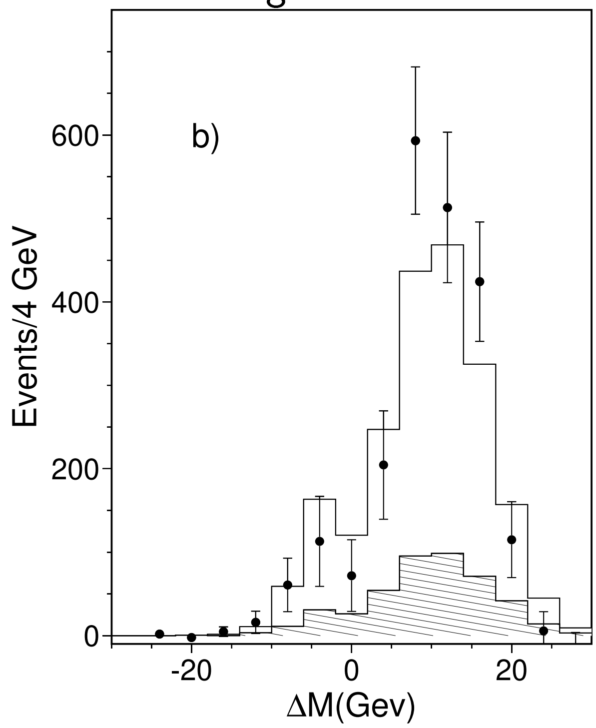
Basic QCD coupling

$$g_{Q\overline{Q}} = \frac{\sigma(Z \to q\overline{q}g, g \to Q\overline{Q})}{\sigma(Z \to hadrons)}$$

Limited knowledge of $g_{c\overline{c}}$ is one main uncertainty in R_b measurements. $\mathcal{O}({\alpha_s}^2)$ + NLLA predictions (D.Miller,M.Seymour: hep-ph/9805414) exist for $n_{g\to c\overline{c}}$ and $n_{g\to b\overline{b}}$ but large theoretical uncertainties.

L3: g$\to$ $c\overline{c}$

In 3 jet events: lepton tag + topological cuts based on a Neural Network and lifetime tag



$$\Delta M = M_2 + M_3 - M_1$$

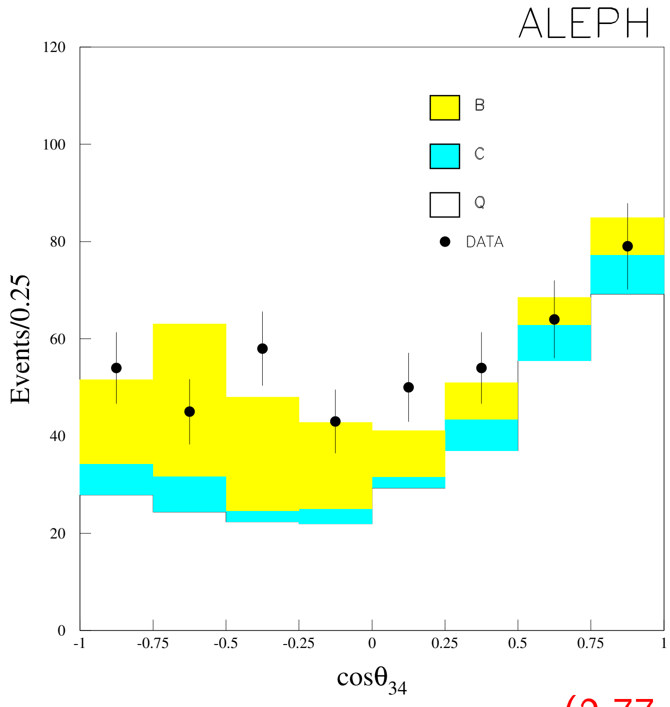
Combined lepton tag and event shape:
$g_{c\overline{c}}$=(2.22±0.18(stat)±0.44(syst))%

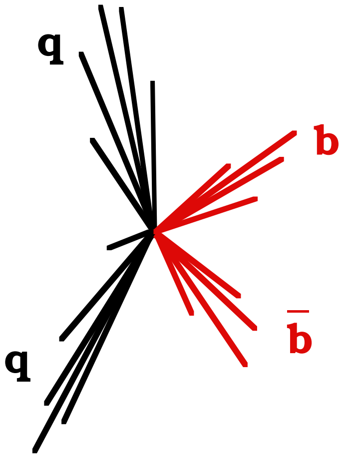
New LEP average (no theory input): $g_{c\overline{c}}$=(2.58±0.18 ±0.35)%

Consistent with perturbative QCD prediction: $g_{c\overline{c}}$=2.007%

gluon splitting into heavy quarks

ALEPH: g$\rightarrow$ $\mathrm{b\bar{b}}$, In 4 jet events: topological cuts and lifetime tag





222 events,
purity = 45%, ϵ=1%

$g_{\mathrm{b\bar{b}}}$=(2.77±0.42(stat)±0.57(syst))10^{-3}

DELPHI: g$\rightarrow$ $\mathrm{b\bar{b}}$

In 3 jet events tag 3 b jets $\rightarrow$ 140 events, $\epsilon_{\mathrm{b\bar{b}b\bar{b}}}$=3.2%

$$R_{4b} = \frac{Br(Z \rightarrow \mathrm{b\bar{b}b\bar{b}})}{Br(Z \rightarrow hadrons)} = (5.4 \pm 1.8 \pm 1.5)10^{-4}$$

$$g_{\mathrm{b\bar{b}}} = \frac{\sigma(Z \rightarrow \mathrm{q\bar{q}g, g \rightarrow Q\bar{Q}})}{\sigma(Z \rightarrow \mathrm{b\bar{b}b\bar{b}})} R_{4b} = (3.0 \pm 1.0(stat) \pm 0.8(syst))10^{-3}$$

New LEP average (no theory input):

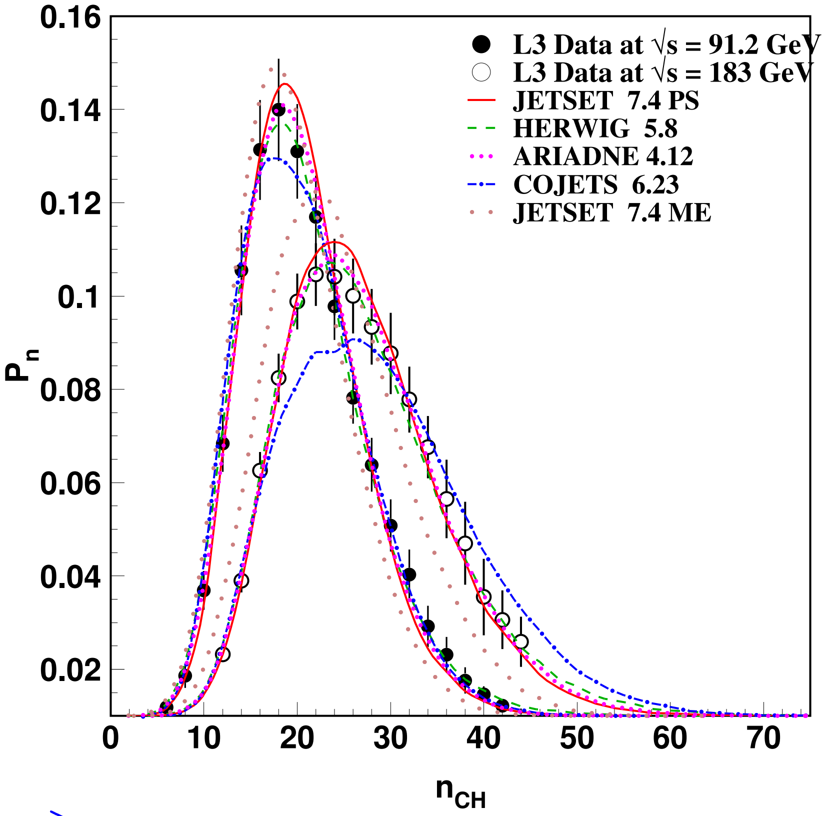
$g_{\mathrm{b\bar{b}}}$=(0.273±0.038 ±0.049)%

Consistent with perturbative QCD prediction: $g_{\mathrm{b\bar{b}}}$=0.175%

errors on R_b from gluon splitting reduced

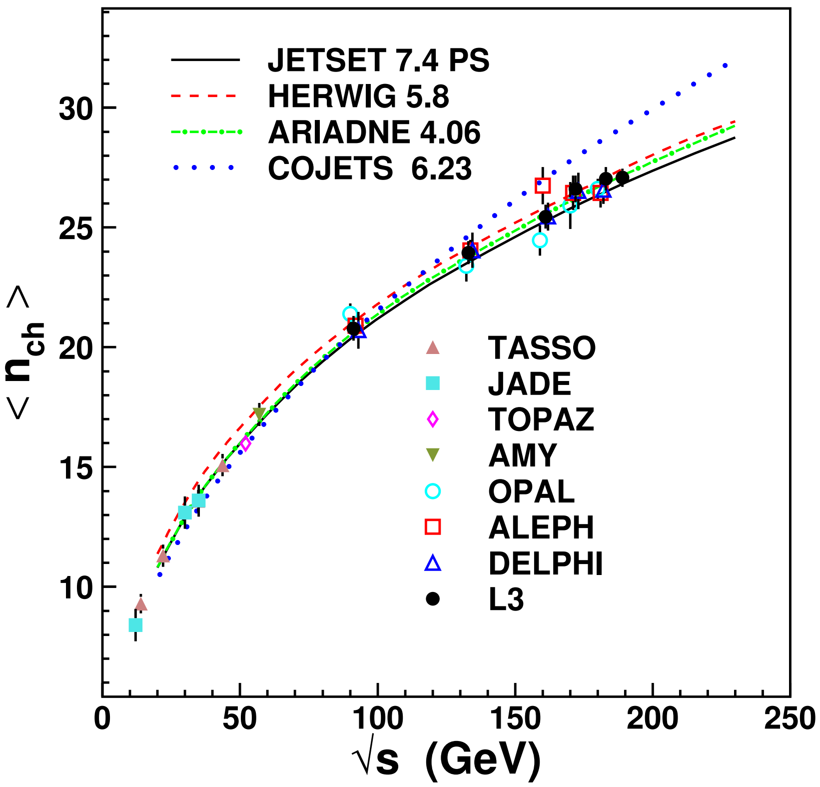
Charged particle multiplicity distributions

Good description for all LEP2 energies by parton shower models tuned at 91 GeV except COJETS without coherence



Mean multiplicity $< n_{ch} >$

Multiple gluon emission including coherence effect is necessary to describe the energy dependence



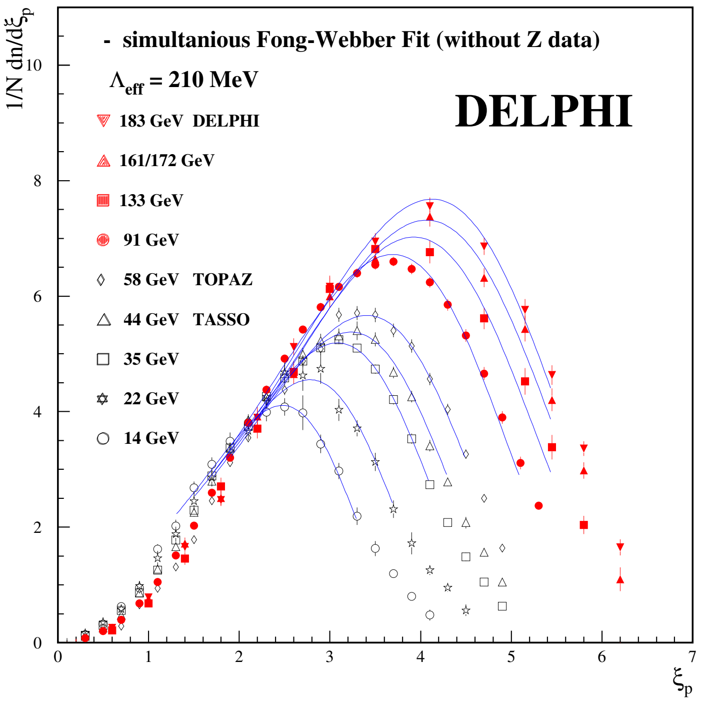
also good agreement with QCD NLLA prediction

Charged particle momentum spectra

QCD Coherence effects $\Rightarrow$ Suppression of soft gluon emission

LPHD: $\Rightarrow$ Supression of hadron production (small $x = \frac{\mathrm{p}}{\mathrm{E_{beam}}}$)

Study $\xi = \log(1/x)$ spectra for charged particles :

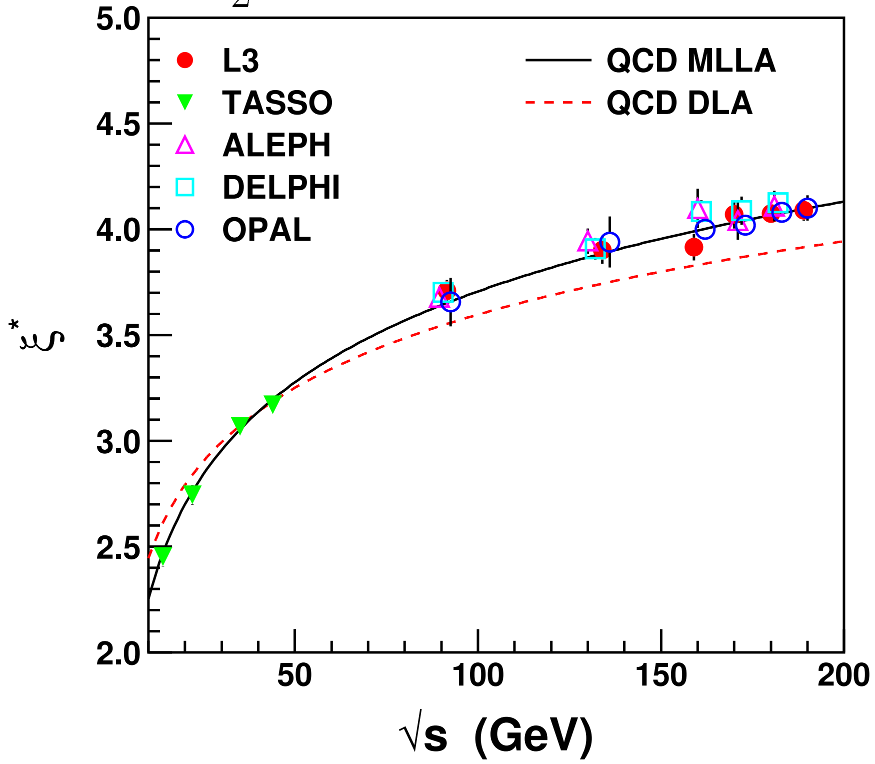


MLLA prediction for shape of ξ spectra: $\approx$ *Distorted gaussian*

MLLA+LPHD: describes data over a wide energy range.

QCD MLLA prediction for energy evolution of peak position $\xi^\star$:

$$\xi^\star = \frac{1}{2}Y + \sqrt{C}\sqrt{Y} - C + \mathcal{O}(Y^{-3}), \mathrm{where Y} = \ln(\mathrm{E_{beam}}/\Lambda)$$

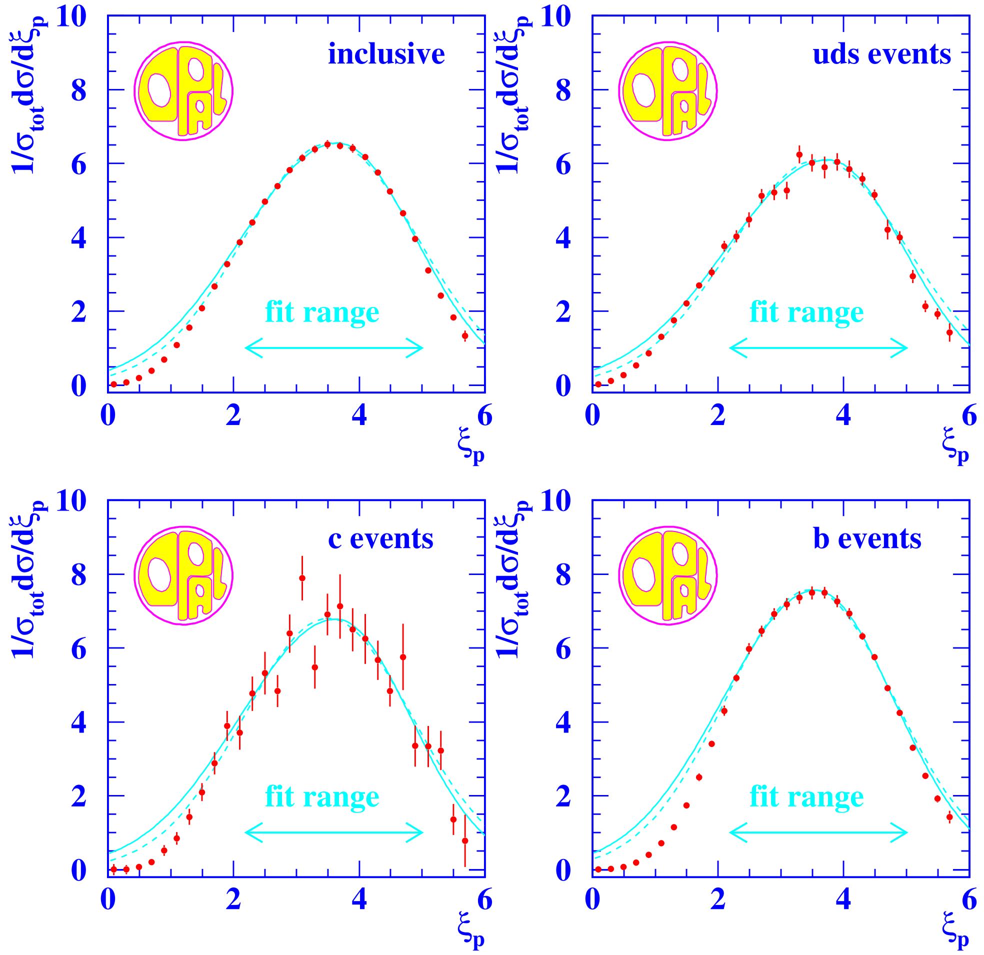


clear evidence for gluon coherence.

Charged particle momentum spectra

Flavour dependence of fragmentation functions

OPAL:



fragmentation function for b quarks significantly softer that for uds

$$\xi^\star_{uds} = 3.74 \pm 0.06 \pm 0.21$$
$$\xi^\star_{c} = 3.63 \pm 0.16 \pm 0.31$$
$$\xi^\star_{b} = 3.55 \pm 0.01 \pm 0.07$$

Other results: Flavour dependence with different hadron species

SLD: $\pi^\pm$, $K^\pm$,K^0, $K^{\star 0}$, p, Λ^0 production in uds, c and b flavor events.

DELPHI: $\pi^\pm$, $K^\pm$, p production in uds, c and b flavor events.

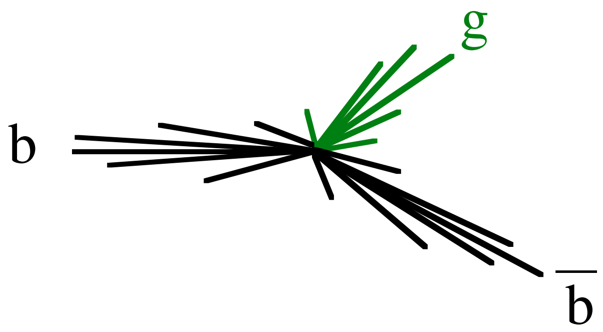
$\longrightarrow$ shape of ξ consistent with MLLA+LPHD prediction near the peak for each hadron species in each flavour

Differences expected due to different colour charge

$C_A = 3$ and $C_F = 4/3$

→ Gluon jets are softer, broader and have larger multiplicity

- Gluon jet selection



Tag b jets in $b\bar{b}g$

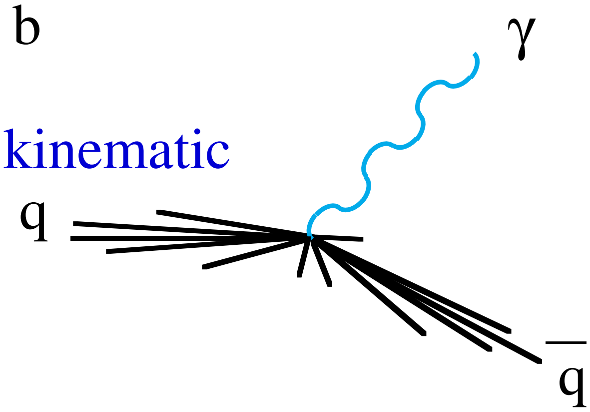
Samples with different purities depending on topology

- light quark jet selection

→ 3 jet events with same kinematic

→ 2 jets + γ

No b jets



⟹ Early analyses: qualitative differences observed

$$r_{ch} = \frac{\langle n \rangle_{gluon}}{\langle n \rangle_{quark}} = 1.0 \to 1.25$$

Theoretical predictions: 1.64 -> 2.25

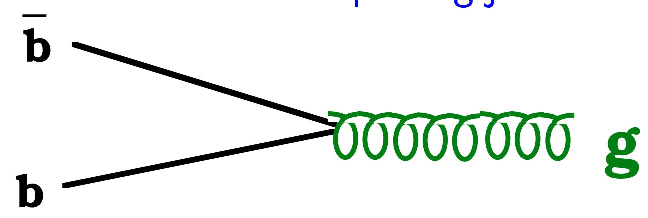
but based on gg and qq separating systems

⟹ major improvements due to:

- experimental jet definition similar to the theoretical one (OPAL)
- relevant energy scale definition to compare q and g (DELPHI)

quark and gluon jet properties

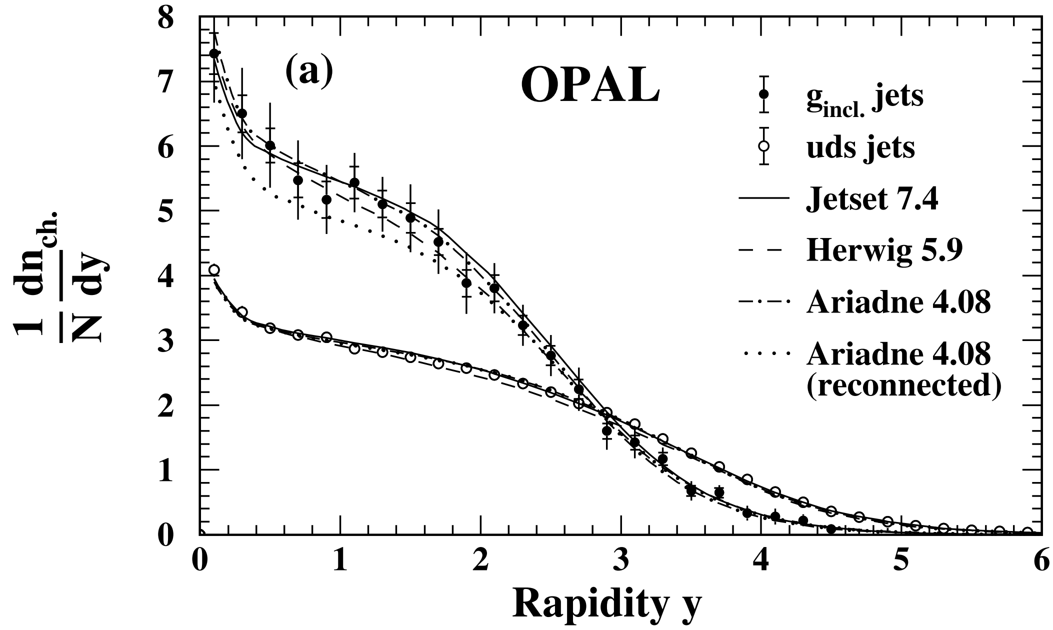
OPAL: inclusive q and g jet selection (method: J.W.Gary, PRD49 (1994))



3M Z decays $\to \approx$ 500 events

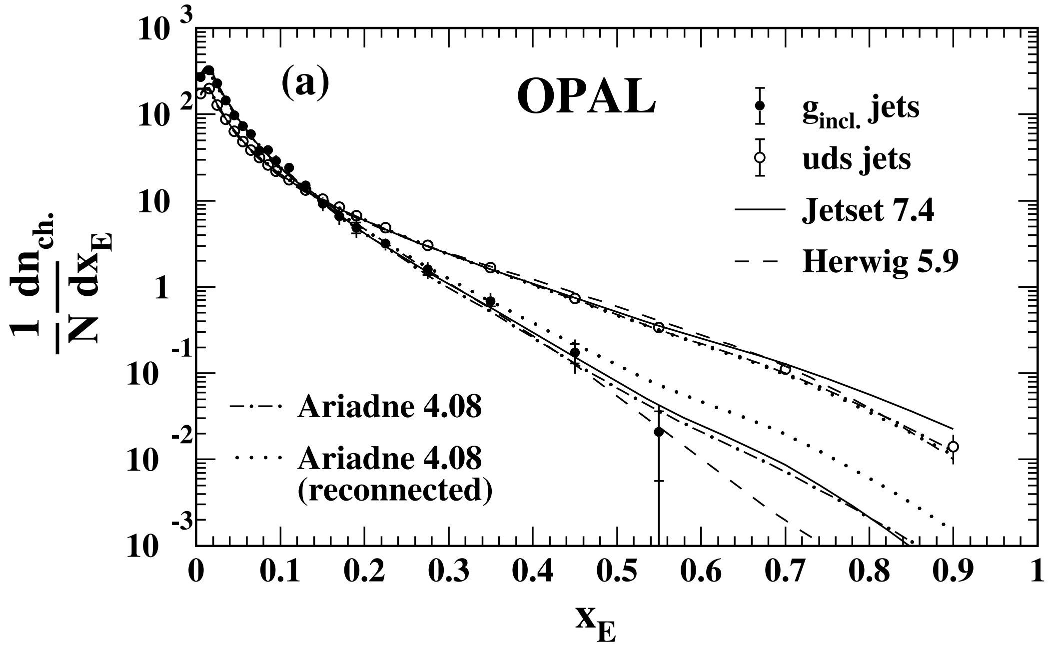
purity: 80%, $< E_g >$=41.6 GeV

light quark jets: $e^+e^- \to q\bar{q} \to < E_q >$=45.6 GeV



$r_{ch}(|y| < 2)$ = 1.815±0.038(stat)±0.062(syst) (soft particles)

difference with QCD expectation = 9/4 due to finite available energy

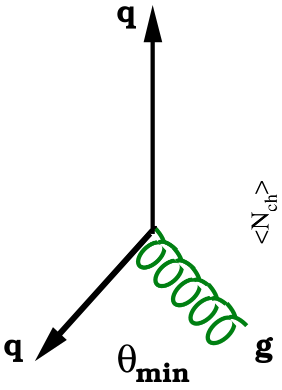


Softer gluon fragmentation clearly seen

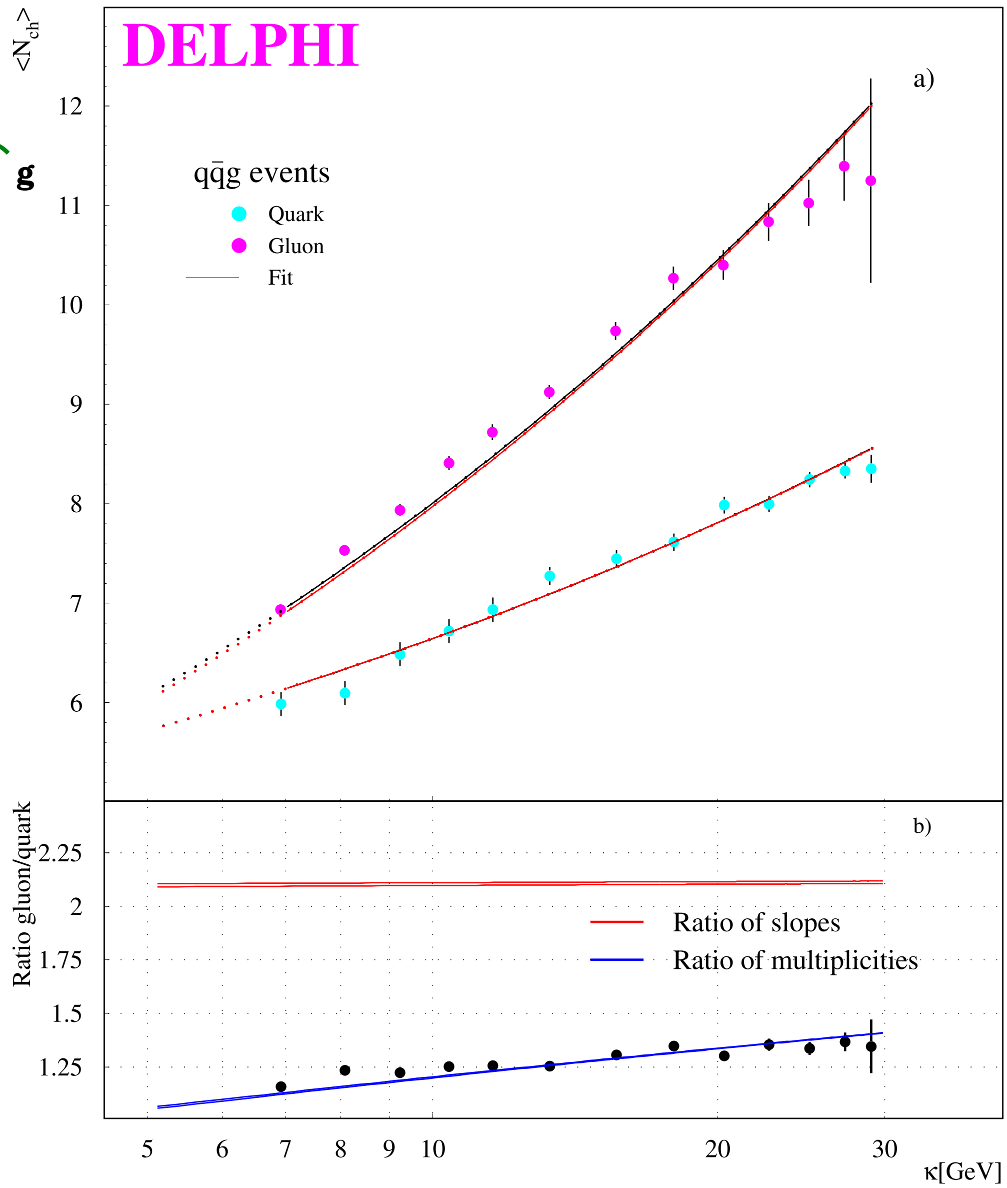
multiplities in q and g jets

- Scale dependence of the q and g jet properties investigated

"Hardness" of the process producing the jet:



$$\kappa = E_{jet} sin(\frac{\theta_{min}}{2})$$



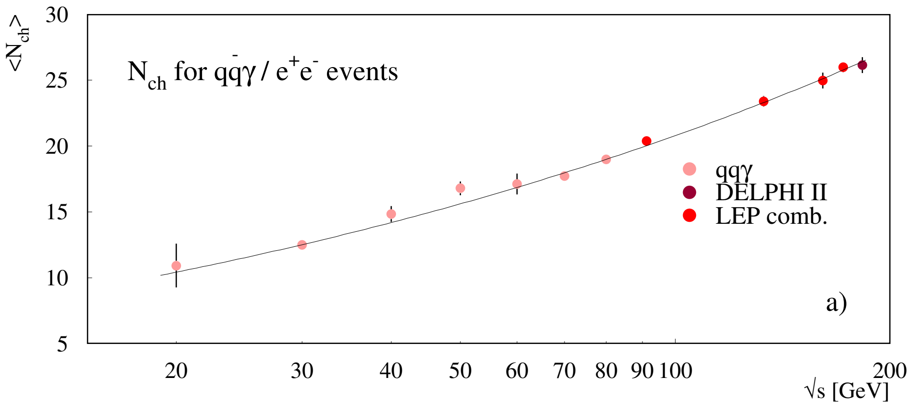
- stronger increase of the multiplicity with scale in gluon jets than in quark jets (stronger radiation)
- at large scale: ratio as well as the slope $\approx C_A/C_F$
- evidence for triple gluon coupling with soft gluons

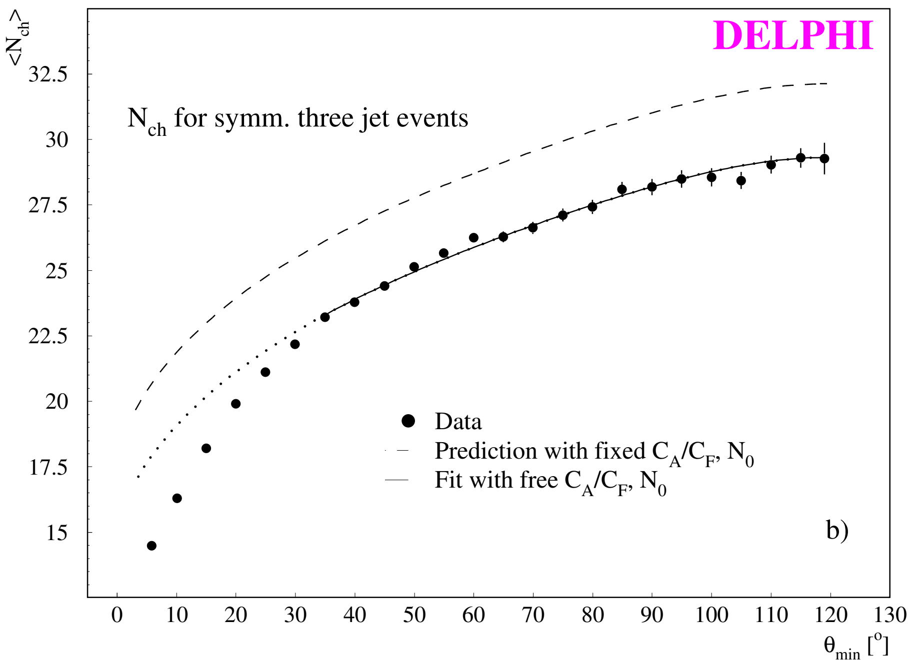
multiplicities in q and g jets

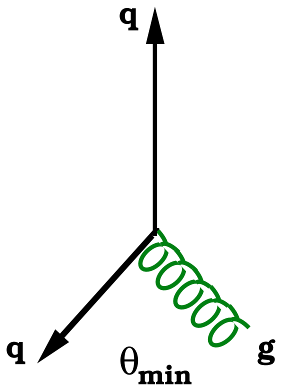
DELPHI: $<N_{ch}>$ in symmetric 3-jet events as a function of q and g scale: MLLA prediction + N_0 term

$$N_{q\bar{q}g} = N_{e^+e^-}(2E^\star) + r(p_{1\perp})(\frac{1}{2}N_{e^+e^-}(p_{1\perp}) - N_0)$$

- r(κ) = C_A/C_F(1+H.O. terms)
- $N_{e^+e^-}(\kappa)$ = NLO prediction for the hadron multiplicity.
- N_0 non-pert. term (differences in fragmentation of leading q and g)







$$\frac{C_A}{C_F} = 2.266 \pm 0.053(stat) \pm 0.055(syst) \pm 0.096(theo)$$

QCD prediction : $9/4 = 2.25$

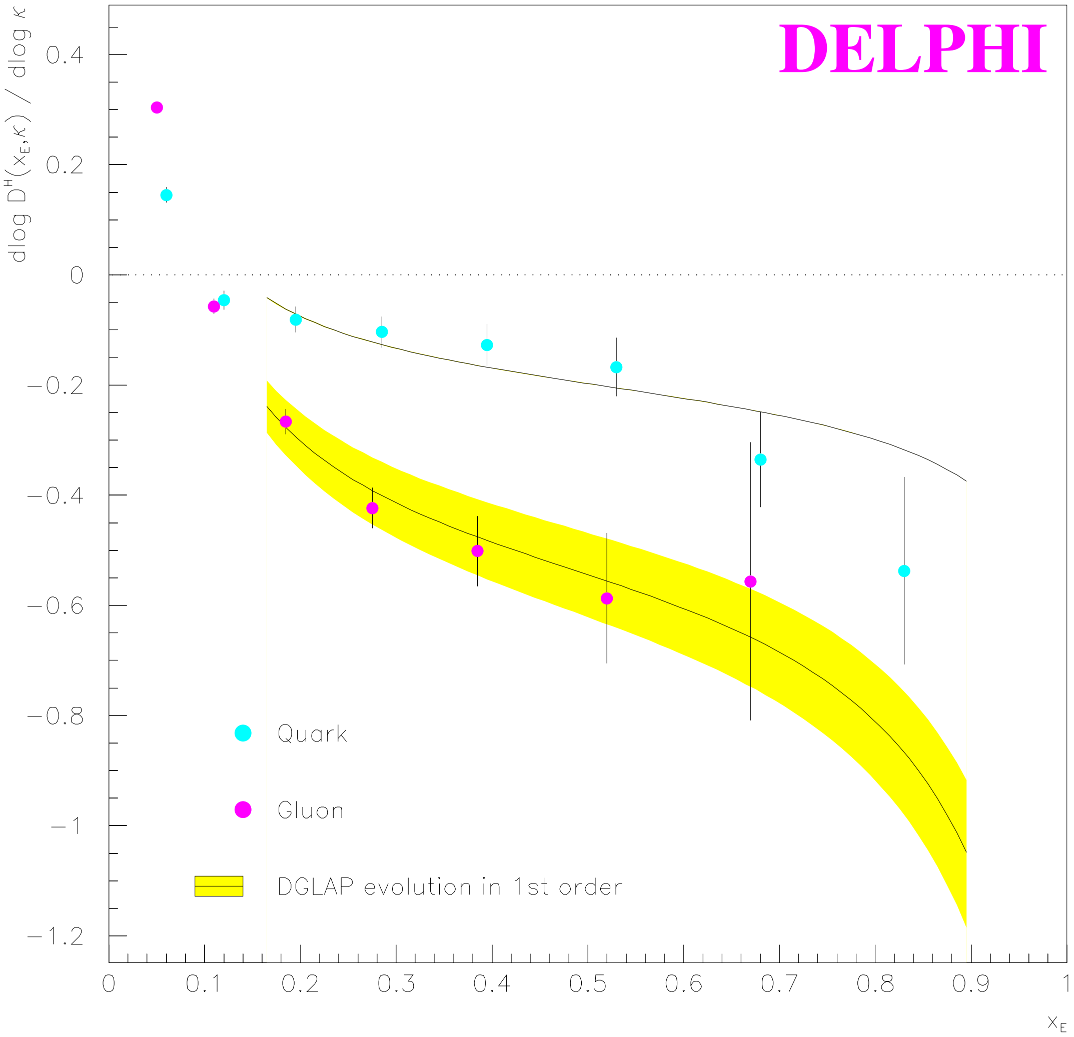
most precise measurement compared to 4-jet analyses where $\Delta(C_A/C_F) = 0.2 - 0.4$

Scaling violation in g jets

DELPHI: Fragmentation function into stable charged hadrons: $D_h^{q(g)}(x_E, \kappa)$ perturbative QCD predicts the Q^2 evolution.

typical scaling violation behaviour observed in g jets as well as in q jets

$$\frac{d\ln D_h^{q(g)}(x_E,\kappa)}{d\ln\kappa}$$ predicted at LO by solving the DGLAP evolution equation



$$x_E = \frac{E_{hadron}}{E_{jet}}$$

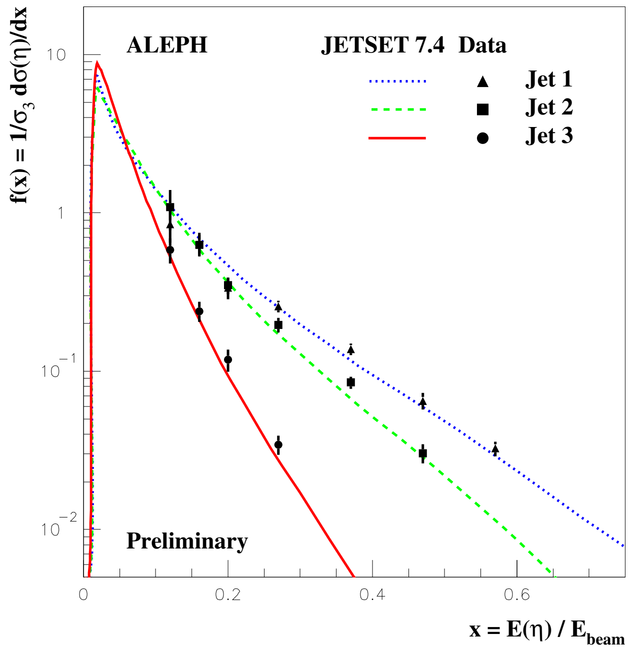
scaling violation for gluons: stronger than for quarks. High sensitivity to C_A

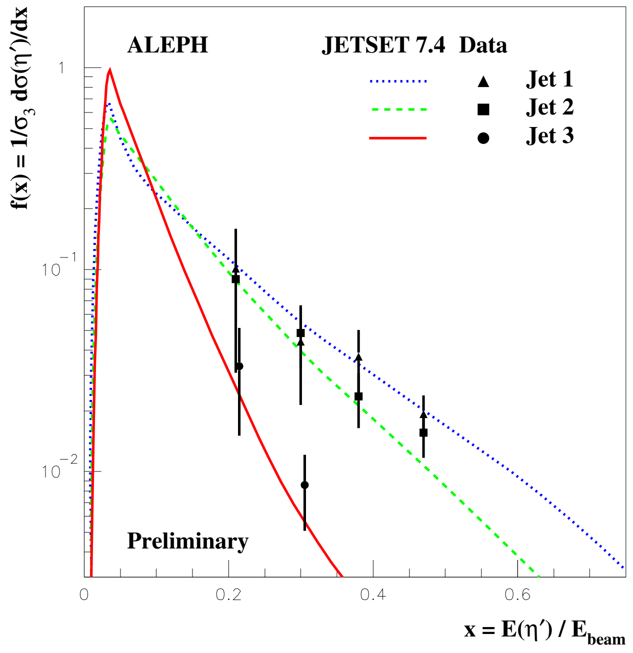
$$\frac{C_A}{C_F} = 2.44 \pm 0.21(stat)$$

Identified particles in quark and gluon jet

QCD models: gluon fragmentation similar to quark fragmentation with different colour factor

- η and $\eta\prime$





good agreement with JETSET prediction and no evidence for enhanced isoscalar production in gluon jets wrt quark jets

- K_s^0 and $\Lambda/\overline{\Lambda}$

ALEPH: momentum spectra in a reasonable agreement with JETSET for 2 and 3-jet events

OPAL: relative particle rates

$$\left(\frac{R_g}{R_q}\right)_i = \frac{\frac{n_g^i}{n_g^{ch}}}{\frac{n_q^i}{n_q^{ch}}}$$

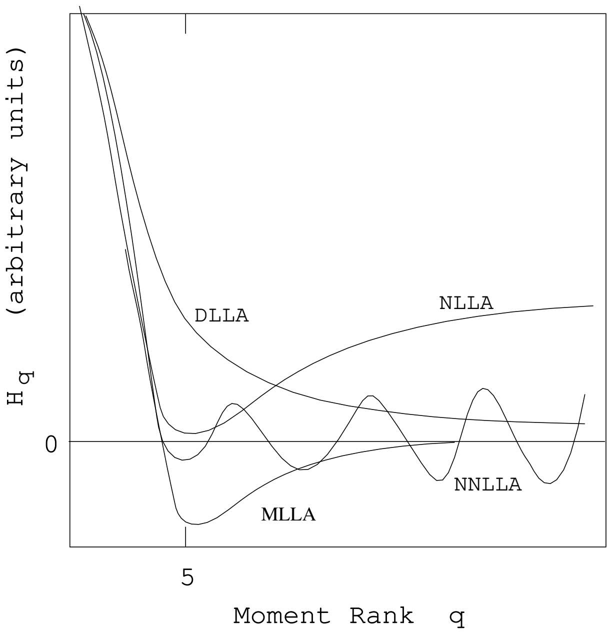
K_s^0: 1.10 $\pm$0.03
$\Lambda/\overline{\Lambda}$: 1.41 $\pm$0.06
$\pi^{\pm}$: 1.02 $\pm$0.01
$K^{\pm}$: 0.95 $\pm$0.03
$p(\overline{p})$: 1.10 $\pm$0.04

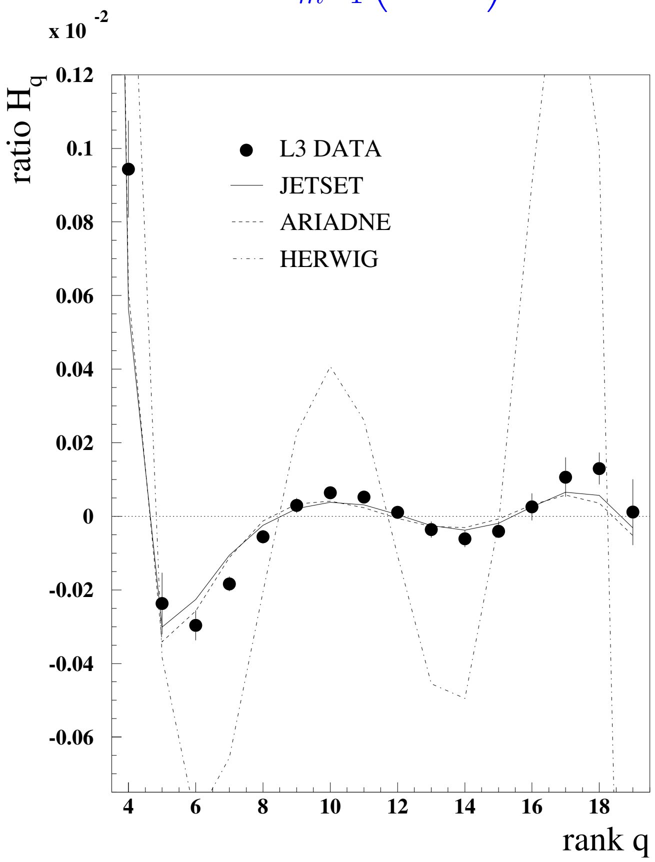
Similar trends found in the models: some differences q vs g

L3: $H_q = \frac{K_q}{F_q}$ from multiplicity in full phase space

$$F_q = \sum_{n=q}^{\infty} n(n-1)....(n-q+1)!P_n \qquad K_q = F_q - \sum_{m=1}^{q-1} \binom{q-1}{m} K_{q-m} F_m$$

QCD predictions:





•minimum + oscillations seen – (similar to SLD, P.L. B371 (1996) 149)

⟶ reproduced by QCD models!

⟶ Effects are probably associated with non-perturbative phase

But MLLA assuming LPHD cannot predict the observed oscillations.

Some disagreement with pQCD +LPHD also reported in New angular intermittency studies (DELPHI #149, L3 #543)

For these observables: more precise calculations needed

Summary

Main achievements from recent studies of $e^+e^- \longrightarrow$ hadrons:

At the Z pole (very large data sample):

- Consistent α_s determination from various approaches with a precision of less than 5% (dominated by theory)
- α_s flavour independence demonstrated at a few % level
- Gluon splitting into $c\bar{c}$ and $b\bar{b}$ measured with improved precision
- Quark and gluon jet differences confirmed by measurements in agreement with theoretical predictions
- Comprehensive studies for particle production and correlations

High energies from LEP2:

- Global event properties studied over a wide energy range (14 GeV $< \sqrt{s} <$ 189 GeV) and compared to models
- Energy evolution of α_s measured from 91 to 189 GeV
- Evidence for soft gluon coherence demonstrated

QCD proves to be a very consistent theory to describe many aspects of jet dynamics and properties in e^+e^- annihilations.