Jet Physics in e^+e^- Annihilation from 14 to 209 GeV

QCD '03, Montpellier, 02.07.03

1 Introduction
2 Hard QCD
3 Gauge Structure
4 Conclusions/Outlook

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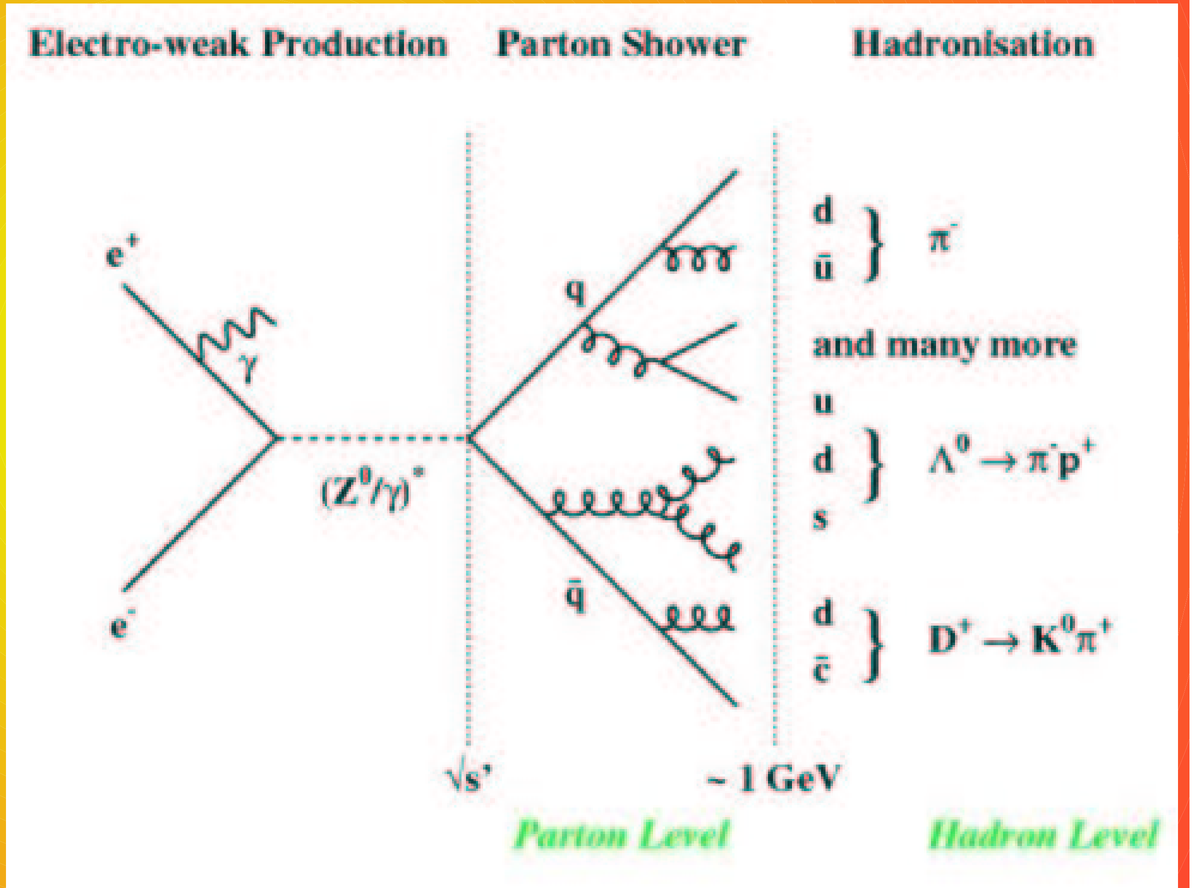
1 Introduction

Hadron production in e^+e^- annihilation is ideal laboratory for QCD studies:

→ no interference between initial and final states

→ maximal energy in laboratory system

→ no p.d.f.s to worry about

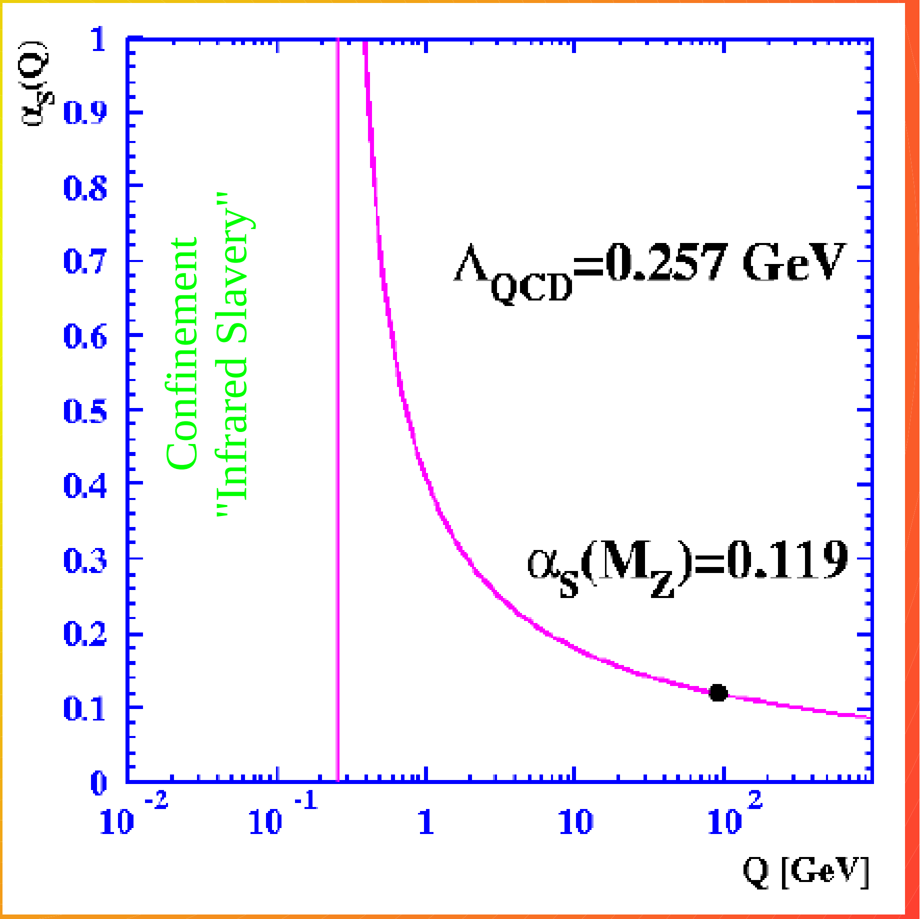


1 Running coupling "constant"

$$\alpha_S(Q) = \frac{\alpha_S(\mu)}{1 + \beta_0 \alpha_S(\mu) \ln(\mu^2/Q^2)}$$

$$= \frac{1}{\beta_0 \ln(Q^2/\Lambda^2_{QCD})}$$

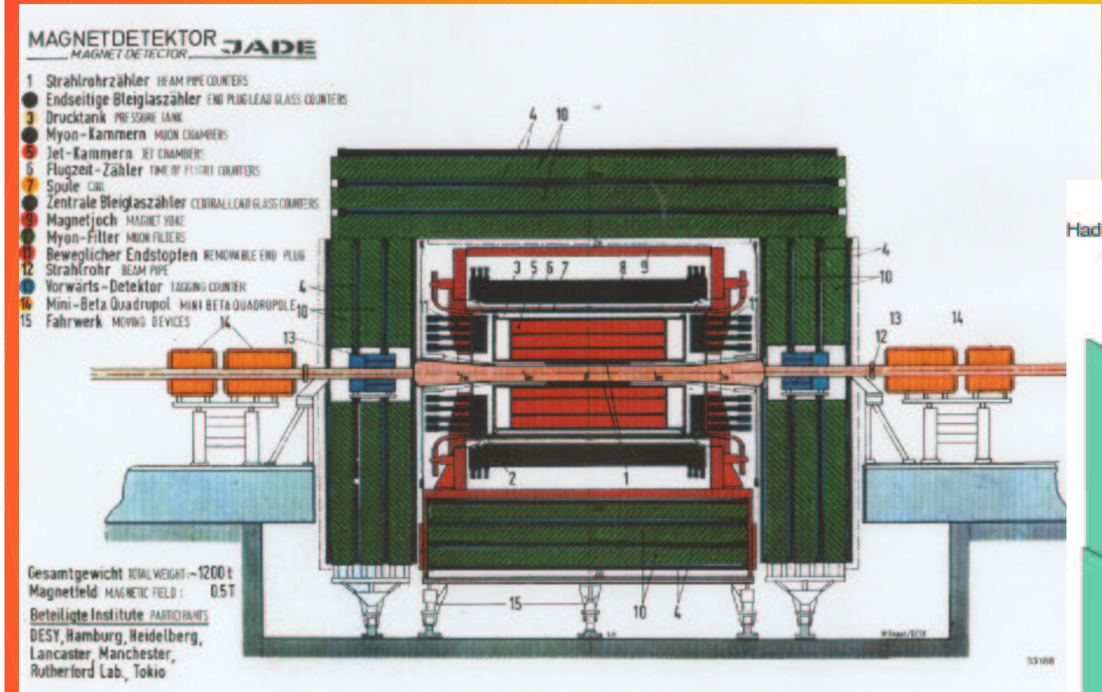
$$\beta_0 = (11 C_A - 2 n_f)/(12\pi)$$

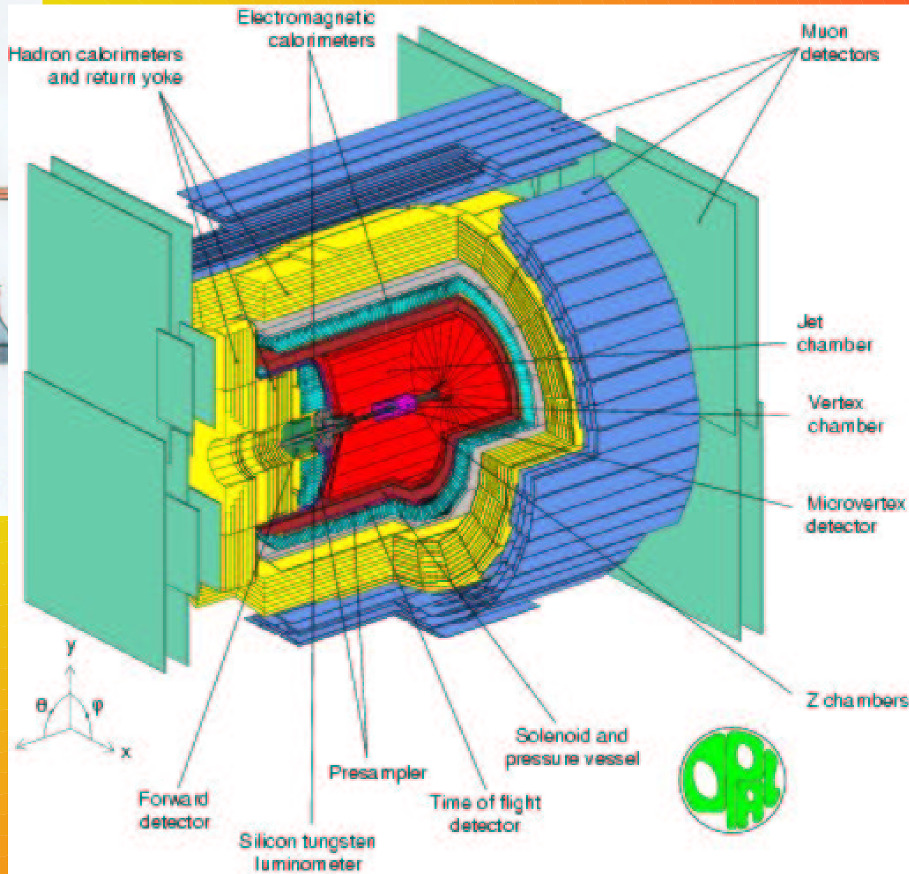


- → Strong coupling "constant" runs
- → Divergence at small Q, the "Landau pole"
- → "Asymptotic freedom" means that $\alpha_s(Q)$ vanishes for infinte Q

1 "QCD Experiments"

OPAL: 1989 to 2000 at LEP (CERN)
$\sqrt{s}$ = 88 to 209 GeV

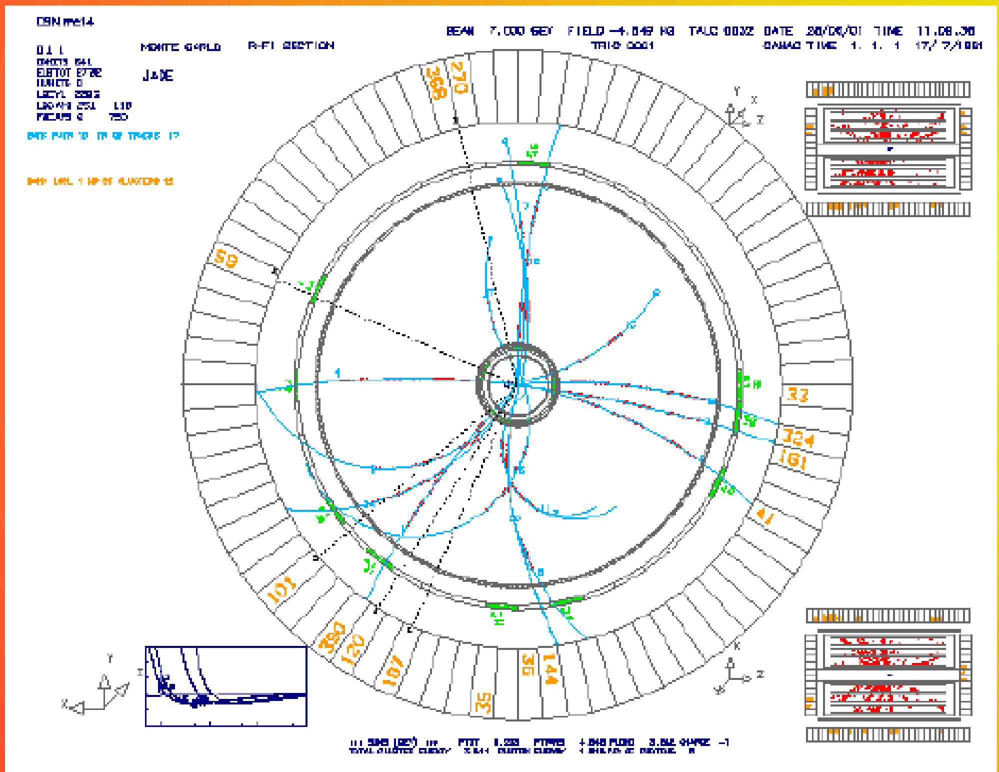




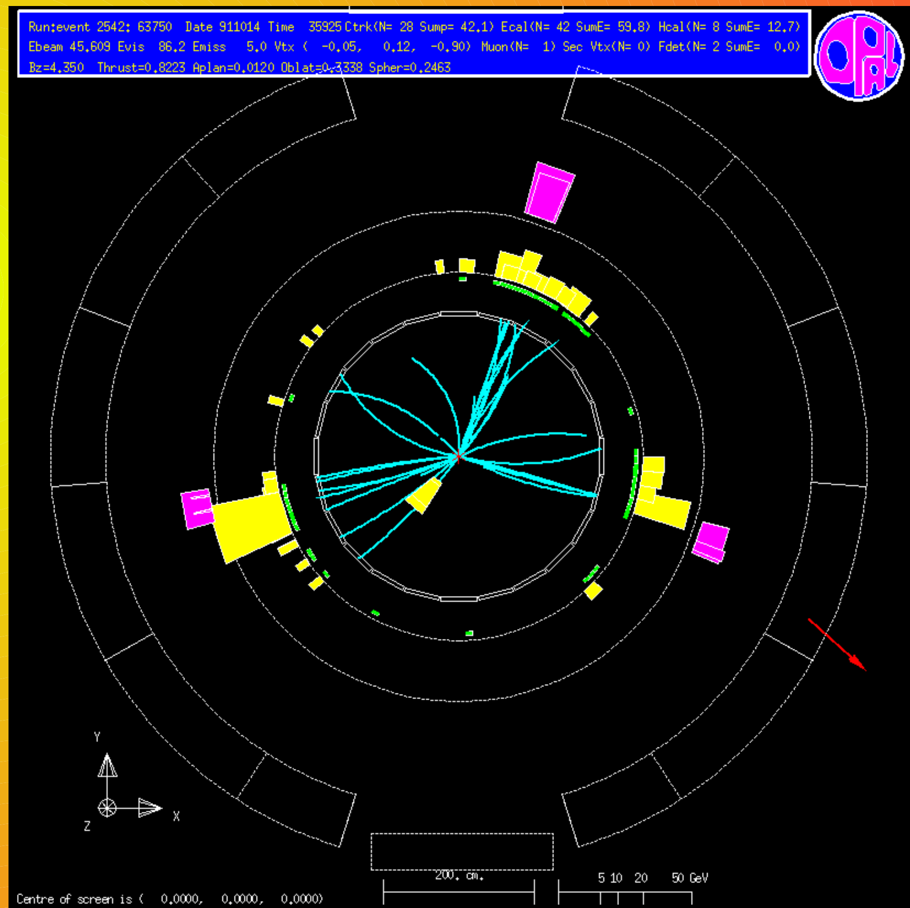
JADE: 1979 to 1986 at PETRA (DESY)
$\sqrt{s}$ = 14 to 44 GeV

1 QCD Events

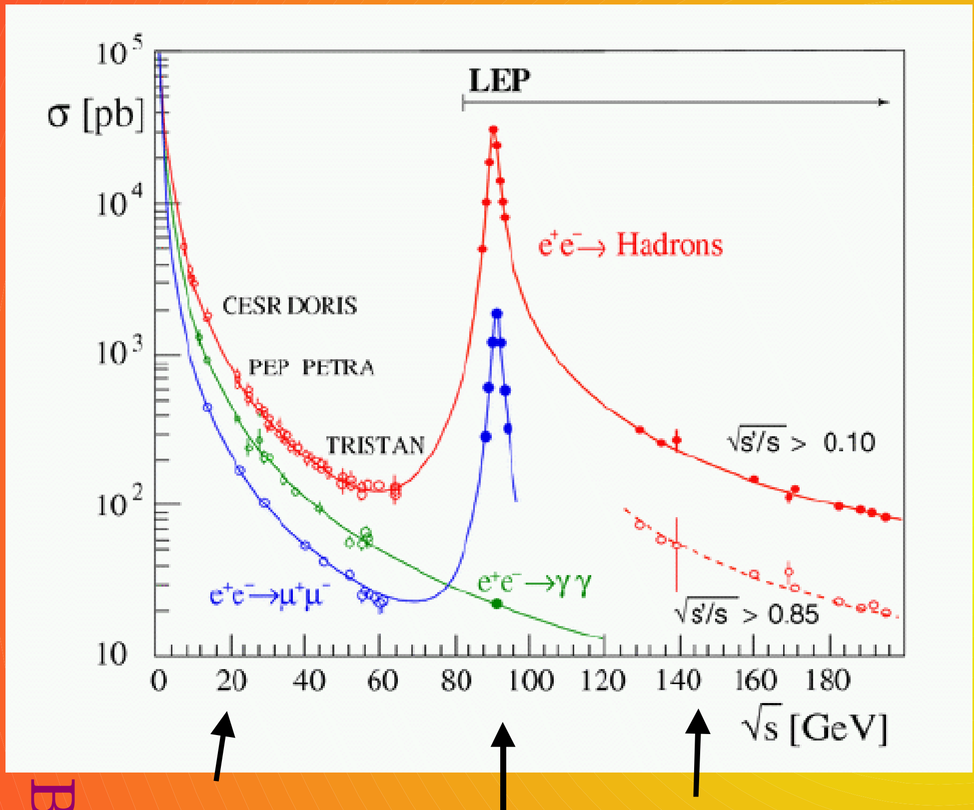
JADE $\sqrt{s}$ = 14 GeV

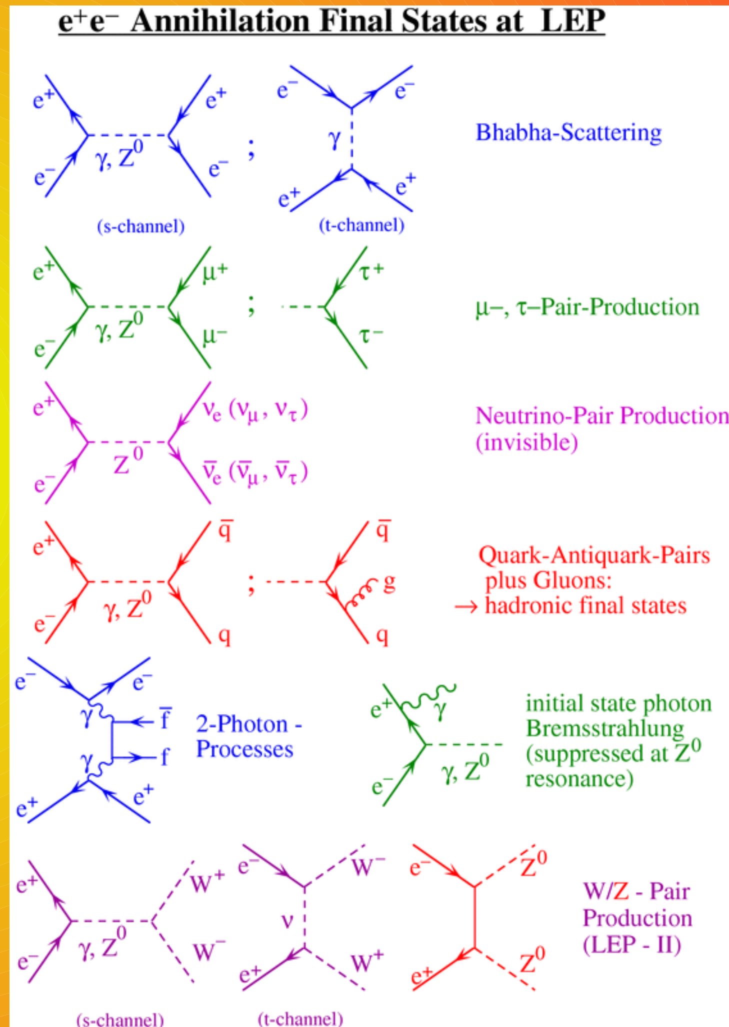


OPAL $\sqrt{s}$ = 91.2 GeV



1 Event Selection



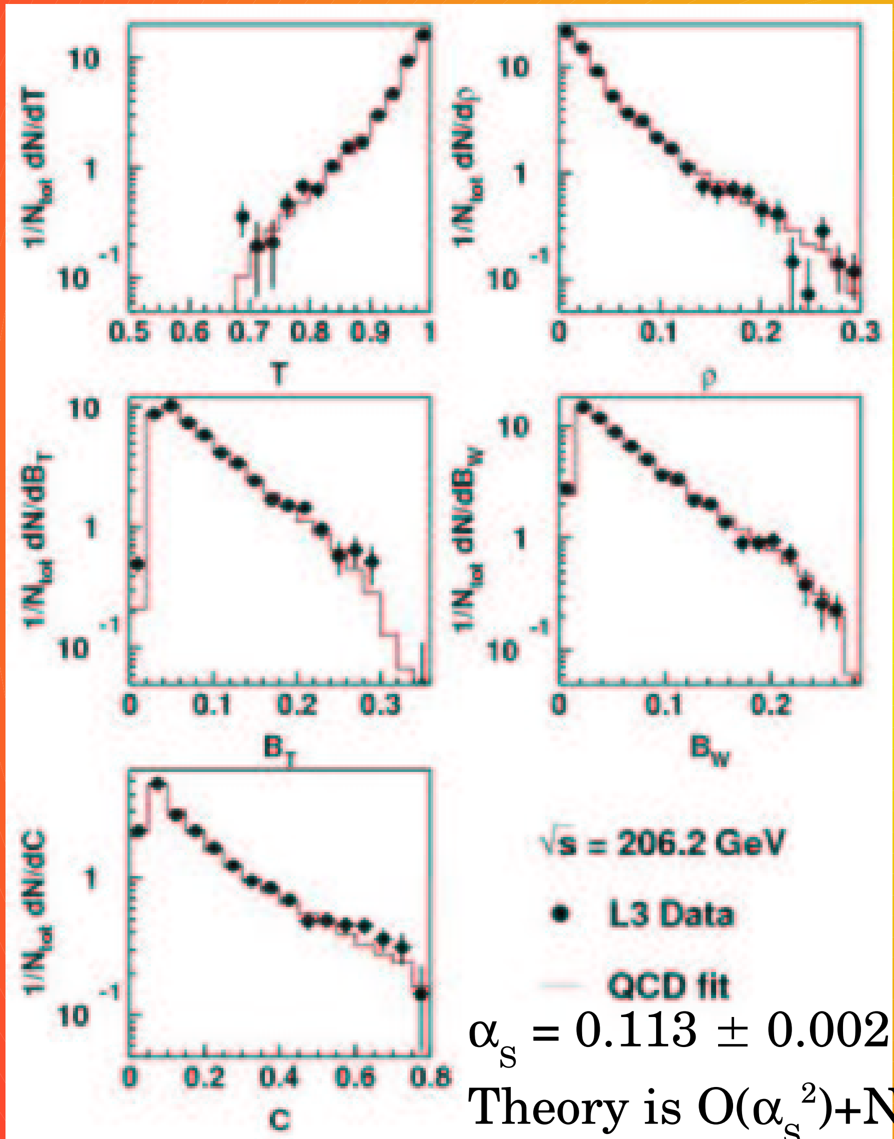


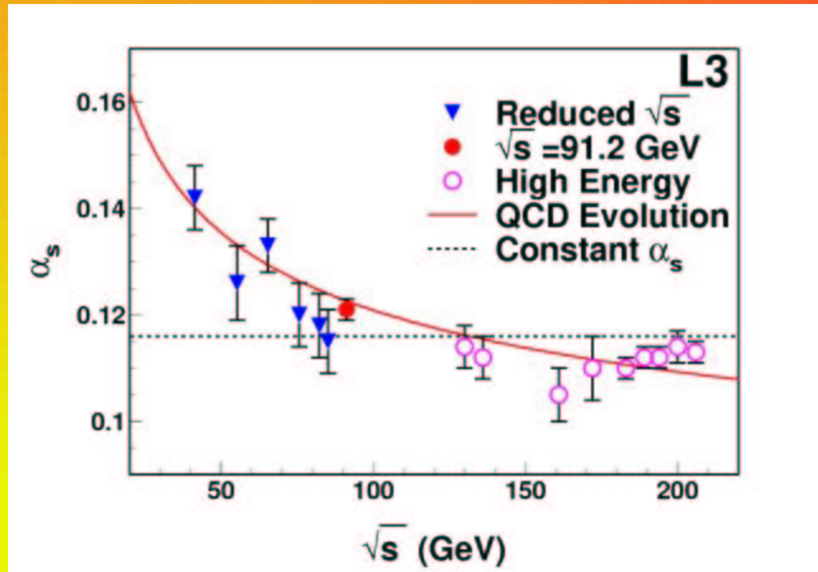
Background

τ-pairs	τ-pairs	τ-pairs
2-photon	2-photon	2-photon
ISR		ISR
		4 fermion

hep-ex/0001023

2 α_S at LEP 2: L3





$\alpha_S(M_Z) = 0.123 \pm 0.001 \pm 0.006$

χ^2/d.o.f. = 18/15 (= 52/15 α_S const)

$\alpha_S = 0.113 \pm 0.002 \pm 0.005$

Theory is $O(\alpha_S^2)$+NLLA QCD

Phys. Lett. B536 (2002) 217

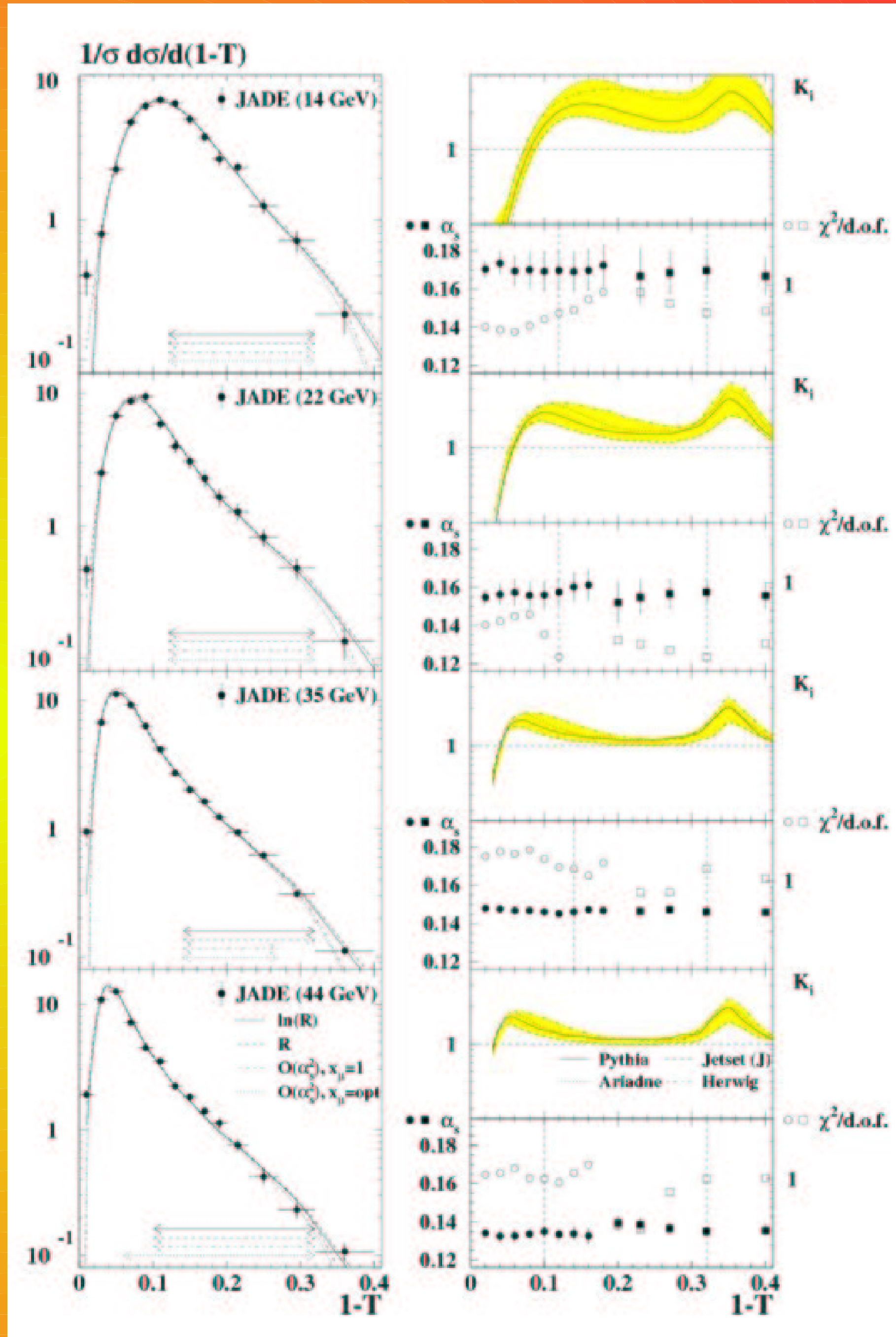
2 α_s from JADE

Re-analysis of JADE data (2002):

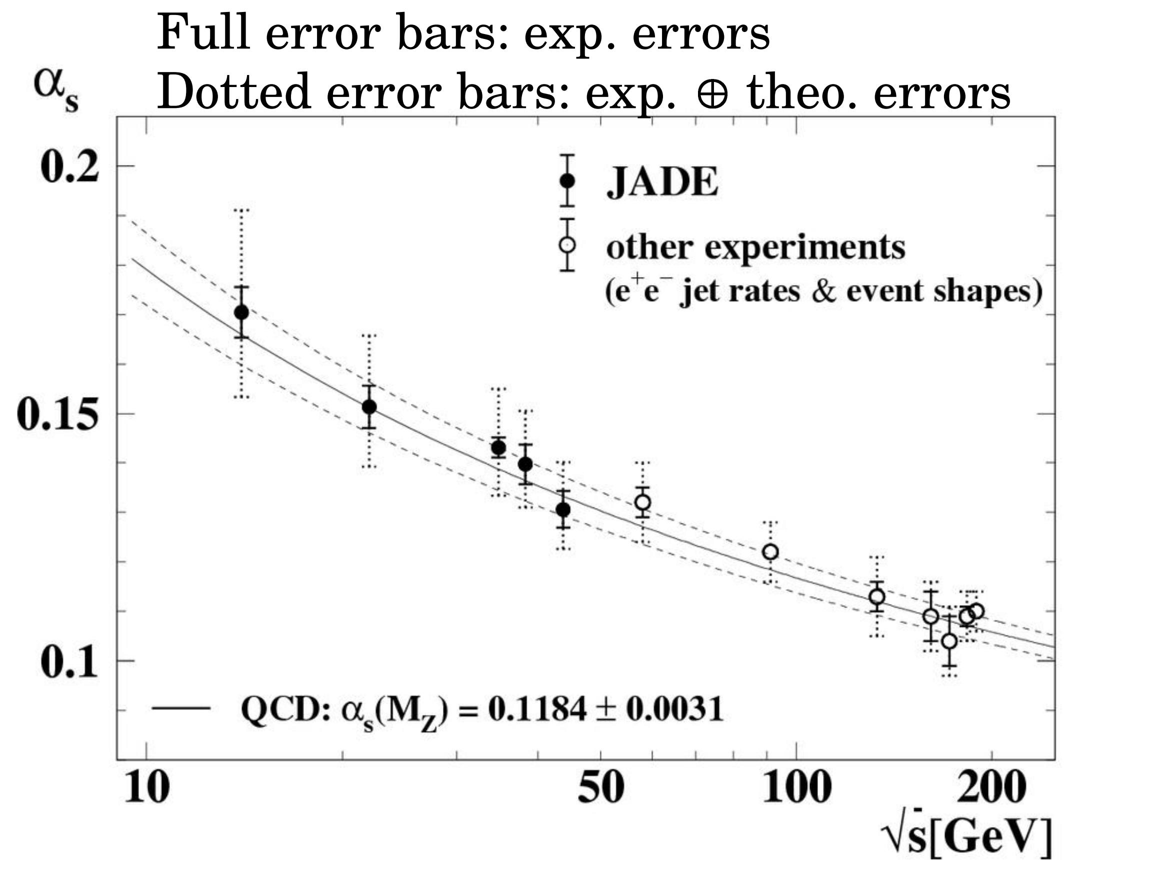
- ☺ new MC generators
- ☺ more MC statistics
- ☺ subtract b-quark events
- ☺ up-to-date QCD calculations

$\sqrt{s}$ [GeV]	$\alpha_s(\sqrt{s})$	$\Delta\alpha_s$
14	0.170	±0.019
22	0.151	±0.013
35	0.146	±0.012
44	0.131	±0.009

JADE note 144, PITHA 03/01



2 Running of α_S



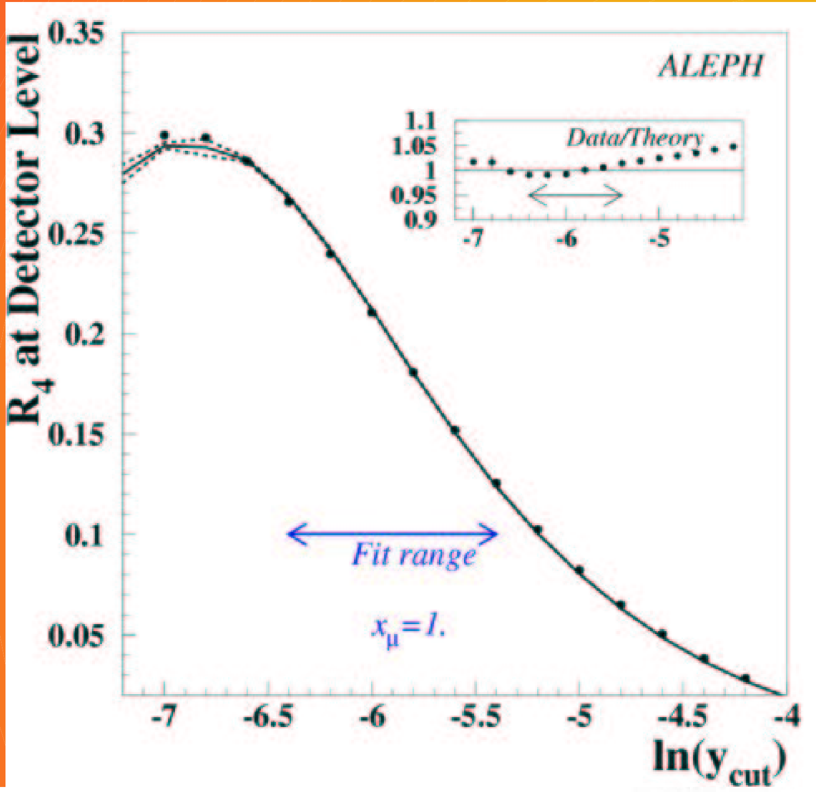
Use data from 14 to 189 GeV, exp. errors only:

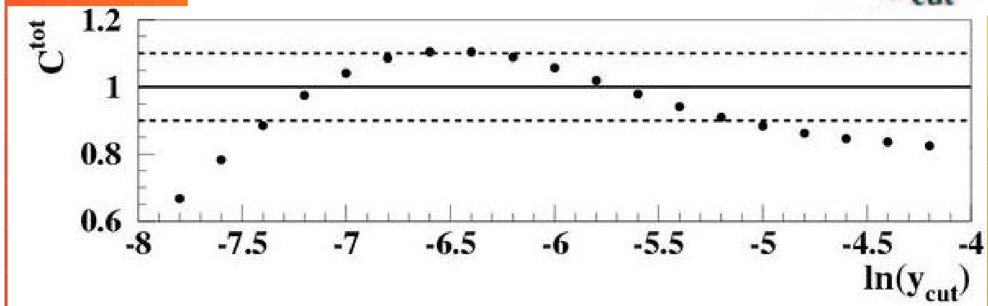
$P(\chi^2)$ of QCD fit = 75 %

$P(\chi^2)$ of α_S=const ~10^{-5}

JADE note 144, PITHA 03/01

2 α_S from 4-jet events





Use $2.5 \cdot 10^6$ Z^0 decays, Durham jet algorithm and $O(\alpha_S{}^3)$+NLLA (R-match) theory

Total corrections < 10%, some cancellation of det. and had. Corr.

Result (fixed RS $x_\mu=1$):

$\alpha_S(M_Z) = 0.1170 \pm 0.0022$

(DELPHI NLO (prelim):
$\alpha_S(M_Z) = 0.1178 \pm 0.0029$, $x_\mu{}^2=0.015$)

Eur. Phys. J. C27 (2003) 1,
DELPHI 2001-059 CONF 487

2 Running b quark mass

$$m_b(Q^2) \approx M_b \cdot \left(\alpha_S(Q^2) \frac{1}{\pi} \right)^{12/23}$$

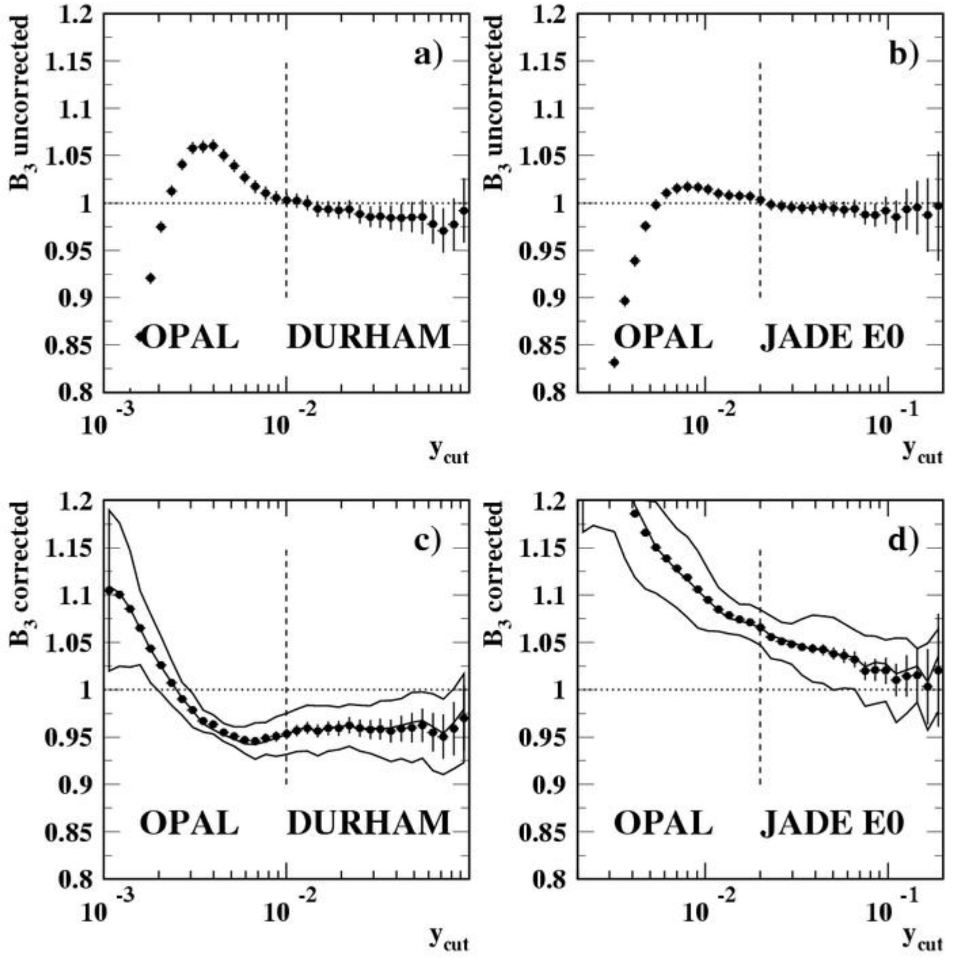
(known in NNLO)

Expect $m_b(M_Z) \sim 3$ GeV

Study e.g. Ratio of 3-jet rates $R_3(M_Z)$:

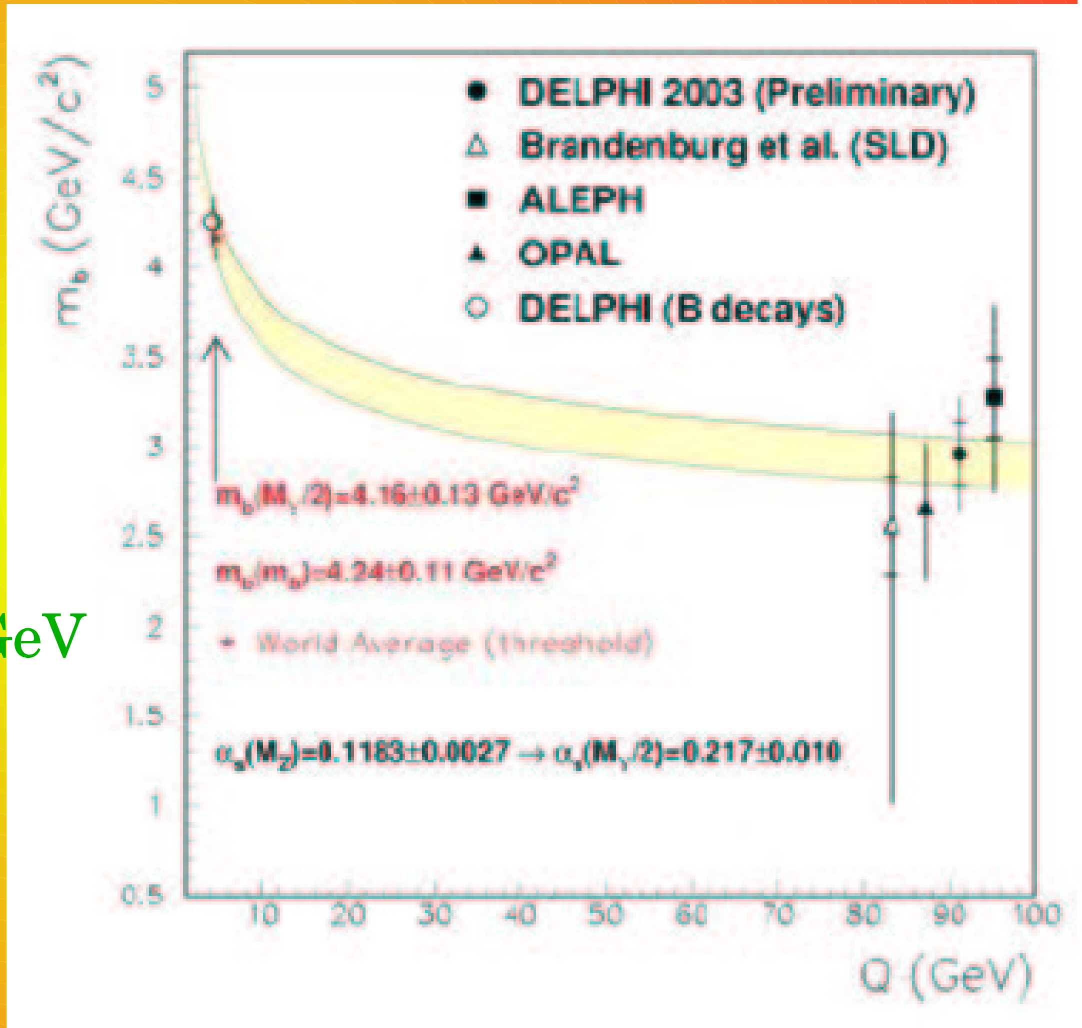
$$B_3(M_Z) = \frac{R_3^b(M_Z)}{R_3^{udsc}(M_Z)}$$

Eur. Phys. J. C 21 (2001) 411-422



2 Running b quark mass

	$m_b(M_Z)$ [GeV]
ALEPH	3.27 ± 0.52
DELPHI*	2.96 ± 0.32
OPAL	2.67 ± 0.38
SLD	2.56 ± 1.04
my average*	2.89 ± 0.26



$m_b(m_b)-m_b(M_Z) = 1.35 \pm 0.28$ GeV

with $m_b(m_b)=4.24\pm0.11$

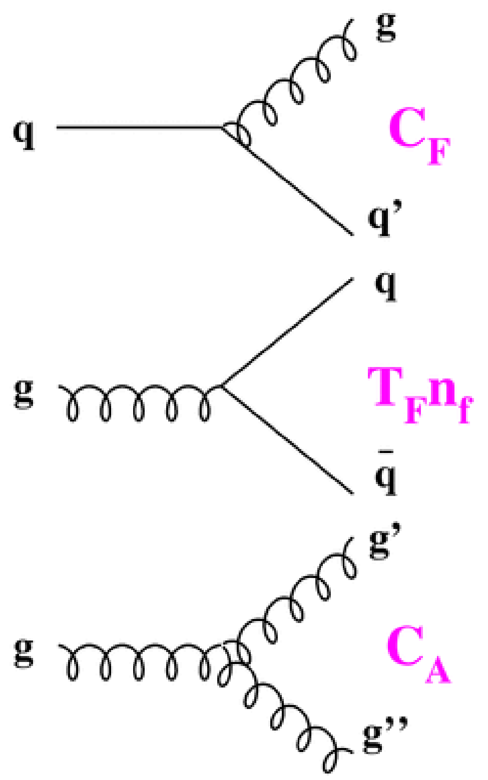
➡ non-zero by 4.8 s.d.

* preliminary

Eur. Phys. J. C18 (2000) 1,
DELPHI 2003-024 CONF 644,
Eur. Phys. J. C21 (2001) 411,
Phys. Lett. B468 (1999) 168

3 QCD Gauge Structure

Experimental tests of the QCD gauge symmetry



QCD has 3 vertices in $O(\alpha_S^2)$

➣ Decomposition of cross sections

$$A(y) \sim C_F$$

$$B(y) = C_F B_{C_F} + C_A B_{C_A} + T_F n_f B_{n_f}$$

$$C(y) = C_F^2 C_1 + C_A^2 C_2 + T_F n_f^2 C_3 + C_F C_A C_4 + C_F T_F n_f C_5 + C_A T_F n_f C_6$$

NLLA = NLLA(C_F,C_A,n_f)

$C_F = 4/3$, $C_A = 3$, $T_F \cdot n_f = 1/2 \cdot 5$ in SU(3) QCD

3 4-jet Events

At LO (α_S^2) 2-fermion+2-boson and 4-fermion 4-jet final states

Gluon decay sensitive to C_A and $T_f n_f$

Select hadronic Z decays to 4-jet final states

Construct angular correlations from

energy-ordered 3-momenta p_i of the four jets:

$$\chi_{BZ} = \sphericalangle(p_1 \times p_2, p_3 \times p_4)$$

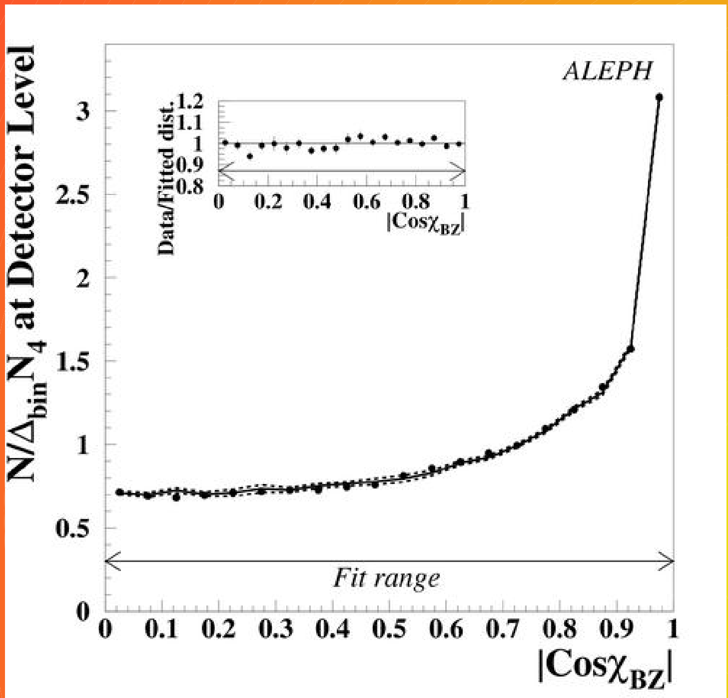
$$\Phi_{KSW} = 1/2(\sphericalangle(p_1 \times p_4, p_2 \times p_3) + \sphericalangle(p_1 \times p_3, p_3 \times p_4))$$

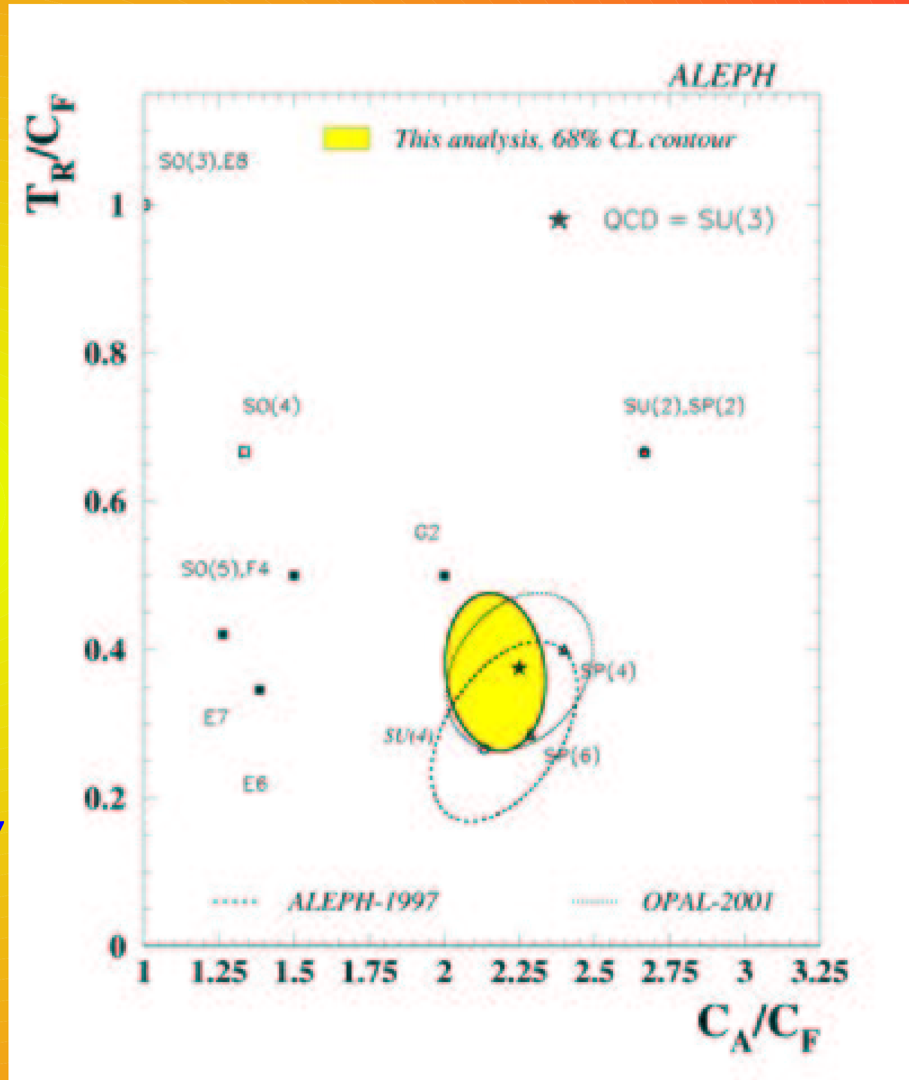
$$\theta_{NR} = \sphericalangle(p_1 - p_2, p_3 - p_4)$$

$$\alpha_{34} = \sphericalangle(p_3, p_4)$$

NLO (α_S^3) corrections available (MENLO PARC, DEBRECEN)

3 4-jet Events

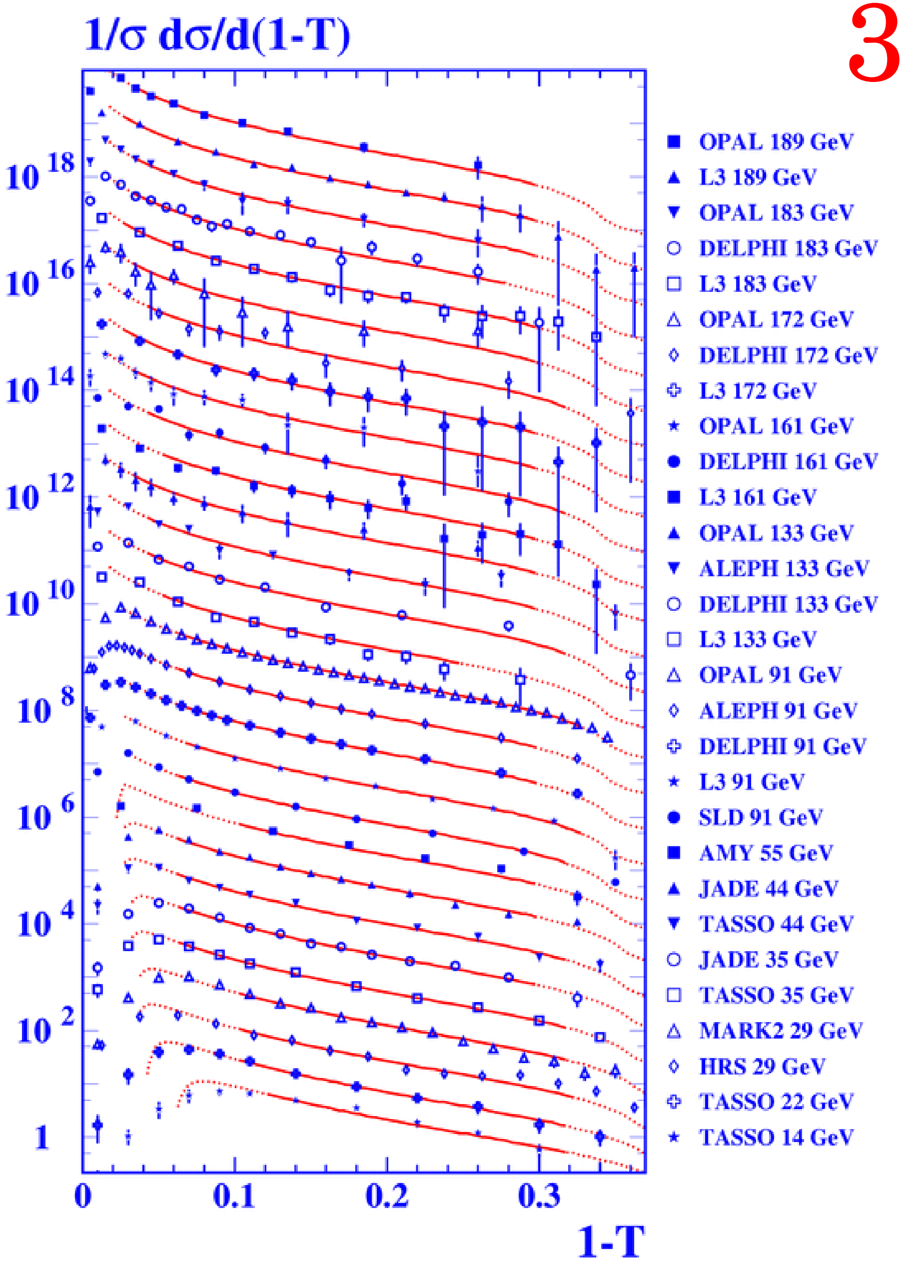




	OPAL	ALEPH
$\alpha_S(M_Z)$	0.120 ± 0.023	0.119 ± 0.027
C_A	3.02 ± 0.55	2.93 ± 0.60
C_F	1.34 ± 0.26	1.35 ± 0.27

Eur. Phys. J. C27 (2003) 1, Eur. Phys. J. C20 (2001) 601

3 Event Shape Fits



Event shapes 14 to 189 GeV

NLO+NLLA QCD (ln(R)-matching)

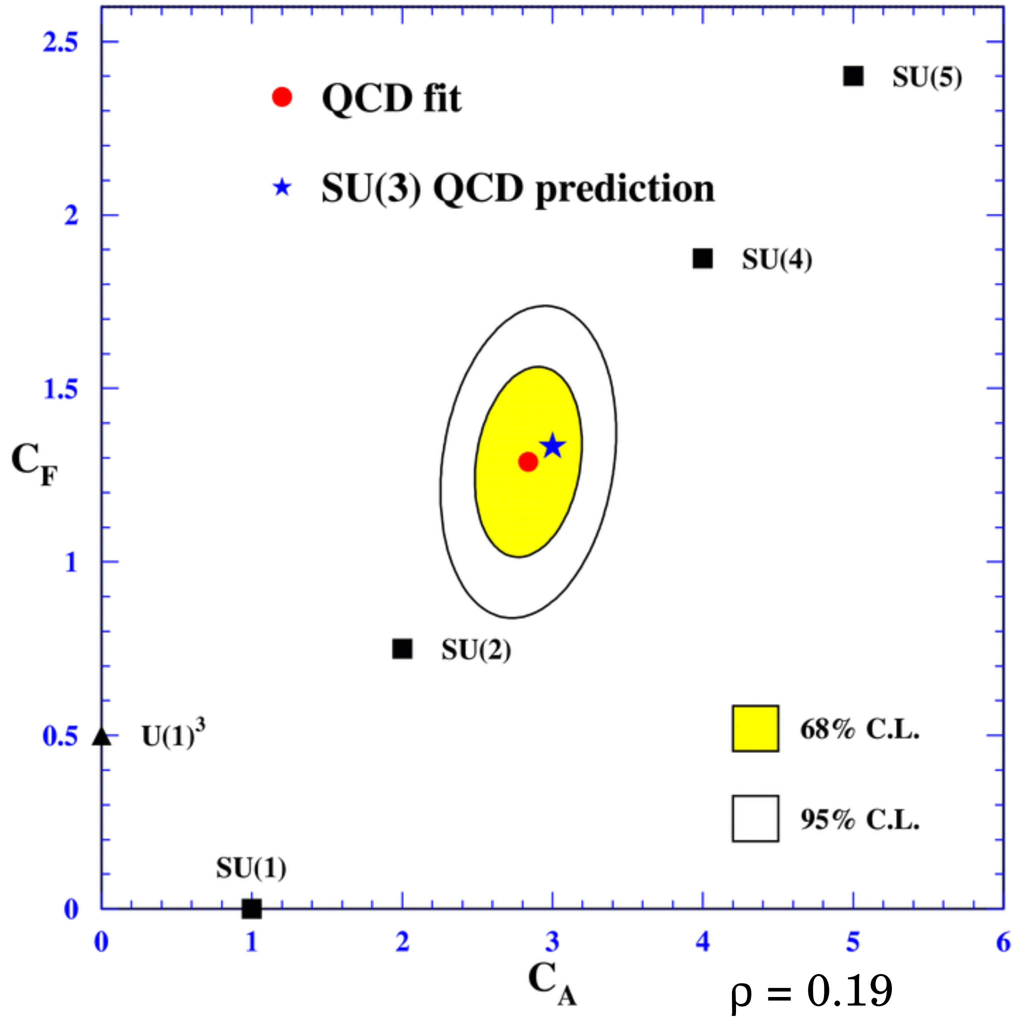
power corrections for had. effects, with explicit colour factors

Sim. fits of α_S, C_A and C_F, α_0 fixed:

➣ stable with 1-T and C

Eur. Phys. J. C21 (2001) 199

3 Event Shape Fits



ρ = 0.19

$C_A = 2.84 \pm 0.24$

$C_F = 1.29 \pm 0.18$

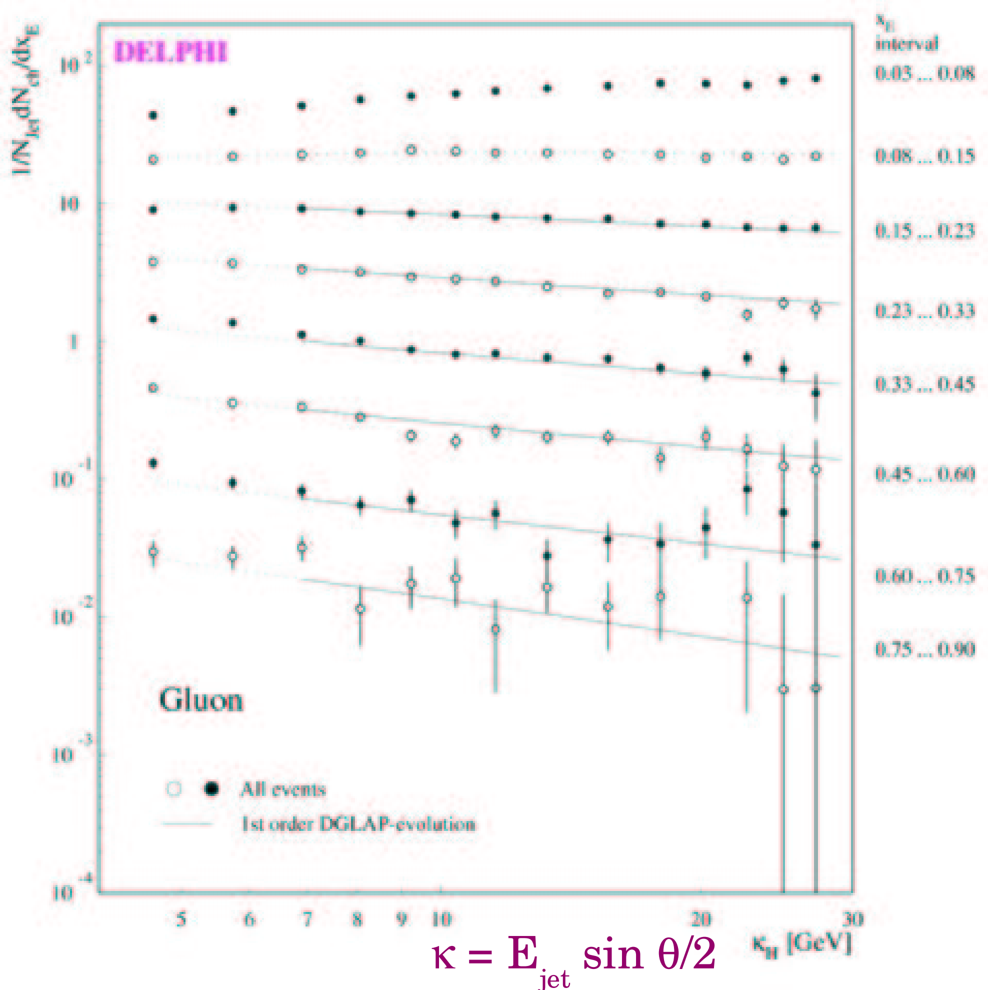
$\alpha_S(M_Z) = 0.119 \pm 0.010$

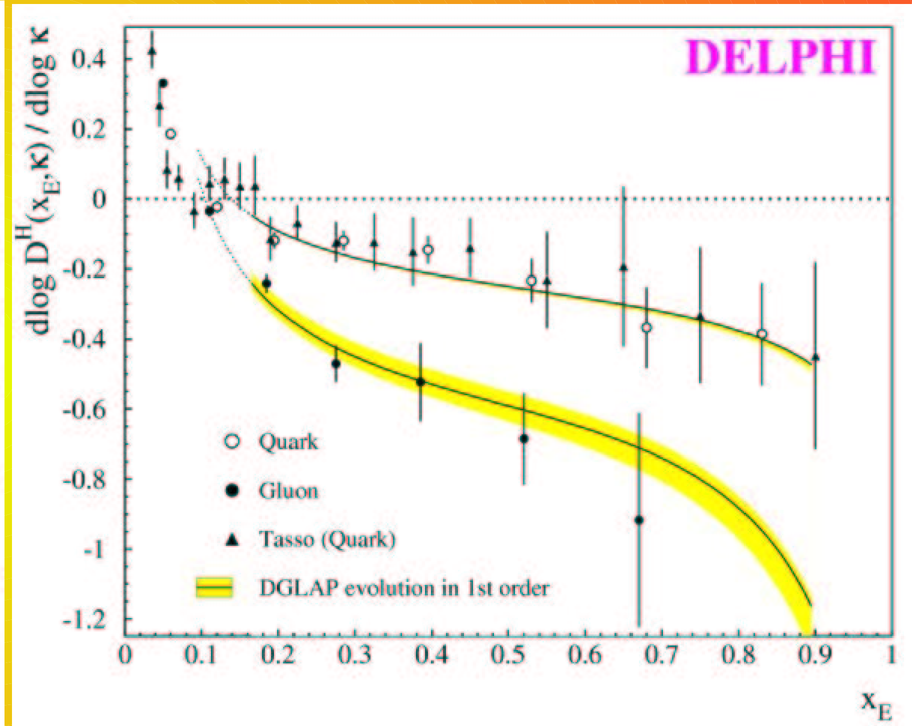
Results consistent with 4-jets, errors compareable or smaller

Eur. Phys. J. C 21 (2001) 199-210

3 Gluon vs Quark Jets

Ratio of scaling violation of FFs in gluon and quark jets
Exclusive jets in Z decays with b-quark-jet tagging





$C_A = 3.01 \pm 0.22$

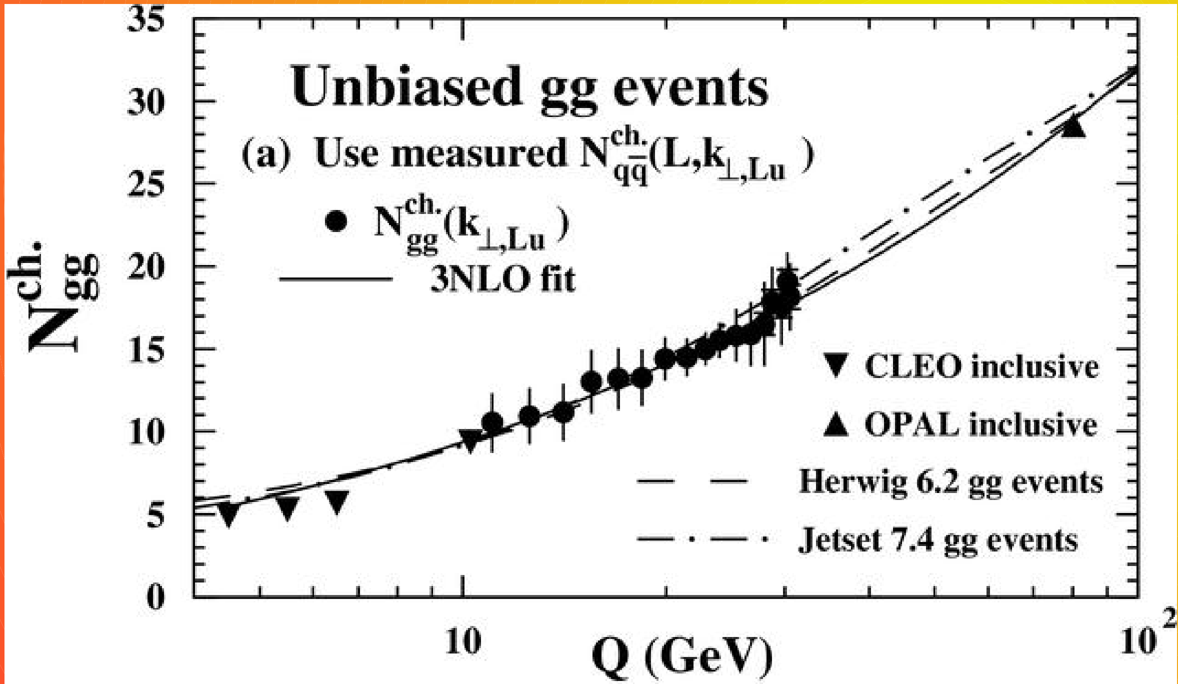
Eur. Phys. J. C13 (2000) 573

3 Gluon vs Quark Jets

$<n_{ch}>$ evolution from unbiased gluon jets

Study $<n_{ch}>$ as function of 3-jet resolution scale $k_\perp$ with DURHAM

Extract unbiased $<n_{ch}>_{gg}$ using $<n_{ch}>_{qq}$ and MLLA QCD

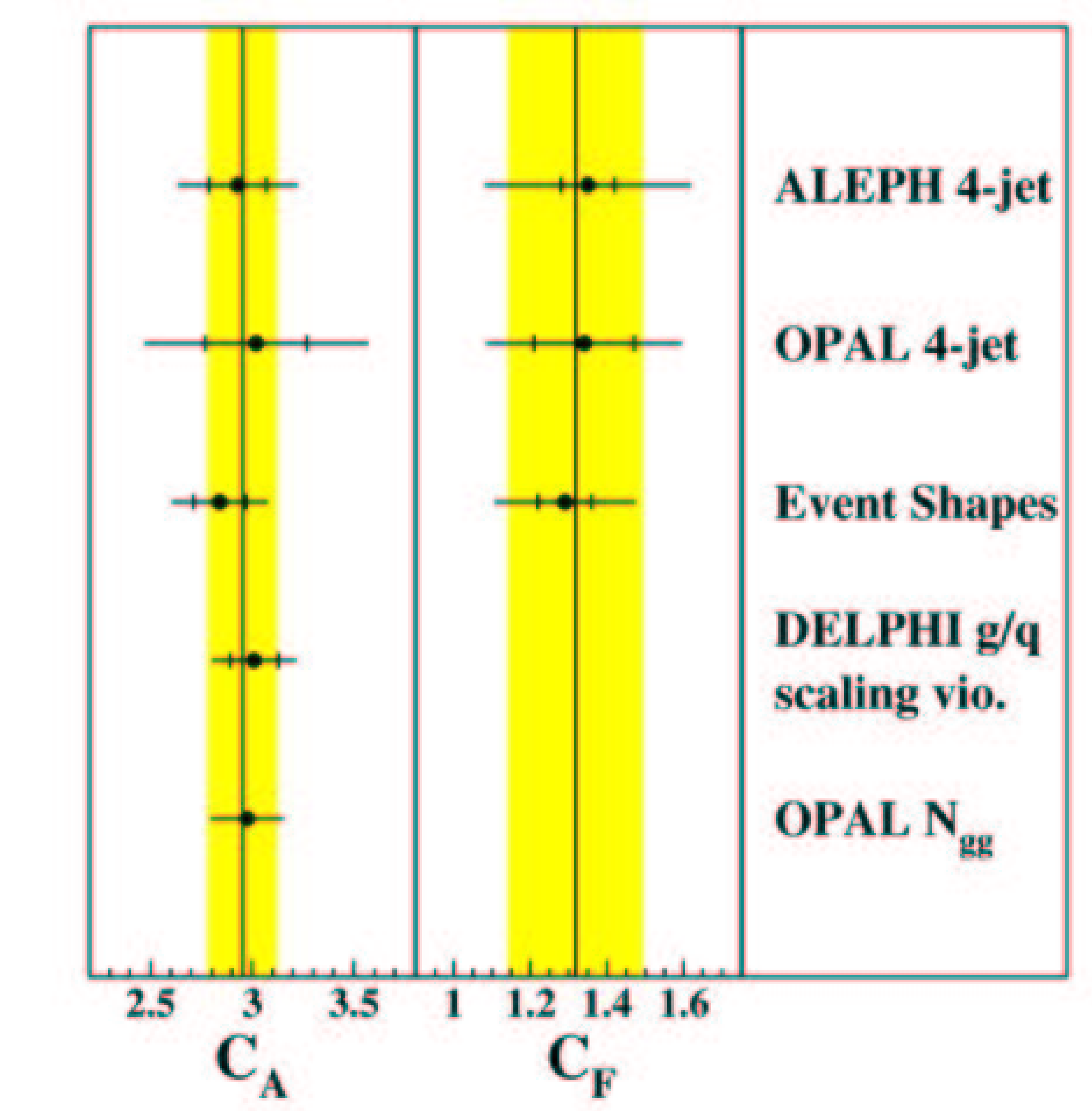


$C_A = 2.98 \pm 0.18$

$k_{\perp,Lu} = \ln(s_{qg} s_{qg}/(s\Lambda^2))$

Eur. Phys. J. C23 (2003) 597

3 QCD Colour Factors



My averages*:

$C_A = 2.95 \pm 0.01 \pm 0.17$

$C_F = 1.32 \pm 0.05 \pm 0.17$

QCD: $C_A = 3$, $C_F = 4/3$

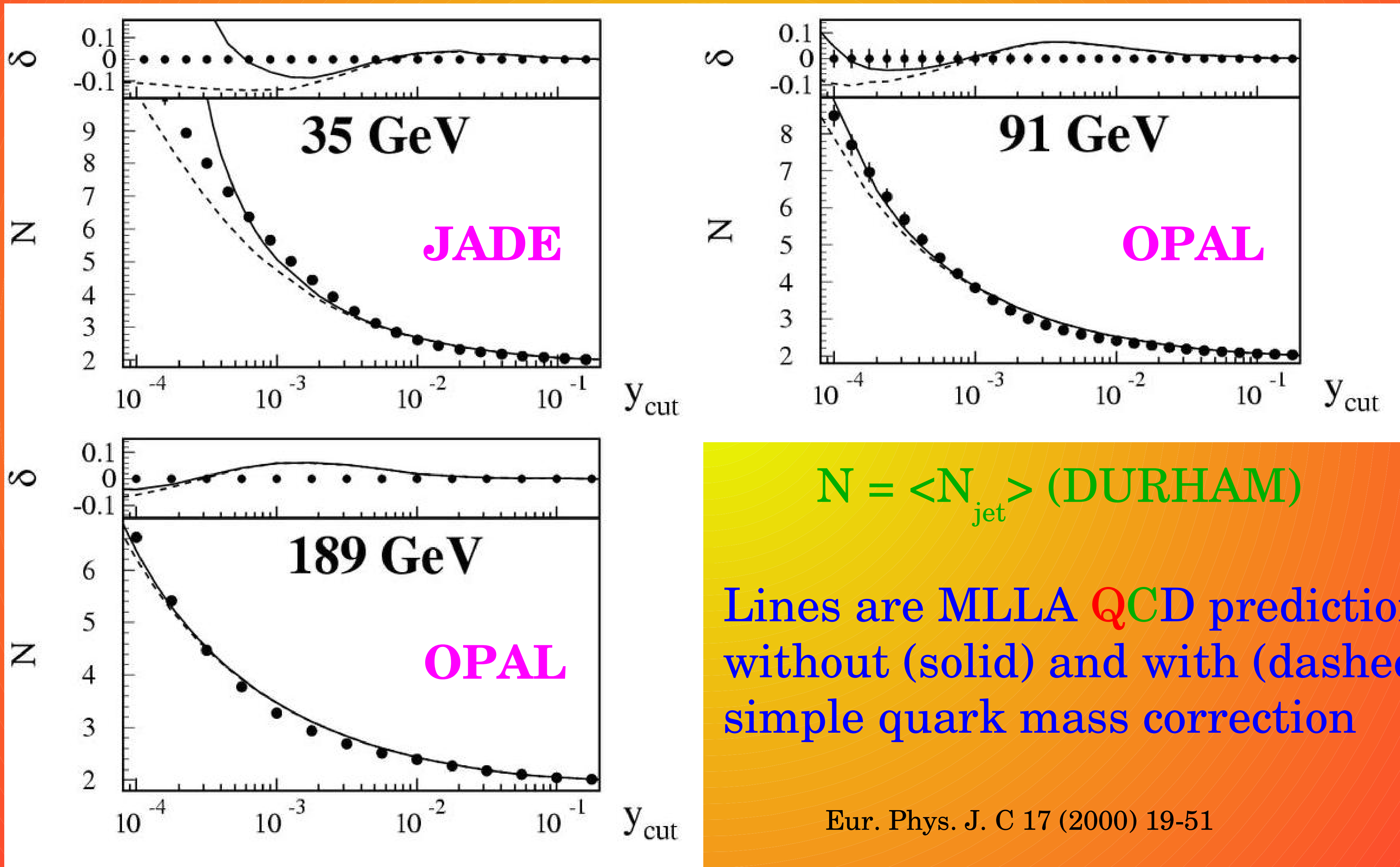
Good agreement, understand gauge structure at ~10% level

* preliminary

Summary

- Jet Physics from $\sqrt{s}$ = 14 to 207 GeV
  - Precision measurements of α_S
  - Study running of α_S
  - Measure running m_b
- Gauge structure of QCD from jets
  - 4-jet angular correlations, event shapes, gluon FF s.v., $\langle n_{ch} \rangle_{gg}$
  - Can measure C_A and C_F to about 10%
- QCD for jets in very good shape!

2 Soft QCD Tests: LPHD



N = <N_{jet}> (DURHAM)

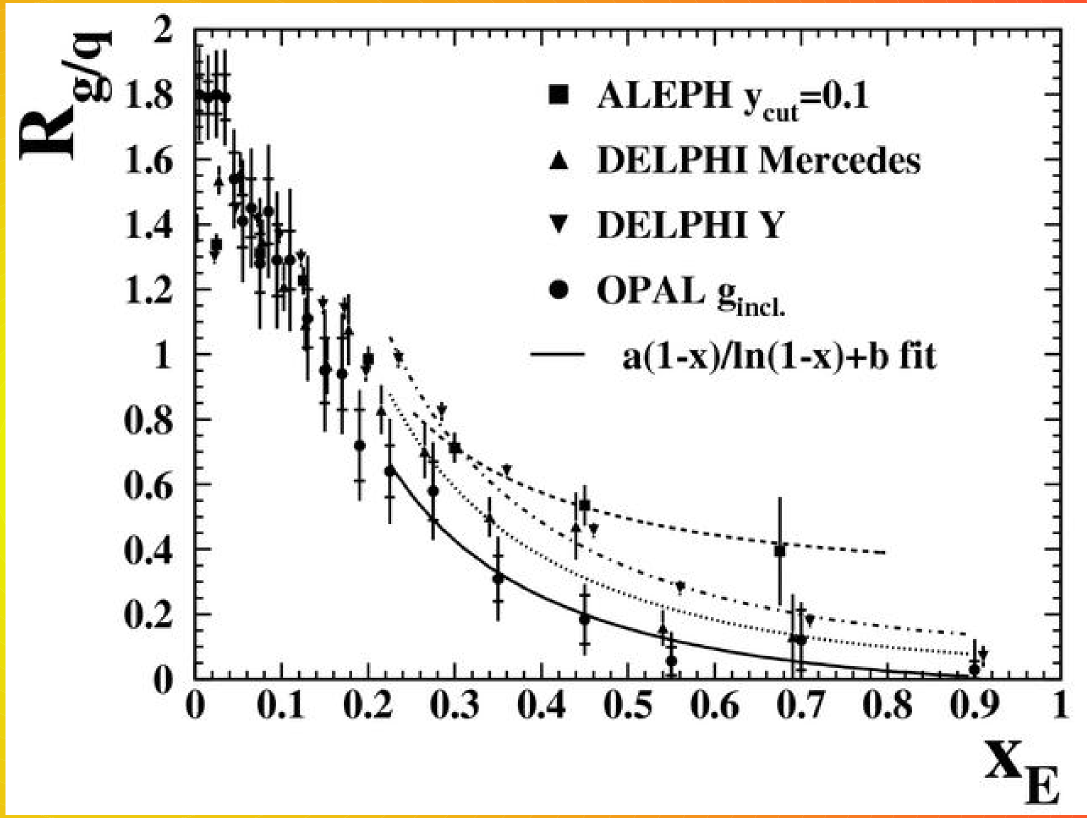
Lines are MLLA QCD prediction without (solid) and with (dashed) simple quark mass correction

Eur. Phys. J. C 17 (2000) 19-51

2 Quark vs Gluon Jets: x_E

LLA QCD prediction ('78):

$R_{g/q} \sim (1-x)/\ln(1-x)$ for $x \approx 1$



Never tested so far.
Can now compare with data,
use total errors, $x_E > 0.2$:

	χ^2/dof
ALEPH	0.03/1
DELPHI M	4.3/4
DELPHI Y	25/5
OPAL g_{incl}	1.3/5

Strong g/q effect in x_E spectra

LLA QCD consistent with data
Better (NLLA) prediction?