Tests of QCD at e^+e^- colliders

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Outline

Part 2

(I) Measurement of the color factors

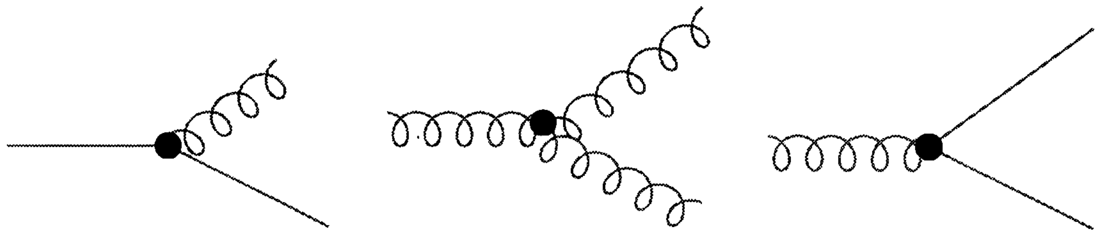
(II) Differences between gluon & quark jets

(III) Coherence and Local Parton Hadron Duality (LPHD)

(IV) Identified particles

Measurement of the color factors

Effective interactions in e$^+$e$^-$ annihilations to $\mathcal{O}(\alpha_S^2)$



Gluon radiation	Triple gluon vertex	Gluon splitting
$q \rightarrow qg$	$g \rightarrow gg$	$g \rightarrow q\bar{q}$
$\boxed{\mathrm{C_F}=\frac{4}{3}}$	$\boxed{\mathrm{C_A}=3}$	$\boxed{\mathrm{T_F}=\frac{1}{2}}$

The "color factors" $\mathrm{C_F}$, $\mathrm{C_A}$, $\mathrm{T_F}$ specify the relative probabilities of the three processes.

$t^{\mathrm{A}}(A{=}1,\cdots 8)$ $\longrightarrow$ <u>generators</u> of SU(3)
(= $\frac{1}{2}$ the 3×3 Gell-Mann matrices)

f^{ABC} $\longrightarrow$ <u>structure constants</u> of SU(3)
$\longrightarrow$ $[t^{\mathrm{A}},t^{\mathrm{B}}] = i f^{\mathrm{ABC}} t^{\mathrm{C}}$

$$\sum_{\mathrm{A}=1,8}\sum_{\mathrm{b}=1,3} t^{\mathrm{A}}_{ab} t^{\mathrm{A}}_{bc} = \delta_{ac}\underline{\mathrm{C_F}} \qquad \sum_{\mathrm{A,B}=1,8} f^{\mathrm{ABC}} f^{\mathrm{ABD}} = \delta^{ac}\underline{\mathrm{C_A}}$$

$$\mathrm{Tr}\left(\mathrm{t}^{\mathrm{A}}_{\mathrm{ab}}\mathrm{t}^{\mathrm{B}}_{\mathrm{ba}}\right) = \delta^{\mathrm{AB}}\underline{\mathrm{T_F}}$$

Ratios C_A/C_F, T_F/C_F

$\longrightarrow$ Can be determined with greater precision than individual color factors C_A, C_F or T_F

$\longrightarrow$ Sufficient to distinguish between gauge groups

Models with 3 color degrees of freedom for quarks:

	SU(3) (QCD)	SO(3)	$U(1)_3$ (Abelian gluon)
C_A/C_F	$\frac{9}{4}$	1	0
T_F/C_F	$\frac{3}{8}$	1	3

Techniques to measure the color factor ratios $\longrightarrow$

- Angular correlations in 4-jet events
- Angular correlations in 5-jet events (not discussed here)
- Event shapes (2- and 3-jet events, α_S)
- Differences between gluon and quark jets $\rightarrow$ next section

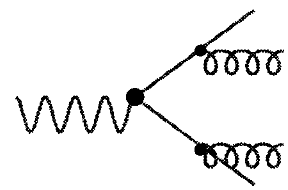
Angular correlations in 4-jet events

Expression for $e^+e^- \rightarrow 4$ jets to $\mathcal{O}(\alpha_S^2)$ (tree level)

[ERT: R.K. Ellis & D.A. Ross, A.E. Terrano, Nucl. Phys. B178 (1981) 421]

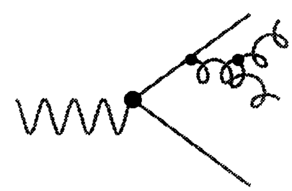
$$\frac{1}{\sigma_0}\frac{d\sigma}{dy} = \left(\frac{\alpha_S C_F}{\pi}\right)^2 \times$$

$$\sigma_A(y) \longrightarrow$$

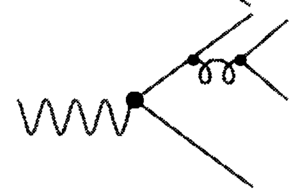


$$+ \left(1 - \frac{1}{2}\frac{C_A}{C_F}\right)\sigma_B(y)$$

$$+ \left(\frac{C_A}{C_F}\right)\sigma_C(y) \longrightarrow$$



$$+ \left(\frac{T_F}{C_F}n_f\right)\sigma_D(y) \longrightarrow$$



$$+ \left(1 - \frac{1}{2}\frac{C_A}{C_F}\right)\sigma_E(y)$$

$\sigma_A \cdots \sigma_E$ $\rightarrow$ kinematic terms, independent of the gauge group ($y \longrightarrow$ 2-jet invariant masses)

The angular correlations between the four jets differ for the three diagrams, cf. $g \rightarrow gg$ (spin 1 $\rightarrow$ 1 1) versus $g \rightarrow q\bar{q}$ (spin 1 $\rightarrow$ 1/2 1/2)

$\longrightarrow$ Allows the relative contributions of the coefficients σ_A, $(C_A/C_F)\,\sigma_C$, etc. to be distinguished experimentally, allowing a determination of the color factor ratios, with $\sigma_A \cdots \sigma_E$ taken from theory

Procedure

$\longrightarrow$ Select 4-jet events using a jet finder ($K_\perp$, JADE, etc.)

$\longrightarrow$ Order jets by energy $E_1 > E_2 > E_3 > E_4$
Jets 1,2 $\longrightarrow$ almost always quark jets

or else

(DELPHI) tag two of the jets as quark jets using b-tagging (jets 1,2= tagged jets; jets 3,4=untagged jets)

$\longrightarrow$ For simplicity, usually employ standard angular correlation variables rather than the 2-jet invariant masses y

- Bengtsson-Zerwas angle:

$$\cos\chi_{\mathrm{BZ}} = \left| \frac{(\vec{p}_1 \times \vec{p}_2)\cdot(\vec{p}_3 \times \vec{p}_4)}{|\vec{p}_1 \times \vec{p}_2|\,|\vec{p}_3 \times \vec{p}_4|} \right|$$

- (modified) Nachtmann-Reiter angle:

$$\cos\Theta_{\mathrm{NR}^*} = \left| \frac{(\vec{p}_1 - \vec{p}_2)\cdot(\vec{p}_3 - \vec{p}_4)}{|\vec{p}_1 - \vec{p}_2|\,|\vec{p}_3 - \vec{p}_4|} \right|$$

- Angle between jets 3 and 4:

$$\cos\alpha_{34} = \frac{\vec{p}_3 \cdot \vec{p}_4}{|\vec{p}_3|\,|\vec{p}_4|}$$

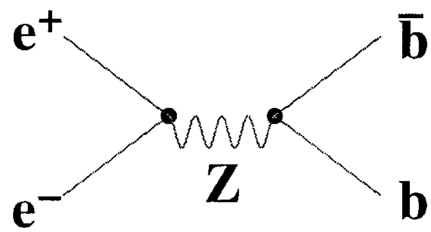
$\longrightarrow$ Account for hadronization using corrections from MC, fit to theoretical expression, using

$$\frac{\mathrm{C_A}}{\mathrm{C_F}},\ \frac{\mathrm{T_F}}{\mathrm{C_F}},\ \text{Overall normalization}$$

as the fitted parameters

B tagging of quark jets in e^+e^-

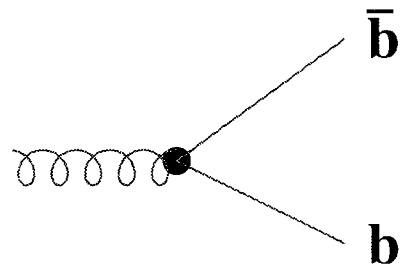
- Almost all b quarks in e^+e^- annihilations at present energies are produced at the electro-weak vertex



$$\frac{\Gamma(\mathrm{Z} \to \mathrm{b\overline{b}})}{\Gamma(\mathrm{Z} \to \ \mathrm{hadrons})} \approx 0.21$$

i.e. about 1 in 5 events is a b event

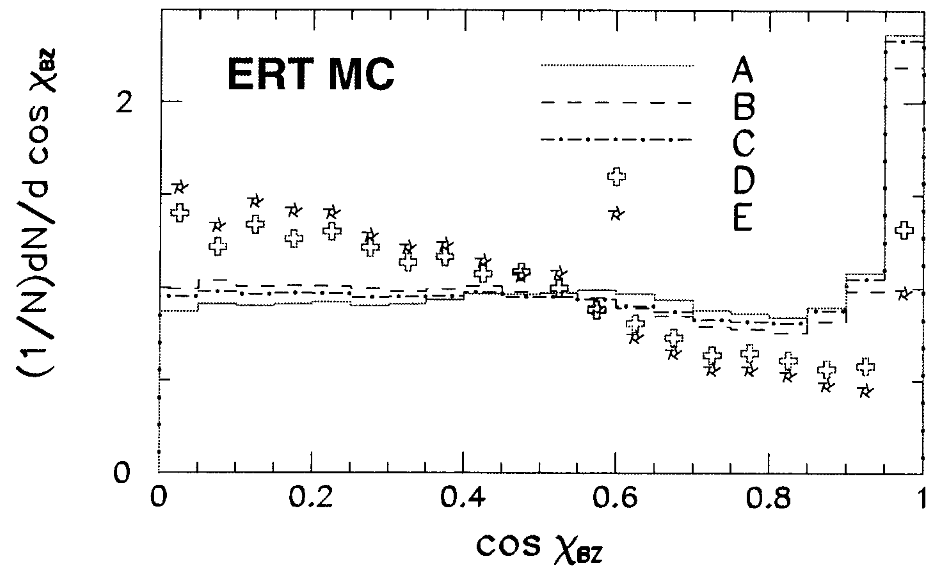
- In contrast, only about 1 in 300 $\mathrm{Z} \to \ \mathrm{hadrons}$ events contains a gluon splitting to $b\bar{b}$

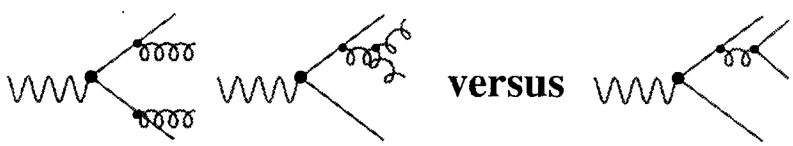


$\longrightarrow$ A jet with a b hadron is overwhelmingly likely to be a QUARK JET

- This is in contrast to hadron colliders where $g \longrightarrow b\bar{b}$ is the dominant production mechanism for b hadrons

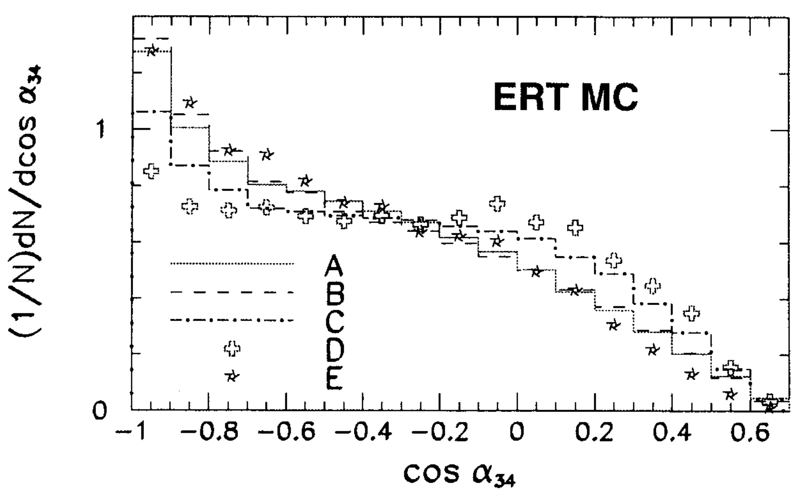
Bengtsson-Zerwas angle →

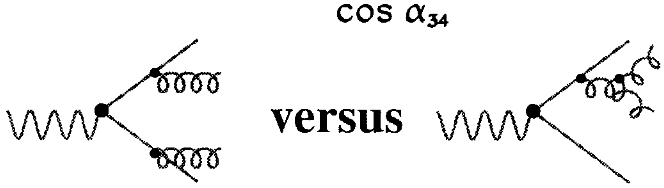




(classes A,B,C) (classes D,E)

Angle between jets 3 and 4 (DELPHI 1991) →

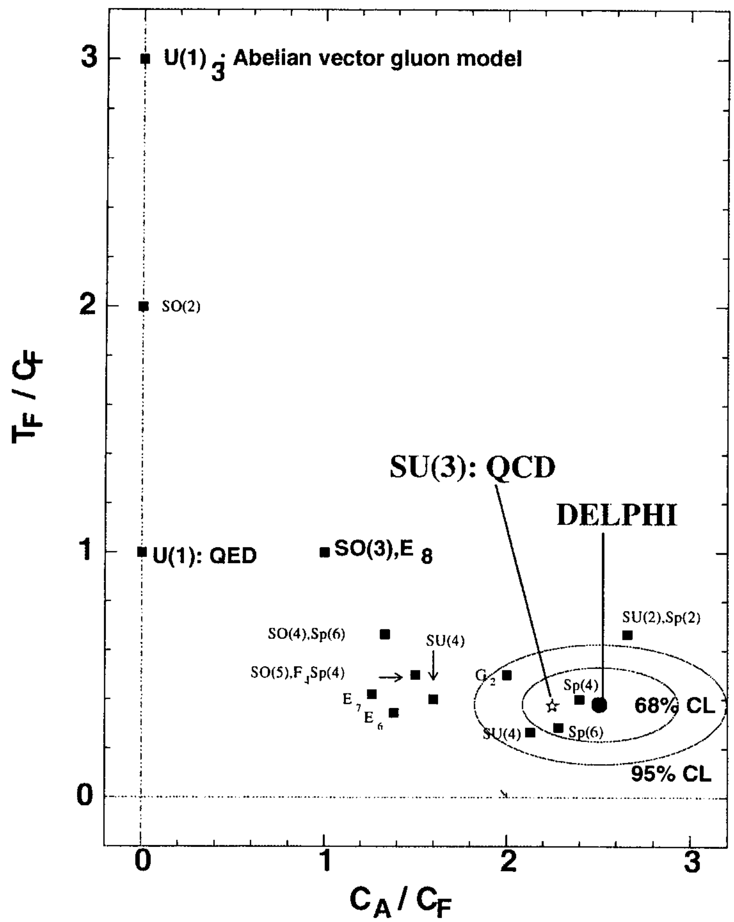




(class A) (class C)

Measured T_F/C_F versus C_A/C_F

DELPHI at LEP-1 (1997) $\longrightarrow$ (b-tagging of jets 1,2)



Of the three gauge groups with three color degrees of freedom

SU(3), SO(3), $U(1)_3$

only SU(3) is consistent with the data

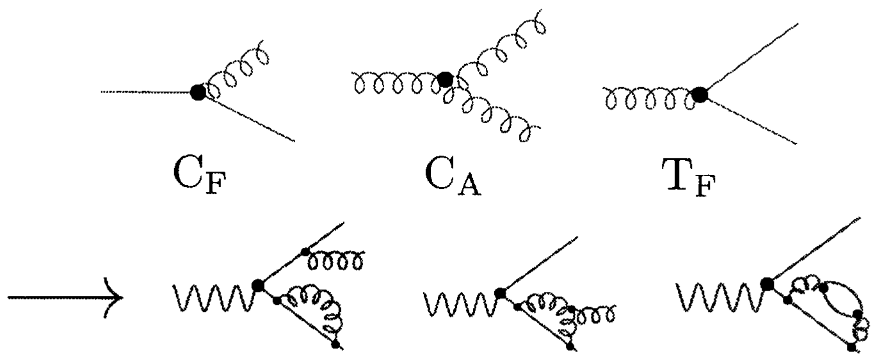
$$SU(3) \longrightarrow C_A/C_F = 2.25,\ T_F/C_F = 0.375$$

Three color degrees of freedom required by

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}, \text{ etc.}$$

Color factors from 2- and 3-jet events (event shapes: Thrust, etc.)

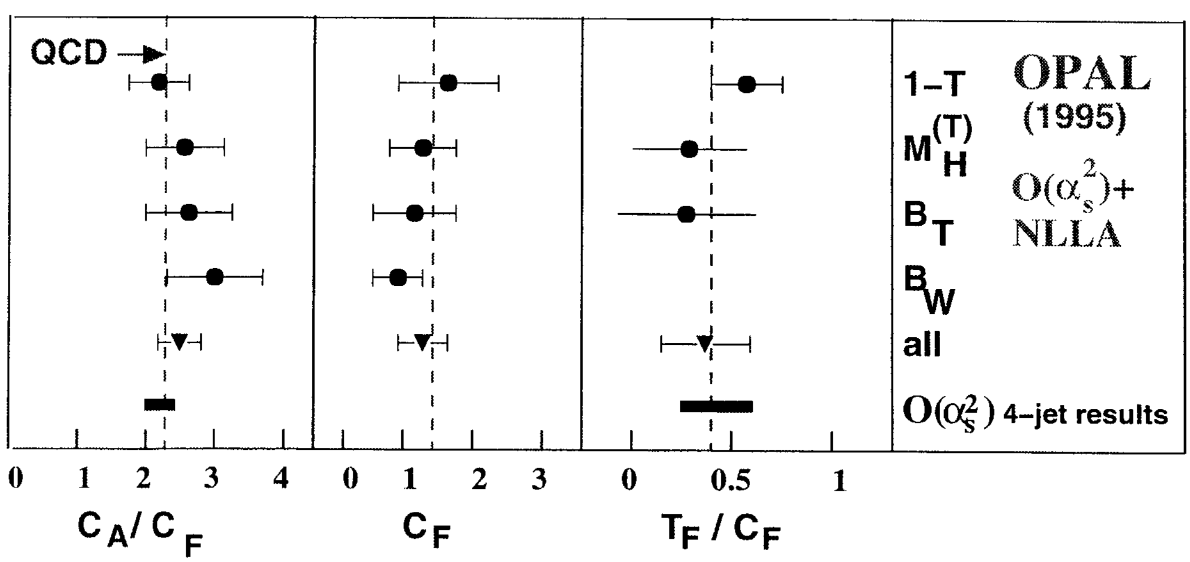
→ Virtual corrections to the $\geq \mathcal{O}(\alpha_S^2)$ 2- and 3-jet cross sections contain the same QCD vertices as the tree level 4-jet cross section:



→ The $\mathcal{O}(\alpha_S^2)$+NLLA expressions for experimental observables like thrust can be decomposed into terms

$$\sim\ C_F^2,\quad C_A C_F,\quad T_F C_F$$

→ Extract measurements of the color factors using theory valid beyond leading order (complementary to the 4-jet results)



ALEPH at LEP-1 (1997)

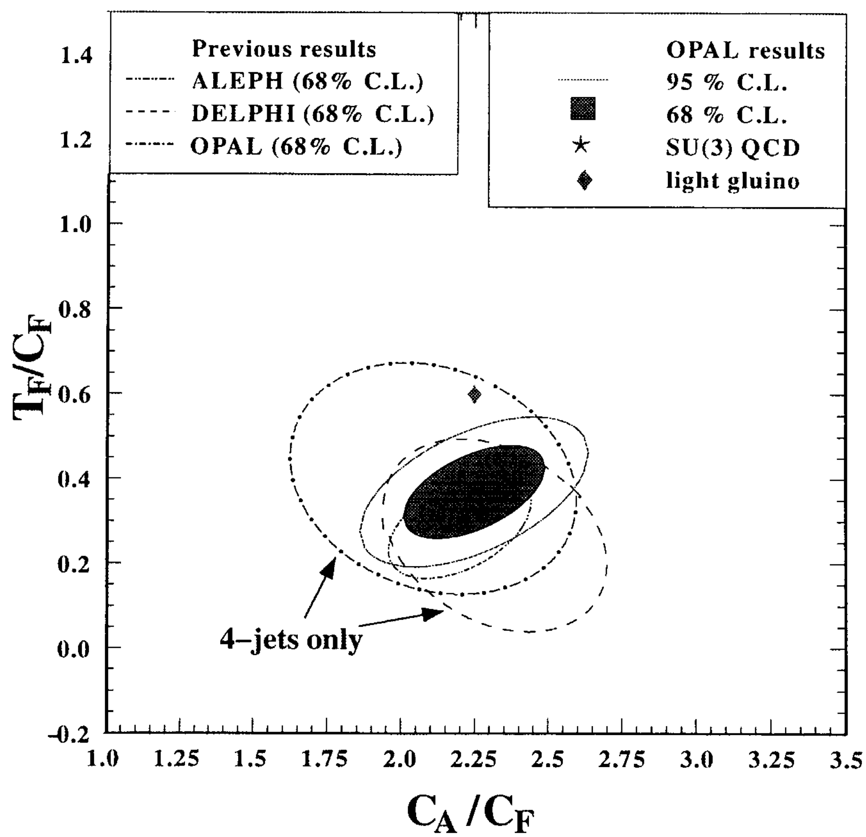
⟶ Fit color factor ratios simultaneously using 4-jet angular correlations AND event shapes

⟶ As the event shape, use the 2- to 3-jet transition variable D_2 (aka y_{23} or y_3) from the $k_\perp$ jet finder

OPAL at LEP-1 (2000)

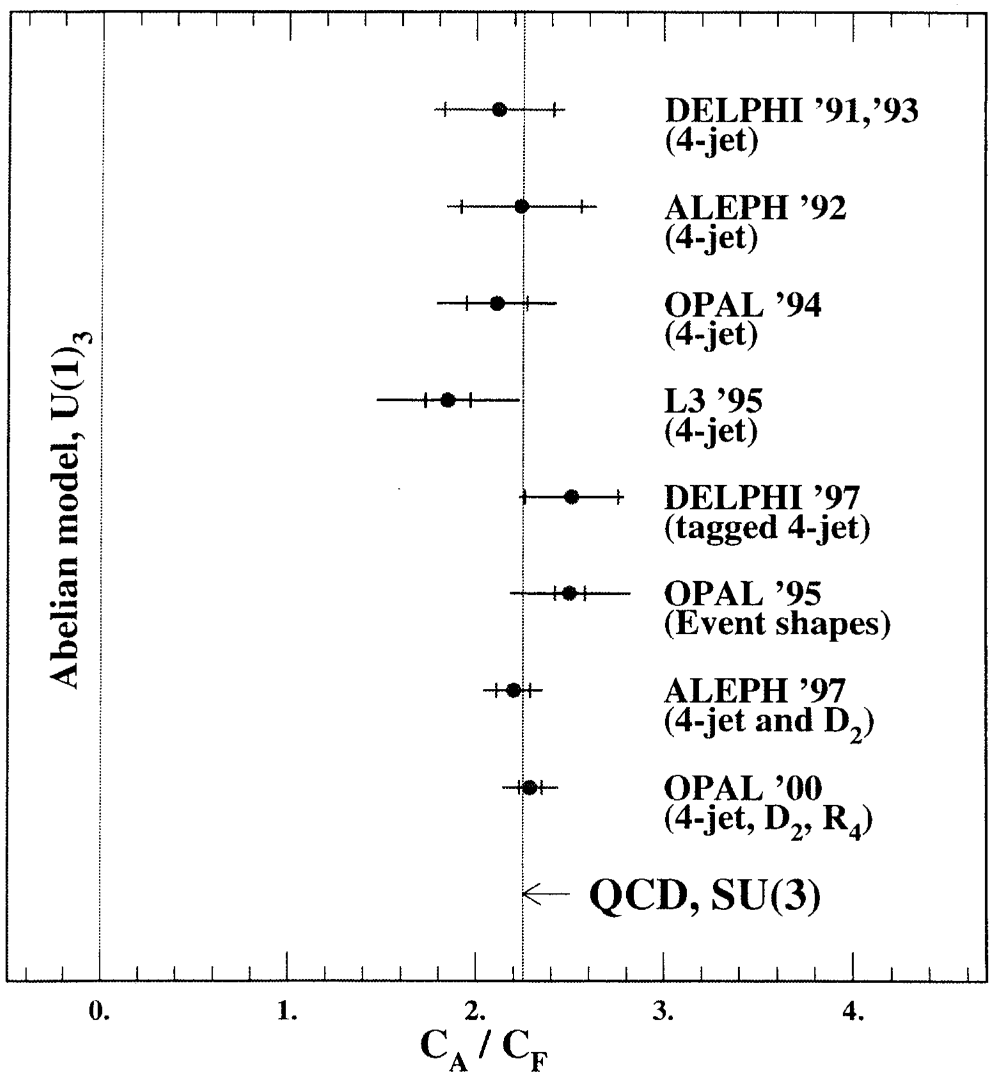
⟶ Same as ALEPH, and, in addition

- Include the 4-jet rate versus y_{cut}, defined with $k_\perp$
- Employ NLO calculations ($\mathcal{O}(\alpha_S^3)$) for the 4-jet angular correlations (1998)



⟶ Substantial reduction in the uncertainties compared to the earlier studies based on 4-jet angular correlations alone

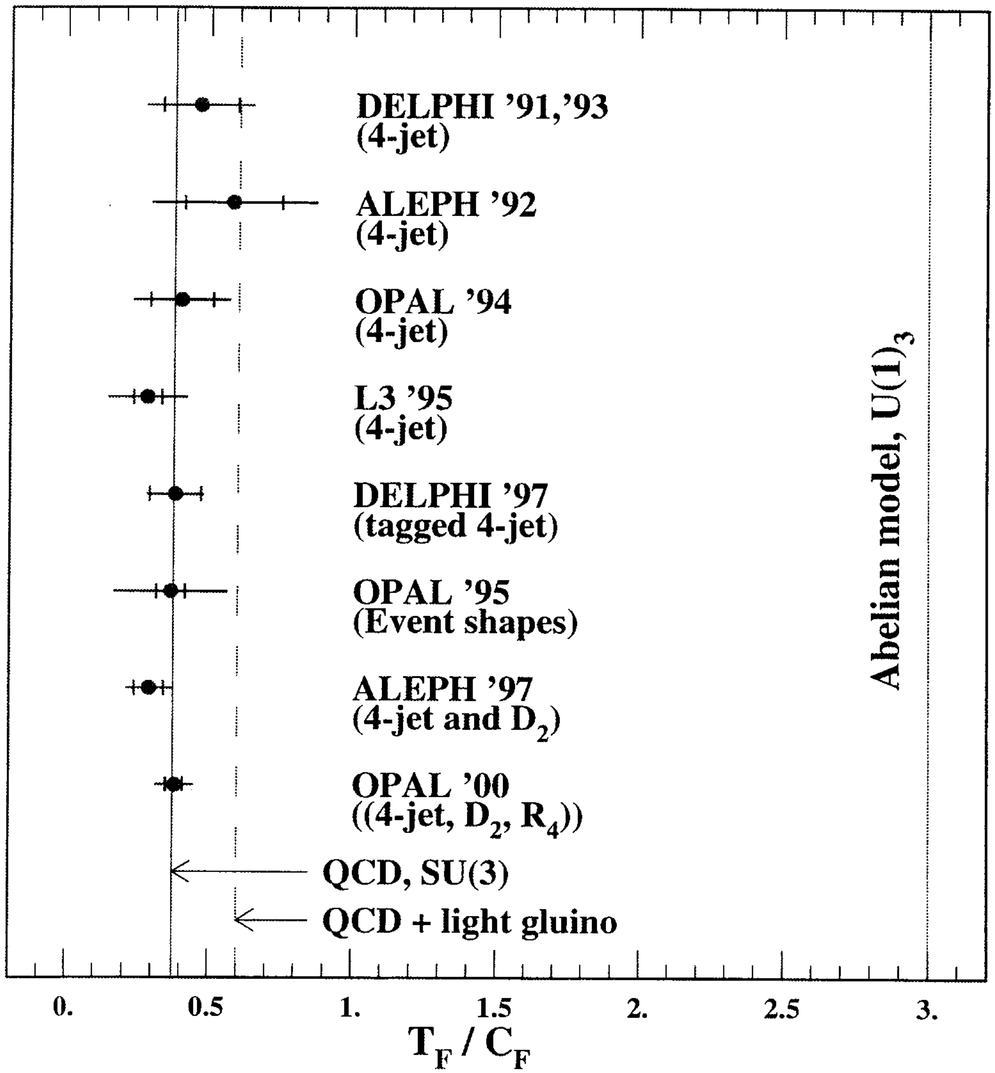
Color factor ratio C_A/C_F from event shapes & 4-jet angular correlations



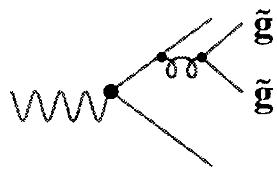
→ Excellent agreement with the QCD value of 2.25

→ Abelian model (no triple gluon vertex) excluded by 15 standard deviations !

Color factor ratio T_F/C_F from event shapes & 4-jet angular correlations



- Agreement with QCD value of 0.375
- Light gluino mimics 4-quark events
  G. Farrar (1990)



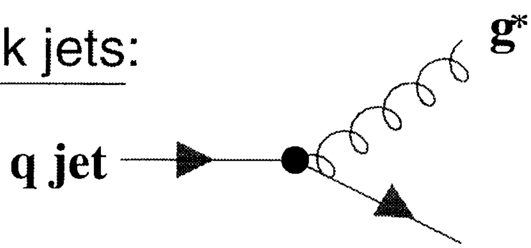
- Effective number of flavors increases from 5 to 8.
- Light gluino hypothesis disfavored by the data (>3 s.d.)

Differences between gluon & quark jets

QUARK and GLUON jets have different coupling strengths for gluon emission:

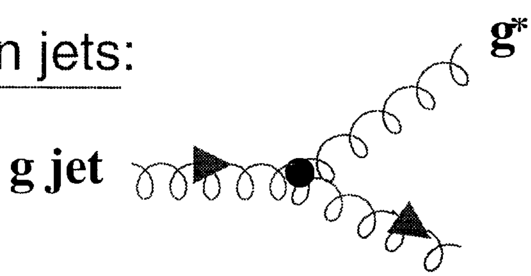
$\longrightarrow$ expressed by the color factors

Quark jets:



qg vertex, $C_F = 4/3$

Gluon jets:



ggg vertex, $C_A = N_C = 3$

The color charge of a gluon is

$$\frac{C_A}{C_F} = \frac{9}{4} = 2.25$$

larger than the color charge of a quark

Greatest theoretical interest in G/Q jet differences $\longrightarrow$ Multiplicity ratio $r_{g/q}$

- Fundamental prediction of QCD $\longrightarrow$

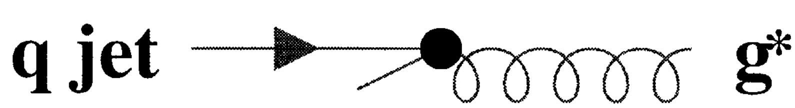
  The number of soft gluons emitted within a gluon jet should be <u>$\sim$ twice</u> that emitted within a quark jet:

$$r_{g/q} \equiv \frac{\langle n \rangle_{gluon}}{\langle n \rangle_{quark}} \approx \frac{C_A}{C_F} = 2.25$$

  This result is valid only for *soft* gluons:

  $E_{gluon} << E_{jet}$ $\longrightarrow$ asymptotic condition

- For *hard* gluon emission, the quark jet develops like a gluon jet $\longrightarrow$

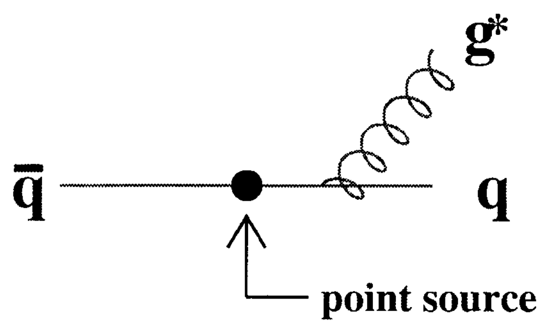


$\longrightarrow r_{g/q} \sim 1$

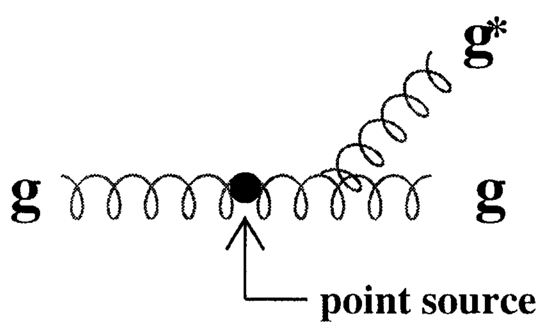
Quark & gluon jets in QCD calculations

→ G and Q jets are defined through pair production from a color singlet point source

Natural Occurrence



e^+e^- annihilations



$\Upsilon \rightarrow \gamma gg$ decays

Jet properties defined by an *inclusive sum* over the event or event hemispheres → UNBIASED JETS

→ No jet-finding algorithm

→ No ambiguity about which particles to associate with gluon or quark jet production

QCD prediction for $r_{g/q}$ (unbiased jets)

$$r_{g/q} = \frac{\langle n \rangle_{gg\ hemis.}}{\langle n \rangle_{q\bar{q}\ hemis.}}$$

$\boxed{= 2.25}$ Asymptotic: E << E_{jet}

$\longrightarrow$ Full phase space (using ALL particles), $E_{jet} \rightarrow \infty$

Brodsky & Gunion (1976)
Veneziano *et al.* (1978)

$\longrightarrow$ Limited phase space (using SOFT particles only), E_{jet} = finite, as applies to experiment

Khoze, Lupia & Ochs (1998)

$\boxed{\sim 1.5}$ Full phase space, finite $E_{jet} \sim 40$ GeV (LEP-1)

$\longrightarrow$ α_S corrections up to n.n.l.o.: $r_{g/q} \approx 2.1$

Malaza & Webber (1984);
Gaffney & Mueller (1985)

$\longrightarrow$ Energy conservation up to n.n.l.o.: $r_{g/q} \approx 1.7$

Dremin (1994)

$\longrightarrow$ Numerical solutions $\rightarrow$ more accurate inclusion of energy conservation and phase space limits:

$r_{g/q} \approx 1.5$

Lupia & Ochs (1997)
Eden & Gustafson (1998)

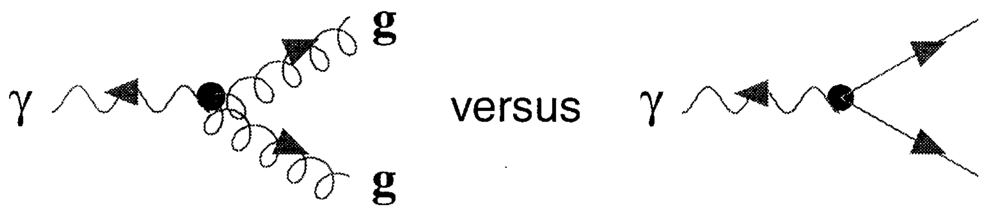
These calculations are based on massless quarks

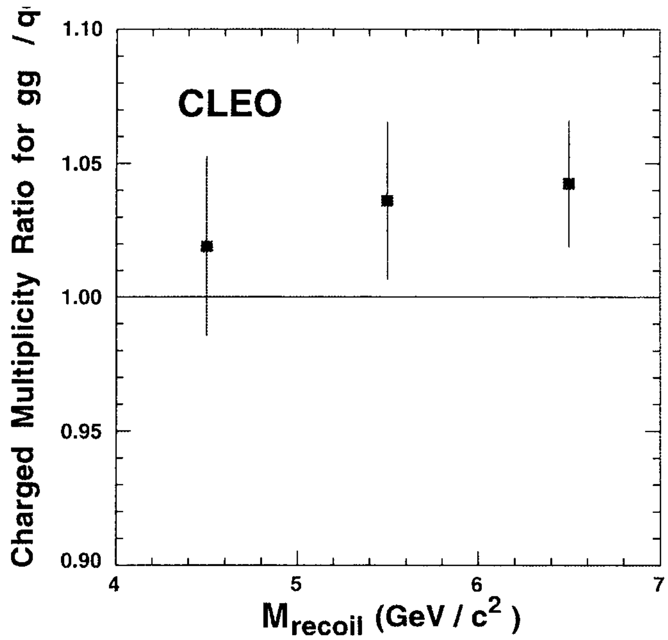
Unbiased gluon jets from Υ decays

CLEO at CESR, e^+e^- $E_{c.m.} \approx$ 10 GeV (1997)

$\longrightarrow$ Radiative Υ decays: $e^+e^- \to \Upsilon(1S) \to \gamma\, gg$

$\longrightarrow$ Compare with $e^+e^- \to \gamma q\bar{q}$ initial state radiation events with the same recoil mass, collected in the continuum.





$$r_{g/q}^{hadron} = 1.04 \pm 0.05$$

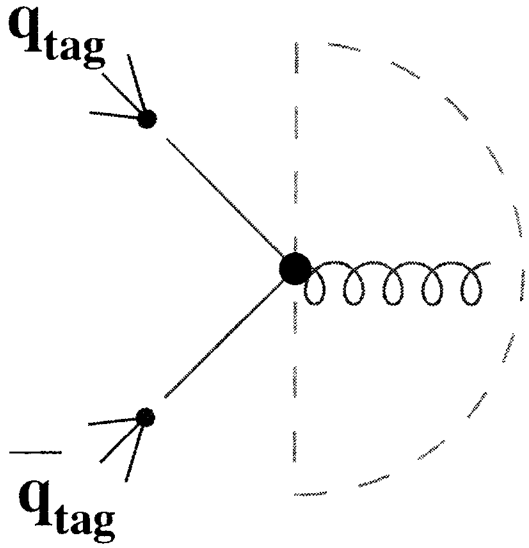
$\longrightarrow$ Jet energy $\sim$ 5 GeV too low to observe a gluon-quark jet difference

$\longrightarrow$ Non-perturbative corrections are likely to be important at this scale

Unbiased gluon jets from Z^0 decays

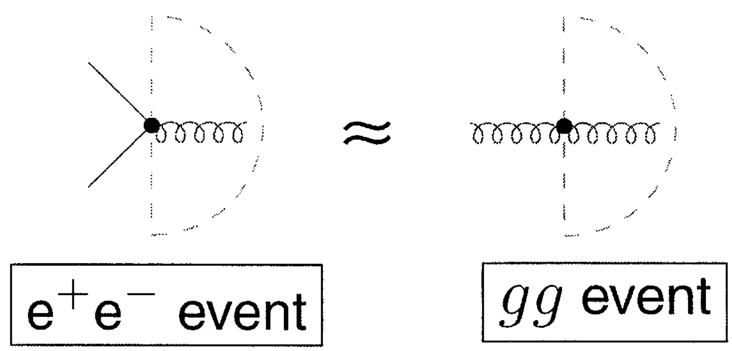
OPAL at LEP-1, e^+e^- $E_{c.m.} \approx$ 91 GeV (1996-1998)

$\longrightarrow$ Gluon jet hemispheres in $e^+e^- \to Z^0 \to q_{tag}\overline{q}_{tag}g_{incl.}$ events



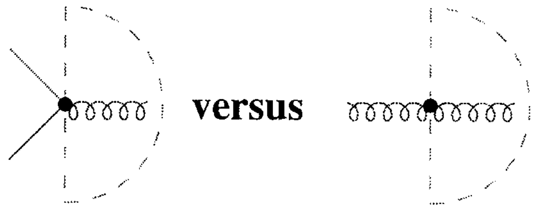
Gluon jet "$g_{incl.}$" defined by the particles in the hemisphere opposite to a hemisphere with two tagged quark jets (tagged quark jet is a b jet)

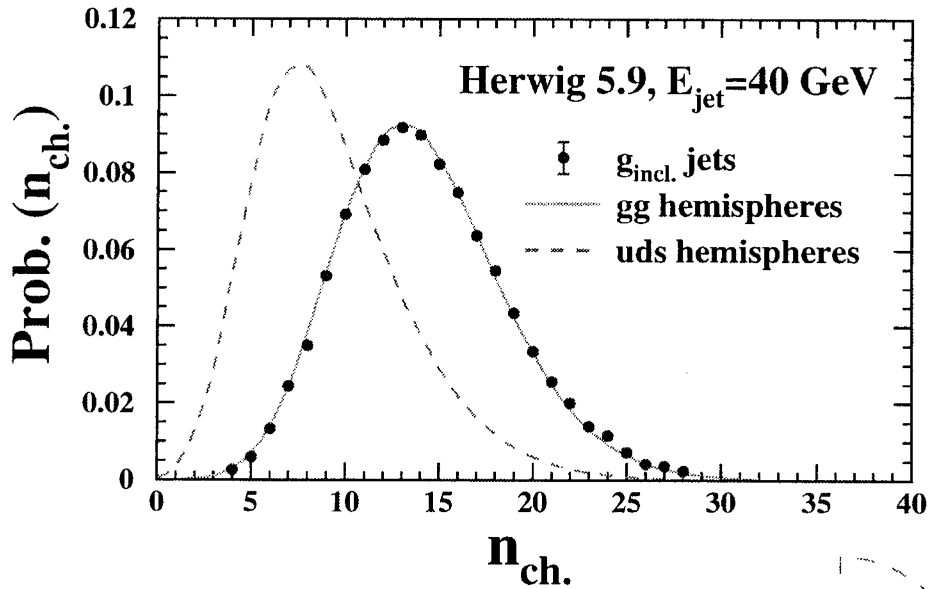
$\longrightarrow$ Invoke the equivalence of the $g_{incl.}$ and gg event hemispheres (exact in the limit of colinear q and $\overline{q}$)



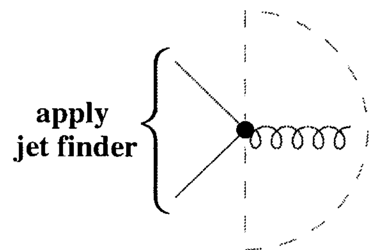
$\longrightarrow$ Tested using the QCD Monte Carlo for which high energy gg production from a color singlet point source is possible !

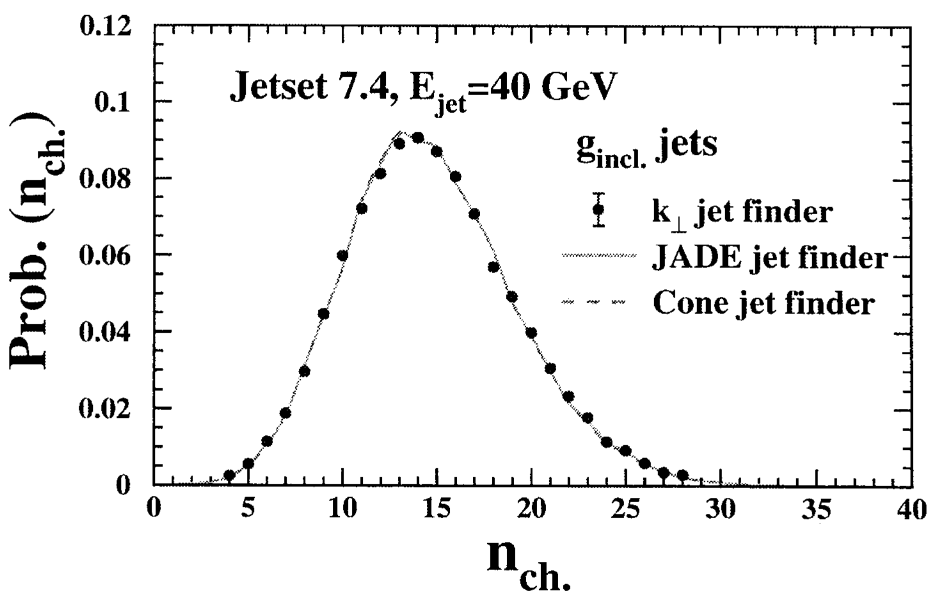
→ Properties of $g_{incl.}$ and gg hemispheres virtually identical · · ·





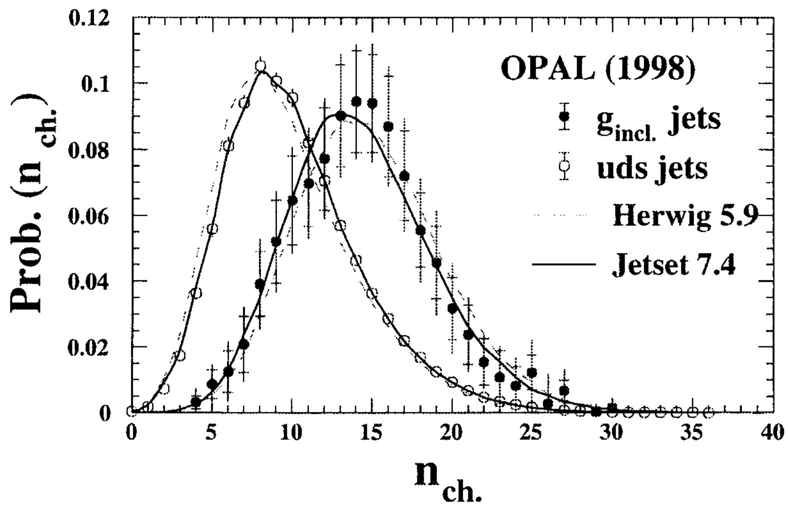
· · · and are independent of the choice of jet finder





Multiplicity distribution $\longrightarrow g_{incl.}$ jets

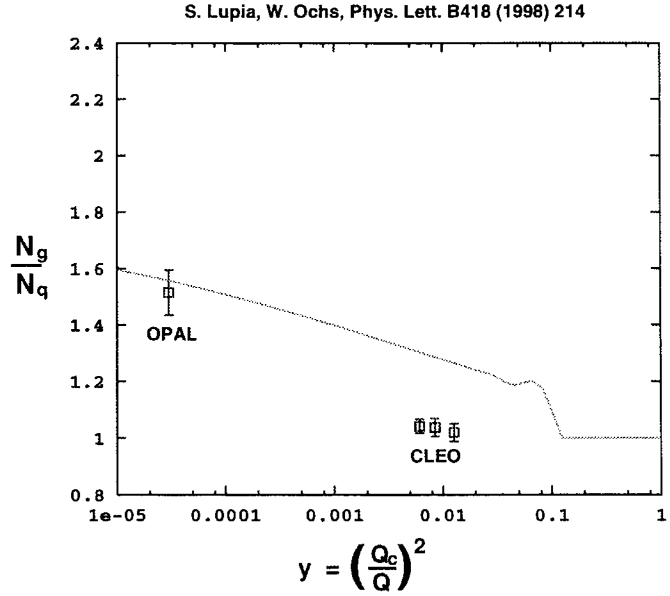
4×10^6 Z^0 decays $\longrightarrow$ 440 selected $g_{incl.}$ jets (82% purity)



$$r_{g/q}^{hadron}(40\,\mathrm{GeV}) = 1.514 \pm 0.039$$

Compare the results of CLEO and OPAL to theory $\longrightarrow$

S. Lupia, W. Ochs, Phys. Lett. B418 (1998) 214



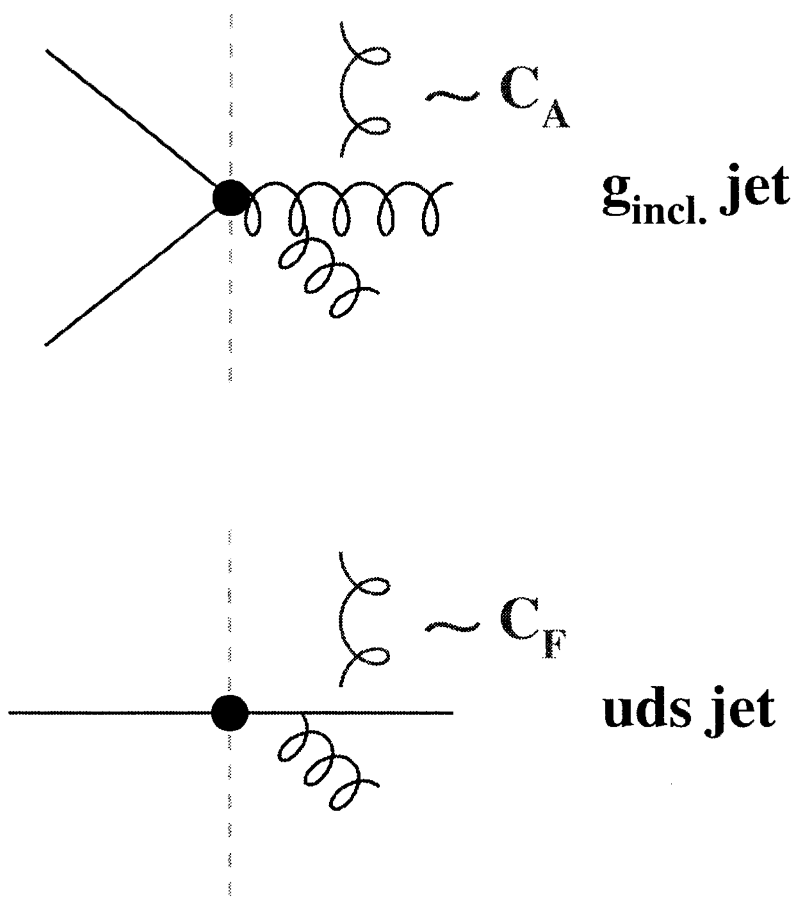
Measurement agrees with QCD prediction at the Z^0 scale

CLEO energies $\rightarrow$ non-perturbative effects are large

Multiplicity under the asymptotic condition for finite jet energies, $E_{particle} << E_{jet}$

$\longrightarrow$ Fulfilled by examining soft particles at large $p_\perp$ in the unbiased gluon and quark jets

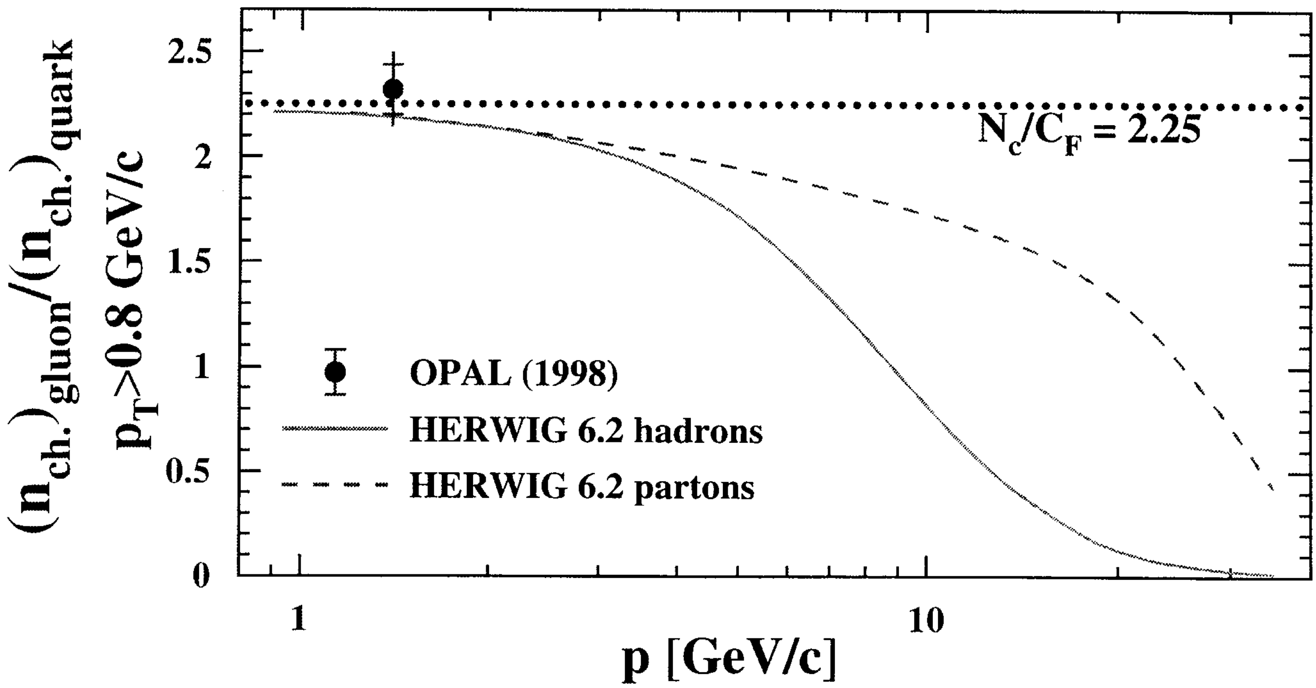
(V. Khoze, S. Lupia & W. Ochs, Eur. Phys. J. C5 (1998) 77)



Provides a means to measure C_A/C_F directly from a ratio of hadron multiplicities

$r_{g/q}$ for soft particles at large $p_\perp$

$p_\perp > 0.8$ GeV/c $\longrightarrow$ $p_\perp < 0.8$ GeV/c dominated by hadronization, decays



Data ($p < 2$ GeV/c)	2.32 ± 0.18
Herwig hadrons, 91 GeV	2.21
Herwig partons, 91 GeV	2.23
Herwig hadrons, 10 TeV	2.24
Herwig partons, 10 TeV	2.25
Jetset partons, 91 GeV, $C_A = C_F$	1.00

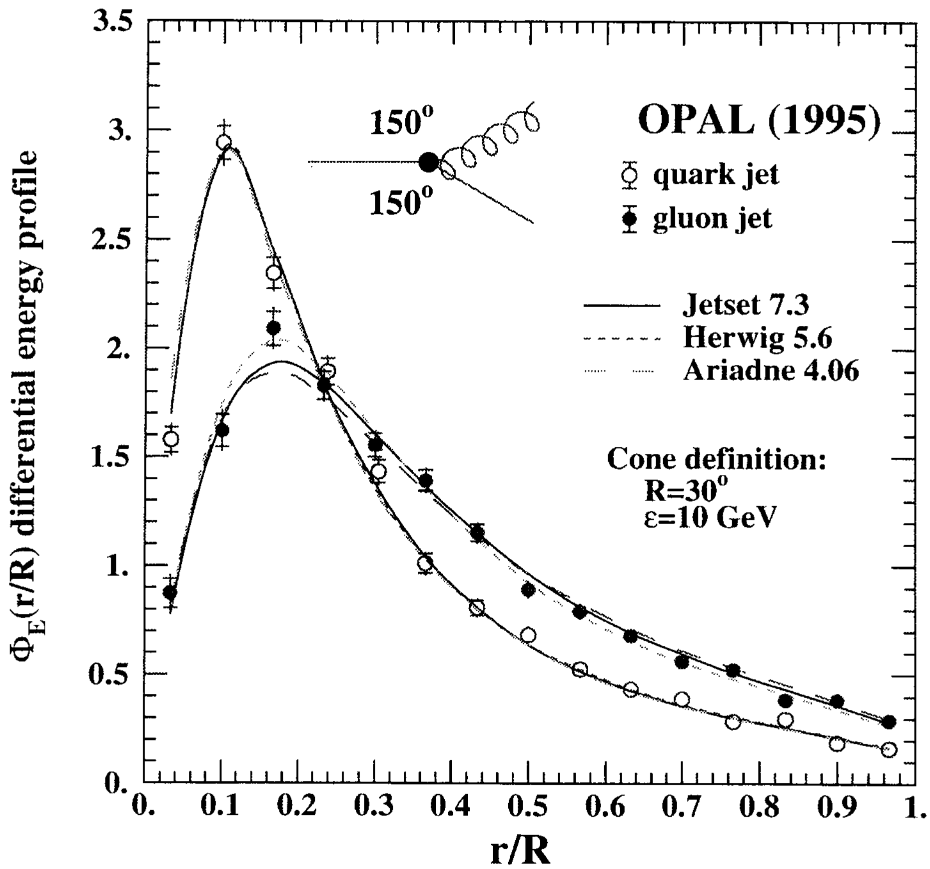
$\longrightarrow$ Quantitative verification of the QCD prediction from 1976 !

Width difference between gluon and quark jets

Gluon jets are predicted to be <u>less collimated</u> than quark jets

⟶ a consequence of the greater radiation of soft gluons in a gluon jet compared to a quark jet

⟶ the fraction of a jet's visible energy close to the jet axis is larger for quark jets than for gluon jets



⟶ The prediction is confirmed experimentally

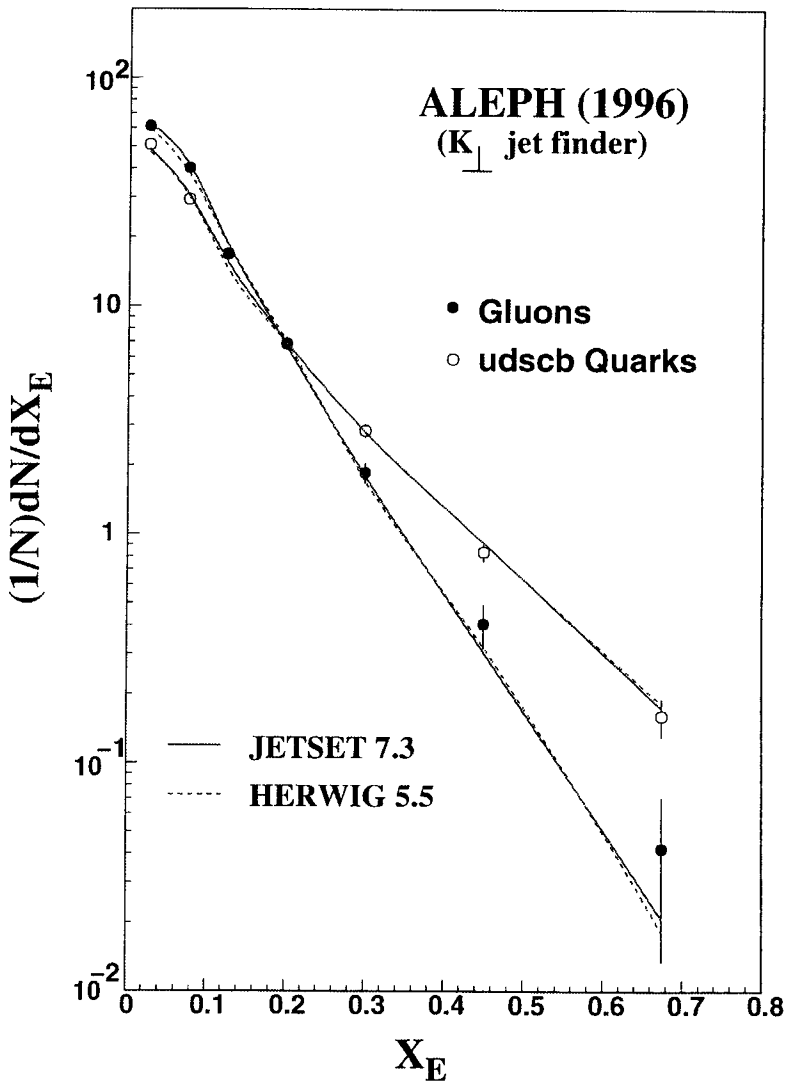
⟶ ~30% of the quark jet's energy is within $4°$ of the jet axis compared to only $\sim 17\%$ for the gluon jets

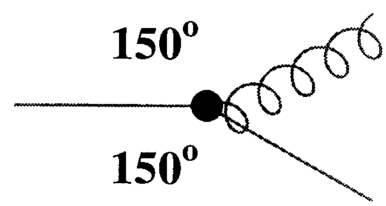
⟶ QCD Monte Carlos agree well with data

Fragmentation function difference ⟶

$$\frac{1}{\sigma_{TOT}} \frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\mathrm{x_E}} \qquad x_E = \frac{2\,E_{particle}}{\sqrt{s}}$$

⟶ The larger multiplicity of gluon jets implies their fragmentation function is softer

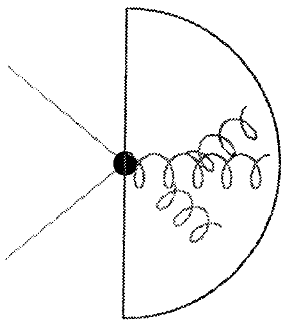




⟶ Effect confirmed experimentally

• Unbiased gluon jets from Z^0 decays

⟶ Provide a quantitative test of the QCD prediction for $r_{g/q}$



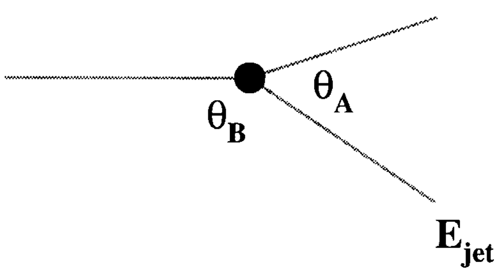
⟶ Fixed scale $Q \approx 40$ GeV

Can differences between gluon & quark jets be used for quantitative tests of QCD at other scales ??
Can we use biased jets from Z^0 decays ??

ANSWER ⟶ YES, if the appropriate scale is chosen for the jets

• QCD coherence

⟶ Evolution of parton cascade depends on a transverse momentum-like “hardness scale”:



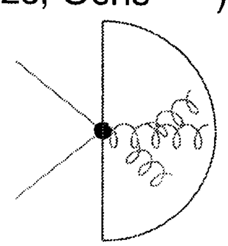
⟶

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

$$\theta_{min} = \min\left(\theta_A, \theta_B\right)$$

(Dokshitzer, Khoze, Ochs $\cdots$)

Corresponds to $\kappa = E_{jet}$ for $\theta \to 180^\circ$



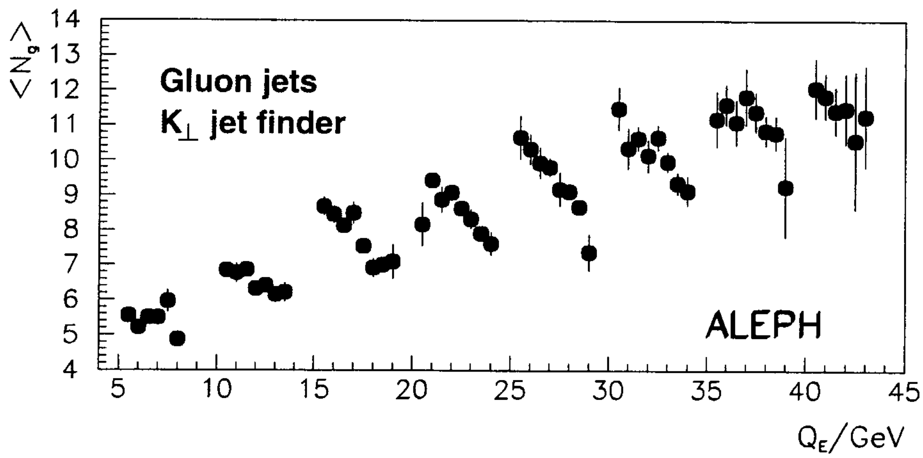
⟶ κ is more appropriate for jets in a general 3-jet topology than the jet energy

Gluon jet $\langle n_{ch.} \rangle \rightarrow$ energy versus κ value

ALEPH at LEP-1 (1997) $\longrightarrow$

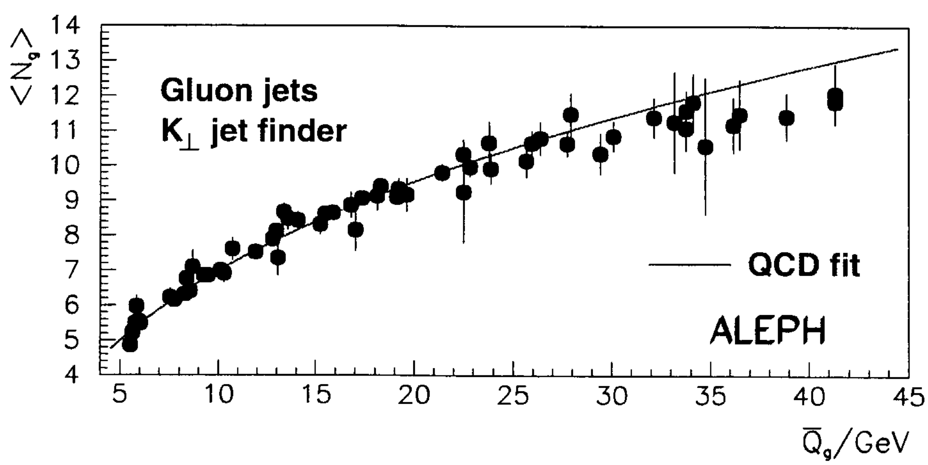
(1) Gluon multiplicity in general 3-jet events versus jet energy

$\longrightarrow$ Each of the eight bands corresponds to jets with the same energy but with a different angle to the nearest jet



$\longrightarrow$ The jet multiplicity in biased events depends critically on the event topology, not just the jet energy

(2) Gluon multiplicity in 3-jet events versus jet κ value

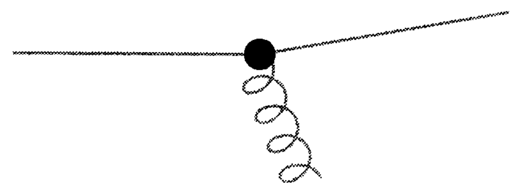


$\longrightarrow$ κ provides a much more meaningful scale for jets embedded in a general 3-jet event topology

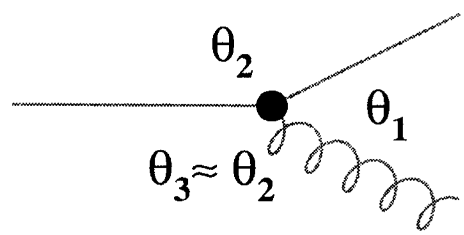
Scale dependence of gluon and quark jet fragmentation functions

DELPHI at LEP-1 (1999) $\longrightarrow$

- Select general 3-jet events:



and also 1-fold symmetric Y events:



using the $k_\perp$ and Cambridge jet finders

- Use b-tagging to identify *gluon jets* and light *udsc quark* events

- Measure the fragmentation functions

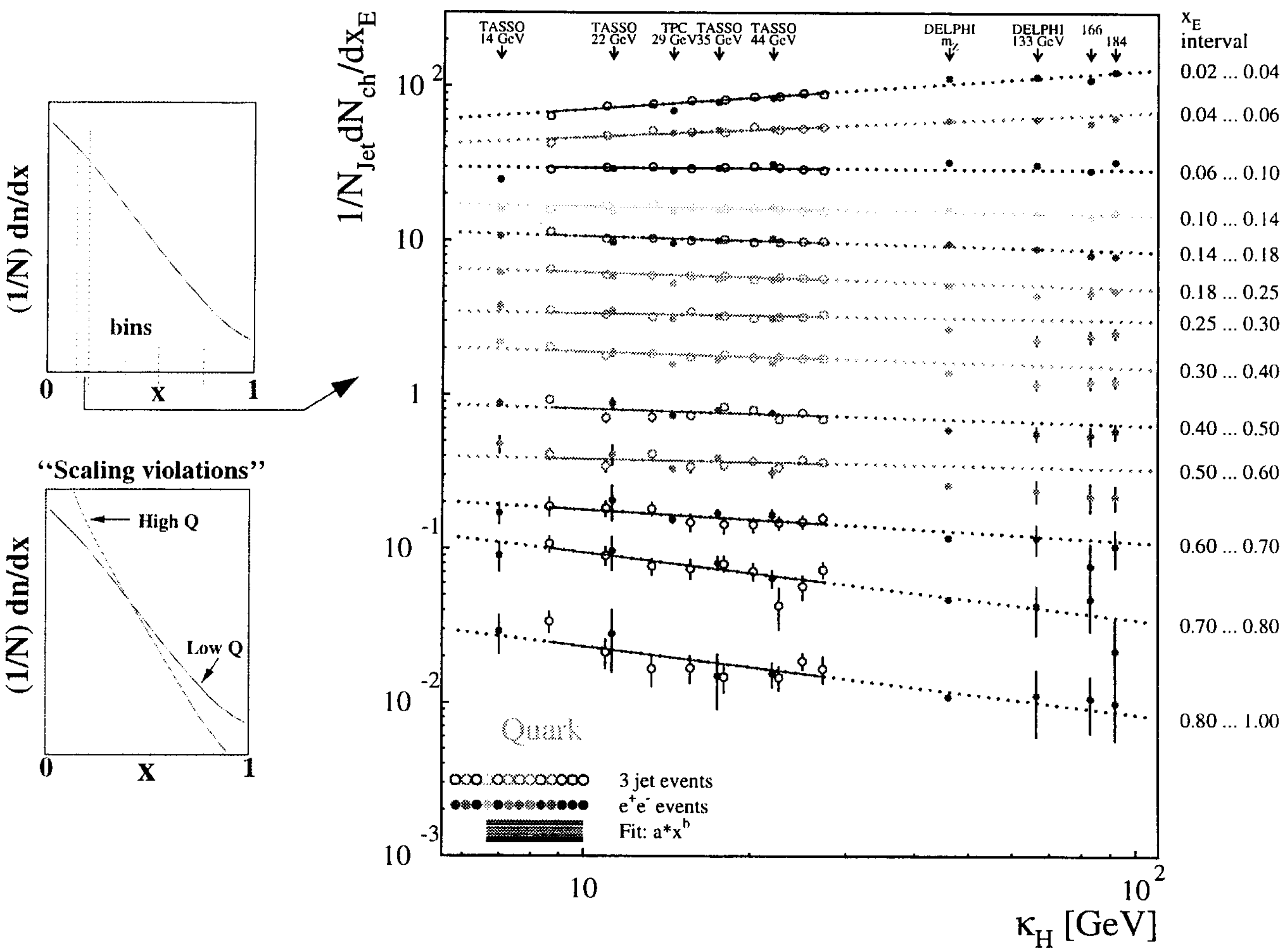
$$\longrightarrow D(x_E,Q) = \frac{1}{N}\frac{dn}{dx_E} \quad ; \quad x_E = \frac{2E}{\sqrt{s}}$$

of the two lower energy jets (one gluon jet, one quark jet) versus the scale $Q = \kappa$

Quark jet fragmentation function versus κ

DELPHI (1999) $\longrightarrow$

Compare the quark jet ff from 3-jet events ($Q = \kappa$) to 0.5 $\times$ the ff function from unbiased quark jets (hemispheres of e^+e^- events, $Q = E_{c.m.}/2$)

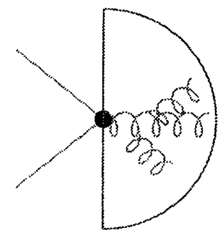


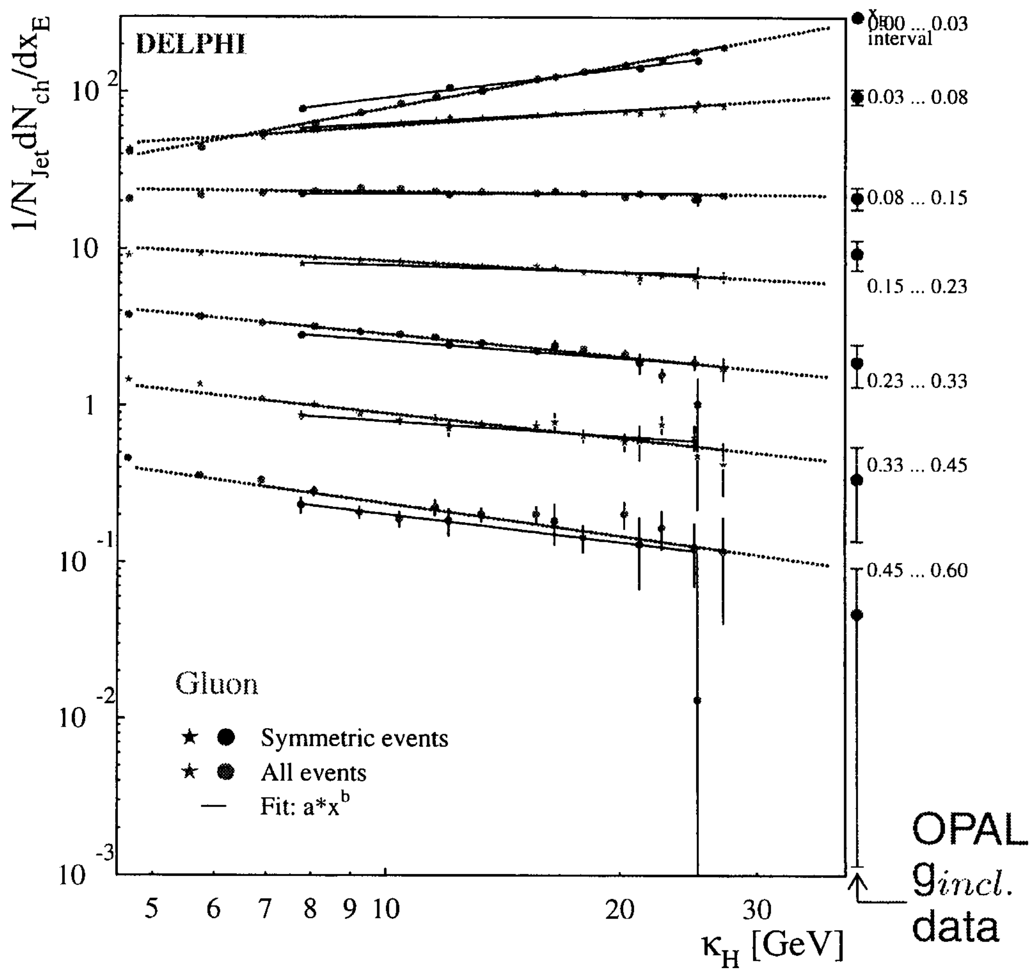
$\longrightarrow$ The quark jet results from 3-jet events correspond well with the results from the unbiased jets

$\longrightarrow$ Another good indication that κ is a meaningful scale for jets in a general 3-jet topology

Gluon jet fragmentation function versus κ

Compare the gluon jet ff from 3-jet events ($Q = \kappa$) to the ff function from the unbiased gluon jet hemispheres $Q \sim 40$ GeV





→ The correspondence of the results between gluon jets from 3-jet events and the unbiased gluon jets seems reasonable

QCD $\longrightarrow$ Scale dependence of fragmentation functions D_g and D_q described by *DGLAP evolution equations*

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Leading order evolution $\longrightarrow$

$$\frac{dD_g(x_E;Q)}{d\ln Q} = \frac{\alpha_S(Q)}{2\pi}\int_{x_E}^{1}\frac{dz}{z}\left[P_{g\to gg}(z)D_g(\tfrac{x_E}{z};Q)+ P_{g\to q\bar{q}}(z)D_q(\tfrac{x_E}{z};Q)\right]$$

$$\frac{dD_q(x_E;Q)}{d\ln Q} = \frac{\alpha_S(Q)}{2\pi}\int_{x_E}^{1}\frac{dz}{z}\left[P_{q\to qg}(z)D_q(\tfrac{x_E}{z};Q)+ P_{q\to gq}(z)D_g(\tfrac{x_E}{z};Q)\right]$$

$\longrightarrow$ Splitting functions $\boxed{P_{g\to gg}\sim \mathrm{C_A}}$, $\boxed{P_{q\to qg}\sim \mathrm{C_F}}$

$\longrightarrow$ Parametrize D_g and D_q at Q = κ = 5.5 GeV :

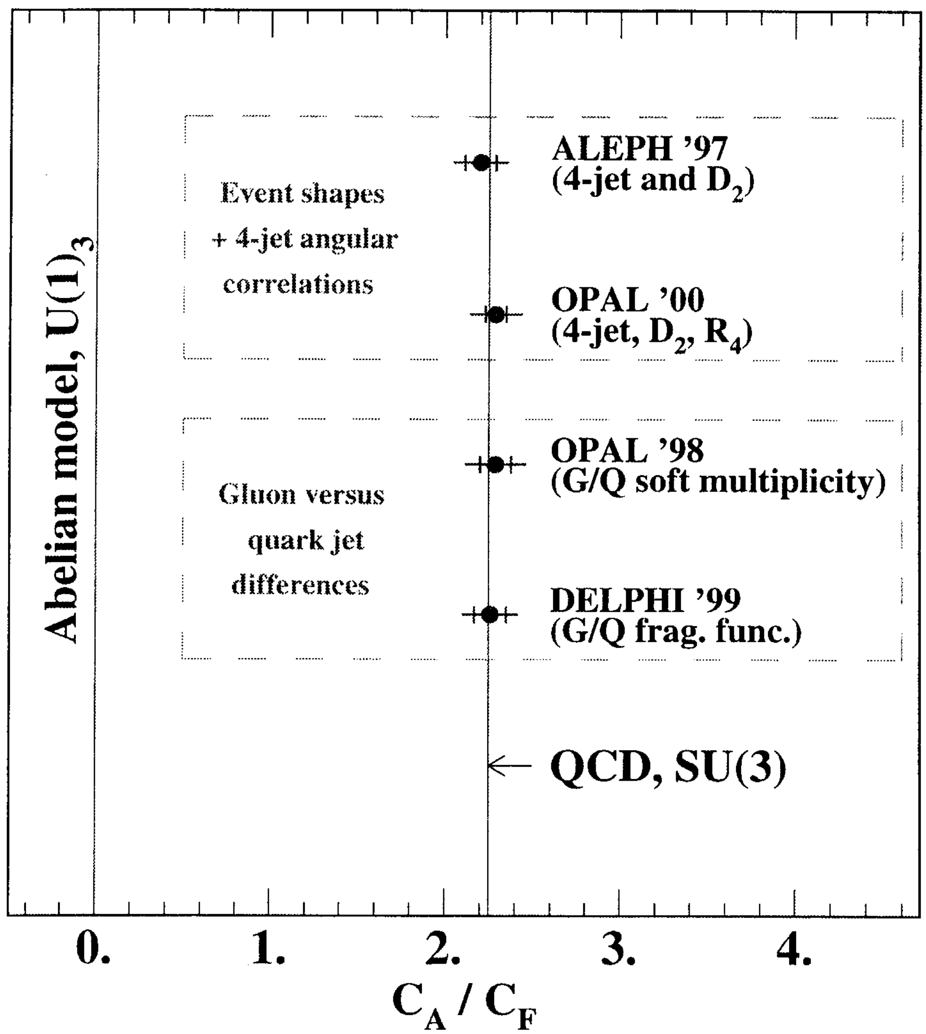
$$D(x_E) = a x_E^b (1-x_E)^c \exp(-d\ln^2 x_E)$$

$\longrightarrow$ Perform *simultaneous fit* of $(a,b,c,d)_p$; p = q,g, C_A and Λ_{QCD} using 1st order DGLAP evolution

$\longrightarrow$ $C_A = 2.97 \pm 0.12$, $\Lambda_{QCD} = 0.40 \pm 0.11$ GeV

$$\boxed{\frac{C_A}{C_F} = 2.26 \pm 0.16}$$

$C_A/C_F \longrightarrow$ Summary



- $\longrightarrow$ Precision of the measurement of C_A/C_F from differences between gluon and quark jets is similar to that from the 4-jet angular correlations & event shapes
- $\longrightarrow$ Precise measurements using very different techniques
- $\longrightarrow$ Direct verification of the SU(3) gauge group underlying strong interactions !

(III) Coherence and LPHD

- Coherence $\longrightarrow$ QCD interference effects affecting the multiplicity and radiation pattern of soft gluons

  General feature $\longrightarrow$ Coherence reduces the multiplicity of soft gluons because of destructive interference

- LPHD $\longrightarrow$ Local Parton-Hadron Duality:
  The conjecture that the angular and energy distributions of soft hadrons are a direct reflection of the corresponding underlying distributions of soft partons

$\longrightarrow$ Three phenomenological parameters in this approach

(1) Λ_{QCD} (effective value of α_S),

(2) $Q_0 \sim m_\pi$ to terminate the perturbative shower

(3) An overall normalization constant K to relate the hadron and parton level distributions

$\longrightarrow$ LPHD was used implicitly for the comparison of $r_{g/q}$ in unbiased gluon and quark jet results with the analytic results, shown earlier

Coherence studies in e^+e^-

(1) Inter-jet multiplicities ("String effect")

(2) Event particle multiplicity versus $\sqrt{s}$

(3) Shape of the particle momentum distribution "Hump-backed spectra"

Due to lack of time I will not discuss:

(4) Heavy versus light quark jet multiplicity

(5) Two particle correlations (azimuthal, momentum, particle-particle correlations (PPC))

There is much additional circumstantial evidence for the existence of coherence effects and the validity of LPHD

$\longrightarrow$ Appropriateness of the $\kappa = E_{jet} \sin\left(\frac{\theta_{\min}}{2}\right)$ scale for jets

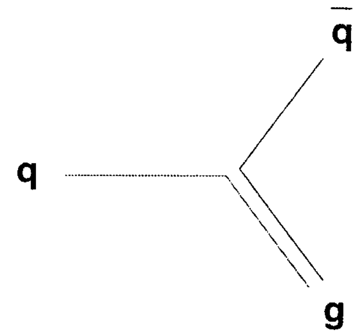
$\longrightarrow$ Near perfect agreement of parton level calculations with data for the ratio $r_{g/q}$ and higher moments of multiplicity in unbiased gluon and quark jets

The evidence taken together provides a rather convincing case for the existence of coherence effects, and by implication the relevance of LPHD for many distributions, providing a basic and comprehensive test of perturbative QCD in the soft domain

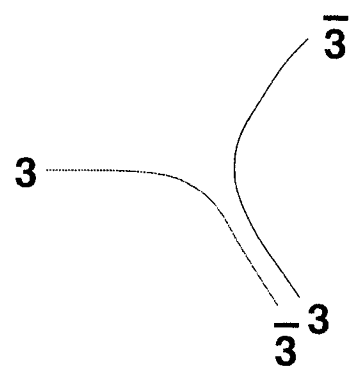
(1) Inter-jet multiplicities: The String effect

First predicted in the context of the LUND string model of hadronization (ca. 1979)

→ Color flow in 3-jet events connects the q and $\overline{q}$ with the g



→ Equivalent to two color dipoles



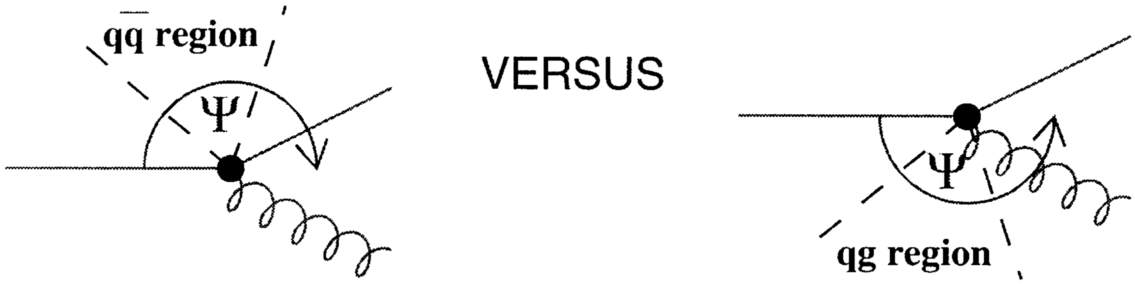
→ Radiation from one dipole interferes with that from the other

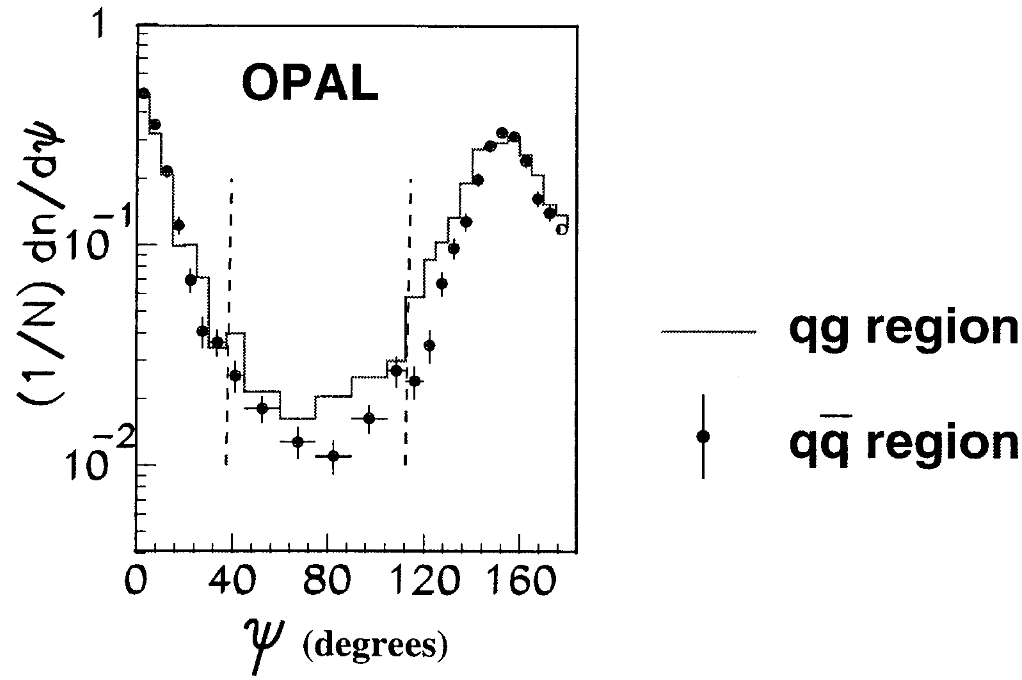
→ *suppression* of soft gluons in the region between the q and $\overline{q}$ relative to the region between the q (or $\overline{q}$) and g

→ A depletion of multiplicity in the $q\overline{q}$ region compared to the qg (or $\overline{q}g$) region

→ First studied experimentally by the JADE Collaboration at PETRA (1981)

OPAL (1991) $\longrightarrow$ Charged particle multiplicity flow in Y events
(First study at LEP)





$\longrightarrow$ Clear depletion in $q\bar{q}$ region compared to qg region

$\longrightarrow$ Integrate over inter-jet region ($\sim$ 25-75% of the range between the peaks $\longrightarrow$ dashed vertical lines)

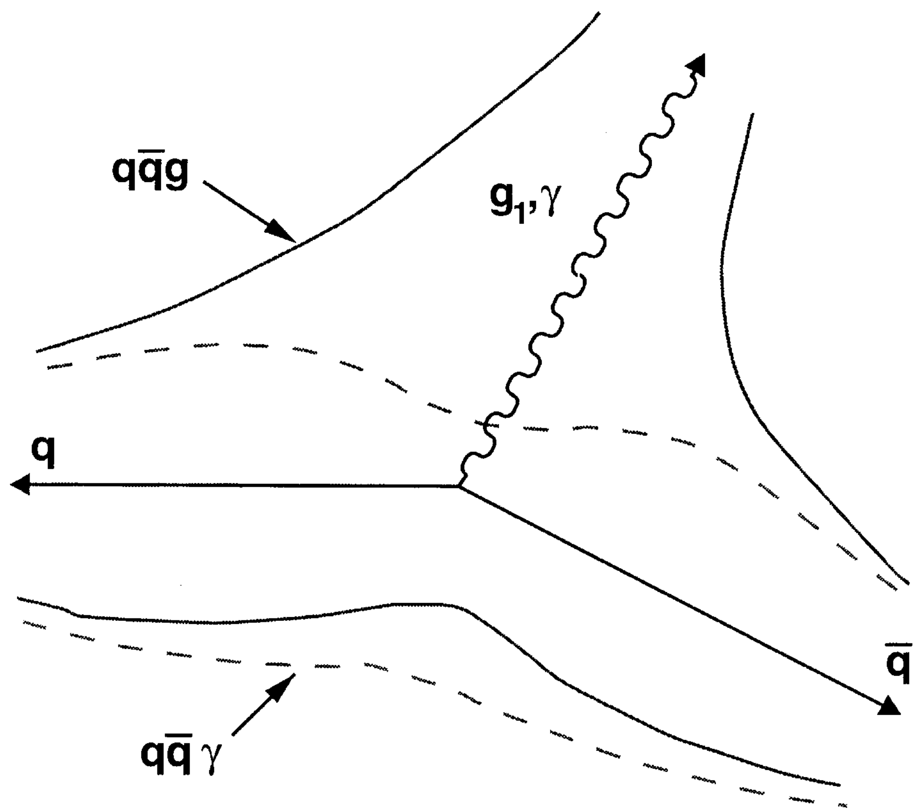
$\longrightarrow$ $n_{q\bar{q}}$ region $/ n_{qg}$ region = 1.66 ± 0.09 (data)
$= 1.54$ (JETSET $\rightarrow$ coherence & string hadronization)
$= 1.02$ (COJETS $\rightarrow$ no coherence & independent hadronization)

$\longrightarrow$ JETSET and COJETS both describe quark gluon jet differences well

$\longrightarrow$ The data provide evidence for coherence

String effect using $q\bar{q}\gamma$ versus $q\bar{q}g$ events

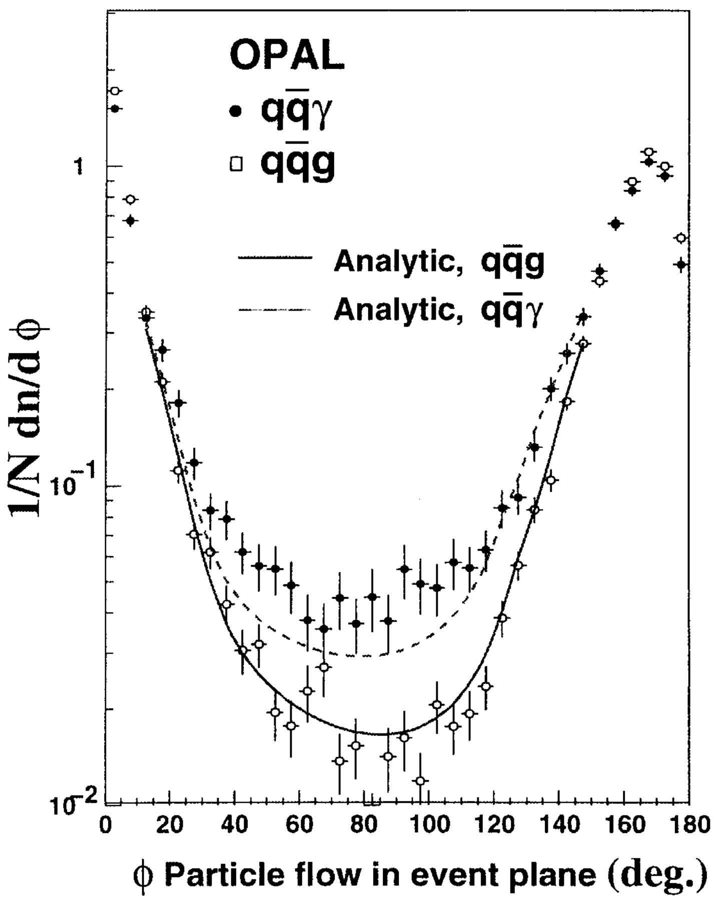
- ⟶ Azimov, Dokshitzer, Khoze & Troyan (1985)
- ⟶ Select 3-jet ($q\bar{q}g$) and radiative 2-jet $q\bar{q}\gamma$ events with similar kinematics

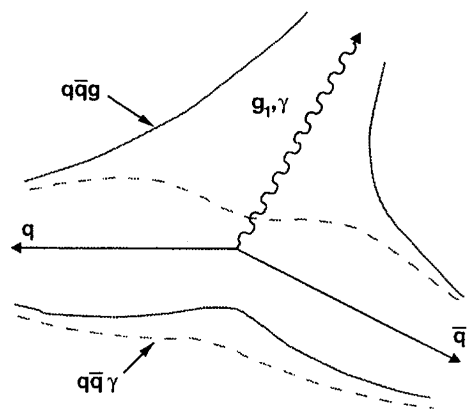


- ⟶ Examine particle multiplicity in the $q\bar{q}$ region
- ⟶ Coherence & LPHD predict a smaller particle density in this region for $q\bar{q}g$ than for $q\bar{q}\gamma$ due to soft gluon interference between the two color dipoles
- ⟶ $q\bar{q}\gamma$ events have only one dipole → no interference

OPAL (1995) $\longrightarrow$

- $\longrightarrow$ Measure particle flow in the $q\bar{q}$ region in $q\bar{q}g$ and $q\bar{q}\gamma$ events
- $\longrightarrow$ Compare data to the leading order prediction for the soft gluon radiation pattern in the corresponding events





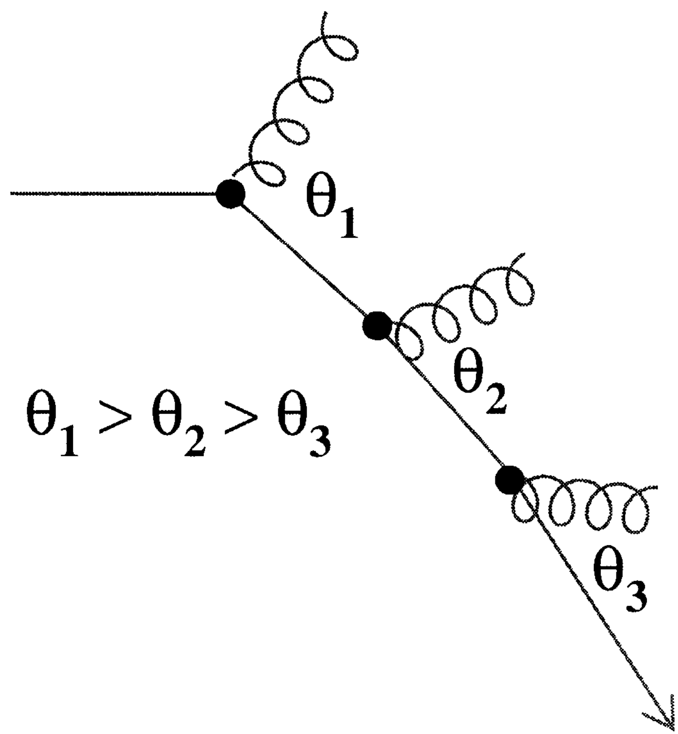
- $\longrightarrow$ The predicted reduction in particle density for $q\bar{q}g$ events compared to $q\bar{q}\gamma$ events <u>is observed</u>
- $\longrightarrow$ The magnitude of the measured effect is very similar to that predicted by the analytic prediction
- $\longrightarrow$ Provides more circumstantial evidence for coherence & LPHD as the origin of the string effect

Multiplicity within jets ⟶
Intra-jet multiplicities & angular ordering

Coherence in the parton shower ⟶

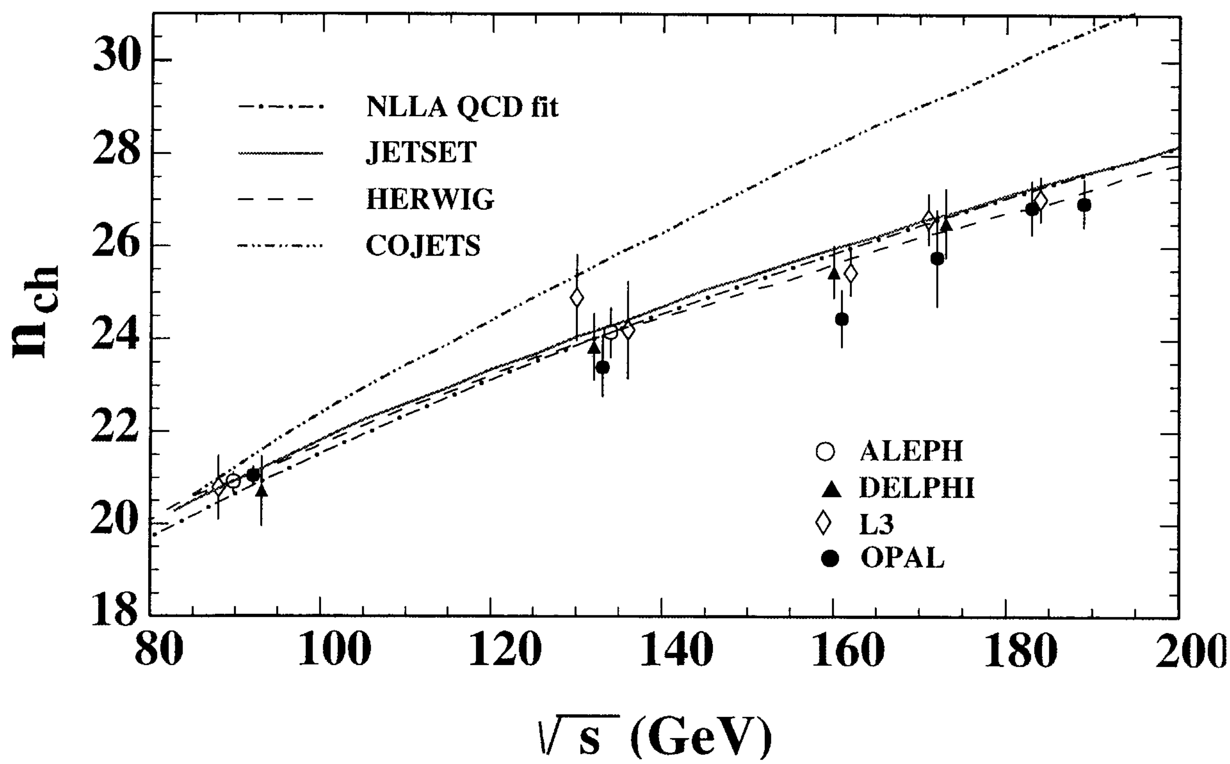
⟶ Destructive interference leads to a reduction in the phase space available for gluon emission

⟶ The principal manifestation is the angular ordering of parton emissions



⟶ This reduction in phase space corresponds to a smaller overall multiplicity and a smaller growth of multiplicity with $\sqrt{s}$ than in the absence of coherence

(2) Event particle multiplicity versus $\sqrt{s}$



Models with coherence (PYTHIA, HERWIG, ARIADNE)

⟶ Energy scaling is consistent with data

Model without coherence (COJETS)

⟶ Growth of multiplicity with $\sqrt{s}$ is too large, as expected from the lack of suppression of phase space

All four MCs are tuned to the 91 GeV data

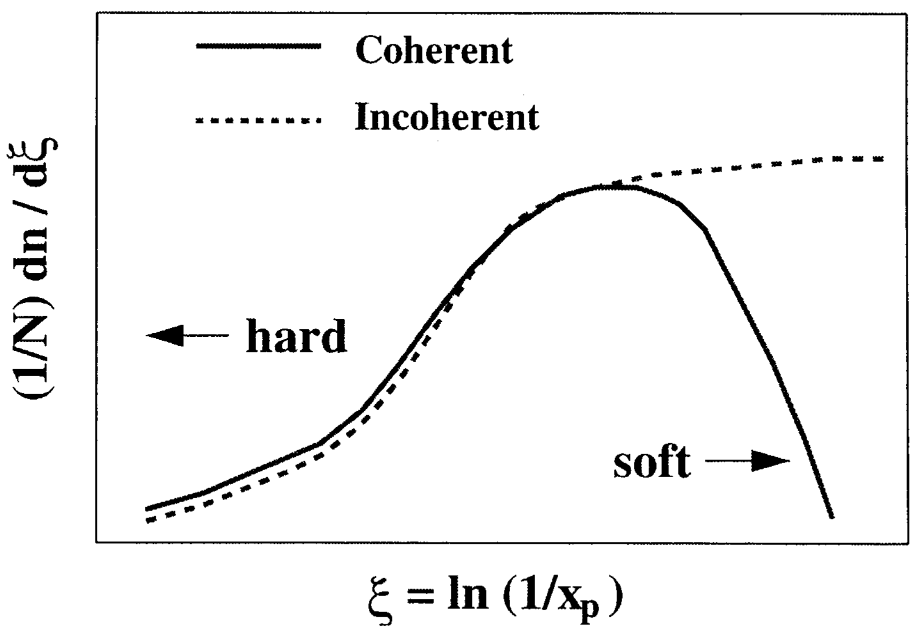
⟶ They provide essentially equivalent descriptions for global event properties like multiplicity

(3) Suppression of soft particle multiplicity: the "Hump-backed" spectra

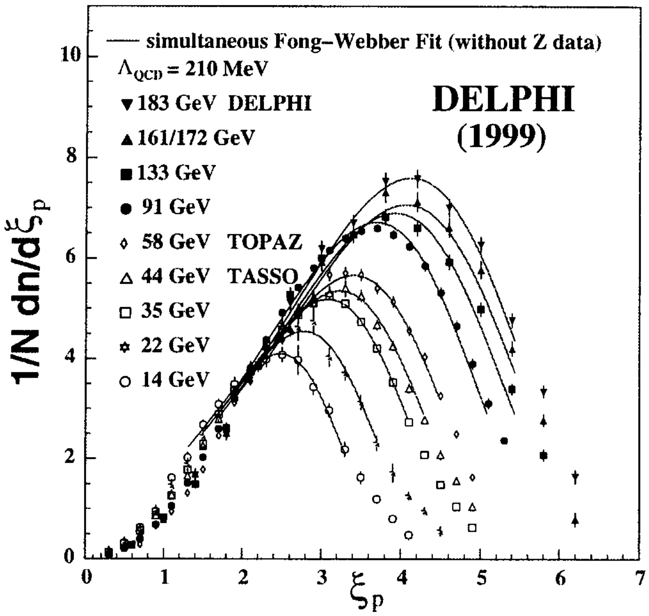
- Angular ordering within jets suppresses the total event multiplicity (as discussed above)
- The suppression mostly affects soft particles
- Examine the differential momentum spectra of particles, not just the mean value $\langle n \rangle$
- QCD predicts an approximately Gaussian shape for the differential particle momentum spectrum when expressed using the variable

$$\xi \equiv \ln\left(\frac{1}{x_p}\right) \quad \text{with} \quad x_p = \frac{2p}{\sqrt{s}}$$

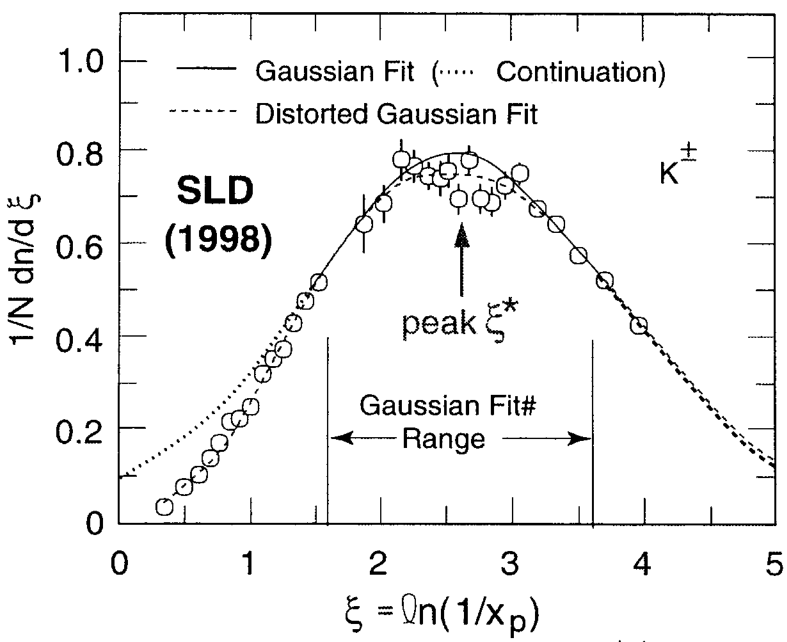
Fong & Webber (1989); Dokshitzer, Khoze & Troyan (1992)



→ The data at the hadron level are indeed observed to follow a shape in close agreement with the parton level prediction of a "distorted Gaussian"

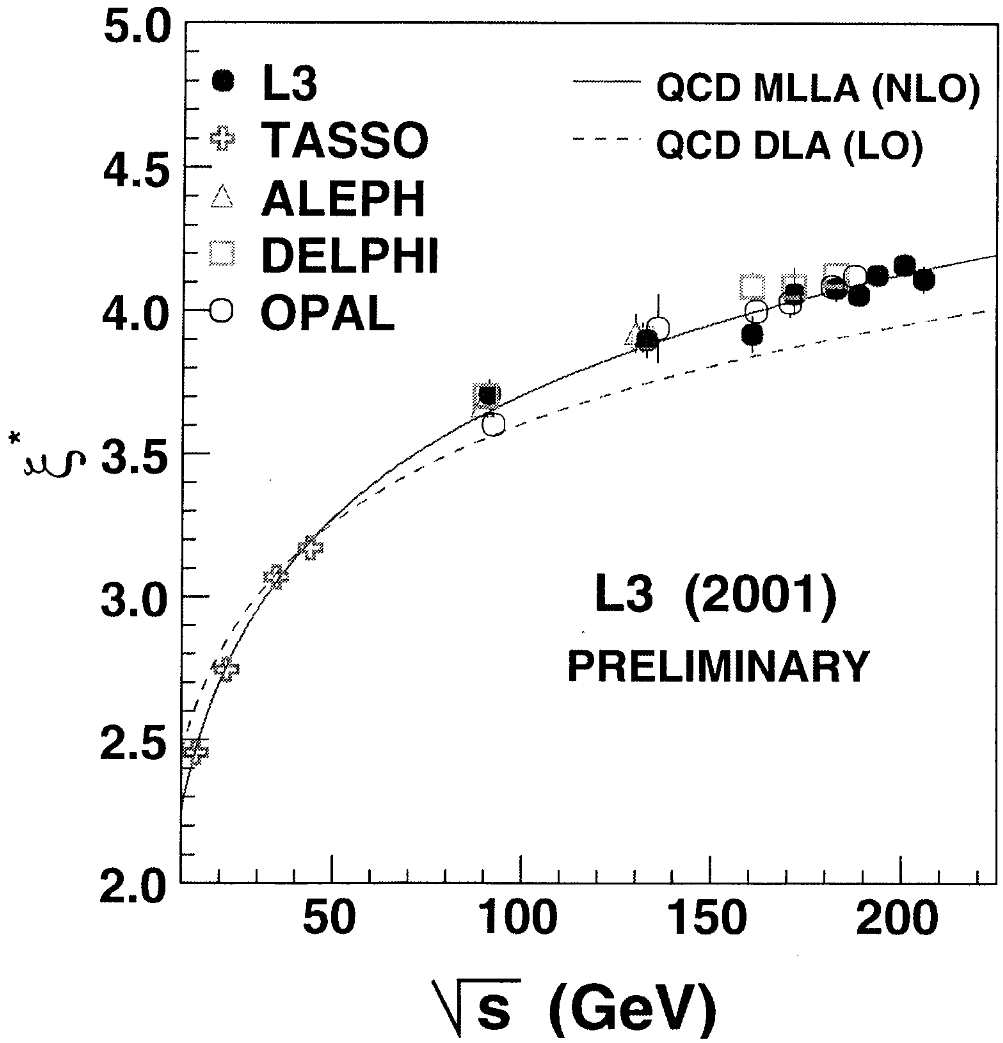


→ Two free parameters: $\Lambda_{\rm QCD}$ and normalization $K(\sqrt{s})$
($Q_0 = \Lambda_{\rm QCD}$ → "limited spectrum approximation")



→ The position of the peak, denoted ξ^*, is independent of the normalization and depends on $\Lambda_{\rm QCD}$ only

Energy evolution of the peak position: ξ^* versus $\sqrt{s}$



- → The one parameter NLO fit agrees well with the data
- → The agreement of the LO prediction with data is <u>much worse</u>, suggesting that the agreement of the NLO result is not "trivial"
- → Similar results have been obtained at HERA and the TEVATRON

(IV) Identified particles

⟶ Much work done at PEP & PETRA ($E_{c.m.} \approx 30 - 35$ GeV)

⟶ LEP/SLC results more precise and more extensive due to the larger data samples ($\sim 4 \times 10^6$ events versus $\sim 10^5$)

Mesons with measured production rates at LEP/SLC:

Ang. mom.	Spin	J^{PC}	
L $= 0$	S $= 0$	0^{-+}	$\pi^\pm$, π^0, η, η', K^0, $K^\pm$, D^0, $D^\pm$, $D_S^\pm$
L $= 0$	S $= 1$	1^{--}	$\rho^\pm$, ρ^0, ω, ϕ, K^{*0}, $K^{*\pm}$, $D^{*\pm}$, $D_S^{*\pm}$, J/Ψ, $\Psi(2S)$, B^*
L $= 1$	S $= 0$	1^{+-}	⟶ none observed
L $= 1$	S $= 1$	0^{++}	$f_0(980)$, $a_0(980)$
		1^{++}	⟶ none observed
		2^{++}	$f_2(1270)$, $f_2'(1525)$
L $= 1$			B_J^* (multiplet(s) not identified)

Baryons with measured production rates at LEP-1:

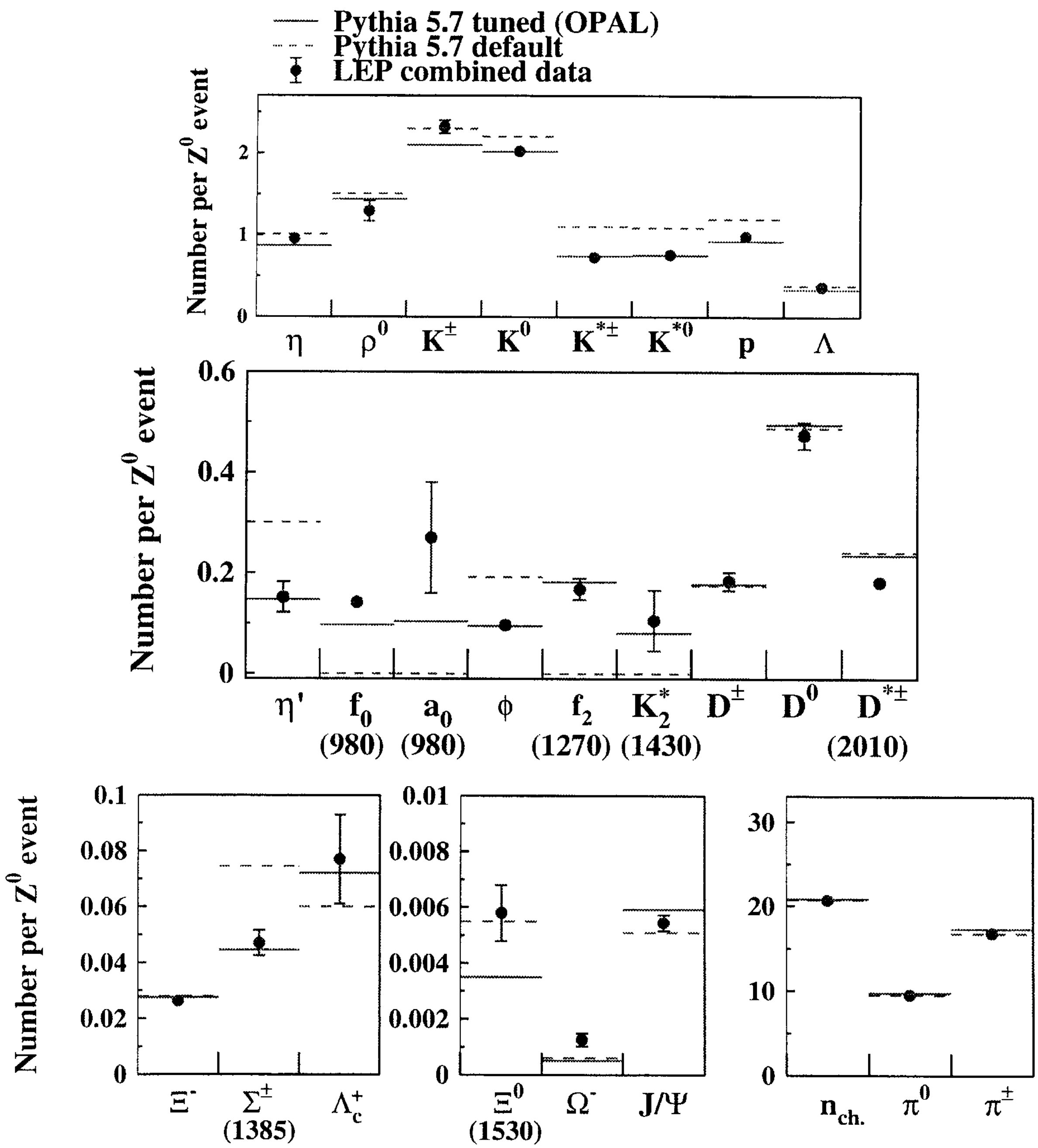
Ang. mom.	Spin	J^P	
L $= 0$	S $= 1/2$	$(1/2)^+$	p, Λ, Σ^+, Σ^-, Σ^0, Ξ^-, Λ_C^+
L $= 0$	S $= 3/2$	$(3/2)^+$	Δ^{++}, $\Sigma(1385)^\pm$, $\Xi(1530)^0$, Ω^-
L $= 1$	S $= 1/2$	$(3/2)^-$	$\Lambda(1520)$

The measured hadron production rates can be used to extract basic information on the hadronization process

- ⟶ Probability to produce strangeness from the vacuum
- ⟶ Probability to produce baryon number from the vacuum
- ⟶ Probability to produce spin from the vacuum
- ⟶ Differences between gluon & quark jet hadronization
- ⟶ Tests of models for baryon production

In addition, these measurements provide basic input to tune of QCD Monte Carlo event generators, used for many other studies

Production rates of identified particles



⟶ The overall description of the hadron production rates by the tuned Monte Carlo is quite good

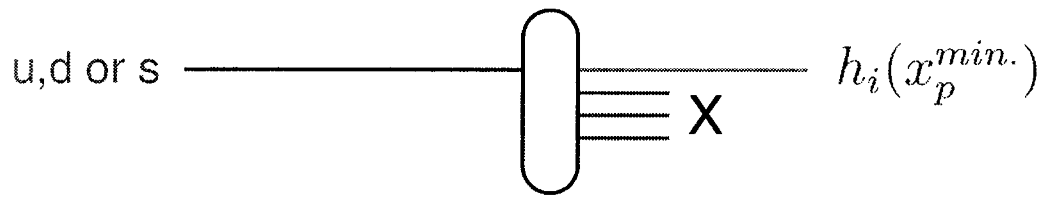
OPAL (1999) $\longrightarrow$

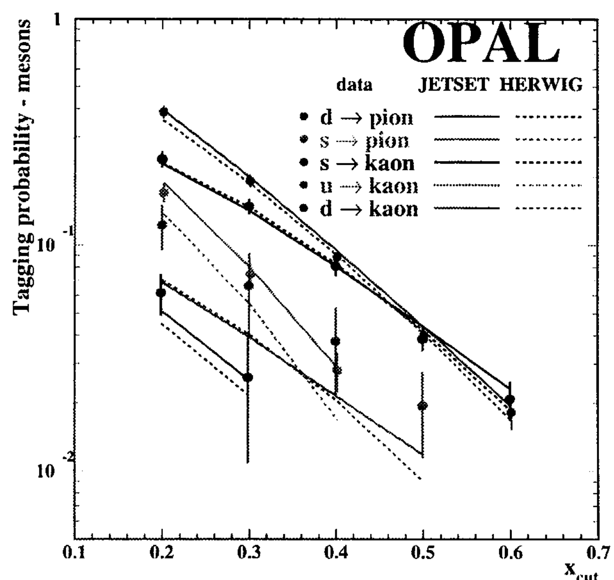
- Measure rates H_i for a hemisphere to contain an identified π^+, K^+, K^0_S, p, Λ or c.c. as its highest momentum particle
- Invert the equations

$$H_i = 2 \sum \eta_{q \to i} \, R_q$$

$$\text{with} \;\; R_q = \Gamma(\mathrm{Z} \to \mathrm{q\overline{q}})/\Gamma(\mathrm{Z} \to \text{ hadrons})$$

to find the tagging probabilities $\eta_{q \to i}$ for a quark of flavor q to appear in a leading hadron of type i





Predominant:	d,u	$\longrightarrow$	π
	s	$\longrightarrow$	K
Suppressed:	d,u	$\longrightarrow$	K
	s	$\longrightarrow$	π

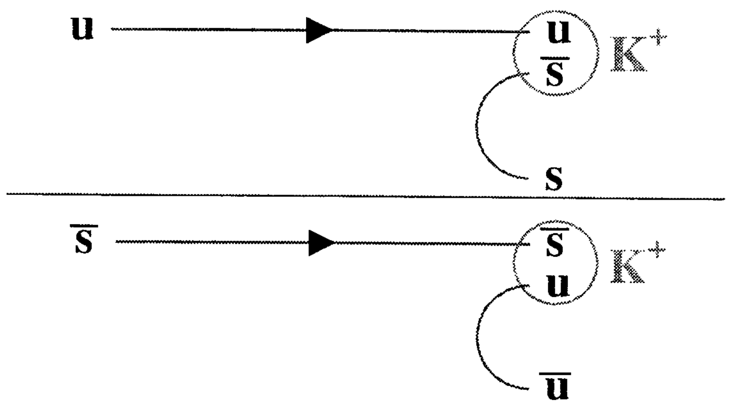
- The primary q, $\overline{\mathrm{q}}$ appear as valence quarks in the highest momentum hadrons (the leading particle effect)

Strangeness suppression factor:

$$\gamma_s \equiv \frac{\text{Prob.(s)}}{\text{Prob.(u,d)}}$$

$u\bar{u}$ ($d\bar{d}$) versus $s\bar{s}$ pair production from the vacuum

$$\frac{\eta_u^{K^\pm}}{\eta_s^{K^\pm}} =$$



$$\approx \gamma_s$$

Similarly, $\dfrac{\eta_u^{K_s^0}}{\eta_s^{K_s^0}} \approx \gamma_s$

Contributions from decays of higher mass resonances, etc., predicted to be small (Jetset/Pythia)

$$\boxed{\gamma_s = 0.422 \pm 0.077}$$

$$(x_p^{min.} > 0.20)$$

Method does not compare yields for hadrons with different masses, e.g. K/π, or rely on tuning of MC parameters

$\longrightarrow$ $\gamma_s = 0.31$ in Jetset/Pythia (OPAL version)

$\longrightarrow$ Similar result, $\gamma_s = 0.26 \pm 0.12$, from SLD (PRL78 (1997) 3442)

Not discussed in these lectures

- Flavor independence of α_S
- Running b quark mass
- $g \to c\bar{c}$ and $g \to b\bar{b}$
- Power corrections to $\sqrt{s}$ evolution of the mean values of event shapes
- Rapidity & flavor correlations, etc.
- 2γ physics