Jet Structure Studies at LEP and HERA

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OPAL #103	Leading particle production in light flavour jets
OPAL #116	Experimental properties of gluon and quark jets from a point source
J.W. Gary, I.M. Dremin, et al. #715	Multiplicity distributions of hadrons in gluon and quark jets
ZEUS #906	Substructure dependence of jet cross sections in photoproduction at HERA
OPAL #250	π^0, η, K^0 and charged particle multiplicities in quark and gluon jets

1 Leading particle production in separated light (u, d and s) quark events

(OPAL Collab: CERN-EP/99-164, Abstract #103)

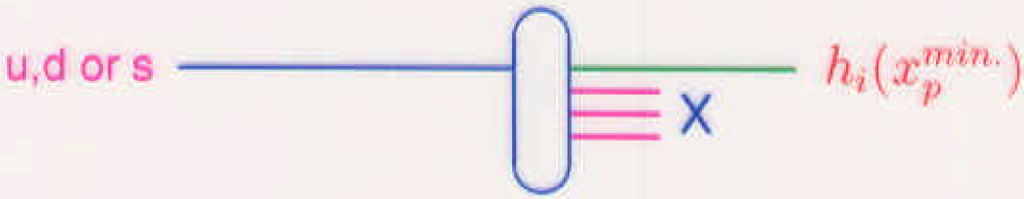
- Separated c and b events in e^+e^- annihilations are well studied:
  - ⟶ c, b mostly produced at electroweak vertex
  - ⟶ displaced 2ndary vertices, high $p_\perp$ leptons
    - ⟶ c and b events "easy" to identify
- Separated u,d and s events not much studied
  - ⟶ u,d,s quarks produced copiously during jet development, not only at EW vertex

This study ⟶ identify $e^+e^- \to q\bar{q} \to \mathrm{hadrons}$ events with q=u, d or s

⟶ measure the flavor separated fragmentation functions for identified hadrons: $\pi^\pm, K^\pm, \cdots$

Determine the probabilities $\eta_{\mathrm{q}}^{i}(x_p^{min.})$ for

$$\text{q (= u,d or s or c.c.)} \longrightarrow h_i(x_p^{min.})$$



where h_i = π^+, K^+, K^0_s, p, Λ + c.c. is the leading particle (has largest momentum p) in the jet and has scaled momentum

$$x_p = 2p/\sqrt{s} > x_p^{min.} \quad (\sqrt{s}\text{=91 GeV})$$

⟶ Unique, detailed information on the hadronization process

⟶ Determination of basic parameters such as the strange quark suppression factor

$$\boxed{\gamma_s \equiv \text{Prob.(s) / Prob. (u or d)}}$$

more directly than in most previous studies

Method $\longrightarrow$ J. Letts, P. Mättig, Z. Phys. C73 (1997), 217

$\longrightarrow$ divide $e^+e^- \rightarrow hadrons$ events into hemispheres using plane $\perp$ to thrust axis

quark jet = an e^+e^- hemisphere
(inclusive definition of jets)

$\longrightarrow$ Measure single and double tag rates:

$$\frac{N_i(x_p^{min.})}{N_{had.}} \text{ and } \frac{N_{ij}(x_p^{min.})}{N_{had.}}$$

$N_i(x_p^{min.})$ = nr. of jets in which the highest momentum particle has $x_p > x_p^{min.}$ and is identified as π^+, K^+, K^0_S, p, Λ or c.c.

$\longrightarrow$ 5 measurements

$N_{ij}(x_p^{min.})$ = analogous result for double tags:
i= identified π^+, K^+, $\cdots$ in one hemisphere and
j= identified π^+, K^+, $\cdots$ in the other, both
with $x_p > x_p^{min.}$

$\longrightarrow$ 15 measurements

$\longrightarrow$ Solve system of equations

$$\frac{N_i(x_p^{min.})}{N_{had.}} = 2 \sum_{q=u,d,s,c,b} \eta_q^i(x_p^{min.}) \mathrm{R_q}$$

$$\frac{N_{ij}(x_p^{min.})}{N_{had.}} = (2-\delta_{ij}) \times \sum_{q=u,d,s,c,b} \rho_{ij}(x_p^{min.}) \eta_q^i(x_p^{min.}) \eta_q^i(x_p^{min.}) \mathrm{R_q}$$

$\mathrm{R_q} = \frac{\Gamma_{Z^0 \to q\bar{q}}}{\Gamma_{Z^0 \to hadrons}}$ $\longrightarrow$ S.M. (u,d,s), LEP (c,b)

ρ_{ij} = (geometric) correlations between hemispheres
$\longrightarrow$ Evaluate using MC ($\rho_{ij} \approx 1.01 - 1.11$)

$\longrightarrow$ 25 unknowns η_q^i

$\longrightarrow$ Add constraints of isospin symmetry, flavor independence of strong interactions:

$\eta_d^{\pi^\pm} = \eta_u^{\pi^\pm}$, $\eta_s^{K^\pm} = \eta_s^{K_s^0}$, etc.

$\longrightarrow$ Add constraints from c and b quark tags (displaced 2ndary vertices, etc.)

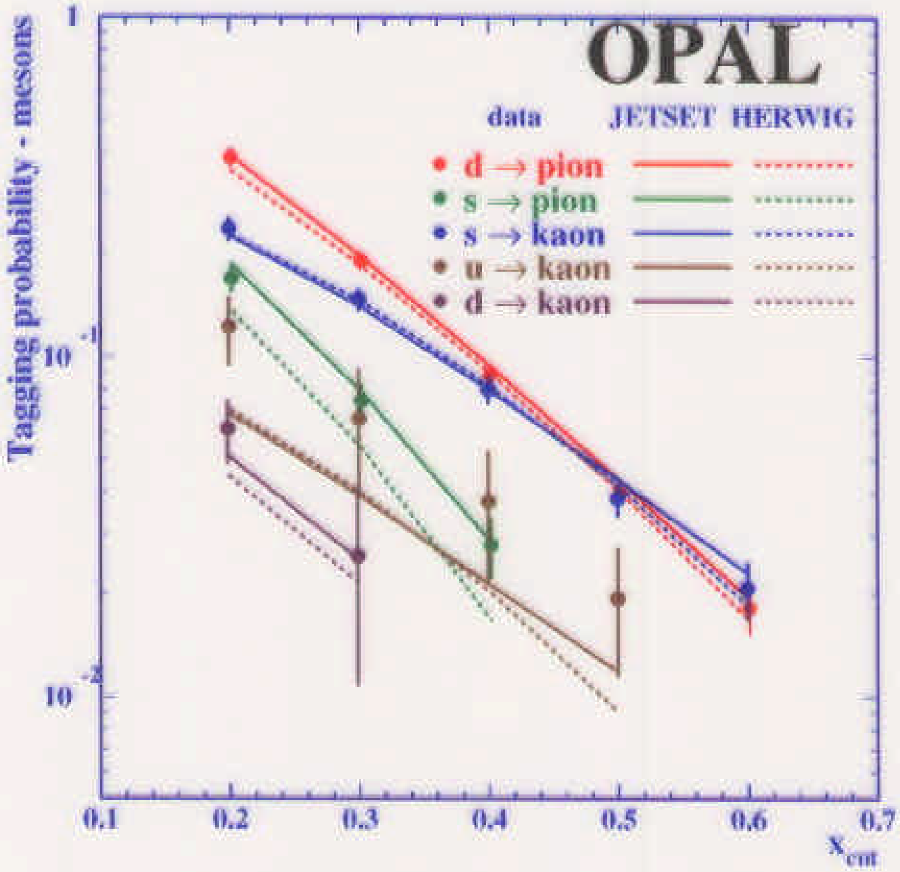
Particle Identification:

$\pi^\pm$, $K^\pm$, p, $\bar{p}$ $\longrightarrow$ dE/dx versus p

K_S^0, Λ $\longrightarrow$ "V-zero" reconstruction

Leading particle effect in u,d,s events:

(see also SLD Collab., Phys. Rev. Lett. 78 (1997) 3442)



Predominant:	d,u	⟶	π
	s	⟶	K
Suppressed:	d,u	⟶	K
	s	⟶	π

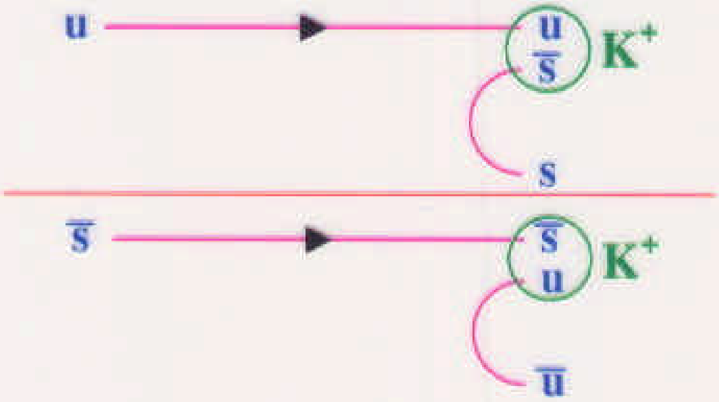
Primary q, $\overline{q}$ appear as valence quarks in the highest momentum hadrons

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

$$\frac{\eta_{\rm u}^{\rm K^\pm}}{\eta_{\rm s}^{\rm K^\pm}} = $$



$$\approx \gamma_s$$

Similarly, $\frac{\eta_{\rm u}^{\rm K_s^0}}{\eta_{\rm s}^{\rm K_s^0}} \approx \gamma_s$

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

$$\boxed{\gamma_s = 0.422 \pm 0.049\,(\text{stat.}) \pm 0.059\,(\text{syst.})}$$

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

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)

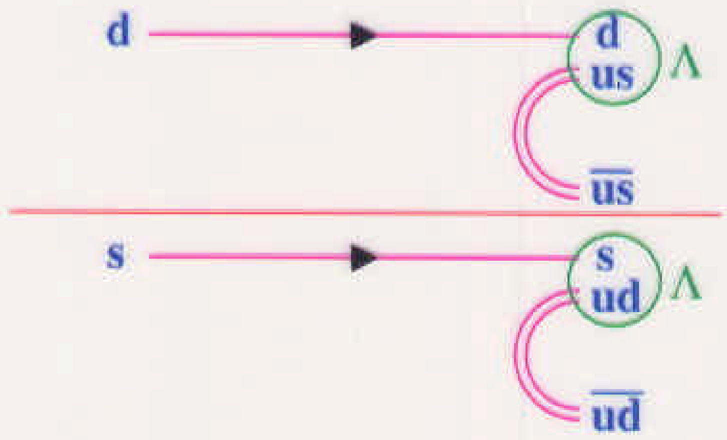
$\longrightarrow$ Similar result, $\gamma_s = 0.26 \pm 0.12$, from SLD (PRL78 (1997) 3442)

Strange diquark suppression factor:

$$\gamma_{us} \equiv \frac{\text{Prob.(us)}}{\text{Prob.(ud)}}$$

us$\overline{\text{us}}$ versus ud$\overline{\text{ud}}$ diquark pair production from the vacuum

$$\frac{\eta_{\mathrm{d}}^{\Lambda}}{\eta_{\mathrm{s}}^{\Lambda}} =$$



$$\approx \gamma_{us}$$

$$\boxed{\gamma_{us} = 0.26 \pm 0.12(\text{tot.})}$$

$(x_p^{min.} > 0.30)$

$\longrightarrow$ $\gamma_{us} = 0.14$ in Jetset/Pythia (OPAL version)

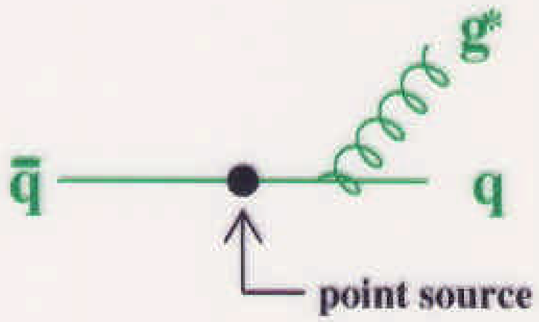
2 Experimental properties of gluon and quark jets from a point source

(OPAL Collab: Eur. Phys. J C11 (1999) 217, Abstract #116)

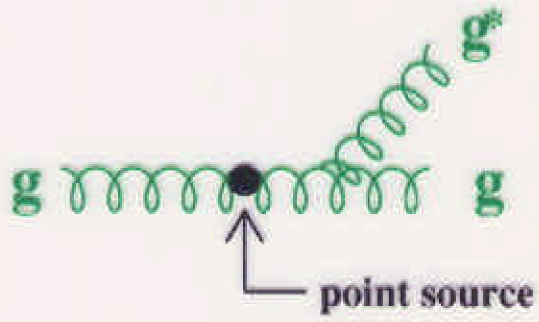
Quark and gluon jets in analytic calculations

→ virtual $q\bar{q}$ and gg pairs from a color singlet point source

Natural Occurrence



e^+e^- annihilations



$\Upsilon \rightarrow \gamma gg$ decays

Jet properties defined by an *inclusive sum* over an event hemisphere:

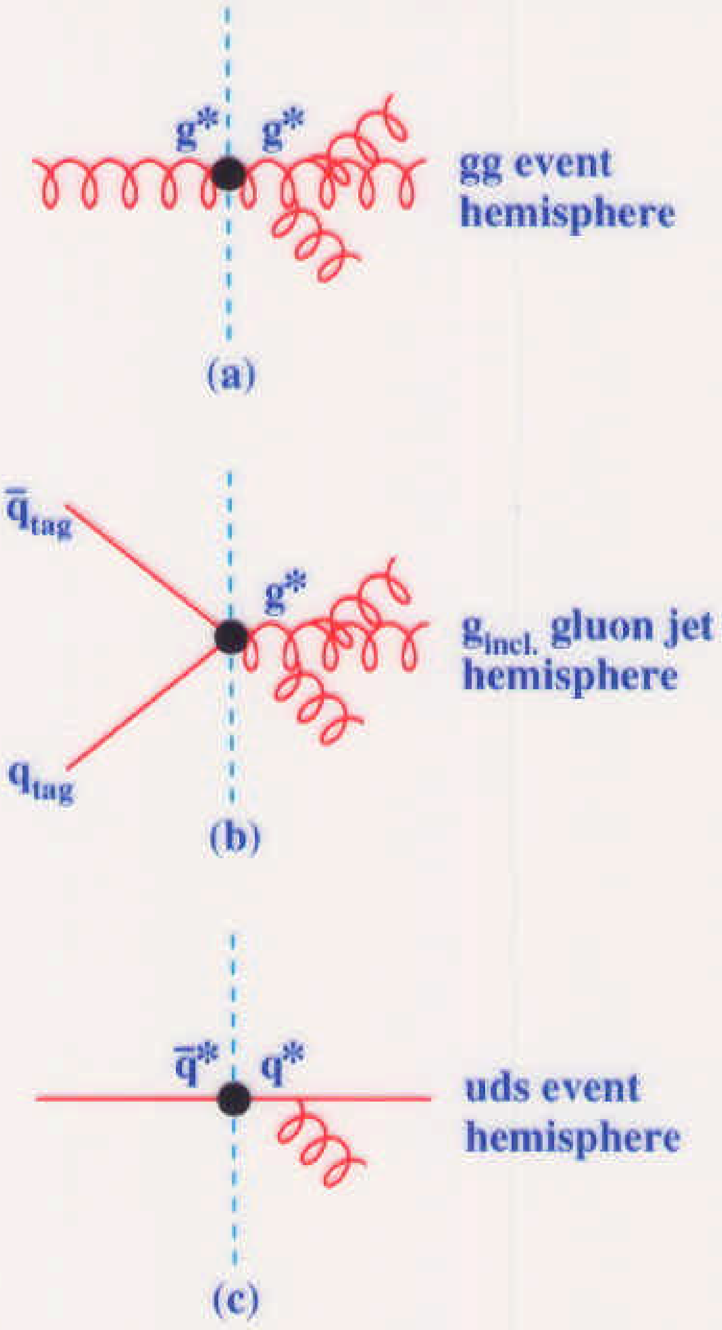
→ No jet-finding algorithm

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

$e^+e^- \rightarrow q_{tag}\bar{q}_{tag}g_{incl.}$ events

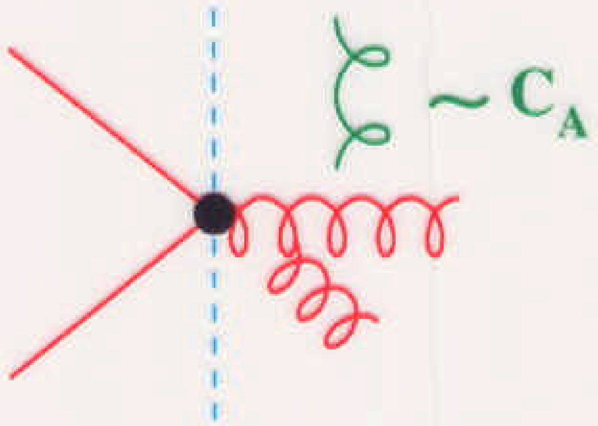
⟶ Unbiased high energy gluon jets

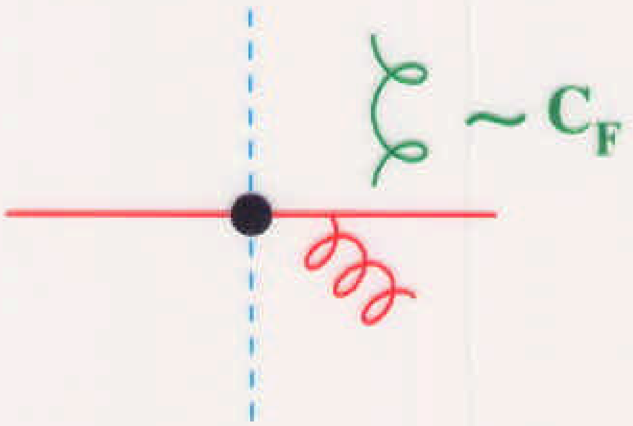
(J.W. Gary, Phys. Rev. D49 (1994) 4503)



OPAL ⟶ Select 439 $g_{incl.}$ jets with 82% purity

Ratio of soft particles at large $p_\perp$ between unbiased gluon and quark jets



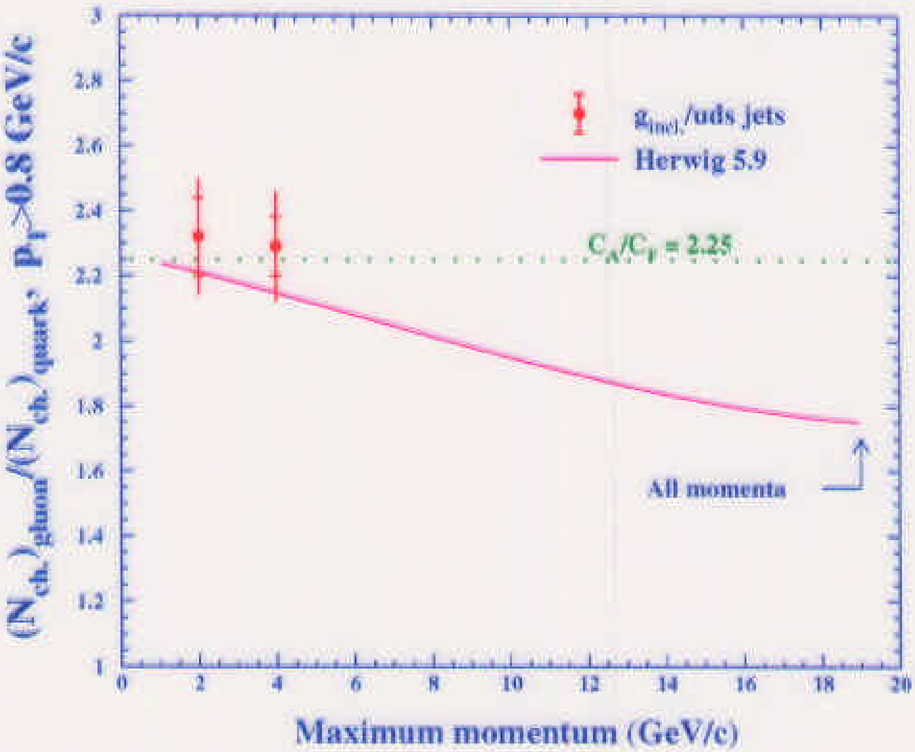


Measures C_A/C_F directly from a ratio of hadron multiplicities

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

$$r \equiv \frac{\langle n_{ch.}\rangle_{gluon}}{\langle n_{ch.}\rangle_{quark}} \text{ versus } p_{\max.}$$

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



Data ($p < 4$ GeV/c)	2.29 ± 0.017 (tot.)
Herwig hadrons, 91 GeV	2.16
Herwig hadrons, 10 TeV	2.24
Herwig partons, 10 TeV	2.25
Jetset partons, 91 GeV, $C_A = C_F$	1.00

3 Multiplicity distributions of hadrons in gluon and quark jets

(Abstract #715)

- I.M. Dremin, J.W. Gary, Phys.Lett. B459 (1999) 341
- I.M. Dremin, J.W. Gary, hep-ph/0004215 (Physics Reports)
- A. Capella, I.M. Dremin, J.W. Gary, V.A. Nechitailo, J. Tran Thanh Van, Phys. Rev. D61 (2000) 074009)

⟶ Analytic description of multiplicity in separated gluon and quark jets to order 3NLO

⟶ Comparison of theory with data

QCD evolution equations for mean multiplicities:
(see, e.g., Yu. Dokshitzer, V.A. Khoze, A.H. Mueller, S.I. Troyan, Basics of Perturbative QCD)

$$G'_G = \int_0^1 dx K_G^G(x)\gamma_0^2[G_G(y+\ln x)G_G(y+\ln(1-x)) - G_G(y)]$$

$$+ n_f \int_0^1 dx K_G^F(x)\gamma_0^2[G_F(y+\ln x)G_F(y+\ln(1-x)) - G_G(y)]$$

$$G'_F = \int_0^1 dx K_F^G(x)\gamma_0^2[G_G(y+\ln x)G_F(y+\ln(1-x)) - G_F(y)]$$

$$G' = dG/dy, \quad y = \ln(Q/\Lambda), \quad F = \text{quark},$$

$$G = \text{gluon}, \quad \mathrm{K} = \text{splitting kernels}, \quad \gamma_0^2 = \frac{2\mathrm{N_c}\alpha_\mathrm{S}}{\pi}$$

Energy evolution of $\langle n_G \rangle$ and $\langle n_F \rangle$ to order γ_0^3:

⟶ I.M. Dremin, J.W. Gary, PLB459 (1999) 341

$$
\begin{aligned}
\langle n_G \rangle &= K y^{-a_1 c^2} \exp(2c\sqrt{y} + \frac{c}{\sqrt{y}}[2a_2c^2 + \frac{\beta_1}{\beta_0^2}(\ln 2y + 2)] \\
&+ \frac{c^2}{y}[a_3c^2 - \frac{a_1\beta_1}{\beta_0^2}(\ln 2y + 1)]) \\
\langle n_F \rangle &= \frac{K}{r_0} y^{-a_1 c^2} \exp(2c\sqrt{y} + \frac{c}{\sqrt{y}}[r_1 + 2a_2c^2 + \frac{\beta_1}{\beta_0^2}(\ln 2y + 2)] \\
&+ \frac{c^2}{y}[a_3c^2 + \frac{r_1^2}{2} + r_2 - \frac{a_1\beta_1}{\beta_0^2}(\ln 2y + 1)])
\end{aligned}
$$

(a_i, r_i, c = constants, K = overall normalization constant)

Multiplicity ratio $r = \langle n \rangle_{gluon} / \langle n \rangle_{quark}$ to γ_0^3 :

⟶ Capella, Dremin, Gary, Nechitailo, Tran, PRD61 (2000) 074009

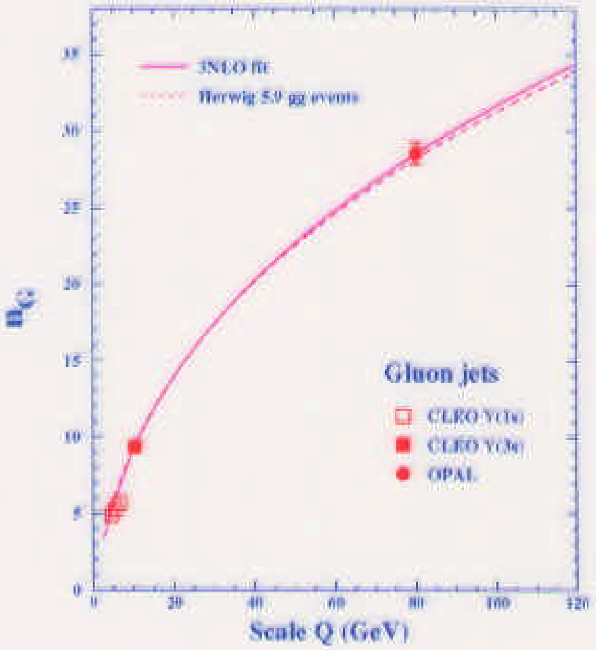
$$r = r_0(1 - r_1\gamma_0 - r_2\gamma_0^2 - r_3\gamma_0^3)$$

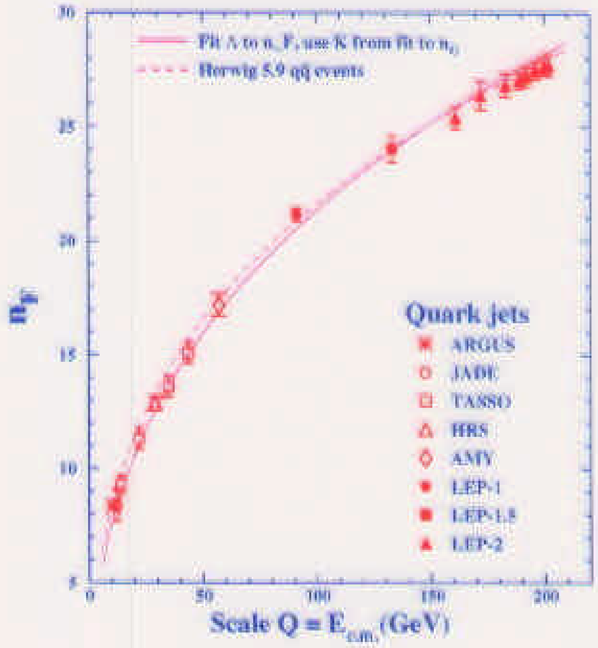
r at the Z^0 scale, $E_{jet} \approx 40$ GeV ($g_{incl.}$ gluon jets) :

LO	⟶	NLO=MLLA	⟶	NNLO	⟶	3NLO
2.25	⟶	2.03	⟶	1.77	⟶	1.74

- Theory approaches the experimental result $r_{ch.} = 1.51 \pm 0.04$ ($Z^0 \to q_{tag}\bar{q}_{tag}g_{incl.}$ events) more closely as higher orders are added
- Numerical solution of evolution eqs. (Lupia, Ochs, PLB418 (1998) 214): ⟶ $r \approx 1.55$

$\langle n \rangle$ versus Q=$E_{c.m.}$: Unbiased gluon and quark jets (hemisphere definition of jets)

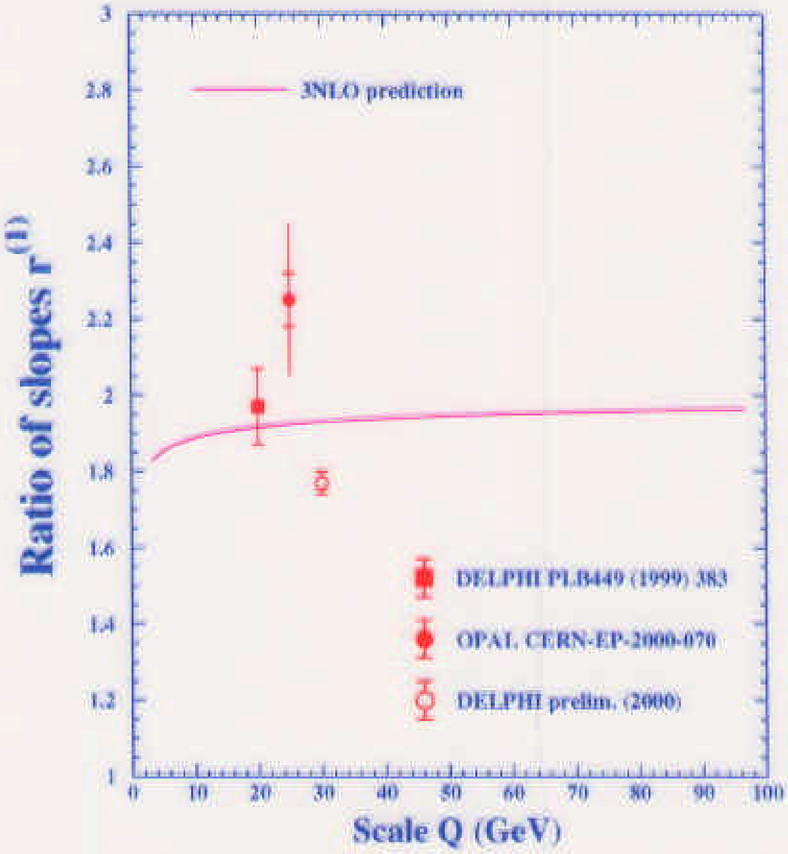




- Fit normalization K and scale parameter Λ to gluon jet data
  $\longrightarrow$ $\alpha_S(M_Z) = 0.14 \pm 0.01$, i.e. $\Lambda \approx \Lambda_{\overline{MS}}$
- Fit Λ to quark jet data using normalization K from gluon jets
  $\longrightarrow$ $\alpha_S(M_Z) = 0.135 \pm 0.002$
- Analytic description of the growth of multiplicity is quite consistent between gluon and quark jets
  ($\longrightarrow$ inclusive definition of jets essential for this result)

Ratio of slopes $r^{(1)} = \frac{d\langle n_G\rangle/dy}{d\langle n_F\rangle/dy}$

⟶ Capella, Dremin, Gary, Nechitailo, Tran, PRD61 (2000) 074009



- Same asymptotic limit ($= C_A/C_F = 2.25$) as the multiplicity ratio $r = \langle n_G\rangle/\langle n_F\rangle$ (cf. DELPHI, PLB449 (1999) 383)
- Smaller pre-asymptotic corrections than r:
  ⟶ $r^{(1)} \approx 1.9$ in Z^0 decays, versus $r \approx 1.5 - 1.7$
- Data are in general agreement with the calculation

4 Substructure dependence of jet cross sections in photoproduction at HERA

(ZEUS Collab: Abstract #906)

- Study of jets from low Q^2 ep scattering:

  $$\gamma p \longrightarrow 2 \text{ jets } (q\bar{q} \text{ or } qg \text{ or } gg) + X$$

  ⟶ Use jet shapes to tag gluon and quark jets

  ⟶ Measure cross sections of the separated 2 jet final states

- Select ≥2-jet final states:

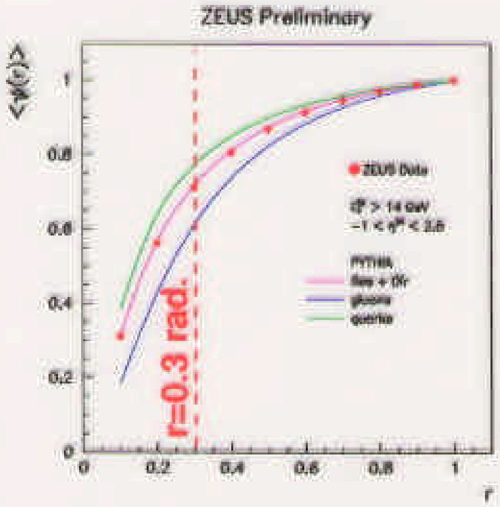
  ⟶ Longitudinally invariant $k_\perp$ jet finder

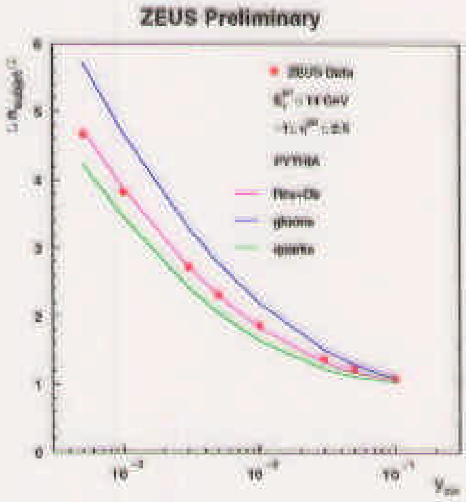
  ⟶ Select events with at least 2 jets with $E_T > 14$ GeV (and $-1 < \eta < 2.5$)

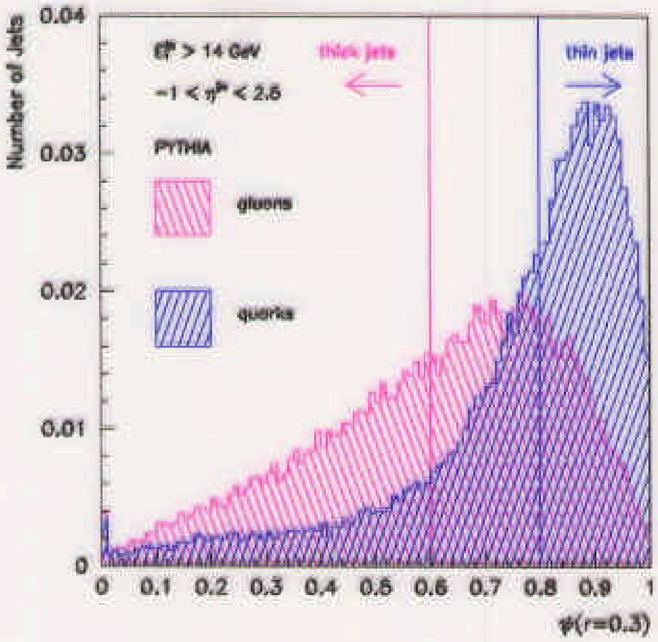
- Select the two jets with highest E_T:

  ⟶ Jet energy profile $\Psi(r)$ = fraction of energy inside a cone of radius $r \leq 1$ around the jet axis, relative to a cone with radius $r = 1$ radians

  ⟶ Sub-jet multiplicity: Re-apply $k_\perp$ jet finder to the particles within a jet, using ever smaller resolution scales y_{cut}







$\Psi(r = 0.3) < 0.6$ ⟶ "thick jets"

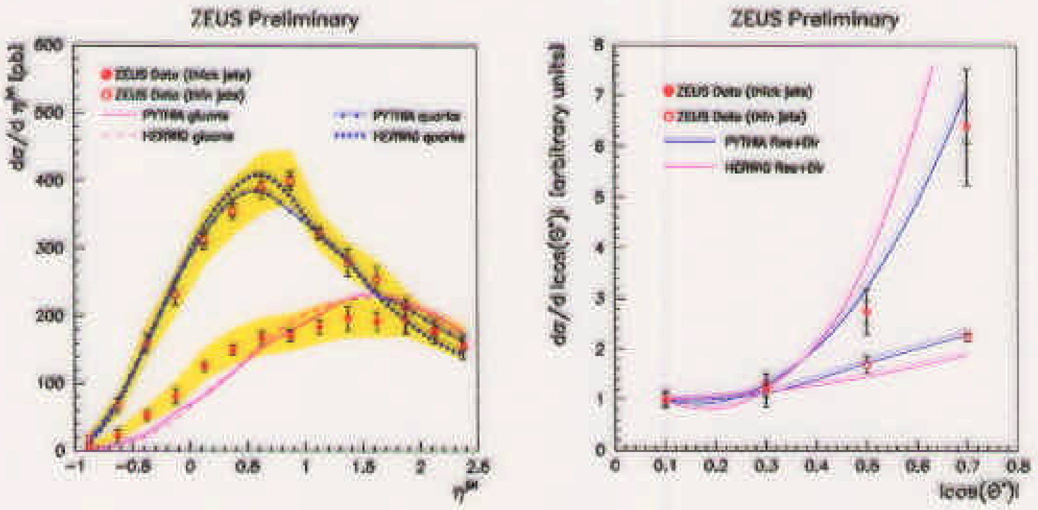
⟶ gluon jet dominated
(MC: gluon purity ~60%)

$\Psi(r = 0.3) > 0.8$ ⟶ "thin jets"

⟶ quark jet dominated
(MC: quark purity ~85%)

Note: Differences between gluon and quark jets based on differences between jet profiles, fragmentation functions, etc., have been well established by LEP using model independent techniques

⟶ Separated gluon and quark jet characteristics well described by the standard MCs (Pythia/Jetset, Herwig, Ariadne)



- $\gamma\,\text{p} \rightarrow\ \text{gg} + \text{X}:$ $\longrightarrow$ Mostly resolved events

  (γ acts as a source of partons)

$\longrightarrow$ $\dfrac{d\sigma}{d\eta_{jet}}$ peaks in a forward direction (towards proton beam axis)

$\longrightarrow$ $\dfrac{d\sigma}{d|\cos\theta^*|} \sim \dfrac{1}{(1-|\cos\theta^*|)^2}$ (t-channel gluon exchange)

Thick-thick events $\sim$ gg

- $\gamma\,\text{p} \rightarrow\ q\bar{q} + \text{X}:$ $\longrightarrow$ Mostly direct events

  (γ couples directly to partons in the proton)

$\longrightarrow$ $\dfrac{d\sigma}{d\eta_{jet}}$ peaks in the central region

$\longrightarrow$ $\dfrac{d\sigma}{d|\cos\theta^*|} \sim \dfrac{1}{1-|\cos\theta^*|}$ (t-channel quark exchange)

Thin-thin events $\sim q\bar{q}$

A Successful separation of the cross sections using differences between gluon and quark jet structure

5 π^0, η, K^0 and charged particle multiplicities in quark and gluon jets

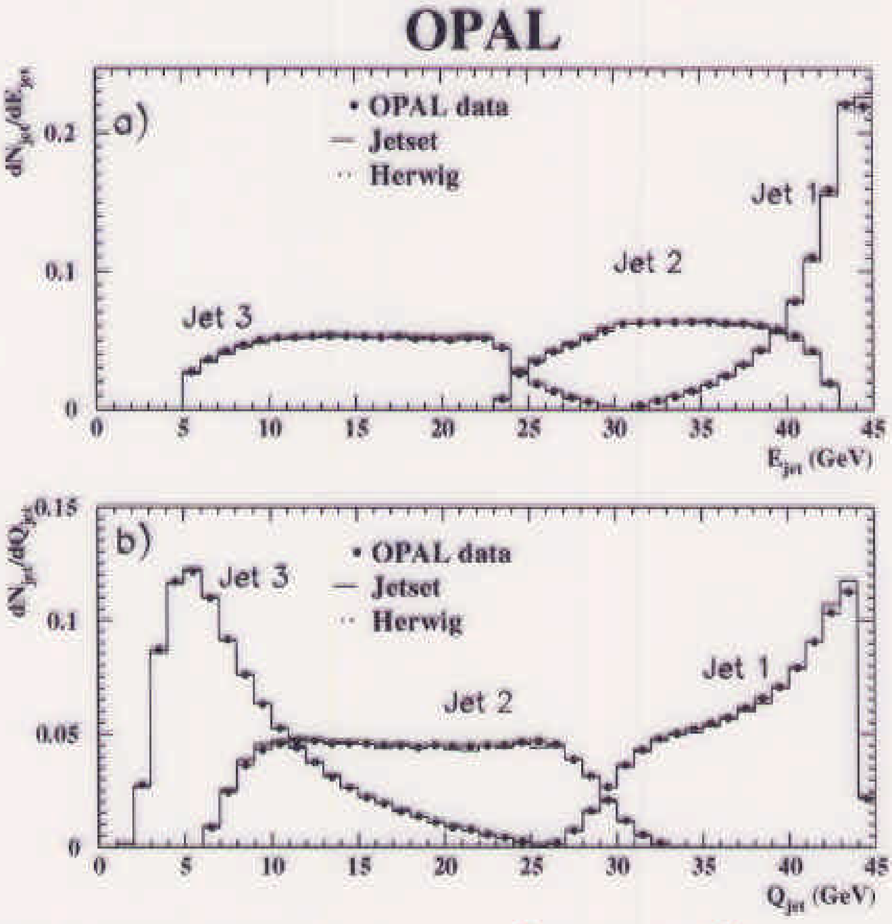
(OPAL Collab: CERN-EP-2000-070, Abstract #250)

- QCD predicts that $r_h = \frac{\langle n_h \rangle_{gluon}}{\langle n_h \rangle_{quark}}$ should be *the same* for all particle types $h = \pi, K, p, \eta \cdots$
- r_h can *be different* for *different particles* because of:
  (1) The decay properties of hadrons:
  ⟶ B hadrons (mostly in quark jets) yield many kaons
  ⟶ $r_K < r_{ch.}$
  (2) Dynamical differences between the hadronization of gluons and quarks:
  ⟶ Lund string model: $r_{baryon} > r_{meson}$
  ⟶ Gluon octet string model (C. Peterson, T.F. Walsh, PLB91 (1980) 455): $r_{isoscalar} > r_{non-isoscalar}$
- Previous LEP results:
  ⟶ Identify pure gluon and quark jets:
  $h = \pi^+, K^+, p, K^0_s, \Lambda$ DELPHI
  $h = K^0_s, \Lambda$ OPAL
  ⟶ Energy order the jets in 3-jet events:
  $h = \pi^0, \eta, \eta', K^0_s, \Lambda$ ALEPH
  $h = \pi^0, \eta, K^0_s, \Lambda$ L3

This study ⟶ First measurement of π^0 and η rates in identified gluon and quark jets

- Reconstruct 3-jet events: $k_\perp$, cone, Luclus
- Order jets by energy: $E_1 > E_2 > E_3$

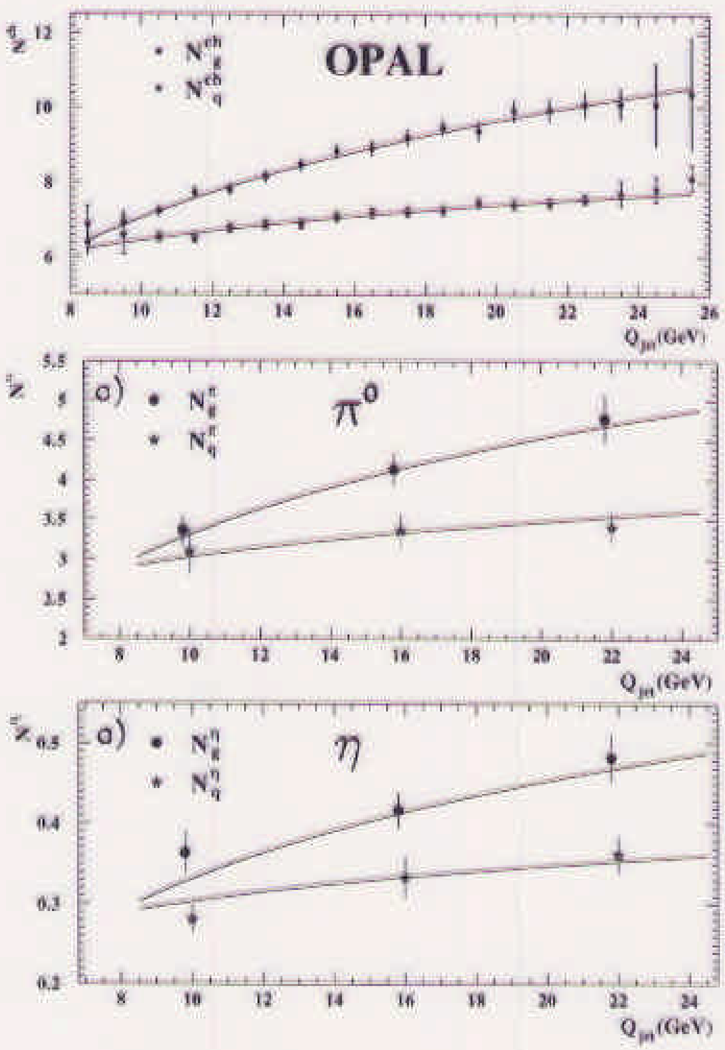
  ⟶ Jet energy gives the *gluon jet content*
- Examine jets vs. scale: $\kappa = Q_{jet} = E_{jet}\sin(\theta_{\min}/2)$



- Measure the $n_{ch.}$, η, π^0 and K^0_s rates in jets 2 and 3 in their overlap region: $7 < Q < 30$ GeV
- Unfold to correspond to pure gluon and quark jets

Data versus polynomial parametrization

→ Fit polynomials to $\langle n_{ch} \rangle_{quark}$ and $\langle n_{ch} \rangle_{gluon}$ versus Q



→ Scale parametrizations of $\langle n_{ch} \rangle_{quark}$ and $\langle n_{ch} \rangle_{gluon}$ by the *same factor* to obtain parametrizations for π^0; similarly for η

→ r_π agrees with $r_{ch.}$ for all Q values

→ *Slight excess* of r_η with respect to $r_{ch.}$ in the lowest Q bin

$r_h = \frac{\langle n_h \rangle_{gluon}}{\langle n_h \rangle_{quark}}$ versus $r_{ch.}$

$\longrightarrow r_\eta / r_{ch.} = 1.09 \pm 0.12$

$\longrightarrow r_{\pi^0} / r_{ch.} = 1.01 \pm 0.04$

$\longrightarrow r_{K^0_s} / r_{ch.} = 0.95 \pm 0.04$

⟶ Previous LEP evidence for dynamical differences between gluon and quark jet hadronization:

$\longrightarrow r_\Lambda / r_{ch.} = 1.41 \pm 0.06$ OPAL, EPJ C8 (1999) 241

$\longrightarrow r_p / r_{ch.} = 1.21 \pm 0.05$ DELPHI, CERN-EP-2000-007

$\longrightarrow \langle n_\eta \rangle_{data} / \langle n_\eta \rangle_{MC} \approx 1.3 \pm 0.1$ in the lowest energy jets of 3-jet events L3, PL B371 (1996) 126 (but not confirmed by ALEPH, CERN-EP-99-105)