Jets at e^+e^- colliders

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Outline

(I) Overview and historical perspective

(II) Basic tools: Monte Carlo simulation programs
($\longrightarrow$ test of the hadronization process)

(III) Basic tools: jet finding algorithms

(IV) Test of matrix elements

(V) Measurement of the color factors

(VI) Differences between gluon & quark jets

(VII) Tests of the hadronization process

Overview and historical perspective

$\boxed{e^+e^- \text{ annihilations}}$ $\longrightarrow$ The simplest type of accelerator experiment currently possible

$\longrightarrow$ No parton distribution functions

$\longrightarrow$ No strong interaction ISR

$\longrightarrow$ No beam remnants (underlying event)

- Uniquely precise with respect to theoretical modeling and clean interpretation of data

- Played a vital role in establishing QCD as the correct theory of strong interactions $\longrightarrow$ "Precision" tests of QCD

- A number of fundamental discoveries in jet physics:
  - $\longrightarrow$ First observation ("discovery") of jets
  - $\longrightarrow$ First direct observation of the gluon
- Many unique & classic studies, first (and often still best) measurements which helped to establish QCD:
  - $\longrightarrow$ Spins of the quark and gluon
  - $\longrightarrow$ Precise, consistent measurements of α_S
  - $\longrightarrow$ Running of α_S
  - $\longrightarrow$ Triple-gluon vertex and other non-Abelian characteristics
  - $\longrightarrow$ Precise measurements of the color factors & establishment of SU(3) gauge structure
  - $\longrightarrow$ Differences between gluon & quark jets
  - $\longrightarrow$ First experimental demonstration of coherence effects in QCD (string effect)

Principal e^+e^- experiments in QCD

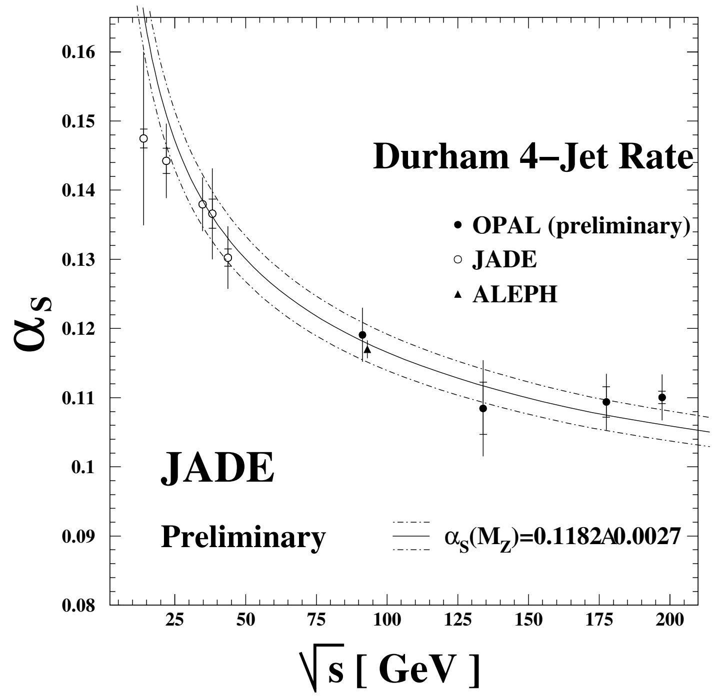
	$\sqrt{s}$ (GeV)	Experiment	Dates
LEP	$88-208$	$\boxed{\text{ALEPH, DELPHI, L3, OPAL}}$	1989-2000
SLC	91	SLD	1991- $\sim$1998
TRISTAN	$52-64$	AMY, TOPAZ, VENUS	1987-1995
PEP	29	DELCO, HRS, MAC, MARK-2, TPC	1980-1990
PETRA	$12-44$	CELLO, $\boxed{\text{JADE}}$, MARK-J, PLUTO, TASSO	1978-1986
CESR	10	CLEO	1979-2003
SPEAR	$3-8$	SLAC-LBL Collab.	1975-1976

$\boxed{\text{EXPERIMENT}}$ $=$ Still producing QCD results in late 2003 or later

α_s from 4-jet event rate at $\sqrt{s} = 14 - 44$ GeV

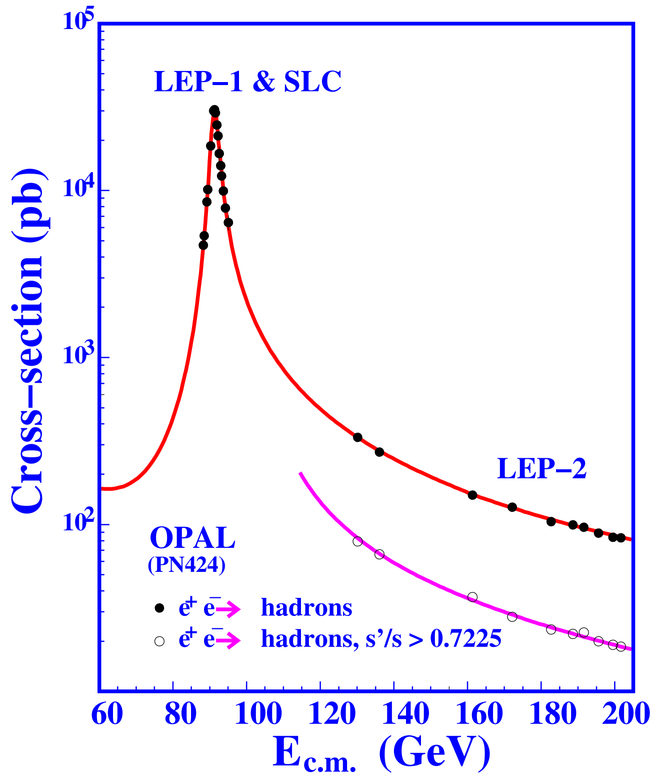
[JADE Collab., hep-ex/0408122 (August 2004)]

- Data collected 1981-1986
- $\mathcal{O}(\alpha_S^3)$+NLLA theory (NLO) from 1998 [Nagy & Trócsányi]
- k_T (Durham) jet-finder from 1991 [Catani et al.]



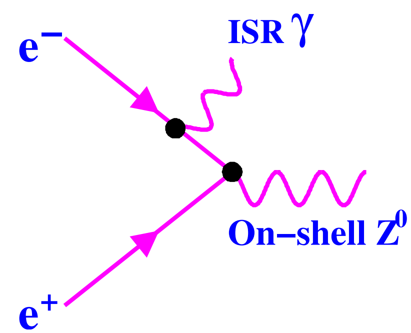
- Re-analyze the old PETRA data using theory unavailable at the time $\longrightarrow$ Joint program in physics & archeology !!

LEP & SLC: the main "QCD machines"



Most LEP-2 QCD events:

Radiative returns:
$e^+e^- \to Z^0\gamma$

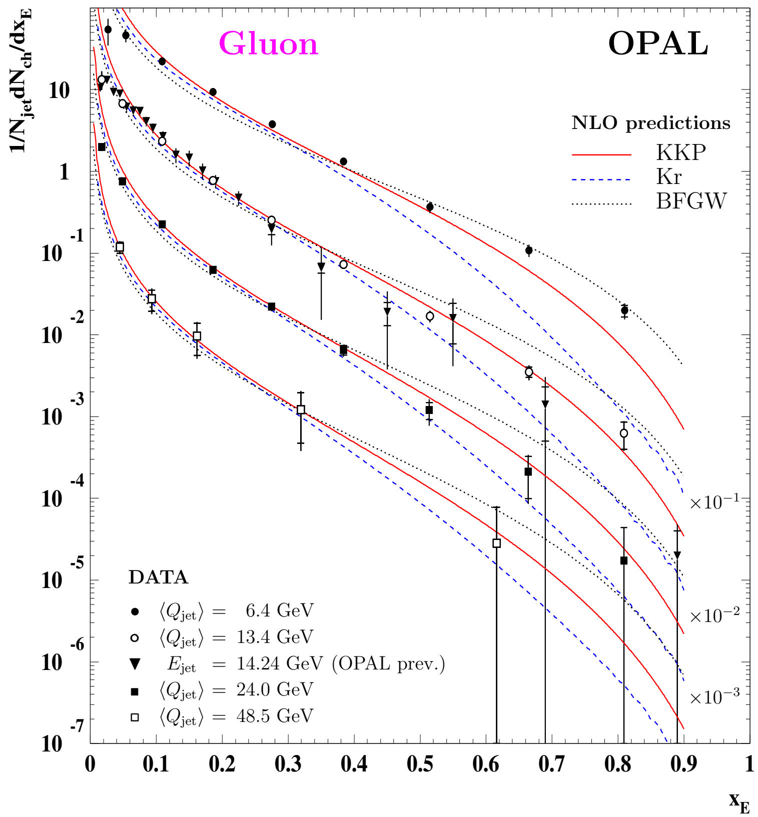


$\longrightarrow$ Cut on hadronic energy s'

- Large e^+e^- energies and data samples [LEP-1: $\sim 4\times10^6$ hadronic events per experiment versus $\sim 10^5$ at PEP/PETRA]
  - $\longrightarrow$ Perturbative calculations more reliable (α_S is smaller)
  - $\longrightarrow$ Hadronization uncertainties less important
  - $\longrightarrow$ Perturbative structure of jets more developed
- LEP/SLC placed experimental jet physics on a quantitative footing

Recent LEP studies · · · since 2003

- Comparison of (gluon) jet fragmentation functions at different energies (LEP-1 & LEP-2 data) [OPAL Collab., Eur. Phys. J C37 (2004) 25]

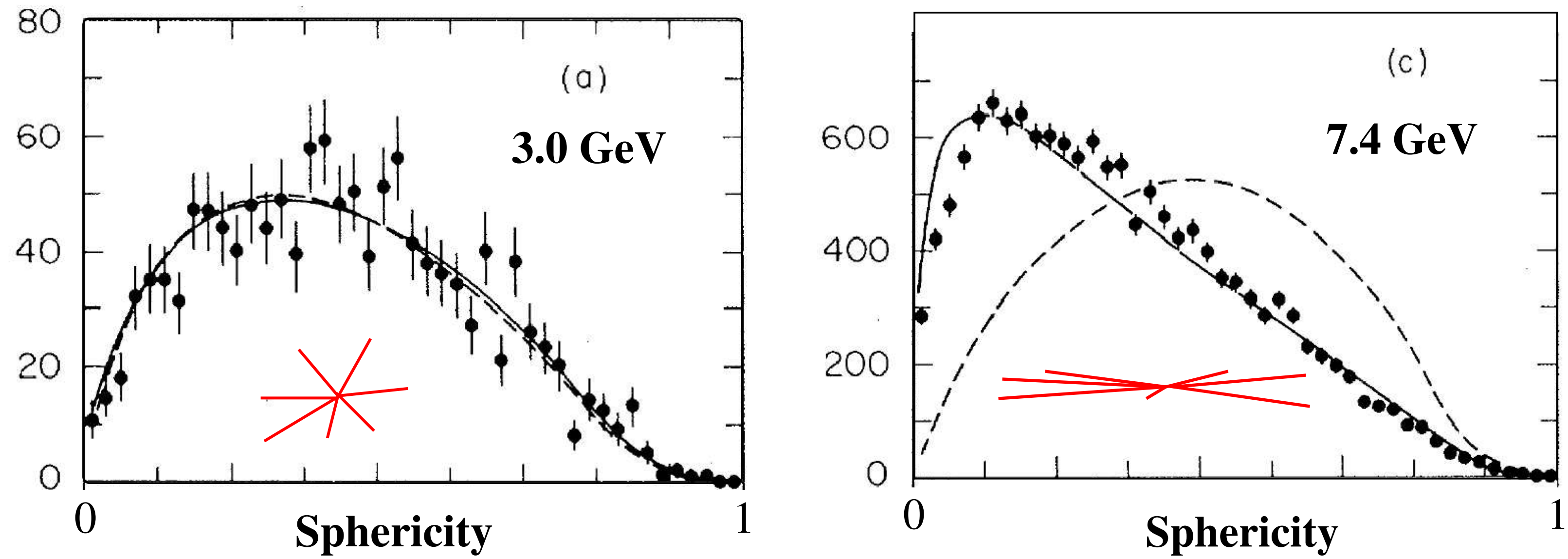


$\longrightarrow$ Scaling violations

- α_s from event shape measurements (Thrust) & four-jet event rates using LEP-1 & LEP-2 data (ALEPH, DELPHI, L3, OPAL)

“Discovery” of Jets: $\mathrm{E}_{\mathrm{c.m.}} \approx$ 7 GeV

[SLAC-LBL Collab., G. Hanson et al., Phys. Rev. Lett. 35 (1975) 1609]



——— Jet model - - - - - - Phase space model

$\longrightarrow$ SPEAR e^+e^- storage ring at SLAC; Sphericity $S = \frac{3}{2}\frac{(\sum_i p^2_{\perp,i})_{\mathrm{min.}}}{\sum_i p_i^2}$

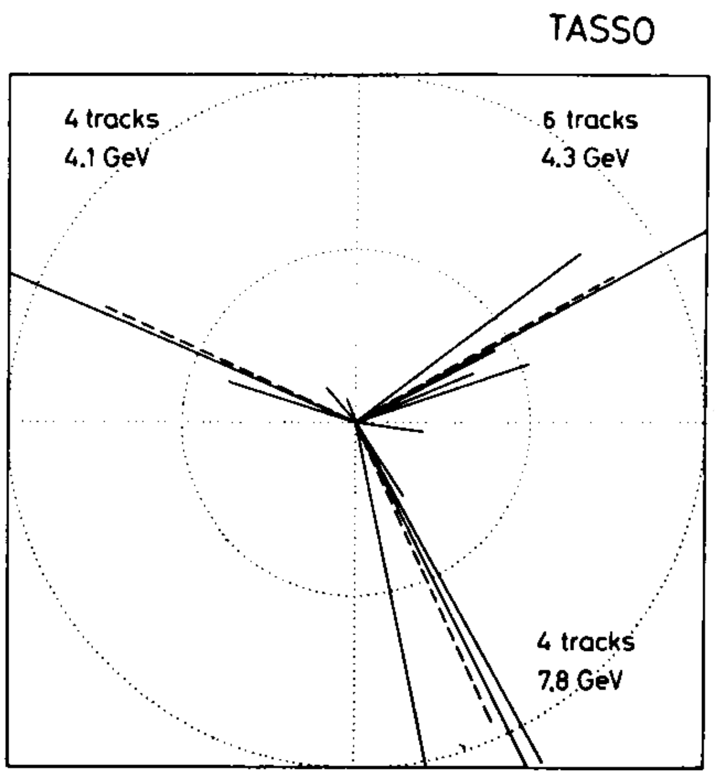
$\longrightarrow$ Isotropic phase space model for particle production, versus model with JETS

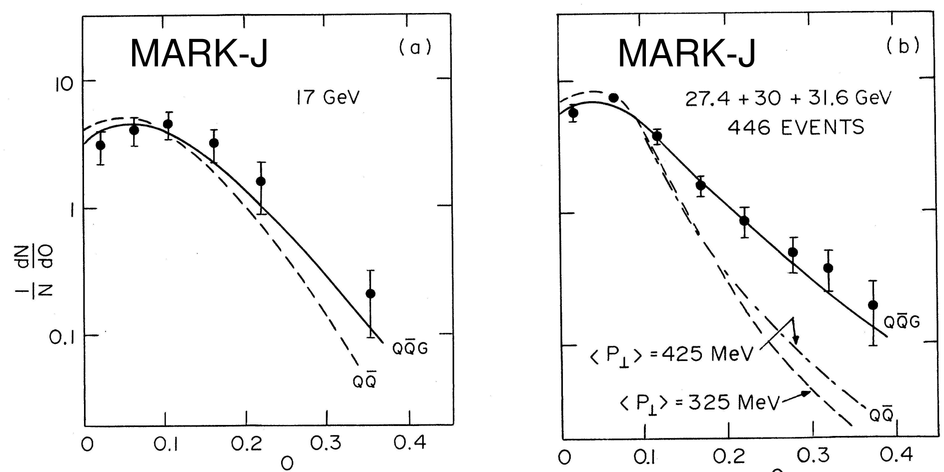
$\longrightarrow$ At higher energies, the data are more clustered around an axis than predicted by isotropic phase space $\longrightarrow$ First observation of jets

“Discovery” of the Gluon: $\mathrm{E_{c.m.}} \approx 30$ GeV

[TASSO Collab., Phys. Lett. B86 (1979) 243; MARK-J Collab., Phys. Rev. Lett. 43 (1979) 830; PLUTO Collab., Phys. Lett. B86 (1979) 418; JADE Collab., Phys. Lett. B91 (1980) 142]

$\longrightarrow$ PETRA e^+e^- storage ring at DESY: $\boxed{e^+e^- \longrightarrow q\bar{q}g}$





Oblateness O = $\mathrm{T_{major}} - \mathrm{T_{minor}}$

Events at $\sqrt{s} \sim 30$ GeV exhibit more Oblateness (planar structure) than the models without gluon radiation

Basic tools: Monte Carlo simulation programs

Essential $\longrightarrow$ to evaluate detector response

$\longrightarrow$ to estimate hadronization effects (corrections)

$\longrightarrow$ to evaluate biases

$\longrightarrow$ to establish sensitivity to physics (e.g. sensitivity to coherence phenomena $\rightarrow$ String Effect)

The principal QCD programs

Jetset / Pythia Herwig Ariadne

have been tuned to LEP-1 data using

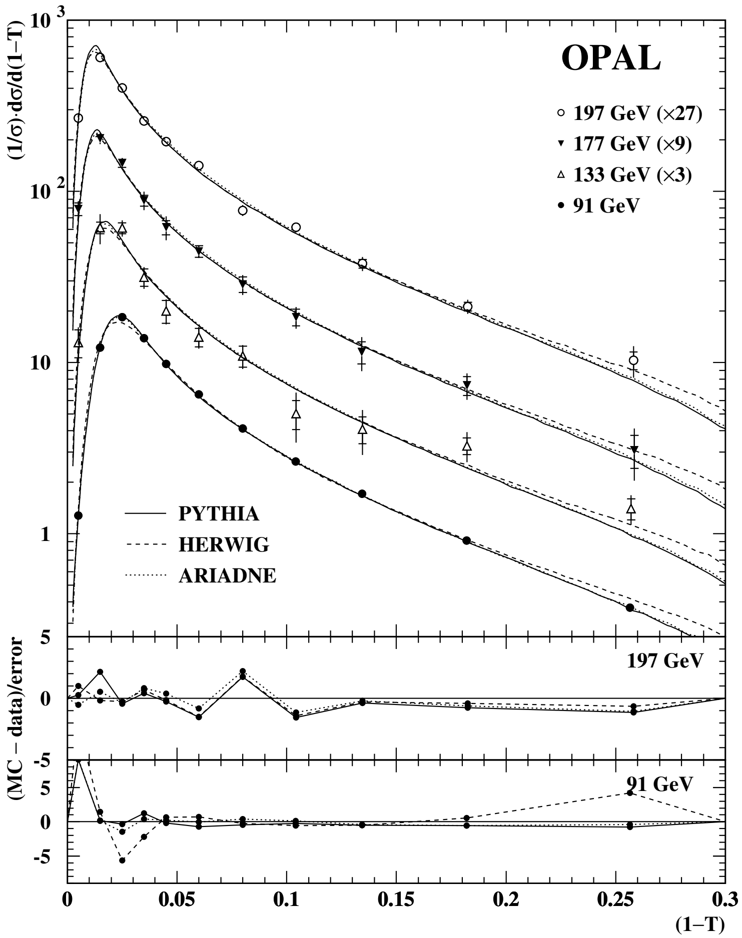
$\longrightarrow$ the mean charged particle multiplicity, $\langle n_{ch} \rangle$

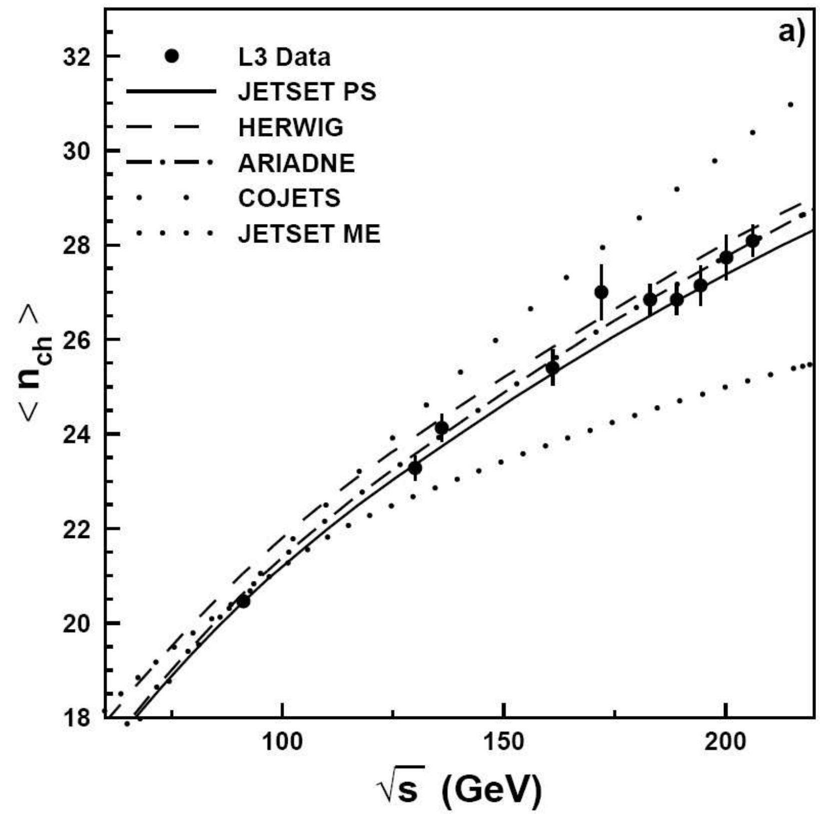
$\longrightarrow$ event shape information, e.g. Thrust, Sphericity, etc. (momentum structure of an event)

$\longrightarrow$ Inclusive identified particle production rates and distributions

Data versus MC at different $\sqrt{s}$

[OPAL Collab., hep-ex/0503051 (Aug. 2004); L3 Collab., Phys. Rep. 399 (2004) 71]



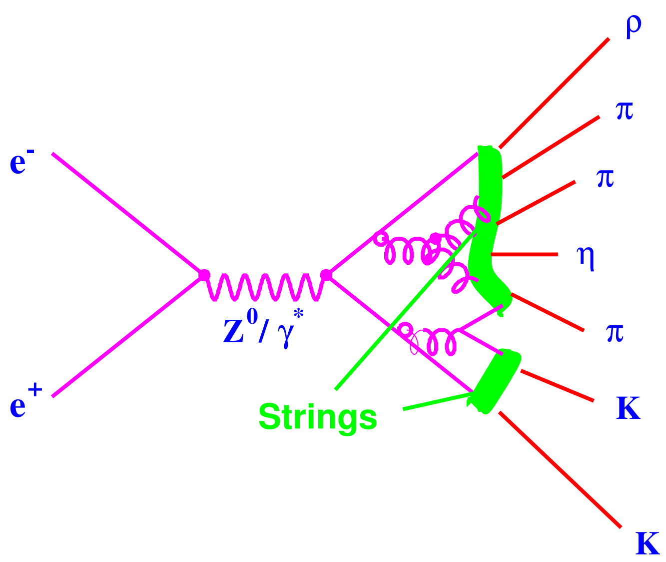


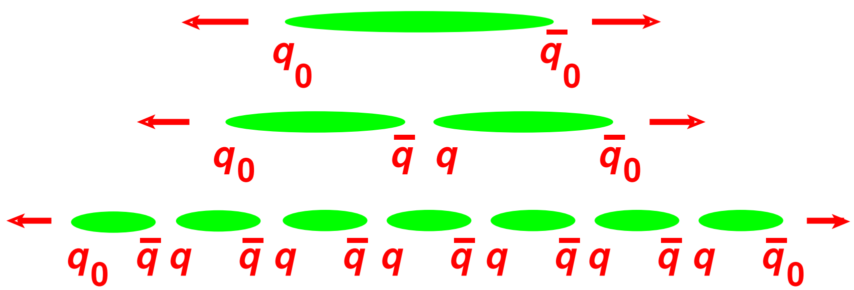
COJETS $\longrightarrow$ No color coherence (destructive interference)

Matrix Elements (ME) $\longrightarrow$ $\mathrm{n}_{\mathrm{parton}}^{\mathrm{max.}} = 4$: improper scaling violation

Jetset/Pythia

- Parton shower based on LO Altarelli-Parisi splitting functions: $q \to qg$, $g \to gg$, $g \to q\overline{q}$ (as an option, fixed order $\mathcal{O}(\alpha_S^2)$ matrix elements)
- Hadronization $\longrightarrow$ the $\boxed{\text{Lund String model}}$





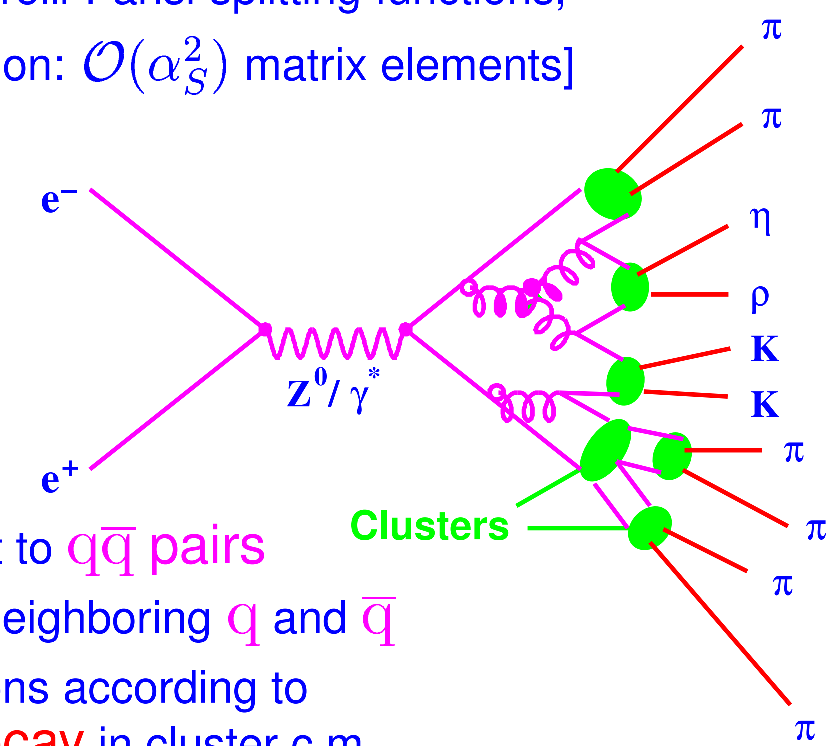
q & $\overline{q}$ terminate each string segment $\longrightarrow$ color triplet fields

Each color triplet string segment hadronizes in its rest frame

$\longrightarrow$ longitudinal phase space model based on analytic parametrizations for momenta spectra and particle species

Herwig

- Parton shower based on LO Altarelli-Parisi splitting functions, with NLO accuracy at high x [option: $\mathcal{O}(\alpha_S^2)$ matrix elements]



- Hadronization
  $\longrightarrow$ the Cluster model

- Gluons from the parton shower are split to $q\overline{q}$ pairs
- Color singlet clusters are formed from neighboring q and $\overline{q}$
- The low mass clusters decay into hadrons according to 2-body phase space $\rightarrow$ isotropic decay in cluster c.m.

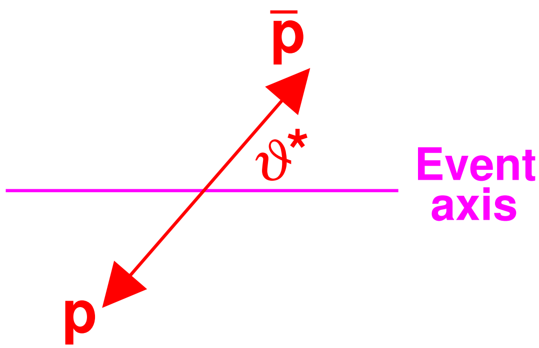
$\longrightarrow$ No analytic functions to parametrize the longitudinal or transverse momentum spectra of hadrons or to specify the relative abundance of different hadrons ($\pi^{\pm}$, $K^{\pm}$, etc.)

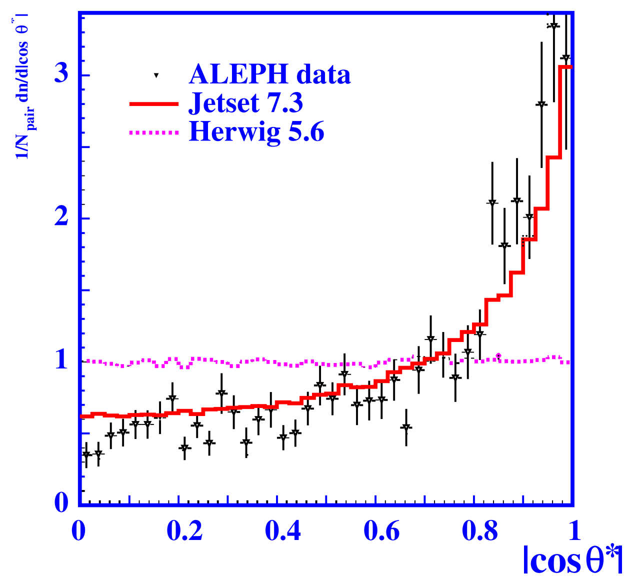
$\longrightarrow$ Intrinsically more simple than String Hadronization, but the overall description of data not as good

Experimental discrimination between string & and cluster hadronization

[TPC Collab., Phys. Rev. Lett. 55 (1985) 1047; ALEPH Collab., Phys. Rep. 294 (1998) 1]

⟶ $\cos\theta^*$ distribution of identified proton-antiproton ($\mathrm{p\overline{p}}$) pairs
[Angle between $\mathrm{p}(\overline{\mathrm{p}})$ and event (sphericity) axis in back-to-back $\mathrm{p\overline{p}}$ frame]





⟶ The simple isotropic cluster decay model is **not correct** !!

⟶ **Tune-able** angular correlations implemented in later versions of Herwig – between perturbatively produced partons and the hadrons containing them – partially correct this problem (CLDIR/CLSMR: turned on by default)

⟶ The **cluster model** becomes more **“string-like”**

Basic tools: jet finding algorithms

Many tests of QCD are based on grouping particles into JETS:

Recombination jet algorithms

$\longrightarrow$ The almost universal choice at e^+e^- colliders

- Recombination metric: $y_{ij} = \dfrac{M_{ij}^2}{E_{c.m.}^2}$

$\longrightarrow$ Combine the particle pair (i, j) with the smallest y_{ij}:

$$(i, j) \rightarrow k$$

$$\underline{\text{E scheme :}} \qquad p_k = p_i + p_j \qquad \longrightarrow \quad \text{massive jets}$$

$$\underline{\text{E}_0\,\text{scheme :}} \qquad E_k = E_i + E_j$$

$$\vec{p}_k = \frac{\vec{p}_i + \vec{p}_j}{|\vec{p}_i + \vec{p}_j|} E_k \qquad \longrightarrow \quad \text{massless jets}$$

- Iterate until all remaining (i, j) pairs satisfy $y_{ij} > y_{cut}$

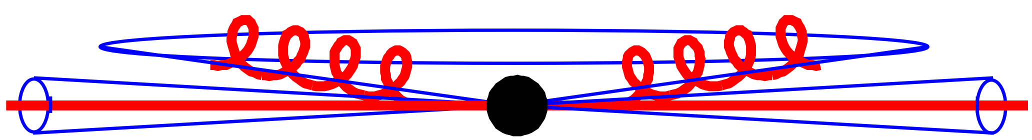
The JADE jet finder

[JADE Collab., Z. Phys. C33 (1986) 23]

$\longrightarrow$ The original recombination jet finder:

- $M_{ij}^2 = 2E_iE_j(1-\cos\theta_{ij}) \approx$ (invariant mass)^2
- Original version based on the E_0 scheme

Sometimes leads to the formation of "junk jets"



$\longrightarrow$ Two-jet events with ≥ 2 soft, collinear gluons can be classified, unnaturally, as three-jet events

$\longrightarrow$ Inhibits re-summation techniques from being applied

The Durham $k_\perp$ jet finder

[S. Catani et al., Phys. Lett. B269 (1991) 432]

$\longrightarrow$ Introduced to reduce the problem of junk jets

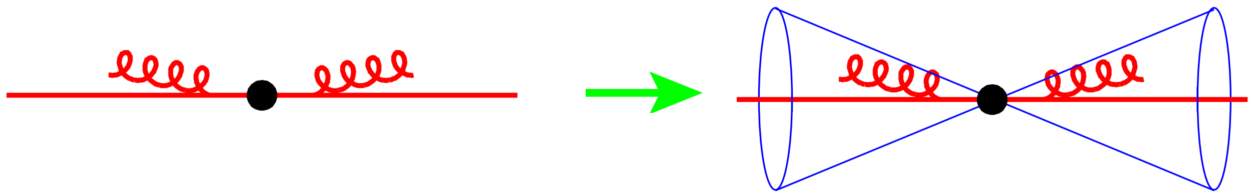
- $M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$
- E scheme combination of particles: $(i,j) \to k$

$\longrightarrow$ Consider small emission angles θ_{ij}:

$$\begin{aligned} M_{ij}^2 &\approx 2\min(E_i^2, E_j^2)\left[1-\left(1-\theta_{ij}^2/2+\cdots\right)\right] \\ &\approx \min(E_i^2, E_j^2)\,\theta_{ij}^2 \approx K_\perp^2 \end{aligned}$$

(min. transverse momenta of one particle w.r.t. the other)

$\longrightarrow$ Soft, collinear radiation is attached to the correct jet

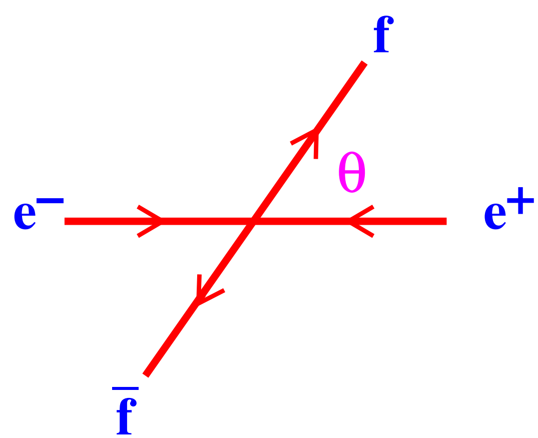


$\longrightarrow$ Facilitates re-summation

Test of matrix elements

- $\longrightarrow$ QCD predictions for the energy and angular distributions of jets
- $\longrightarrow$ Sensitive to the spin of the partons, and to the underlying group structure of strong interactions

e.g. the two-jet matrix element $\longrightarrow$ spin of the quark



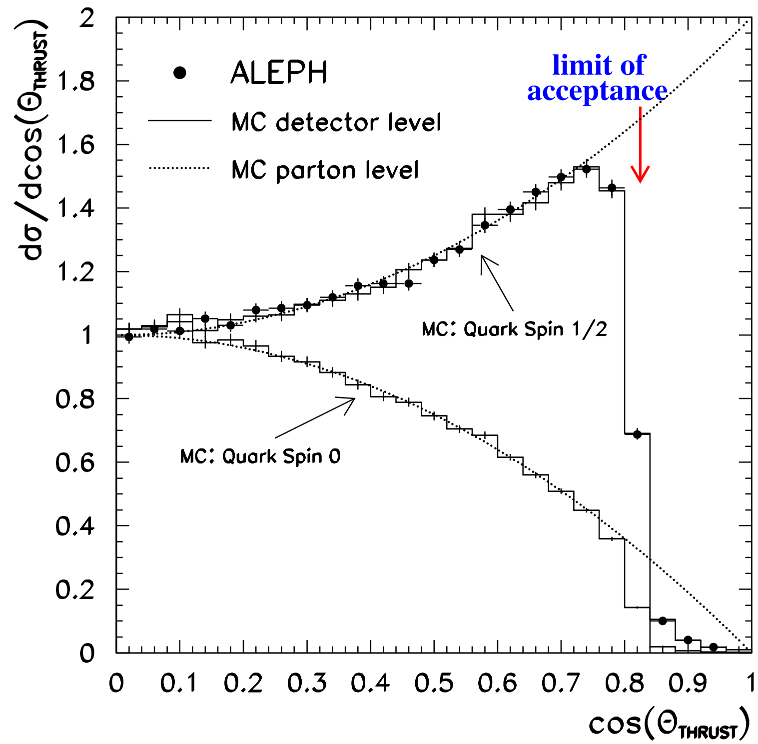
$$\longrightarrow \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = 1+\cos^2\theta \quad \text{(spin 1/2 fermions)}$$

$$= \sin^2\theta \quad \text{(spin 0 fermions)}$$

(f and $\overline{\mathrm{f}}$ assumed massless, and are not distinguished from each other, so that the forward-backward asymmetry averages to zero)

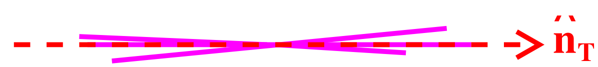
Angle $\theta_{\rm thrust}$ between the thrust and beam axes

[ALEPH Collab., Phys. Rep. 294 (1998) 1]



Thrust axis: the direction $\hat{n}_T$ which maximizes the longitudinal momentum sum of particles with respect to a chosen direction

$$\mathrm{T} = \max\left(\frac{\sum \vec{\mathrm{p}}_\mathrm{i}\cdot\hat{\mathrm{n}}_\mathrm{T}}{\sum|\vec{\mathrm{p}}_\mathrm{i}|}\right) = \mathrm{Thrust}$$



T ~ 1

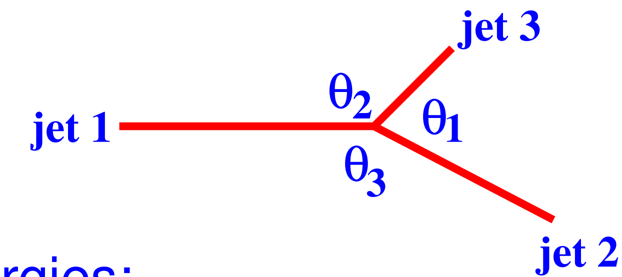
$\hat{n}_T$ approximately gives direction of q (or $\overline{\mathrm{q}}$) in narrow $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q}\overline{\mathrm{q}}$ events

Three-jet matrix element: spin of the gluon

[SLD Collab., Phys. Rev. D55 (1997) 2533]

- Select 3-jet events: $\longrightarrow$ JADE jet finder, $y_{cut} = 0.02$

  (25% of events are classified as having 3-jet structure)



- Calculated jet energies:

  $\longrightarrow$ Impose energy-momentum conservation, assuming the jets are massless

$$E_i = E_{c.m.} \cdot \frac{\sin\theta_i}{\sum\limits_{i=1,3} \sin\theta_i}$$

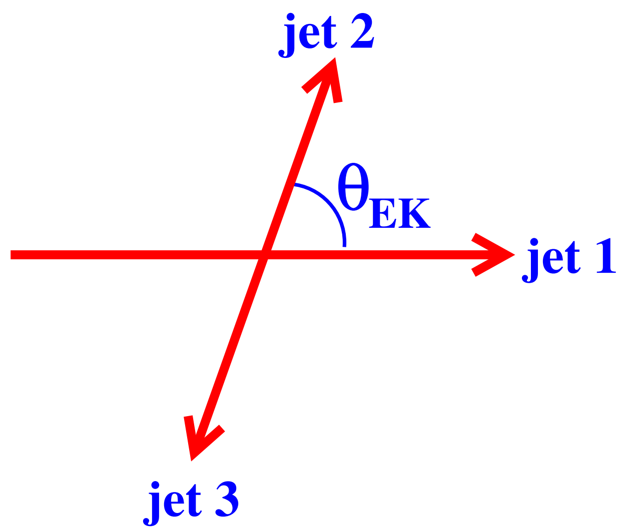
- Energy tagging of the jets: $E_1 > E_2 > E_3$

  $\longrightarrow$ Jet 3 is the gluon jet in $\sim 75\%$ of the events

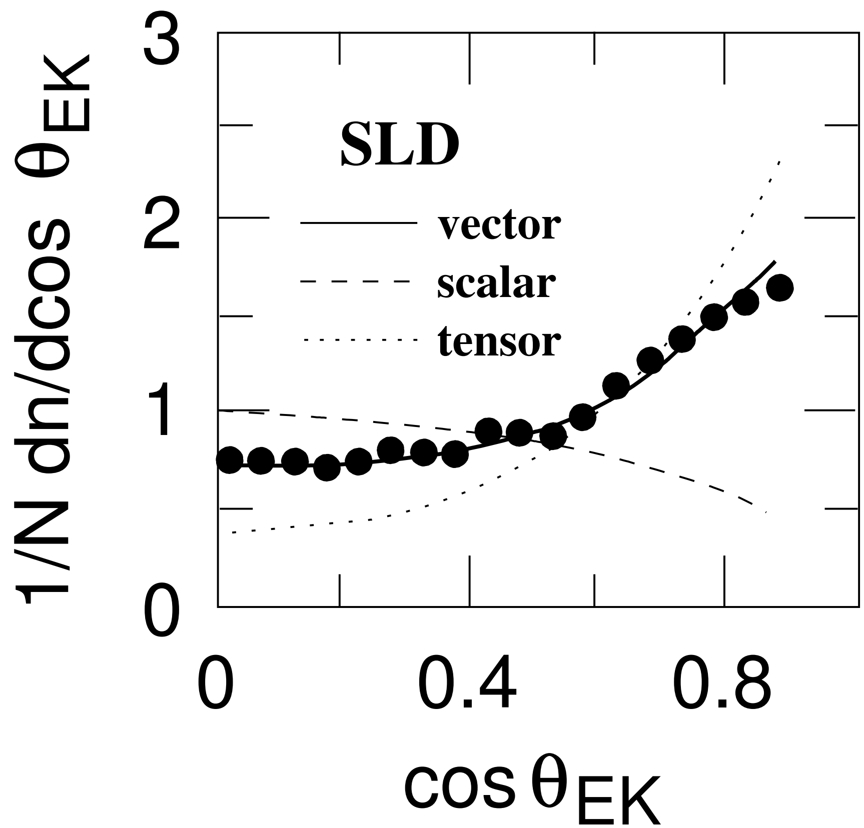
- Scaled jet energies: $x_i = \frac{2E_i}{E_{c.m.}}$; $x_1 + x_2 + x_3 = 2$

Ellis-Karliner angle, $\theta_{\mathrm{EK}} \equiv \dfrac{x_2 - x_3}{x_1}$

[J. Ellis & I. Karliner, Nucl. Phys. B148 (1979) 141]



Boost along jet 1 to the frame where jets 2 & 3 are back−to−back
(massless partons at tree level)



Four-jet matrix element: Existence of the 3-gluon vertex

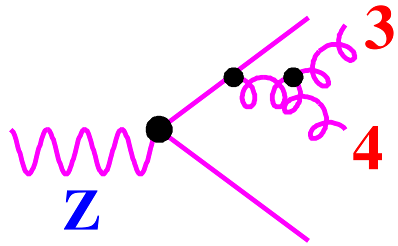
[L3 Collab., Phys. Lett. B248 (1990) 227]

- Select 4-jet events: $\longrightarrow$ JADE jet finder, $y_{cut} = 0.02$

  (8.6% of events are classified as having 4-jet structure)

- Order jets by energy: $E_1 > E_2 > E_3 > E_4$

$\longrightarrow$ Jets 3 and 4 are more likely to be the "radiated" particles



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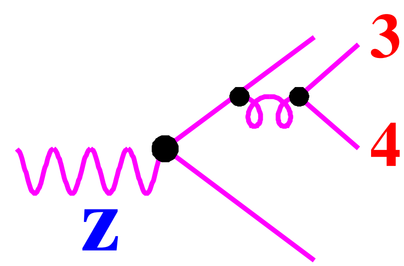
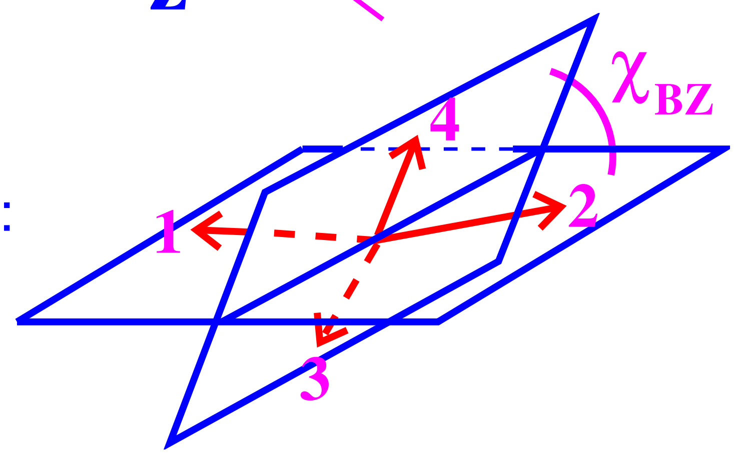
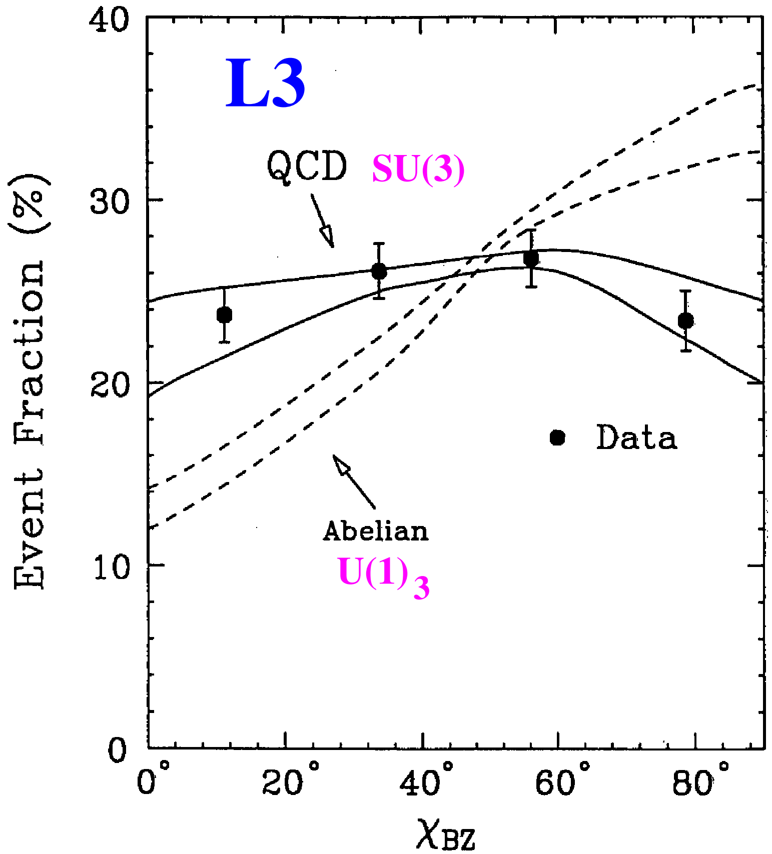


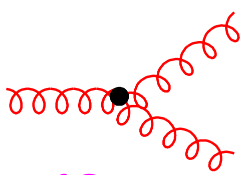
- The Bengtsson-Zerwas angle, χ_{BZ}:



Bengtsson-Zerwas angle, χ_{BZ}



Abelian model U(1)$_3$: $\longrightarrow$ No 3-gluon coupling

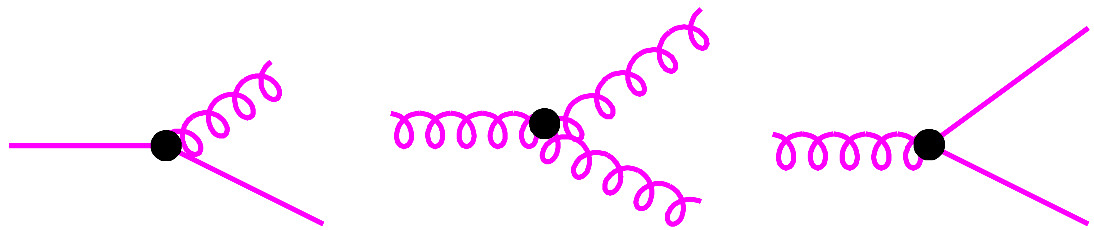


$\longrightarrow$ χ_{BZ} is sensitive to the gauge group structure of strong interactions

$\longrightarrow$ Some of the earliest direct evidence for the 3-gluon coupling

Measurement of the color factors

The color factors $\mathrm{C_F}, \mathrm{C_A}, \mathrm{T_F}$ specify the relative probabilities of $\cdots$



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

$\cdots$ the most important numbers in QCD besides α_S !!

In $\mathrm{e^+e^-}$ annihilations, the color factors can be measured precisely !

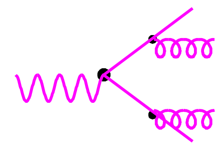
- Angular correlations in 4-jet events
- Event shapes: 2- and 3-jet events, 4-jet rates
- Ratio of soft particle multiplicities in gluon and quark jets

Angular correlations in 4-jet events

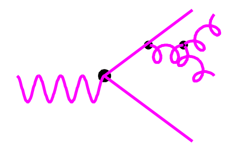
Expression for $\boxed{e^+e^- \to 4 \text{ jets}}$ to $\mathcal{O}(\alpha_S^2)$ (tree level)

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

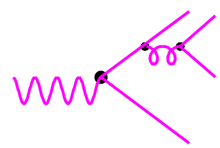
$$\frac{1}{\sigma_0}\frac{d\sigma}{dy} = \left(\frac{\alpha_S C_F}{\pi}\right)^2 \times \left[\boxed{\sigma_A(y)} \longrightarrow\right.$$



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



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



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

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

- The angular correlations between the four jets <u>differ</u> for the 3 diagrams, cf. $g \to gg$ (spin 1 $\to$ 1, 1) versus $g \to q\bar{q}$ (spin 1 $\to$ 1/2, 1/2)
- Allows the relative contributions of the terms to be distinguished, can determine the color factor ratios C_A/C_F and T_F/C_F, with $\sigma_A \cdots \sigma_E$ taken from theory

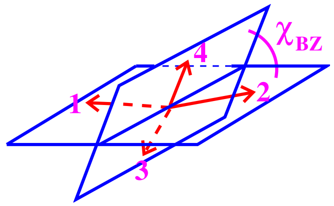
Procedure

→ Select 4-jet events using a jet finder: $K_\perp$, JADE, etc.

→ Order jets by energy: $E_1 > E_2 > E_3 > E_4$

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

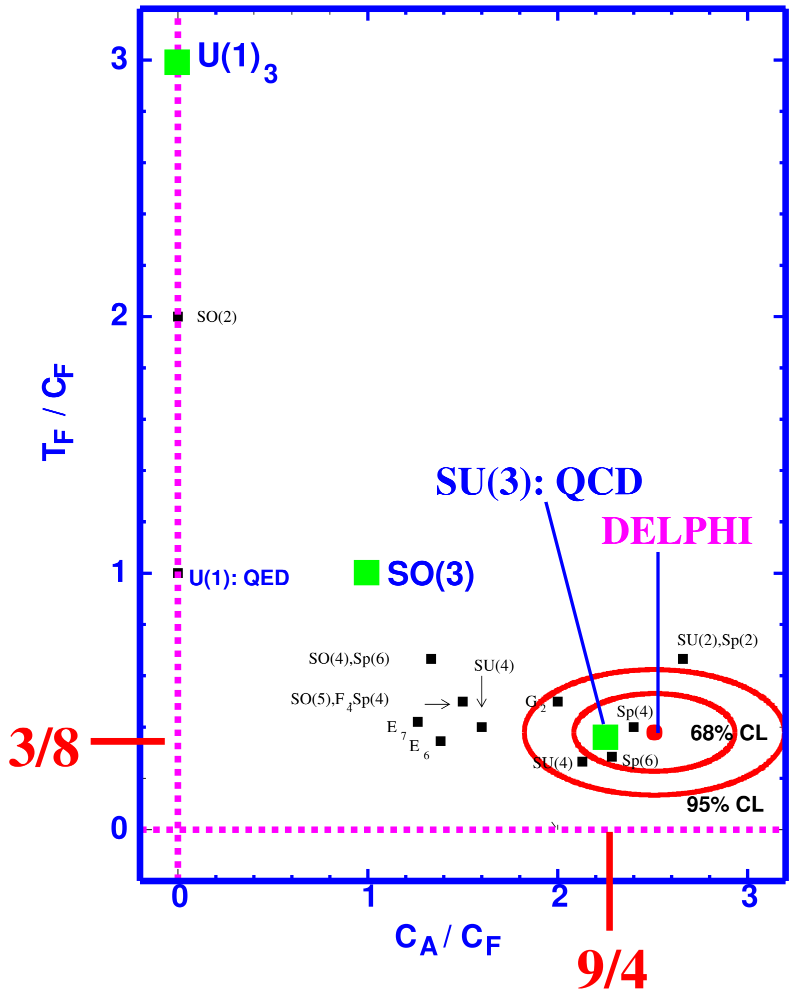
- Angle between jets 3 and 4: $\cos\alpha_{34} = \frac{\vec{p}_3 \cdot \vec{p}_4}{|\vec{p}_3|\, |\vec{p}_4|}$

→ Account for the effects of hadronization using corrections from the MC

→ Fit theoretical expression to the data to find $\frac{\mathrm{C_A}}{\mathrm{C_F}}$ and $\frac{\mathrm{T_F}}{\mathrm{C_F}}$

T_F/C_F versus C_A/C_F

[DELPHI Collab., Phys. Lett. B414 (1997) 401]



Of the three gauge groups with three color degrees of freedom:

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

only $\boxed{\text{SU(3)}}$ is consistent with data

Three color degrees of freedom are required by

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

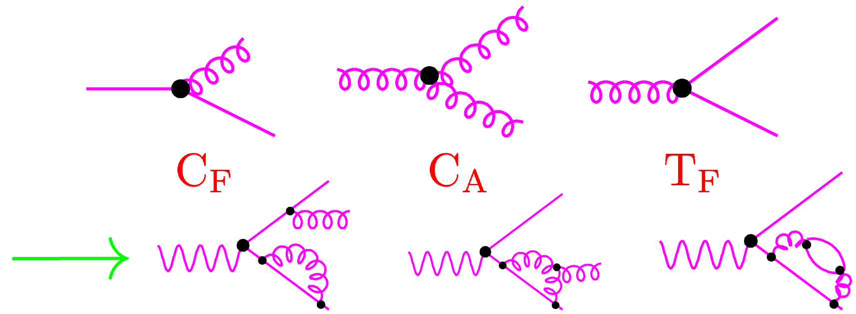
and other measurements

$\longrightarrow$ Direct verification of the SU(3) gauge group structure of strong interactions

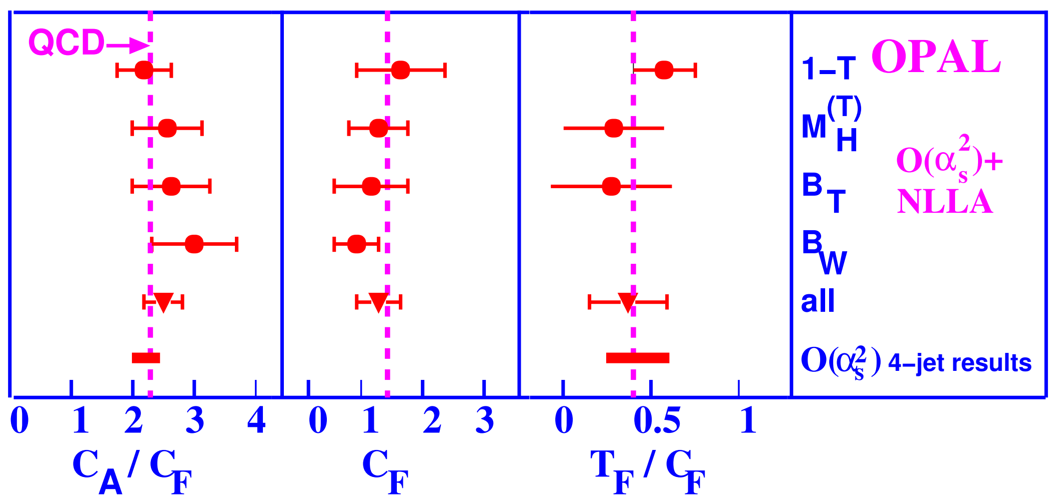
Color factors from 2- and 3-jet events (event shapes: Thrust, etc.)

[OPAL Collab., Z Phys. C68 (1995) 519]

$\longrightarrow$ 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:



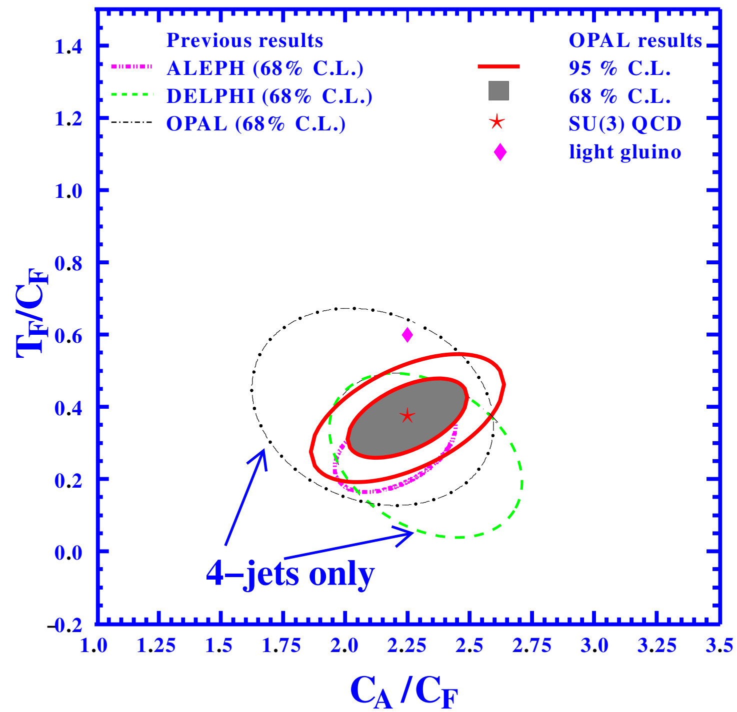
$\longrightarrow$ The $\mathcal{O}(\alpha_S^2)$+NLLA expressions for experimental observables like thrust can be decomposed into terms $\sim\ \mathrm{C_F^2},\ \ \mathrm{C_A C_F},\ \ \mathrm{T_F C_F}$



Color factors from a simultaneous fit of event shapes and 4-jet angular correlations

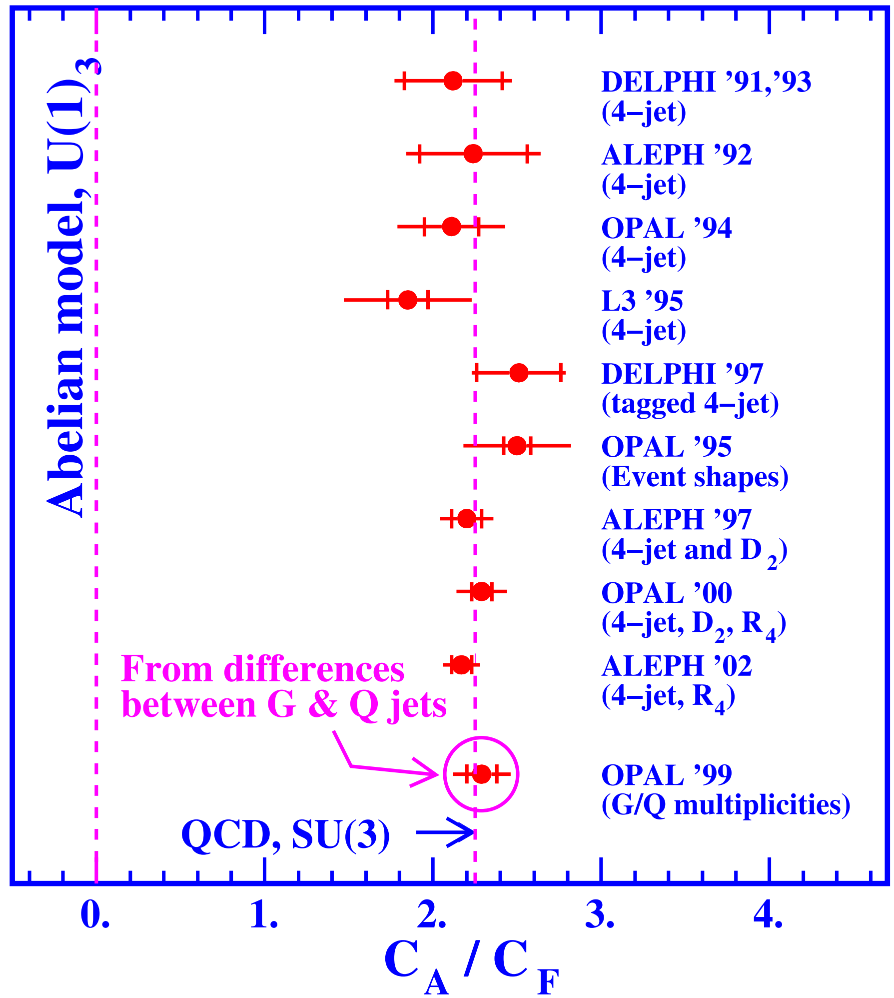
[OPAL Collab., Eur. Phys. J. C20 (2001) 601]

- Include the 4-jet event rate versus y_{cut}, using the $k_\perp$ jet finder
- Employ NLO calculations $[\mathcal{O}(\alpha_S^3)]$ for the 4-jet angular correlations
  [Z.Nagy & Z. Trócsányi, PRD57 (1998) 5793]



$\longrightarrow$ Substantial reduction in the uncertainties compared to the studies based on 4-jet angular correlations or event shapes alone

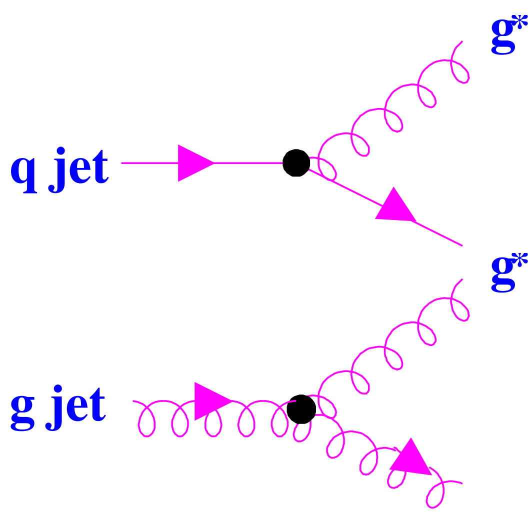
Color factor ratio C_A/C_F from event shapes & 4-jet angular correlations



$\rightarrow$ Precise test of QCD, direct verification of the SU(3) gauge group

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, $\boxed{C_F = 4/3}$

Gluon jets: ggg vertex, $\boxed{C_A = N_C = 3}$

The color charge of a gluon is $\frac{C_A}{C_F} = \frac{9}{4} = 2.25$ larger than that of a quark

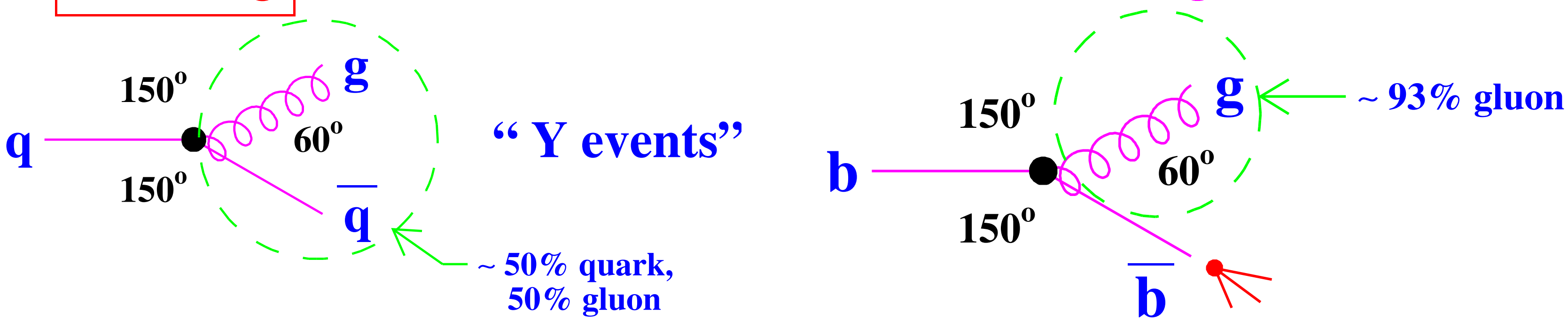
Larger color charge $\longrightarrow$ gluon jets have a larger multiplicity, softer fragmentation function, and are less collimated (“broader”)

[These differences proved difficult to verify experimentally: many inconclusive studies at PEP, PETRA & TRISTAN; a major puzzle in jet physics]

Particle multiplicity difference: $r_{g/q}$

[OPAL Collab., ZPC58 (1993) 387]

- Biased jets: the jet properties depend on the choice of jet finder
- Select 1-fold symmetric 3-jet events ($k_\perp$ jet finder, $y_{cut} = 0.02$)
- Anti-tag the gluon jet by identifying b quark jets in $\mathrm{b\bar{b}g}$ events



- Compare the two samples (green circles):

$\longrightarrow$ Algebraically combine to obtain results corresponding to pure G & Q jets

$\longrightarrow$ The tagged b jets are not used to compare with gluon jets

$$\boxed{r^{ch.}_{g/q} \equiv \frac{\langle n_{ch.}\rangle_{gluon}}{\langle n_{ch.}\rangle_{quark}} = 1.25 \pm 0.04}$$

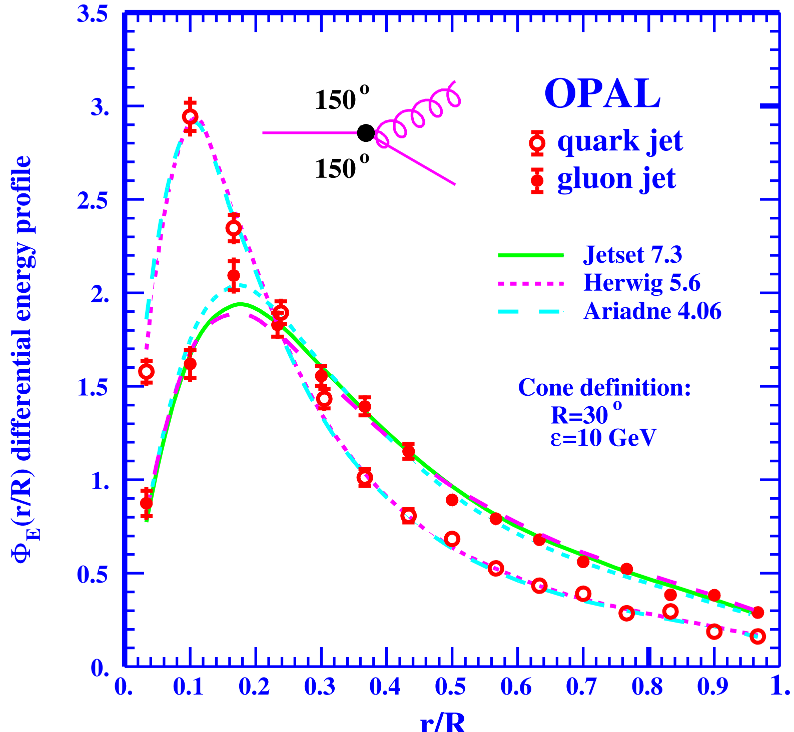
$\longrightarrow$ First successful analysis demonstrating that $\langle n\rangle_{gluon} > \langle n\rangle_{quark}$, following almost ~ 15 years of unsuccessful effort (1979-1993) !!

Jet widths & fragmentation functions from Y events

[OPAL Collab., Z. Phys. C68 (1995) 179]

Jet energy profile:

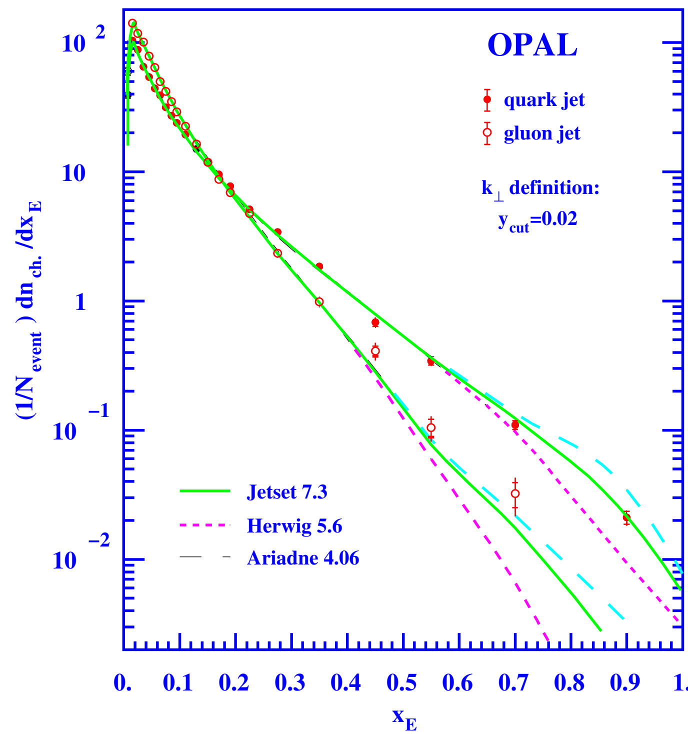
Polar angle distribution of a jet's visible energy w.r.t the jet axis



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

Fragmentation function

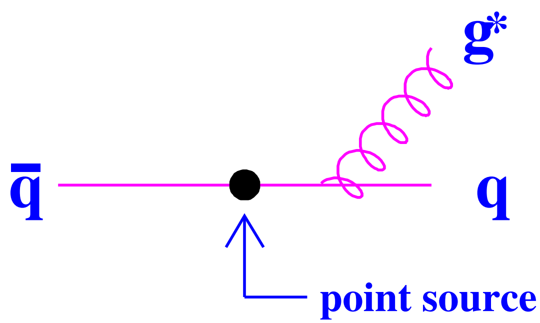
Scaled particle energy spectrum, $x_E = E_{particle}/E_{jet}$



⟶ The gluon ff is much softer than the quark jet ff, as predicted by QCD

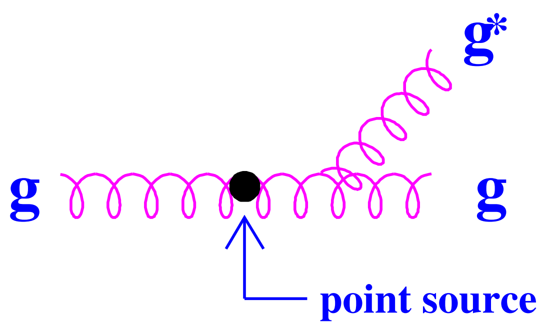
Unbiased jets: Quantitative tests of QCD

QCD Calculations $\longrightarrow$ G and Q jets are defined through pair production from a color singlet point source



Natural Occurrence

Inclusive
e^+e^- annihilations



$\Upsilon \rightarrow \gamma gg$ decays

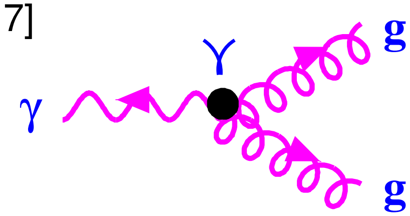
$\longrightarrow$ Jet properties defined by an inclusive sum over the event or event hemispheres

$\longrightarrow$ No jet-finding algorithm, or ambiguity about which particles to associate with G or Q jet production: UNBIASED JETS

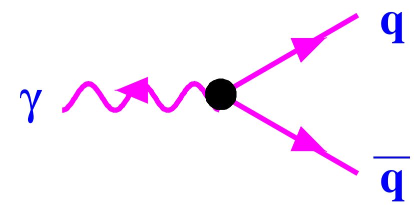
Unbiased gluon jets from Υ decays

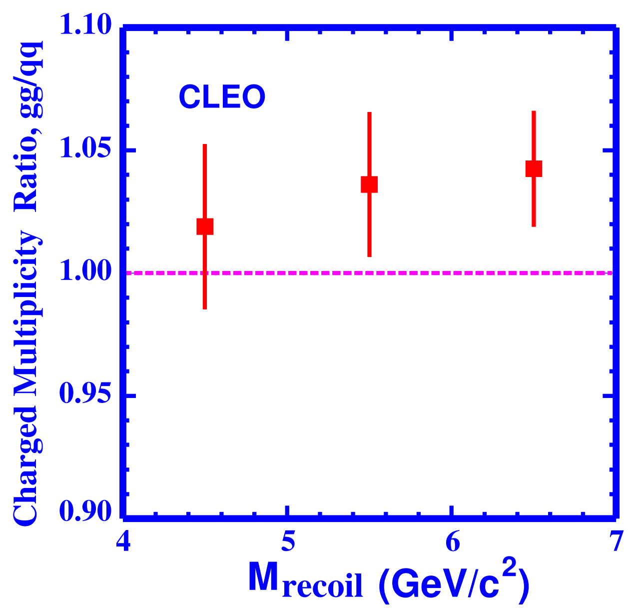
[CLEO Collab., Phys. Rev. D56 (1997) 17]

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



$\longrightarrow$ Compare with $e^+e^- \to \gamma q\bar{q}$ events with the same recoil mass, from the nearby continuum





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

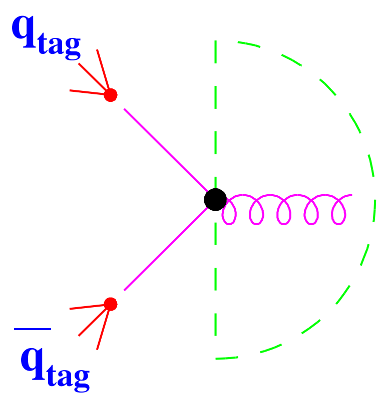
$\rightarrow$ Jet energy $\sim$ 2-3 GeV too low to observe a gluon–quark jet difference

$\rightarrow$ Non-perturbative effects (limited phase space) important at this scale

Unbiased gluon jets from Z^0 decays

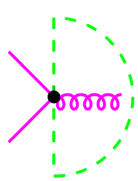
[J.W. Gary, Phys. Rev. D49 (1994) 4503]

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

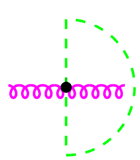


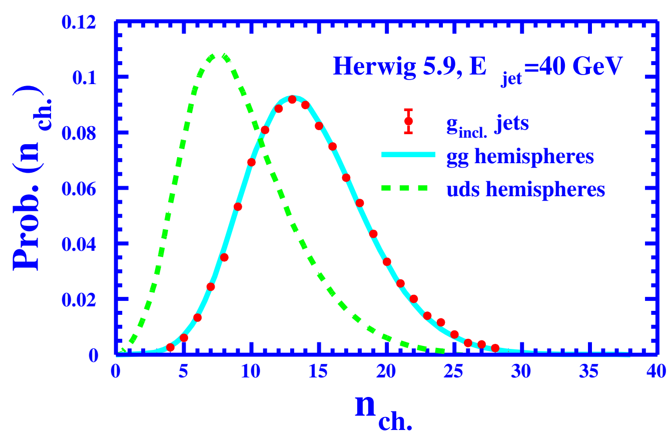
Gluon jet $\boxed{g_{incl.}}$ defined by the particles in the hemisphere opposite to a hemisphere with two b-tagged quark jets

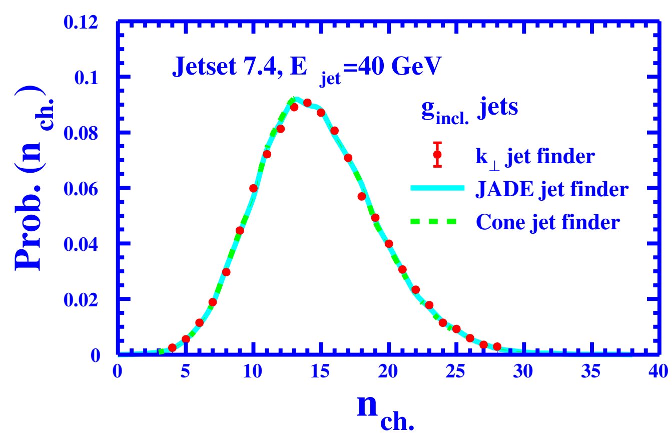
$\longrightarrow$ Properties of $g_{incl.}$ and gg hemispheres are virtually identical, and are independent of the choice of jet finder: truly unbiased gluon jets !

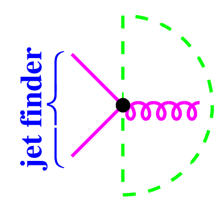


versus







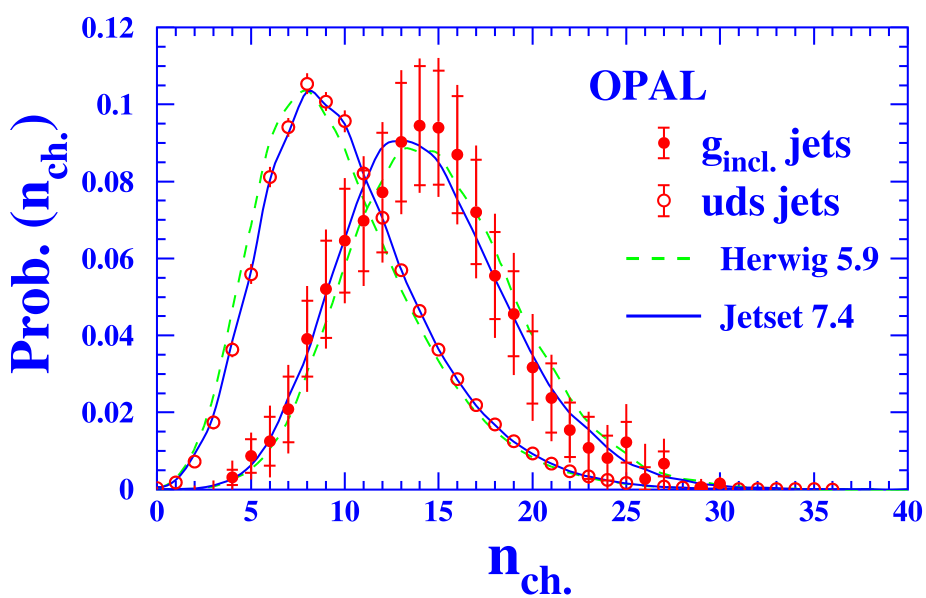


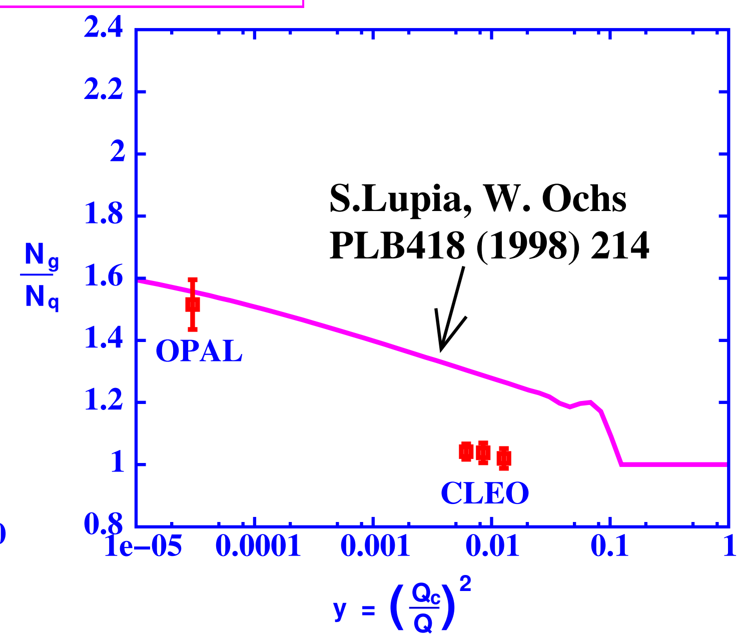
Multiplicity distributions of unbiased gluon and quark jets, $E_{\rm jet} \approx 40$ GeV

[OPAL Collab., Eur. Phys. J. C11 (1999) 217]

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

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





Z^0 scale $\rightarrow$ Perfect agreement between data and theory

(MC: hadronization correction predicted to be unity)

CLEO energy scale $\rightarrow$ Non-perturbative effects dominate

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

(Unbiased jets; assume massless quarks)

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

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

[Brodsky & Gunion, PRL 37 (1976) 402; Veneziano et al. PL B78 (1978) 243]

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

[Khoze, Lupia & Ochs EPJ C5 (1998) 77]

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

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

[Malaza & Webber, Nucl. Phys. B267 (1986) 702;
Gaffney & Mueller, Nucl. Phys. B250 (1985) 109]

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

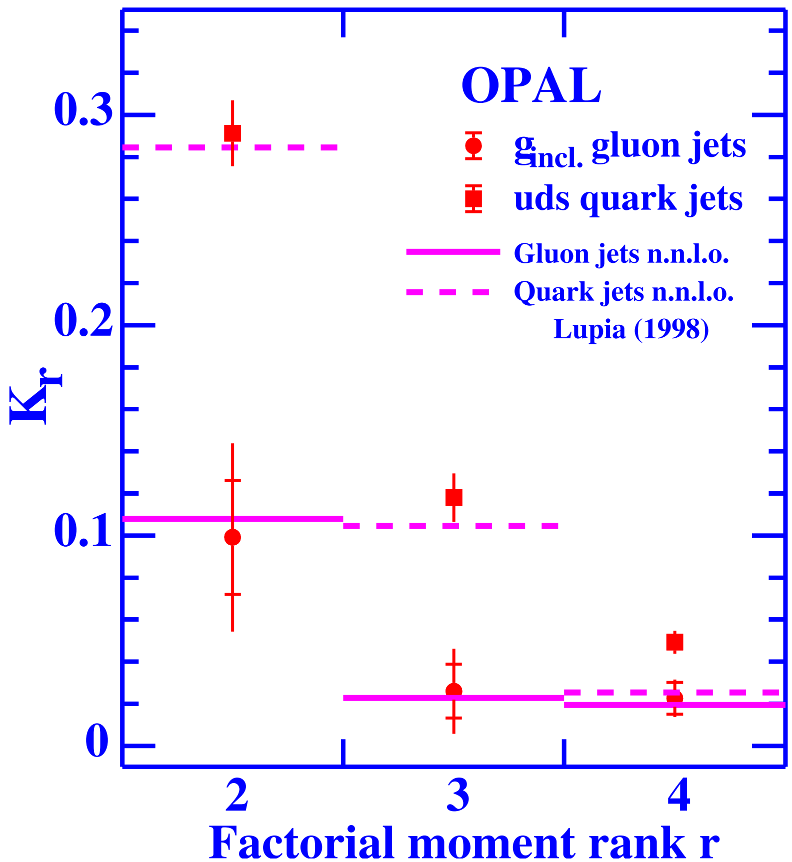
[Dremin & Nechitailo, Mod.Phys.Lett.A9(1994)1471]

$\longrightarrow$ Numerical solutions $\rightarrow$ more accurate inclusion of energy conservation and phase space limits: $r_{g/q} \approx 1.5$

[Lupia & Ochs, PL B418 (1998) 214; Eden & Gustafson, JHEP 09 (1998) 015]

Higher moments of the multiplicity distribution (shape of the multiplicity distribution)

[OPAL Collab., Eur. Phys. J. C1 (1998) 479]



"Factorial Cumulants"

$\longrightarrow$ K_2, K_3, K_4

$\longrightarrow$ Equivalent to dispersion, skew & kurtosis

Higher moments:

$\boxed{\text{Quark jet result} > \text{gluon jet result}}$

$\longrightarrow$ Quark jets exhibit larger event-to-event fluctuations: a longer tail

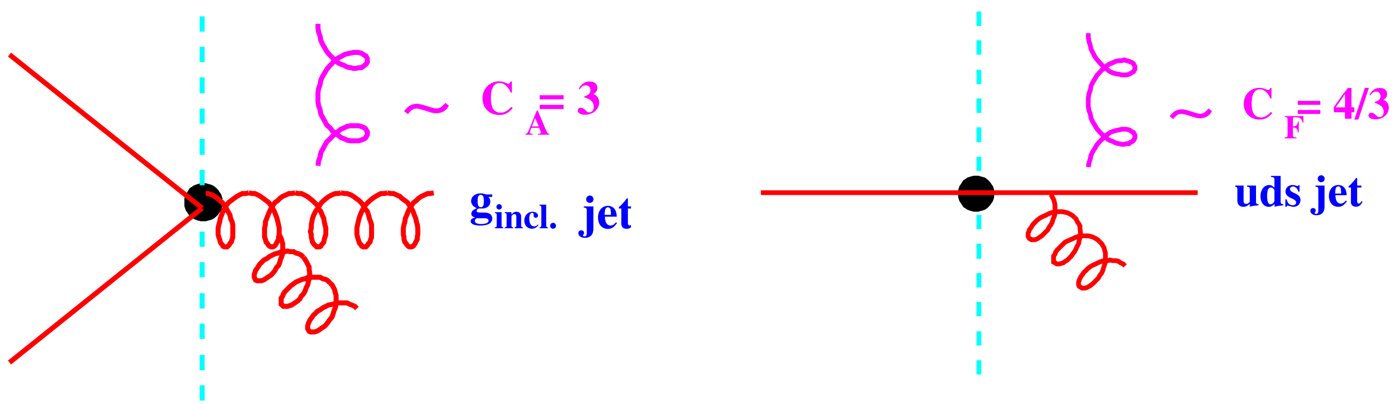
Remarkable agreement

between theory and data and success for jet physics !

Multiplicity in G & Q jets under the asymptotic condition $E_{particle} << E_{jet}$

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

[V.A. Khoze, S. Lupia & W. Ochs, Eur. Phys. J. C11 (1999) 217]



Count the number of soft particles at large $p_\perp$ to the jet axes

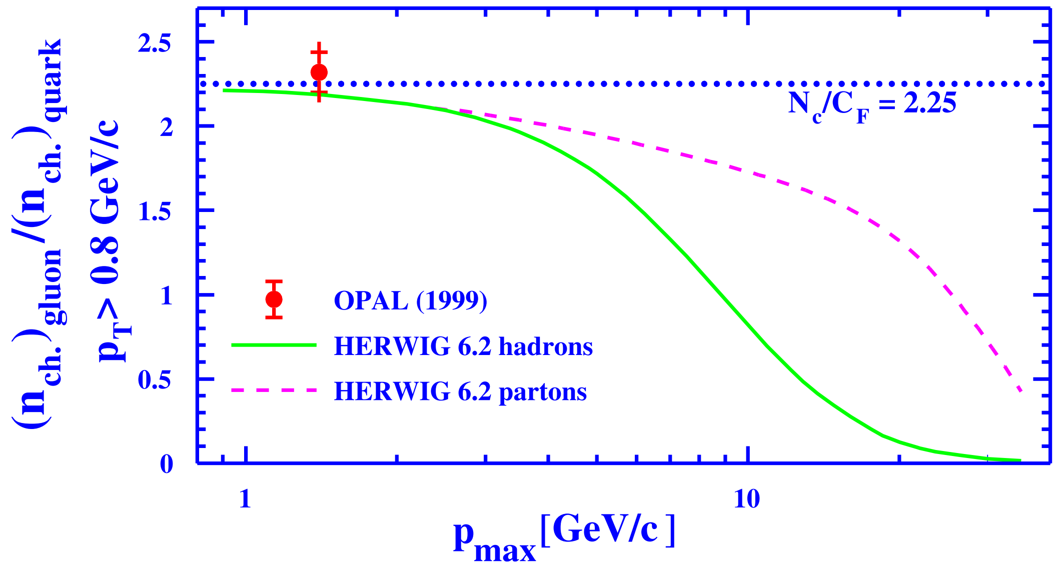
$\longrightarrow$ Test the asymptotic prediction from 1976 that $\boxed{\mathrm{r}_{\mathrm{g/q}} = 2.25}$

$\longrightarrow$ Measure the color factor ratio $\mathrm{C_A/C_F}$ directly from a ratio of hadron multiplicities (not from fitting a theoretical expression to data)

$r_{g/q}$ in the asymptotic limit, $E_{particle} << E_{jet}$

[OPAL Collab., Eur. Phys. J. C11 (1999) 217]

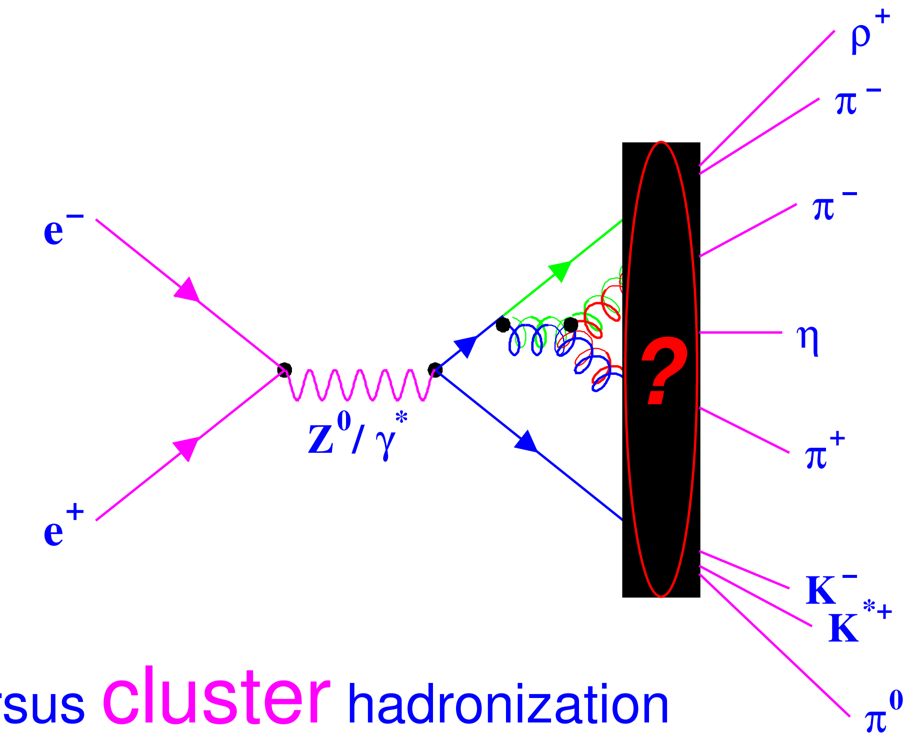
- Determine $r_{g/q}$ as the particle momentum p gets <u>smaller</u>: $p \leq p_{max}$
- Require $p_\perp > 0.8$ GeV/c: $p_\perp < 0.8$ GeV/c dominated by hadronization
- Parton and hadron level MC predictions **both** converge to $r_{g/q} = 2.25$ for soft particles (note: $r_{g/q} \to 0$ for hard particles, G ff softer than that of Q)



$$p_{max} = 2 \text{ GeV} \longrightarrow \boxed{r_{g/q} = 2.32 \pm 0.18}$$

$\longrightarrow$ Verification of the fundamental prediction from 1976 that $r_{g/q} = C_A/C_F$ after more than 20 years of effort !!

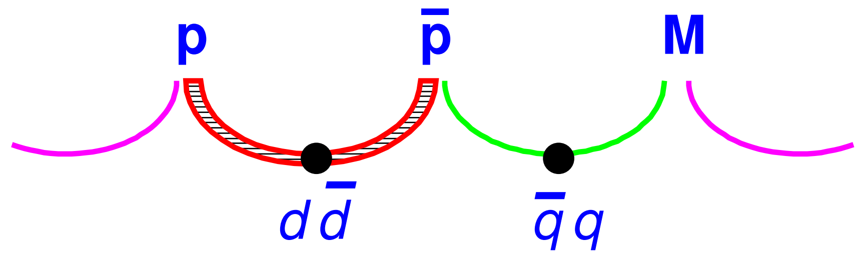
Tests of the Hadronization Process



- String versus cluster hadronization
  - $\longrightarrow$ $\cos\theta^*$ distribution of $\mathrm{p\overline{p}}$ pairs (already discussed)
  - $\longrightarrow$ Baryon production in gluon jets
- The baryon production mechanism
  - $\longrightarrow$ Diquarks versus popcorn

Baryon production in string hadronization

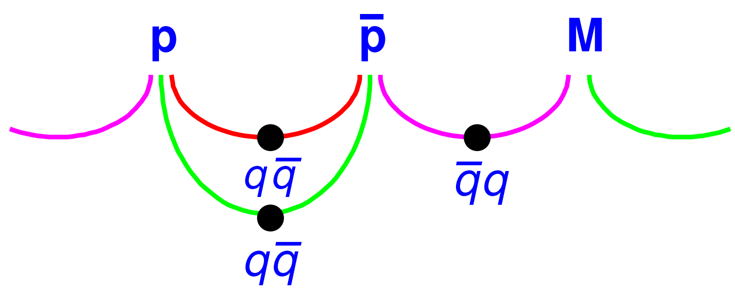
- Either diquark-antidiquark $d\bar{d}$ pair production occurs from the vacuum in place of $q\bar{q}$ production (Prob. $\sim$ 10%); Diquark d: tightly bound qq state

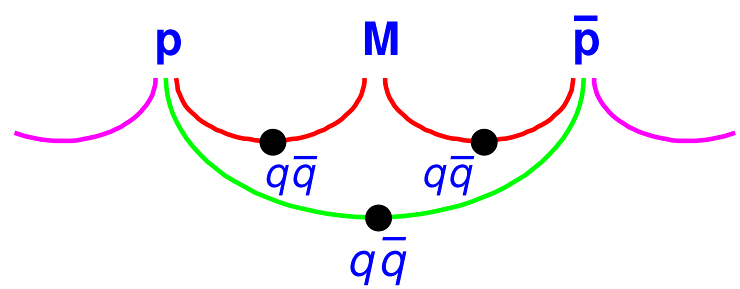


$\longrightarrow$ The baryon and antibaryon are neighbors in rank (order along the string)

$\longrightarrow$ Tight correlations in phase space (rapidity) between the baryon and antibaryon

- Or the baryon is formed by successive production of $q\bar{q}$: "Pop-corn"



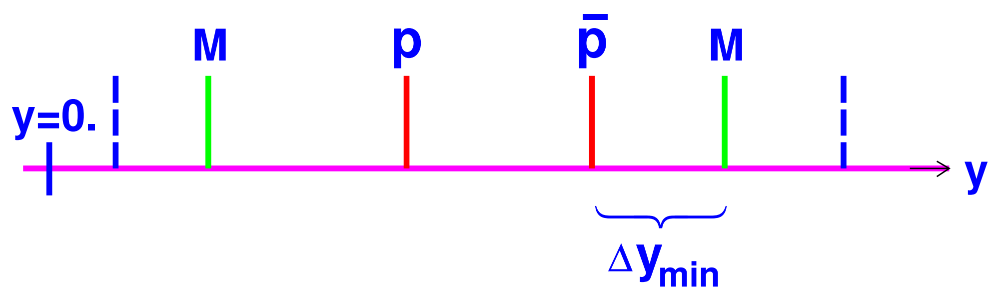


$\longrightarrow$ A meson can sometime appear between the baryon and antibaryon, yielding looser correlations in rapidity

Experimental discrimination between the diquark & popcorn models

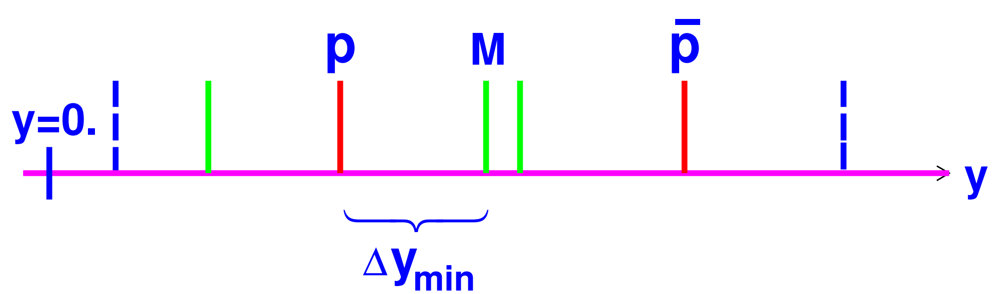
[DELPHI Collab., Phys. Lett. B490 (2000) 61]

- Select events with exactly one proton p and one anti-proton $\overline{\mathrm{p}}$ in a hemisphere (63% purity)
- Count events $\mathrm{N}_{\mathrm{p}\overline{\mathrm{p}}}$ with p and $\overline{\mathrm{p}}$ adjacent in rapidity, vs. $\Delta\mathrm{y}_{\mathrm{min.}}$



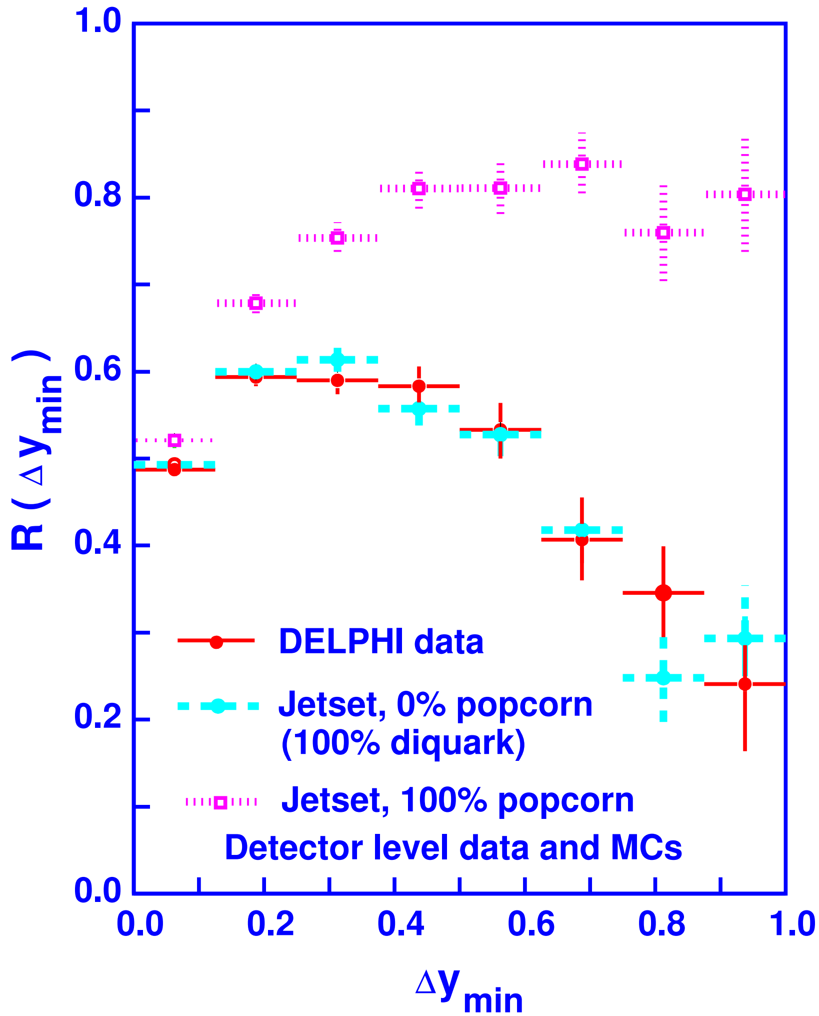
$\longrightarrow$ $\Delta\mathrm{y}_{\mathrm{min.}} \equiv$ rapidity difference between the p or $\overline{\mathrm{p}}$ and the nearest meson

- Count events $\mathrm{N}_{\mathrm{pM}\overline{\mathrm{p}}}$ with a meson M between the p & $\overline{\mathrm{p}}$, vs. $\Delta\mathrm{y}_{\mathrm{min.}}$



$\longrightarrow$ $\Delta\mathrm{y}_{\mathrm{min.}} \equiv$ rapidity diff. between p or $\overline{\mathrm{p}}$ and nearest meson in-between

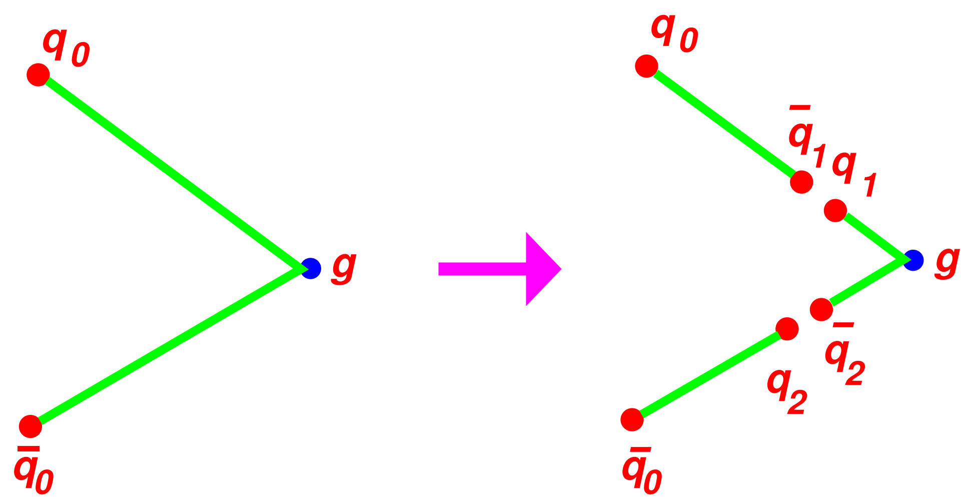
$$R \equiv \frac{N_{pM\bar{p}}}{N_{pM\bar{p}} + N_{p\bar{p}}} \text{ versus } \Delta y_{min.}$$



- $\longrightarrow$ Much more sensitive to pop-corn/diquark model differences than previous studies
- $\longrightarrow$ Data strongly support the diquark hypothesis
- $\longrightarrow$ The "diquark" behaves as a fundamental entity (the qq pair is strongly bound together when produced from the vacuum, similarly for the $\overline{qq}$ pair)

Gluons in the Lund String model $\longrightarrow$ Kinks on the string

Gluon jets $\longrightarrow$ Two color triplet fields



$\longrightarrow$ The string breaks on both sides of the kink through $q\overline{q}$ production

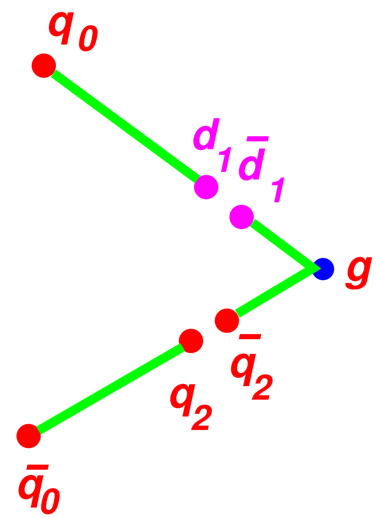
$\rightarrow$ $q_1\overline{q}_1, q_2\overline{q}_2,$ etc.

$\longrightarrow$ The q_1-g-$\overline{q}_2$ system is constrained to appear as an on-shell hadron

$\longrightarrow$ The $q_0\overline{q}_1$ and $q_2\overline{q}_0$ systems hadronize in the usual way

$\longrightarrow$ The gluon jet is effectively the sum of two quark jets

Baryon production in gluon jets



- String hadronization: Occasionally, a diquark pair $d_1\overline{d}_1$ or $d_2\overline{d}_2$ will be produced in place of the the quark pair $q_1\overline{q}_1$ or $q_2\overline{q}_2$

$\longrightarrow$ A gluon jet has two chances to acquire a baryon as its leading particle, compared to a quark jet which has only one

$\longrightarrow$ An enhancement of ~ 2 in the rate of high energy baryons in gluon jets compared to quark jets, beyond the enhancement due to the color factors, discussed earlier, which is common to all particle species

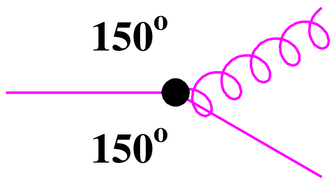
- Cluster hadronization & octet strings:

$\longrightarrow$ No mechanism for an enhancement of baryons in gluon jets beyond that observed for all particles

Baryon production in gluon jets

[DELPHI Collab., Eur. Phys. J. C17 (2000) 207]

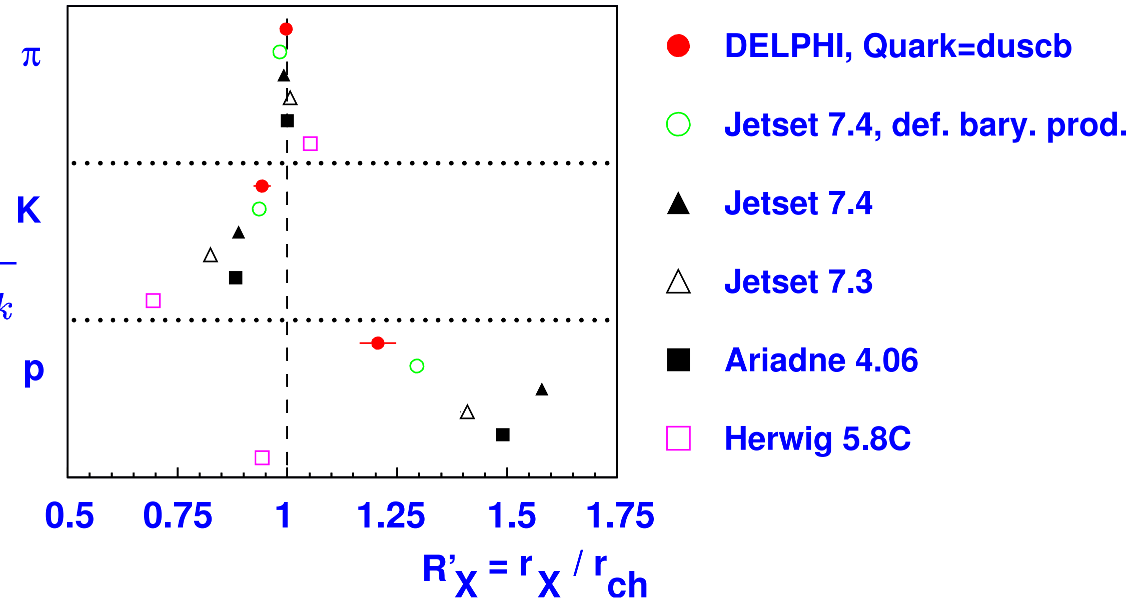
$\longrightarrow$ Use the Y event technique to compare particle production rates in gluon and quark jets



$\longrightarrow$ Ratio of rates:

$$R'_h = \frac{\langle n_h \rangle_{gluon} / \langle n_h \rangle_{quark}}{\langle n_{ch.} \rangle_{gluon} / \langle n_{ch.} \rangle_{quark}}$$

$$h = \pi^{\pi}, \mathrm{K}^{\pm}, \mathrm{p}(\overline{\mathrm{p}})$$



$\longrightarrow$ Production of baryons $\sim$ 20% larger in G than in Q jets BEYOND the enhanced production of all charged particles in gluon jets

$\longrightarrow$ Qualitative support for the $2\times$color-triplet model of gluons, additional evidence against the cluster hadronization model

Summary: e^+e^- jets

- $\longrightarrow$ Discovery of jets & direct observation of the gluon
- $\longrightarrow$ Quark and gluon spins
- $\longrightarrow$ SU(3) nature of strong interactions
- $\longrightarrow$ Precise measurements of α_S, its running, and the color factors $\mathrm{C_A} = 3$, $\mathrm{C_F} = 4/3$
- $\longrightarrow$ Differences between gluon and quark jets:

$$\frac{\langle \mathrm{n_{gluon}} \rangle}{\langle \mathrm{n_{quark}} \rangle} = \frac{9}{4} \text{ verified}$$

- $\longrightarrow$ Some conclusive information about the hadronization process (based on baryons and gluon jets)
  - $\longrightarrow$ Cluster hadronization disfavored
  - $\longrightarrow$ Diquark model for baryon production seems to be OK