

Introduction: Jet Physics

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- Motivate some of the detailed studies presented in following talks
- Recent experimental results in jet physics, topics of current interest, otherwise not discussed
- Concentrate on soft aspects (hard aspects covered in talks by Gwenlan, Metzger & Demine)

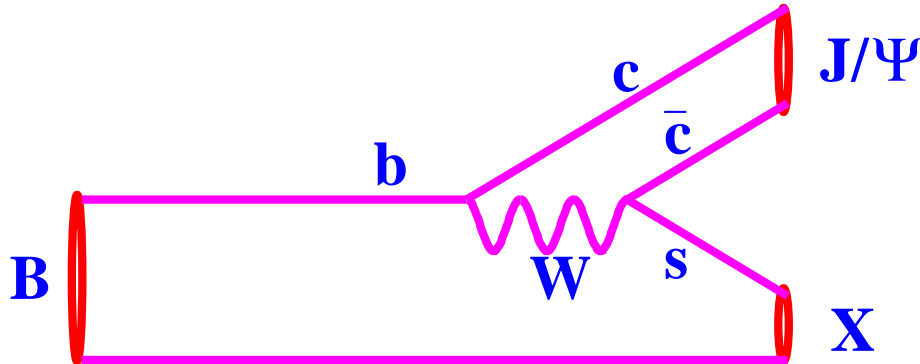
General themes:

- Color reconnection
 - Rapidity gaps
 - Particle multiplicities in jets
 - Differences between gluon & quark jets
- Data from e^+e^- , $p\bar{p}$ & ep collisions

Color reconnection

→ Soft color exchange between “final-state” partons alters the color structure of an event from its original (hard scattering) configuration

- A well known example: $B \rightarrow J/\Psi + X$ decays
[T. Sjöstrand & V. Khoze, Z. Phys. C62 (1994) 281]



- Color reconnection (CR) has been postulated as the source of rapidity gap and diffractive events in ep and $p\bar{p}$ events
[cf. R. Enberg, G. Ingelman & N. Timneanu, Phys. Rev. D64 (2001) 114015.]

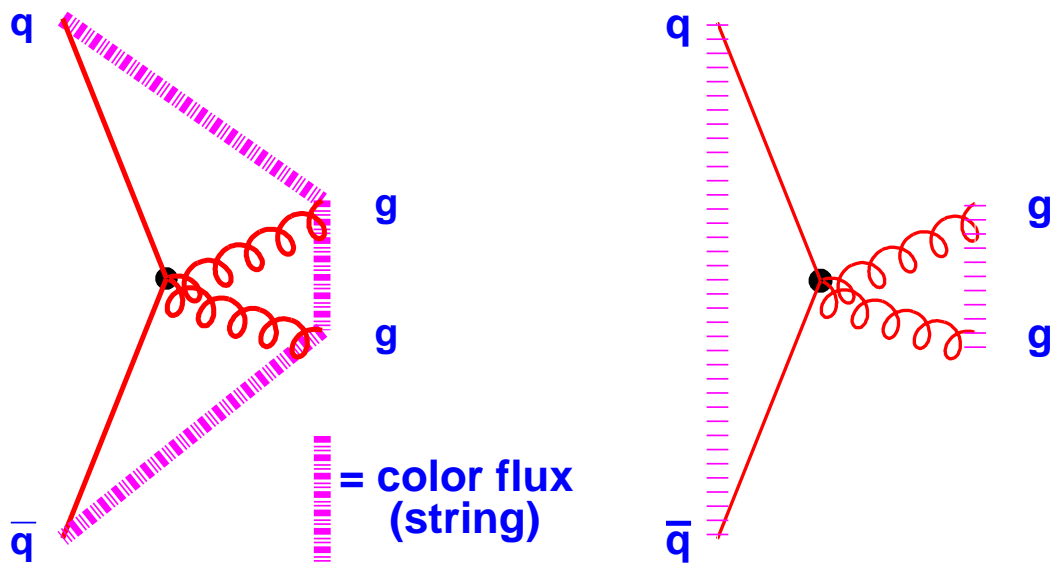
→ Soft color interaction (SCI) model
[A. Edin, G. Ingelman & J. Rathsman, PLB 366 (1996) 371]

→ Generalized area law (GAL) model
J. Rathsman, PLB 452 (1999) 364]

CR appears as a higher order process, suppressed by $\mathcal{O}(1/N_c^2)$ with $N_c = 3$

CR in e^+e^- annihilations

- In contrast to ep and $p\bar{p}$ events, inclusive e^+e^- events do not exhibit “anomalous” rates of events with a large rapidity gap [SLD Collaboration, PRL 76 (1996) 4886]
- Nonetheless, CR should yield events with a significant rate of rapidity gaps in $e^+e^- \rightarrow q\bar{q}g$ 3-jet events



- A reduction in particle production in the central rapidity region of reconnected events
- An increase in the probability for a rapidity gap

CR models

CR expected to be primarily a **non-perturbative** phenomenon

→ Color exchange at scales below the cutoffs for perturbative radiation, i.e. the hadronization phase

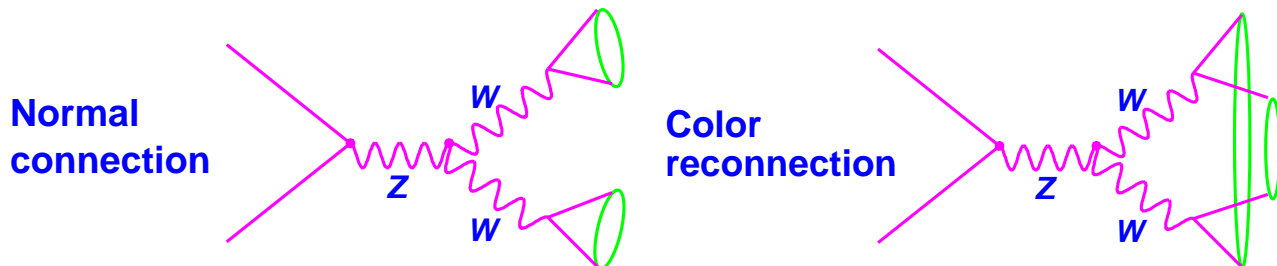
To assess the sensitivity of the data to CR, **simulations** of color reconnection have been incorporated into standard QCD Monte Carlo programs

- **Ariadne-CR**: Reconnection occurs with **probability 1/9** if the string length in the reconnected diagram is smaller than for normal connection.
- **Rathsman-CR** model (generalized area law, GAL),
 - Implemented in Pythia (Jetset)
 - Reconnection occurs with probability $R_0[1 - \exp(-b\Delta A)]$ with ΔA the difference in the space-time area spanned by strings in normal and reconnected events, and $R_0 = 0.1$
- **Sjöstrand-Khoze (SK) CR** models
 - Implemented in Pythia for $e^+e^- \rightarrow W^+W^-$ events only
 - SK-I**: reconnection occurs with probability $1 - \exp(-k_I V)$ if two color flux tubes overlap in space-time volume V
 - k_I an adjustable parameter

Color reconnection in $e^+e^- \longrightarrow W^+W^- \longrightarrow \text{hadrons}$

[G. Gustafson, U. Pettersson, P.M. Zerwas, PLB209 (1988) 90]

- W decay vertices separated by $\sim 0.1 \text{ fm}$
- The hadronization scale is a $\sim 1 \text{ fm}$
- The hadronization of the two W bosons should not be independent



The reconstructed W mass distribution is significantly different in CR and non-CR events, leading to large shifts

CR Model	% reconnection	W mass shift
Ariadne (AR2)	49%	70 MeV
Herwig	11%	30 MeV
SK-I ($k_I = 100$)	98%	300 MeV

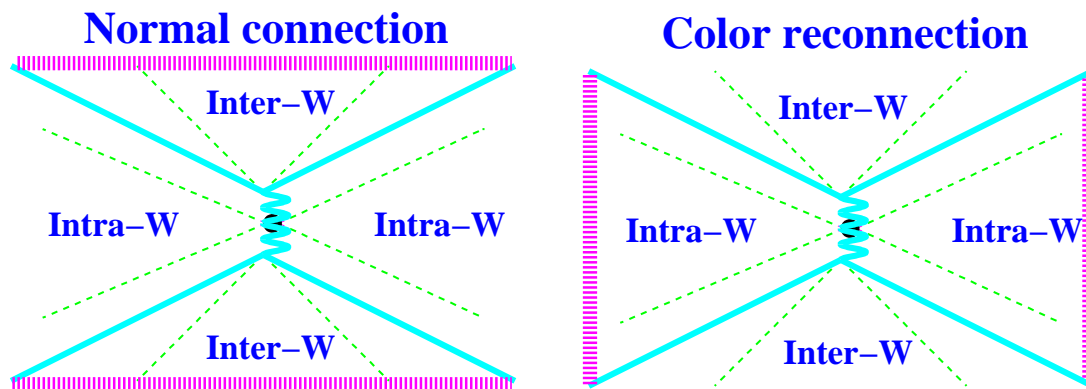
CR forms the largest systematic uncertainty in the W mass measurement at LEP (statistical uncertainty $\approx 30 \text{ MeV}$)

It has proved difficult to find experimental variables which are sensitive to CR, to determine if CR is present and potentially reduce the size of this systematic uncertainty.

Particle flow method (LEP WW working group)

- One of the most sensitive variables to CR in $e^+e^- \rightarrow WW$ events yet found (introduced by L3)
- In four-jet W^+W^- events, associate a pair of jets with each W based on the event kinematics (angles between jets, kinematic fits, etc.)
- Project particles into the plane defined by two jets, measure the number of particles in the region from 20% to 80% between the jet peaks, and iterate over the four jet pairs
- Compare the particle density in the inter-W regions to that in the intra-W regions

$$R \equiv \frac{\int_{0.2}^{0.8} dn/d\phi_n(\text{inter} - W)}{\int_{0.2}^{0.8} dn/d\phi_n(\text{intra} - W)}$$



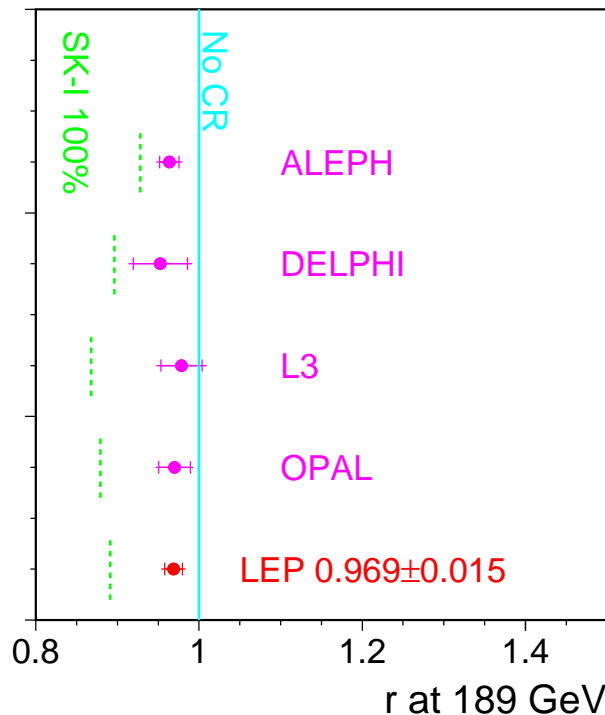
- For CR events, the particle density in the intra-W regions is enhanced \rightarrow R is smaller

Particle flow in WW events, cont.

- To avoid biases, the data & MC predictions are examined at the “detector level”
- Normalize R to the **non-CR version** of each model being tested (eliminates differences between selection criteria, allows combination of the LEP results)

$$r \equiv \frac{R_i}{R_{MC}^{\text{no-CR}}} \quad i = \text{data or CR model}$$

- Results for the SK-I model versus Pythia:

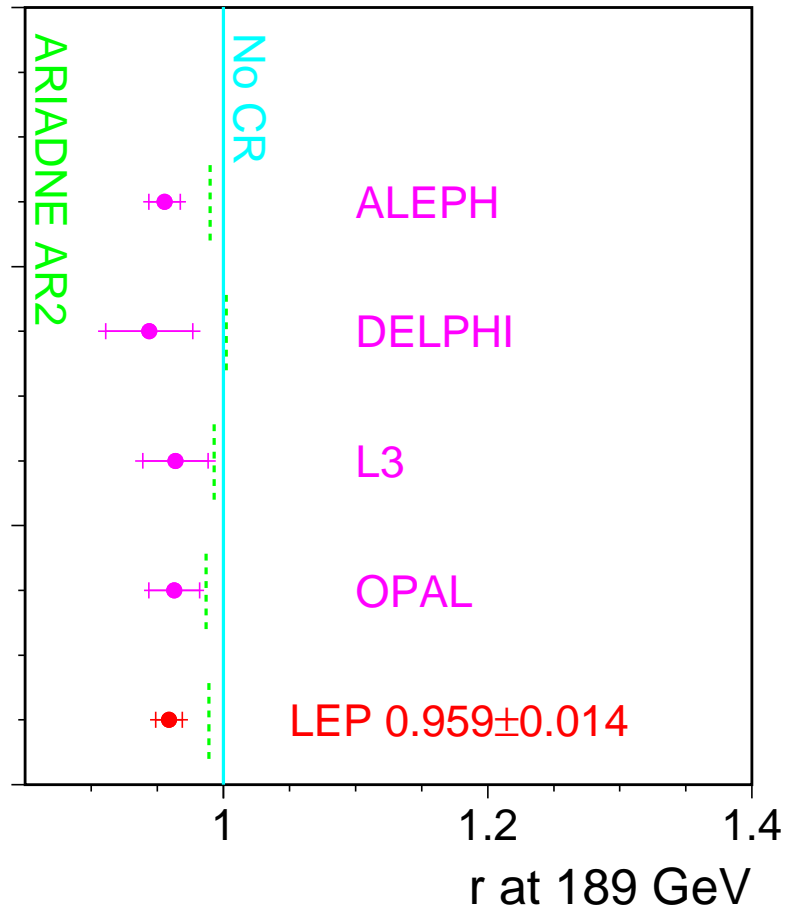


- Particle flow method exhibits **good sensitivity** to CR in the SK-I framework, data are consistent with some CR

Best fit + 1σ yields $k_I = 2.1 \rightarrow$ 90 MeV shift in the W mass

Particle flow in WW events, cont.

Results for Ariadne:



But . . .

Method not sensitive to CR in Ariadne → The reasons for this not understood

→ Implies that the discrepancy of the data with the non-CR models may be unrelated to CR

→ There are systematic uncertainties unrelated to CR which compromise the conclusiveness of the study

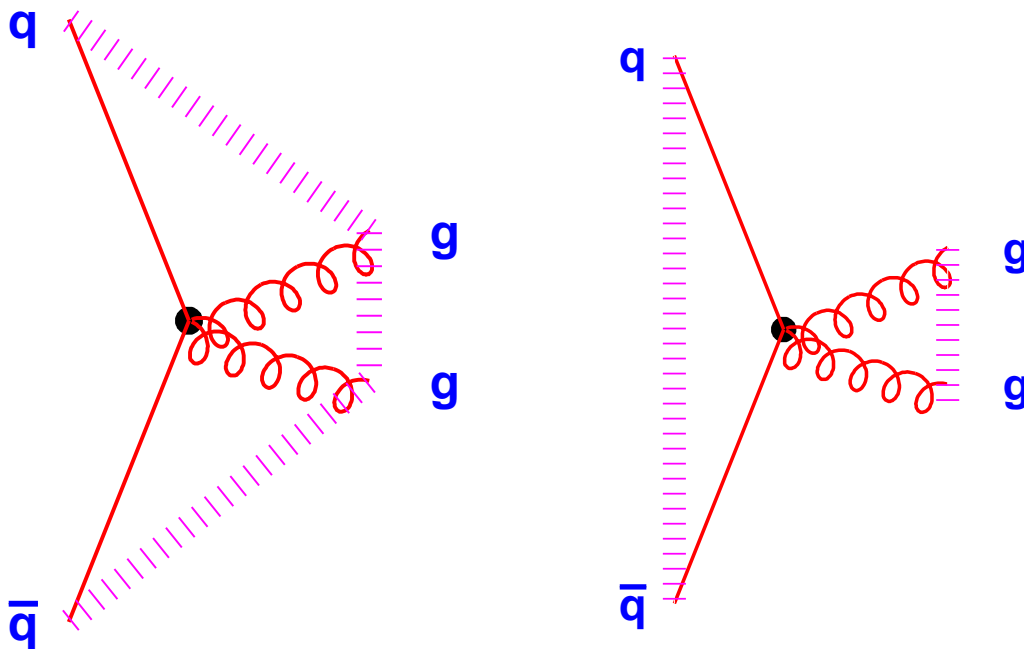
Color reconnection in $q\bar{q}g$ events

QCD $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}g$ events are potentially much more sensitive to CR than WW events

- Rapidity gaps between jets [L3 Note 2807 (June 2003)]:

→ See talk by Wes Metzger

- Rapidity gaps within gluon jets [OPAL CERN-EP-2003-031 (May 2003); ALEPH CONF 2003-005 (July 2003)]:



→ CR leads to an excess of events with a rapidity gap in the gluon jet compared to non-CR, for which the leading part of the jet (high rapidity) is electrically neutral

Rapidity gaps in gluon jets

- Identify gluon jets in 3-jet $q\bar{q}g$ events

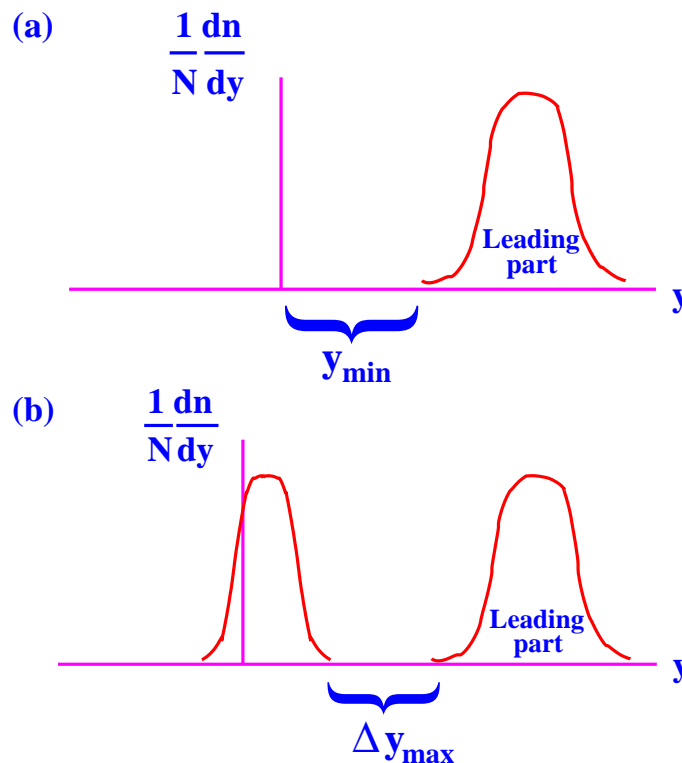
OPAL: tag b and \bar{b} jets in $b\bar{b}g$ events

→ high purity, high energies (higher sensitivity to CR), low number of events

ALEPH: use energy tagging, i.e. assume the gluon is the lowest energy jet

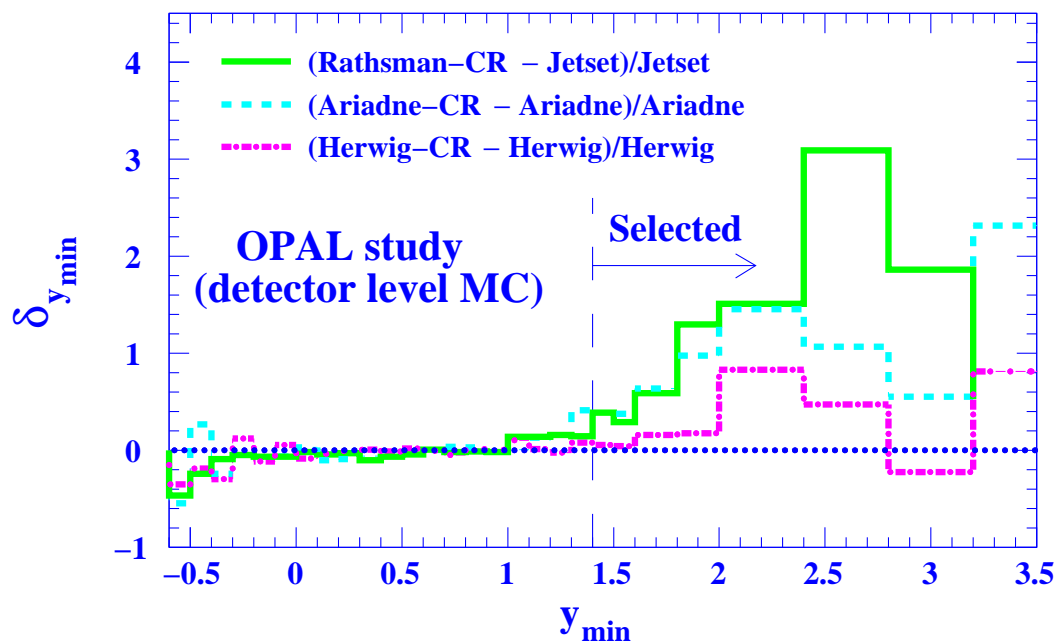
→ lower purity, lower energies, large number of events

- Select gluon jets with a rapidity gap:



Rapidity gaps in gluon jets, cont.

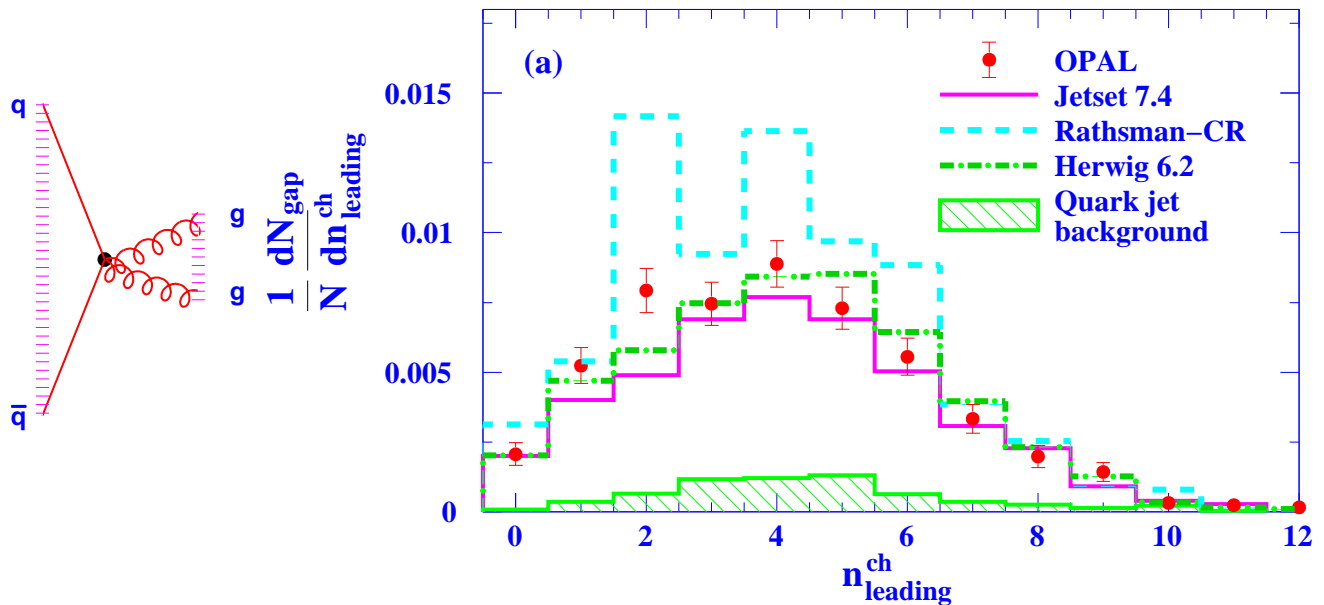
OPAL study: A clear excess of gluon jets with a rapidity gap in the CR models compared to the non-CR models



- Unlike the distributions studied in WW events, the method is sensitive to CR in Ariadne and, to a lesser extent, CR in Herwig
- Also sensitive to CR in the Rathsman (GAL) model
- OPAL: use charged and neutral particles, with $y_{\min} > 1.4$
 - 655 gluon jets, 86% purity, $E_{\text{jet}} \approx 22$ GeV
- ALEPH: use charged particles only, with $y_{\min} > 1.5$
 - $\sim 60\,000$ gluon jets, 52% purity, $E_{\text{jet}} \approx 16$ GeV

Rapidity gaps in gluon jets, cont.

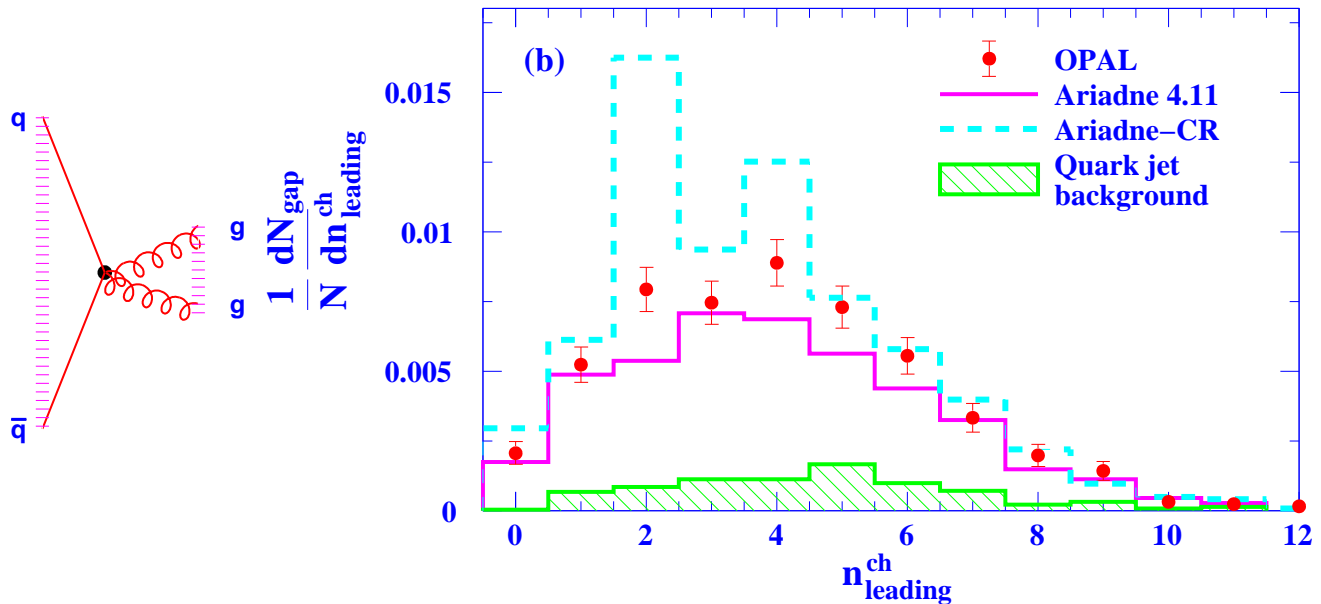
Detector level charged particle multiplicity distribution in the leading part of gluon jets with a rapidity gap



- Description of data by non-CR models (Pythia, Herwig) not perfect → analogous to situation with r in WW events but the spikes at even values of charged multiplicity provide an unambiguous signal for CR
- Raising the perturbative cutoff parameter in the model from $Q_0 = 1.9 \text{ GeV}/c^2$ to $\sim 4 \text{ GeV}/c^2$ brings the Rathsman-CR model into agreement with these data, but at the expense of a good description of inclusive Z^0 measurements: global χ^2 for 81 bins of event shape distributions increases from 244 to 1118
- Rathsman-CR (GAL) model effectively excluded

Rapidity gaps in gluon jets, cont.

Detector level charged particle multiplicity distribution in the leading part of gluon jets with a rapidity gap



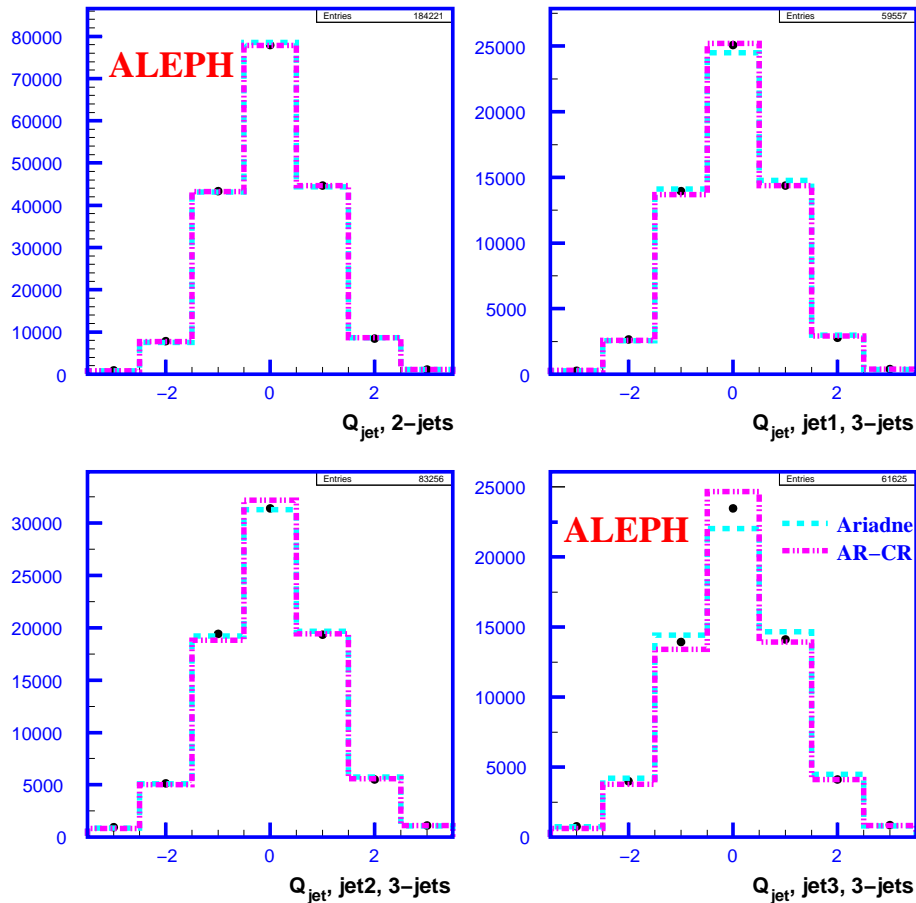
- Results for the Ariadne-CR model qualitatively similar to those of the Rathsmann-CR model
- Raising the perturbative cutoff $p_{T,\text{min.}}$ from $0.7 \text{ GeV}/c$ to $\sim 4 \text{ GeV}/c$ brings the Ariadne-CR model into agreement with the data, but also at the expense of a good description of inclusive Z^0 measurements: global χ^2 for 81 bins of event shape distributions increase from 32 to 3019
- The Ariadne-CR model is also effectively excluded

Rapidity gaps in gluon jets, cont.

Total electric charge in the leading part of jets with a rapidity gap

[P. Minkowski & W. Ochs, PLB485 (2000) 139]

ALEPH preliminary



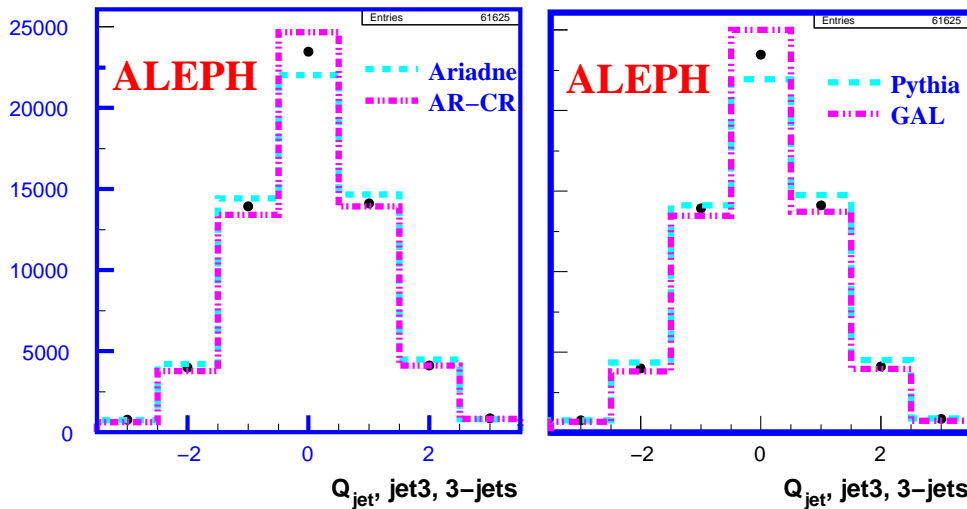
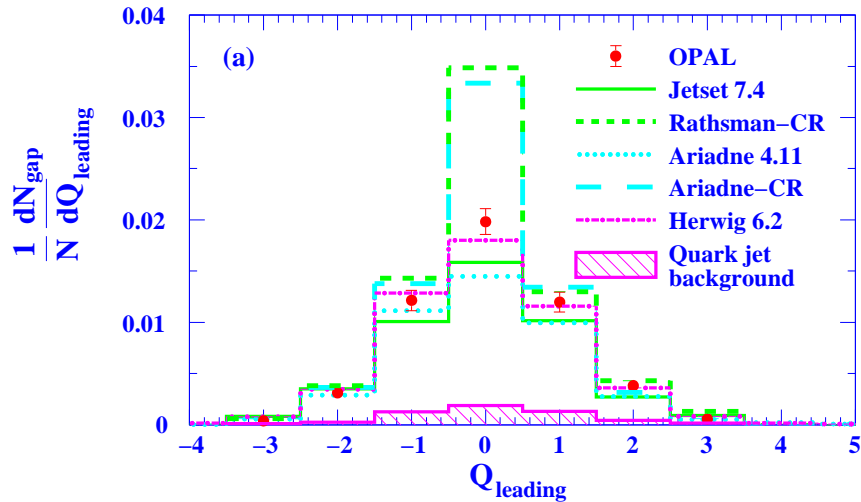
Very similar results (without the CR models) shown by F. Mandl, ISMD 2001 (Datong, China), see DELPHI note 2002-053

There are more electrically neutral gluon jets in the data than in the standard versions of Ariadne or Pythia

→ nominally consistent with the presence of some CR (reminiscent of the SK-I results for WW events)

Rapidity gaps in gluon jets, cont.

Comparison of the OPAL and ALEPH results for Q_{leading}



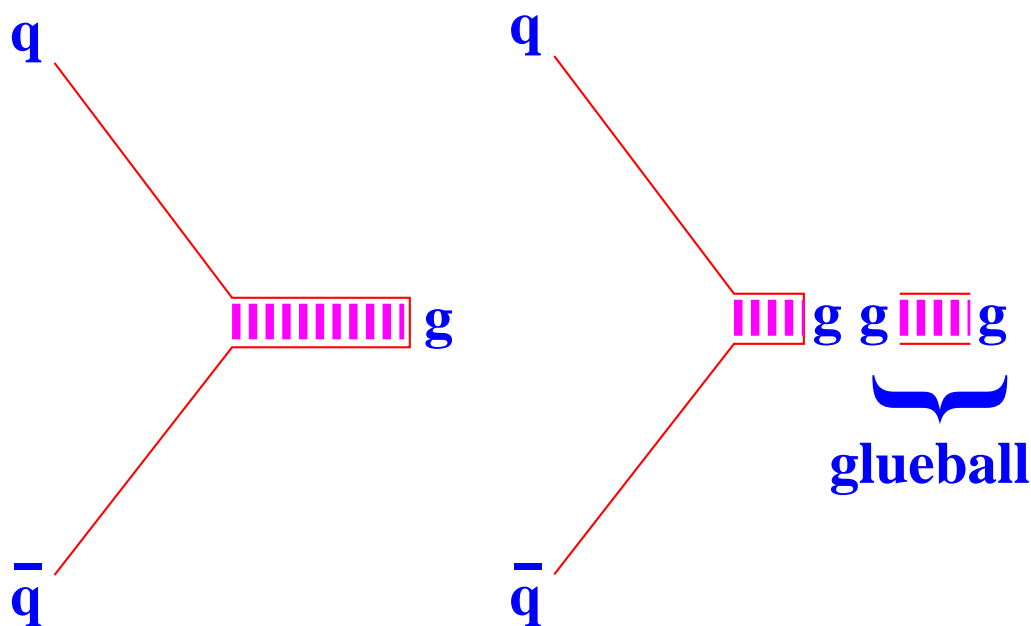
- OPAL more sensitive to CR (higher jet energies, purities)
 - Herwig without CR is in reasonable agreement with data
 - No significant spiking at even values of n_{ch} .
- The discrepancies of the non-CR models with the data are consistent with deficiencies in the simulations for reasons other than CR

Rapidity gaps & glueballs

Gluon jets with a rapidity gap represent an environment which may favor the creation of glueballs

[P. Minkowski and W. Ochs, PLB485 (2000) 139;
ibid, hep-ph/0304144 (April 2003)]

- An isolated hard gluon with a rapidity gap might build up an extended color octet field with the $q\bar{q}$ pair
- Analogy to the color triplet strings which connect a quark with an antiquark



- The most natural mechanism to neutralize an octet field is through gg pair production from the vacuum, resulting in glueballs

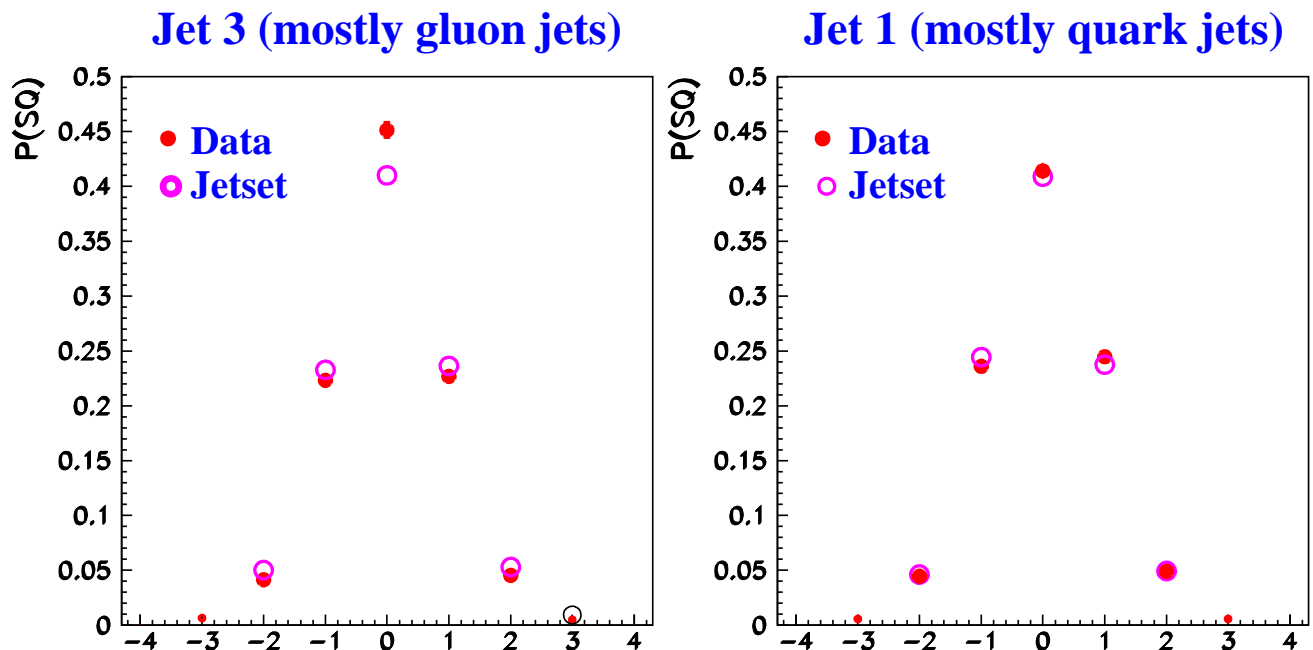
Rapidity gaps & glueballs, cont.

- Resonant production of glueballs could produce an enhancement in the rate of $q\bar{q}g$ events in which the leading part of the gluon jet is electrically neutral
- Such an enhancement is observed relative to the predictions of

- Pythia/Jetset (DELPHI, OPAL, ALEPH)
- Ariadne (OPAL, ALEPH)

but not relative to Herwig (OPAL)

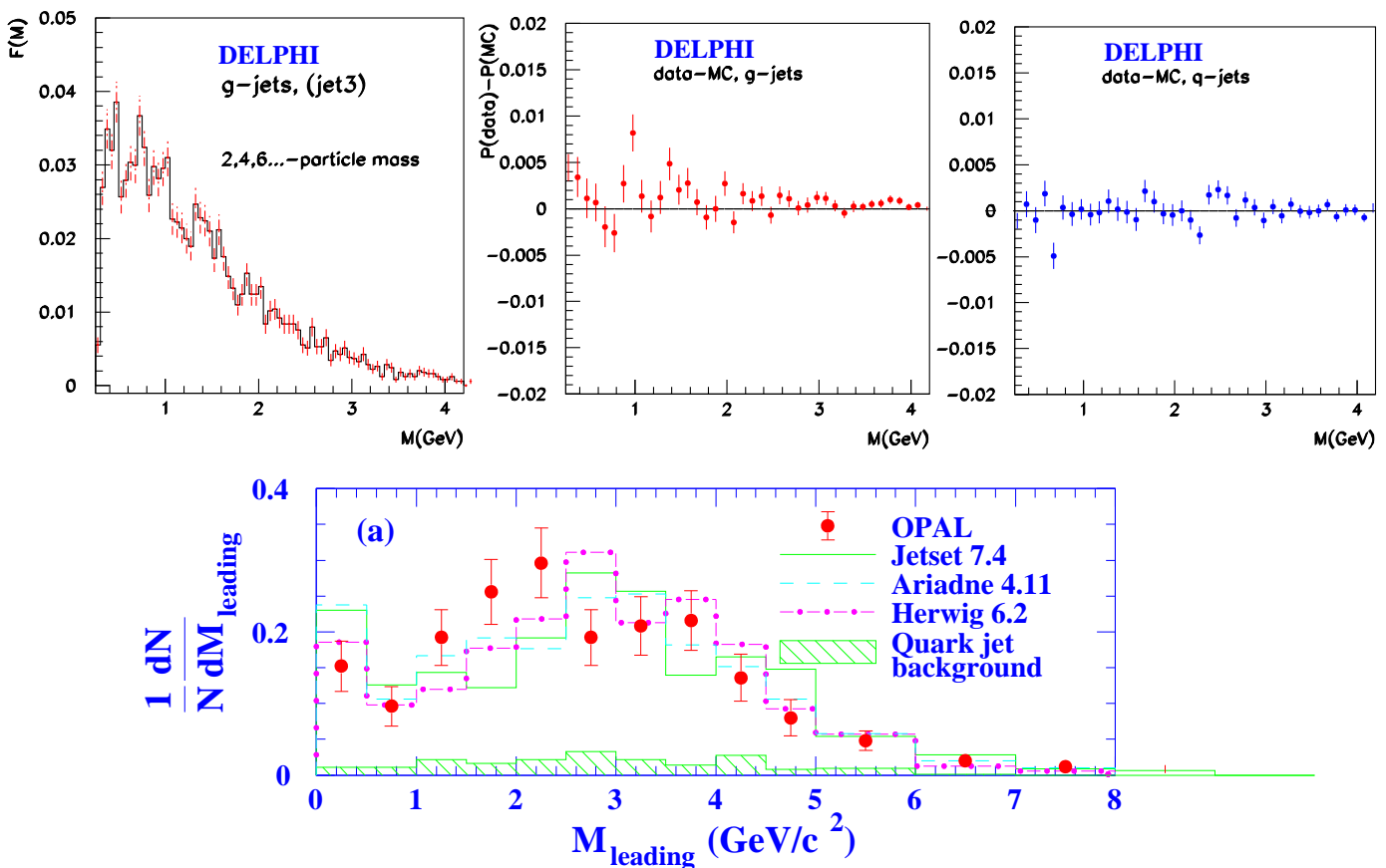
Total electric charge in leading part of gluon jets with rapidity gap



[from DELPHI 2002-053 (June 2002), B. Buschbeck & F. Mandl]

Rapidity gaps & glueballs, cont.

- Expect lightest glueball in range from about $1\text{--}2 \text{ GeV}/c^2$
- One of the best candidates is the $f_0(1500)$
- Detector level invariant mass spectra of the leading part of gluon jets, for $Q_{\text{leading}} = 0$:



- Purity of gluon jets $\sim 50\%$ (DELPHI), $\sim 86\%$ (OPAL)
- Some evidence for $2\text{--}3\sigma$ discrepancy with data for $M_{\text{leading}} \approx 1\text{--}3 \text{ GeV}/c^2$
- Better agreement of data with Ariadne and Herwig than with Pythia/Jetset

Differences between gluon & quark jets

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

→ expressed by the color factors

Quark jets:



Gluon jets:



The color charge of a gluon is

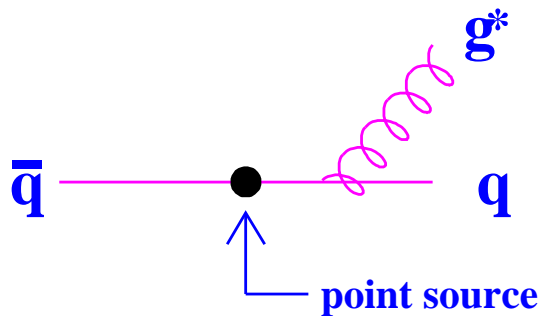
$$\frac{C_A}{C_F} = \frac{9}{4} = 2.25$$

larger than the color charge of a quark

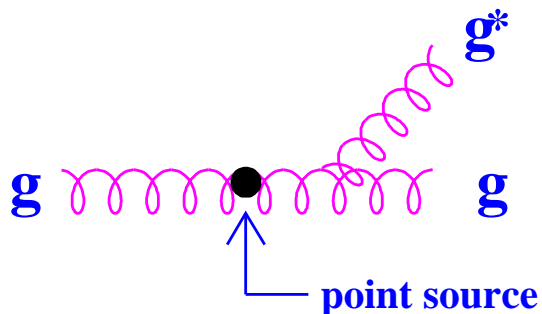
Quark & gluon jets in QCD calculations

→ 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

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)

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

= 2.25

Asymptotic: $E \ll E_{\text{jet}}$

~ 1.5

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

→ 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

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

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

→ 3NLO: $r_{g/q} \approx 1.7$

Capella, Dremin, Gary, Nechitailo,, Tran,
Phys. Rev. D61 (2000) 074009

→ Numerical solutions → more accurate inclusion
of energy conservation and phase space limits:

$$\underline{r_{g/q} \approx 1.5}$$

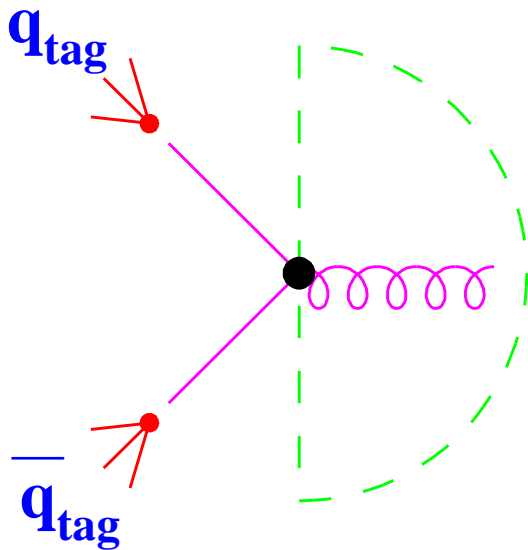
Lupia & Ochs, PL B418 (1998) 214
Eden & Gustafson, JHEP 09 (1998) 015

These calculations are based on massless quarks

“Direct” measurements of unbiased gluon jets

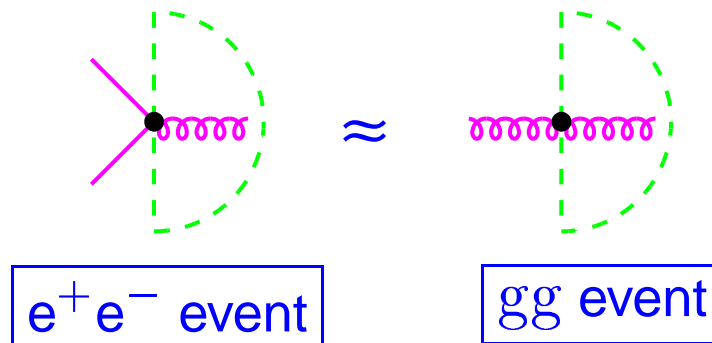
→ Radiative Υ decays: $e^+e^- \rightarrow \Upsilon \rightarrow \gamma gg$
(CLEO)

→ Gluon jet hemispheres in
 $e^+e^- \rightarrow Z^0 \rightarrow q_{\text{tag}}\bar{q}_{\text{tag}}g_{\text{incl.}}$ events (OPAL)



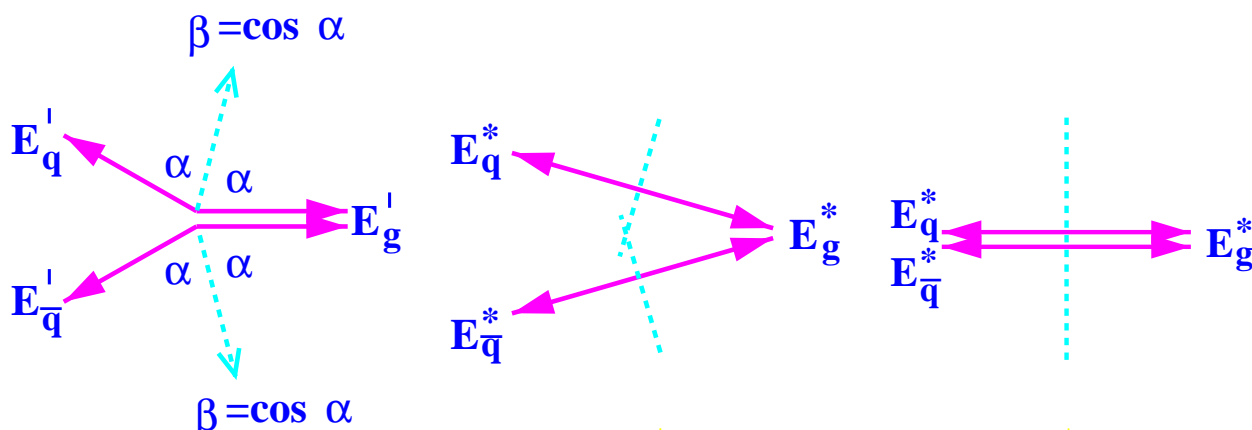
Gluon jet $g_{\text{incl.}}$ defined by the particles in the hemisphere opposite to a hemisphere with two tagged quark jets (tagged quark jet is a b jet)

→ Utilize the equivalence of the $g_{\text{incl.}}$ and gg event hemispheres (exact for colinear q and \bar{q})



Particle multiplicity of unbiased gluon jets using the jet boost algorithm

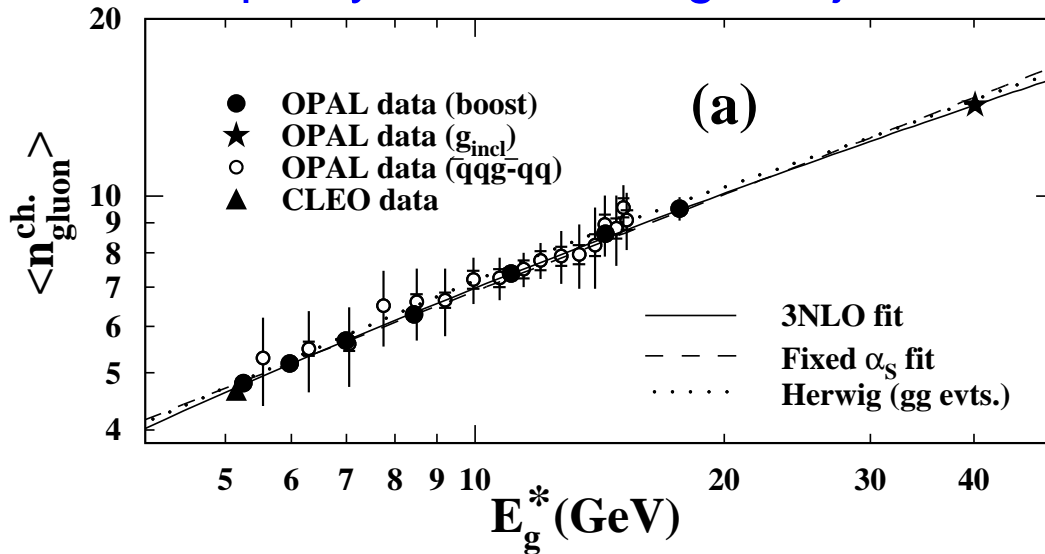
- OPAL Collab., prelim. → See talk by Simone Campana
- Based on the QCD dipole model [G. Gustafson, PLB75 (1986) 453]
- Method proposed in: P. Edén & G. Gustafson, JHEP **9809** (1998) 015



- Any three-jet $q\bar{q}g$ event can be boosted to the symmetric frame where $\theta_{qg} = \theta_{\bar{q}g} (= 2\alpha)$
- The two dipoles can be independently boosted to back-to-back frames along the bisectors of the dipoles, and combined to yield an event with the color structure of a **gg event** from a color singlet
- An indirect way to measure properties of unbiased gluon jets

Unbiased gluon jets using the jet boost algorithm. cont.

Particle multiplicity of unbiased gluon jets:



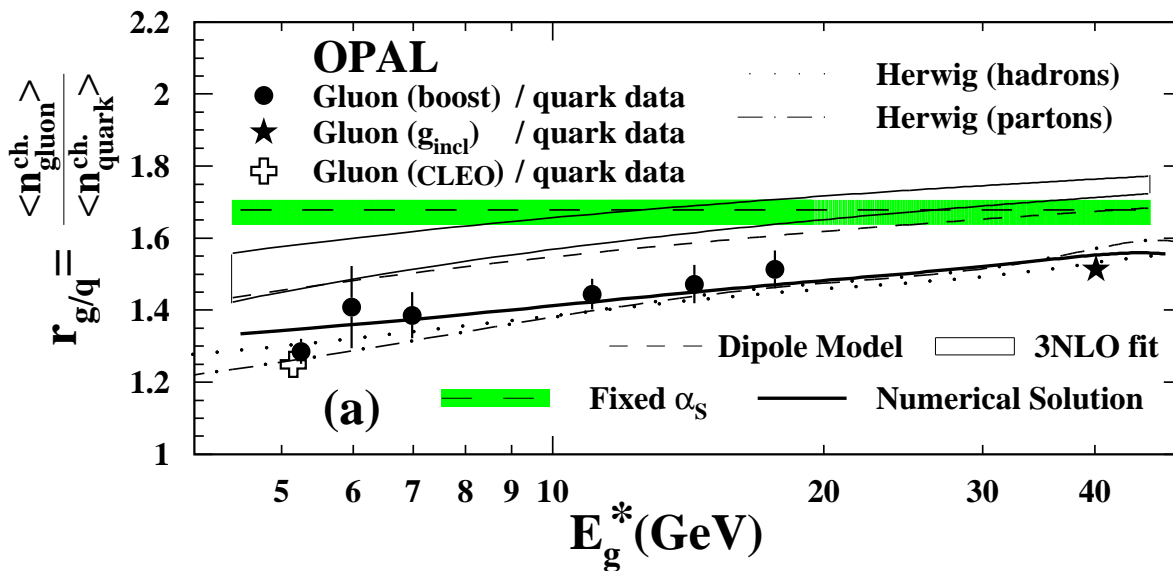
- The data from the boost method interpolate well between the direct measurements at 5 and 40 GeV
- The predictions of Herwig for gg events are in good agreement with the measurements
- Fitted QCD analytic curves also in good agreement, using reasonable values of the parameters ($\Lambda \approx 300 \text{ MeV}$)
- Boost method yields much smaller uncertainties than those from a previous study based on subtracting results from two-jet $q\bar{q}$ events from those from three-jet $q\bar{q}g$ events (open points)

[P.Edén, G. Gustafson, V.A. Khoze, EPJC11(1991)345;
OPAL Collab., EPJC23(2002)597]

Unbiased gluon jets using the jet boost algorithm. cont.

Multiplicity ratio between unbiased g and q jets:

- Divide the results from the unbiased gluon jets by the results from hemispheres of inclusive $e^+e^- \rightarrow hadrons$ events (measured by different experiments)



- Remarkable overall agreement with QCD numerical results of Lupia & Ochs.
- Good agreement with the prediction of Herwig at both the parton & hadron levels.
- QCD analytic curves with fitted parameters from the energy evolution of $\langle n_{gluon}^{ch.} \rangle$ lie about **15–20%** above the data
 → Incomplete treatment of energy conservation, phase space limits

Particle multiplicity of gluon jets in $p\bar{p}$ collisions

- CDF Collab., prelim., \longrightarrow See talk by Andrey Korytov
- Define jets using the cone jet finder

$$R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7 \text{ radians}$$

- Select di-jet and $\gamma + \text{jet}$ event samples with similar kinematics (E_T balance, etc.)
- For systematic checks on jet finder dependence, repeat using $R = 0.4$ and 1.0 radians
- Examine the jets in two bins of “di-jet” invariant mass M_{jj} , with the γ treated as a “jet:”

$$M_{jj} = 82 \text{ \& } 105 \text{ GeV}/c^2$$

- Jet energies given by $E_{\text{jet}} = M_{jj}/2$
- Boost to c.m. frame of the “di-jet” systems, count number of charged tracks in cones of size

$$\theta_c = 0.28, 0.36, 0.47$$

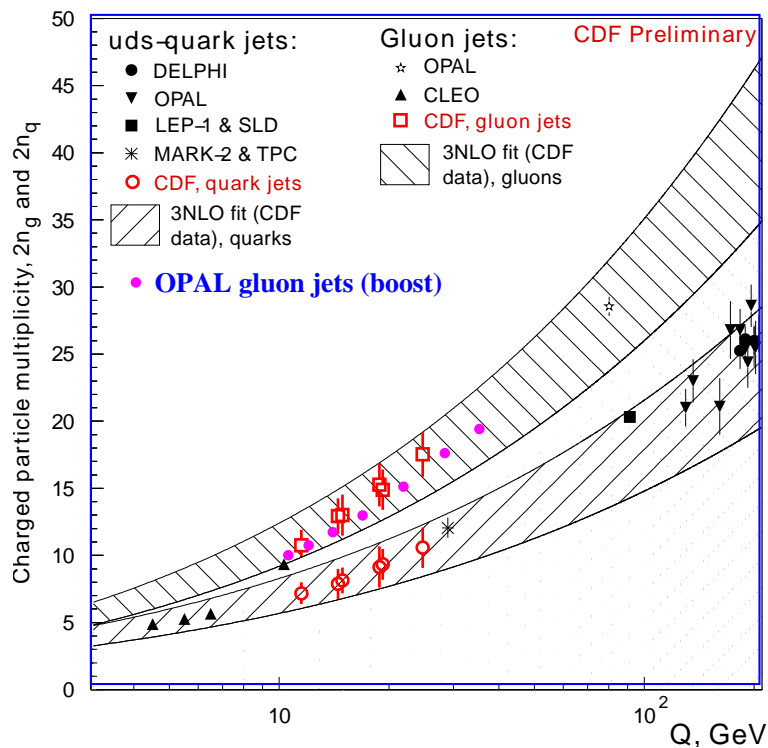
radians around the jet axis

- Energy scale of the measurements given by $Q = E_{\text{jet}}\theta_c$

Particle multiplicity of gluon jets in $p\bar{p}$ collisions, cont.

Gluon jet fraction $\sim 60\%$ di-jet events
 $\sim 20\%$ γ + jet events

→ Assume that the gluon and quark jet properties are the same in the two samples, unfold algebraically to obtain \mathbf{n}_g and \mathbf{n}_q , the mean charged particle multiplicities in gluon and quark jets

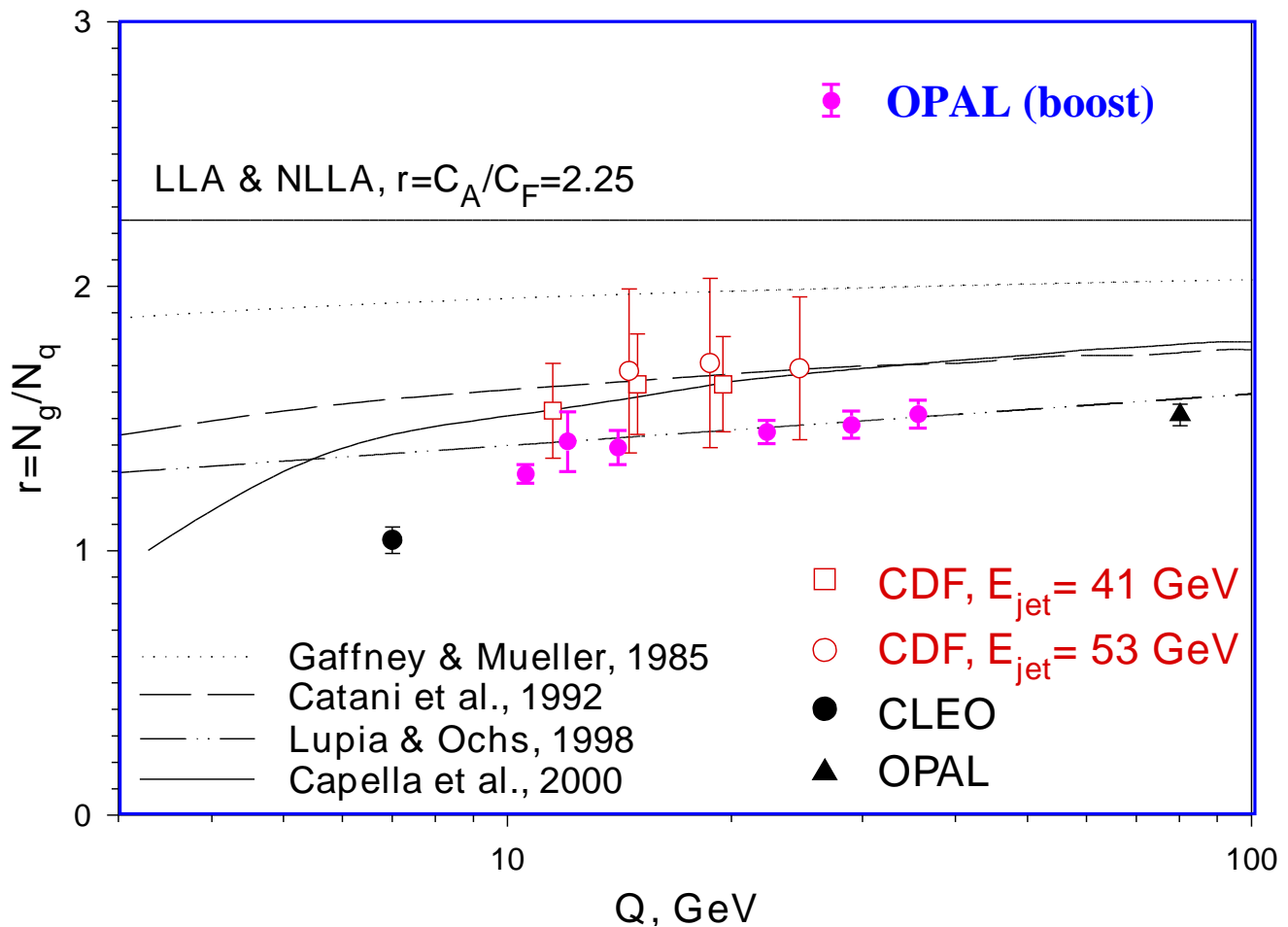


[3NLO curves: Use fitted value of Λ from a previous CDF study, with normalization fitted to the CDF \mathbf{n}_g and \mathbf{n}_q results separately; width of band corresponds to the uncertainty in the normalization]

→ Gluon jet multiplicity from $p\bar{p}$ collisions consistent with unbiased gluon jet data from e^+e^- annihilations

Particle multiplicity of gluon jets from $p\bar{p}$ collisions, cont.

Multiplicity ratio between gluon and quark jets:



- The results from e^+e^- and $p\bar{p}$ exhibit remarkable overall consistency
- Higher orders and consideration of recoil effects yields a generally satisfactory theoretical description of the data

Differences between G & Q jets from ep collisions

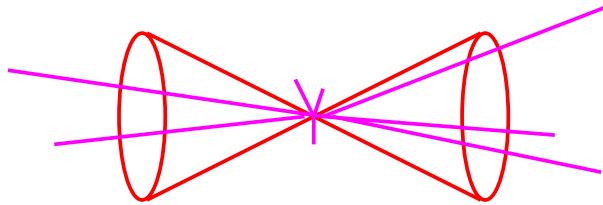
- Zeus Collab., prelim. → Contributed paper to EPS meeting (Aachen, 2003)
- Photoproduction of di-jets
 - Low Q^2 scattering, γ quasi-real
 - $$\gamma p \rightarrow (q\bar{q} \text{ or } gg \text{ or } qg) + X$$
- Define jets using the longitudinally invariant k_{\perp} jet finder
- Select di-jet systems:
 - $E_T^{\text{jet1}} > 17 \text{ GeV}, E_T^{\text{jet2}} > 14 \text{ GeV}$
 - $-1 < \eta^{\text{jet}} < 2.5$
- Identify the final-state gluon and quark jets using differences in their properties:
 - Sub-jet multiplicities: gluon jets have a larger sub-jet multiplicity than quark jets
 - Jet energy profile: gluon jets are less collimated (are broader) than quark jets

Both these features distinguishing gluon & quark jets have been **well established** at e^+e^- & $p\bar{p}$ colliders using model independent techniques

Subject multiplicities

- Define jets using the k_{\perp} jet finder with a large resolution scale $y_{cut} = y_0$

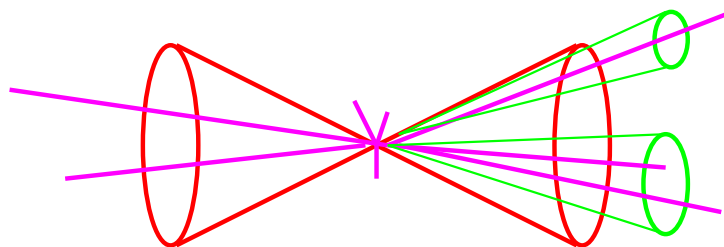
→ Include higher order radiation in the jets



- Re-apply the jet finder to the jets using a smaller and smaller resolution scale $y_{cut} = y_1$

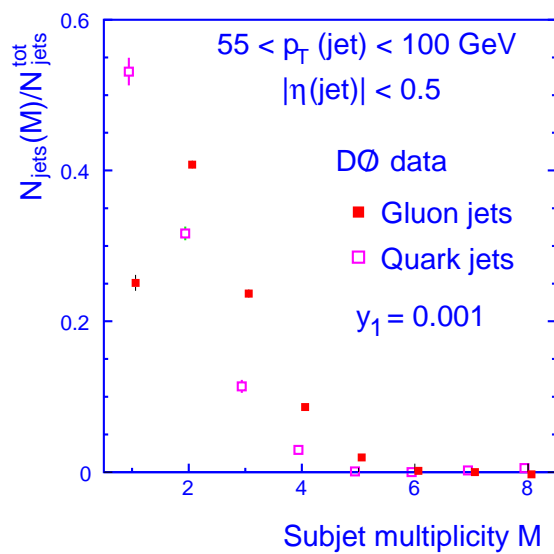
→ resolve the “subset” structure of the jet

→ Determine the number of subsets as a function of y_1



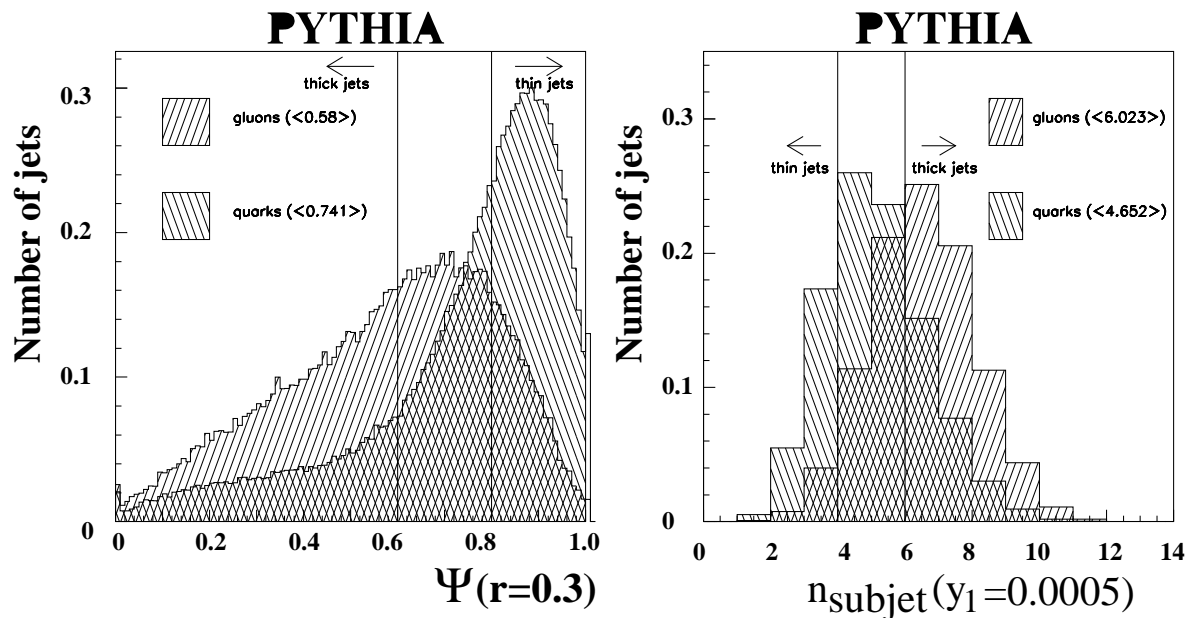
- D0:** [Phys.Rev.D65(2002)052008]

Use jets selected using the same criteria at $\sqrt{s} = 630$ and 1800 GeV



Differences between G & Q jets from ep collisions, cont.

Hadron level Monte Carlo results for gluon and quark jets selected using the same kinematic cuts applied to the data:



Jet energy profile $\Psi(r)$: fraction of a jet's visible energy within a cone of half angle r around the jet axis

$$\underline{\Psi(r = 0.3) < 0.6 \ \& \ n_{\text{subjet}}(y_1 = 0.0005) \geq 6:}$$

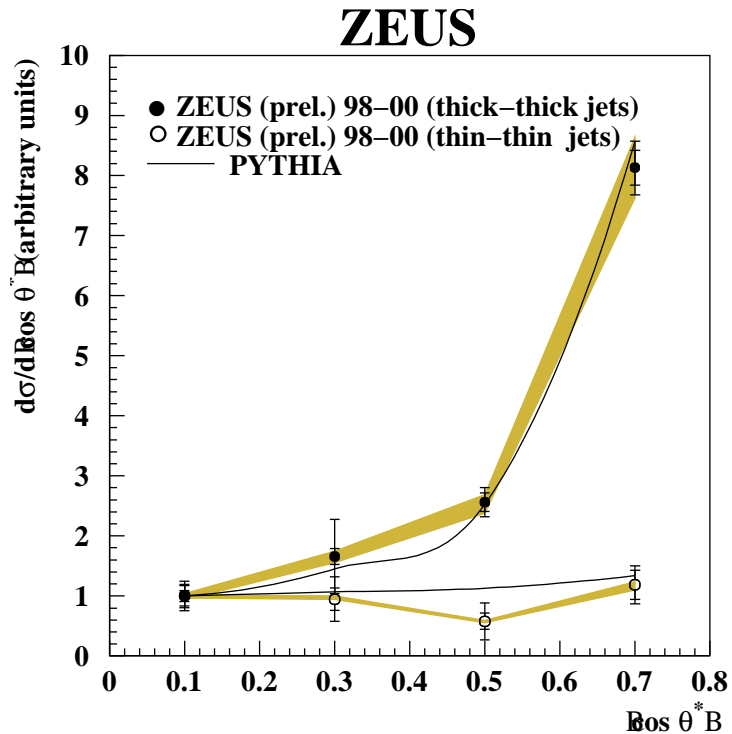
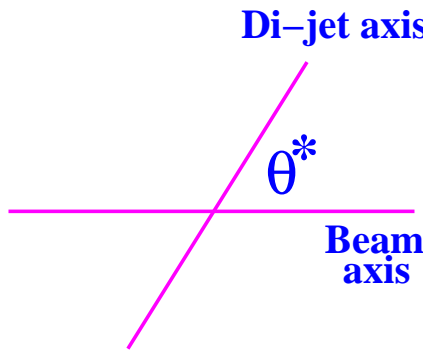
- **“thick jets:”** gluon jet enriched
- MC gluon jet purity $\sim 65\%$

$$\underline{\Psi(r = 0.3) > 0.8 \ \& \ n_{\text{subjet}}(y_1 = 0.0005) \leq 3:}$$

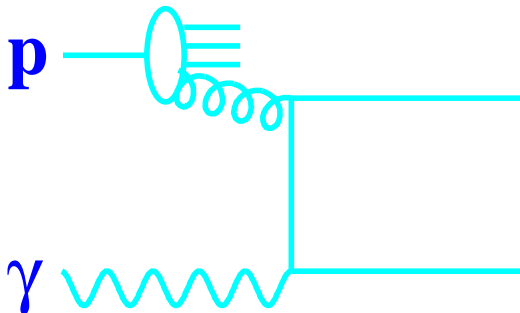
- **“thin jets:”** quark jet dominated
- MC quark jet purity $\sim 99\%$

Differences between G & Q jets from ep collisions, cont.

Angular distributions of “thick-thick” and “thin-thin” events in the di-jet rest frame: $d\sigma/d|\cos\theta^*|$



- $\gamma p \rightarrow q\bar{q} + X$ (thin-thin): Mostly direct events
(γ couples directly to partons in the proton)



$$\frac{d\sigma}{d|\cos\theta^*|} \sim \frac{1}{1 - |\cos\theta^*|}$$

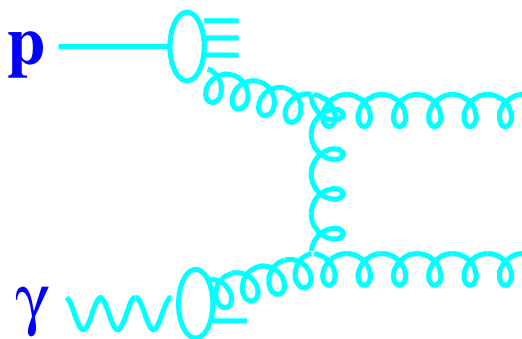
(t-channel quark exchange)

→ Selecting a thin jet selects a quark jet

Differences between G & Q jets from ep collisions, cont.

- $\gamma p \rightarrow gg$ (or gq) + X (thick-thick):

Mostly resolved events
(γ acts as a source of partons)



$$\frac{d\sigma}{d|\cos\theta^*|} \sim \frac{1}{(1 - |\cos\theta^*|)^2}$$

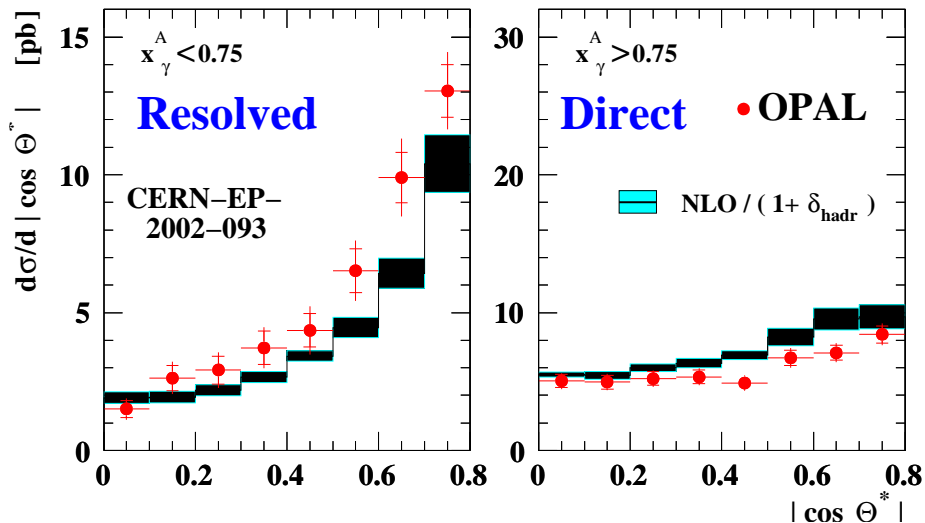
(t-channel gluon exchange)

→ Selecting a thick jet selects a gluon jet

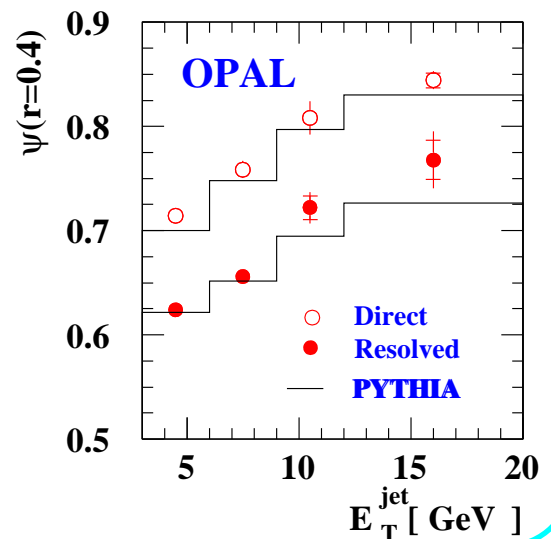
- The thick-thick and thin-thin cross sections follow the expectations for gg (or gq) and $q\bar{q}$ scattering, respectively
- Experimental verification of differences between gluon and quark jets in the ep environment
- Complements the observations in e^+e^- and $p\bar{p}$ events, emphasizing the **universality of jets**

Differences between G & Q jets from $e^+e^- \rightarrow e^+e^- + X$ collisions

- Di-jet events in no-tag events \rightarrow both γ quasi-real
- Select kinematic regions to enhance direct and double resolved events
 - \rightarrow **Direct:** t-channel quark exchange, quark jet final states
 - \rightarrow **Double resolved:** t-channel gluon exchange, gluon jet final states



Jets from the resolved events are broader than jets from the direct events, demonstrating the differences between gluon & quark jets for e^+e^- “ 2γ ” events



Summary

- Color reconnection (CR) an important issue in e^+e^- physics
 - W mass measurement at LEP
 - Understanding higher order QCD processes not included in the standard QCD MC programs
 - Gluon jets with a rapidity gap provide a means to place strong constraints on CR models
 - Current versions of the Ariadne-CR and Rathsman-CR (GAL) models are effectively excluded
- DELPHI, OPAL, ALEPH observe an enhancement in the rate of events in which the leading part of gluon jets (beyond a rapidity gap) is electrically neutral, compared to models with string hadronization (Ariadne, Pythia/Jetset)
 - Consistent with production of glueballs through neutralization of color octet strings, but nothing conclusive
- Much recent (2002-2003) progress in establishing the characteristic differences between gluon and quark jets in different environments
 - New results from e^+e^- annihilations, $p\bar{p}$, ep , and e^+e^- “ 2γ ” processes
 - Universality of jet production