Experimental study of rapidity gaps in gluon jets

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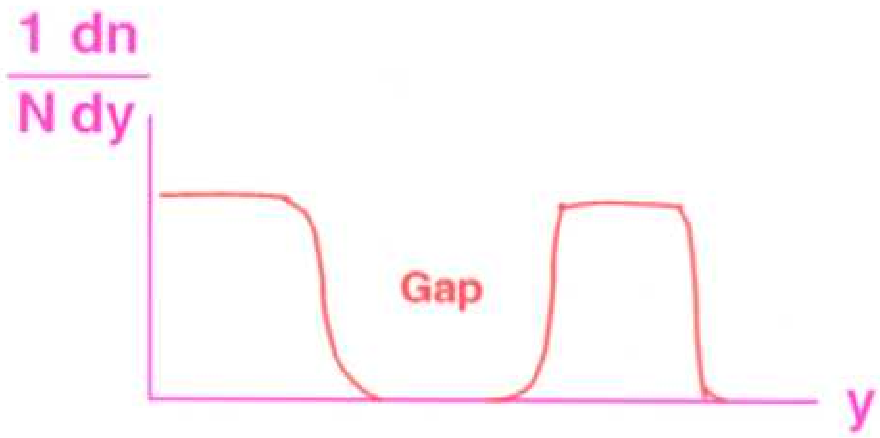
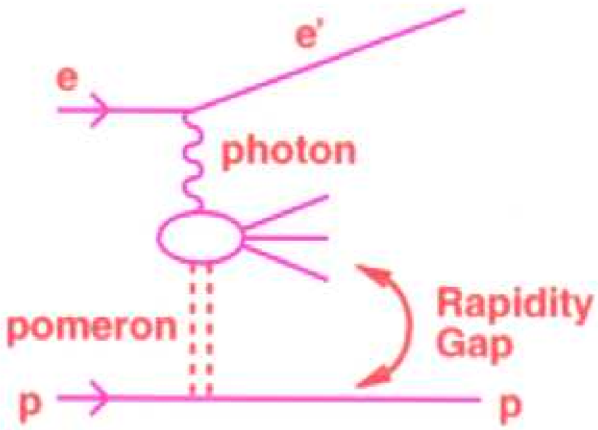
Rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_{\|}}{E-p_{\|}} \right)$

- A standard variable to characterize the phase space distribution of particles
- $p_{\|}$ calculated with respect to the jet, thrust, or beam axis

Of recent interest $\longrightarrow$ events with a rapidity gap



$\longrightarrow$ A signal for the exchange of a strongly interacting color singlet object, e.g. ep scattering at HERA



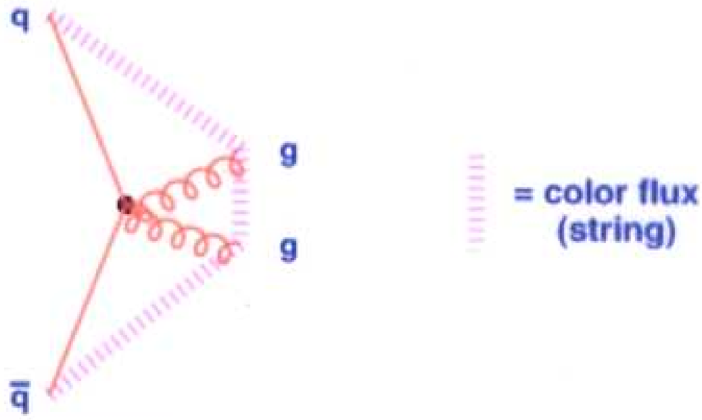
(from H1 Collab., EPJ C24 (2002) 517)

Another source of rapidity gaps

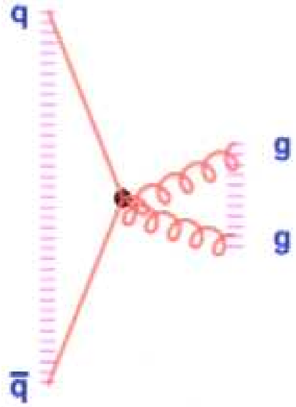
⟶ Color reconnection

A manifestation of higher order QCD

1 : Planar (unsuppressed) diagrams, $e^+e^- \rightarrow q\bar{q}g$ 3-jet events



2 : "Reconnected" diagrams, suppressed by $\mathcal{O}(\frac{1}{N_c^2})$, $N_c = 3$



⟶ There is a reduction in particle production in the central rapidity region of reconnected events

⟶ An increase in the probability for a rapidity gap

Rapidity gaps in gluon jets provide a sensitive means to search for manifestations of color reconnection

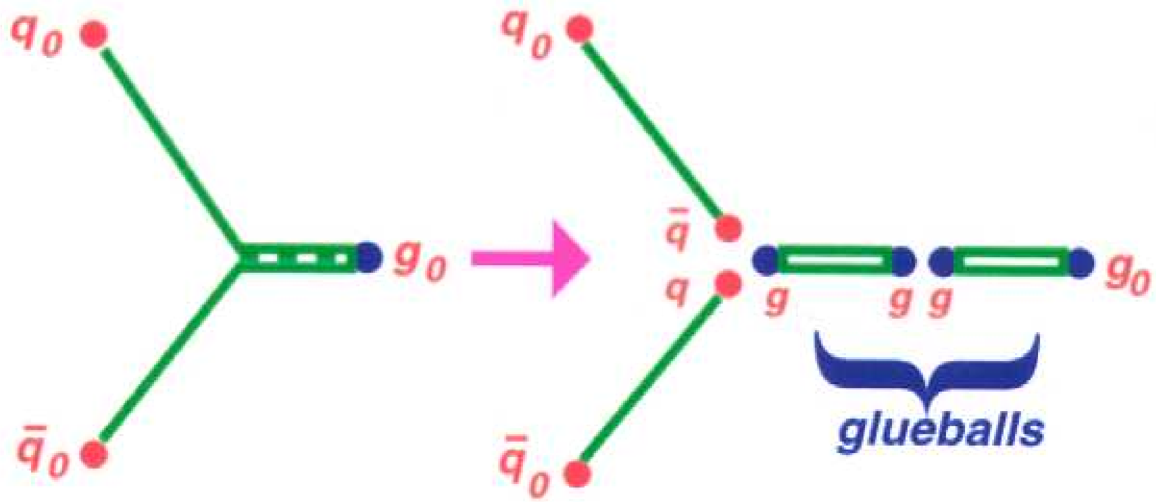
Rapidity gaps & glueballs

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

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

→ An isolated hard gluon with a rapidity gap might build up an extended color octet field with the $q\overline{q}$ 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

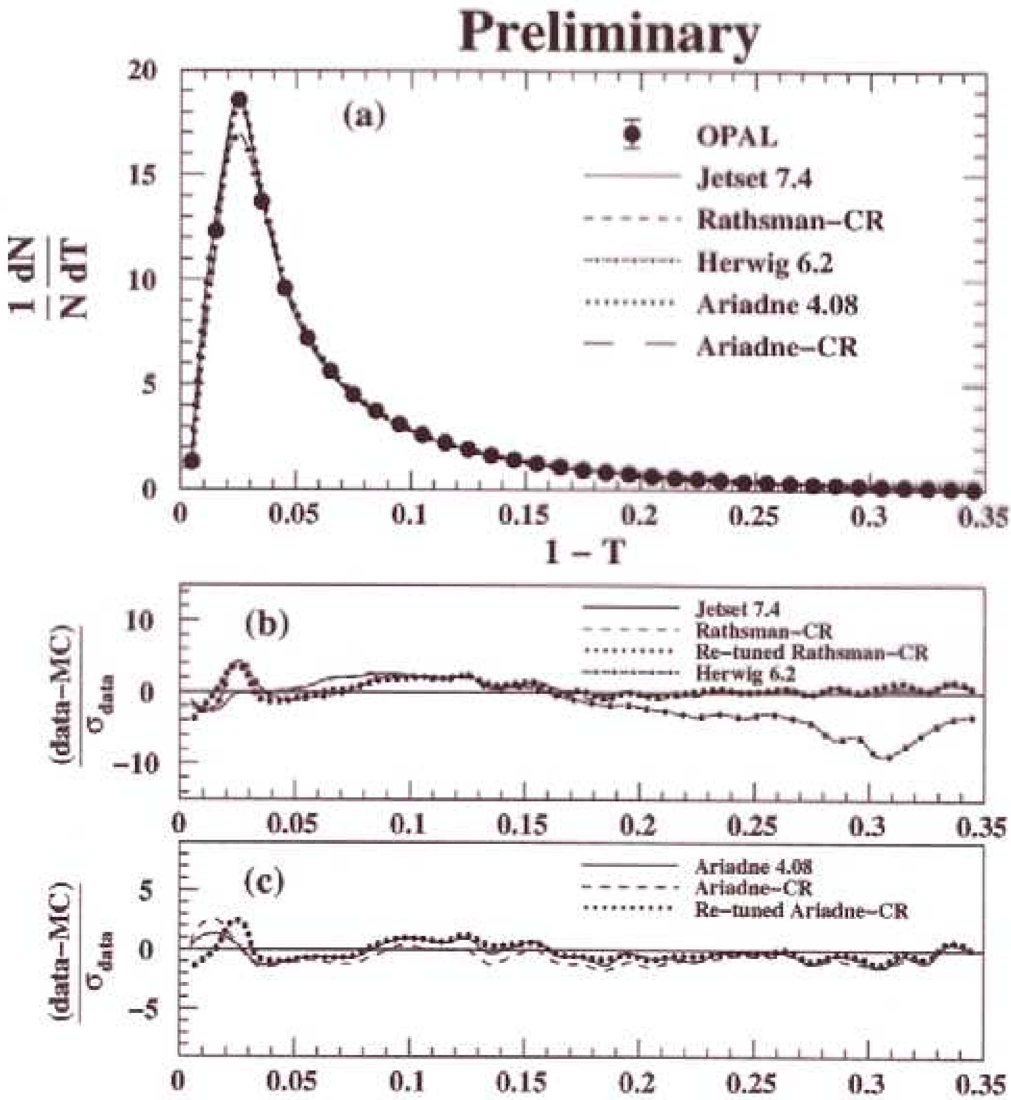
[See F. Mandl, Proceedings of the 31st ISMD (Datong, 2001), and DELPHI note 2002-053 CONF 587]

QCD models in this study

- Models without color reconnection:
  - → Herwig 6.2: Parton shower & cluster hadronization
  - → Jetset 7.4: Parton shower & string hadronization
  - → Ariadne 4.08: Dipole cascade & string hadronization
- Models with color reconnection:
  - → Rathsman model [J. Rathsman, PLB452(1999)364]
    - → Implemented in Pythia (Jetset)
    - → Provides a good description of rapidity gap measurements in ep and $p\overline{p}$ scattering [e.g. R. Enberg,G.Ingelman & N.Timneanu, PRD64(2001)114015]
    - → Referred to here as the Rathsman-CR model
  - → Gustafson-Häkkinen-Lönnblad model [G. Gustafson & J. Häkkinen, ZPC64(1994)659; L. Lönnblad, ZPC70(1996)107]
    - → Implemented in Ariadne
    - → Referred to here as the Ariadne-CR model
- All five models provide an equally good description of global event properties in inclusive hadronic Z^0 decay events

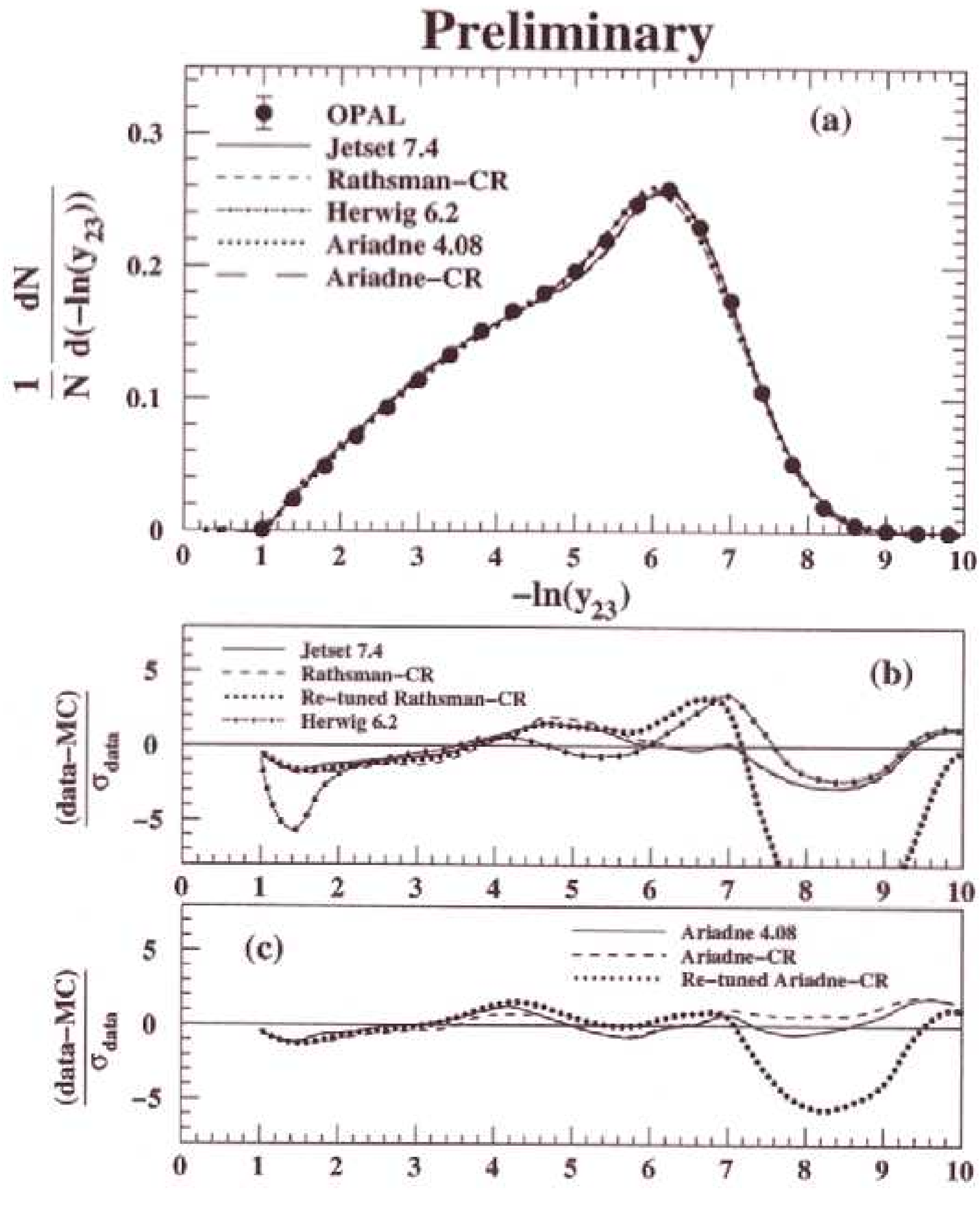
Inclusive hadronic Z^0 decays: Thrust

$$T = \max\left(\frac{\sum_i \vec{p}_i \cdot \hat{n}}{\sum |\vec{p}_i|}\right) \quad i = particles$$



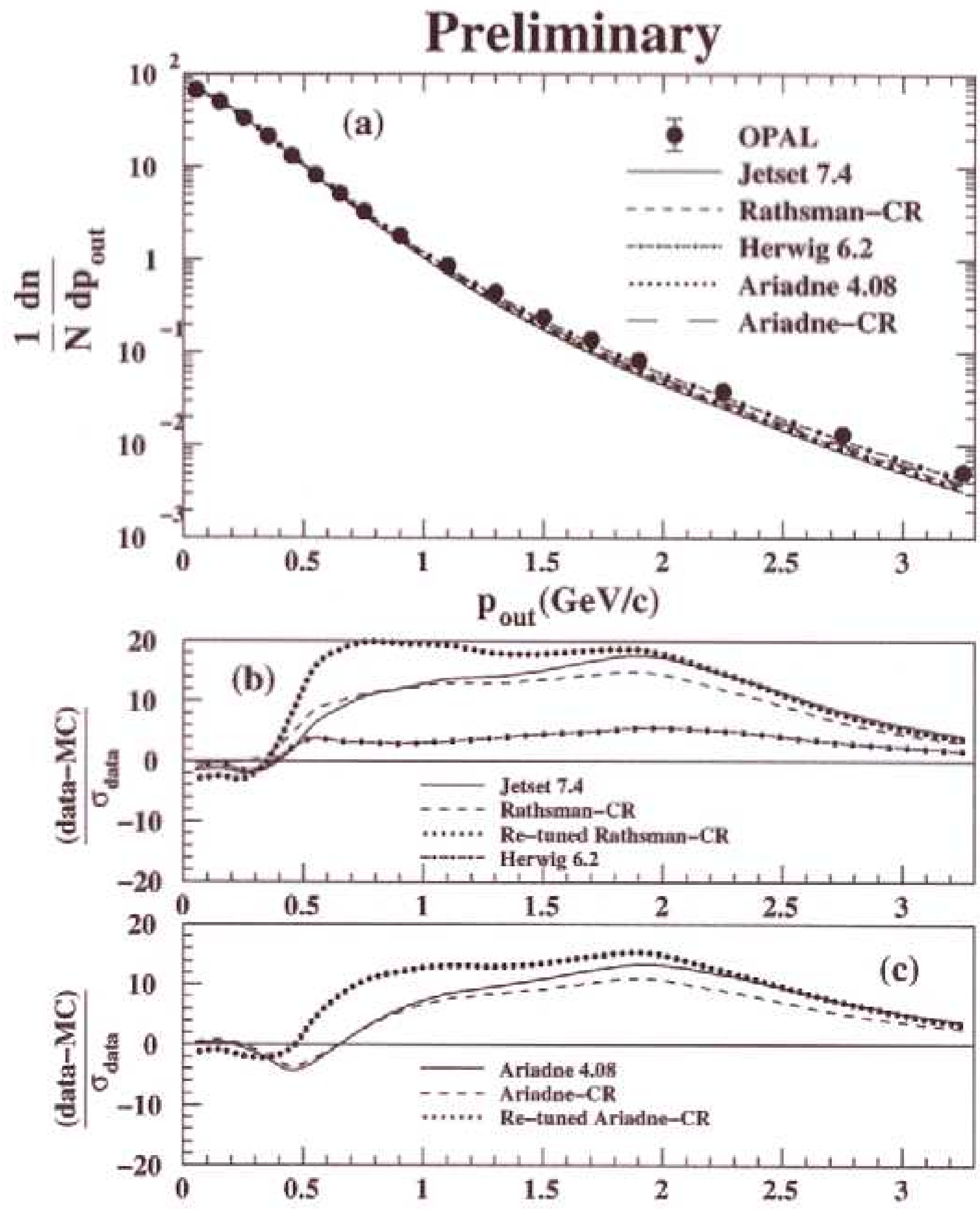
Inclusive hadronic Z^0 decays: y_{23}

y_{23}: the value of the resolution parameter y_{cut} at which an event changes from being classified as a 2-jet event to a 3-jet event, using the $k_\perp$ jet finder



Inclusive hadronic Z^0 decays: p_{out}

p_{out}: the distribution of particle momentum along the **thrust minor direction** (out of the 3-jet event plane)



Inclusive hadronic Z^0 decays: χ^2

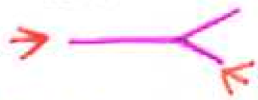
Model (Nr. bins)	$1-T$ (35)	A (15)	B_W (28)	$-\ln(y_{23})$ (27)	y_T (21)	p_{out} (17)	Total (143)
Jetset	53	69	55	41	30	1887	2135
Rathsman-CR	54	105	127	52	57	1606	2001
Herwig	415	45	283	83	120	195	1141
Ariadne	20	69	24	15	79	888	1095
Ariadne-CR	33	84	40	20	90	612	879

- The largeness of the χ^2 values reflects the smallness of the experimental uncertainties
- The systematic differences between the model predictions and data are, in general, not large
- The χ^2 results are intended to be used only as a relative measure of the description of the data by the models
- Correlations between distributions are not taken into account
- The total χ^2 result from the Rathsman-CR is about the same as from Jetset; same thing for Ariadne-CR with respect to Ariadne.

Gluon jet analysis

- OPAL Z^0 hadronic decay sample: ~ 2.7 Mevents
- Standard track & event selection
- Apply the $k_\perp$ jet algorithm, adjust the resolution scale y_{cut} separately for each event so three jets are always reconstructed
- Identify the GLUON JET in the $e^+e^- \rightarrow q\bar{q}g$ events

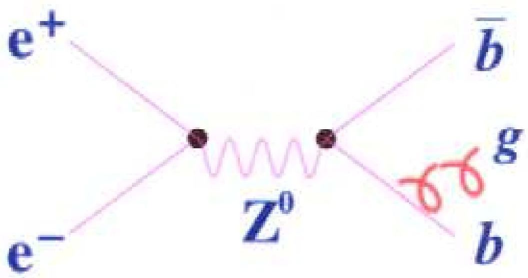
⟶ Require a displaced 2ndary vertex BOTH in the highest energy jet and in ONE of the two lower energy jets



⟶ Displaced 2ndary vertices tag b quarks

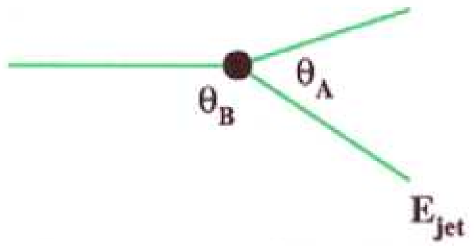
⟶ At LEP, b quarks are produced almost exclusively through the electroweak decay of the Z^0:

$$Z^0 \rightarrow b\bar{b}(g)$$



⟶ The gluon jet is the lower energy jet WITHOUT the 2ndary vertex

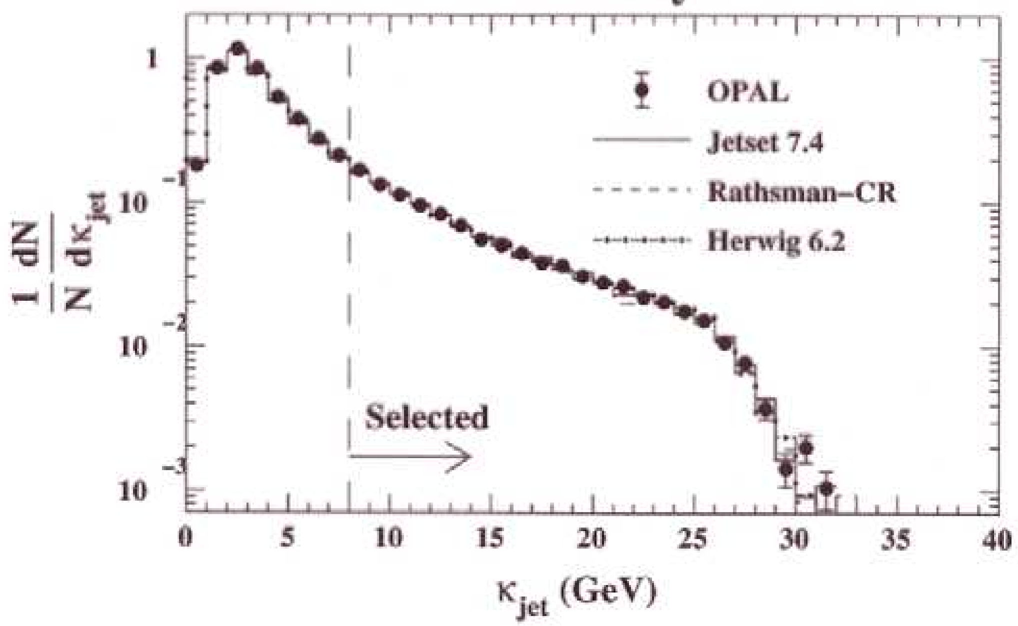
Gluon jet scale $\kappa_{jet} = E_{jet} \sin\left(\frac{\theta_{min}}{2}\right)$



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

More appropriate than E_{jet} for jets defined using a jet finder
[See, e.g. DELPHI Collab., Phys. Lett. B449 (1999) 383]

Preliminary



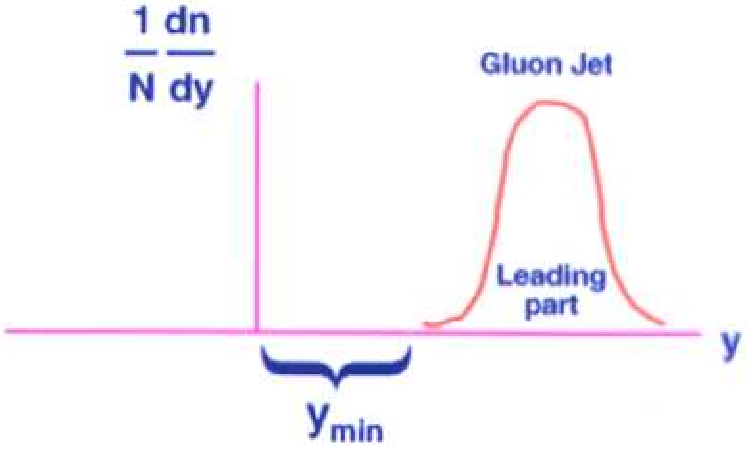
- We require $\kappa_{jet} \geq 8$ GeV to select hard acolinear gluon jet and $E_{jet} < 35$ GeV because the gluon jet purity drops rapidly for larger energies

$\longrightarrow$ 10,357 gluon jets with $\langle E_{jet} \rangle \sim 23$ GeV and purity 94%

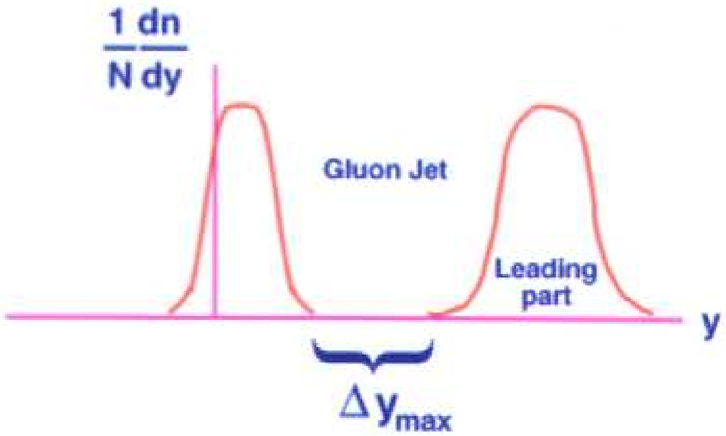
Rapidity gap analysis

Select gluon jets with a large rapidity gap:

EITHER



OR



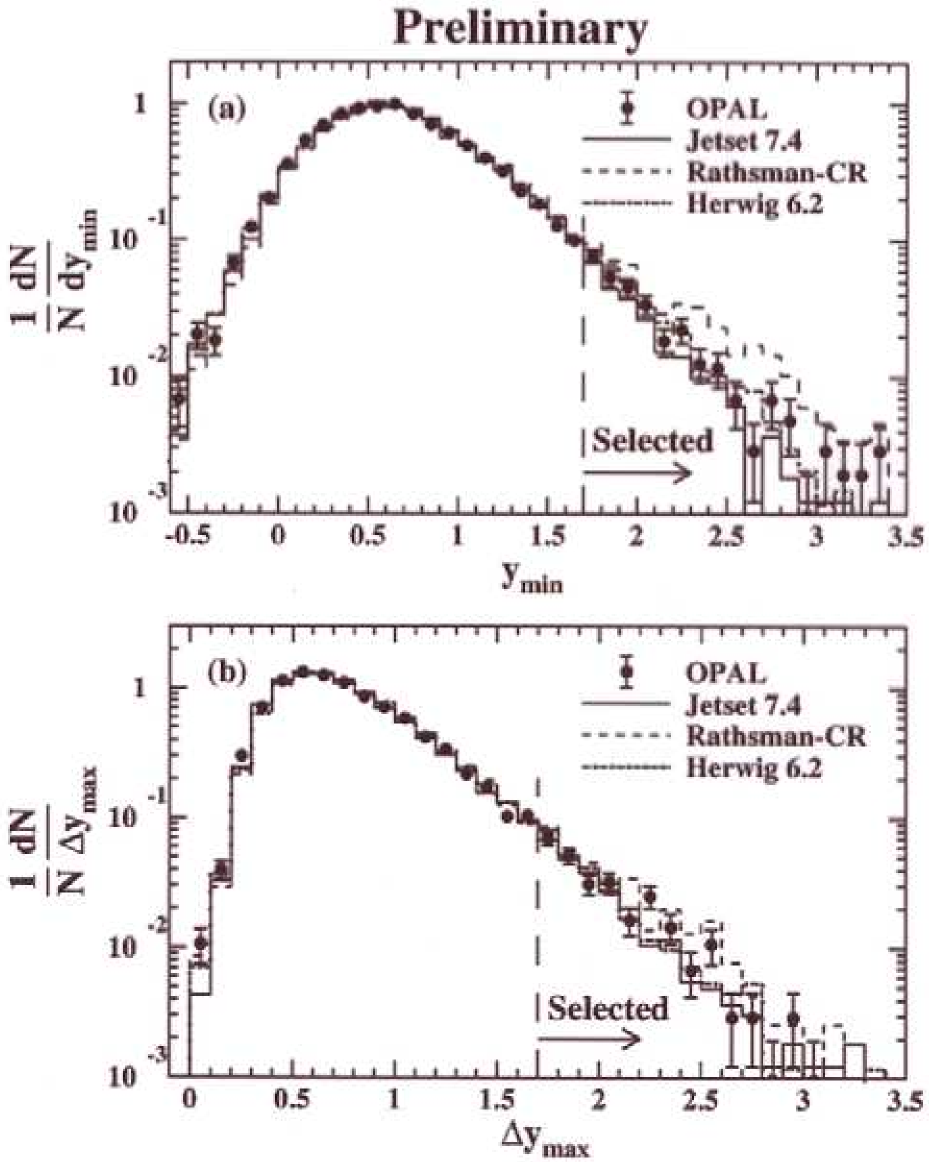
→ Rapidity is calculated with respect to the gluon jet axis

→ Study the properties of the leading parts of the gluon jets to test the models with Color Reconnection

Rapidity gap analysis, cont.

(Detector level)

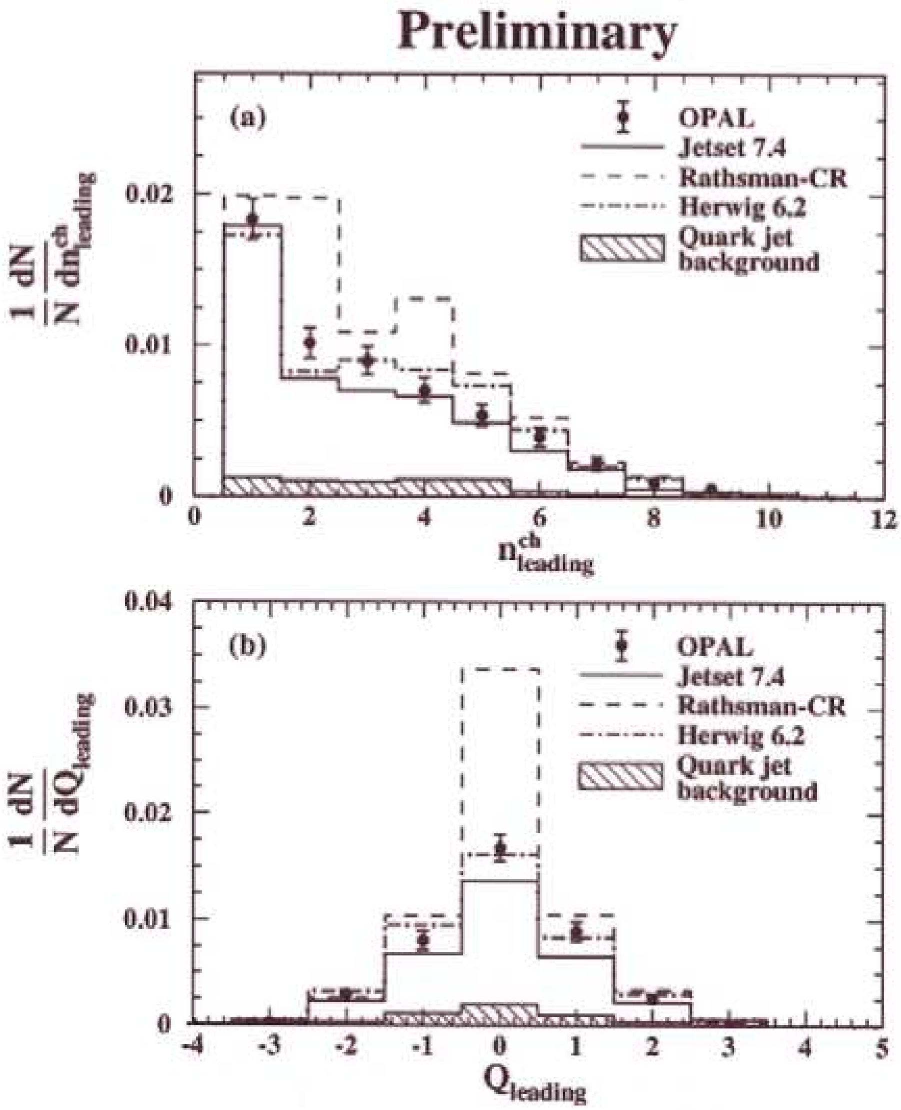
Distributions of y_{min} and Δy_{max} in the gluon jets:

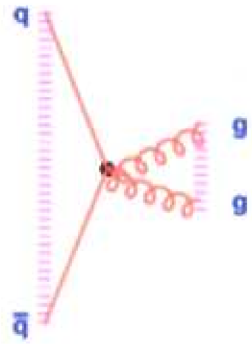


⟶ In total, 409 gluon jets with a rapidity gap are selected, about 4% of the entire gluon jet sample

Charged particle multiplicity $n^{ch}_{leading}$ and total electric charge $Q_{leading}$

(Detector level)





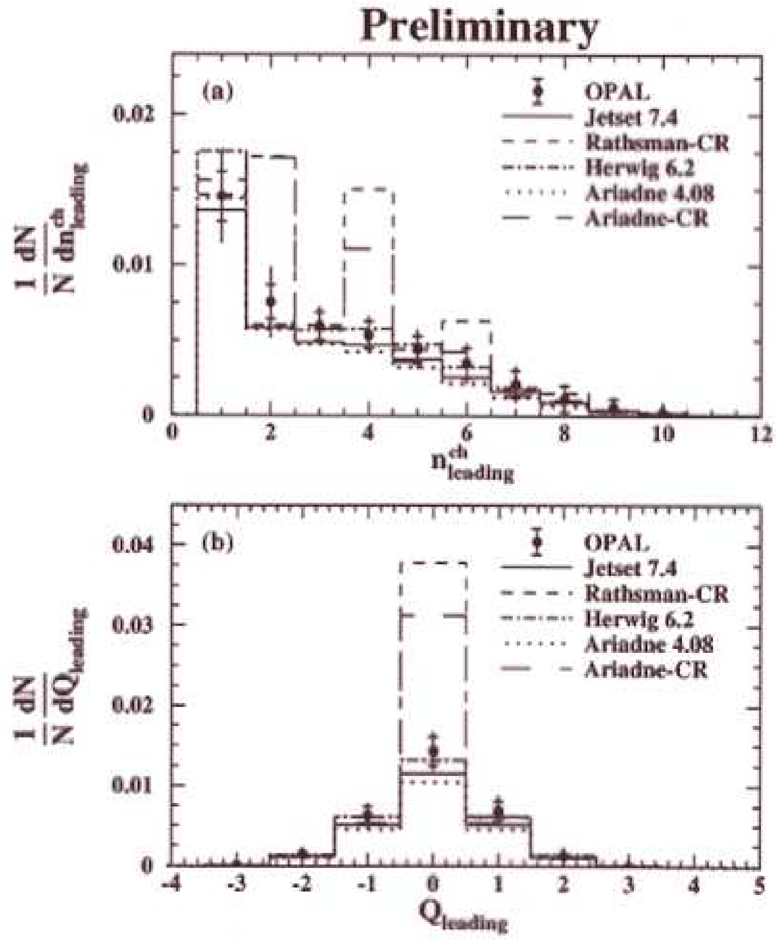
(Normalized to the number of gluon jets before the rapidity gap requirement)

⟶ The isolated, electrically neutral system in the leading part of gluon jets in reconnected events decays into an even number of charged particles

⟶ A very sensitive signal for color reconnection

Charged particle multiplicity $n^{ch}_{leading}$ and total electric charge $Q_{leading}$

(Corrected for detector acceptance & resolution)



Herwig, Jetset & Ariadne (models without CR)

⟶ In general agreement with the data

Rathsman-CR & Ariadne-CR

⟶ A large excess of events with a large rapidity gap, for which the leading part of the jet is electrically neutral

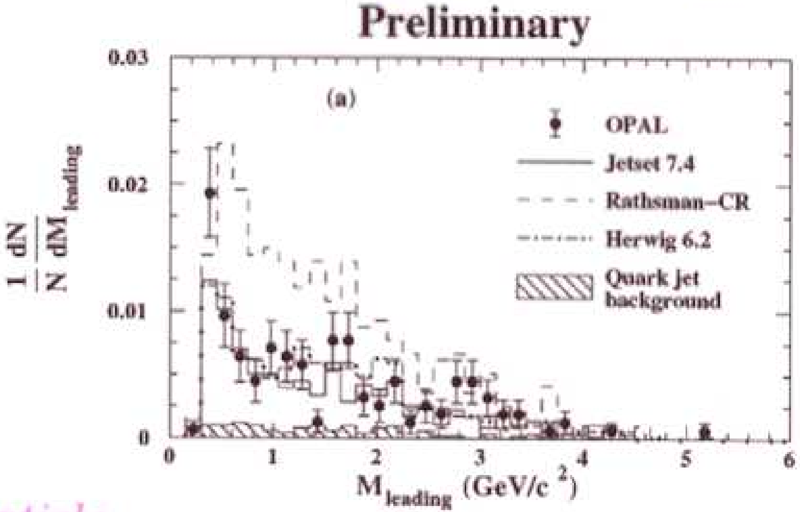
No evidence for color reconnection

[L3 note 2728, February 2002: similar conclusion for the Rathsman-CR model based on particle flow asymmetries *between* jets]

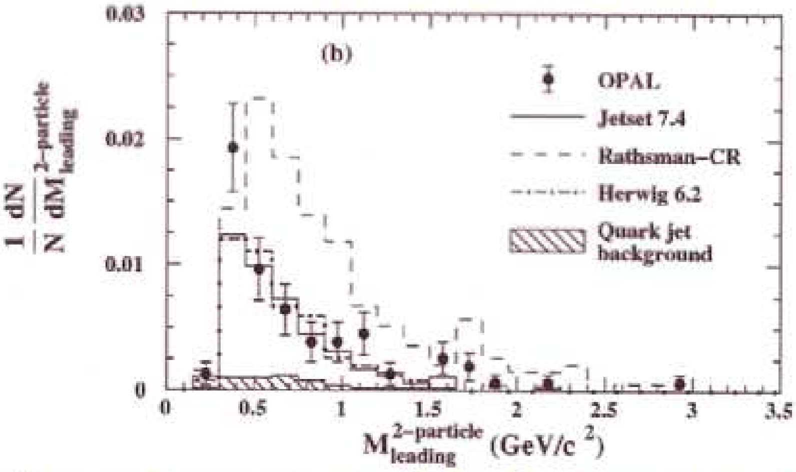
Invariant mass distributions for gluon jets with $Q_{leading} = 0$

(Detector level)

- $M_{leading}$: Mass of the leading part of the gluon jets (based on charged particles only)



- $M_{leading}^{2-particle}$: Mass of all 2-particle combinations of oppositely charged particles



$\longrightarrow$ No evidence for an anomalous feature at $\sim 1-2$ GeV/c^2

No clear evidence for glueballs

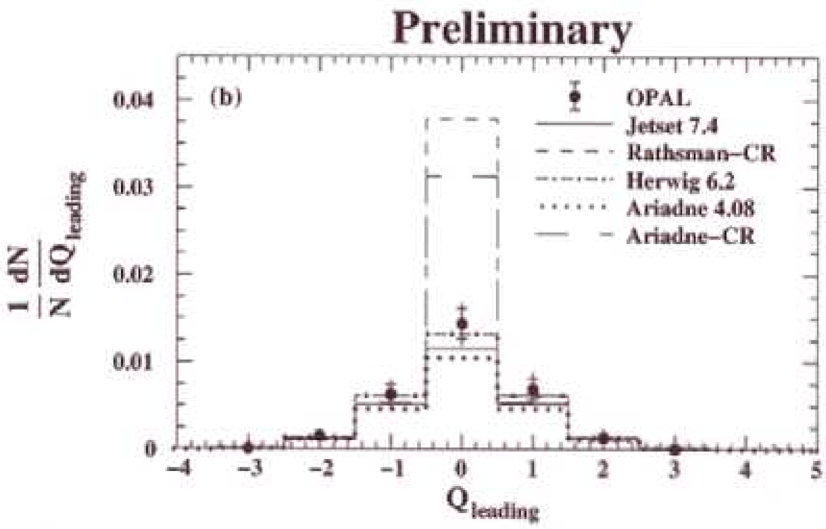
[P. Minkowski & W. Ochs, PLB485 (2000) 139; see also DELPHI note 2002-053 CONF 587]

Parameter tuning

Can the Rathsman-CR or Ariadne-CR model be tuned to describe our data on gluon jets with a rapidity gap WHILE CONTINUING to provide a reasonable description of inclusive Z^0 decays ??

Strategy

- Define $\Delta Q_{leading}^{MC-data}$ to be the difference between the Monte Carlo prediction and the data for $Q_{leading} = 0$



- Vary the principal parameters of the models by large amounts to see if it is possible to obtain

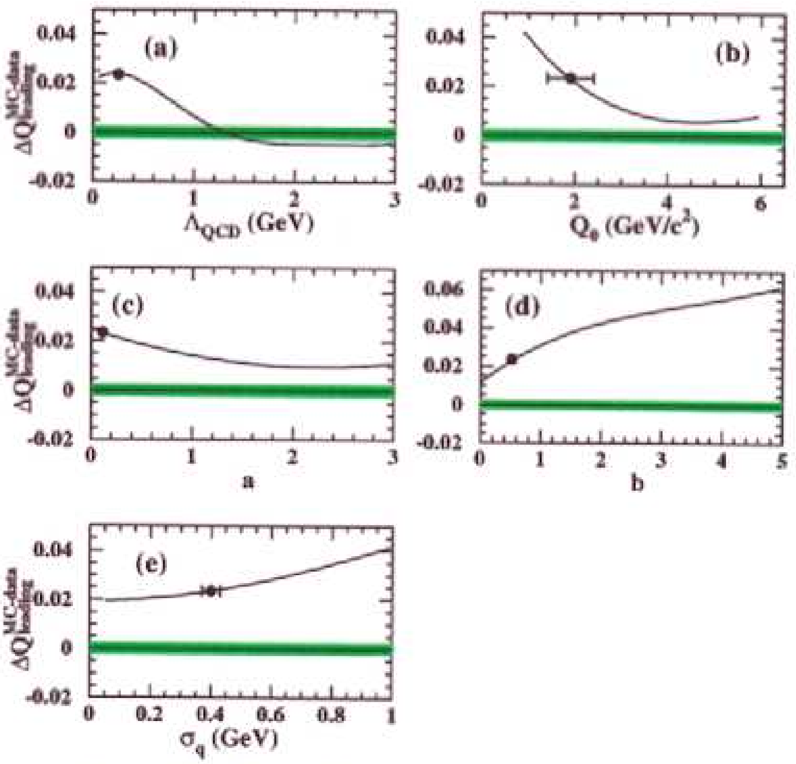
$$\Delta Q_{leading}^{MC-data} \approx 0$$

and the correct result: $\langle n_{ch.} \rangle_{inclusive\ Z} = 21.15 \pm 0.29$

- Monitor the consequences for the description of global event shape distributions $1 - T$, etc., from inclusive Z^0 events

Λ_{QCD}, Q_0, a, b, σ_q: the Rathsman-CR model

$\longrightarrow$ The principal parameters controlling the multiplicity and momentum distributions of hadrons



- Solid dots: standard values of the parameters
- Horizontal error ranges: uncertainties attributed to the parameters (too small to be visible for some parameters)
- Curves: results for $\Delta Q^{MC-data}_{leading}$ as each parameter is varied with the others held at their standard values

$\longrightarrow$ $\Delta Q^{MC-data}_{leading} \approx 0$ for $\Lambda_{QCD} \approx 1.3$ GeV or for $Q_0 \approx 3.5$ GeV/c^2

(representing very large excursions from their standard values)

Tuning procedure

Attempt a series of two-parameter adjustments:

(1) Vary Q_0 and b:

⟶ Set $Q_0 = 3.5$ GeV/c^2

⟶ Adjust b to yield $\langle n_{ch.} \rangle = 21.15$

⟶ Iterate the adjustment of Q_0 and b to simultaneously obtain $\Delta Q^{MC-data}_{leading} \approx 0$ and $\langle n_{ch.} \rangle = 21.15$

⟶ $Q_0 =$ 4.7 GeV/c^2, $b =$ 0.30 GeV
versus OPAL defaults, $Q_0 = 1.9$ GeV/c^2, $b = 0.52$

⟶ The "Re-tuned" Rathsman-CR model

⟶ Yields $\Delta Q^{MC-data}_{leading} = 1.4 \times 10^{-4}$

BUT

- The resulting total χ^2 with the inclusive event shape distributions increases from 2001 to 5044
- Most of this increase is contributed by y_{23} and p_{out}

⟶ Setting $Q_0 \sim 5$ GeV/c^2 results in a severe truncation of events with prominent multi-jet structure (4-jet events, etc.), in disagreement with the data.

Tuning procedure, cont.

(2) Vary Λ_{QCD} and b:

⟶ Set $\Lambda_{QCD} = 1.3$ GeV, adjust b to yield $\langle n_{ch.}\rangle = 21.15$, iterate to minimize $\Delta Q^{MC-data}_{leading}$ while maintaining $\langle n_{ch.}\rangle = 21.15$

⟶ The best solution we could find was $\Lambda_{QCD} = 1.8$ GeV and $b = 6.5$, which yielded

$$\Delta Q^{MC-data}_{leading} = 0.011 \quad (4.6\sigma(\text{tot.}) \text{ above the data})$$

$$\chi^2_{global} = 3.7 \times 10^5$$

(3) Vary Λ_{QCD} and Q_0:

⟶ The best solution we could find was $\Lambda_{QCD} = 0.6$ GeV and $Q_0 = 4.9$ GeV/c^2, which yielded

$$\Delta Q^{MC-data}_{leading} = 0.004 \quad (1.7\sigma(\text{tot.}) \text{ above the data})$$

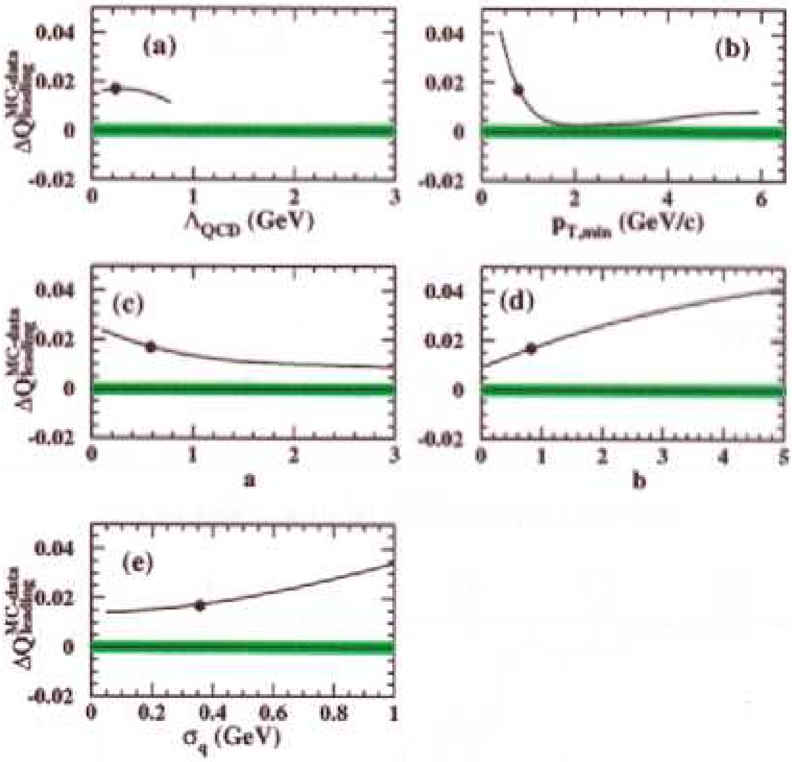
$$\chi^2_{global} = 1.2 \times 10^4$$

Conclusion:

⟶ It is unlikely the Rathsman-CR model can be tuned to describe our gluon jet data and still provide a reasonable description of inclusive Z^0 events

⟶ Compelling evidence to DISFAVOR color reconnection as it is implemented in this model

Λ_{QCD}, $p_{T,min.}$, a, b, σ_q: the Ariadne-CR model



(Note: Λ_{QCD} constrained to be smaller than $p_{T,min.}$ in Ariadne)

⟶ Iterate the adjustment of $p_{T,min.}$ and b to simultaneously obtain $\Delta Q^{MC-data}_{leading} \approx 0$ and $\langle n_{ch.} \rangle = 21.15$

⟶ $p_{T,min.} =$ 1.8 GeV/c, $b =$ 0.60 GeV

versus OPAL defaults, $p_{T,min.} = 0.79$ GeV/c, $b = 0.82$

⟶ The "Re-tuned" Ariadne-CR model

⟶ Yields $\Delta Q^{MC-data}_{leading} = -4 \times 10^{-6}$

BUT

- The resulting total χ^2 with the inclusive event shape distributions increases from 879 to 1885
- Most of this increase is contributed by y_{23} and p_{out}
- By varying a Λ_{QCD} and $p_{T,min.}$ together, we did not find a solution with $\Delta Q^{MC-data}_{leading} \approx 0$, analogous to the situation found for the Rathsman-CR model for Λ_{QCD} and Q_0
- As for the Rathsman-CR model, we conclude it is unlikely the Ariadne-CR model can be tuned describe our gluon jet data and still provide a reasonable description of inclusive Z^0 events
- The Ariadne color reconnection model is similarly disfavored

Summary

- Gluon jets from Z^0 decays $E \sim 23$ GeV, purity 94%
- Select a 4% sub-sample with a large rapidity gap
- Examine the predictions of QCD models for the charged particle multiplicity, total electric charge, and invariant mass, in the leading part of these jets
- The models with color reconnection (Rathsman-CR & Ariadne-CR) predict a large excess of events with a large rapidity gap, for which the leading part is electrically neutral
- The analysis is very sensitive to color reconnection
- No evidence for color reconnection is observed
- The analysis is also potentially sensitive to the production of glueballs, for which no evidence is observed
- The Rathsman-CR & Ariadne-CR models can provide a satisfactory description of the gluon jet data and $\langle n_{ch.} \rangle$ in inclusive Z^0 events only if very large values of the cutoff parameters are used

$$Q_0 \sim 5\,\mathrm{GeV}/c^2 \qquad p_{T,min.} \sim 2\,\mathrm{GeV}/c$$

Summary, cont.

- The description of event shapes in inclusive Z^0 events is then severely degraded
- We conclude that color reconnection as currently implemented in these two models is strongly disfavored.