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Study of leading hadrons in gluon and quark fragmentation

DELPHI Collaboration

J. Abdallah[z], P. Abreu[w], W. Adam[bc], P. Adzic[l], T. Albrecht[r], R. Alemany-Fernandez[i], T. Allmendinger[r], P.P. Allport[x], U. Amaldi[ad], N. Amapane[av], S. Amato[az], E. Anashkin[ak], A. Andreazza[ac], S. Andringa[w], N. Anjos[w], P. Antilogus[z], W.-D. Apel[r], Y. Arnoud[o], S. Ask[aa], B. Asman[au], J.E. Augustin[z], A. Augustinus[i], P. Baillon[i], A. Ballestrero[aw], P. Bambade[u], R. Barbier[ab], D. Bardin[q], G.J. Barker[r], A. Baroncelli[an], M. Battaglia[i], M. Baubillier[z], K.-H. Becks[be], M. Begalli[g], A. Behrmann[be], E. Ben-Haim[u], N. Benekos[ag], A. Benvenuti[e], C. Berat[o], M. Berggren[z], L. Berntzon[au], D. Bertrand[b], M. Besancon[ao], N. Besson[ao], D. Bloch[j], M. Blom[af], M. Bluj[bd], M. Bonesini[ad], M. Boonekamp[ao], P.S.L. Booth[x,✠], G. Borisov[v], O. Botner[ba], B. Bouquet[u], T.J.V. Bowcock[x], I. Boyko[q], M. Bracko[ar], R. Brenner[ba], E. Brodet[aj], P. Bruckman[s], J.M. Brunet[h], B. Buschbeck[bc], P. Buschmann[be], M. Calvi[ad], T. Camporesi[i], V. Canale[am], F. Carena[i], N. Castro[w], F. Cavallo[e], M. Chapkin[aq], Ph. Charpentier[i], P. Checchia[ak], R. Chierici[i], P. Chliapnikov[aq], J. Chudoba[i], S.U. Chung[i], K. Cieslik[s], P. Collins[i], R. Contri[n], G. Cosme[u], F. Cossutti[ax], M.J. Costa[bb], D. Crennell[al], J. Cuevas[ai], J. D'Hondt[b], J. Dalmau[au], T. da Silva[az], W. Da Silva[z], G. Della Ricca[ax], A. De Angelis[ay], W. De Boer[r], C. De Clercq[b], B. De Lotto[ay], N. De Maria[av], A. De Min[ak], L. de Paula[az], L. Di Ciaccio[am], A. Di Simone[an], K. Doroba[bd], J. Drees[be,i], G. Eigen[d], T. Ekelof[ba], M. Ellert[ba], M. Elsing[i], M.C. Espirito Santo[w], G. Fanourakis[l], D. Fassouliotis[l,c], M. Feindt[r], J. Fernandez[ap], A. Ferrer[bb], F. Ferro[n], U. Flagmeyer[be], H. Foeth[i], E. Fokitis[ag], F. Fulda-Quenzer[u], J. Fuster[bb], M. Gandelman[az], C. Garcia[bb], Ph. Gavillet[i], E. Gazis[ag], R. Gokieli[i,bd], B. Golob[ar,at], G. Gomez-Ceballos[ap], P. Goncalves[w], E. Graziani[an], G. Grosdidier[u], K. Grzelak[bd], J. Guy[al], C. Haag[r], A. Hallgren[ba], K. Hamacher[be], K. Hamilton[aj], S. Haug[ah], F. Hauler[r], V. Hedberg[aa], M. Hennecke[r], H. Herr[i,✠], J. Hoffman[bd], S.-O. Holmgren[au], P.J. Holt[i], M.A. Houlden[x], J.N. Jackson[x], G. Jarlskog[aa], P. Jarry[ao], D. Jeans[aj], E.K. Johansson[au], P.D. Johansson[au], P. Jonsson[ab], C. Joram[i], L. Jungermann[r], F. Kapusta[z], S. Katsanevas[ab], E. Katsoufis[ag], G. Kernel[ar], B.P. Kersevan[ar,at], U. Kerzel[r], B.T. King[x], N.J. Kjaer[i], P. Kluit[af], P. Kokkinias[l], C. Kourkoumelis[c], O. Kouznetsov[q], Z. Krumstein[q], M. Kucharczyk[s], J. Lamsa[a], G. Leder[bc], F. Ledroit[o], L. Leinonen[au], R. Leitner[ae], J. Lemonne[b], V. Lepeltier[u], T. Lesiak[s], W. Liebig[be], D. Liko[bc], A. Lipniacka[au], J.H. Lopes[az], J.M. Lopez[ai], D. Loukas[l], P. Lutz[ao], L. Lyons[aj], J. MacNaughton[bc], A. Malek[be], S. Maltezos[ag], F. Mandl[bc], J. Marco[ap], R. Marco[ap], B. Marechal[az], M. Margoni[ak], J.-C. Marin[i], C. Mariotti[i], A. Markou[l], C. Martinez-Rivero[ap], J. Masik[m], N. Mastroyiannopoulos[l], F. Matorras[ap], C. Matteuzzi[ad], F. Mazzucato[ak], M. Mazzucato[ak], R. Mc Nulty[x], C. Meroni[ac], E. Migliore[av], W. Mitaroff[bc], U. Mjoernmark[aa], T. Moa[au], M. Moch[r], K. Moenig[i,k], R. Monge[n], J. Montenegro[af], D. Moraes[az], S. Moreno[w], P. Morettini[n], U. Mueller[be], K. Muenich[be], M. Mulders[af], L. Mundim[g], W. Murray[al], B. Muryn[t], G. Myatt[aj], T. Myklebust[ah], M. Nassiakou[l], F. Navarria[e], K. Nawrocki[bd], R. Nicolaidou[ao], M. Nikolenko[q,j], A. Oblakowska-Mucha[t], V. Obraztsov[aq], A. Olshevski[q], A. Onofre[w], R. Orava[p],

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K. Osterberg[p], A. Ouraou[ao], A. Oyanguren[bb], M. Paganoni[ad], S. Paiano[e], J.P. Palacios[x], H. Palka[s], Th.D. Papadopoulou[ag], L. Pape[i], C. Parkes[y], F. Parodi[n], U. Parzefall[i], A. Passeri[an], O. Passon[be], L. Peralta[w], V. Perepelitsa[bb], A. Perrotta[e], A. Petrolini[n], J. Piedra[ap], L. Pieri[an], F. Pierre[ao], M. Pimenta[w], E. Piotto[i], T. Podobnik[ar,at], V. Poireau[i], M.E. Pol[f], G. Polok[s], V. Pozdniakov[q], N. Pukhaeva[q], A. Pullia[ad], J. Rames[m], A. Read[ah], P. Rebecchi[i], J. Rehn[r], D. Reid[af], R. Reinhardt[be], P. Renton[aj], F. Richard[u], J. Ridky[m], M. Rivero[ap], D. Rodriguez[ap], A. Romero[av], P. Ronchese[ak], P. Roudeau[u], T. Rovelli[e], V. Ruhlmann-Kleider[ao], D. Ryabtchikov[aq], A. Sadovsky[q], L. Salmi[p], J. Salt[bb], C. Sander[r], A. Savoy-Navarro[z], U. Schwickerath[i], R. Sekulin[al], M. Siebel[be], A. Sisakian[q], G. Smadja[ab], O. Smirnova[aa], A. Sokolov[aq], A. Sopczak[v], R. Sosnowski[bd], T. Spassov[i], M. Stanitzki[r], A. Stocchi[u], J. Strauss[bc], B. Stugu[d], M. Szczekowski[bd], M. Szeptycka[bd], T. Szumlak[t], T. Tabarelli[ad], A.C. Taffard[x], F. Tegenfeldt[ba], J. Timmermans[af,*], L. Tkatchev[q], M. Tobin[x], S. Todorovova[m], B. Tome[w], A. Tonazzo[ad], P. Tortosa[bb], P. Travnicek[m], D. Treille[i], G. Tristram[h], M. Trochimczuk[bd], C. Troncon[ac], M.-L. Turluer[ao], I.A. Tyapkin[q], P. Tyapkin[q], S. Tzamarias[l], V. Uvarov[aq], G. Valenti[e], P. Van Dam[af], J. Van Eldik[i], N. van Remortel[p], I. Van Vulpen[i], G. Vegni[ac], F. Veloso[w], W. Venus[al], P. Verdier[ab], V. Verzi[am], D. Vilanova[ao], L. Vitale[ax], V. Vrba[m], H. Wahlen[be], A.J. Washbrook[x], C. Weiser[r], D. Wicke[i], J. Wickens[b], G. Wilkinson[aj], M. Winter[j], M. Witek[s], O. Yushchenko[aq], A. Zalewska[s], P. Zalewski[bd], D. Zavrtanik[as], V. Zhuravlov[q], N.I. Zimin[q], A. Zintchenko[q], M. Zupan[l]

[a] *Department of Physics and Astronomy, Iowa State University, Ames, IA 50011-3160, USA*
[b] *IIHE, ULB-VUB, Pleinlaan 2, B-1050 Brussels, Belgium*
[c] *Physics Laboratory, University of Athens, Solonos Str. 104, GR-10680 Athens, Greece*
[d] *Department of Physics, University of Bergen, Allégaten 55, NO-5007 Bergen, Norway*
[e] *Dipartimento di Fisica, Università di Bologna and INFN, Via Irnerio 46, IT-40126 Bologna, Italy*
[f] *Centro Brasileiro de Pesquisas Físicas, rua Xavier Sigaud 150, BR-22290 Rio de Janeiro, Brazil*
[g] *Instituto de Física, Universidade Estadual do Rio de Janeiro, rua São Francisco Xavier 524, Rio de Janeiro, Brazil*
[h] *Collège de France, Laboratoire de Physique Corpusculaire, IN2P3-CNRS, FR-75231 Paris cedex 05, France*
[i] *CERN, CH-1211 Geneva 23, Switzerland*
[j] *Institut de Recherches Subatomiques, IN2P3-CNRS/ULP-BP20, FR-67037 Strasbourg cedex, France*
[k] *Now at DESY-Zeuthen, Platanenallee 6, D-15735 Zeuthen, Germany*
[l] *Institute of Nuclear Physics, N.C.S.R. Demokritos, PO Box 60228, GR-15310 Athens, Greece*
[m] *FZU, Institute of Physics of the C.A.S. High Energy Physics Division, Na Slovance 2, CZ-180 40, Praha 8, Czech Republic*
[n] *Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, IT-16146 Genova, Italy*
[o] *Institut des Sciences Nucléaires, IN2P3-CNRS, Université de Grenoble 1, FR-38026 Grenoble cedex, France*
[p] *Helsinki Institute of Physics and Department of Physical Sciences, PO Box 64, FIN-00014 University of Helsinki, Finland*
[q] *Joint Institute for Nuclear Research, Dubna, Head Post Office, PO Box 79, RU-101 000 Moscow, Russian Federation*
[r] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 6980, DE-76128 Karlsruhe, Germany*
[s] *Institute of Nuclear Physics PAN, Ul. Radzikowskiego 152, PL-31142 Krakow, Poland*
[t] *Faculty of Physics and Nuclear Techniques, University of Mining and Metallurgy, PL-30055 Krakow, Poland*
[u] *Université de Paris-Sud, Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Bât. 200, FR-91405 Orsay cedex, France*
[v] *School of Physics and Chemistry, University of Lancaster, Lancaster LA1 4YB, UK*
[w] *LIP, IST, FCUL-Av. Elias Garcia, 14-1°, PT-1000 Lisboa Codex, Portugal*
[x] *Department of Physics, University of Liverpool, PO Box 147, Liverpool L69 3BX, UK*
[y] *Department of Physics and Astronomy, Kelvin Building, University of Glasgow, Glasgow G12 8QQ, UK*
[z] *LPNHE, IN2P3-CNRS, Université Paris VI et VII, Tour 33 (RdC), 4 place Jussieu, FR-75252 Paris cedex 05, France*
[aa] *Department of Physics, University of Lund, Sölvegatan 14, SE-223 63 Lund, Sweden*
[ab] *Université Claude Bernard de Lyon, IPNL, IN2P3-CNRS, FR-69622 Villeurbanne cedex, France*
[ac] *Dipartimento di Fisica, Università di Milano and INFN-MILANO, Via Celoria 16, IT-20133 Milan, Italy*
[ad] *Dipartimento di Fisica, Università di Milano-Bicocca and INFN-MILANO, Piazza della Scienza 3, IT-20126 Milan, Italy*
[ae] *IPNP of MFF, Charles University, Areal MFF, V Holesovickach 2, CZ-180 00, Praha 8, Czech Republic*
[af] *NIKHEF, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands*
[ag] *National Technical University, Physics Department, Zografou Campus, GR-15773 Athens, Greece*
[ah] *Physics Department, University of Oslo, Blindern, NO-0316 Oslo, Norway*
[ai] *Departamento de la Fisica, Universidad Oviedo, Avda. Calvo Sotelo s/n, ES-33007 Oviedo, Spain*
[aj] *Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[ak] *Dipartimento di Fisica, Università di Padova and INFN, Via Marzolo 8, IT-35131 Padua, Italy*
[al] *Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK*
[am] *Dipartimento di Fisica, Università di Roma II and INFN, Tor Vergata, IT-00173 Rome, Italy*
[an] *Dipartimento di Fisica, Università di Roma III and INFN, Via della Vasca Navale 84, IT-00146 Rome, Italy*

[ao] *DAPNIA/Service de Physique des Particules, CEA-Saclay, FR-91191 Gif-sur-Yvette cedex, France*
[ap] *Instituto de Fisica de Cantabria (CSIC-UC), Avda. los Castros s/n, ES-39006 Santander, Spain*
[aq] *Institute for High Energy Physics, Serpukov, PO Box 35, Protvino, Moscow Region, Russian Federation*
[ar] *J. Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*
[as] *Laboratory for Astroparticle Physics, University of Nova Gorica, Kostanjeviska 16a, SI-5000 Nova Gorica, Slovenia*
[at] *Department of Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia*
[au] *Fysikum, Stockholm University, PO Box 6730, SE-113 85 Stockholm, Sweden*
[av] *Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Via P. Giuria 1, IT-10125 Turin, Italy*
[aw] *INFN, Sezione di Torino and Dipartimento di Fisica Teorica, Università di Torino, Via Giuria 1, IT-10125 Turin, Italy*
[ax] *Dipartimento di Fisica, Università di Trieste and INFN, Via A. Valerio 2, IT-34127 Trieste, Italy*
[ay] *Istituto di Fisica, Università di Udine and INFN, IT-33100 Udine, Italy*
[az] *Universidade Federal do Rio de Janeiro, C.P. 68528 Cidade Universidade, Ilha do Fundão, BR-21945-970 Rio de Janeiro, Brazil*
[ba] *Department of Radiation Sciences, University of Uppsala, PO Box 535, SE-751 21 Uppsala, Sweden*
[bb] *IFIC, Valencia-CSIC, and DFAMN, Universidade de Valencia, Avda. Dr. Moliner 50, ES-46100 Burjassot (Valencia), Spain*
[bc] *Institut für Hochenergiephysik, Österreich Akademie der Wissenschaft, Nikolsdorfergasse 18, AT-1050 Vienna, Austria*
[bd] *Institute Nuclear Studies and University of Warsaw, Ul. Hoza 69, PL-00681 Warsaw, Poland*
[be] *Fachbereich Physik, University of Wuppertal, Postfach 100 127, DE-42097 Wuppertal, Germany*

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Abstract

The study of quark jets in e^+e^- reactions at LEP has demonstrated that the hadronisation process is reproduced well by the Lund string model. However, our understanding of gluon fragmentation is less complete. In this study enriched quark and gluon jet samples of different purities are selected in three-jet events from hadronic decays of the Z collected by the DELPHI experiment in the LEP runs during 1994 and 1995. The leading systems of the two kinds of jets are defined by requiring a rapidity gap and their sum of charges is studied. An excess of leading systems with total charge zero is found for gluon jets in all cases, when compared to Monte Carlo simulations with JETSET (with and without Bose–Einstein correlations included) and ARIADNE. The corresponding leading systems of quark jets do not exhibit such an excess. The influence of the gap size and of the gluon purity on the effect is studied and a concentration of the excess of neutral leading systems at low invariant masses ($\lesssim 2\ \text{GeV}/c^2$) is observed, indicating that gluon jets might have an additional hitherto undetected fragmentation mode via a two-gluon system. This could be an indication of a possible production of gluonic states as predicted by QCD.

1. Introduction

The study of quark jets provides us with remarkable insights into the mechanism of hadronisation. It gives strong evidence for chain-like charge ordered particle production in excellent agreement with string Monte Carlo models like JETSET [1]. This is shown e.g. by several contributions [2–5] of the DELPHI experiment at LEP, where the compensation of quantum numbers, in particular that of charge, has been extensively studied. Much less is, however, known about the behaviour of gluon jets. On the theoretical side, besides the fragmentation via two strings as implemented in JETSET/PYTHIA and ARIADNE [6], the direct neutralisation of the colour octet field by another gluon with the creation of a two-gluon system has been considered by Minkowski and Ochs [7,8] and also by Spiesberger and Zerwas [9]. Older references exist by Montvay [10] and Peterson and Walsh [11]. Additional references can be found in [7] where it is also emphasised that an experimental study of the gluon corner in three-jet events could contribute valuably to the question of the existence of glueballs, an early expectation of QCD [12]. No quantitative prediction however exists up to now. This has triggered an experimental investigation by the DELPHI Collaboration on gluon fragmentation in a leading system defined by a rapidity gap [13,14]. The preliminary results revealed that electrically neutral systems of leading particles in gluon jets occur more often than predicted by JETSET, in agreement with the expectations of the above theoretical argumentations, while there was no disagreement observed in quark jets. This phenomenon, experimentally observed for the first time, has meanwhile also been seen by ALEPH and OPAL [15,16].

The JETSET (ARIADNE) model of a $q\bar{q}g$ event stretches a string from the q to the g and on to the $\bar{q}$. The string fragments for example by the creation of $q\bar{q}$ pairs, similar to what happens for quark fragmentation (Fig. 1(a)). Thus the JETSET (and ARIADNE) model regards gluon fragmentation as a *double colour triplet fragmentation* (most clearly sketched in Fig. 1 of Ref. [7]) and the leading system can obtain the charge ±1 or 0 in the limiting configuration. The process proposed by Minkowski and Ochs, namely the *octet neutralisation* of the gluon field by another gluon has the signature of an *uncharged* leading system due to the requirement that the sum of charges (*SQ*) of the decay products of a two-gluon system is zero (Fig. 1(b)). In [7,8] it is also proposed to enhance the possible

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[*] Corresponding author.
E-mail address: timmerma@mail.cern.ch (J. Timmermans).

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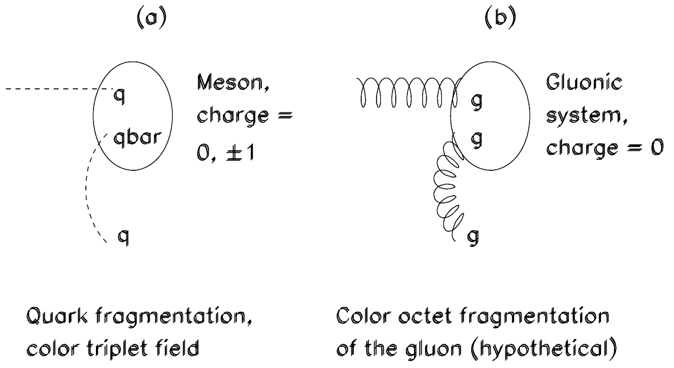

Fig. 1. Diagrams to illustrate the processes of colour triplet fragmentation (a) and colour octet fragmentation (b). The dashed lines represent the colour triplet strings and the helixes represent the colour octet strings.

contribution of this process by selecting events where a leading particle system is separated from the rest of the low energy particles by a large rapidity gap, empty of hadrons. In this situation of a hard isolated gluon the octet field is expected not to have been distorted by multiple gluon emission and by related colour neutralisation processes of small rapidity ranges [7]. The price to pay for such a selection is, however, a strong reduction of the number of events because of the Sudakov form factor [17]. A different mechanism—colour reconnection [18]—can produce similar effects. Two experiments, however, agree that the present colour reconnection models, as implemented in some versions of Monte Carlo simulations, cannot reproduce quantitatively the observed excess of $SQ = 0$ systems [15,19].

The present study aims to consolidate the results of the preceding analyses [13–16] by studying the dependence of the excess of neutral leading systems in enriched gluon jets on the gap size and gluon content, by studying their mass spectra and by investigating if there are possible trivial origins for the observed effect. This is especially important, since a significant failure of the string model to describe gluon jets might generally reveal the presence of hitherto undetected processes. The size of the effect for a *pure* gluon jet is estimated. As a cross-check, the same investigation is done for quark jets.

2. Data sample and 3-jet event selection

The data sample used has been collected by the DELPHI experiment at the LEP collider at the peak of the Z resonance during 1994 and 1995. Three-jet events have been selected by using the appropriate cuts for track quality and for the hadronic event type [20] as well as applying a k_t cluster algorithm (Durham) [21] to all observed charged and neutral particles with $y_{\text{cut}} = 0.015$.[1] The jet energies were recalculated based on the direction of the jet momenta and the jets were sorted by decreasing energy, i.e. $E_3 \leqslant E_2 \leqslant E_1$. Events with $\Theta_2, \Theta_3 = 135° \pm 35°$ have been used, where Θ_i is the inter-jet angle opposite to jet i. All jets are required to lie in a plane, to consist of $\geqslant 2$ particles and the jets must be at least 30° away from the beam direction [22–24]. About 314 000 events meet all these conditions.

Without any additional tag the jet with the highest energy E_1 (jet1) is in most cases a quark jet and that with the smallest energy E_3 (jet3) the gluon jet. The measured mean jet energies are: $\bar{E}_1 = 41.4$, $\bar{E}_2 = 32.2$ and $\bar{E}_3 = 17.7$ GeV.[2] In the first data sample (**sample 1**), where the gluon and quark jet identification is based on energy ordering only, events are required not to exhibit any b-signal (235 080 events). Monte Carlo simulations show for the above mentioned conditions a quark jet contribution of about 90% for jet1[3] and a gluon jet contribution of about 70% for jet3. In a more detailed study of the gluon purity a second independent sample (**sample 2**) is selected, where jet1 and jet2, contrary to jet3, are required to exhibit a b-signal [24,25] (Section 4.3). This additional tag results in a gluon purity of jet3 of about 90% and consists of 31 400 events. A third sample (**sample 3**) is selected to enable purity unfolding for special cases. It is defined by the requirement that jet3 has a b-tag. For this jet3 sample consisting of 12 200 events the gluon content is very much diminished (about 26%).

3. Monte Carlo models

For comparisons a suitable number of Monte Carlo simulations using JETSET 7.3 [1] and ARIADNE [6] have been performed. In contrast to JETSET, ARIADNE incorporates dipole radiation of gluons instead of the parton shower used by JETSET. Since Bose–Einstein correlations (BEC) are present in nature, like-charged particles will stick together in momentum space and local charge compensation is expected to be diminished. The implementation of Bose–Einstein correlations into the Monte Carlo simulation, however, is highly problematic and the magnitude of the effect on charge compensation is unknown. Nevertheless, the possible effect of BEC has to be investigated and the possible uncertainties have to be considered.

Three different Monte Carlo event samples have been created by using different generators:

Model (1): JETSET with BEC included (BE32 [26]);
Model (2): JETSET without BEC;
Model (3): ARIADNE without BEC.

The number of events generated for each sample corresponds roughly to that of the data.

The data are compared to these Monte Carlo event samples with full simulation of the DELPHI detector. The same reconstruction and analysis chain has been applied to the data and Monte Carlo (MC) samples.

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[1] This value has been obtained from a study optimising simultaneously purity and statistics [22].

[2] Although the mean energies of jet1 and jet3 differ by more than a factor 2, the maximum possible rapidities and mean multiplicities for charged particles differ much less (e.g. $\langle nch_{\text{jet3}} \rangle = 6.04$, $\langle nch_{\text{jet1}} \rangle = 7.36$).

[3] All quark jet selections (jet1) shown in the figures for comparisons are defined by sample 1.

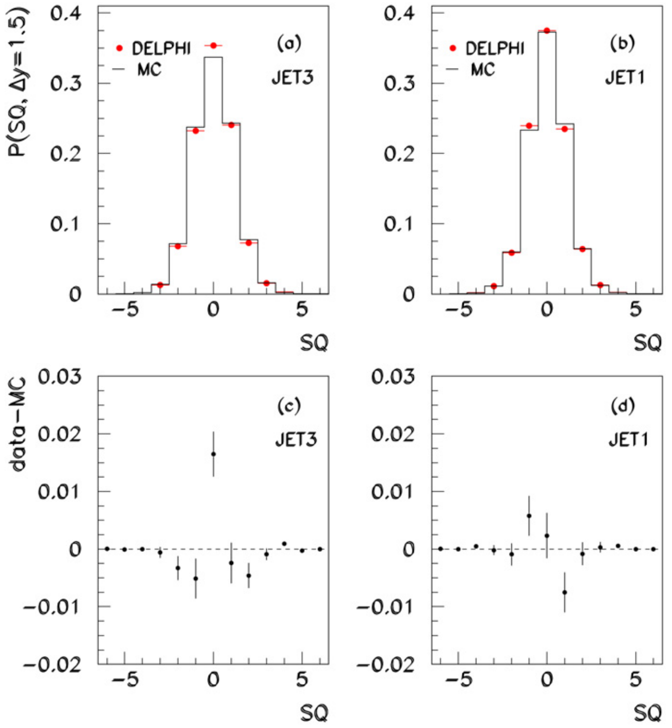

Fig. 2. Fraction of jets $P(SQ, 1.5)$ as a function of the sum of charges SQ of the leading system for both (a) enriched gluon jets and (b) quark jets. Full circles represent the data, lines the Monte Carlo simulation, model (3). The difference (data-MC) is shown in (c) for enriched gluon jets and in (d) for quark jets.

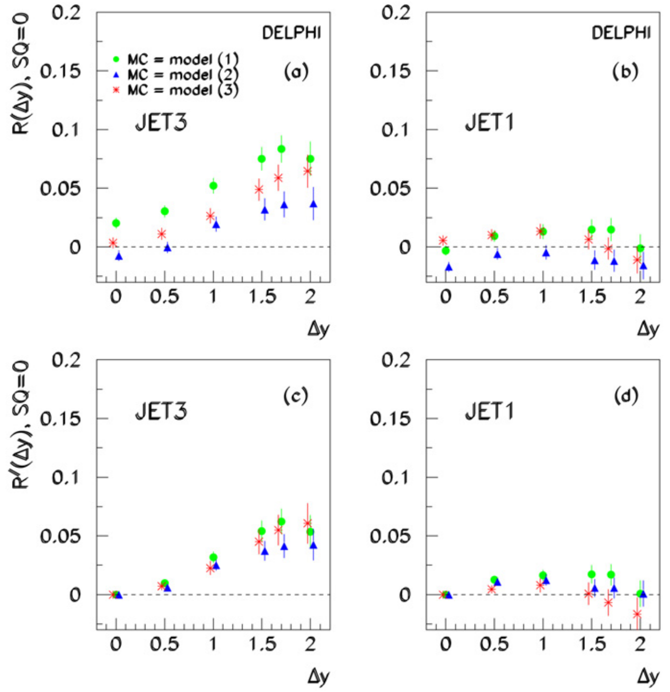

Fig. 3. (a), (b): Relative deviations $R(\Delta y)$ of the number of neutral leading systems in gluon and quark jets for the three Monte Carlo models defined in Section 3 and for various sizes of Δy. R is defined in Eq. (2). (c), (d): $R'(\Delta y)$ as defined in Eq. (3). Because of the nature of the cut Δy, the bins are correlated.

4. Analysis

4.1. *The sum of charges in the leading system with a rapidity gap (sample 1)*

After the selection of 3-jet events and the determination of enriched quark and gluon jet samples, the leading system of a jet is defined by requiring that all charged particles assigned to the jet must have a rapidity y with respect to the jet axis of $y \geqslant \Delta y$. The quantity Δy represents a lower limit and defines a rapidity gap extending at least up to $y = \Delta y$. By this requirement, also jets are discarded, if they include some particles (fraction 10^{-3}) with negative rapidity. The size of the demanded gap below this leading system is a compromise between the requirement of a gap as large as possible and the considerable loss of statistics at a larger gap. The requirement that the rapidity interval $\delta y \geqslant \Delta y$ (with $\Delta y = 1.5$) below the leading system be empty of charged particles reduces the number of jets appreciably. About 38 000 enriched gluon jets and 39 000 quark jets meet this condition. This reduction rate f_1 of enriched gluon jets is quite well reproduced by the three Monte Carlo event samples: $f_1(\text{data}) = 0.160$, $f_1(\text{MC1}) = 0.169$, $f_1(\text{MC2}) = 0.158$, $f_1(\text{MC3}) = 0.157$, with the mean value $f_1(\text{MC-mean}) = 0.161$. In principle, there could be neutral hadrons in the gap. It has been verified that removing in addition topologies where observed neutrals are contained in the gap (mainly γ's from the decay of π^0's), leads to results that are fully consistent with the ones presented here, but with about 15% larger statistical errors.

The sum of charges (SQ) of the particles belonging to the leading system defined as above is shown in Fig. 2(a) for enriched gluon jets and in Fig. 2(b) for quark jets and compared to ARIADNE. $P(SQ, \Delta y)$ is generally defined as the fraction of a jet sample with a gap and a given value of SQ,

$$P(SQ, \Delta y) = \frac{N(SQ, \Delta y)}{N(\Delta y)} \tag{1}$$

and is an estimate for the probability of a jet with a gap to have a certain SQ. The SQ distribution of the leading system for the *gluon jet* (Fig. 2(a)) exhibits for $SQ = 0$ a significant enhancement of the data over the Monte Carlo. This effect is predicted, if the process of colour octet neutralisation is present [7,8]. On the other hand, there is no significant difference between the data and the Monte Carlo simulation in the case of *quark jets* (Fig. 2(b)).

The lower parts of Fig. 2 show quantitatively the differences of the $P(SQ, 1.5)$ between the data and the Monte Carlo simulation. This difference for the gluon jet (Fig. 2(c)) amounts to about 4 standard deviations (statistical errors only), for the quark jet (Fig. 2(d)) this difference is compatible with zero.

4.2. *The dependence on the size of the rapidity gap*

Fig. 3(a), (b) shows, for neutral leading systems ($SQ = 0$), the dependence of the relative deviation $R(\Delta y)$ on the size of

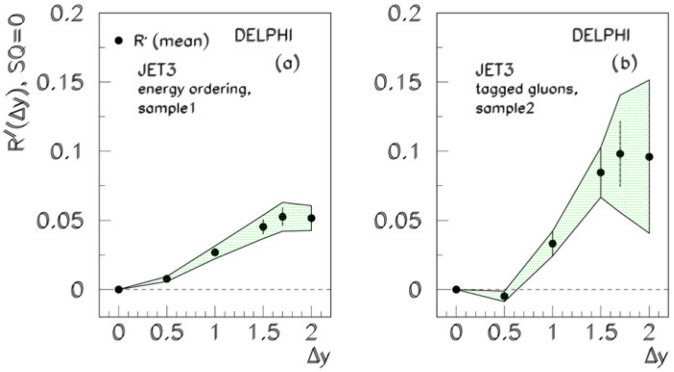

Fig. 4. $R'(\Delta y)$ using model averages. The gluon jet3 is tagged using energy ordering in (a) and b-tagging is used for the selection in (b).

the lower limit (Δy) of the rapidity gaps considered[4]:

$$R(\Delta y) = \frac{P(0,\Delta y)_{\text{data}} - P(0,\Delta y)_{\text{MC}}}{P(0,\Delta y)_{\text{MC}}}. \tag{2}$$

For all three types of Monte Carlo simulations (models (1), (2) and (3), see Section 3), $R(\Delta y)$ $(\Delta y > 0.5)$ is positive and *increasing* with Δy for jet3 (Fig. 3(a)). This clearly shows that the surplus of neutral leading systems in the data, compared to the Monte Carlo simulations, *increases* with the gap size. This corroborates the arguments of Minkowski and Ochs [7,8]. ARIADNE without BEC (model (3)) lies between the JETSET models. In the case of jet1 (Fig. 3(b)) all values are scattered around zero and no rise can be seen. When comparing JETSET with and without BEC included, one notices for jet3 and also for jet1 a difference for all values of Δy. The effect of introducing BEC into the Monte Carlo models causes a shift of $R(\Delta y)$, essentially independent of Δy, to higher values. The dependence on Δy is approximately the same for all three models. Arguing that only the rise and not implementation effects of BEC are of interest here and that the surplus of neutral systems is expected to be small and in a first approximation negligible in jets without a gap requirement, the following quantity is calculated:

$$R'(\Delta y) = R(\Delta y) - R(0) \tag{3}$$

and shown in Fig. 3(c), (d). The residual spread between the models is considered as systematic uncertainty.

4.3. *The dependence of $R'(\Delta y)$ on the gluon purity*

In Fig. 4(a) the mean values of R' with models (1), (2) and (3), which are presented in Fig. 3(c) for sample 1, are drawn together with the statistical errors (symbols with error bars) and systematic uncertainty (shaded area). As a cross-check, an independent second sample (sample 2) of gluon jets with a much higher purity is selected. The dependence of $R'(\Delta y)$ on Δy for this sample is given in Fig. 4(b). Although the statistics are smaller in Fig. 4(b) (3870 jet3 at $\Delta y = 1.5$, which is only about 1/10 of sample 1), the effect is increased, which is expected if it is connected to the gluon jet only. At $\Delta y = 1.5 R'(\Delta y)$ is about 0.09 ± 0.02 (*statistical*) because of the higher purity.

To estimate the amount of disagreement between data and Monte Carlo in pure gluon jets the gluon purity has to be estimated for jet3 at the gap size Δy for both data selections in Fig. 4. In principle, it can be directly obtained from the Monte Carlo. At the same scale, gluon and quark jets exhibit different rapidity distributions, i.e. gluon jets emit more particles per unit at small rapidity. Demanding a gap reduces therefore not only the number of jets, but also the gluon content in a mixed sample of gluon and quark jets. This is observed in the MC. An estimation of the gluon purity at gap Δy however depends on the correct modelling of the rapidity distribution of pure gluon jets. Therefore another method has been used in addition. It uses the measured reduction rates of the number of jets $f_i(\Delta y)$ in sample-i by demanding a gap (see Section 4.1) and from the MC only the composition at gap zero. Let us define $N_1(\Delta y) = f_1(\Delta y) N_1(0)$ in sample 1, and $N_2(\Delta y) = f_2(\Delta y) N_2(0)$ in sample 2, where $N_1(\Delta y)$ $(N_2(\Delta y))$ is the number of jets counted at Δy in sample 1 (sample 2). Since these samples are an admixture of pure $q(=$ light quark) jets, $g(=$ gluon) jets and $b(=b$-quark) jets, the corresponding $f_1(\Delta y)$, $f_2(\Delta y)$ (and also $f_3(\Delta y)$ for sample 3) are also an admixture of the reduction rates $f_q(\Delta y)$, $f_g(\Delta y)$, $f_b(\Delta y)$ of the pure light-quark, pure gluon and pure b-quark subsamples, e.g.

$$f_1(\Delta y) = a_{1q} f_q(\Delta y) + a_{1g} f_g(\Delta y) + a_{1b} f_b(\Delta y) \tag{4}$$

with two analogous equations for $f_2(\Delta y)$ and $f_3(\Delta y)$. The resulting system of three linear equations can be written in short:

$$F = A F_{\text{pure}} \tag{5}$$

with the solution

$$F_{\text{pure}} = A^{-1} F. \tag{6}$$

The vector $F(f_1(\Delta y), f_2(\Delta y), f_3(\Delta y))$ is measured, and the vector $F_{\text{pure}}(f_q(\Delta y), f_g(\Delta y), f_b(\Delta y))$ is the solution. The matrix A represents the q, g, b compositions for the three selections at gap $= 0$, estimated from Monte Carlo (e.g. a_{1g} is the gluon purity of jet3 in sample 1, a_{2g} that of sample 2, and a_{3g} that of sample 3 and so on). With the solution of Eq. (6), the numbers of true gluon jets at Δy can be determined in sample 1 and sample 2:

$$N_1^{\text{gluon}}(\Delta y) = f_g(\Delta y) a_{1g} N_1(0), \tag{7}$$

$$N_2^{\text{gluon}}(\Delta y) = f_g(\Delta y) a_{2g} N_2(0). \tag{8}$$

The fraction of gluon jets $c_g^{\Delta y}$ at Δy is given by:

$$c_g^{\Delta y}(\text{sample 1}) = N_1^{\text{gluon}}(\Delta y)/N_1(\Delta y) = a_{1g} f_g(\Delta y)/f_1(\Delta y), \tag{9}$$

$$c_g^{\Delta y}(\text{sample 2}) = N_2^{\text{gluon}}(\Delta y)/N_2(\Delta y) = a_{2g} f_g(\Delta y)/f_2(\Delta y). \tag{10}$$

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[4] In this representation, the bins are not independent: each point represents a subsample of the previous one.

Applied to the two data sets in Fig. 4(a), (b) the following numbers for the gluon content have been obtained:

(1) The sample in Fig. 4(a) (sample 1): $c_g^0 = 0.65$, $c_g^{1.5} = 0.46$ (from Eq. (9)), and $c_g^{1.5} = 0.45$ (directly from the Monte Carlo at $\Delta y = 1.5$).
(2) The sample in Fig. 4(b) (sample 2): $c_g^0 = 0.88$, $c_g^{1.5} = 0.80$ (from Eq. (10)), and $c_g^{1.5} = 0.82$ (directly from the Monte Carlo at $\Delta y = 1.5$).

The statistical errors on these numbers are below 1%, systematic errors can be obtained by comparing the estimates with different Monte Carlo models (1), (2) and (3). They are $\leqslant 2.6\%$. The purity estimates obtained above allow the determination of the excess of neutral systems R'_g in *pure* gluon jets by dividing by $c_g^{1.5}$. The following values of R'_g have been obtained for the two samples defined above:

$$\text{Sample 1:}\quad R'_g(1.5) = 0.100 \pm 0.012(\text{stat}) \pm 0.025(\text{syst}), \tag{11}$$

$$\text{Sample 2:}\quad R'_g(1.5) = 0.107 \pm 0.022(\text{stat}) \pm 0.028(\text{syst}). \tag{12}$$

The samples are statistically independent. Adding statistical and systematic errors quadratically, a significance of about 3.6σ is obtained in sample 1 and of almost 3σ in sample 2. Combining finally both samples results in:

$$\text{Combined:}\quad R'_g(1.5) = 0.102 \pm 0.011(\text{stat}) \pm 0.026(\text{syst}). \tag{13}$$

This number can be used to make a first estimate of $R_g(0)$, the amount of the excess of neutral systems in pure gluon jets without any gap selection. Taking into account the estimated value of $f_g(1.5) = 0.112 \pm 0.003$ from Eq. (6) which tells that 11% of the pure gluon jets meet the gap condition $\Delta y = 1.5$, one obtains:

$$R_g(0) \simeq R'_g(\Delta y = 1.5) f_g(\Delta y = 1.5) = 0.011. \tag{14}$$

Extending this analysis to samples which allow also for smaller gap sizes $1.5 > \Delta y \geqslant 1.0$ leads to $R_g(0)$ values between 0.01 and 0.02. Extending this furthermore to all gluon jets by taking into account that $P_g(0,0) \simeq 0.26$ (from sample 2, not shown here) leads to the conclusion that the amount of a possible octet neutralisation of the gluon field is of the order of 0.5%.

4.4. Discussion of the systematic uncertainties

The following sources of systematic errors have been considered:

(a) Quality of event reconstruction. Bad reconstructions and losses of particles (mainly neutrals) in the detector and wrong assignments to the jets can lead to differences of several GeV between the jet energy calculated from the angles between jets (E_{calc}) [24] and the sum of energies of all particles assigned to the jet (E_{sum}). Improving the quality by cutting away about 1/3 of the jets with the largest difference $E_{\text{calc}} - E_{\text{sum}}$ does not significantly change the signals at $SQ = 0$ both in gluon and quark jets;

(b) The dependence of the effect on the polar angle of the jet with respect to the collision axis has been investigated: the effect is stable;

(c) The influence of track finding efficiency in the detector. In order to investigate the influence of track finding efficiency the effect of a reduction of the efficiency by 1% has been simulated. No significant change in the signals at $SQ = 0$ has been observed. Since R is a ratio with respect to the Monte Carlo simulation (including the detector effects) and the deviation which has been observed between data and MC below 10%, it can be expected that efficiency effects cancel to a large extent;

(d) To investigate whether the good agreement between data and Monte Carlo in quark jets is only due to the larger particle momenta, in a test-run only particles with momenta less than 30 GeV/c have been accepted in jet1. The agreement with the Monte Carlo remains.

(e) The estimations leading to (11) and (12) assume that quark jets, also at the lower energies of jet3, do not exhibit any excess of neutral leading systems. This is further tested by measuring the excess in sample 3 which exhibits at $\Delta y = 1.5$ an admixture of only 20% gluon jets. As expected, the signal is reduced, and is even negative with large error: $R'_3(1.5) = -0.02 \pm 0.02$. Adopting the same procedure as in Section 4.3 by using matrix inversion with the measured values $R'_i(1.5)$, $i = 1,2,3$ for the 3 selected samples as input, the resulting excess for *pure* quark and gluon jets could be estimated: $R'_q(1.5) = 0.00 \pm 0.02$, $R'_g(1.5) = 0.11 \pm 0.03$ and $R'_b(1.5) = -0.06 \pm 0.04$. These results do not show any evidence that quark jets exhibit an excess of neutral leading systems for the lower jet3 energies;

(f) At the generator level of JETSET and for pure gluon jets the effect of changing parameters within limits has been studied. For example, different DELPHI tunings have been used, the DELPHI tuning [27] has been replaced by that of OPAL [28] and by the JETSET default,[5] and the popcorn parameter has been varied. Some changes of $P(SQ, \Delta y = 1.5)$ at $SQ = 0$ are revealed in gluon jets and to a lesser extent in pure quark jets. At a gap size of $\Delta y = 1.5$ a maximum variation of $R(\Delta y)$ of 0.027 is observed.

The systematic error from (f) amounting to 18% is taken into account. This is a conservative estimate with a factor 0.68 of the maximum variation, corresponding to 1σ of a Gauss distribution. The contributions from (a)–(e) are negligible. The systematic errors for samples 1 and 2 are estimated as follows:

Sample 1
(a) from the spread in Fig. 4(a) at $\Delta y = 1.5$: $\Delta R' = 0.017$;
(b) uncertainty in purity: 0.0026 (see Section 4.3);
(c) uncertainty from (f): 0.018.

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[5] All these studies have been done with BE correlations included.

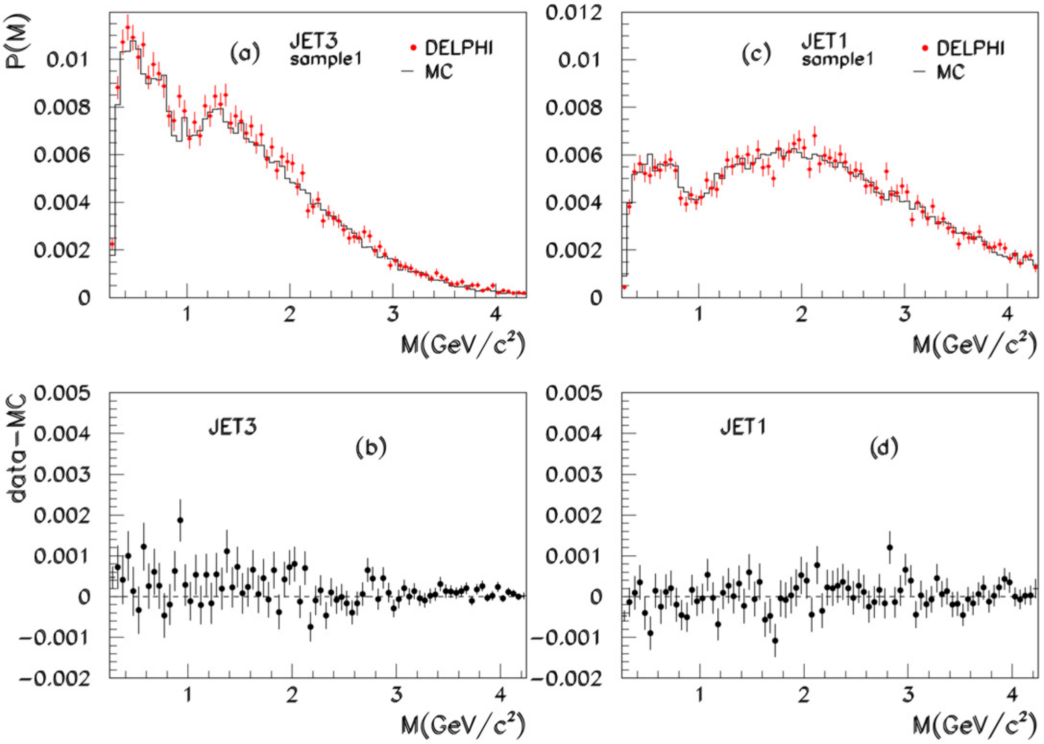

Fig. 5. (a), (c): Invariant mass distribution $P(M)$ of the leading system ($SQ = 0$) (considering only charged particles) (a) for gluon-enriched jets (sample 1), (c) for quark jets. P is defined in Eq. (15). The dots with error bars are the data, the histograms are the mean values of the three Monte Carlos. (b), (d): $P^{\text{data}}(M) - P^{\text{MC}}(M)$.

By quadratically adding all 3 contributions a systematic error of 0.025 is obtained.

Sample 2
(a) from the spread in Fig. 4(b) at $\Delta y = 1.5$: $\Delta R' = 0.021$;
(b) uncertainty in purity: 0.0028 (see Section 4.3);
(c) uncertainty from (f): 0.019.

By quadratically adding all 3 contributions a systematic error of 0.028 is obtained.

5. Mass spectra

Colour octet neutralisation of the gluon field could produce a resonance spectrum which differs from that of colour triplet fragmentation [29] implemented in JETSET. In order to investigate in which region of the mass spectrum the observed excess of the leading neutral systems is located, the invariant mass (M) distributions

$$P(M) = \frac{N(M, SQ = 0, \Delta y)}{N(\Delta y)} \tag{15}$$

of the leading systems with total charge zero at $\Delta y = 1.5$ have been calculated and compared with the mean values of models 1–3 for the two cases:

(a) M is computed using only charged particles with a momentum $p \geqslant 0.2$ GeV/c and assuming pion mass. This distribution is shown in Fig. 5(a) for gluon enriched jets and in Fig. 5(c) for quark jets. Two broad bumps can be observed in Fig. 5(a), (c) which are the result of a superposition of a rapidly decreasing two-particle spectrum which dominates for $M \lesssim 1$ GeV/c^2, with an increasing spectrum consisting of 4 and more particles. The latter dominates and peaks at ~ 1.5 GeV/c^2. The region below 0.8 GeV/c^2 consists only of two particles. One peak around $M \sim 0.8$ GeV/c^2 can be attributed to the ρ resonance, another at $M \leqslant 0.5$ GeV/c^2 to a reflection of η, η' and ω. The latter statement is corroborated by the fact that in events with no neutrals, the peak at $M \leqslant 0.5$ GeV/c^2 vanishes. Only in Fig. 5(a) a third peak is indicated by the data points just below 1 GeV/c^2, in the region of the $f_0(980)$ resonance. In this region $0.9 \leqslant M \leqslant 1$ GeV/c^2 the two particle contribution amounts to about 70%. Fig. 5(b), (d) shows the difference between the data and the Monte Carlo event sample. For gluon enriched jets the distribution in Fig. 5(b) exhibits possible evidence for a mass enhancement[6] in the region $0.9 \leqslant M \leqslant 0.95$ GeV/c^2, but no signal is seen in this region for quark jets in Fig. 5(d). This peak is the remaining part of the original peak in Fig. 5(a) after the subtraction of a small and narrow but significant signal in the MC at 0.95–1.0 GeV/c^2. Without emphasising too much this remaining narrow peak in Fig. 5(b), it has to be noted that it survived a quality cut (by accepting only jets with a polar angle $\geqslant 50°$) well above 3σ, whereas all other deviations from zero in isolated bins in Fig. 5(b), (d) were decreased. Whether this narrow signal in gluon enriched jets can be attributed to $f_0(980)$ production remains an open interest-

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[6] The experimental mass resolution is below 10 MeV/c^2, the binwidth in Fig. 5 is 50 MeV/c^2.

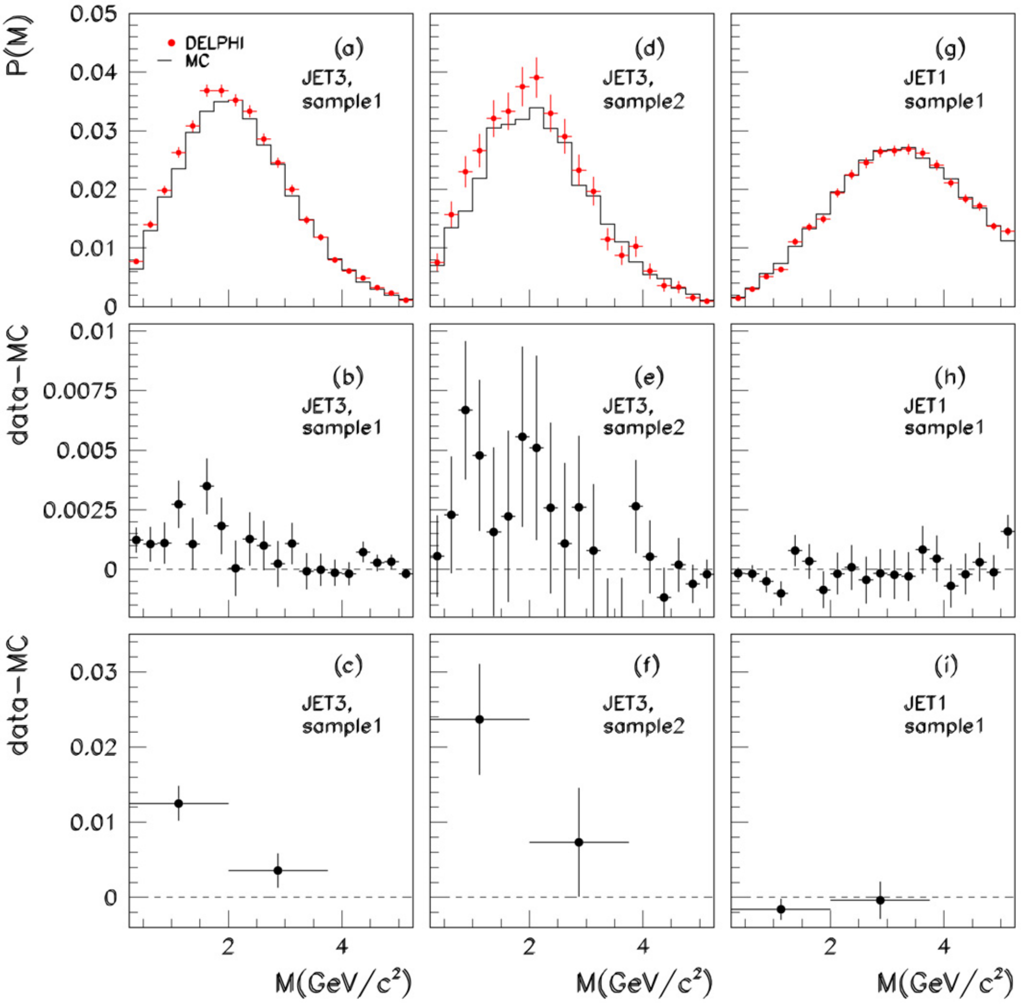

Fig. 6. (a), (d): Invariant mass distributions $P(M)$ of the leading system ($SQ = 0$) (with charged and neutral particles) for gluon-enriched jets, samples 1 and 2 respectively. (g): Same for quark jets (jet1, sample 1). The dots with error bars are the data, the histograms are the mean values of the three Monte Carlos. The quantity $P(M)$ is defined in Eq. (15). Second row (b), (e), (h): $P^{\text{data}}(M) - P^{\text{MC}}(M)$; Last row (c), (f), (i): $P^{\text{data}}(M) - P^{\text{MC}}(M)$ for 2 bins: (0.25–2 GeV/c^2) and (2–3.75 GeV/c^2).

ing question for future studies with increased statistics. In the mass range below 2 GeV/c^2 an overall excess is observed in Fig. 5(b).

(b) M is computed for all charged particles (with $p \geqslant 0.2$ GeV/c and pion mass assumed) and neutrals (photons with $E \geqslant 0.5$ GeV). Fig. 6(a), (d) shows $P(M)$ for gluon enriched jets and Fig. 6(g) for quark jets. Both gluon enriched samples exhibit an excess of data compared to the MC for low invariant masses (below 2 GeV/c^2), which is emphasised in Fig. 6(b), (e) where the mass distributions of data and MC have been subtracted. Separating the mass ranges below and above 2 GeV/c^2 in Fig. 6(c) for sample 1, an excess of about 5σ (stat) is observed in the low mass range. Comparing Fig. 6(c) with Fig. 6(f), one observes that the excess is increasing according to increasing gluon purity, namely about a factor 2 between sample 1 and sample 2. For quark jets, the corresponding distributions (Fig. 6(g)–(i)) do not exhibit any significant difference between data and MC.

An important remark concerns all mass spectra in Fig. 6. As stated in Section 3, all the comparisons to Monte Carlo event samples are done with full detector simulation. Consequently, due to the loss of neutral particles, all spectra and in particular the excess spectra in Fig. 6(b), (e) are shifted by about 0.3 to 0.5 GeV/c^2 to lower mass values. It has been verified, however, by a special Monte Carlo study using the detector response matrix (not shown here) that, after the correction of all spectra for this shift, the excess is still clearly concentrated in the low mass region. On the other hand, the spectra of leading systems consisting only of charged particles (Fig. 5) are not affected by shifts.

The observations in Fig. 5 confirm the first preliminary results presented in 2001 [13] for leading gluonic systems by considering charged particles only. In 2002 the OPAL Collaboration reported [16] a 2σ excess in the mass distribution of neutral leading systems, consisting of charged and neutral particles, between 1 and 2.5 GeV/c^2 in gluon jets.

The observation that the excess of neutral leading systems in gluon jets is limited to the low mass region (Figs. 5 and 6) supports arguments in favour of gluonic states. The existence of glueballs, i.e. bound states of two or more gluons, is a prediction of QCD [12]. The experimental results and their interpretations, however, are still controversial [30]. Theoretically there is general agreement that the lightest glueball should be in the scalar channel with $J^{PC} = 0^{++}$. Quantitative results are derived from the QCD lattice calculations [31] which predict the lightest glueball to be around 1600 MeV/c^2, or from QCD sum rules [32], which predict also a possible gluonic state near 1 GeV/c^2. Alternatively, it could also be a very broad object [33,34]. The gluonic state could mix with ordinary 0^{++} states, like the $f_0(980)$, $f_0(1370)$, $f_0(1500)$ or $f_0(1710)$. As an example there are scenarios, where the largest gluonic component is included in the $f_0(1500)$ [35], or alternatively in the $f_0(1710)$ [36]. Recent discussions with various references can be found in [30,37].

6. Summary

In the present study the leading systems defined by a rapidity gap have been investigated for gluon and quark jets. The statistics of 1994 and 1995 at $\sqrt{s} = 91.2$ GeV obtained by the DELPHI Collaboration is used to select 3-jet events and to single out quark jets (purity $\sim 90\%$) and gluon enriched jets (purity $\sim 70\%$) by energy ordering (sample 1). For the (enriched) gluon jets a higher rate of neutral leading systems than predicted by the Lund string model JETSET/ARIADNE (with and without Bose–Einstein correlations) is observed but no such enhancement is seen for the quark jets. Various checks have been performed which suggest that this effect is not a spurious one. An increase of the effect with increasing gluon purity, obtained by a tagging procedure in a second sample (sample 2), is observed corroborating that it is indeed connected with the gluon jets.

The excess of neutral leading systems in pure gluon jets at a gap size $\Delta y = 1.5$ has been measured to be about 10%, with a significance of 3.6σ. It is expected to be of the order of 0.5% in pure gluon jets without any charge or gap selection.

The mass spectra of the neutral leading systems of gluon jets, both with and without including neutral particles have been studied. Mass spectra which include charged and neutral particles, show clearly that the excess mentioned above is concentrated at low invariant masses ($\lesssim 2$ GeV/c^2). The significance is enhanced there and amounts to about 5σ(statistical) in sample 1 and the excess is increased roughly proportionally to the gluon purity in sample 2.

The corresponding mass spectra of leading systems in quark jets do not exhibit any excess in the low mass regions.

The observed excess of neutral systems in gluon jets and its increase with the gap size and with the gluon purity is in agreement with expectations, if the hitherto unobserved but predicted process of octet neutralisation of the gluon field takes place in nature. Although colour reconnection could in principle alternatively explain the excess, the specific mass concentration at low mass seems to favour the first case and could be a signal of gluonic states predicted by QCD.

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