

Identified Particles in Quark and Gluon Jets

Preliminary

DELPHI Collaboration

P.Abreu¹, J.Dahm², A.De Angelis³, O.Klapp², R.Henriques¹, P.Langefeld² and E.Schyns²

Abstract

A sample of about 1.4 million hadronic Z decays, selected among the data recorded by the DELPHI detector at LEP during 1994, was used to measure for the first time the momentum spectrum of K^+ (K^-), K^0 (\bar{K}^0), p (\bar{p}) and Λ ($\bar{\Lambda}$) in gluon and quark jets. As observed for inclusive charged particles, the production spectrum of identified particles was found to be softer in gluon jets compared to quark jets, with a higher total multiplicity. For all identified particles the ratio of the average multiplicity in gluon jets with respect to quark jets was found to be consistent with the ratio measured for charged particles.

¹LIP, IST, FCUL - Av. Elias Garcia, 14-1^o, P-1000 Lisboa Codex, Portugal

²Fachbereich Physik, University of Wuppertal, Postfach 100 127, D-42097 Wuppertal 1, Germany

³CERN, CH-1211 Geneva 23, Switzerland

1 Introduction

In Quantum Chromodynamics (QCD) quarks and gluons carry distinct colour charges, and therefore they differ in their relative coupling strength to emit additional gluons. Due to this fact, jets originating from the fragmentation of energetic quarks and gluons are expected to show differences in their particle multiplicity, energy spectrum, and angular distributions.

The LEP detectors can select gluon jets in $b\bar{b}g$ events, by tagging the b quarks using selections based on the presence of particles with large impact parameters. This technique recently allowed conclusive measurements of the different behaviour of quark and gluon jets from LEP data (see for example Ref. [1, 2, 3], and Ref. [4] for a review). Although the hadron multiplicity in gluon jets, from first order QCD and in the asymptotic limit, is expected to be twice the multiplicity in quark jets [5], the experimental results point to a multiplicity ratio of about 1.25, increasing with energy [3]. Gluon jets appear to be broader than quark jets and their fragmentation appears to be softer [1, 2, 3].

The DELPHI detector at LEP, equipped with a powerful system for particle identification [6], can provide information on the spectra of identified particles in quark and gluon jets, providing hints for their separation and testing in detail the predictions of QCD based models.

The study of the spectra of identified particles (K^+ , K^0 , p and Λ)⁴ in quark jets and gluon jets from selected symmetric topologies is the subject of this paper. The paper is organized as follows. In Section 2 the hadronic event selection, the quark/gluon separation and the particle identification are described. The experimental results are presented and discussed in comparison with the predictions of models in Section 3. Finally the conclusions are presented in Section 4.

2 Experimental Technique and Event Sample

2.1 Event selections

A sample of hadronic events was selected by demanding a charged particle multiplicity (with $p > 100 \text{ MeV}/c$, $20^\circ < \theta < 160^\circ$, a track length of at least 30 cm in the TPC and consistent with coming from the interaction point) larger than four and a total charged energy greater than $0.12 \times E_{cm}$ [6]. The selection efficiency is of the order of 95% for hadronic Z decays. The data sample passing the hadronic criteria contained about $1.4 \cdot 10^6$ events with a small contamination ($< 0.7\%$) arising from $\tau^+\tau^-$ pairs, beam-gas scattering and $\gamma\gamma$ interactions [6]. Only the data collected during 1994 were used in the analysis, to profit from the full operation of the main particle identification detector of DELPHI (RICH [6]).

The influence of the detector, which is described elsewhere [6], on the analysis was studied with the full DELPHI simulation program, DELSIM [7]. Events were generated with the JETSET 7.3 Parton Shower (PS) Monte Carlo program [8] with parameters tuned by DELPHI [9]. The particles were followed through the detailed geometry of DELPHI giving simulated digitizations in each detector. These data were processed with the same reconstruction and analysis programs as the real data. Simulations based on

⁴Unless otherwise stated, antiparticles are included as well.

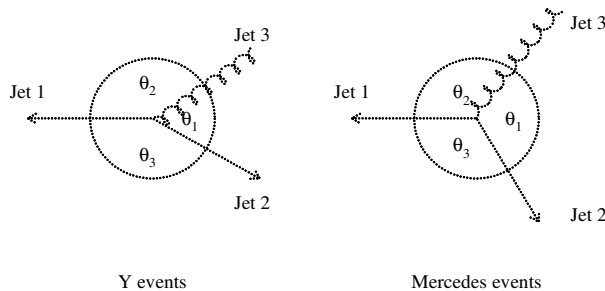


Figure 1: *Geometry of Y and Mercedes type events.*

JETSET 7.4 PS Monte Carlo with default parameters and HERWIG 5.8 with parameters tuned by DELPHI [9] were also used.

Three-jet events were selected by means of the k_{\perp} (or Durham) jet algorithm [10]. A jet resolution variable y_{ij} is defined for pairs of particles:

$$y_{ij} = \frac{2 \cdot \min(E_i^2, E_j^2) \cdot (1 - \cos \alpha_{ij})}{E_{vis}^2} \quad (1)$$

where α_{ij} is the angle between the two particles, E_i (E_j) is the particle energy, and E_{vis} is the sum of all particle energies in the event. Both charged and neutral particles were used in this jet reconstruction algorithm. The particle pair with the smallest y_{ij} is replaced by a pseudo-particle with four-momentum equal to the sum of the four-momenta of particles i and j , provided that y_{ij} is smaller than a cut value y_{cut} . This procedure is repeated until y_{ij} is greater than y_{cut} . At the end of the procedure, the remaining (pseudo)particles are the jets. The value used for the cut-off, $y_{cut} = 0.015$, was optimized using the JETSET 7.3 PS Monte Carlo, by maximizing the statistics available and the purity attained in the three-jet event samples [3]. The number of 3-jet events selected was 359084.

Two samples of 3-jet events with different geometries were used:

- Y events, two-fold symmetrical events with each of the two angles θ_2 and θ_3 in Figure 1 in the interval between 135° and 165° . The polar angle of the jets was required to be between 30° and 150° . The condition of planarity $\theta_1 + \theta_2 + \theta_3 \geq 355^\circ$, and the condition $|\theta_2 - \theta_3| \leq 15^\circ$ (to limit the energy difference between jet 2 and jet 3, in order to allow a direct comparison between them) were required in addition. Only the symmetric jets (jets 2 and 3 in Figure 1) were used in the analysis.
- Mercedes events, three-fold symmetrical events with each of the three angles θ_1 , θ_2 and θ_3 in Figure 1 in the interval between 100° and 140° . The polar angle of the jets was required to be between 30° and 150° . The condition of planarity $\theta_1 + \theta_2 + \theta_3 \geq 355^\circ$ was required in addition. All jets were used in the analysis.

The advantage of Mercedes and Y events (discarding the cases in which the gluon jet is the most isolated : jet 1 in Figure 1 left) is that the gluon and at least one quark jet are symmetrical, thus removing phase space effects. The disadvantage is a severe limitation of the statistics and of the parton energies spanned. The number of 3-jet events in the Mercedes and Y samples was equal to 9805 and 59166 respectively.

To each of the jets a calculated energy was assigned as derived from the jet directions and the angles between them. Assuming massless kinematics, the jet energy can be expressed as:

$$p_j^{calc} = E_j^{calc} = \frac{\sin\theta_j}{\sin\theta_1 + \sin\theta_2 + \sin\theta_3} \sqrt{s}, \quad j = 1, 2, 3 \quad (2)$$

where θ_j is the inter-jet angle as defined in Figure 1. Studies using full simulation[3] of the DELPHI detector showed that, for the range of the calculated jet energy, E_j^{calc} gives a better representation of the true underlying jet energy (i.e. before detector simulation) than does the reconstructed (or visible) jet energy. The use of expression (2) corrects for the energy shift towards low values due to particle loss, and improves the energy resolution from about 5 GeV to about 2 GeV .

Less than 1% of the gluon jets are expected to contain particles originating from the fragmentation of b quarks [11]. Gluon jets can thus be collected from a sample of reconstructed $b\bar{b}g$ three-jet events, by directly identifying the two quark jets as originating from b quarks. The experimental techniques employed in the present analysis detect with good performance b quark initiated jets, enabling reasonable high gluon jet purities to be attained, and thus allowing the study of an almost background free set of gluon jets.

The b tagging was done as follows. The probability that none of the charged particles with positive impact parameter in the event comes from a secondary vertex was required to be smaller than 2×10^{-2} [12]. The $b\bar{b}$ purity attained was about 71.2% and 69.5% in the Mercedes and Y samples, respectively. In the sample of Mercedes events, the gluon jet was selected as the jet with largest P_J (probability that none of the charged particles with positive impact parameter in the jet comes from a secondary vertex), provided it was greater than 0.1, and that the two other possible candidates verified $P_J \leq 0.1$. In Y events, a candidate gluon jet was selected as the jet with largest P_J , provided it was greater than 0.1. If this was the most isolated (jet 1 in Figure 1 left), the event was discarded. It was required in addition that the nearest jet had $P_J \leq 0.1$.

After b tagging, the number of 3-jet events in the Mercedes and Y samples was equal to 1090 and 7017, respectively.

The average energy and RMS spread of the jets selected as b and gluon, are indicated in Table 1 for both the Mercedes and Y events.

Class	gluon	b
Mercedes Events		
Average energy (GeV)	29.5	30.9
RMS spread (GeV)	3.4	3.2
Y Events		
Average energy (GeV)	23.5	25.0
RMS spread (GeV)	3.3	3.2

Table 1: Average energy and RMS spread of b and gluon selected jets of the Mercedes and Y events.

Three classes of jets were considered :

- A g -enriched class, including the gluon candidates selected as described in the previous paragraph.
- A b -enriched class. This was constructed from the two jets not selected for the g -enriched class in the Mercedes sample, and from the non-gluon jet among jet 2 and jet 3 in the Y sample.
- A reference class, which included all jets before b tagging. In order to reduce the bias in the Y class, for Y events only jet 2 and jet 3 were used.

The purity calculations were performed using events generated with JETSET 7.3 PS Monte Carlo, which were passed through the full simulation program (DELSIM [7]) of the DELPHI detector. Generated events were clustered into the same number of jets as after reconstruction (three in the selected samples). Two independent methods were used to assign the reconstructed jets to the generated jets :

- Generated heavy hadrons were assigned to the generated jets, and it was assumed that the reconstructed jet which had the largest angle to the generated jet containing heavy hadrons would be the gluon induced jet (Hadron assignment).
- Partons were clustered in three jets and reconstructed jets were associated to the parton jet closest in angle (Angle assignment).

Both methods are in a good agreement.

Using these procedures the compositions of the three jet classes were determined, they are summarized in Table 2 for Mercedes and Y events.

Class	g	b	$udsc$
Mercedes Events			
g -enriched	0.828	0.069	0.102
b -enriched	0.076	0.774	0.146
Reference	0.334	0.143	0.521
Y Events			
g -enriched	0.837	0.068	0.093
b -enriched	0.104	0.720	0.173
Reference	0.462	0.110	0.425

Table 2: Fractional composition of the three jet classes for Mercedes and Y events (using Angle assignment).

2.2 Identification of Final State Particles

For the measurement of K^+ and p a tagging procedure based on the Cherenkov angle measurement in the RICH detector and on the ionization energy loss (dE/dx) in the TPC was applied.

The dE/dx information was used for momenta below $0.7 \text{ GeV}/c$ for K^+ where no RICH information is available. Up to $0.9 \text{ GeV}/c$ the dE/dx provides the tagging tool for proton identification. Due to the better resolution and separation between the particular expectation curves, the tagging performance of the RICH is higher compared to the dE/dx . Thus in the remaining momentum range the tagging was performed by the RICH measurement. The analysis is restricted to the barrel RICH region ($41^\circ \leq \theta_{track} \leq 139^\circ$). The RICH hadron identification was based on three standard (DELPHI-RICH) software-packages called 'RIBMEAN', 'RICFIX' and 'NEWTAG' [13]. 'RIBMEAN' estimates the average Cherenkov angle in liquid and gas-radiator by application of a clustering algorithm and simultaneously links a quality-flag to each track passing through the RICH. 'RICFIX' corrects the RICH data and Monte Carlo concerning detector related effects (such as slight fluctuations in pressures and refractive indices, background arising from photon feedback, crosstalk between readout strips and wires, δ -rays, track ionization photoelectrons, etc.).

In the momentum range below $0.9 \text{ GeV}/c$ the clearly separated bands corresponding to electron, pion, kaon and proton in the dE/dx versus momentum were used for identification (muons can not be distinguished from pions). Detailed calibration has been pursued as described in [14].

The efficiency averaged over the momentum spectrum, was estimated from full detector simulation to be 56% (46%) with a purity of 75% (92%) for K^+ (p), in the sample of events selected for this analysis.

K_S^0 and Λ candidates were detected by their decay in flight into $\pi^+\pi^-$ and $p\pi^-$ respectively. Candidate secondary decays, V^0 , in the selected sample of hadronic events were found by considering all pairs of oppositely charged particles. The vertex defined by each such pair was determined such that the χ^2 of the hypothesis of a common vertex was minimized. The tracks were then refitted to the common vertex. The selection criteria were the "tight" ones described in [6]. The average detection efficiency from this procedure is about 36% for $K_S^0 \rightarrow \pi^+\pi^-$ and about 28% for $\Lambda \rightarrow p\pi^-$ in multihadronic events. The background under the invariant mass peaks was subtracted, separately for each bin of V^0 momentum, by linearly interpolating two sidebands in invariant mass:

- the regions between 0.40 and $0.45 \text{ GeV}/c^2$ and between 0.55 and $0.60 \text{ GeV}/c^2$ for the K_S^0
- the regions between 1.08 and $1.10 \text{ GeV}/c^2$ and between 1.14 and $1.18 \text{ GeV}/c^2$ for the Λ .

3 Analysis and Results

The production of identified particles in the final state was studied in 4 momentum bins for K^0 's and Lambdas and in 6 momentum bins for charged kaons and protons, as indicated in Table 3.

The ratios of the momentum distributions, uncorrected for the contamination of the different jet classes, are shown in Figure 2 for the g -enriched class relative to the reference class, together with the same ratios for charged particles. The simulation sample used consisted of about $4.6 \cdot 10^6$ hadronic Z decays generated with the JETSET 7.3 PS Monte Carlo program, JETSET 7.4 PS and HERWIG 5.8.

Particle	K^0, Λ					
Momentum bins (GeV/c)	bin 1 0.5-2.0	bin 2 2.0-5.0	bin 3 5.0-10.0	bin 4 10.0-25.0		
Particle	K^+, p					
Momentum bins (GeV/c)	bin 1 0.3-0.5	bin 2 0.5-0.9	bin 3 0.9-2.3	bin 4 2.3-4.5	bin 5 4.5-9.0	bin 6 9.0-25.0

Table 3: *Momentum bins used for the study of identified particles.*

The spectra of all identified particles in the class enriched in gluon jets appear to be softer than the corresponding spectra in the reference class.

The ratios can be unfolded from the effect of the contamination in the jet classes by applying an algebraic correction method to the momentum distributions. This method uses as the only input from the simulation the composition of the classes of jets in Table 2. If $M_{g-enriched}(m_i)$, $M_{b-enriched}(m_i)$ and $M_{reference}(m_i)$ represent the momentum distributions constructed from the g -enriched class, b -enriched class and reference class, respectively, where m_i is the content of bin i , then

$$M_j(m_i) = P_g(j) \cdot G(m_i) + P_b(j) \cdot B(m_i) + P_q(j) \cdot Q(m_i) \quad (3)$$

where $G(m_i)$, $B(m_i)$ and $Q(m_i)$ are the distributions for pure g , pure b and pure $q = udsc$, respectively, with $P_g(j)$, $P_b(j)$ and $P_q(j)$ the fraction of the jets which are g , b and $q = udsc$ in the enriched class j ($j = g$ -enriched, b -enriched and reference).

Two pure classes were considered in the analysis : the class of pure gluons and a pure quark class including all quarks ($q = udscb$). This $q = udscb$ class, was obtained from the compositions of $udsc$ and b quarks in the enriched classes and reference class of Table 2 in the proportions predicted by the standard model for the Z decay into quarks. In this procedure all quarks, $udsc$, were considered as equal. The effect of the c -enrichment in the b -enriched class was afterwards estimated and accounted for in the systematic uncertainty.

Reconstruction efficiencies were determined, using the Monte Carlo JETSET 7.3 PS, by comparing the simulated with the generated momentum distributions of the identified particles in the two pure classes of jets considered.

The ratios unfolded from the contamination of the jet classes and corrected for the reconstruction efficiency of the particles in the pure jet classes, are shown in Figure 3, together with the unfolded ratios for charged particles.

The ratio of the average charged multiplicities in gluon jets relative to quark jets, r_{ch} , was averaged over the momentum spectrum. Values of $r_{ch} = 1.16 \pm 0.01$ and $r_{ch} = 1.28 \pm 0.02$ were found for Y and Mercedes events, respectively. *Normalized ratios*, $R'_X(p)$, are defined by :

$$R'_X(p) = \frac{r_X(p)}{r_{ch}(p)}, \quad (4)$$

where $r_X(p)$ and $r_{ch}(p)$ are respectively the ratio of the multiplicity measured as a function of the momentum, $p(GeV/c)$, for the identified particle $X = K^0, \Lambda, K^+, p$ in gluon

jets relative to quark jets, and the ratio of the multiplicities measured as a function of the momentum for charged particles.

From the ratios in Figure 3, one can compute these normalized ratios shown in Figure 4. The normalized ratios integrated over the momentum spectrum, R'_X , are listed in Table 4 (M stands for “Mercedes”; the first uncertainty quoted is statistical, the second is systematic), and compared with the predictions from the Monte Carlo simulations.

R'_X	Measured	JETSET 7.4 PS	JETSET 7.3 PS	HERWIG 5.8
R'_{K^0}, Y	$1.13 \pm 0.10 \pm 0.10$	0.99	0.94	0.82
R'_Λ, Y	$1.43 \pm 0.30 \pm 0.19$	1.46	1.40	0.92
R'_p, M	$1.17 \pm 0.21 \pm 0.09$	1.19	1.62	1.17
R'_{K^+}, M	$0.83 \pm 0.08 \pm 0.06$	0.94	0.97	0.70

Table 4: Normalized ratios R'_X (see text) compared to the predictions from the Monte Carlo simulations.

The systematic uncertainties on these ratios were estimated by summing in quadrature the following sources:

1. The uncertainty on the performance of particle identification. Related to K^+ and p identification, it was assumed that the contamination from misidentified particles was varying by $\pm 10\%$, folded by the different multiplicities of charged particles in the g -enriched and in the reference classes. For K^0 and Λ , this systematic uncertainty was taken to be $\pm 15\%$.
2. The flavour composition in Table 2. This was varied by assuming that all the c quark jets in the g -enriched and b -enriched classes are indeed b quark jets. In addition, the gluon jet purity was varied by 5% in the Y and Mercedes samples. The maximum of the two variations was taken as estimator of the systematic effects associated to the uncertainty on the flavour composition.
3. The effect of considering all quarks $udsc$ as equal, when the unfolding from the effect of the contamination of the jet classes is performed. It was estimated the effect, on the ratios, of considering all c quarks as b 's, and all uds quarks as b 's. The half distance between the two values was taken as a conservative estimator of this systematic uncertainty.

The effect of these sources of systematic uncertainty on the normalized ratios is summarized in Table 5.

The average yield of identified particles agree with the predictions from the Monte Carlo simulations.

4 Conclusions

Based on a sample of 1.4 million hadronic Z decays collected by the DELPHI detector at LEP, the production spectra of identified particles in jets initiated by gluons and jets

R'_X	1	2	3	Total
R'_{K^0}, Y	0.102	0.010	0.010	0.103
R'_{Λ}, Y	0.182	0.030	0.060	0.194
R'_p, M	0.090	0.002	0.013	0.091
R'_{K^+}, M	0.060	0.020	0.012	0.064

Table 5: *Sources of systematic uncertainty on the normalized ratios.*

initiated by quarks, was analysed in order to search for possible differences between gluons and quarks jets.

As observed for inclusive charged particles, the production spectrum of identified particles was found to be softer in gluon jets compared to quark jets, with a higher total multiplicity. The ratio of the average multiplicity of identified particles in gluon jets with respect to quark jets was found to be consistent with the ratio measured for charged particles.

References

- [1] OPAL Coll., G. Alexander et al., Phys. Lett. **B265** (1991) 462;
OPAL Coll., P.D. Acton et al., Z. Phys. **C58** (1993) 387;
OPAL Coll., R. Akers et al., Z. Phys. **C68** (1995) 179.
- [2] ALEPH Coll., D. Buskulic et al., Phys. Lett. **B346** (1995) 389.
- [3] DELPHI Coll., P. Abreu et al., Z. Phys. **C70** (1996) 179.
(and references therein)
- [4] J. Fuster and S. Marti, “Charged Particle Production in the Fragmentation of Quark and Gluon Jets”, Valencia Preprint IFIC/95-60 (November 1995), to be published in the Proceedings of the EPS-HEP Conference, Bruxelles 1995.
- [5] S.J. Brodski and J. Gunion, Phys. Rev. Lett. **37** (1976) 402.
- [6] DELPHI Coll., P. Abreu et al., “Performance of the DELPHI Detector”, CERN-PPE/95-194, subm. to Nucl. Instr. Meth. **A**;
DELPHI Coll., P. Abreu et al., Nucl. Instr. Meth. **A303** (1991) 233.
- [7] DELPHI Coll., P. Abreu et al., “DELPHI event generation and detector simulation”, DELPHI 89-67 PROG-142.
- [8] T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.
- [9] K. Hamacher and M. Weierstall, “Tuning and Test of Fragmentation Models Based on Identified Particles and Precision Event Shape Data”, Contributed paper eps0548 to the EPS-HEP Conference, Bruxelles 1995 (DELPHI 95-80 and CERN-PPE to appear).
- [10] S. Bethke et al., Nucl. Phys. **B370** (1992) 310.
- [11] M. L. Mangano, P. Nason, Phys. Lett. **B285** (1992) 160;
M. H. Seymour, Z. Phys. **C63** (1994) 99;
M. H. Seymour, Nucl. Phys. **B436** (1995) 163.
- [12] DELPHI Coll., P. Abreu et al., Z. Phys. **C65** (1995) 555.
- [13] E.Schyns “NEWTAG, π^\pm , K^\pm and $p\bar{p}$ tagging for DELPHI RICHes”, DELPHI 96-103 RICH-89.
- [14] J. Dahm, M. Reale and M. Elsing, DELPHI 95-48 TRACK 81.
- [15] DELPHI Coll., P. Abreu et al., Phys. Lett. **B347** (1995) 447.

g-enriched/Reference

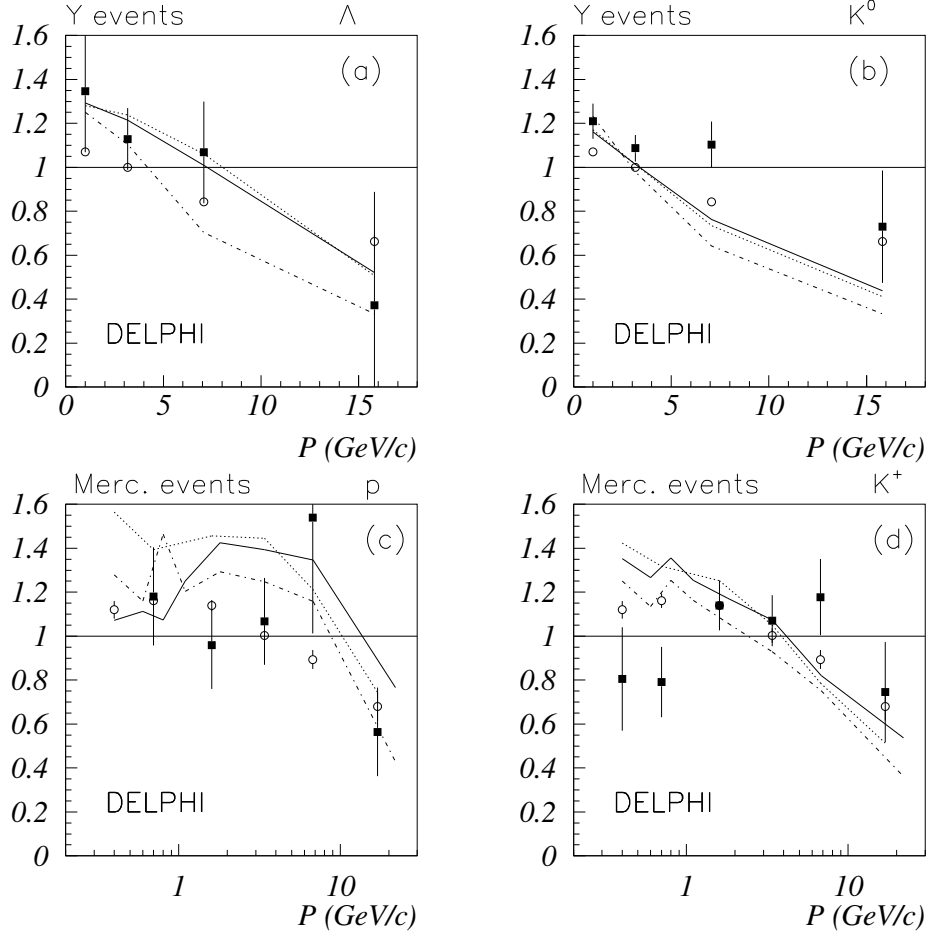


Figure 2: Ratio of the yields of Λ (a), K^0 (b), p (c) and K^+ (d) in the g-enriched class with respect to the reference class (black squares), for Y and Mercedes events as indicated. The circles represent the data points on the ratio of the yields of charged particles in the g-enriched class with respect to the reference class. The predictions from the simulation JETSET 7.3 PS are shown as dotted line, the solid line represents the predictions from the simulation JETSET 7.4 PS and the dash-dotted line represents the predictions from HERWIG 5.8.

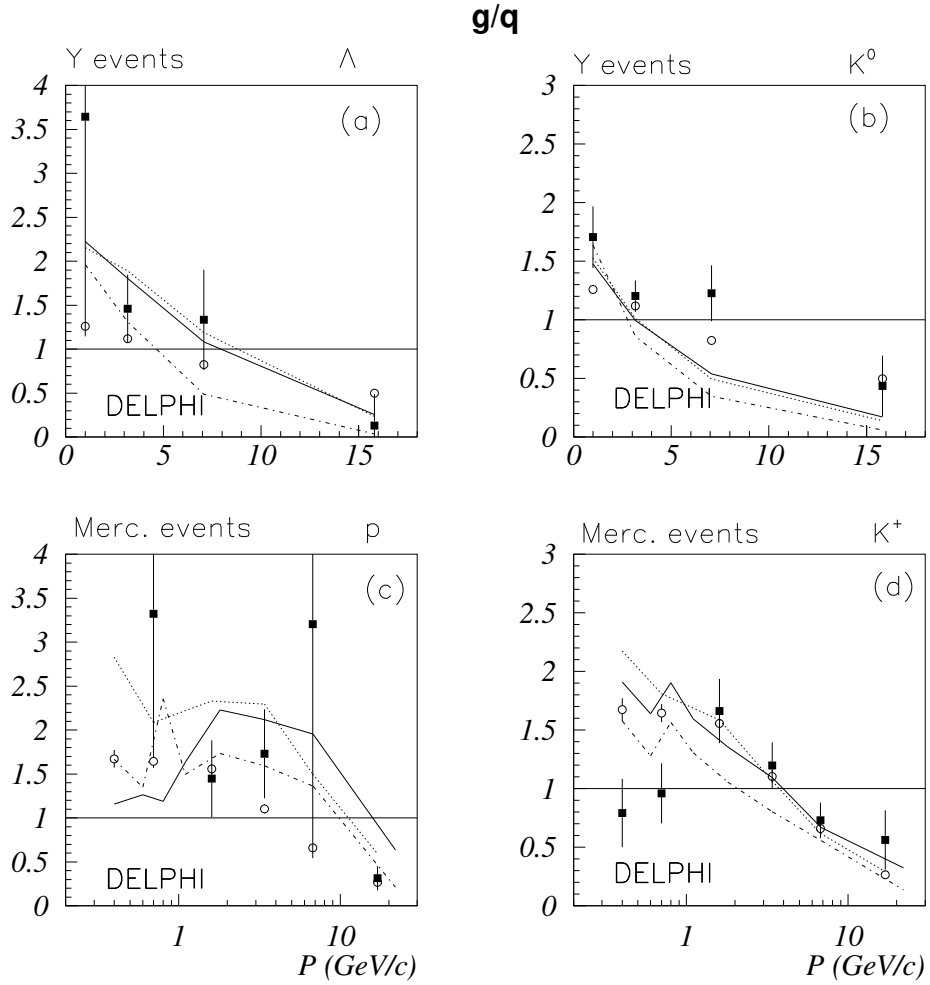


Figure 3: Ratio of the yields of Λ (a), K^0 (b), p (c) and K^+ (d) in gluon jets with respect to quark jets (black squares), for Y and Mercedes events as indicated. The circles represent the data points on the ratio of the yields of charged particles in g jets with respect to q jets. The predictions from the simulation JETSET 7.3 PS are shown as dotted line, the solid line represents the predictions from the simulation JETSET 7.4 PS and the dash-dotted line represents the predictions from HERWIG 5.8.

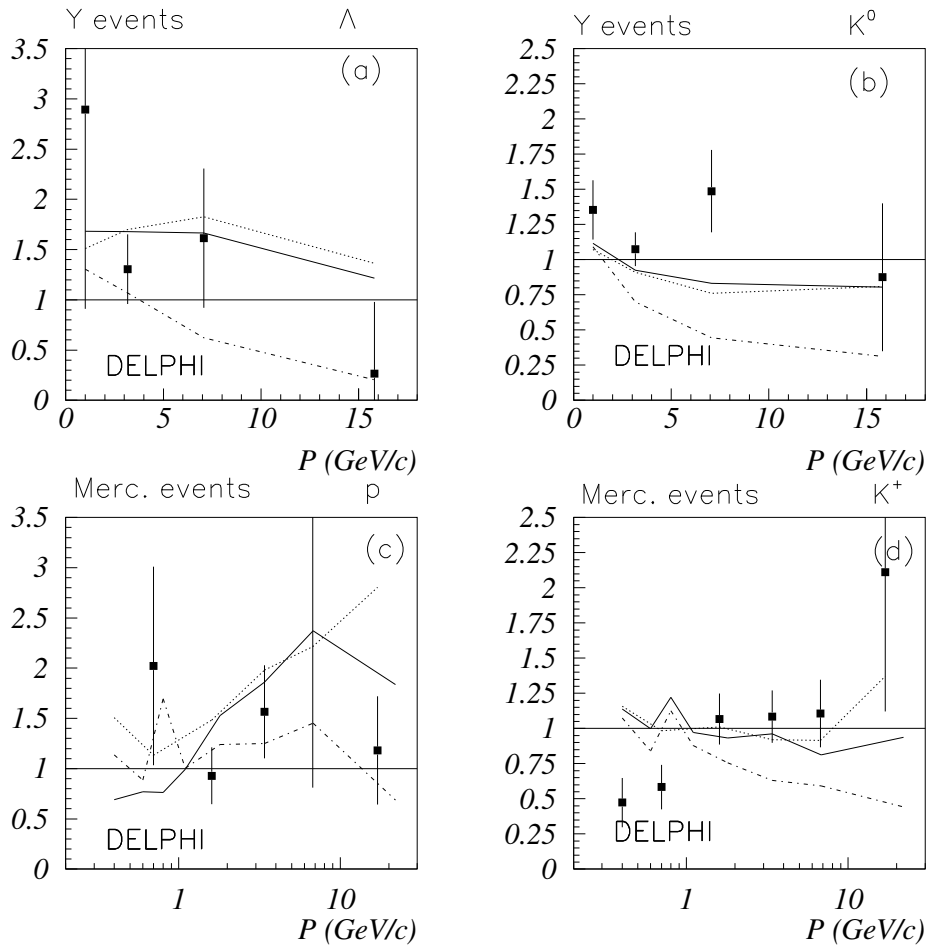


Figure 4: Normalized ratio of Λ (a), K^0 (b), p (c) and K^+ (d), for Y and Mercedes events as indicated. The black squares represent the data points. The predictions from the simulation JETSET 7.3 PS are shown as dotted line, the solid line represents the predictions from the simulation JETSET 7.4 PS and the dash-dotted line represents the predictions from HERWIG 5.8.