EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-EP/88-54
April 28th, 1988

Two - Jet Mass Distributions at the CERN Proton - Antiproton Collider

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen[1] - Amsterdam (NIKHEF)[2] - Annecy (LAPP)[3] - Birmingham[4] - CERN[5] - Harvard[6] - Helsinki[7] - Kiel[8] - Imperial College, London[9] - Queen Mary College, London[10] - Madrid (CIEMAT)[11] - MIT[12] - Padua[13] - Paris (College de France)[14] - Riverside[15] - Rome[16] - Rutherford Appleton Lab[17] - Saclay (CEN)[18] - Victoria[19] - Vienna[20] - Wisconsin[21] Collaboration

C. Albajar[5], M.G. Albrow[17], O.C. Allkofer[8], A. Astbury[19], B. Aubert[3], T. Axon[9], C. Bacci[16], T. Bacon[9], N. Bains[4], J. R. Batley[10], G. Bauer[6], S. Beingessner[19], A. Bettini[13], A. Bezaguet[5], R. Bonino[4], K. Bos[2], E. Buckley[6], G. Busetto[13], P. Catz[3], P. Cennini[5], S. Centro[13], F. Ceradini[16], D.G. Charlton[4], G. Ciapetti[16], S. Cittolin[5], D. Clarke[10], D. Cline[21], C. Cochet[18], J. Colas[3], P. Colas[18], M. Corden[4], J.A. Coughlan[17], G. Cox[4], D. Dau[8], J.P. deBrion[18], M. DeGiorgi[13], M. Della Negra[5], M. Demoulin[5], D. Denegri[5,18], A. DiCiaccio[5,16], F.J. Diez Hedo[11], L. Dobrzynski[14], J. Dorenbosch[2], J. D. Dowell[4], E. Duchovni[5], K. Eggert[1], E. Eisenhandler[10], N. Ellis[4], P. Erhard[1], H. Faissner[1], I.F. Fensome[10], A. Ferrando[11], M. Fincke-Keeler[19], P. Flynn[17], G. Fontaine[14], J. Garvey[4], D. Gee[15], S. Geer[6], A. Geiser[1], C. Ghesquiere[14], P. Ghez[3], C. Ghiglino[3], Y. Giraud-Heraud[14], A. Givernaud[5,18], A. Gonidec[5], H. Grassmann[1], J. Gregory[4], W. Haynes[17], S.J. Haywood[4], D.J. Holthuizen[2], M. Ikeda[15], W. Jank[5], M. Jimack[4], G. Jorat[5], D. Joyce[15], P.I.P. Kalmus[10], V. Karimäki[7], R. Keeler[19], I. Kenyon[4], A. Kernan[15], A. Khan[9], W. Kienzle[5], R. Kinnunen[7], M. Krammer[20], J. Kroll[6], D. Kryn[14], F. Lacava[16], M. Landon[10], J.P. Lees[3], R. Leuchs[8], S. Levegrün[8], S. Li[19], M. Lindgren[15], D. Linglin[3], P. Lipa[20], E. Locci[5], T. Markiewicz[21], C. Markou[9], M. Markytan[20], M.A. Marquina[11], G. Maurin[5], J.-P. Mendiburu[14], A. Meneguzzo[13], J. P. Merlo[15], T. Meyer[5], M.-N. Minard[3], M. Mohammadi[21], K. Morgan[15], H.-G. Moser[1], A. Moulin[1], B. Mours[3], Th. Muller[5], L. Naumann[5], P. Nedelec[14], A. Nisati[16], A. Norton[5], F. Pauss[5], C. Perault[3], E. Petrolo[16], G. Piano Mortari[16], E. Pietarinen[7], C. Pigot[18], M. Pimiä[7], A. Placci[5], J.-P. Porte[5], M. Preischl[8], E. Radermacher[5], T. Redelberger[1], H. Reithler[1], J.-P. Revol[12], D. Robinson[9], T. Rodrigo[11], J. Rohlf[6], C. Rubbia[5], G. Sajot[14], G. Salvini[16], J. Sass[5], D. Samyn[5], D. Schinzel[5], M. Schröder[8], A. Schwartz[6], W. Scott[17], C. Seez[9], T. P. Shah[17], I. Sheer[15], I. Siotis[9], D. Smith[15], R. Sobie[19], P. Sphicas[12], J. Strauss[20], J. Streets[4], C. Stubenrauch[18], D. Summers[21], K. Sumorok[6], F. Szoncso[20], C. Tao[14], A. Taurok[20], I. ten Have[2], S. Tether[12], G. Thompson[10], E. Tscheslog[1], J. Tuominiemi[7], W. van de Guchte[2], A. van Dijk[2], B. van Eijk[2], J.P. Vialle[3], L. Villasenor[21], T.S. Virdee[9], W. von Schlippe[10], J. Vrana[14], V. Vuillemin[5], K. Wacker[1], G. Walzel[20], A. Wildish[9], I. Wingerter[3], S. J. Wimpenny[5], X. Wu[12], C.-E. Wulz[20], T. Wyatt[5], M. Yvert[3], C. Zaccardelli[16], I. Zacharov[2], N. Zaganidis[18], L. Zanello[16] and P. Zotto[13].

(Submitted to Physics Letters B)

Abstract

Two-jet mass distributions have been measured as a function of centre-of-mass scattering angle for high-mass jet pairs produced in proton-antiproton collisions at the CERN collider operating at a centre-of-mass energy of 630 GeV. The agreement between QCD expectations and the experimental measurements has been used to place limits on the production cross-section of an object X decaying into two jets. In particular we consider the existence of a massive colour octet of vector gauge bosons (axigluons). We exclude axigluons with a width $\Gamma_A \leq 0.4\ m_A$ and a mass m_A in the range $150 < m_A < 310$ GeV/c^2 (95% C.L.).

1. Introduction

Measurements of hadronic jet production at the CERN proton-antiproton collider have enabled quantitative tests of perturbative quantum chromodynamics (QCD) to be made. Data on inclusive jet rates and transverse momentum distributions [1,2], two-jet rates, angular distributions and mass spectra [3-7], and the properties of three- and four- jet events [8,9] have been shown to be consistent with theoretical expectations. In this paper measurements of the two-jet mass distribution obtained with the UA1 detector are presented for jet pairs with masses in the range $110 < m_{2j} < 350$ GeV/c^2. The event density in the two-jet mass versus centre-of-mass scattering angle plane is well described by QCD expectations. This agreement has been used to place limits on the production and decay of a massive vector or scalar particle X decaying into two jets as a function of the mass m_X and width Γ_X.

Recently it has been proposed [10] that strong interactions may be described by a gauge theory based on the chiral colour group $SU(3)_L \times SU(3)_R$, which breaks to diagonal $SU(3)_C$ at some scale, leaving standard QCD at low energies. This requires the existence of a massive colour octet of gauge bosons (axigluons), where the axigluon coupling is equal to the QCD coupling α_s. The axigluon width Γ_A depends on the effective number of open decay channels N (normalised so that a Dirac quark contributes $\Delta N = 1$) and for an axigluon mass m_A is given by $\Gamma_A = N\alpha_s m_A/6$. If axigluons decay only into the known quarks and antiquarks N = 5, and the axigluon width is comparable with the UA1 two-jet mass resolution. The value of N can be larger than this, up to N = 18 if all the particles described in reference 10 contribute, hence Γ_A is expected to be somewhere in the range $0.1\ m_A < \Gamma_A < 0.4\ m_A$. For any given axigluon mass the cross-section for axigluon production at the collider can be calculated [11], and our more general limit on the production of a vector particle X decaying into two jets can be used to place limits on the axigluon mass m_A.

2. Data Sample and Jet Reconstruction

Results are based on an integrated luminosity of 487 nb^{-1} recorded during the collider running periods of 1984 and 1985 at a proton-antiproton centre-of-mass energy of 630 GeV. The UA1 detector, trigger, and data taking conditions have been described elsewhere and we refer the reader to ref. 2 for details. The trigger required a localized transverse energy deposition E_T in the central calorimeters (pseudorapidity $|\eta| < 3.0$) with thresholds $E_T > 25$ or 30 GeV depending on running conditions. Jets were defined off-line using the UA1 jet algorithm [4]. In essence the energy and momentum of a jet are obtained by making the scalar and vector sums of energies deposited in all calorimeter cells within a cone $\Delta R < 1$ with respect to the jet axis, where $(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$, and $\Delta\eta$ and $\Delta\phi$ are the separation in pseudorapidity and azimuthal angle (measured around the beam direction) respectively. Events with two or more jets with transverse momentum $p_T > 20$ GeV are retained for further analysis provided there is at least one jet with $p_T > 40$ GeV.

Corrections ($\approx +15$ %) are applied to the energy and momentum of each jet to account mainly for the loss of jet energy outside the jet cone. The corrections also take into account instrumental effects, and the average contribution inside the cone from the spectator system. These jet energy corrections [12] have been obtained using the ISAJET Monte Carlo program [13] together with a full simulation of the UA1 detector. Further corrections ($\leq +12\%$) are applied to account for changes in the response of the calorimeters (ageing) as a function of time. The experimental jet energy resolution function, determined from a Monte Carlo simulation, is Gaussian with a width given by $\sigma_E/E = A + B/\sqrt{p_T}$, where the parameters A and B depend upon the jet direction and are in the ranges $0.035 < A < 0.080$ and $0.57 < B < 0.85$ GeV$^{1/2}$. There is an additional systematic error of 9% on the jet energy scale which arises from the uncertainties on (i) the absolute calibration of the calorimeters (5%), (ii) the correction for the ageing of the calorimeters (5%), and (iii) the correction for the loss of jet energy outside of the jet cone (5%).

To ensure a good jet finding efficiency (~ 100%) above the jet p_T threshold, we retain only those events with at least one jet with corrected $p_T > 50$ GeV. In addition, to ensure that part of the jet energy is not lost in the vertical crack in the UA1 detector, we require that the azimuthal angle ϕ is more than 20 degrees from the vertical direction for the two highest p_T jets . To eliminate multiple interactions and events with associated beam-halo hits, events with total energy greater than 700 GeV, or with missing transverse energy greater than 2.5 σ (where $\sigma = 0.7 \sqrt{\Sigma E_T}$) are rejected from the sample. Finally, from the sample of 28170 events which survive these cuts we select an exclusive two-jet sample by requiring that there are only two jets (uncorrected $p_T > 20$ GeV) in the event. We are left with a sample of 24893 two-jet events satisfying these requirements.

3. Two-Jet Mass Distribution

The procedures used to calculate two-jet kinematic variables are described in a previous publication [5]. For each event the two-jet mass m_{2j} is calculated using the fully corrected four-momenta of the jets. The two-jet mass resolution function, determined from a Monte Carlo simulation, is Gaussian with a width given by $\sigma \sim 0.11\, m_{2j}$.

The observed two-jet mass distribution extends up to masses $m_{2j} \sim 350$ GeV/c^2, and is shown in Fig. 1 for four angular intervals covering the range of good experimental acceptance $0 < |\cos\theta| < 0.8$. The centre-of-mass scattering angle θ is the angle between the axis of the jet pair and the average beam direction in the two-jet rest frame [14]. Note that due to the fixed jet p_T threshold the corresponding two-jet mass threshold increases with decreasing scattering angle. Also shown in Fig. 1 are the predicted two-jet mass distributions based on a lowest order QCD Monte Carlo program [15] modified to include (i) a parametrisation of the detector response to jets [12] (parametrised as a function of jet energy and direction, and based on a full simulation of the UA1 detector), (ii) the observed transverse momentum distribution of jet pairs, and (iii) the reconstructed single-jet mass distribution. The Monte Carlo uses the lowest order QCD subprocess cross-sections from reference 16 together with the structure functions of EHLQ set 1 [17] with $\Lambda = 0.2$ GeV, taking $Q^2 = p_T^2$, and assuming six quark flavours. The resulting predictions give a good description of the shapes of the observed two-jet mass distributions. The Monte Carlo program has therefore been used to (a) find for each cos θ interval the two-jet mass threshold above which there is no loss of events due to the jet p_T cut, and (b) to correct for the experimental two-jet mass resolution.

The resulting fully corrected two-jet differential cross-sections are tabulated in table 1 and shown in Fig. 2 where they are compared with the lowest order QCD predictions from the Monte Carlo. There is good agreement between the QCD expectations and the measured distributions. The best agreement is obtained if the QCD expectations are scaled upwards by a factor of 1.5. This factor is expected to reflect the contributions from higher order QCD processes (the K-factor). However, there is a relatively large systematic uncertainty on the normalisation of the measured cross-section which arises from the uncertainty on the jet energy scale. This uncertainty, which is mass dependent, is indicated on Fig. 2. For masses $m_{2j} \sim 200$ GeV/c^2 a change of the energy scale by one standard deviation results in a change in the normalisation of the cross sections by a factor of 2.5. There are additional but relatively small systematic uncertainties on the overall normalisation of the differential cross section of $\pm$ 15% arising from the uncertainty on the integrated luminosity of the data sample, and $\pm$ 10% arising from the uncertainty on the experimental two-jet mass resolution.

The predicted shapes of the mass distributions are not very sensitive to the choice of structure function, and we note that with the present systematic uncertainty on the jet energy scale and the uncertain contribution from higher order processes, we cannot differentiate between different structure functions or Q^2 scales. We conclude that within the experimental and theoretical uncertainties there is good agreement between the predicted and observed m_{2j} distributions.

4. Limits

The quantitative agreement between the shapes of the observed and expected two-jet mass distributions can be used to place limits on possible extensions of QCD.

We consider first the production of a massive vector particle X decaying into two hadronic jets. We have simulated the production and decay of X in the UA1 detector using a modified ISAJET Monte Carlo program in which a massive spin 1 object with a width $\Gamma_X = 0.1\ m_X$ is produced with the same longitudinal- and transverse- momentum distributions as those expected for Z^0 production. Following a full simulation of the UA1 detector the generated events have been processed with the UA1 reconstruction, selection, and analysis programs. The predicted contribution from X decays to the observed two-jet mass distribution is shown in Fig. 1 for two values of m_X. Note that the predictions take into account the experimental acceptance and correspond to the X production cross-sections times two-jet decay branching ratios shown in the figure. The experimental losses are dominated by geometrical acceptance losses. The experimental efficiency is therefore approximately mass independent, equaling 36% for masses $m_X > 200$ GeV/c^2, and falling to 24% for $m_X = 150$ GeV/c^2.

Allowing the relative contributions from QCD and from the production and decay of particle X to vary, the shapes and relative normalisations of the four measured mass distributions shown in Fig. 1 have been fitted using the method of maximum likelihood. The fit is therefore done in the two-jet mass versus angle plane and exploits the different two-jet mass- and angular- distributions expected for QCD processes and processes involving the production and decay of a massive particle. The fit has been repeated for different masses m_X. In all cases the best fit is consistent with zero contribution from the production and decay of particle X, enabling a limit to be placed on the cross-section times two-jet decay branching ratio $\sigma.B(X \rightarrow jet + jet)$. The largest experimental source of uncertainty on this limit arises from the systematic uncertainty on the jet energy scale. We define the scale factor $f \equiv \langle true\ m_{2j} \rangle / \langle measured\ m_{2j} \rangle$. If f is greater than 1 the true two-jet mass distributions are flatter than the measured distributions shown in Fig. 2, and the limits on $\sigma.B(X \rightarrow jet + jet)$ are weaker than those obtained from our fit. To gain some insight into this problem we have used the low mass part of the measured distributions to place an upper limit on f. Taking the lowest order QCD prediction for the shape of the m_{2j} distribution and allowing the scale factor f to vary, a fit to the shape of the observed m_{2j} distribution over the mass interval $110 < m_{2j} < 150$ GeV/c^2, and in the angular interval $\cos\theta < 0.2$, yields $f = 0.89^{+0.10}_{-0.15}$, and $f < 1.06$ at 95% confidence level. Similar results are obtained by fitting the measured two-jet mass distribution over other low mass intervals or in other angular regions. We conclude that (i) the shape of the mass distributions in the low mass region are consistent with the lowest order QCD expectations and the nominal jet energy scale $f = 1$, and (ii) if lowest order QCD describes the shape of the m_{2j} distribution over the low mass region the jet energy scale is not overestimated by more than 6% (95% C.L.). We therefore use the mass interval $110 < m_{2j} < 150$ GeV/c^2 to obtain a limit on f, and also to fix the normalisation of the QCD contribution to the two-jet mass distribution. The remainder of the measured distributions, $m_{2j} > 150$ GeV/c^2, are then used to place a limit on $\sigma.B(X \rightarrow jet + jet)$. In propagating the errors we have taken into account a possible 6% increase in the jet energy scale. We note that there still remains the possibility that the contributions from higher order QCD processes change the shape of the predicted mass distributions. In particular if the contributions from higher order processes steepen the predicted distributions our limits will be weakened.

We now consider the production and two-jet decay of both scalar and vector particles X with widths $\Gamma_X \leq 0.4\ m_X$. The predicted observed two-jet mass distributions associated with the decay of a vector particle X with width $\Gamma_X = 0.1\ m_X$ (shown in Fig. 1) obtained using the ISAJET Monte Carlo program together with a full simulation of the UA1 detector can be reproduced with a much simpler Monte Carlo program in which a Breit-Wigner distribution, with mass $m = 0.95\ m_X$ and width $\Gamma = 0.95\ \Gamma_X$, is folded together with a Gaussian resolution function with width $\sigma = 0.11\ m_{2j}$. This simple description of the observed two-jet mass distribution associated with the two-jet decay of a particle X, which does not depend on the chosen $\cos\theta$ interval, has been used to extend our analysis and extract limits on the production and decay of both scalar and vector particles with widths $\Gamma_X \leq 0.4\ m_X$. To obtain limits for $J_X = 0$ we assume that the fraction of particles X populating the decay angular interval from $\cos\theta_{min}$ to $\cos\theta_{max}$ is modified by a factor $Z \equiv Z_{spin\,0} / Z_{spin\,1}$ where $Z_{spin\,0} = (y_{max} - y_{min})$, $y = |\cos\theta|$, $Z_{spin\,1} = 0.75 \int dy\,(1 + y^2)$, and the integral is over the relevent interval of y, namely y_{max} to y_{min}. The resulting limits (95% C.L.), which are shown in Fig. 3, depend on the width Γ_X. The limits for spin 1 and spin 0 particles are essentially identical except for a small difference due to different geometrical acceptances for the two cases. The most stringent limits are for the decay of an object with a width much narrower than the experimental resolution, $\Gamma_X << 0.1m_X$. As Γ_X increases to ~ 0.4 m_X the limits weaken by up to a factor of two. Very broad resonances ($\Gamma_X > 0.4$ m_X) with masses $m_X >$ 150 GeV/c^2 more easily populate the two-jet mass distribution in the region $m_{2j} > 350$ GeV/c^2, where no events are observed, and the resulting limits become more stringent again.

Finally, we consider axigluon production. A recent theoretical evaluation [11] of the axigluon production cross-section at the collider is compared with the limit on the two-jet decay of a massive vector particle X in Fig. 3. The predicted axigluon cross-section times branching ratio lies in the excluded region (95% C.L.) for axigluon masses $m_A < 310$ GeV/c^2. Note that the predicted cross-section is approximately 1 nb (20 nb) for masses $m_A = 250$ (150) GeV/c^2. These production rates correspond to the modified mass distributions shown for illustration in Fig. 1. We have checked that once the experimental resolution has been taken into account the predicted shape of the axigluon modified two-jet mass distribution based on the complete lowest order sub-process cross-sections from ref. 11 is indistinguishable from our naive model (QCD plus Breit-Wigner resonance). Therefore, at the 95% confidence level, our data exclude axigluons with masses in the range $150 < m_A < 310$ GeV/c^2. This range of excluded masses is similar to the preliminary range excluded in ref. 11 ($125 < m_A < 275$ GeV/c^2) which was based on the single jet inclusive cross-section at the collider and used an approximate model for the detector resolutions and acceptance. It should be noted that our limits are based on a comparison of the two-jet mass distribution using events in which there are two- and only two-jets (no third jet with $p_T > 20$ GeV) with lowest order theoretical expectations.

5. Summary

Lowest order QCD predictions give a good description of the observed two-jet event density in the two-jet mass versus scattering angle plane. This agreement can be used to obtain quantitative limits on possible extensions of QCD. In particular, at the 95% confidence level, the data exclude (i) the production and two-jet decay of a massive particle X with width $\Gamma_X \leq 0.4$ m_X and cross-section times branching ratio exceeding the limits shown in Fig. 3, and (ii) the existence of axigluons with a mass in the range $150 < m_A < 310$ GeV/c^2.

Acknowledgments

We are thankful to the management and staff of CERN and of all participating institutes for their vigorous support of the experiment. The following funding agencies have contributed :

Fonds zur Förderung der Wissenschaftlichen Forschung, Austria.
Valtion luonnontieteellinen toimikunta, Suomen Akatemia,Finland.
Institut National de Physique Nucléaire et de Physique des Particules and
Institut de Recherche Fondamentale (CEA), France.
Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.
Istituto Nazionale di Fisica Nucleare, Italy.
Science and Engineering Research Council, United Kingdom.
Stichting Voor Fundamenteel Onderzoek der Materie, The Netherlands.
Department of Energy, USA.
The Natural Sciences and Engineering Research Council of Canada.

Thanks are also due to the following people who have worked with the collaboration in the preparations for and data collection on the runs described here: L.Baumard, F.Bernasconi, D. Brozzi, R.Conte, L.Dumps, G.Fetchenhauer, G.Gallay, J.C. Michelon and L.Pollet.

Table 1 : Fully corrected differential two-jet cross-section $d\sigma/dm_{2j}$ (pb per GeV/c^2) for four intervals of centre-of-mass scattering angle θ . The errors quoted are statistical only. There is an additional systematic uncertainty arising from the uncertainty on the jet energy scale. This uncertainty, which is mass dependent, is indicated on Fig. 2. For masses $m_{2j} \sim 200$ GeV/c^2 a change of the energy scale by one standard deviation results in a change in the normalisation of the cross sections by a factor of 2.5.

Mass (GeV/c^2)	**Angular Interval** $0.0 < \lvert\cos\theta\rvert < 0.2$	$0.2 < \lvert\cos\theta\rvert < 0.4$	$0.4 < \lvert\cos\theta\rvert < 0.6$	$0.6 < \lvert\cos\theta\rvert < 0.8$
110 - 120	283 ± 8	-	-	-
120 - 130	176 ± 6	223 ± 7	-	-
130 - 140	115 ± 5	138 ± 5	218 ± 7	-
140 - 150	61 ± 4	88 ± 4	155 ± 6	-
150 - 160	38 ± 3	51 ± 3	91 ± 4	-
160 - 170	18 ± 2	30 ± 2	65 ± 4	-
170 - 180	16 ± 2	15 ± 2	35 ± 3	113 ± 5
180 - 190	9.7 ± 1.4	12.0 ± 1.6	21 ± 2	76 ± 4
190 - 200	4.6 ± 0.9	5.5 ± 1.0	14 ± 2	46 ± 3
200 - 250	1.4 ± 0.2	1.9 ± 0.3	4.3 ± 0.4	19 ± 1
250 - 300	0.18 ± 0.08	0.22 ± 0.09	0.39 ± 0.12	2.3 ± 0.3
300 - 350	< 0.07*)	< 0.05*)	0.16 ± 0.07	0.21 ± 0.08

*) 90 % confidence level.

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Figure Captions

Fig. 1 : Differential two-jet cross-section ($d\sigma/dm_{2j}$), before correcting for the detector resolution and acceptance, shown for four intervals of centre-of-mass scattering angle θ. The solid curves show the predicted lowest order QCD [16] mass distributions (using the structure functions of EHLQ set 1 [17] with $\Lambda = 0.2$ GeV, taking $Q^2 = p_T^2$, and assuming six quark flavours) modified by the detector resolution and acceptance, and multiplied by a factor of 1.5. The broken curves show the expected modification of the QCD prediction corresponding to the production and two-jet decay of a massive vector particle X with mass $m_X = 250$ (150) GeV/c^2 and production rate $\sigma.B = 1$ nb (20 nb).

Fig. 2 : Fully corrected differential two-jet cross-section ($d\sigma/dm_{2j}$) shown for four intervals of centre-of-mass scattering angle θ. The systematic error on the measurements arising from the uncertainty on the jet energy scale is also shown. The curves show the lowest order QCD[16] expectations (using the structure functions of EHLQ set 1 [17] with $\Lambda = 0.2$ GeV, taking $Q^2 = p_T^2$, and assuming six quark flavours) multiplied by a factor of 1.5.

Fig. 3 : Upper limits on the cross-section times decay branching ratio for the production of a particle X decaying into two hadronic jets, shown as a function of mass m_X. The 95% C.L. limits are shown for $\Gamma_X << 0.1\ m_X$, and $\Gamma_X \leq 0.4\ m_X$. The limits are for the decay of vector and scalar particles. The broken line shows a recent prediction [11] for the production of axigluons at the CERN collider ($\sqrt{s} = 630$ GeV).

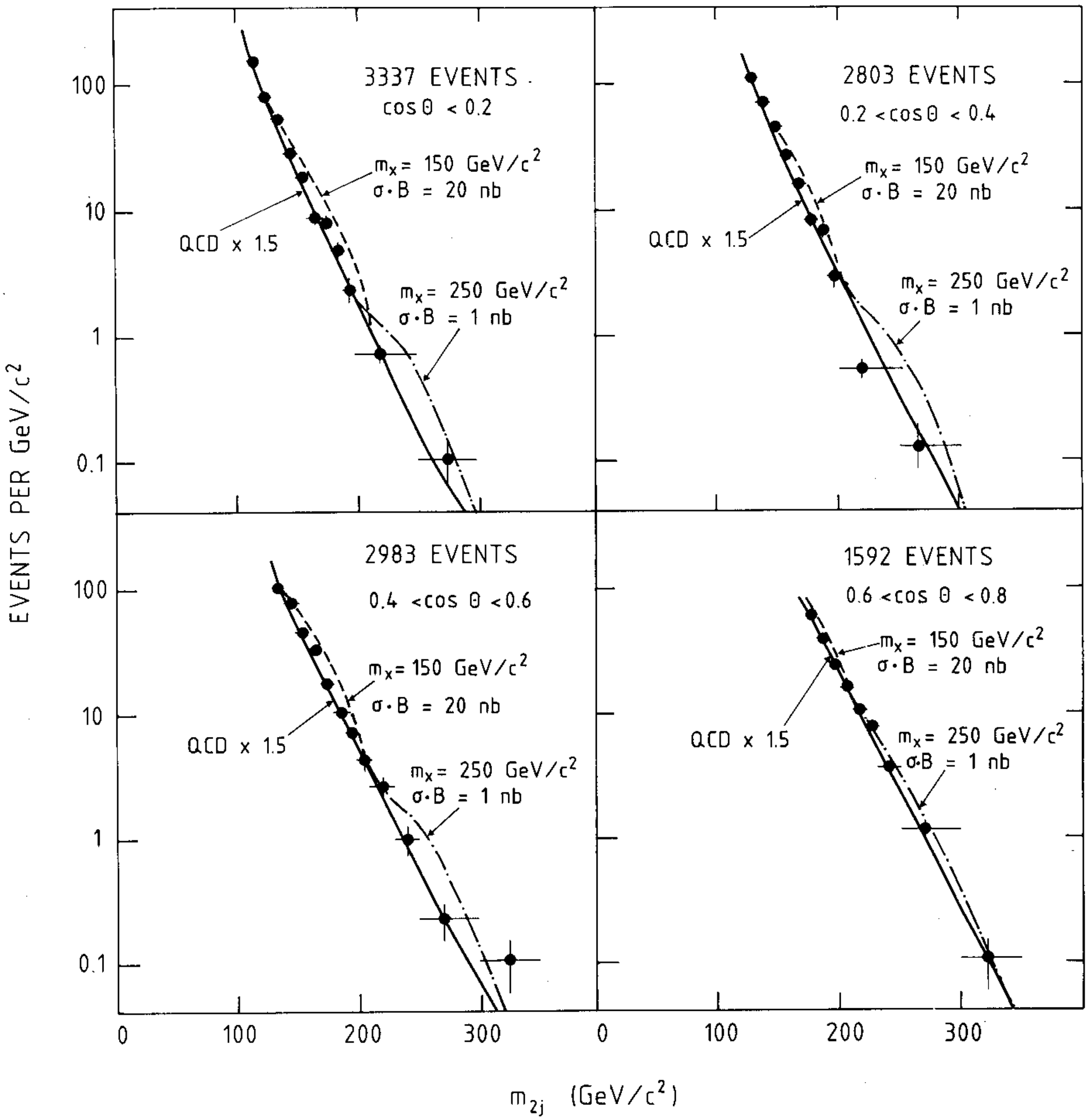
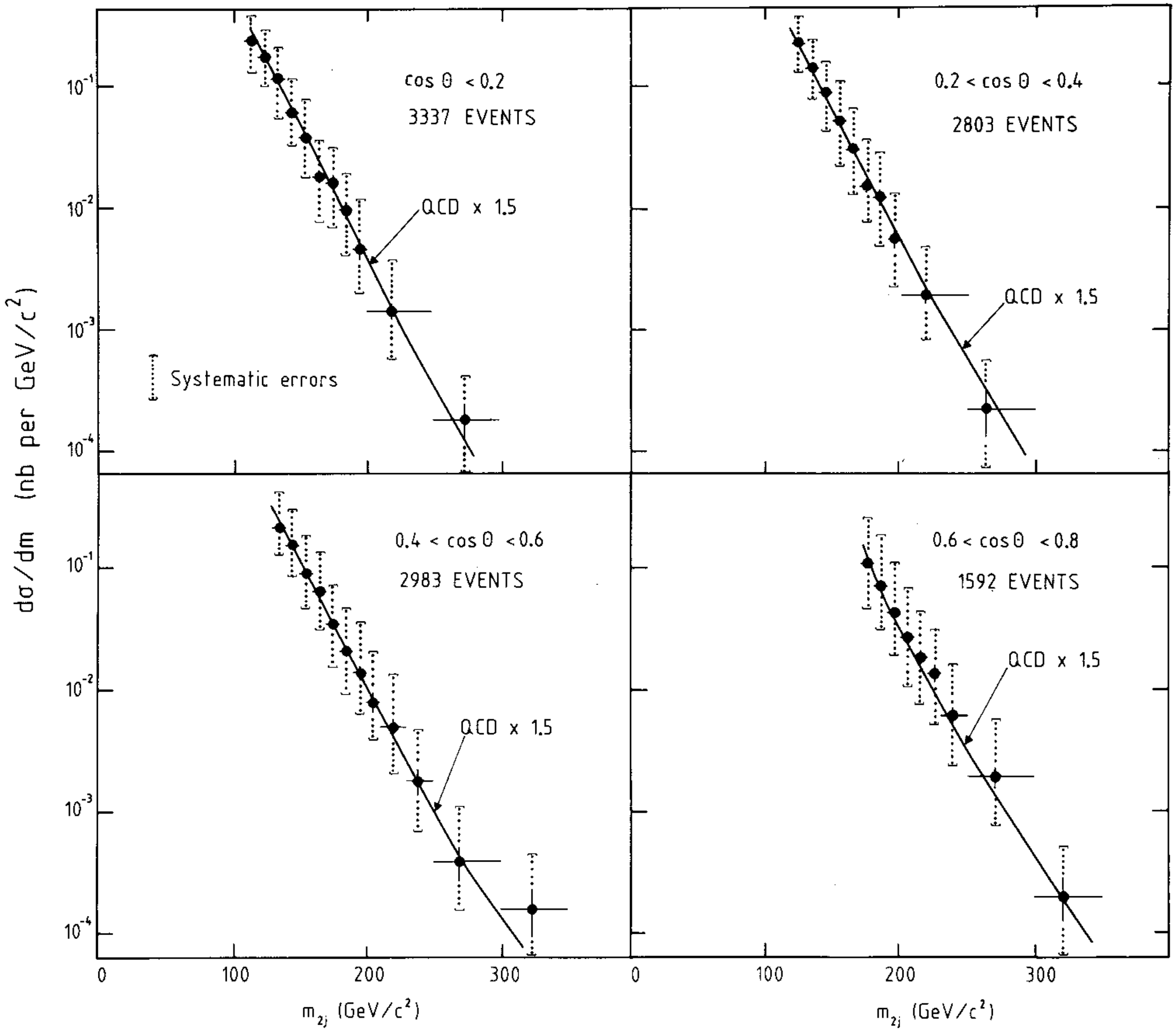

3337 EVENTS
cos θ < 0.2
m_x = 150 GeV/c²
σ·B = 20 nb
QCD x 1.5
m_x = 250 GeV/c²
σ·B = 1 nb
2803 EVENTS
0.2 < cos θ < 0.4
2983 EVENTS
0.4 < cos θ < 0.6
1592 EVENTS
0.6 < cos θ < 0.8
EVENTS PER GeV/c²
m_2j (GeV/c²)

FIG. 1



cos θ < 0.2
3337 EVENTS
QCD x 1.5
Systematic errors
0.2 < cos θ < 0.4
2803 EVENTS
QCD x 1.5
0.4 < cos θ < 0.6
2983 EVENTS
QCD x 1.5
0.6 < cos θ < 0.8
1592 EVENTS
QCD x 1.5
dσ/dm (nb per GeV/c²)
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
100
200
300
m₂ⱼ (GeV/c²)

FIG. 2

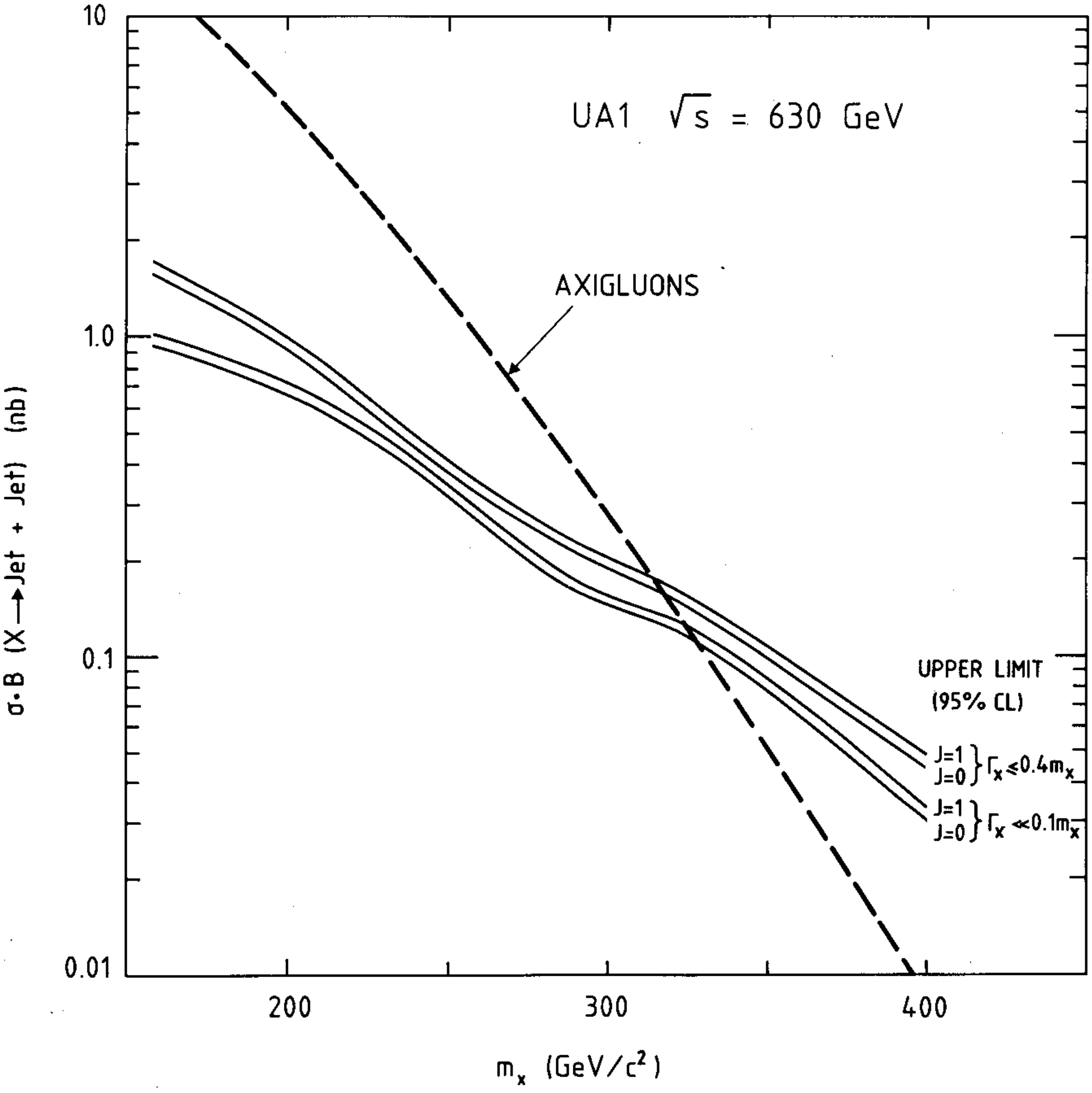

UA1 $\sqrt{s}$ = 630 GeV
AXIGLUONS
UPPER LIMIT
(95% CL)
J=1
J=0
$\Gamma_x \leq 0.4 m_x$
J=1
J=0
$\Gamma_x \ll 0.1 m_x$
10
1.0
0.1
0.01
200
300
400
σ·B (X ⟶ Jet + Jet) (nb)
m_x (GeV/c^2)

FIG. 3