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RAL Report
RAL-94-070

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V Barger E Mirkes R J N Phillips and T Stelzer

August 1994

Rutherford Appleton Laboratory Chilton DIDCOT Oxfordshire OX11 0QX

Rutherford Appleton Laboratory

MAD/PH/844
RAL-94-070

July 1994

CALCULATION OF Z PLUS FOUR JET PRODUCTION AT THE TEVATRON

V. Barger and E. Mirkes

Physics Department, University of Wisconsin, Madison, WI 53706, USA

R.J.N. Phillips

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

and

T. Stelzer

Physics Department, Durham University, Durham DH1 3LE, UK.

Abstract

We present the first calculation of $Z + 4$ jet production with heavy quark flavor identification at the Tevatron $p\bar{p}$ collider. The $Z + 4$ jet channel is especially interesting as a normalizer for the $W + 4$ jet background to top quark signals, as a background to a possible $t \to cZ$ flavor-changing neutral-current (FCNC) decay signal, and as a background to missing-p_T signals from gluino pairs. We also calculate the contributions to $W + 4$ jet production from all the different heavy-flavor final states. The MADGRAPH program is used to generate all leading order subprocess helicity amplitudes. We present Monte Carlo results with separation and acceptance criteria suitable for the Tevatron experimental analyses.

There are many potential new physics processes at hadron colliders, that would lead to final states with a weak boson plus multi-jets, where the weak boson is identified by its leptonic decay; these signals sometimes also contain a second weak boson, whose hadronic decay is less easily identified. Since a weak boson can also be produced along with gluon and quark jets, a knowledge of these QCD backgrounds is essential to the identification of new physics signals. Considerable effort has been devoted in recent years to the calculation of QCD $W+n$ jet $(n=1,2,3,4)$ and $Z+n$ jet $(n=1,2,3)$ cross sections; for the cases of high jet multiplicities n, that would be given by many interesting new physics signals, these calculations can currently be made at tree level only [1, 2, 3, 4]. We present first results for Z production with four QCD jets, evaluated for the Tevatron $p\bar{p}$ collider at $\sqrt{s}=1.8$ TeV, including a separation of contributions from different heavy quark flavors. We also calculate $W+4$ jets with heavy quark flavor identification; this goes beyond previous $W+4$ jet results that flag only b-flavor [1].

Major areas of physics interest in a QCD $Z+4$ jet calculation are the following.
(a) The most immediate interest is related to the top-quark search at the Tevatron [5, 6], where in the single-lepton signal with a b-tag the QCD $W+4$ jet channel gives the major background, and a comparison of the W/Z ratio could provide a calibration; this ratio should be insensitive to theoretical uncertainties in the individual cross sections. Furthermore, experimental acceptance and detector effects are also expected to cancel in the ratio. By calculating separate cross sections for different final-state quark flavors, we are able to apply our results to the case where a heavy quark is tagged.
(b) Possible isosinglet heavy quarks x would have both charged-current and neutral-current decay modes, with branching fraction ratios [7, 8, 9, 10, 11]

$$B(x \to qW) \;:\; B(x \to q'Z) \simeq 2 \;:\; 1. \tag{1}$$

(c) A related question is the possible existence of a prominent FCNC decay mode of the top quark [12, 13, 14, 15], $t \to cZ$ along with the standard $t \to bW$ decay. In this scenario, $t\bar{t}$ production would lead to a $t\bar{t} \to (cZ)(bW) \to Z+4$ jet signal, that must be distinguished from QCD background.
(d) The production of supersymmetric particles gives rise to missing-p_T plus multijet signals at hadron colliders. In particular, production of gluino pairs $\tilde{g}\tilde{g}$ with decays $\tilde{g} \to \chi_1^0 q\bar{q}$ to the lightest neutralino χ_1^0 are expected to be a source of missing-p_T plus 4 jets. Here $Z+4$ jet production with invisible $Z \to \nu\bar{\nu}$ decays is the dominant standard physics background. In the case of b-tagged events, there are regions of parameter space where $\tilde{g} \to t\bar{t}$ or $\tilde{g} \to b\bar{b}$ decays are dominant [16].

We now turn to the method used in our $Z+4$ jet calculation. An impediment in calculating subprocesses with many final partons is the large number of Feynman diagrams to be enumerated and expressed as amplitudes. For example, the $gg \to Zq\bar{q}gg$ subprocess involves 516 diagrams. This phase of the calculation can be accomplished for any given subprocess by the MADGRAPH program [17], which automatically generates all Feynman graphs and their helicity amplitudes, employing the HELAS approach [18]. However, MADGRAPH does not enumerate the contributing subprocesses, which must be entered individually, nor does it carry through the cross section calculation, folding in initial parton distributions and final phase space integration. We have added a phase-space generator and folded in the MRS set D'_- parton distributions [19], evaluated at a scale $Q^2 = \langle p_T \rangle^2 + M_Z^2$. The renormalization scale in α_s is set equal to Q^2 and the Λ value is chosen accordingly to the value in the parton distribution functions with five flavors. A similar procedure is followed in our $W + 4$ jet calculations.

For semi-realistic simulations, we make parton-level calculations of $p\bar{p} \to W(Z) + 4$ jets at $\sqrt{s} = 1.8$ TeV. We identify final partons with jets when

$$p_T(j) > 20\,\mathrm{GeV},\ |\eta(j)| < 2,\ \Delta R(jj) > 0.4, \tag{2}$$

where $[\Delta R(jj)]^2 = [\Delta\eta(jj)]^2 + [\Delta\phi(jj)]^2$ defines the angular separation between two jets. A correction must be made in comparing the parton transverse momentum p_T with the observed (uncorrected) jet transverse energy E_T; according to CDF simulations [5], typically 5 GeV or more must be added to the latter. A full simulation including fragmentation and detector characteristics must be made for detailed comparisons with experiment.

For the case that Z is detected by $Z \to e\bar{e}$ and W is detected by $W \to e\nu$, we take the electron and missing transverse momentum $\not{p}_T$ acceptance to be

$$p_T(e) > 20\ GeV, \quad |\eta(e)| < 1, \tag{3}$$

$$\not{p}_T > 20\ \mathrm{GeV} \quad (\text{for } W \text{ events}), \tag{4}$$

and require that the electrons are isolated from jets by $\Delta R(ej) > 0.4$. These acceptance criteria approximate but do not exactly duplicate those used in Tevatron experimental analyses.

Unless otherwise stated, in the following Z denotes $Z \to e^+e^-$ and W denotes $W^\pm \to e^\pm\nu$; with these leptonic branching fractions included, the cross sections times branching fractions are denoted $B\sigma$. Comparison with experiment requires the inclusion of instrumental efficiencies also.

The total cross sections with these acceptance criteria are

$$B\sigma(Z + 4\mathrm{jet}) = 21\ \mathrm{fb}, \quad B\sigma(W + 4\mathrm{jet}) = 318\ \mathrm{fb}. \tag{5}$$

The relative numerical contributions to the total cross section from different subprocesses according to the number of quarks involved in the process are (in percentages):

	$2q-4g$	$4q-2g$	$6q$
$Z+4$jet	55	43	2
$W+4$jet	55	43	2 .

(6)

Thus the six-quark contributions are not very important. The percentage contributions from the different initial state configurations are

	gg	qg	gq	$qq, q\bar{q}, \bar{q}\bar{q}$
$Z + 4$jet	3	20.5	20.5	56
$W + 4$jet	3	24	24	49 .

(7)

The gluon-gluon initiated production is rather insignificant at the Tevatron energy.

Tagging of b-quarks is an important means of selecting final states such as $t\bar{t}$ and $\tilde{g}\tilde{g}$, containing heavy quarks. In the CDF top-quark search, two means of tagging are employed, a silicon vertex detector (SVX) and a soft-lepton tag (SLT); the former identifies displaced vertices and the latter identifies leptons from $b \to \ell\nu X$ and $b \to c \to \ell\nu X$. However, the situation is complicated by the possibility that a c-jet or a light parton jet may be mistagged as a b-jet. The probability of tagging any particular final state therefore depends on the separate probabilities ϵ_j that any single jet $j = b, c, q/g$ satisfies the tagging criteria. In our later assessments of tagging, we will assume the values $\epsilon_b = 0.18$ (e.g. 0.11 from SVX and 0.07 from SLT), $\epsilon_c = 0.05$ and $\epsilon_{q/g} = 0.01$, which are approximately the efficiencies in the CDF top-quark search [5].

For application to tagging studies, we present here the cross sections in fb for different final flavor configurations.

b	c	q/g	$B\sigma(Z + 4\text{jets})$	$B\sigma(W + 4\text{jets})$
4	–	–	0.002	0.05
3	1	–	$< 1 \cdot 10^{-3}$	$< 1 \cdot 10^{-3}$
3	–	1	0.004	0.006
2	2	–	0.013	0.11
2	1	1	0.006	0.25
2	–	2	1.05	9.8
1	3	–	$< 1 \cdot 10^{-3}$	$< 1 \cdot 10^{-3}$
1	2	1	0.003	0.006
1	1	2	0.001	0.04
1	–	3	0.14	0.58
–	4	–	0.006	0.05
–	3	1	0.006	0.25
–	2	2	0.92	9.9
–	1	3	0.21	17.5
–	–	4	18.5	280

(8)

Folding in the b-tagging efficiencies given above, we obtain the following tagged cross sections:

no. of tags	$B\sigma(Z+4\text{jets})$	$B\sigma(W+4\text{jets})$	
≥ 0	21	318.	
≥ 1	1.25	17.2	(9)
≥ 2	0.06	0.65	
≥ 3	0.001	0.01	

To compare these numbers with experimental event rates, one has to multiply these cross sections by efficiency factors for the electrons and muons and also take into account effects of detector simulations. However, these effects (together with theoretical uncertainties) are expected to cancel approximately in the ratio of $(W+4\text{jet})/(Z+4\text{jet})$ cross sections.

The predicted W/Z ratio in 4-jet events with at least one b-tag is about 14. This number is fairly insensitive to the jet threshold p_T cut. Even if we relax the p_T and η requirements on the fourth jet (as CDF does to increase statistics in the top-quark sample), this W/Z ratio remains about 14. This ratio does however depend on the lepton rapidity cut; for $|\eta(\ell)| < 2.5$ we obtain a W/Z ratio of about 10.

With 19.2 pb^{-1} luminosity, CDF finds two b-tagged $Z+4$ jet events and seven b-tagged $W+4$ jet events, with relaxed E_T and η requirements on the fourth jet. Although the statistics are small, this observed W/Z ratio in 4-jet events appears to be anomalously low in comparison with the QCD prediction. If future statistics confirm that the b-tagged $W4j/Z4j$ ratio is indeed significantly lower than the pure QCD ratio, then there must be new physics in the $Z+4$-jet channel. Furthermore, if the tagged $W+4$-jet events are indeed dominated by $t\bar{t}$ production, as suggested by the CDF analysis [5] and by our results above, then the tagged $Z+4$-jet events are dominated by new physics beyond the standard model.

Interesting possibilities for such new physics include (i) a singlet charge -1/3 quark x_b, that mixes with the b-quark and therefore has a prominent $x_b \to bZ$ decay mode [8], or (ii) FCNC decays of the top quark $t \to cZ$ that would follow from mixing of t with a charge 2/3 singlet quark [12]. In case (ii), the b-tag would have to be faked by the c-jet.

We next consider the QCD $(Z \to \nu\bar{\nu}) + 4$ jet background to the missing-p_T signals of supersymmetry. We here consider missing-p_T requirements of

$$\not{p}_T > 50 \text{ or } 100 \text{ GeV} \quad , \tag{10}$$

along with the same jet cuts as before. The integrated cross sections are

$$B\sigma(\not{p}_T > 50; 4\text{jets}) = 290 \text{ fb} \qquad B\sigma(\not{p}_T > 100; 4\text{jets}) = 101 \text{ fb} \tag{11}$$

The contribution for different final flavor configurations are:

b	c	q/g	$B\sigma(\not{p}_T > 50 + 4\,\text{jets})$	$B\sigma(\not{p}_T > 100 + 4\,\text{jets})$
4	–	–	0.022	0.006
3	1	–	$< 1 \cdot 10^{-3}$	$< 1 \cdot 10^{-3}$
3	–	1	0.036	0.008
2	2	–	0.144	0.054
2	1	1	0.062	0.014
2	–	2	12.7	4.44
1	3	–	$< 1 \cdot 10^{-3}$	$< 1 \cdot 10^{-3}$
1	2	1	0.035	0.008
1	1	2	0.01	0.002
1	–	3	1.56	0.36
–	4	–	0.07	0.026
–	3	1	0.06	0.013
–	2	2	11.9	4.17
–	1	3	2.24	0.52
–	–	4	261.	92.

(12)

Including the tagging efficiences assumed above, the tagged cross sections are as follows.

no. of tags	$B\sigma(\not{p}_T > 50 + 4\,\text{jets})$	$B\sigma(\not{p}_T > 100 + 4\,\text{jets})$
≥ 0	290.	101.
≥ 1	16.6	5.77
≥ 2	0.72	0.25
≥ 3	0.01	0.004

(13)

A detailed consideration of the dynamical distributions of $Z+4$-jet events will be presented elsewhere.

Acknowledgments

We thank C. Campagnari for a helpful correspondence. This research was supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76ER00881 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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