ISAJET:

A Monte Carlo Event Generator for pp and $\bar{p}p$ Interactions

Version 3

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Summary

ISAJET is a Monte Carlo computer program which simulates pp and $\bar{p}p$ reactions at high energy. It can generate minimum bias events representative of the total inelastic cross section, high p_T hadronic events, and Drell-Yan events with a virtual γ, $W^{\pm}$, or Z^0. It is based on perturbative QCD and phenomenological models for jet fragmentation.

Introduction

ISAJET is a Monte Carlo computer program to simulate pp and $\bar{p}p$ interactions at high energy. It generates three classes of hadronic reactions, called MINBIAS, TWOJET, and DRELLYAN, plus e^+e^- reactions through a virtual γ or Z^0. MINBIAS simulates a minimum bias trigger, that is, the total inelastic cross section. Each beam jet contains a leading baryon plus mesons with a multiplicity distribution that satisfies approximate KNO[1] scaling as seen experimentally[2-3]. The user can selectively generate high multiplicty events. The transverse momentum distribution is limited, and diffractive processes are not included.

TWOJET simulates the production of high p_T hadrons and also the associated production of heavy quark states. High p_T jets are generated according to the leading-order perturbative QCD cross section[4-5]. The outgoing jets are evolved into a cascade of quarks and gluons using the leading-log approximation with exact non-collinear kinematics[6-7]. This incorporates the QCD scaling violations for the jet fragmentation[8-9], and it also produces multijet events. Each quark or gluon from the cascade is then fragmented into hadrons by the Field-Feyman ansatz[10], and MINBIAS beam jets with the correct energies are added.

DRELLYAN simulates Drell-Yan processes[11], including the production and decay of a virtual γ, $W^{\pm}$, or Z^0. ISAJET includes both the standard Drell-Yan cross section with zero transverse momentum and a phenomenological model with non-zero q_T. The latter is based on the standard lowest order QCD cross sections[12] for $q + \bar{q} \to W + g$ and $g + q \to W + q$. A Q^2-dependent cutoff of the singularity at $q_T = 0$ is made to reproduce approximately the results of Parisi and Petronzio[13]. This prescription is not well justified theoretically, but it gives reasonable results for all q_T.

The following sections describe in more detail the assumptions used in generating MINBIAS, TWOJET, and DRELLYAN events.

For each ISAJET run the user selects the energy and the number of events to be generated, the reaction type, any desired limits on the jet momenta or types, and various other optional parameters. Events are then generated with uniform weights, and for each event the particles and their momenta are written onto the output tape. The total cross section for the run is also calculated to provide the overall normalization. The user can analyze this output with any standard histogramming package.

The cross sections for the production of new particles in hadronic reactions are typically quite large. The problem is to assess the backgrounds, and this usually requires generating many events. Hence an effort has been made to use fairly efficient algorithms in ISAJET. Depending on the parameters, each event typically requires 20-50 ms on a Control Data 7600 computer.

MINBIAS Events

MINBIAS events simulate the total inelastic cross section, i.e., a minimum bias trigger. The multiplicity distribution observed at the SPS Collider[3] for such a trigger agrees very well with the KNO scaling distribution[1] seen at lower energies[2]. This implies that the multiplicity fluctuations are large,

$$\langle n^2\rangle - \langle n\rangle^2 \sim \langle n\rangle^2 .$$

Furthermore, an event with high multiplicity in the central region usually has high multiplicity at smaller angles. These observations imply the existence of substantial long-range correlations. However, most pictures of multiparticle production -- including the multiperipheral or Regge model[14], the Field-Feynman jet model[10], and the QCD string picture[15] -- are based on the idea of short-range correlations and give essentially a Poisson multiplicity distribution with

$\langle n^2\rangle - \langle n\rangle^2 \sim \langle n\rangle$.

A way of obtaining long-range correlations from a fundamentally short-range model is provided by cut Reggeon field theory[16]. In this picture the basic multiparticle production mechanism is described by a simple Regge pole, the Pomeron, which can be thought of as a ladder graph and has only short-range correlations. Unitarity in the t channel then requires that multi-Pomeron graphs be included. The s channel discontinuities of these graphs can be analyzed by noting that a cut passing through only part of a Pomeron (or ladder graph) leaves a high-mass multiparticle state hanging from a single line. Since obtaining a simple Regge pole from a ladder graph requires a strong p_T cutoff, such a cut is small. Thus each Pomeron must be cut either completely or not at all. In particular the two-Pomeron graph in Fig. 1

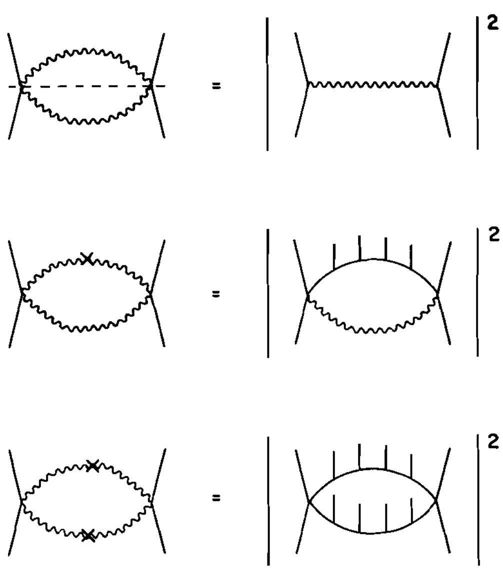

Fig. 1: The cuts of the two-Pomeron graph.

has cuts through 0, 1 or 2 Pomerons, giving respectively elastic scattering and diffractive events, absorptive corrections to average multiplicity events and events with twice the average multiplicity. A detailed analysis[16] shows that the relative weights of these cuts are respectively +1: -4: +2. In any case, all have cross sections of order $\sigma_{elastic}$ so the multiplicity fluctuations are large.

A simplified version of cut Reggeon field theory is implemented in ISAJET. For each event the number n of cut Pomerons is selected according to

$$P_n = (1 + 4.0\ n^2)\ e^{-1.8n},$$

chosen so that the resulting multiplicity distribution agrees with the data. Once n is selected, the beam jet in each direction is treated independently. Its momentum is divided among a leading $1/2^+$ or $3/2^+$ baryon and the n cut Pomerons, all flat in x_F. To include diffractive events, a gap in x_F is cut in one of the Pomerons with a probability $P_{gap} = 0.3$, and the extra momentum is added to the leading baryon. Then hadrons are generated for each half of each cut Pomeron.

The hadronization procedure uses a modified version of the Field-Feynman algorithm[10]. At each step a $q\bar{q}$ pair is generated with

$$u : d : s = 0.46 : 0.46 : 0.08,$$

giving the right K/π ratio in the central region, and with the quantum number flow shown in Fig. 2.

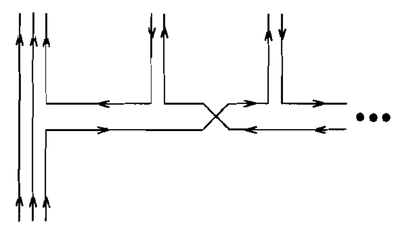

Fig. 2: The quantum number flow for MINBIAS events.

A 0^- or 1^- meson is formed carrying a fraction x of the remaining momentum, with

$$\frac{dN}{dx} = f(x) = 1 - a + a(b + 1)(1 - x)^b$$

$$a = 0.9$$

$$b = 1.0 + 0.2\ \ell n\left(\frac{\sqrt{s}}{60\ \text{GeV}}\right) .$$

Baryon pair production is ignored. The energy dependence of f(x) reproduces the observed rise of the rapidity plateau. (In the language of Reggeon field theory it corresponds to a more complicated Pomeron than a simple pole, presumably generated by Pomeron interactions.) The transverse momenta are selected according to

$$\frac{dN}{dp_T^2} = \frac{A}{(1 + bp_T^2)^4}\ , \quad \langle p_T\rangle = .35\ \text{GeV}.$$

This approximates an exponential for $p_T < 2$ GeV and has a long tail. The whole procedure is repeated until all the momentum has been used.

While the algorithm just described does have some reasonable basis, its details are obviously rather arbitrary. The general properties of the events agree fairly well with data at ISR[2] and SPS Collider[3] energies. In particular the multiplicity distribution, Fig. 3, has about the right shape,

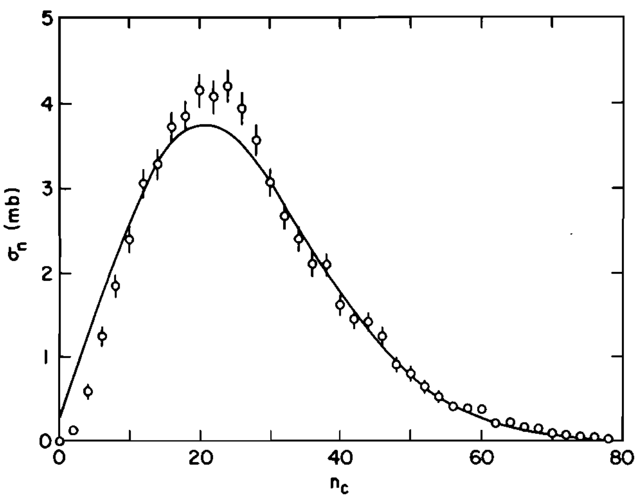

Fig. 3: The MINBIAS multiplicity distribution at $\sqrt{s}$ = 540 GeV and the KNO scaling curve.

although it is somewhat high at the average multiplicity and low at low multiplicity. More detailed properties, especially the short-range correlations and the distributions for p_T > 1-2 GeV, have not been examined.

TWOJET Events

TWOJET events simulate the production of high-p_T hadrons and also the associated production of heavy quarks. In perturbative QCD these processes are described to lowest order by the various two-body parton (quark or gluon) cross sections[4-5],

$$q + q \to q + q, \quad q + g \to q + g, \quad g + g \to q + \bar{q}\ , \ \ldots$$

multiplied by the appropriate structure functions. Each outgoing parton fragments into a jet of hadrons, so to this order each event contains two high-p_T jets plus the beam jets. Higher order QCD processes produce extra gluons or quark-antiquark pairs and so extra jets. If all the partons are well separated in phase space, then the multijet cross sections are higher order in $\alpha_s(Q^2)$. However, if two partons are collinear, then their matrix element is singular, and a correction of order $\alpha_s(Q^2)\ell n\ Q^2$ results. The sum of such terms builds up the scaling violations in the structure and jet fragmentation functions.

Two different approaches have been adopted to handle the higher order contributions in QCD Monte Carlo programs. One approach[17-18] is to use the exact cross sections up to a given order in $\alpha_s(Q^2)$ and to make a cutoff to remove the collinear singularities. This treats the multijet events properly over the whole phase space, but it is limited to just a few jets. The other approach[6-7] is to retain only the singular part of the cross section but to use exact, non-collinear kinematics. This is known as the leading pole approximation. It makes possible the inclusion of an arbitrary number of jets, but the matrix element for widely separated jets is only approximate. In general the second approach seems more suitable for very high energies, and therefore it has been adopted in ISAJET.

TWOJET events are generated in several steps. First, the jet momenta are selected according to the leading-log QCD cross section. Kinematic limits and jet types can be selected by the user. Next, each of the outgoing jets is evolved into an ensemble of partons using the leading pole approximation. This produces the leading-log scaling violations[8-9] and jet broadening, and it also yields multijet events. The corresponding evolution of the incoming partons is not included except for the QCD scaling violations in the structure functions. Then each parton is fragmented into hadrons using the Field-Feynman ansatz[10]. Finally, beam jets with the proper momenta are added using the MINBIAS algorithm.

Jet Cross Section

While interactions with spectator quarks cause complications[19], it seems likely that high-p_T hadronic processes can be calculated systematically in QCD[20]. To leading order the jet cross section is given by a sum of the two-body parton cross sections multiplied by the appropriate structure functions. In this approximation the two jets balance p_T exactly, so the cross section depends on three variables[21-22]. If s', t', u' are the standard invariants for the parton-parton scattering and y' is the rapidity of its center of mass, then

$$\left.\frac{d\sigma}{ds'dt'dy'}\right|_{pp\to k\ell} = \frac{1}{s}\sum_{ij}\left.\frac{d\sigma}{dt'}\right|_{ij\to k\ell} f_i(x_1,Q^2)f_j(x_2,Q^2)$$

where the incoming momentum fractions are

$$x_1 = \left(\frac{s'}{s}\right)^{1/2} e^{y'}, \qquad x_2 = \left(\frac{s'}{s}\right)^{1/2} e^{-y'}$$

and Q^2 is chosen to be

$$Q^2 = \frac{2s't'u'}{s'^2 + t'^2 + u'^2}.$$

The effective coupling constant is

$$\alpha_s(Q^2) = \frac{1}{b_o\ \ell n(Q^2/\Lambda^2)}\ , \quad b_o = \frac{33 - 2n_f}{12\pi}$$

where Λ is the QCD scale parameter. The parton cross sections are computed to lowest order in QCD perturbation theory[4] treating the quarks and gluons as physical particles, e.g., for $q_1 + q_2 \to q_1 + q_2$

$$\frac{d\sigma}{dt'} = \frac{\pi\alpha_s^2}{s'^2}\ \frac{4}{9}\left(\frac{s'^2 + u'^2}{t'^2}\right).$$

Masses are neglected except for $b + \bar{b}$ and $t + \bar{t}$ production[23], and the heavy quark content of the proton is assumed to be small.

The structure functions are related to deep inelastic scattering by

$$\nu W_2(x,Q^2) = \sum_i e_i^2\ f_i(x,Q^2).$$

The parametrization of Baier et al.[24] is used. It is derived from the deep inelastic data plus the leading-log QCD scaling violations and is generally in agreement with all existing data.

A more useful set of variables than s', t', y' is p_T^2, y_1, y_2, where p_T is the transverse momentum of either jet and $y_i = -\ln\tan\theta_i/2$ is a pseudorapidity. Then

$$\frac{d\sigma}{dp_T^2\ dy_1 dy_2} = s'\ \left(\frac{p_1}{E_1}\right)\ \left(\frac{p_2}{E_2}\right)\ \frac{d\sigma}{ds'dt'dy'}$$

This cross section varies rapidly as a function of p_T^2. To generate events efficiently, an envelope

$$\frac{d\sigma}{dp_T^2 dy_1\ dy_2} < F(p_T) = A\ p_T^{-b}$$

is found for each run. Then for each event p_T is generated according to $F(p_T)$, and uniformly weighted events are produced by rejecting an event if its QCD cross section is less than a random number times $F(p_T)$. The weighted sum of all events is used to determine the integrated jet cross section for the run.

Jet Fragmentation

In the parton model the two high-p_T jets would be fragmented into hadrons with limited transverse momentum with respect to the jet axis. Higher order QCD effects modify this picture, allowing multijet events. The most important configurations are those in which partons are collinear[6-7]. Then the matrix element is singular, and a term of order $\alpha_s(Q^2)\ln Q^2$ results. Such terms cannot be ignored; indeed they are responsible for scaling violations.

In ISAJET the higher order corrections to the final jets are treated in the leading pole approximation[6-7]. This involves keeping only the singular part of the matrix element but using exact non-collinear kinematics. For nearly collinear events (which experimentally would be called a single jet) this should be a good approximation. For widely separated jets the kinematics are treated properly but the matrix element is only qualitatively correct[25]. The corresponding corrections to the initial partons are not included except for the scaling violations in the structure functions. Such terms should not be important for the appearance of a single jet, but they will affect the balance between the jets and the total transverse energy distribution[26].

In the leading pole approximation there are no interference terms. Hence the results must be equivalent to a classical evolution -- described only by probabilities -- of a highly virtual parton into a shower of partons[27]. Three types of branching are allowed in this evolution: $q \to q + g$, $g \to g + g$, and $g \to q + \bar{q}$. The probability that a parton i of mass t will branch into j + k is given by

$$\frac{\alpha_s(t)}{2\pi t}\ P_{i\to jk}(z)$$

where $P_{i\to jk}$ is the appropriate Altarelli-Parisi function[27],

$$P_{q\to qg}(z) = \frac{4}{3}\left[\frac{1 + z^2}{1 - z}\right]_+ ,$$

$$P_{g\to gg}(z) = 6\left[\frac{1 - z + z^2}{z(1 - z)}\right]_+ ,$$

$$P_{g\to q\bar{q}}(z) = \frac{1}{2}\left[z^2 + (1 - z)^2\right] ,$$

and z is the momentum fraction

$$z = \frac{E_j + p_j}{E_i + p_i}$$

in the parton-parton center of mass.

Since the partons are massless, an infrared cutoff must be made to prevent an infinite cascade. The simplest cutoff would be to assume that any parton with $z < z_c$ could not be resolved and was included in the nonperturbative part of the model. Then the factorized structure leads directly to a simple expression for the probability $\Pi_i(t,t')$ that a parton i of mass t will evolve to mass t' emitting no resolvable partons[6-7]:

$$\Pi_i(t,t') = \left[\frac{\alpha_s(t)}{\alpha_s(t')}\right]^{\frac{2}{b_o}\gamma_i(z_c)}$$

$$\gamma_i(z_c) = \sum_{jk}\int_{z_c}^{1-z_c} dz\ P_{i\to jk}(z).$$

From $\Pi_i(t,t')$ the distribution of the t' at which the first resolvable radiation occurs can be readily obtained.

A cutoff at fixed z_c is not physically reasonable. Instead, the cutoff should be made at a fixed mass scale $t_c = \mu_c^2$. The equivalent z_c then depends on both t and t_c,[6-7]

$$z_c = \frac{1}{2}\left[1 - \left(1 - \frac{4t_c}{t}\right)^{1/2}\right],$$

so the probability for emitting no resolvable radiation is no longer simple. Therefore an iterative procedure is used:

(1) Calculate $\Pi_i(t,t')$ using a fixed z_c appropriate to the initial t. (This minimizes z_c and so maximizes the probability of radiation.) Use $\Pi_i(t,t')$ to generate the t' at which the first radiation occurs.

(2) Similarly generate t_1 and t_2 for $t' \to t_1 + t_2$, starting both at t'.

(3) Generate z according to the appropriate $P_{i\to jk}(z)$. If z is kinematically allowed, accept it. Otherwise, discard t_1 and t_2 and return to (1).

(4) Continue until all partons reach t_c.

The main point to be realized from this discussion is that while the parton cascade is based on QCD, many of the details are arbitrary.

Once the partons have been evolved to μ_c, they must be turned into hadrons. The procedure for doing this is purely phenomenological. The most ambitious scheme[7] is to take $\mu_c \sim 1$ GeV and to use a trivial hadronization model such as phase space. A less ambitious possibility[7] is to take a larger value of μ_c and to use the Field-Feynman ansatz to generate a jet of hadrons for each parton. This is done in ISAJET. The fragmentation is performed in the parton-parton center of mass, and transverse momenta are generated according to

$$\frac{dN}{dp_T^2} = \frac{A}{(1 + bp_T^2)^4}, \quad \langle p_T \rangle = .35 \text{ GeV}.$$

Baryon pair production is ignored. The values of Λ and μ_c are correlated with each other and depend on the hadronization scheme[7]. A reasonable fit to the PETRA data is obtained from ISAJET with

$$\Lambda = .1 \text{ GeV}, \quad \mu_c = 7. \text{ GeV}.$$

Heavy quarks require some additional discussions. Relativistic kinematics suggest that as the quark mass increases the heavy quark meson should carry on increasing fraction of the quark momentum[28]. The limited data on c quark fragmentation is consistent with a flat x distribution for D mesons[29]. ISAJET therefore uses for heavy quark fragmentation

$$\frac{dN}{dx} = f(x) = (p + 1)\, x^p,$$

$$p = 0 \text{ for c}, \quad p = 2 \text{ for b}, \quad p = 4 \text{ for t}.$$

For charm decays the measured branching ratios[30] plus the π^0 modes estimated from statistical isospin weights[31] account for 69% of the D^+ decays and 49% of the D^0 ones. The rest are constructed from high multiplicity modes, and the F^+ decays are guessed from phase space[31]. For b and t mesons the heavy quarks are decayed into lighter ones, which are fragmented using the jet algorithm.

Experimental Test

Experiment R807 at the CERN ISR has recently compared[32] experimental data obtained from a trigger on transverse energy in a solid angle $\Delta\Omega = 1.7$ sr with a combination of TWOJET and MINBIAS events generated by ISAJET. The observed thrust and related distributions agree very well with the predictions. Furthermore, the jet cross sections obtained agree with the QCD predictions within significantly less than a factor of two. Given the many uncertainties in the model, including the jet fragmentation, the gluon structure function, and higher order QCD effects, agreement at this level must be regarded as fortuitous. Nevertheless, the data do suggest that high-p_T hadronic processes may be correctly described by perturbative QCD.

DRELLYAN Events

DRELLYAN events simulate the production and decay of a virtual γ, $W^\pm$, or Z^0 (generically called a W) in the standard model[33]. In perturbative QCD[20] the W cross section integrated over its transverse momentum q_T is calculable and is given to leading order by the Drell-Yan formula. The cross section for $q_T \sim Q$, where $Q = (q^2)^{1/2}$ is the W mass, is also calculable[12]. However, the dominant q_T region, and that which controls the shape of the Jacobean peak from $W^\pm \to e^\pm\nu$, is $q_T \ll Q$. Simple perturbation theory cannot be used for the q_T dependence in this region.

The first analysis of the region $q_T \ll Q$ was given by Dokshitser, D'Yakanov, and Troyan[34]. Summing up the leading series of logarithms, namely powers of $\alpha_s(q_T^2)\ \ell n^2\ (Q^2/q_T^2)$, they found that the probability of emitting no gluons with $k_T > q_T$ is suppressed by the square of a Sudakov[35] form factor

$$S = \exp\left\{-\frac{4}{3\pi}\,\alpha_s(q_T^2)\ \ell n^2\ (Q^2/q_T^2)\right\}.$$

This vanishes faster than any power of Q^2. The physical reason for this result is that since the gluon is massless, the probability for radiating no gluons is zero (just like the probability for a scattered electron to emit no photons).

Parisi and Petronzio[13] observed that such a Sudakov suppression makes it possible to calculate the W cross section even for $q_T = 0$. The reason is that a low-q_T W must be accompanied by several gluons with substantial transverse momenta k_{iT} but with

$$\sum_i \vec{k}_{iT} = -\vec{q}_T .$$

These k_{iT} remove any sensitivity to the primordial transverse momenta of the quarks. Even though the gluons carry substantial k_{iT}, they are still soft compared to Q. Thus to leading-log accuracy it is sufficient to make a soft gluon approximation (like the soft-photon approximation used for QED radiative corrections). The result is[13]

$$\frac{1}{\sigma}\frac{d\sigma}{dq_T{}^2} = \frac{1}{4\pi}\int d^2b\; e^{-iq_T \cdot b}\; e^{\Delta(b)}$$

$$\Delta(b) = \frac{4}{3\pi^2}\int d^2k_T\left[e^{ib\cdot k_T} - 1\right]\alpha_s(k_T{}^2)\,\frac{\ln\,(Q^2/k_T{}^2)}{k_T{}^2}$$

This predicts a flat region at low q_T with a width at half height

$$\Delta q_T \approx 3 \text{ GeV for } Q = m_Z$$

and a high q_T perturbative QCD tail.

While the Parisi-Petronzio result is very reasonable physically, the calculation is based only on the summation of a leading-log series with alternating signs. Collins and Soper[36] have reported progress in proving that the form of the result is preserved when non-leading terms are included. Nevertheless, the result seems less reliable than standard perturbative QCD calculations; comparison with experiment will be interesting.

The Parisi-Petronzio calculation involves rather delicate cancellations, and it uses approximations which do not naturally match onto the high-q_T perturbative region. Therefore, a simpler although theoretically less satisfactory model is used in ISAJET. This model is based on the perturbative QCD cross section for the production and decay of a W via

$$q + \bar{q} \to W + g \text{ and } g + q \to W + q.$$

For large q_T this cross section is presumably correct, but at low q_T it behaves like $1/q_T{}^2$. A Q^2-dependent cutoff of this singularity is made,

$$\frac{1}{q_T{}^2} \to \exp\left\{-\frac{1}{2}\ln\left[q_T{}^4 + \mu^4(Q)\right]\right\},$$

$$\mu^2(Q) = \mu_0{}^2\left(\frac{Q}{1\text{ GeV}}\right)^{\nu},\ \mu_0{}^2 = .075\text{ GeV}^2,\ \nu = 1.2,$$

with the parameters adjusted to give about the same shape at low q_T as the Parisi-Petronzio formula for $\sqrt{s} = 800$ GeV. The jets from the W and the recoil jet are fragmented into hadrons as in TWOJET, and MINBIAS beam jets with the correct energies are added.

The ISAJET model does not satisfy the requirement of perturbative QCD that the cross section integrated over q_T be given by the Drell-Yan formula. The agreement is not bad; for $\sqrt{s} = 800$ GeV,

$$\sigma = 1.4\ \sigma_{\text{Drell-Yan}} \quad \text{for } Q = m_Z,$$

$$\sigma = 2.0\ \sigma_{\text{Drell-Yan}} \quad \text{for } Q = 10\text{-}20 \text{ GeV}.$$

Higher order QCD corrections increase the cross section by a similar amount. The rapidity distribution of the W is likewise similar but not identical to the Drell-Yan distribution. ISAJET can also generate events with the standard Drell-Yan cross section and $q_T = 0$, and the user is strongly urged to compare the two models whenever appropriate. For $\sqrt{s} = 63$ GeV a larger value of the cutoff $\mu^2(Q)$ is needed to fit the q_T distribution because the energy required for the jet is more significant.

Perhaps the most important defect of the ISAJET model is that the q_T of the W is balanced by only a single jet, while the Parisi-Petronzio calculation is based on multiple gluon emission. These extra gluons contribute a significant amount of transverse energy, which should be observable experimentally[37].

Single lepton distributions from $W^\pm \to e^\pm\nu$ and the backgrounds including semileptonic decays of heavy quarks have been calculated using ISAJET and published previously[38]. The transverse momentum of the W smears the Jacobean peak from $W^\pm \to e^\pm\nu$ only slightly, although it adds a long tail with $p_T \gg m_W/2$. The Jacobean peak is still well above all known backgrounds of prompt leptons.

DRELLYAN might also be used to simulate the production of J/ψ, Υ, and heavier vector mesons. The resonance cross sections are approximately proportional to the continuum, with[39]

$$\left.\frac{d\sigma}{dy}\right|_{\text{resonance}} \approx R_0\Gamma_{ggg}\left.\frac{d\sigma}{dMdy}\right|_{\gamma\to e^+e^-},$$

$$R_0 = 1.5\times 10^7$$

where Γ_{ggg} is the theoretical three-gluon width[40],

$$\Gamma_{ggg} = \frac{10}{81}\,\frac{(\pi^2-9)}{\pi\alpha^2 e_Q^2}\,\alpha_s^3\,(M^2)\,\Gamma_{\ell\bar{\ell}}\ .$$

Implementation

ISAJET is written in FORTRAN 4 for a Control Data 7600 computer. The code is approximately 7000 lines long. While ANSI standards have not been strictly followed, conversion to other computers is relatively straightforward. A copy of the program and of detailed instructions for using it is available upon request from the authors. Please specify the required tape format and if possible furnish a blank tape.

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