Jimmy4: Multiparton Interactions in Herwig for the LHC

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Abstract

The Jimmy package allows the simulation of multiple parton scattering in hadron-hadron, photon-hadron and photon-photon collisions, in the context of the Herwig general purpose Monte Carlo program. A new version is described which allows the simulation of underlying events for a much wider range of scattering processes, important for the LHC as well as other applications. The implementation of the model, and its adjustable parameters, are discussed.

1 Introduction

In high energy physics, the most interesting component of high energy hadronic collisions is described in terms of short-distance interactions between the quarks and gluons (partons) which make up the hadron. The quarks and gluons are treated as asymptotically free, that is, the fact that they are confined in hadrons is often neglected. The distribution of partons in the hadron is extracted from measurements of standard processes such as deep inelastic scattering, and is used to predict cross sections for more exotic processes. However, the effects of the "remnant" of the hadron, *i.e.* those parts of the proton which do not participate in the short-distance interaction, can be significant. Further interactions between the remnant may lead to activity in the final state which can disrupt the measurement of the short distance process of interest. The description of such effects is beyond the scope of perturbative quantum chromodynamics (pQCD). However, perturbative ideas combined with other assumptions can be used to build models of such effects. Jimmy[1] is one such model. Since many analyses rely upon jet rates, jet energies and particle multiplicities, all of which may be affected by remnant-remnant interactions, the ability to model and control such effects at hadron colliders is likely to be a significant factor in determining the eventual precision and discovery reach of such experiments. In this paper we present a update of Jimmy which allows the model to efficiently simulate pp events at LHC energies. Some expectations of and uncertainties in the model, in terms of the final state and the total cross section, are presented.

2 Eikonal Treatment of Multiparton Interactions

The basic ideas of the eikonal model implemented in Jimmy are discussed in a previous publication [1]. Essentially the model derives from the observation that for partonic scatters above some minimum transverse momentum, $\hat{p}_T^{\min}$, the values of the hadronic momentum fraction x which are probed decrease as the centre-of-mass energy, s, increases, and since the proton structure function rises rapidly at small x [2], high parton densities are probed. Thus the perturbatively-calculated cross section grows rapidly with s. However, at such high densities, the probability of more than one partonic scattering in a single hadron-hadron event may become significant. Allowing such multiple scatters reduces the total cross section, and increases the activity in the final state of the collisions.

The Jimmy model assumes some distribution of the matter inside the hadron in impact parameter (b) space, which is independent of the momentum fraction, x. The multiparton interaction rate is then calculated using the cross section for the hard subprocess, the conventional parton densities, and the area overlap function, $A(b)$.

3 Implementation of Multiple Scattering Cross Sections in Jimmy

The exact formula for implementing multiple scattering of several types is complicated by the fact that all cross sections for hard subprocesses eikonalize. This does not easily fit into the current JII framework, since the cross section for all scattering types as a function of $\sqrt{s}$ would be needed at initialization time. For processes in which $\sqrt{s}$ varies, like photoproduction and $\gamma\gamma$ collisions in $\mathrm{e}^{\pm}\mathrm{e}^{-}$, this is never explicitly calculated. Even for fixed $\sqrt{s}$, like hadron–hadron collisions, the information is not available at initialization time.

Rather than completely rewriting Jimmy, in this note we show an approximate formula, valid when all cross sections except QCD $2 \to 2$ are small, which is true in most cases of interest. In particular, we ensure that it is correct both for two different scattering types (eg the underlying event in Drell–Yan events) and multiple scatters of one type with a selection criterion placed on at least one scatter (e.g. the underlying event in high-p_T jet events).

We begin by recapping the formalism of standard Jimmy, then show how to extend it to multiple collision types. The resulting formulae can be easily inserted into Jimmy.

3.1 Standard Jimmy

The starting point for the multiple scattering model is the assertion that, at fixed impact parameter, b, different scatters are independent, so obey Poission statistics. It is then straightforward to show that the cross section for events in which there are n scatters of type a is given by

$$\sigma_n = \int \mathrm{d}^2b \, \frac{(A(b)\sigma_\mathrm{a})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_\mathrm{a}}, \tag{1}$$

where σ_a is the parton–parton cross section and $A(b)$ is the matter density distribution, obeying

$$\int \mathrm{d}^2b \, A(b) = 1. \tag{2}$$

It is straightforward to show that the inclusive cross section for scatters of type a is σ_a and the total cross section for events with at least one scatter of type a is

$$\sigma_\mathrm{tota} = \int \mathrm{d}^2b \left(1 - \mathrm{e}^{-A(b)\sigma_\mathrm{a}}\right). \tag{3}$$

These can then be combined to give the probability that an event has exactly n scatters of type a, given that it has at least 1 scatter of type a,

$$P_n = \frac{\int \mathrm{d}^2b \, \frac{(A(b)\sigma_\mathrm{a})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_\mathrm{a}}}{\int \mathrm{d}^2b \, (1 - \mathrm{e}^{-A(b)\sigma_\mathrm{a}})}, \qquad n \geq 1. \tag{4}$$

This is the probability distribution pretabulated (as a function of $\sqrt{s}$) by Jimmy.

Jimmy's procedure can then be summarized as:

1. Give all events cross section σ_tota.

2. In a given event, choose n according to Eq. (4).

3.2 Correct Result for Different Scattering Types

If we consider two distinct scattering types, a and b, with cross sections $\sigma_{\rm a}$ and $\sigma_{\rm b}$, then it is straightforward to write down the cross section for events with n scatters of type a and m of type b, since each is given by an independent Poisson distribution,

$$\sigma_{n,m} = \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\rm a})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\rm a}} \, \frac{(A(b)\sigma_{\rm b})^m}{m!} \, \mathrm{e}^{-A(b)\sigma_{\rm b}}. \tag{5}$$

Using this result, we can easily construct the equivalent result for the case in which b is a subset of a (so that $\sigma_{\rm b} \le \sigma_{\rm a}$). If there are n scatters of type a, m of which are also of type b, then $n-m$ of them are not of type b (with cross section $\sigma_{\rm a}-\sigma_{\rm b}$). We therefore have

$$\sigma_{n,m} = \int \mathrm{d}^2 b \, \frac{(A(b)\,(\sigma_{\rm a}-\sigma_{\rm b}))^{n-m}}{(n-m)!} \, \mathrm{e}^{-A(b)(\sigma_{\rm a}-\sigma_{\rm b})} \, \frac{(A(b)\sigma_{\rm b})^m}{m!} \, \mathrm{e}^{-A(b)\sigma_{\rm b}}. \tag{6}$$

In principle these could be implemented into a Jimmy-like algorithm, to pretabulate these cross sections as functions of $\sqrt{s}$, but this is not easy within the existing framework, so we seek an alternative formulation. First it is useful to prove that standard Jimmy does work correctly (if inefficiently) for the distribution of high-p_T scatters.

3.3 High-p_T Scattering in Standard Jimmy

It is useful to check that the distribution of number of high-p_T scatters is given correctly by Jimmy. We do this by considering the cross section for scatters of type b, which are a subset of scatters of type a. The cross section Jimmy produces for events with n scatters of type a of which m are also of type b is then given by Jimmy's cross section for σ_n multiplied by the binomial distribution for m scatters of type b, given n of type a,

$$P(m|n) = \frac{n!}{m!(n-m)!} \left(\frac{\sigma_{\rm b}}{\sigma_{\rm a}}\right)^m \left(1-\frac{\sigma_{\rm b}}{\sigma_{\rm a}}\right)^{n-m}. \tag{7}$$

It is perhaps useful to point out that as $\sigma_{\rm b} \to \sigma_{\rm a}$, $P(m|n) \to \delta_{mn}$.

We therefore obtain

$$\sigma_{n,m} = \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\rm a})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\rm a}} \quad \frac{n!}{m!(n-m)!} \left(\frac{\sigma_{\rm b}}{\sigma_{\rm a}}\right)^m \left(1-\frac{\sigma_{\rm b}}{\sigma_{\rm a}}\right)^{n-m}. \tag{8}$$

After a little rearranging, it is clear that this is identical to the correct result, Eq. (6).

If we then sum over all n for fixed m, we can easily check that we obtain

$$\sigma_m = \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\rm b})^m}{m!} \, \mathrm{e}^{-A(b)\sigma_{\rm b}}, \tag{9}$$

the correct result.

It is interesting to note that Jimmy's procedure, despite integrating over b once-and-for-all at initialization time, correctly reproduces the correlation between different scatters, whose physical origin is a b-space correlation: small cross section scatters are more likely to come from events with a large overlap and hence be accompanied by a larger-than-average number of large cross section scatters. We can illustrate this by calculating the average number of scatters of type a for events with at least one scatter of type b,

$$\langle n|m \geq 1\rangle = \frac{\sum_{m\geq 1,n} n\,\sigma_{n,m}}{\sum_{m\geq 1,n}\sigma_{n,m}} \tag{10}$$

$$= \frac{\int \mathrm{d}^2b\left(\left(1-\mathrm{e}^{-A(b)\sigma_\mathrm{b}}\right)A(b)(\sigma_\mathrm{a}-\sigma_\mathrm{b})+A(b)\sigma_\mathrm{b}\right)}{\int \mathrm{d}^2b\,(1-\mathrm{e}^{-A(b)\sigma_\mathrm{b}})}. \tag{11}$$

We plot this function below, in the simple analytical model described later. It is clear that there is a correlation, and that it saturates for $p_T \gtrsim 10$ GeV.

3.4 Two Different Scattering Types

We consider the possibility that there are two different scattering types, described by Eq. (5), but that σ_b is small enough that events with more than one scatter of type b are negligible. The probability distribution for number of scatters of type a, n, in events with at least one of type b is given by

$$P(n|m \geq 1) = \frac{\int \mathrm{d}^2b\,\frac{(A(b)\sigma_\mathrm{a})^n}{n!}\,\mathrm{e}^{-A(b)\sigma_\mathrm{a}}\left(1-\mathrm{e}^{-A(b)\sigma_\mathrm{b}}\right)}{\int \mathrm{d}^2b\,(1-\mathrm{e}^{-A(b)\sigma_\mathrm{b}})}, \qquad n \geq 0. \tag{12}$$

Since σ_b is small, we can expand the exponentials and obtain

$$P(n|m \geq 1) \approx \int \mathrm{d}^2b\,A(b)\,\frac{(A(b)\sigma_\mathrm{a})^n}{n!}\,\mathrm{e}^{-A(b)\sigma_\mathrm{a}}, \qquad n \geq 0. \tag{13}$$

Note that this expression is independent of σ_b. It is therefore ideal for implementing into the current Jimmy structure.

It is useful to rewrite this equation, as follows. We redefine n to be the total number of scatters, including the one of type b (i.e. "new n"="old n"+1) and rewrite, to obtain

$$P_n \approx \frac{\int \mathrm{d}^2b\,n\,\frac{(A(b)\sigma_\mathrm{a})^n}{n!}\,\mathrm{e}^{-A(b)\sigma_\mathrm{a}}}{\sigma_\mathrm{a}}, \qquad n \geq 1. \tag{14}$$

Note the similarity with Eq. (4), making this form even easier to implement into Jimmy. All that has to be done is to multiply the integrand in the numerator by a combinatorial factor of n and to replace the eikonalized cross section in the denominator, σ_tota, by the inclusive cross section σ_a.

Note however that these differences are important and Eq. (14) yields significantly different results to Eq. (4), which was used in previous versions of Jimmy. In particular, making a small-σ_a expansion of each, we obtain a mean number of additional scatters of $\sim \sigma_\mathrm{a}\int \mathrm{d}^2b\,A(b)^2$ from the correct formula and $\sim \frac{1}{2}\sigma_\mathrm{a}\int \mathrm{d}^2b\,A(b)^2$ from the old one, meaning that it underestimated the amount of underlying event activity by a factor of 2. We have checked numerically that this factor gets reduced somewhat for a realistic amount of eikonalization, but it is still significant (e.g. in our simple analytical model, old Jimmy would predict an average of one additional scatter per event while the correct formula predicts 1.6).

The Monte Carlo implementation of this procedure is straightforward:

1. Give all events cross section $\sigma_{\rm b}$.
2. In a given event choose n according to Eq. (14).
3. Generate 1 scatter of type b and $n-1$ of type a.

3.5 High-p_T Scattering – First Attempt

We now do the same job, but for the case in which b is a subset of a. We calculate the probability for n scatters of type a, at least one of which is also of type b,

$$P(n|m \geq 1) = \frac{\int \mathrm{d}^2 b \left(\frac{(A(b)\sigma_{\rm a})^n}{n!} - \frac{(A(b)(\sigma_{\rm a}-\sigma_{\rm b}))^n}{n!}\right) \mathrm{e}^{-A(b)\sigma_{\rm a}}}{\int \mathrm{d}^2 b \,(1-\mathrm{e}^{-A(b)\sigma_{\rm b}})}, \qquad n \geq 1. \tag{15}$$

Since $\sigma_{\rm b}$ is small, we can expand the exponential and the power in the numerator to obtain

$$P(n|m \geq 1) \approx \int \mathrm{d}^2 b \, A(b) \frac{(A(b)\sigma_{\rm a})^{n-1}}{(n-1)!} \mathrm{e}^{-A(b)\sigma_{\rm a}}, \qquad n \geq 1. \tag{16}$$

This is again independent of $\sigma_{\rm b}$. It can be rewritten as

$$P(n|m \geq 1) \approx \frac{\int \mathrm{d}^2 b \, n \frac{(A(b)\sigma_{\rm a})^n}{n!} \mathrm{e}^{-A(b)\sigma_{\rm a}}}{\sigma_{\rm a}}, \qquad n \geq 1. \tag{17}$$

That is, it is identical to Eq. (14), so the Monte Carlo implementation is also identical, namely:

1. Give all events cross section $\sigma_{\rm b}$.
2. In a given event choose n according to Eq. (14).
3. Generate 1 scatter of type b and $n-1$ of type a.

3.6 High-p_T Scattering – Improved

There is one important difference between the cases in which b is distinct from a and b is a subset of a: some of the n–1 scatters of type a could also be of type b. Although this is a small fraction of the total, it can be phenomenologically important, so it is useful to check that the distribution of number of scatters of type b is described reasonably well, within the confines of the small-$\sigma_{\rm b}$ approximation.

We can calculate this in exactly the same way as in Section 3.3. The cross section for events with m scatters of type b is given by the cross section for n scatters, multiplied by the probability that $m-1$ of the $n-1$ additional scatters are of type b, summed over n,

$$\begin{aligned} \sigma_m &= \sum_n \sigma_{\rm b} \frac{\int \mathrm{d}^2 b \, n \frac{(A(b)\sigma_{\rm a})^n}{n!} \mathrm{e}^{-A(b)\sigma_{\rm a}}}{\sigma_{\rm a}} \frac{(n-1)!}{(m-1)!(n-m)!} \left(\frac{\sigma_{\rm b}}{\sigma_{\rm a}}\right)^{m-1} \left(1-\frac{\sigma_{\rm b}}{\sigma_{\rm a}}\right)^{n-m} && (18) \\ &= \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\rm b})^m}{(m-1)!} \mathrm{e}^{-A(b)\sigma_{\rm b}}. && (19) \end{aligned}$$

This is clearly wrong (too large) by a factor of m. This is an overcounting, because we have singled out the first scattering as being special, when it is not.

Formally, this is not a problem, since we are using the small-σ_{b} limit, and in that limit the probability of having more than one collision of type b is negligible. However, as already mentioned, it is desirable to correct the algorithm, so that it also gets this cross section right, at least to leading order in σ_{b}. We can do this, by adding the following step to the algorithm:

4. If, out of the n scatters of type a, m of them are also of type b, reject the set of scatters (but keep the value of n) and regenerate them, with probability $1 - 1/m$.

Since the total fraction of sets of scatters that gets rejected is higher order in σ_{b}, the correct distribution of low-p_T scatters is retained, but since the fraction of generated sets of scatters that gets kept is $1/m$, the missing factor of $1/m$ gets introduced for high-p_T scatters.

We prefer to implement this correction slightly differently, as follows: As each scatter of type a is generated, a check is made as to whether it is also of type b. The mth scatter of type b generated so far is rejected with probability $1/(m+1)$. It is straightforward to show that the end result is identical. It will run faster though, because only individual scatters are rejected and regenerated, not whole sets of scatters.

3.7 Proof That the Proposed Algorithm is Continuous at the Boundary of b

We can check the continuity by considering scatters of type c, a subset of a, which have extremely small cross section (we think of the differential cross section, i.e. the cross section in an infinitely small bin) either in, or not, b.

If c is not a subset of b, then the cross section for events with one scatter of type c and at least one of type b is simply given by the cross section for n scatters of type a, at least one of which is of type b, times the binomial probability that one of the $n-1$ others is of type c, summed over n, with $\sigma_{\mathrm{c}} \ll (\sigma_{\mathrm{a}}, 1/A(b))$,

$$\sum_n \sigma_b \frac{\int \mathrm{d}^2 b \, n \, \frac{(A(b)\sigma_{\mathrm{a}})^n}{n!} \, \mathrm{e}^{-A(b)\sigma_{\mathrm{a}}}}{\sigma_{\mathrm{a}}} \quad (n-1) \, \frac{\sigma_{\mathrm{c}}}{\sigma_{\mathrm{a}}} = \sigma_{\mathrm{b}}\sigma_{\mathrm{c}} \int \mathrm{d}^2 b \, A(b)^2. \tag{20}$$

If c is a subset of b, then the cross section for events with one scatter of type c and at least one other of type b is simply given by the cross section for m scatters of type b, times the binomial probability that one of them is of type c, summed over $m \geq 2$, with $\sigma_{\mathrm{c}} \ll \sigma_{\mathrm{b}} \ll (\sigma_{\mathrm{a}}, 1/A(b))$,

$$\sum_{m \geq 2} \int \mathrm{d}^2 b \, \frac{(A(b)\sigma_{\mathrm{b}})^m}{m!} \quad m \, \frac{\sigma_{\mathrm{c}}}{\sigma_{\mathrm{b}}} = \sigma_{\mathrm{b}}\sigma_{\mathrm{c}} \int \mathrm{d}^2 b \, A(b)^2. \tag{21}$$

Explicit calculation shows that at higher orders in σ_{b} there is still a mismatch at the boundary, which can never be removed without an exact calculation, but provided σ_{b} is small the mismatch is small. In fact this could serve as a useful cross-check that $\sigma_{\rm b}$ is small enough for the algorithm to be reliable.

Note that the correction of Section 3.6 is essential for this agreement: without it the second equation would be a factor of 2 larger than the first.

4 Using Jimmy at the LHC

The modifications above, while not changing the physics input to the Jimmy model, make it practically useable for the first time for simulations of rare high E_T events in high energy pp or $p\bar{p}$ interactions. The tuneable parameters are those described previously [1], with the obvious exception of those parameters which only concern the photon. Those remaining are therefore the minimum transverse momentum of a hard scatter, the proton structure, and the effective radius of the proton. The appendices give details on how to adjust these parameters.

Tuning the model to data at current colliders is a large task, beyond the scope of this note, and tuning with LHC data will of course be essential - the assumptions and uncertainties in the model are such that any extrapolation to high energies cannot really be treated as a prediction, more as a physically reasonable possibility, or range of possibilities. In this section therefore, a small selection of results is presented using an *a priori* reasonable set of parameters, some of which are based on previous work tuning to data, and suggestions for further work are made.

4.1 Underlying events

The main effect of Jimmy is that the additional hard scatters increase the activity in high energy collisions. The existance of a minumum p_T cut-off, and the absence of low-t diffractive physics from Herwig, means that Jimmy cannot be used to simulate minimum-bias events. However, the cut-off can and should be rather low, and therefore low p_T events, as well as low p_T activity in high-p_T events, can be simulated.

Some work has been done looking at CDF data [6] with Jimmy [7] (as well as with a modified model [8]), and photoproduction data from HERA [**?**] has also been used along with the Tevatron data [9]. In general the results favour a minimum transverse momentum cut-off of 3 GeV and a proton radius a factor of $\sqrt{3}$ smaller than the default (see Appendix 1). They can be seen as a starting point for further work. Several results are available at the JetWeb [10] MC validation site (see for example fits 627, 714 and 720).

4.2 Total cross section

Even before the modifications described in this paper, Jimmy could be used to calculate the "hard" part of the total pp cross section, that is, the part of the cross section which is due to parton-parton scattering. In fact, calculating total cross sections for photoproduction was one of the initial motivations for the model [3].

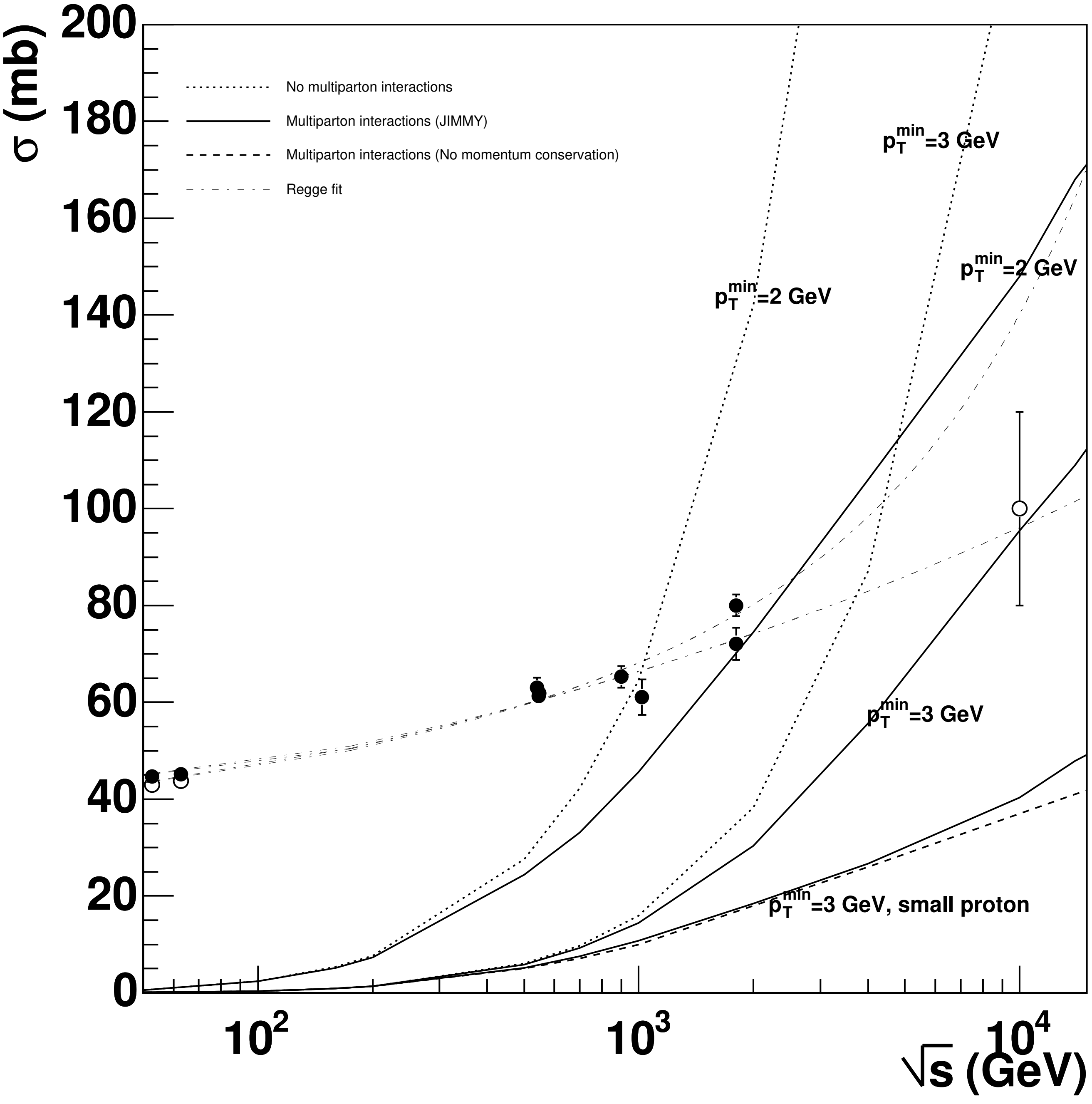

Figure 1: The total proton-(anti)proton cross section as a function of centre-of-mass energy. A selection of pp (open circles) and $p\bar{p}$ (closed circles) data [11] is shown, along with two Regge fits [4, 5] and various JIMMY calculations (see text).

Some predictions of HERWIG, both with and without multiparton interactions, are shown in Fig. 1. Several features are apparent:

- The HERWIG predictions only describe a fraction the total cross section. For $\sqrt{s} \lesssim 100$ GeV, the jet cross section is a negligible fraction of the total cross section. Thus there is a substantial soft component to the cross section at $\sqrt{s} = 100$ GeV, with an unknown energy dependence about which HERWIG and JIMMY can say nothing, and it is not possible to draw strong conclusions regarding the energy dependence of the total. Nevertheless, those predictions which lie well above the data can be excluded.

- For $\sqrt{s} \lesssim 100$ GeV, the measured pp and $p\bar{p}$ cross sections diverge, as do the Regge fits, due to pion exchange. The JIMMY predictions are dominated by the gluon and are the same for pp and $p\bar{p}$.

- The jet cross section predictions rise rapidly with $\sqrt{s}$. Those models with none of the unitarity corrections provided by multiparton interactions are already ruled out by the data for values of $\hat{p}_T^{\min} < 3$ GeV. The inclusion of multiparton interactions moderates the rise such that for $\hat{p}_T^{\min} = 3$ GeV the jet cross section remains below or consistent with the total cross section data. However, for $\hat{p}_T^{\min} = 2$ GeV the JIMMY curve is still above the cosmic-ray data. Finally, for the curve corresponding to the parameters tuned to the hadronic final state (see Section 4.1), the cross section remains well below the data. Furthermore, the enhanced unitarity corrections caused by the reduction in the proton radius lead to a gentler rise which is rather similar to the rise seen the the Regge fits [4, 5]. Since the energy dependence of the soft cross section is unknown, this may be nothing more than a coincidence. Nevertheless it is tempting to speculate that this qualitative agreement in the behaviour of the total cross section, which is achieved using paremeters tuned on completely independent data, suggests that the physical assumptions in such Eikonal models do indeed have something to do with reality.

- The proton PDF set used is CTEQ5 (LO). The rise in the cross section and rise the number of multiparton interactions are driven by the rise in the parton densities at low-x, and therefore different PDFs will in general given different results.

- The naive calculation of the multiparton interaction rate does not impose longitudinal momentum conservation, and the sum of the x values of the incoming partons can therefore be above 1. The JIMMY implementation imposes momentum conservation [1] and thus reduces the number of multiple scatters. This effect is fairly small, and is indicated in Fig. 1 for the "small proton" model.

Appendix 1: Parameters

The integer switch `JMUEO` (Underlying event option) determines the mode in which JIMMY is run. If it is set to zero, the original JIMMY will be recovered, with all its limitations. That is, all scatters have the same $\hat{p}_T^{\min}$, and the only valid process is QCD

$2 \rightarrow 2$ scattering. This is desireable if one wishes to calculate the total eikonalised jet cross section above some $\hat{p}_T^{\rm min}$. Another application for this is if one wishes to generate jets so low in p_T that is is not possible to leave a sufficently large gap between the minimum p_T of the hardest scatter and that of the secondary scatters, in which case the approximation discussed in Section 3.3 are invalid. However, in this case, the efficiency for generating jets with the original JIMMY will acceptable anyway, and `JMUEO = 0` should be used. In all other cases `JMUEO` should be left at its default value (1 for QCD $2 \rightarrow 2$, 2 otherwise - this is determined automatically by the program.

The JIMMY parameters which should be considered tuneable by the user are:

Name	Default	Explanation	Tuneable range
`PTJIM`	3.0	Minimum transverse momentum of secondary scatters	It must be above all the soft cut-offs in HERWIG. A good practical minimum is around 1 - 1.5 GeV. As it is raised, the amount of multiple scattering drops rapidly. It will be negligible in terms of underlying events for values of more than a few GeV - though the jet-pair cross section may remain significant.
`JMRAD(73)`	0.71 GeV^{-2}	Inverse proton-radius squared (μ^2 in Eq.8 of [1])	The default is based on the electromagnetic form-factor. Multiplying by a factor 0.25 - 4.0 is certainly reasonable. For antiprotons, `JMRAD(91)` should also be changed.
`PRSOF`	1.0	Probability of a soft underling event. A standard HERWIG parameter which may be used to add extra, soft particle production.	0 - 1

Appendix 2: Program Flow

Running JIMMY requires some changes to the main program flow of HERWIG. An example program is provided on the JIMMY web page [12]. Briefly, there are two initialisation routines: JIMMIN should be called immediately after HWIGIN, and sets the parameters to default values. The user then makes any changes to HERWIG or JIMMY parameters, as desired. Then the user calls the second stages of HERWIG initialisation, and in addition calls JMINIT immediately after HWEINI.

In the main event-generation loop of HERWIG, the multiple scattering routine HWMSCT(ABORT) is called after the parton cascades from the first scatter have been generated (HWBGEN). If the output parameter ABORT is return .TRUE., the event should be abandoned, for example as follows:

```
c     Loop over events.
      DO LOOP=1,MAXEV
 50      CONTINUE

C---  INITIALISE EVENT
         CALL HWUINE
C---  GENERATE HARD SUBPROCESS
         CALL HWEPRO
C---  GENERATE PARTON CASCADES
         CALL HWBGEN
C---  GENERATE MULTIPARTON INTERACTIONS
         IF (MSFLAG.EQ.1) THEN
            CALL HWMSCT(ABORT)
            IF (ABORT) GOTO 50
         ENDIF
C---  DO HEAVY QUARK DECAYS
         CALL HWDHOB
C---  DO CLUSTER HADRONIZATION
         CALL HWCFOR
C---  DO CLUSTER DECAY
         CALL HWCDEC
C---  DO UNSTABLE PARTICLE DECAYS
         CALL HWDHAD
C---  DO HEAVY FLAVOUR DECAYS
         CALL HWDHVY
C---  ADD SOFT UNDERLYING EVENT IF NEEDED
         CALL HWMEVT
C---  FINALISE EVENT
         CALL HWUFNE

         IF (IERROR.NE.0) GOTO 50

C---  Fill your histograms here.
         CALL HWANAL

      ENDDO
```

Finally, on termination, JMEFIN should be called immediately after HWEFIN.

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