**DISASTER++**

Version 1.0

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**Abstract**

DISASTER++ is a C++ class library for the calculation of (1+1) and (2+1)-jet-like quantities in deeply inelastic lepton–nucleon scattering for one-photon exchange in next-to-leading-order QCD perturbation theory. The calculation is based on the subtraction formalism. The user has access to an event record such that an arbitrary set of infrared-safe observables can be calculated in a single run. Compared to other existing universal programs, the full dependence on the number of flavours and on the renormalization and factorization scales is made explicit. An interface class providing a simple interface from C++ to existing FORTRAN programs is available. In a preliminary study DISASTER++ is compared to two other programs for various bins of the lepton variables $x_B$ and $y$, where a particular emphasis is put on different behaviours for $\xi \to 1$ of the parton densities $f(\xi)$. We find good agreement of DISASTER++ and DISENT (Version 0.1). The comparison of DISASTER++ and MEPJET (Version 2.0) leads to several discrepancies.
1 Introduction

For studies of the hadronic final state in high-energy collisions, versatile programs for the calculation of QCD corrections are required. The extraction of scale-dependent physical quantities such as the running strong coupling constant $\alpha_s (Q^2)$ and parton densities $f_i (\xi, Q^2)$ requires precise predictions in next-to-leading order of QCD perturbation theory. At the electron–proton collider HERA at DESY in Hamburg, the strong coupling constant has been measured via jet rates [1, 2]. There is also a direct fit of the gluon density $f_g (\xi, Q^2)$ [3] based on a Mellin transform method [4, 5]. Calculations for jet cross sections in deeply inelastic scattering for the case of the modified JADE scheme have been performed [6–10] and implemented in the two programs PROJET [11] and DISJET [12].

In the meantime, calculations for arbitrary infrared-safe observables in deeply inelastic scattering have become available [13, 14]. In the last few years, the technology for the calculation of QCD corrections in next-to-leading order has developed considerably. The main problem in higher-order QCD calculations is the occurrence of severe infrared singularities (they ultimately cancel for infrared-safe observables, or are absorbed into process-independent, physical distribution functions such as parton densities and fragmentation functions). There are explicit algorithms available which permit the calculation to be done in a “universal” way: the infrared singularities are subtracted such that arbitrary infrared-safe observables can be calculated numerically. In principle, all existing algorithms are variations on a common theme, namely the interplay of the factorization theorems of perturbative QCD and the infrared-safety of the observables under consideration. There are two different ways to achieve the separation of divergent and finite contributions: the phase-space-slicing method [13] and the subtraction method [16]. Both methods have their merits and drawbacks.

(a) The phase-space-slicing method relies on a separation of singular phase-space regions from non-singular ones by means of a small slicing parameter $s \to 0$. The divergent parts are evaluated under the assumption that terms of $O(s (\log s)^n)$ can be dropped. The analytically evaluated phase-space integrals yield terms of the form $(\log s)^m$, which explicitly cancel against equivalent terms of opposite sign from a numerically performed phase-space integration. The simplicity of this scheme is obvious. The main problem is the residual dependence on the technical cut parameter $s$ (in practice the limit $s \to 0$ is not checked for every observable, but it is assumed that a fixed small value will be sufficient). Moreover, the numerical cancellation of the logarithmic terms by means of a Monte-Carlo integration is delicate. There is a calculational scheme available for the determination of the explicit phase space integrals over the singular regions [17]. For initial and final-state hadrons this scheme moreover requires the introduction of so-called crossing functions [18], to be evaluated for every parton density parametrization. For deeply-inelastic lepton–nucleon scattering, an implementation of this calculational scheme is provided by Mirkes and Zeppenfeld in MEPJET [19].

(b) The subtraction method is technically more involved, since the infrared singularities are cancelled point-by-point in phase space. The subtraction terms have, owing to the factorization theorems of perturbative QCD, a simple form. The problem is to arrange the subtractions in such a way that in the numerical evaluation no spurious singularities appear. A general framework, using a specific phase space mapping besides the factorization theorems, is given by Catani and Seymour in Ref. [20], and implemented in DISENT [21].

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1 In these calculations, terms of the form $c \log c$, $c$ being the jet cut, have been neglected. This implies in particular a certain insensitivity with respect to the jet recombination scheme. The set-up of the calculations [6–10] is such that a jet consisting of two partons is always mapped onto a massless jet. Therefore the jet definition scheme which is used on experimental data should be a “massless” scheme (this excludes, for example, the E-scheme). The variation of jet cross sections within the possible massless schemes cannot be modelled by that calculation.
The approach of the present paper is to use a generalized partial fractions formula to separate the singularities \[22\]. The method is briefly explained in Section 2. We will describe in some detail the implementation \texttt{DISASTER++} in the form of a C++ class library.

There are two reasons for a new calculation. (a) The existing programs have the restriction that the number of flavours is fixed (\(N_f = 5\) in the case of \texttt{MEPJET} and \(N_f\) fixed, but arbitrary for \texttt{DISENT}). For studies of the scale-dependence it is necessary to have a variable number of flavours, in order to be consistent with the scale evolution of the strong coupling constant and the parton densities. \texttt{DISASTER++} makes the \(N_f\) dependence explicit in the “user routine” on an event-by-event basis, and thus results for several renormalization and factorization scales can be calculated simultaneously. (b) \texttt{DISASTER++} is already set up such that the extension to one-particle-inclusive processes will be possible without the necessity of re-coding the contributions which are already present for the jet-type observables. This option will be made available in future versions of the program, as soon as the remaining contributions for one-particle-inclusive processes are implemented.

The outline of this paper is as follows. In Section 2 we briefly review the algorithm employed in the present calculation. In Section 3 the \texttt{FORTRAN} interface to the C++ class library is described. Some remarks concerning the installation of the package are made in Section 4. A comparison of the available universal programs \texttt{DISASTER++} (Version 1.0), \texttt{MEPJET} (Version 2.0) and \texttt{DISENT} (Version 0.1) is presented in Section 5. In a previous version of this paper, we have drawn the conclusion that we find an overall, but not completely satisfactory agreement of \texttt{DISASTER++} and \texttt{MEPJET}, and that there are large deviations when comparing \texttt{DISASTER++} and \texttt{DISENT}. One of the purposes of this paper is to present the results of a comparison of \texttt{DISASTER++} and a new, corrected version (0.1) of \texttt{DISENT}. We now find good agreement of the two programs. We also give a few more results for \texttt{MEPJET}, in particular for the dependence on the technical cut \(s\). It turns out that even for very small values of \(s\) we do not achieve agreement with the \texttt{DISASTER++} / \texttt{DISENT} results for several cases under consideration\[3\]. The paper closes with a summary. The contents of this paper are mainly technical. The details of the calculation and phenomenological applications will be described in a forthcoming publication.

2 The Algorithm

The calculation is based on the subtraction method. A simple example to illustrate this method in general, and a comparison with the phase-space-slicing method, is given in Ref. \[27\]. For a more detailed exposition of the contents of this section, see Ref. \[22\].

The subtraction method is one of the solutions for the problem of how to calculate numerically infrared-safe observables without having to modify the calculation for every observable under consideration. In QCD calculations, infrared singularities cancel for sufficiently inclusive observables. The factorization theorems of perturbative QCD (see Ref. \[26\] and references therein) together with the infrared-safety of the observable under consideration guarantee that the structure of the limit of the convolution of the parton-level cross section with the observable in soft and collinear regions of phase space is well-defined and factorizes in the

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\[2\] This is an acronym for “Deeply Inelastic Scattering: All Subtraction Through Evaluated Residues”.

\[3\] In a very recent paper \[23\], E. Mirkes quotes the results of the comparison of the three programs as performed in the previous version of this paper \[24\] as resulting in a “so far satisfactory agreement”. This is a misquotation. The formulation in Ref. \[23\] was that for \texttt{MEPJET} and \texttt{DISASTER++} we find an “overall, though not completely satisfactory agreement”, and that the results of \texttt{DISENT} (Version 0.0) “differ considerably”. Moreover, in the summary of Ref. \[24\] we mention that a few deviations of \texttt{MEPJET} and \texttt{DISASTER++} are present. We wish to stress that there is a certain semantic gap between the expression “satisfactory agreement” and the results just quoted.
form of a product of a kernel and the Born term. This property allows, for the real corrections, the definition of a subtraction term for every phase-space point. Formally:

\[
\int \text{dPS}^{(n)} \sigma \, \mathcal{O} = \sum_A \int \text{dPS}_{i_A} \, k_A \left( \int \text{dPS}^{(n-1)} \tau_A - \left[ \int \text{dPS}^{(n-1)} \tau_A \right]_{\text{soft/coll. limit}} \right) \\
+ \sum_A \int \text{dPS}_{i_A} \, k_A \left[ \int \text{dPS}^{(n-1)} \tau_A \right]_{\text{soft/coll. limit}},
\]

where \( \sigma \) is the parton-level cross section, \( \mathcal{O} \) is the infrared-safe observable, \( k_A \) is a singular kernel, and \( \tau_A \) is the non-singular part of the product \( \sigma \, \mathcal{O} \). The index \( A \) runs over all possible soft, collinear and simultaneously soft and collinear singularities of \( \sigma \). The first integral is finite and can be calculated numerically. The second integral contains all infrared singularities. The term in the square bracket has a simple structure because of the factorization theorems of QCD, and the one-particle integral over the kernel \( k_A \) and the factorization contribution from the term in the square brackets can be performed easily. This subtraction formula works only if the subtraction terms do not introduce spurious singularities for the individual terms that eventually cancel in the sum. This is achieved by a separation of all singularities by means of a general partial fractions formula

\[
\frac{1}{x_1 \, x_2 \cdots x_n} = \sum_{\sigma \in S_n} \frac{1}{x_{\sigma_1} (x_{\sigma_1} + x_{\sigma_2}) \cdots (x_{\sigma_1} + \cdots + x_{\sigma_n})},
\]

where the sum runs over all \( n! \) permutations of \( n \) objects.

In DISASTER++, the processes for (1+1) and (2+1)-jet production for one-photon exchange are implemented. The program itself, however, is set up in a much more general way. The implemented subtraction procedure can handle arbitrary number of final-state partons, and zero or one incoming partons (an extension to two incoming partons is possible). The C++ class library is intended to provide a very general framework for next-to-leading-order QCD calculations for arbitrary infrared-safe observables. Of course, the explicit matrix elements (Born terms, virtual corrections and factorized real corrections) have to be provided for every additional process to be included.

3 Program Structure

We now describe the FORTRAN interface to the C++ class library. The C++ user interface will be documented in a forthcoming extension of this manual.

To set the stage, let us first introduce some terminology. The user has to provide several subroutines which are called by DISASTER++ for every generated event. Each event \( e_n, n = 1 \ldots N \) consists of a set of phase spaces \( \mathcal{P}_{nr}, r = 1 \cdots R_n \), and a set of contributions \( C_{ni}, i = 1 \ldots L_n \). Phase spaces \( \mathcal{P} \) provide a set of four-vectors of initial and final-state particles, which are used to calculate observables \( \mathcal{O}(\mathcal{P}) \). Contributions \( C_{ni} \) consist of a list of weights \( w_{nij}, j = 1 \cdots K_{ni} \) (here: \( K_{ni} = 11 \)) which have to be multiplied by certain flavour factors \( F_{nij} \). Every contribution \( C_{ni} \) has an associated phase space \( \mathcal{P}_{nr_{ni}} \); it is generally the case that particular phase spaces are used for different contributions. Flavour factors are products of parton densities, quark charges, powers of the strong coupling constant, and powers of the electromagnetic coupling constant.

The expectation value \( \langle \mathcal{O} \rangle \) of a particular observable is given by the following sum:

\[
\langle \mathcal{O} \rangle = \sum_{n=1}^{N} \sum_{i=1}^{L_n} \sum_{j=1}^{K_{ni}} \mathcal{O}(\mathcal{P}_{nr_{ni}}) \, w_{nij} \, F_{nij}.
\]

The first sum is the main loop of the Monte Carlo integration.

The user has to provide a subroutine \texttt{user1} and a function \texttt{user2}. The subroutine \texttt{user1(iaction)} is called from DISASTER++ in the following cases:


\textbf{iaction=1:}

after start-up of \textsc{DISASTER++}

\textbf{iaction=2:}

before the end of \textsc{DISASTER++}

\textbf{iaction=3:}

before the start of the grid-definition run of the adaptive Monte-Carlo routine, or before the final run of the adaptive integration, in case that there is no grid-definition run

\textbf{iaction=4:}

before the start of the final run of the adaptive Monte-Carlo routine

\textbf{iaction=5:}

after the final run of the adaptive Monte-Carlo routine

\textbf{iaction=6:}

once for every event (to initialize intermediate weight sums, etc.)

\textbf{iaction=7:}

signals that the event has to be dropped for technical reasons

The function \texttt{user2(\ldots)} is called from \textsc{DISASTER++} after an event has been constructed. It has the following arguments (in an obvious notation):

\begin{verbatim}
  double precision function
  & user2(   & integer nr,   & integer nl,   & double precision fvect(0..3, -10..10, 1..30),
  &                   & integer npartons(1..30),
  &                   & double precision xb(1..30),
  &                   & double precision q2(1..30),
  &                   & double precision xi(1..30),
  &                   & double precision weight(1..11, 1..50),
  &                   & integer irps(1..50),
  &                   & integer ialphas(1..50),
  &                   & integer ialphaem(1..50),
  &                   & integer lognf(1..50)
  & )
\end{verbatim}

Here \texttt{nr} stands for $R_n$, \texttt{nl} stands for $L_n$. \texttt{fvect(mu, iparticle, ir)} is the $\mu$\textsuperscript{th} component of the four-vector of the particle with label \texttt{iparticle} ($\mu=0$ corresponds to the energy component) in units of [GeV] in the Breit frame for the phase space \texttt{ir}; \texttt{npartons(ir)} is the number of final-state partons, \texttt{q2(ir)} is the value of $Q^2$, and \texttt{xi(ir)} is the momentum fraction of the incident parton. The particle labels \texttt{iparticle} are given by

\begin{verbatim}
iparticle=-8: proton remnant

iparticle=-7: incident proton

iparticle=-5: outgoing electron
\end{verbatim}
iparticle=-4: incident electron
iparticle=-1: incident parton
iparticle=0..(npartons-1): outgoing partons

The array \( \text{weight}(j, i) \) is a list of the weights for contribution \( i \) in units of \([\text{pb}]\), \( \text{irps}(i) \) gives the index of the phase space for this particular contribution, \( \text{ialphas}(i) \) and \( \text{ialphaem}(i) \) are the powers of the strong and electromagnetic coupling constant, respectively, and \( \text{lognf}(i) \) is an index that specifies whether the weights have to be multiplied by a factor \( \lambda \) consisting of a product of a logarithm of a scale and/or a factor of \( N_f \):

- \( \text{lognf}=0: \lambda = 1 \)
- \( \text{lognf}=1: \lambda = \ln \left( \frac{\mu_r^2}{Q^2} \right) \)
- \( \text{lognf}=2: \lambda = N_f \ln \left( \frac{\mu_r^2}{Q^2} \right) \)
- \( \text{lognf}=3: \lambda = \ln \left( \frac{\mu_r^2}{Q^2} \right) \)
- \( \text{lognf}=4: \lambda = N_f \ln \left( \frac{\mu_r^2}{Q^2} \right) \)

Here \( \mu_r \) and \( \mu_f \) are the renormalization and factorization scales, respectively. The total flavour factor for contribution \( i \) is given by

\[
F_{nij} = \lambda \alpha_s^{\text{ialphas}(i)} \alpha^{\text{ialphaem}(i)} \rho_{ij},
\]  

where the quantity \( \rho_{ij} \) is a product of squares of quark charges \( Q_\alpha \) in units of \( e \) and parton densities. In particular:

\[
\begin{align*}
\rho_{i1} &= \sum_{\alpha=1}^{N_f} Q_\alpha^2 f_\alpha \\
\rho_{i2} &= \sum_{\alpha=1}^{N_f} Q_\alpha^2 f_\pi \\
\rho_{i3} &= \sum_{\alpha=1}^{N_f} Q_\alpha^2 f_g \\
\rho_{i4} &= \rho_{i1} \\
\rho_{i5} &= \rho_{i2} \\
\rho_{i6} &= \rho_{i1} (N_f - 1) \\
\rho_{i7} &= \rho_{i2} (N_f - 1) \\
\rho_{i8} &= \sum_{\alpha=1}^{N_f} f_\alpha \sum_{\beta=1, \beta \neq \alpha}^{N_f} Q_\beta^2 \\
\rho_{i9} &= \sum_{\alpha=1}^{N_f} f_\alpha \sum_{\beta=1, \beta \neq \alpha}^{N_f} Q_\beta^2 \\
\rho_{i10} &= \sum_{\alpha=1}^{N_f} f_\alpha Q_\alpha \sum_{\beta=1, \beta \neq \alpha}^{N_f} Q_\beta
\end{align*}
\]
\[
\rho_{i11} = \sum_{\alpha=1}^{N_f} f_{i \alpha} Q_\alpha \sum_{\beta=1, \beta \neq \alpha}^{N_f} Q_\beta
\]

The \( f_\alpha \) are parton densities evaluated for momentum fractions \( x_i (\text{irps}(i)) \) and factorization scale \( \mu_f \), and \( f_{i \pi} \) stands for the parton density of the anti-flavour of the flavour \( \alpha \). The renormalization and factorization schemes are the \( \overline{\text{MS}} \) scheme. The correction terms for the DIS factorization scheme will be implemented in the near future.

We wish to note that the product of the weights, the flavour factors and the values of the observable is normalized in such a way that the sum yields the expectation value in units of \([\text{pb}]\). No additional factor such as \( 1/N \), \( N \) being the total number of generated events, has to be applied in Eq. 3.

Since phase spaces are used several times for different contributions, it is a good strategy to first evaluate the observable(s) under consideration for every phase space and to store the corresponding results. Then there should be the loop over the various contributions (the second sum). The innermost loop is the one over the flavour factors.

The Monte Carlo integration itself employs the program \textsc{vegas} \[27, 28\]. \textsc{vegas} is an adaptive multi-dimensional integration routine. Integrations proceed in two steps. The first step is an adaptation step in order to set up a grid in the integration variables which then steers the final integration step. The adaptation step itself refines the grid in a sequence of several iterations. \textsc{vegas} requires, as parameters, the number of Monte Carlo points to be used in the first and second step, respectively, and the number of iterations to refine the grid. In the framework of \textsc{disaster++}, \textsc{vegas} can be used in three different ways:

- As an adaptive integration routine. The routine \texttt{user2} should return a value. This value is handed over to \textsc{vegas} as the value of the integrand at the particular phase space point, and summed up. The final integral quoted by \textsc{vegas} is the sum of these weights for the final integration. This is the best choice if just one observable, for example a jet cross section, is to be evaluated.

- As a routine that merely supplies random numbers for the events. If the number of iterations is set to zero, then \textsc{vegas} just performs the final integration run. The user is then responsible for the correct summation of the weights, and for the determination of the statistical error. It should be noted that, since all weights are available individually in the user routine, an arbitrary number of observables can be evaluated in a single run. In particular, since the dependence on the renormalization and factorization scales and on \( N_f \) is fully explicit, the study of the scale dependence of observables can be done in a very convenient way. For example, all plots from Ref. \[22\] have been obtained in a single run of \textsc{disaster++}.

- As a combination of the two preceeding alternatives. Here the adaptation steps are included. A “typical” infrared-safe observable, in the following called the \textit{adaptation variable}, is evaluated, and its value is returned to \textsc{vegas}. This observable serves to optimize the distribution of points over phase space. A convenient observable of this kind is provided by \textsc{disaster++} (see below). The “real” observables under consideration are evaluated as in the second alternative in the final integration step.

\textsc{disaster++} is initialized by a call of the subroutine \texttt{disaster\_ca()}. It is recommended to end a \textsc{disaster++} run by a call of the subroutine \texttt{disaster\_cb()} in order to free dynamically allocated memory.

Parameters can be set or commands be executed by means of three routines:

\begin{verbatim}
disaster_ci(str, i)
  sets the integer parameter denoted by the character string \texttt{str} to the value \texttt{i}
\end{verbatim}
disaster_cd(str, d)
    sets the double precision parameter denoted by the character string str to the value d

disaster_cc(str)
    executes the command given by the character string str

The following parameters are available (there are a few more to optimize the generation of the phase space points; they will be documented in forthcoming versions of this manual):

ECM:
    the centre-of-mass energy in [GeV]

LEPTON_INTEGRATION:
    1: integration over \( x_B \) and \( y \)

XBMIN:
    minimum value of \( x_B \)

XBMAX:
    maximum value of \( x_B \)

YMIN:
    minimum value of \( y \)

YMAX:
    maximum value of \( y \)

QMIN:
    minimum value of \( Q \)

QMAX:
    maximum value of \( Q \)

WMIN:
    minimum value of \( W \)

WMAX:
    maximum value of \( W \)

PROCESS_INDEX:
    1: leading order
    2: next-to-leading order

NUMBER_OF_FINAL_STATE_PARTONS_IN_BORN_TERM:
    1, 2, 3 for the process under consideration:
    1: (1+1)-jet-type observables (leading and next-to-leading order)
    2: (2+1)-jet-type observables (leading and next-to-leading order)
    3: (3+1)-jet-type observables (leading order only)

POINTS:
    POINTS \times (FACT_PREP + FACT_FINAL) is the number of generated points in the Monte Carlo integration

FACT_PREP:
    the number of points for the grid-definition run is given by FACT_PREP \times POINTS
FACT\_FINAL:
the number of points for the final integration step is given by FACT\_FINAL * POINTS

RUN\_MC:
to start the Monte-Carlo integration

A convenient adaptation observable can be evaluated by a call of the following function:

```c
double precision function disaster_cao(
    & integer ipdf_collection,
    & integer ipdf_parametrization,
    & integer ipdf_set,
    & integer ialphas_variant,
    & integer ialphas_order,
    & double precision dalphas_lambdaqcd4,
    & integer ialphaem_variant
)
```

The arguments of the function call are:

- **ipdf\_collection:**
  the collection of parton densities;
  1: PDFLIB

- **ipdf\_parametrization:**
  parametrization of parton densities (cf. PDFLIB)

- **ipdf\_set:**
  set of parton densities (cf. PDFLIB)

- **ialphas\_variant:**
  function which is used to evaluate the strong coupling constant;
  1: running coupling $\alpha_s(Q^2)$ with flavour thresholds at the single heavy quark masses

- **ialphas\_order:**
  1: one-loop formula
  2: two-loop formula
  for the running strong coupling constant

- **dalphas\_lambdaqcd4:**
  the QCD parameter $\Lambda_{QCD}^{(4)}$ for four flavours

- **ialphaem\_variant:**
  function which is used to evaluate the electromagnetic coupling constant;
  1: fine structure constant
  2: 1/137
  (an implementation of the running electromagnetic coupling constant is in preparation)

To simplify the calculation of the flavour factors, a DISASTER++ routine can be called which returns the required coupling constants and the combinations of parton densities and quark charges:
subroutine disaster_cff(
   & integer ipdf_collection,
   & integer ipdf_parametrization,
   & integer ipdf_set,
   & integer ialphas_variant,
   & integer ialphas_order,
   & double precision dalphas_lambdaqcd4,
   & integer ialphaem_variant,
   & integer nf,
   & double precision ffactin(4),
   & double precision ffactout(13)
   &
   )

The arguments of the function call are the same as in the case of the routine disaster_cao (see above), except for the following:

nf: 
   the number of flavours $N_f$

ffactin: 
   input parameters;
   ffactin(1): the momentum fraction variable $\xi$
   ffactin(2): the factorization scale in [GeV] (i.e. the scale argument of the parton densities)
   ffactin(3): the renormalization scale in [GeV] (i.e. the scale argument of the running strong coupling constant)
   ffactin(4): the scale argument of the running electromagnetic coupling constant

ffactout: 
   output parameters;
   ffactout(1..11): the quantities $\rho_{i1} \ldots \rho_{i11}$,
   ffactout(12): the running strong coupling constant
   ffactout(13): the electromagnetic coupling constant

It is strongly recommended to use this routine, since it uses a cache that stores a few of the most recent values temporarily, such that the sums $\rho_{ij}$ and the parton densities do not have to be reevaluated. This routine is supplied for the convenience of the user. The weights and events generated by DISASTER++ do not depend on this routine.

The description of the program structure just given may sound complicated. It is actually quite simple to use the program; an example for the calculation of the (2+1)-jet cross section for the JADE algorithm in the E-scheme is given in the files disaster.f.f and clust.f, as described in Section 4.

4 Program Installation

Source code: The source code of the class library is available on the World Wide Web:

   http://wwwcn.cern.ch/~graudenz/disaster.html
Files: The package consists of a number of files. To facilitate the installation, and to enable the C++ compiler to perform certain optimizations, the complete C++ part of the program is provided as one file onefile.n.cc (the individual files are available on request). An example for the FORTRAN interface is given in the file disaster.f.f (calculation of the (2+1) jet cross section for the JADE algorithm in the E-scheme), together with a simple cluster routine in the file clust.f. The number of Monte Carlo events in the example is set to a tiny number (100) in order to terminate the program after a few seconds. Realistic values for the parameter POINTS are of the order of $10^6$. An example “make file” is given in makedisaster.

Mixed Language Programming: DISASTER++ is mainly written in the C++ programming language. The reason for the choice of this language are twofold: Object-oriented programming allows for programs that are easily maintained and extended and in high-energy physics there is a trend in the experimental domain for a transition from FORTRAN to C++. Although the goal has been to write a self-contained C++ package, a few parts of the program are still coded in FORTRAN. Moreover, the standard parton density parametrizations are only available as FORTRAN libraries. This means that the DISASTER++ package cannot be run as a stand-alone C++ program. In most cases, users may wish to interface the program to their existing FORTRAN routines. An elegant and machine-independent way for mixed language programming for the case of C, C++ and FORTRAN is supported by the cfortran.h package described in Ref. [30]. For every FORTRAN routine to be called by a C++ method, an extern "C" routine has to be defined as an interface, and vice versa. The explicit calls are then generated by means of macros from cfortran.h. The most convenient way is, after compilation, to link the FORTRAN and C++ parts via the standard

```
f77 -o disaster onefile_n.o ...
```

command such that the FORTRAN part supplies the entry point. The required C++ libraries have to be stated explicitly via the -L and -l options. The library paths can be obtained by compiling and linking a trivial program hw.cc of the type

```c
#include <stdio.h>
main() { printf("Hello world!\n"); }
```

with

```
gcc -v hw.cc
```

(for the GNU C++ compiler). An example for the required libraries can be found in the prototype “make file” makedisaster. Some machine-specific information is mentioned in the manual of cfortran.h.

In the DISASTER++ package, the explicit FORTRAN interface, as described in Section 3, is already provided. Thus from the outside the C++ kernel is transparent and hidden behind FORTRAN subroutines and functions.

Template instantiation: In DISASTER++, heavy use is made of templates. At present, there is not yet a universally accepted scheme for template instantiations. The solution adopted here is the explicit instantiation of all templates. This requires that the compiler itself does not instantiate templates automatically. This is achieved for the GNU compiler by means of the switch

```
-fno-external-templates
```

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4 It could even be said that object-oriented programming is a kind of applied ontology: the central categories of this approach are given by objects and methods that define their relationships.

5 The procedure is described here for the UNIX operating system.
**Output files:** There is a small problem with the output from the C++ and FORTRAN parts of DISASTER++. It seems to be the case that generally C++ (FILE* stdout and ostream cout) and FORTRAN (UNIT=6) keep different file buffers. This is no problem when the output is written to a terminal, since then the file buffers are immediately flushed after each line-feed character. When writing to a file (as is usually the case for batch jobs), the file buffers are not immediately flushed, and this leads to the problem that the output on the file is mixed in non-chronological order. This problem will be solved by the introduction of a particular stream class which hands over the output to a FORTRAN routine.

**Miscellaneous:** DISASTER++ employs the ANSI C signal facility to catch interrupts caused by floating point arithmetic. If the signal SIGFPE is raised, a flag in DISASTER++ is set, which eventually leads to the requirement that the event has to be dropped (via a call of user1(7)). Similarly a non-zero value of the variable errno of the ANSI C errno facility is treated. The signal handler is also active when the user routine is executed, which leads to the effect that in the case of a floating point exception the program does not crash, but continues under the assumption that the event has been dropped. Forthcoming version of DISASTER++ will make a flag available that can be used to access the status of the signal handler in the user routines. Moreover, it is checked whether the weight returned to DISASTER++ via user2 fulfills the criterion for IEEE NaN (“not a number”). If this is the case, it is also requested that the event be dropped.

### 5 Comparison of Available Programs

In this section, we compare the three available programs MEPJET (Version 2.0)\(^6\), DISENT (Version 0.1)\(^7\) and DISASTER++ (Version 1.0) numerically for various bins of \(x_B\) and \(y\) as defined in Table \(^1\), and for various choices of the parton density parametrizations.

| \(0.01 < y < 0.03\) | \(0.03 < y < 0.1\) | \(0.1 < y < 0.3\) |
|----------------------|----------------------|----------------------|
| \(0.005 < x_B < 0.01\) | Bin 1 \((Q^2 > 4.6\,\text{GeV}^2)\) | Bin 2 \((Q^2 > 13.5\,\text{GeV}^2)\) | Bin 3 \((Q^2 > 45.0\,\text{GeV}^2)\) |
| \(0.05 < x_B < 0.1\) | Bin 4 \((Q^2 > 45\,\text{GeV}^2)\) | Bin 5 \((Q^2 > 135\,\text{GeV}^2)\) | Bin 6 \((Q^2 > 450\,\text{GeV}^2)\) |
| \(0.2 < x_B < 0.4\) | Bin 7 \((Q^2 > 180\,\text{GeV}^2)\) | Bin 8 \((Q^2 > 540\,\text{GeV}^2)\) | Bin 9 \((Q^2 > 1800\,\text{GeV}^2)\) |

Table 1: Bins in \(x_B\) and \(y\). The values in parentheses give the resulting lower bounds on \(Q^2\).

The centre-of-mass energy is set to 300 GeV. To facilitate the comparison, the strong coupling constant is set to a fixed value of \(\alpha_s = 0.1\), and the number of flavours is set to \(N_f = 5\), even below the bottom threshold (\(N_f = 5\) is hard-wired into MEPJET). The electromagnetic coupling constant is chosen to be \(\alpha = 1/137\) (the value is hard-wired into DISENT, but this could be changed trivially, in principle). The factorization- and renormalization schemes of the hard scattering cross sections are \(\overline{\text{MS}}\), and the factorization and renormalization scales \(\mu_f\) and \(\mu_r\), respectively, are set to \(Q\).

\(^6\) For the very-high statistics runs the default random number generator (generating a Sobol sequence of pseudo-random numbers) of MEPJET ran out of random numbers. We therefore had to modify the program such that it uses another generator which is also part of the MEPJET package. — The crossing functions for the “artificial” parton densities have been obtained by means of a modification of the program make_str_pdf1.f.

\(^7\) An earlier version of this paper \(^2\) reported results of a comparison with DISENT Version 0.0. We found large discrepancies for some choices of the parton density parametrization. In the meantime, an error in DISENT has been fixed, and the results of DISENT and DISASTER++ are now in good agreement, see below.
The quantity under consideration is the (2+1)-jet cross section, shown in Tables 2–8 in Appendix \ref{app}. For simplicity we consider the modified JADE clustering scheme with resolution criterion $S_{ij} \leftrightarrow \epsilon W^2$ and the E recombination scheme, where $S_{ij} = (p_i + p_j)^2$, $W$ is the total hadronic energy, and $c = 0.02$ is the jet resolution parameter. We require, in the laboratory frame ($E_e = 27.439$ GeV, $E_p = 820$ GeV), a minimum transverse momentum of 1 GeV and a pseudo-rapidity of $-3.5 < \eta < 3.5$ for all jets.

The parton density parametrizations employed in the comparison are:

(a) the MRSD$^\prime$ parton densities [31] (Table 2),
(b) $q(\xi) = (1 - \xi)^5, \ g(\xi) = 0$ (Table 3),
(c) $q(\xi) = 0, \ g(\xi) = (1 - \xi)^5$ (Table 4),
(d) $q(\xi) = (1 - \xi)^2, \ g(\xi) = 0$ (Table 5),
(e) $q(\xi) = 0, \ g(\xi) = (1 - \xi)^2$ (Table 6),
(f) $q(\xi) = (1 - \xi), \ g(\xi) = 0$ (Table 7),
(g) $q(\xi) = 0, \ g(\xi) = (1 - \xi)$ (Table 8).

Here $q(\xi)$ generically stands for valence and sea distributions, and $g(\xi)$ is the gluon distribution. We wish to point out that the comparison involving the “artificial” parton densities is not just of academic interest. On the contrary, for the extraction of, for instance, the gluon density from jet data it is convenient to replace the parton densities by simple functions with special properties (such as powers of the momentum fraction $\xi$ or functions of an orthonormal basis system), in order to achieve a fast fit. These functions usually do not have the shape of physical parton densities, in particular they do not have to fall off rapidly for $\xi \rightarrow 1$. Moreover, next-to-leading-order calculations yield unique and well-defined results for the hard scattering cross sections to be convoluted with observables and parton densities. We employ the “artificial” parton densities also in order to have a stricter test of the hard scattering cross sections.

The leading-order results of all three programs are in excellent agreement. The next-to-leading-order results of DISASTER++ and DISENT are in good agreement within about two to (sometimes) three standard deviations of the larger of the two errors quoted by the two programs. An exception is bin 7 for $g(\xi) = (1 - \xi)^2$. A run of DISENT with higher statistics yields a value of $0.1836 \pm 0.0025$, which is within two standard deviations of the DISASTER++ result, indicating that there was indeed a statistical fluctuation in the original result.

The comparison of the next-to-leading-order results of MEPJET and DISASTER++ requires a more detailed discussion:

8 These cuts in $p_T$ and $\eta$ are employed in order to facilitate event generation with MEPJET; the phase space generator implemented in that program is reminiscent of a generator for pp collider physics where $p_T$ and $\eta$ cuts in the laboratory frame are a standard experimental procedure. It is thus complicated to generate events with MEPJET in the full phase space of the laboratory system, as usually required for $e\bar{p}$ scattering, where “natural” cuts in transverse momentum and pseudo-rapidity would be performed in the hadronic centre-of-mass frame or in the Breit frame.

9 This means that $u_v(\xi), d_v(\xi), u_s(\xi), d_s(\xi), s_s(\xi), c_s(\xi), b_s(\xi)$ have been set to $g(\xi)$.

10 We wish to note that the error estimates quoted by the programs are usually not rigorous estimates because of the non-Gaussian distribution of the Monte-Carlo weights. Therefore, in principle, it is not possible to infer probabilities for the consistency of data samples produced by two programs based on these estimates. A more precise, but in general unfeasible way to obtain an estimate of the Monte Carlo error would be to run the programs a number of times with different random number seeds and to analyze the spread of the quoted results around their central value. Such a study has recently been done by M. Seymour for DISENT with the result that the individual error estimates are quite reliable. [32].
• For the MRSD\_ parton densities, the results for bins 3–9 are compatible within about two standard deviations of the statistical error of the Monte-Carlo integrations. The results for bins 1 and 2 differ considerably. Runs with a smaller value of the internal MEPJET cut-off variable s, which is set by default to \( s = 0.1 \text{ GeV}^2 \), yield the following results for bin 1: \( 580.6 \pm 6.7 \text{ pb} \) (\( s = 0.01 \text{ GeV}^2 \)), \( 564.8 \pm 10.5 \text{ pb} \) (\( s = 0.001 \text{ GeV}^2 \)) and \( 575.4 \pm 13.0 \text{ pb} \) (\( s = 0.0001 \text{ GeV}^2 \)). The statistical error is increased for decreased \( s \) because the integration volume of the (3+1) parton contributions is extended into the singular domain. Because of the increased statistical error, we also performed a high-statistics runs with \( \sim 4 \cdot 10^9 \) (!) Monte Carlo events of MEPJET for this bin. For \( s = 0.001 \text{ GeV}^2 \) we obtain \( 576.3 \pm 6.7 \text{ pb} \) and for \( s = 0.0001 \text{ GeV}^2 \) the result is \( 583.2 \pm 7.4 \text{ pb} \). These values from MEPJET are compatible with the DISASTER++ and DISENT results\[1\].

• For the parton density parametrization (b) (quarks only, with a steeply falling distribution \( q(\xi) \) for \( \xi \to 1 \)), DISASTER++ and MEPJET are in good agreement.

• The results for parametrization (c) (steeply falling gluon parametrization) are in good agreement, except for bin 1.

• For parametrization (d), DISASTER++ and MEPJET are in agreement except for bins 1 and 4. Runs with a smaller value of the MEPJET cut-off variable \( s \) yield the following results for bin 1: \( 59.6 \pm 1.8 \text{ pb} \) (\( s = 0.01 \text{ GeV}^2 \)), \( 56.7 \pm 5.8 \text{ pb} \) (\( s = 0.001 \text{ GeV}^2 \)) and \( 54.9 \pm 10.4 \text{ pb} \) (\( s = 0.0001 \text{ GeV}^2 \)). A high-statistics run (\( \sim 4 \cdot 10^9 \) events) of MEPJET for bin 1 with \( s = 0.0001 \text{ GeV}^2 \) gives the cross section \( 60.0 \pm 1.9 \text{ pb} \). Contrary to the observation in case (a), for small \( s \) we do not get agreement of the MEPJET result with the DISASTER++ / DISENT result of about 48–49 pb.

• The MEPJET results for parametrization (e) (\( g(\xi) = (1 - \xi)^2 \)) deviate considerably from the DISASTER++ results in bins 1, 2, 4 and 7.

• For parametrization (f), DISASTER++ and MEPJET are incompatible for bins 1, 2, 4, 6 and 7.

• For parametrization (g), MEPJET and DISASTER++ are compatible in bins 3, 5, 8 and 9 only. A high-statistics run (\( \sim 4 \cdot 10^9 \) events) of MEPJET for bin 4 with \( s = 0.0001 \text{ GeV}^2 \) yields the cross section \( 1.29 \pm 0.02 \text{ pb} \). This value is different from the result for \( s = 0.1 \text{ GeV}^2 \), but still inconsistent with the DISASTER++ / DISENT result of about 0.69 pb.

The overall picture is thus: Out of the three programs, DISASTER++ and DISENT (Version 0.1) are in good agreement within about two, sometimes three standard deviations of the quoted integration errors, both for “physical” and “artificial” parton densities. This agreement is very encouraging, but not yet perfect, and much more detailed studies involving different sets of observables and differential distributions are required. For the two programs, a direct comparison of the “jet structure functions” should also be feasible.

For several bins, in particular for the “artificial” parton distribution functions, the MEPJET results for the default setting of the internal parameters deviate considerably from the DISASTER++ and DISENT results. For one particular bin studied in more detail for the MRSD\_ parton densities, the discrepancy disappears in the case of an extremely small internal technical cut \( s \) of MEPJET, for a substantial increase of the number of generated events to obtain a meaningful Monte Carlo error. A few MEPJET results employing “artificial” parton densities have been studied in more detail. We observed that in these cases a reduction of the \( s \) parameter does not lead to an improvement of the situation. For lack of computer time, we could not study

\[1\] These results underline that, for the phase space slicing method, results generally have to be validated \textit{ex post} by a cross-check with a smaller technical cut \( s \) and much higher statistics. It may be argued that there are jet algorithms (the \( k_T \) algorithm, for example) which show a better convergence for \( s \to 0 \). However, the point here is that one does not know in advance whether this is the case for the observable under consideration. — In Ref. [2] we find the statement that \( s \)-independence in MEPJET is achieved for \( s = 0.1 \text{ GeV}^2 \). Our study shows that this is generally not the case, and that extremely small values of \( s \), possibly of the order of \( s = 0.0001 \text{ GeV}^2 \), might be necessary.
all bins with a smaller $s$ cut. The overall situation is thus still inconclusive and unclear. An independent cross check of the MEPJET results, in particular of those using the implementation of the crossing functions for the “artificial” parton densities, is highly desirable.

6 Miscellaneous

- If you intend to install and use DISASTER++, please send me a short e-mail message, and I will put your name on a mailing list so that I can inform you when there is a new version of the package.

- Suggestions for improvements and bug reports are welcome.

- In case that there are problems with the installation of the program, please send me an e-mail message.

7 Summary

We have presented the C++ class library DISASTER++ for the calculation of (1+1) and (2+1)-jet type observables in deeply inelastic scattering. The program is based on the subtraction formalism and thus does not require a technical cut-off for the separation of the infrared-singular from the infrared-finite phase-space regions. A FORTRAN interface to the C++ class library is available. DISASTER++ is actually intended to be a general object-oriented framework for next-to-leading order QCD calculations. In particular, the subtraction formalism is implemented in a very general way.

We have performed a comparison of the three available programs MEPJET, DISENT and DISASTER++ over a wide range of the parameters for the lepton phase space. We find good agreement of DISASTER++ and the Catani-Seymour program DISENT (Version 0.1). The comparison of DISASTER++ and the Mirkes-Zeppenfeld program MEPJET (for the MEPJET default parameters) leads to several discrepancies, both for physical and for “artificial” parton densities. For the MRSD′ parton densities a reduction of the internal MEPJET phase-space slicing cut-off variable $s$, the number of Monte Carlo events kept fixed, leads to a certain improvement of the central values of the results, accompanied by a substantially increased statistical error and fluctuating central values. A considerable increase of the number of generated events (up to of the order of several billion events) eventually leads to an agreement of the MEPJET results with the DISASTER++ / DISENT results for a particular bin of the lepton variables which has been studied in detail. For “artificial” parton densities and a selected set of bins of the lepton variables, a reduction of the internal cut $s$ does not resolve the discrepancies. Other bins are not considered for the lack of computer time for very-high statistics runs. It should be stressed that the present study is still limited in scope. An independent cross check of the MEPJET results for the “artificial” parton densities has to be done until a firm conclusion can be reached. Moreover, the study has to be repeated for a wider range of observables and much higher Monte Carlo statistics. The $s$ dependence of the MEPJET results should also be studied in more detail.

Compared to the other two programs MEPJET and DISENT, DISASTER++ makes the full $N_f$ dependence and the dependence on the renormalization and factorization scales available in the user routine. This is required for consistent studies of effects such as the scale dependence when the bottom threshold is crossed.

8 Acknowledgements

I wish to thank M. Seymour for sending me the numerical results for the new DISENT version. D. Zeppenfeld made a few cross checks of the results for the MRSD′ parton densities. J. Collins has provided me with the FORTRAN routine to test the IEEE NaN condition. I am also grateful to Th. Hadig for a few comments on the first version of this paper, and for suggestions for improvements of the program.
A Numerical Results

This appendix contains the numerical results which are discussed in Section 5. The entries in the tables are the (2+1)-jet cross sections in units of [pb].

| bin | DISASTER++ | MEPJET | DISENT  | DISASTER++ | MEPJET | DISENT  |
|-----|------------|--------|---------|------------|--------|---------|
| 1   | 402.1± 1.13 | 399.9± 0.53 | 399.6± 1.1 | 585.0± 2.6 | 564.1± 1.9 | 578.4± 7.1 |
| 2   | 207.6± 0.59 | 207.5± 0.34 | 207.4± 0.15 | 364.8± 1.5 | 347.3± 2.4 | 361.1± 3.5 |
| 3   | 60.0± 0.16  | 59.9± 0.14  | 59.9± 0.15  | 119.1± 1.71 | 118.0± 1.05 | 120.1± 0.94 |
| 4   | 82.9± 0.16  | 82.9± 0.10  | 82.6± 0.21  | 98.1± 1.11  | 95.1± 0.61  | 95.4± 0.87  |
| 5   | 42.9± 0.08  | 42.9± 0.06  | 42.6± 0.28  | 55.3± 0.46  | 54.4± 0.49  | 54.9± 0.40  |
| 6   | 11.9± 0.02  | 11.9± 0.02  | 11.9± 0.08  | 17.5± 0.06  | 16.8± 0.22  | 17.3± 0.13  |
| 7   | 9.60± 0.03  | 9.58± 0.01  | 9.59± 0.04  | 12.1± 0.50  | 12.7± 0.07  | 12.3± 0.15  |
| 8   | 6.24± 0.01  | 6.23± 0.01  | 6.24± 0.02  | 8.61± 0.12  | 8.55± 0.15  | 8.52± 0.08  |
| 9   | 1.78± 0.003 | 1.78± 0.003 | 1.78± 0.06  | 2.65± 0.03  | 2.57± 0.06  | 2.63± 0.02  |

Table 2: Comparison for MRSD' parton densities.
### Table 3: Comparison for $q(\xi) = (1 - \xi)^5$

| bin | DISASTER++ | MEPJET | DISENT | DISASTER++ | MEPJET | DISENT |
|-----|------------|--------|--------|------------|--------|--------|
| 1   | 36.2 ± 0.09 | 36.3 ± 0.05 | 36.3 ± 0.12 | 39.1 ± 0.33 | 40.9 ± 0.89 | 38.2 ± 0.53 |
| 2   | 17.8 ± 0.04 | 17.8 ± 0.03 | 17.7 ± 0.05 | 23.2 ± 0.37 | 22.7 ± 0.41 | 22.6 ± 0.22 |
| 3   | 5.21 ± 0.01 | 5.21 ± 0.01 | 5.21 ± 0.02 | 8.24 ± 0.22 | 7.86 ± 0.12 | 8.14 ± 0.06 |
| 4   | 27.3 ± 0.06 | 27.3 ± 0.03 | 27.2 ± 0.09 | 28.0 ± 0.52 | 29.2 ± 0.18 | 30.0 ± 0.21 |
| 5   | 14.8 ± 0.03 | 14.8 ± 0.02 | 14.7 ± 0.04 | 17.4 ± 0.29 | 16.9 ± 0.10 | 17.0 ± 0.11 |
| 6   | 4.33 ± 0.008 | 4.32 ± 0.006 | 4.31 ± 0.01 | 5.62 ± 0.10 | 5.44 ± 0.05 | 5.54 ± 0.03 |
| 7   | 6.38 ± 0.02  | 6.37 ± 0.01  | 6.38 ± 0.03 | 8.49 ± 0.17 | 8.59 ± 0.10 | 8.37 ± 0.11 |
| 8   | 4.44 ± 0.01  | 4.43 ± 0.007 | 4.44 ± 0.02 | 6.11 ± 0.08 | 6.05 ± 0.07 | 6.07 ± 0.06 |
| 9   | 1.36 ± 0.002 | 1.36 ± 0.002 | 1.36 ± 0.05 | 2.02 ± 0.02 | 2.00 ± 0.05 | 2.01 ± 0.01 |

### Table 4: Comparison for $g(\xi) = (1 - \xi)^5$

| bin | DISASTER++ | MEPJET | DISENT | DISASTER++ | MEPJET | DISENT |
|-----|------------|--------|--------|------------|--------|--------|
| 1   | 4.89 ± 0.017 | 4.89 ± 0.007 | 4.87 ± 0.01 | 5.38 ± 0.07 | 6.03 ± 0.06 | 5.22 ± 0.13 |
| 2   | 2.66 ± 0.009 | 2.66 ± 0.007 | 2.65 ± 0.007 | 3.67 ± 0.08 | 3.66 ± 0.04 | 3.58 ± 0.05 |
| 3   | 0.825 ± 0.003 | 0.826 ± 0.002 | 0.826 ± 0.002 | 1.44 ± 0.07 | 1.37 ± 0.03 | 1.39 ± 0.02 |
| 4   | 1.60 ± 0.005 | 1.60 ± 0.003 | 1.60 ± 0.003 | 1.20 ± 0.05 | 1.30 ± 0.01 | 1.12 ± 0.04 |
| 5   | 0.904 ± 0.003 | 0.900 ± 0.001 | 0.899 ± 0.002 | 0.833 ± 0.027 | 0.801 ± 0.008 | 0.764 ± 0.019 |
| 6   | 0.279 ± 0.001 | 0.278 ± 0.001 | 0.278 ± 0.001 | 0.314 ± 0.007 | 0.287 ± 0.004 | 0.299 ± 0.006 |
| 7   | 0.130 ± 0.001 | 0.131 ± 0.001 | 0.130 ± 0.001 | 0.119 ± 0.005 | 0.118 ± 0.002 | 0.110 ± 0.006 |
| 8   | 0.0981 ± 0.001 | 0.0980 ± 0.001 | 0.0981 ± 0.001 | 0.105 ± 0.002 | 0.096 ± 0.001 | 0.099 ± 0.004 |
| 9   | 0.0313 ± 0.0001 | 0.0310 ± 0.001 | 0.0313 ± 0.001 | 0.0396 ± 0.001 | 0.034 ± 0.001 | 0.0386 ± 0.001 |
| bin | DISASTER++ | MEPJET | DISENT | DISASTER++ | MEPJET | DISENT |
|-----|------------|--------|--------|------------|--------|--------|
| 1   | 46.1± 0.11 | 46.2± 0.07 | 46.2± 0.14 | 49.4± 0.67 | 58.8± 0.65 | 47.8± 1.2 |
| 2   | 23.8± 0.05 | 23.8± 0.09 | 23.8± 0.07 | 30.6± 0.33 | 31.4± 0.71 | 29.0± 0.54 |
| 3   | 7.28± 0.02 | 7.28± 0.02 | 7.29± 0.02 | 11.2± 0.21 | 11.0± 0.24 | 11.4± 0.14 |
| 4   | 42.4± 0.09 | 42.3± 0.06 | 42.3± 0.12 | 38.4± 0.30 | 41.9± 0.26 | 38.4± 0.31 |
| 5   | 23.9± 0.04 | 23.9± 0.03 | 23.8± 0.06 | 24.8± 0.46 | 24.2± 0.19 | 23.9± 0.16 |
| 6   | 7.31± 0.01 | 7.30± 0.01 | 7.27± 0.02 | 8.11± 0.19 | 8.04± 0.41 | 8.24± 0.05 |
| 7   | 20.3± 0.05 | 20.3± 0.08 | 20.3± 0.08 | 23.3± 0.64 | 25.1± 0.18 | 22.4± 0.24 |
| 8   | 15.4± 0.03 | 15.4± 0.02 | 15.4± 0.01 | 18.6± 0.36 | 18.3± 0.47 | 18.4± 0.15 |
| 9   | 4.87± 0.01 | 4.86± 0.01 | 4.87± 0.04 | 6.47± 0.08 | 6.38± 0.07 | 6.41± 0.05 |

Table 5: Comparison for \( q(\xi) = (1 - \xi)^2 \)

| bin | DISASTER++ | MEPJET | DISENT | DISASTER++ | MEPJET | DISENT |
|-----|------------|--------|--------|------------|--------|--------|
| 1   | 6.24± 0.02 | 6.22± 0.01 | 6.21± 0.02 | 6.73± 0.13 | 8.94± 0.12 | 6.67± 0.24 |
| 2   | 3.59± 0.01 | 3.58± 0.01 | 3.57± 0.01 | 4.77± 0.06 | 5.24± 0.09 | 4.43± 0.11 |
| 3   | 1.18± 0.004 | 1.18± 0.004 | 1.18± 0.003 | 1.93± 0.04 | 1.89± 0.04 | 1.86± 0.03 |
| 4   | 2.65± 0.007 | 2.65± 0.003 | 2.65± 0.006 | 1.13± 0.03 | 1.66± 0.02 | 0.94± 0.07 |
| 5   | 1.62± 0.004 | 1.61± 0.002 | 1.61± 0.003 | 1.04± 0.04 | 1.09± 0.02 | 0.993± 0.03 |
| 6   | 0.535± 0.001 | 0.534± 0.001 | 0.533± 0.001 | 0.433± 0.018 | 0.412± 0.009 | 0.430± 0.010 |
| 7   | 0.452± 0.002 | 0.452± 0.001 | 0.451± 0.001 | 0.221± 0.026 | 0.292± 0.010 | 0.129± 0.02 |
| 8   | 0.398± 0.001 | 0.398± 0.001 | 0.397± 0.001 | 0.298± 0.01 | 0.271± 0.005 | 0.237± 0.01 |
| 9   | 0.136± 0.001 | 0.135± 0.001 | 0.135± 0.001 | 0.130± 0.003 | 0.109± 0.002 | 0.120± 0.004 |

Table 6: Comparison for \( g(\xi) = (1 - \xi)^2 \)
| bin | DISASTER++ | MEPJET | DISENT | DISASTER++ | MEPJET | DISENT |
|-----|------------|--------|--------|------------|--------|--------|
| 1   | 50.6± 0.12 | 50.7± 0.13 | 50.7± 0.15 | 58.6± 1.29 | 72.9± 1.56 | 54.7± 2.1 |
| 2   | 27.1± 0.05 | 27.1± 0.16 | 27.0± 0.07 | 36.4± 0.57 | 40.0± 0.84 | 34.9± 1.0 |
| 3   | 8.51± 0.02 | 8.51± 0.02 | 8.52± 0.02 | 13.8± 0.35 | 13.3± 0.43 | 13.9± 0.2 |
| 4   | 49.8± 0.10 | 49.7± 0.05 | 49.6± 0.14 | 41.2± 0.55 | 47.2± 0.91 | 41.9± 0.38 |
| 5   | 29.0± 0.05 | 29.0± 0.03 | 28.8± 0.07 | 27.3± 0.52 | 28.2± 0.42 | 26.4± 0.19 |
| 6   | 9.09± 0.01 | 9.07± 0.01 | 9.04± 0.02 | 9.58± 0.06 | 9.16± 0.15 | 9.54± 0.06 |
| 7   | 30.6± 0.08 | 30.5± 0.04 | 30.5± 0.12 | 32.0± 0.34 | 36.3± 0.59 | 32.4± 0.52 |
| 8   | 24.3± 0.04 | 24.3± 0.03 | 24.3± 0.07 | 27.6± 0.56 | 28.4± 0.35 | 27.6± 0.21 |
| 9   | 7.88± 0.01 | 7.86± 0.01 | 7.87± 0.02 | 9.63± 0.21 | 9.50± 0.15 | 9.47± 0.06 |

Table 7: *Comparison for* $q(\xi) = (1 - \xi)$

| bin | DISASTER++ | MEPJET | DISENT | DISASTER++ | MEPJET | DISENT |
|-----|------------|--------|--------|------------|--------|--------|
| 1   | 6.84± 0.02 | 6.84± 0.01 | 6.82± 0.02 | 8.20± 0.25 | 11.6± 0.14 | 8.26± 0.45 |
| 2   | 4.09± 0.01 | 4.07± 0.01 | 4.07± 0.01 | 5.70± 0.11 | 6.69± 0.16 | 5.68± 0.17 |
| 3   | 1.39± 0.004 | 1.39± 0.005 | 1.39± 0.003 | 2.41± 0.07 | 2.33± 0.05 | 2.34± 0.05 |
| 4   | 3.19± 0.01 | 3.19± 0.01 | 3.19± 0.01 | 0.686± 0.09 | 1.65± 0.03 | 0.691± 0.10 |
| 5   | 2.06± 0.005 | 2.06± 0.002 | 2.05± 0.003 | 1.00± 0.08 | 1.14± 0.03 | 0.866± 0.05 |
| 6   | 0.711± 0.001 | 0.710± 0.001 | 0.709± 0.001 | 0.500± 0.006 | 0.471± 0.01 | 0.442± 0.017 |
| 7   | 0.712± 0.003 | 0.711± 0.001 | 0.710± 0.002 | 0.157± 0.026 | 0.373± 0.008 | 0.082± 0.038 |
| 8   | 0.692± 0.002 | 0.690± 0.001 | 0.690± 0.001 | 0.411± 0.020 | 0.408± 0.022 | 0.340± 0.023 |
| 9   | 0.245± 0.001 | 0.245± 0.001 | 0.245± 0.001 | 0.194± 0.012 | 0.172± 0.007 | 0.161± 0.008 |

Table 8: *Comparison for* $g(\xi) = (1 - \xi)$
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