Appendix C

Monte Carlo Models and Generators

C.1 Introduction

This section presents a short description of the basic event generators used in CMS during preparation of PTDR (see CMS "Generator Tools group" for details). A comprehensive review of the present Monte Carlo models and generators is given elsewhere [805]. Note, that only MC generators used in CMS are described here, and a full description of several popular packages (like ISAJET or ACERMC, see [805]) is omitted.

There are several available Monte Carlo event generators for pp, pA, and AA collisions, namely HERWIG [195], HIJING [806], ISAJET [672], PYTHIA [68], and SHERPA [807]. Each of these simulates a hadronic final state corresponding to some particular model of the underlying physics. The details of the implementation of the physics are different in each of these generators, however the underlying philosophy of the generators is the same.

The cross section values and the differential distribution for almost all processes are evalueated as follows:

$$\sigma(pp \to CX) = \sum_{ij} \int f_i^p(x_1, Q^2) f_j^p(x_2, Q^2) \hat{\sigma}(ij \to C) dx_1 dx_2, \qquad (C.1)$$

where $f_i^p(x, Q^2)$ are the Parton Distribution Functions (PDF) of ith parton, that carried a fraction x of the initial proton momentum at a scale (Q^2); $\sigma(ij \to C)$ is the cross section for the hard process (i.e. describing two partons, i and j, interaction).

A general scheme of event generation assumes the evaluation of the hard process (the cross section value, the incoming and outgoing particle's momenta and colours), then evolves the event through a parton showering and hadronisation step, and the decay of the unstable particles. The event information (stored in /HEPEVT/ common block [68]) contains the momenta of the final hadrons, leptons and photons and positions of their decay vertexes. Typically such information contains also the characteristics (momenta, colours, KF-codes, mother's and daughter's relations) of all intermediate partons (quarks, gluons, gauge bosons, unstable physical particles, etc) that provide a trace-back the history of particle production inside of an event. By using an acceptance-rejection methods weighted events can be returned.

Parton showering is based on the expansion around the soft and collinear evolution limits and is often ascribed to either the initial or final state. The algorithm used by HERWIG and SHERPA also include some effects due to quantum interference. The events that have more energy in the parton process have more showering, and consequently more jet activity.

The collection of quarks and gluons must then be hadronised into mesons and baryons. This is done differently in each of the event generators, but is described by a set of (fragmentation) parameters that must be adjusted to agree with experimental results. HERWIG looks for colour singlet collections of quarks and gluons with low invariant mass and groups them together; this set then turns into hadrons. PYTHIA splits gluons into quark-anti-quark pairs and turns the resulting set of colour singlet quark-anti-quark pairs into hadrons via a string model. ISAJET simply fragments each quark independently paying no attention to the colour flow.

The dominant cross-section at the LHC consists of events with no hard scattering. There is little detailed theoretical understanding of these minimum-bias events and the event generators must rely on present data. These minimum-bias events are important at LHC, particularly at design luminosity, as they overlap with interesting hard-scattering events. The generators use a different approach in this case. HERWIG uses a parametrisation of data mainly from the CERN $p\bar{p}$ Collider. PYTHIA uses a mini-jet model where the jet cross-section is used at very low transverse momenta, i.e the hard scattering process is extrapolated until it saturates the total cross-section. CMS has used the PYTHIA approach with dedicated modifications that agree with present data from Tevatron [68]. The model of the hadronic interactions implemented in the physics generator has a direct impact on physical observables such as jet multiplicity, their average transverse momentum, internal structure of the jets and their heavy flavour content. This led to the choice to use PYTHIA for most processes, allowing for a consistent set of signal and background events to be generated.

Table C.2 presents the predicted cross-section values for the basic SM processes, as used in the simulations for PTDR. The cross-section values (at leading order) were calculated by using PYTHIA 6.327 with CTEQ5L (default PDF for PTDR) and with CTEQ6M PDFs. α_s at 1st (2nd) order is used with CTEQ5L (CTEQ6M) PDFs. For CTEQ6M the quoted errors are related to the uncertainties due to PDFs (see Subsection B.1.9).

C.2 General scheme of generator usage in CMS

All event generators, included in CMS simulation software, can be separated into two groups.

The first group (HERWIG, HIJING, ISAJET, PYTHIA) provides the *full simulation* of events. The basic package explored in CMS is PYTHIA and only few specific processes were simulated with HERWIG or HIJING.

Pure schematically the data flow in PYTHIA and HERWIG is presented on Fig. C.1.

After initialisation the package (HERWIG or PYTHIA) calls "hard process" routines (see "1" arrow lines on Fig. C.1). Then information (the momenta of initial and final partons, the colours and KF-codes) is passed to package for parton showering, hadronisation, fragmentation and decays of the unstable particles.

However, all these "full event simulation" generators have very limited number of the hard process matrix elements (typically for $2 \rightarrow 2$ reaction at LO). Therefore, several special generators are used for simulation of many other LO processes. In fact, such packages generate the hard processes kinematic quantities, such as masses and momenta, the spin, the colour connection, and the flavour of initial- and final-state partons. The information is stored in the "Les Houches" format [808] (/HEPEUP/ common block) and is passed to full event simulation package like PYTHIA or HERWIG (see thick "output" line on Fig. C.1).

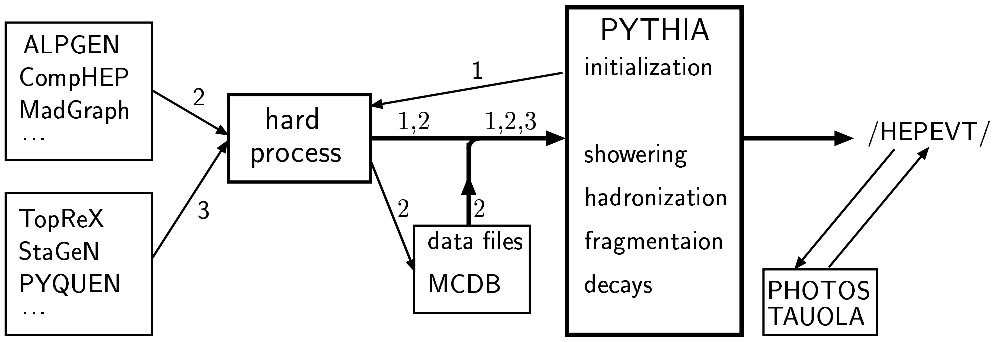

Figure C.1: Pure schematically data flow in PYTHIA and HERWIG.

Three generators, namely ALPGEN [160], COMPHEP [354], and MADGRAPH [80, 493], are widely used for simulation of many processes, especially for the generation of the hard processes with multi-jet final states. For example, ALPGEN allows to generate $Q\bar{Q}$ pair production with up to 6 jets. Due to the complexity of the matrix elements, describing the multi-jet processes, and a re-weighting procedure the generation of events is very CPU-time consuming. As a result, the information with kinematics is stored in the output files. (see "2" lines on Fig. C.1). Then, like in a generic PYTHIA process, such information is passed to PYTHIA (see thick "output" line on Fig. C.1).

There are several *"dedicated generators"*, TOPREX [44], STAGEN, SINGLETOP, COSMIC, SIMUB, PHASE, PYQUEN [809, 810], HYDJET [811], EDDE. These generators are used for simulation of several specific process (see below for a short description of these codes). The information with hard processes kinematic quantities is stored in /HEPEUP/ common block [808] and is passed to the "full event simulation" package (see "3" lines on Fig. C.1).

After full simulation of event with PYTHIA or HERWIG the output information is stored in the /HEPEVT/ common block. In addition two *special functionality* codes provide a better description of photon radiation from a charge final particles (PHOTOS [39]) and $\tau^{\pm}$-lepton decays (TAUOLA [154]). Typically, these codes read information from /HEPEVT/ common, perform simulation and then add generated information (new particles) into the /HEPEVT/ common block (see Fig. C.1).

C.3 CMKIN

Almost all generators available in CMS could be used with the CMKIN package. Now the CMKIN is used for OSCAR and FAMOS detector simulation input. This software package provides a common interface between physics event generators and CMS detector simulation (see Fig. C.2). It also provides an environment to make physics plots of generated events. CMKIN provides an interface to a number of physics generators like PYTHIA, ISAJET and HERWIG. It also offers the possibility to use different 'external generators' like ALPGEN [160], COMPHEP [354], MADGRAPH [80, 493] and TOPREX [44]. Cosmic muon simulation is available as well. Simple particle generation is also included, *i.e.* single and double particles as well as simple multi particle events. The interface is based on a common block HEPEVT - a HEP standard to store particle kinematics information for one event [68]. The

/HEPEVT/ common block is converted to HBOOK n-tuples. The event output format follows the HEPEVT standard and additional information can be included by the user in the block /MC_PARAM/.

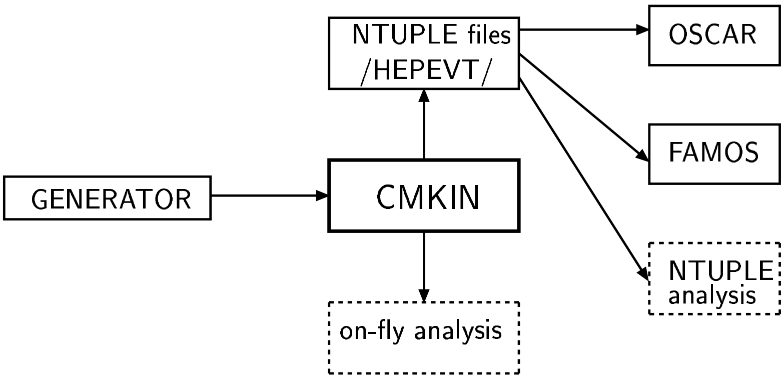

Figure C.2: Illustration of the CMKIN interface.

There is a unified compilation script which is used as follows:

```
kine_make_ntpl.com <generator> [lhapdf]
```

where the first parameter can have one of the following values: *pythia, herwig, isajet, simple, single, double, simplemulti, cosmic, comphep, alpgen, madgraph, phase, toprex* or *stagen*. The optional second parameter *lhapdf* is given when the user wants to use LHAPDF library [94].

C.4 Full event simulation generators

C.4.1 PYTHIA

The PYTHIA package [68] is a general-purpose generator for hadronic events in pp, e^+e^- and ep colliders. It contains a subprocess library and generation machinery, initial- and final-state parton showers, underlying event, hadronisation and decays, and analysis tools. PYTHIA contains around 240 different $2 \to 2$ (and some $2 \to 1$ or $2 \to 3$) subprocesses, all at leading order. The subsequent decays of unstable resonances (W, Z, top, Higgs, SUSY, ...) brings up the partonic multiplicity, for many processes with full spin correlations in the decays. The external processes can be evolved through the showering and hadronisation (like internal ones).

The final-state shower is based on forward evolution in terms of a decreasing timelike virtuality m^2, with angular ordering imposed by veto. The framework is leading-log, but includes many NLL aspects such as energy–momentum conservation, $\alpha_s(p_\perp^2)$ and coherence. Further features include gluon polarisation effects and photon emission.

The initial-state shower is based on backward evolution, i.e. starting at the hard scattering and moving backwards in time to the shower initiators, in terms of a decreasing spacelike virtuality Q^2. Initial and final showers are matched to each other by maximum emission cones.

The composite nature of hadrons (and resolved photons) allows for several partons from each of the incoming hadrons to undergo scatterings. Such multiple parton–parton interactions are instrumental in building up the activity in the underlying event, in everything from charged multiplicity distributions and long-range correlations to minijets and jet pedestals. The interactions are described by perturbation theory, approximated by a set of more or less separate $2 \to 2$ scatterings; energy conservation and other effects introduce (anti)correlations. The scatterings are colour-connected with each other and with the beam remnants.

The Lund string model, used for hadronisation, is based on a picture with linear confinement, where (anti)quarks or other colour (anti)triplets are located at the ends of the string, and gluons are energy and momentum carrying kinks on the string. The string breaks by the production of new $q\bar{q}$ pairs, and a quark from one break can combine with an anti-quark from an adjacent one to form a colour singlet meson.

Unstable particles are allowed to decay. In cases where better decay models are available elsewhere, e.g. for $\tau^{\pm}$ with spin information or for B hadrons, such decays can be delegated to specialised packages.

At present the parameters from almost all PYTHIA common blocks (see `BLOCK DATA PYDATA`) could be set via data cards. With the CMKIN these parameters could be set in data card file with the following format (note, that only capital letters should be used):

PYTHIA	CMKIN	comment
	parameter	
MSEL = 6	MSEL 6	$t\bar{t}$ production
	one- and two-dimensional arrays	
CKIN(1) = 100.	CKIN 1 = 100.	min. $\sqrt{\hat{s}}$
i.e. PMAS(6,1) = 178.	PMAS 6,1 = 178.	top-quark mass

• *Common cards for* CMKIN

Below we present a list of PYTHIA parameters used for full event simulation for PTDR. Some of these parameters correspond to the old multiple interactions scenario, namely *Tune A* [812].

`MSTP(2)` = 1 : 1(first)/2(second) order running α_s

`MSTP(33)` = 0 : do not include of K-factors in hard cross sections

`MSTP(51)` = 7 : PDF set (here is CTEQ5L)

`MSTP(81)` = 1 : multiple parton interactions is switched ON

`MSTP(82)` = 4 : defines the multiple parton interactions model

`PARP(67)` = 1. : amount of initial-state radiation

`PARP(82)` = 1.9 : P_T cut-off for multi-parton interactions

`PARP(83)` = 0.5 : fraction of total hadronic matter in core

`PARP(84)` = 0.4 : radius of core

`PARP(85)` = 0.33 : gluon production mechanism in multiple interactions

`PARP(86)` = 0.66 : gluon prod. mechanism in multiple interactions

`PARP(88)` = 0.5

`PARP(89)` = 1000. : reference energy scale for which `PARP(82)` is set

`PARP(90)` = 0.16 : effective P_T cut-off = [PARP(82)/PARP(89)]**PARP(90)

`PARP(91)` = 1.0 : width of Gaussian primordial $k_\perp$ distribution inside hadron

`PARJ(71)` = 10. : maximum average $c\tau$ for particles allowed to decay

`MSTJ(11)` = 3 : choice of the fragmentation function

`MSTJ(22)` = 2 : allow to decay those unstable particles

`PMAS(5,1)` = 4.8 : the mass of the b-quark

`PMAS(6,1)` = 175.0 : the mass of the t-quark

C.4.2 HERWIG

HERWIG contains a wide range of Standard Model, Higgs and supersymmetric processes [195]. HERWIG uses the parton-shower approach for initial- and final-state QCD radiation, including colour coherence effects and azimuthal correlations both within and between the jets.

In the treatment of supersymmetric processes, HERWIG itself doesn't calculate the SUSY mass spectrum or decay rates, but reads in an input file containing the low-energy parameters (masses, couplings, decays, ...). This file can be written by hand or more conveniently be generated with the ISAWIG program. This program provides an interface to ISAJET (and therefore to all models in ISASUSY and ISASUGRA), to HDECAY (for NLO Higgs decays), and can also add R-parity violating decays.

Colour coherence effects of (initial and final) partons are taken into account in all hard subprocesses, including the production and decay of heavy quarks and supersymmetric particles. HERWIG uses the angular ordered parton shower algorithm which resumes both soft and collinear singularities. HERWIG includes spin correlation effects in the production and decay of top quarks, tau leptons and supersymmetric particles. For the SUSY decays, there is an option for using either the matrix elements (fast) or the full spin correlations. HERWIG uses a cluster hadronisation model based on non-perturbative gluon splitting, and a similar cluster model for soft and underlying hadronic events. This model gives a good agreement with the LEP data on event shapes, but doesn't fit the identified particle spectrum well.

C.4.3 ISAJET

ISAJET is a Monte Carlo program which simulates pp, $\bar{p}p$, e^+e^- interactions at high energies [672]. ISAJET is based on perturbative QCD plus phenomenological models for parton and beam jet fragmentation. At CMS ISAJET is used for calculations of SUSY parameters.

C.4.4 HIJING

Hard or semi-hard parton scatterings with transverse momentum of a few GeV/c are expected to dominate high energy heavy ion collisions. The HIJING (Heavy Ion Jet INteraction Generator) Monte Carlo model [806] was developed by M. Gyulassy and X.-N. Wang with special emphasis on the role of minijets in pp, pA and AA reactions at collider energies.

Detailed systematic comparison of HIJING results with a very wide range of data demonstrates that a quantitative understanding of the interplay between soft string dynamics and hard QCD interaction has been achieved. In particular, HIJING reproduces many inclusive spectra two particle correlations, and can explain the observed flavour and multiplicity dependence of the average transverse momentum.

C.5 Tree level matrix element generators

C.5.1 ALPGEN

ALPGEN is designed for the generation of Standard Model processes in hadronic collisions, with emphasis on final states with large jet multiplicities [160]. It is based on the exact leading order evaluation of partonic matrix elements and t and gauge boson decays with helicity correlations. The code generates events in both a weighted and unweighted mode. Weighted generation allows for high-statistics parton-level studies. Unweighted events can be processed in an independent run through shower evolution and hadronisation programs.

The current available processes are:

- $W/Z/H\, Q\bar{Q} + N$ jets ($Q = c, b, t$) with $N \leq 4$
- $Q\bar{Q} + N$ jets, with $N \leq 6$
- $Q\bar{Q}Q'\bar{Q}' + N$ jets, with $N \leq 4$
- $W +$ charm $+ N$ jets, with $N \leq 5$
- N jets, $W/Z + N$ jets, with $N \leq 6$
- $nW + mZ + lH + N$ jets, with $n + m + l + N \leq 8$, $N \leq 3$
- $N\gamma + M$ jets, with $N \geq 1$, $N + M \leq 8$ and $M \leq 6$
- $H + N$ jets ($N \leq 4$), with the Higgs produced via ggH vertex
- single top production.

C.5.2 COMPHEP

COMPHEP [813] is a package for evaluating Feynman diagrams, integrating over multiparticle phase space and generating events with a high level of automation. COMPHEP includes the Feynman rules for SM and several versions of MSSM (SUGRA,GMSB,MSSM with R-parity violation).

COMPHEP computes squared Feynman diagrams symbolically and then numerically calculates cross sections and distributions. After numerical computation one can generate the unweighted events with implemented colour flow information. The events are in the form of the Les Houches Accord event record [808] to be used in the PYTHIA program for showering and hadronisation.

COMPHEP allows for the computation of scattering processes with up to 6 particles and decay processes with up to 7 particles in the final state.

C.5.3 MADGRAPH and MADEVENT

MADEVENT [80] is a multi-purpose, tree-level event generator which is powered by the matrix element generator MADGRAPH [493]. Given a user process, MADGRAPH automatically generates the amplitudes for all the relevant subprocesses and produces the mappings for the integration over the phase space. This process-dependent information is packaged into MADEVENT, and a stand-alone code is produced. It allows the user to calculate cross sections and to obtain unweighted events automatically. Once the events have been generated – event information, (*e.g.* particle id's, momenta, spin, colour connections) is stored in the "Les Houches" format [808]. Events may be passed directly to a shower Monte Carlo program (interfaces are available for HERWIG and PYTHIA).

The limitation of the code are related to the maximum number of final state QCD particles. Currently, the package is limited to ten thousand diagrams per subprocess. So, for example, W+5 jets is close to its practical limit. At present, only the Standard Model Feynman rules are implemented and the user has to provide his/her own rules for beyond Standard Model physics, such as MSSM.

C.5.4 TOPREX

The event generator TOPREX [44] provides the simulation of several important processes in pp and $p\bar{p}$ collisions, not implemented in PYTHIA. In the matrix elements used in TOPREX the decays of the final t-quarks, $W^{\pm}$, Z and charged Higgs bosons are also included. The final top quark could decay into SM channel ($t \to qW^{+}$, $q = d, s, b$), b-quark and charged Higgs ($t \to bH^{+}$) and the channels with flavour changing neutral current (FCNC): $t \to u(c)\ V$, $V = g$, γ, Z. The implemented matrix elements take into account spin polarisations of the top quark, that provides a correct description of the differential distributions and correlations of the top quarks decay products.

C.6 Supplementary packages

C.6.1 PHOTOS

PHOTOS is a universal package to simulate QED photon radiative corrections [39]. The precision of the generation may in some cases be limited, in general it is not worse than the complete double bremsstrahlung in LL approximation. The infrared limit of the distributions is also correctly reproduced. The action of the algorithm consists of generating, with internally calculated probability, bremsstrahlung photon(s), which are later added to the `/HEPEVT/` record. Kinematic configurations are appropriately modified. Energy-momentum conservation is assured. When using PHOTOS, the QED bremsstrahlung of the principal generator must be switched off. For example in case of PYTHIA one has to use `MSTJ 41=1`.

C.6.2 TAUOLA

TAUOLA is a package for simulation of the $\tau^{\pm}$-lepton decays [154]. It uses the PHOTOS package to simulate radiative corrections in the decay. The TAUOLA interface is made with the PYTHIA generator. This interface evaluates also the position of τ-lepton decay (i.e. the information on the production vertex of the decay products of τ-lepton).

C.6.3 PYQUEN

The event generator PYQUEN (PYthia QUENched) [809, 810] provides the simulation of rescattering and energy loss of hard partons in dense QCD-matter (quark-gluon plasma) created in ultrarelativistic heavy ion collisions. The approach relies on an accumulative energy losses, when gluon radiation is associated with each scattering in expanding medium together including the interference effect by the modified radiation spectrum $dE/d\ell$ as a function of decreasing temperature T. The model is implemented as fast Monte-Carlo tool, to modify standard PYTHIA jet event.

C.6.4 HYDJET

The event generator HYDJET [811] (HYDrodynamics + JETs) provides the fast simulation of heavy ion events at LHC energy including longitudinal, transverse and elliptic flow effects together with jet production and jet quenching (rescattering and energy loss of hard partons in dense QCD-matter, quark-gluon plasma). The model merges a fast generator of flow effects HYDRO [814] with PYTHIA (for jet production) and PYQUEN [809, 810] (for jet quenching) by simulating full heavy ion event as a superposition of soft, hydro-type state and hard multi-jets.

First of all, HYDJET calculates the number $N^{\mathrm{h}ard}$ of hard nucleon-nucleon sub-collisions and number $N^{\mathrm{p}art}$ nucleons-participants (at given impact parameter b of AA collision and minimum P_T of hard parton scattering) and generates the initial parton spectra by calling PYTHIA $N^{\mathrm{h}ard}$ times (fragmentation off). After each jet parton affected by medium-induced rescattering and energy loss according with PYQUEN model. In the end of each PYTHIA sub-event adding new (in-medium emitted) gluons into PYTHIA parton list and rearrangements of partons to update string formation are performed. Then PYQUEN forms final hadrons with PYEXEC subroutine (fragmentation on). Finally, HYDJET calculates the multiplicity of soft, hydro-induced part of the event and add new particles in the end of the event record.

C.7 K-factors for dilepton production

Some event generators such as PYTHIA do not employ the most advanced matrix-element calculations. They must be reasonably fast since in most applications, many millions of events must be generated. Experimenters apply an *ad-hoc* correction or "kludge" called the K-factor so that the cross-section value used for, say, the production of muon pairs, is correct. This K-factor amounts to the ratio of a highly accurate cross-section calculation to a less accurate one, typically a leading-order calculation:

$$K_{\mathrm{NLO}} = \frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}} \qquad \text{and} \qquad K_{\mathrm{NNLO}} = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}}.$$

Clearly the K-factor reflects the accuracy of the better theoretical calculation, and there can be significant differences between K_{NNLO} and K_{NLO}. The most significant contributions to the K-factor come from QCD radiative corrections are expected to be on the order of 10% or more. Usually one does not include electroweak radiative corrections in the K-factor.

We have examined the K-factor for the Drell-Yan production of charged lepton pairs, as well as the signal for new Z' neutral gauge bosons. The program PHOZPRMS is used to compute mass-dependent cross-sections [347], and a generalised version called WUWD is used to study Z' cross-sections [815]. We checked carefully the differential cross-section, $d\sigma/dM$ obtained from PHOZPRMS with the program RESBOS [816, 817] and found very good agreement. We use the MRST parton distribution functions [818] for these calculations. Very similar results are obtained using CTEQ6M [12].

Usually experimenters use a constant value for the K-factor, but in fact this is not accurate. The variation of the K-factor with mass is substantial, as shown in Fig. C.3. (There is a similar, though different, variation in the K-factor for Drell-Yan production at the Tevatron

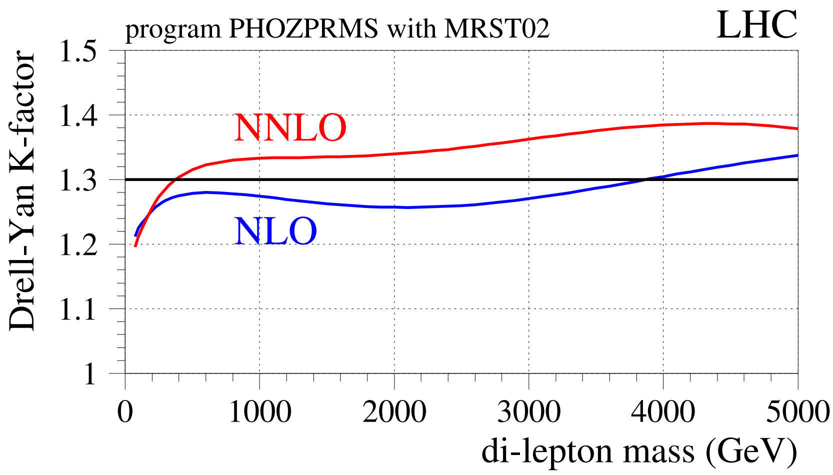

Figure C.3: *K-factors as a function of mass for the LHC*

– see Fig. C.4.) Notice that $K_{\rm NLO} \neq K_{\rm NNLO}$, in general, and the difference can be as large as 7%. A number of values for the K-factor are listed in Table C.1.

It is customary to take the difference $K_{\rm NNLO} - K_{\rm NLO}$ as a measure of the theoretical uncertainty due to missing higher orders. According to the results obtained with PHOZPRMS, this uncertainty is on the order of 5%. It is interesting to compare this to the uncertainty coming from the parton distribution functions (PDF's). We used the CTEQ6M set which contains "error" PDF's with which one can estimate this uncertainty [12]. The relative uncertainty of the Drell-Yan cross-section as a function of mass is shown in Fig. C.5. The positive and negative variations of the cross-section were summed separately. The error bands show the full uncertainty obtained from the twenty error-PDF's – no rescaling was done to take into account the fact that these error-PDF's correspond to 2σ variations of the PDF parameters. One sees that the PDF uncertainty varies from about 3% at low masses to 20% toward the upper reach of the LHC. Of course, these uncertainties will be reduces as data from HERA, the Tevatron and fixed-target experiments are used to improve the PDF's.

The variation of the K-factors with mass comes in part because of the Z-resonance. The size of the Z-peak relative to the continuum production of lepton pairs is therefore relevant. This relative size depends on the coupling of the Z-boson to the up and down quarks in the proton. There is practically no uncertainty on those couplings, and they are completely determined in the Standard Model. However, if a new Z' resonances is present, its couplings will not be known *a priori*. Thus it is interesting to consider to what extent the K-factor will depend on those couplings.

We have considered two examples of possible Z' resonances, and computed $K_{\rm NLO}$ as a function of the resonance mass, as shown in Fig. C.6. The first model, labelled "η," illustrates the case of a Z' which couples primarily to up-quarks, and the second one, labelled "I," couples mainly to down-quarks [815]. As is clear from the figure, the radiative corrections as a function of mass are quite different in these two extreme cases. Thus, there will be an ambiguity in the cross-section measurement of a new Z' resonance at the level of about 5% until the relative couplings of that Z' to up and down quarks can be established.

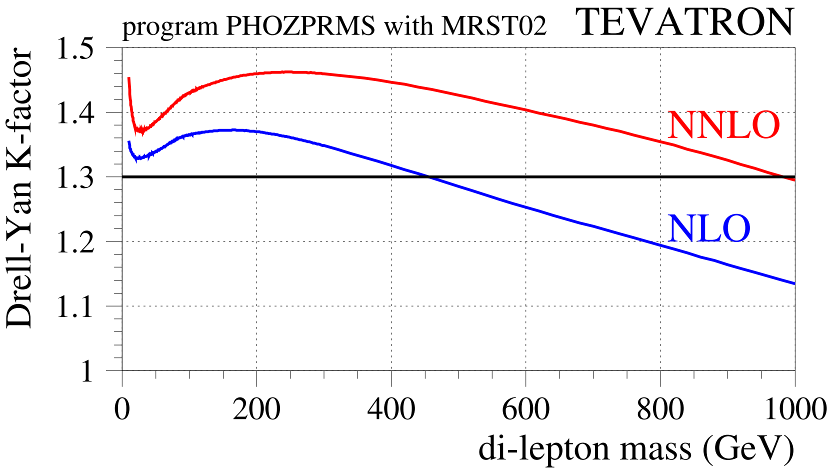

Figure C.4: *K-factors as a function of mass for the Tevatron*

Table C.1: Values for K_{NNLO}, K_{NLO} and $K_{\mathrm{NNLO}}/K_{\mathrm{NLO}}$ as a function of mass

mass (GeV/c^2)	K_{NNLO}	K_{NLO}	$K_{\mathrm{NNLO}}/K_{\mathrm{NLO}}$
100	1.212	1.225	0.989
200	1.256	1.252	1.003
300	1.286	1.268	1.014
400	1.303	1.275	1.022
600	1.323	1.280	1.033
800	1.330	1.278	1.040
1000	1.333	1.274	1.046
2000	1.339	1.257	1.065
3000	1.362	1.270	1.073
4000	1.385	1.304	1.061
5000	1.378	1.338	1.031

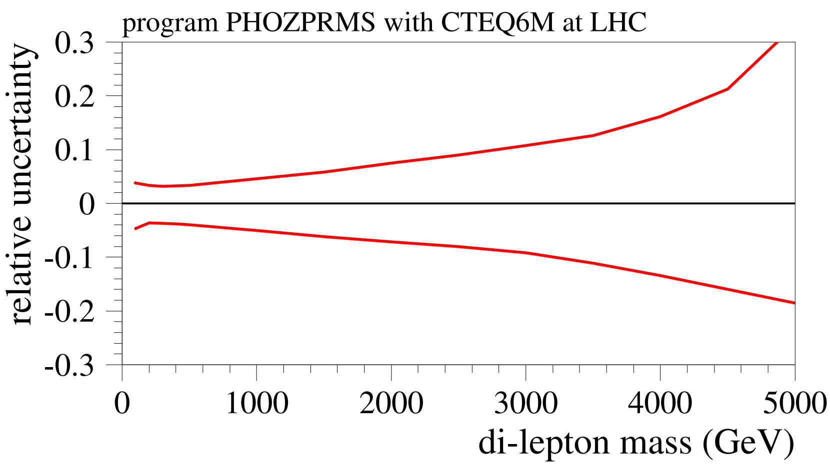

Figure C.5: Uncertainty from the parton distribution functions, evaluated using the CTEQ6M set.

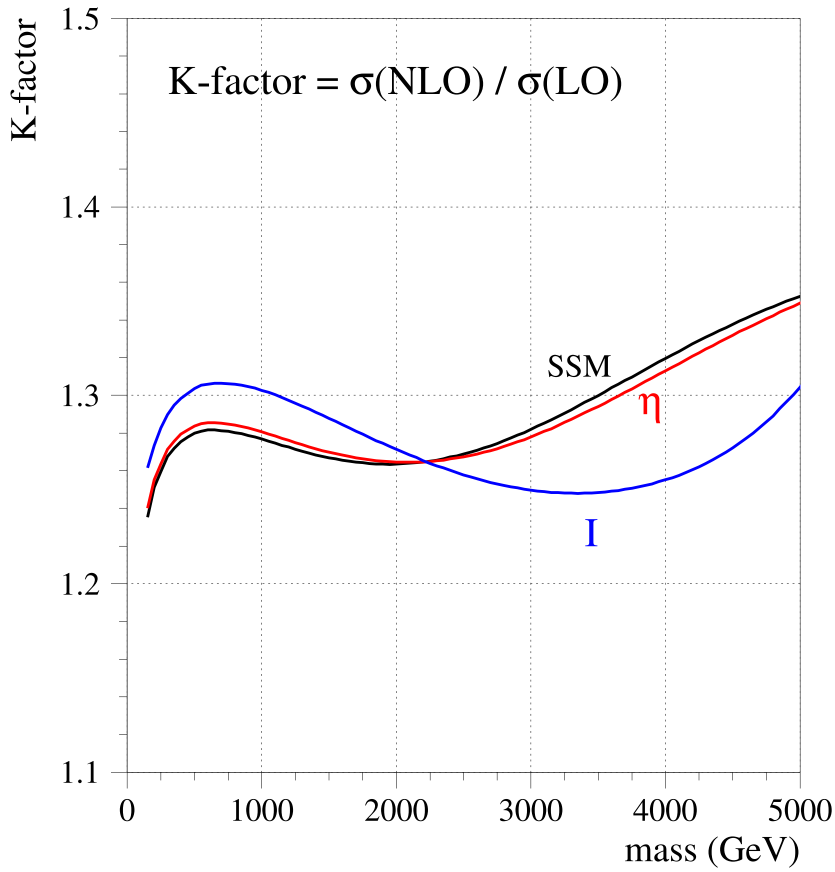

Figure C.6: K-factors as a function of mass of a new Z' resonance, for two cases: η and I (see text). The curve 'SSM' refers to a sequential Standard Model Z'

Table C.2: Leading order cross sections for some typical process at the LHC calculated by using PYTHIA 6.327 with CTEQ5L (default PDF for PTDR) and with CTEQ6M PDFs. P_0 denotes $\hat{p}_T$-min. for the hard process

process	**cross section**	**comment**	
$\sigma_{\rm tot}(pp \to X)$	110 ± 10 mb	different models	
$\sigma_{\rm tot}(pp \to X)$	$111.5 \pm 1.2^{+4.1}_{-2.1}$ mb	COMPETE Coll.	
process	CTEQ5L	CTEQ6M	**comment**
Z-boson	48.69 nb	$50.1^{+4.19\%}_{-4.76\%}$ nb	
$Z+$jet($g+q$)	13.94 nb	$12.73^{+3.16\%}_{-3.94\%}$ nb	$P_0 = 20$ GeV
$q\bar{q} \to Z\,\gamma$	44.21 pb	$46.7^{+3.93\%}_{-4.22\%}$ nb	$P_0 = 20$ GeV
$W^{\pm}$-boson	158.5 pb	$161.3^{+4.32\%}_{-4.93\%}$ nb	
$W^{\pm}+$jet($g+q$)	41.42 nb	$37.24^{+3.34\%}_{-4.10\%}$ nb	$P_0 = 20$ GeV
$W^{\pm}\,\gamma$	56.21 pb	$56.42^{+4.11\%}_{-4.38\%}$ nb	$P_0 = 20$ GeV
W^+W^-	69.69 pb	$75.0^{+3.87\%}_{-4.03\%}$ pb	
$W^{\pm}Z$	26.69 pb	$28.76^{+3.93\%}_{-4.08\%}$ pb	
$q\bar{q} \to ZZ$	11.10 pb	$10.78^{+4.02\%}_{-4.21\%}$ pb	
$WQ\bar{Q}$	$m_b = 4.8$ GeV, $m_c = 1.5$ GeV, TopReX		
$W^{\pm}c\bar{c}$	1215 pb	$1086^{+4.12\%}_{-4.53\%}$ pb	$M_{c\bar{c}} \geq 3.0$ GeV
$W^{\pm}c\bar{c}$	33.5 pb	$31.3^{+4.00\%}_{-4.18\%}$ pb	$M_{c\bar{c}} \geq 50$ GeV
$W^{\pm}b\bar{b}$	328 pb	$297^{+4.04\%}_{-4.37\%}$ pb	$M_{b\bar{b}} \geq 9.6$ GeV
$W^{\pm}b\bar{b}$	34.0 pb	$31.3^{+4.00\%}_{-4.18\%}$ pb	$M_{b\bar{b}} \geq 50$ GeV
$Zb\bar{b}$, $m_b = 4.62$ GeV	789.6 ± 3.66 pb	MCFM	$M_{b\bar{b}} \geq 9.24$ GeV
dijet processes	819 μb	$583^{+4.78\%}_{-6.02\%}$ μb	$P_0 = 20$ GeV
$\gamma+$jet	182 nb	$135^{+4.92\%}_{-6.14\%}$ nb	$P_0 = 20$ GeV
$\gamma\,\gamma$	164 pb	$137^{+4.62\%}_{-5.65\%}$ pb	$P_0 = 20$ GeV
$b\bar{b}$, $m_b = 4.8$ GeV	479 μb	$187^{+9.7\%}_{-13.2\%}$ μb	
$t\bar{t}$, $m_t = 175$ GeV	488 pb	$493^{+3.24\%}_{-3.31\%}$ pb	
$t\bar{t}$, $m_t = 175$ GeV	830 ± 90 pb	NLO+NNLO	
$t\bar{t}\,b\bar{b}$	10 pb		AcerMC 1.2
inclusive Higgs	$m_H = 150$ GeV	23.8 pb	
inclusive Higgs	$m_H = 500$ GeV	3.8 pb	