

# MC generators in CHORUS

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This note presents an overview of general-purpose and specific Monte-Carlo event generators used in the simulation of the CERN - CHORUS experiment, aiming to search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations and charm particle decays in an emulsion target.

## 1. Introduction

CHORUS is an experiment primarily designed to search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations in the CERN wide-band neutrino beam. It also aims to investigate a wide range of charm physics. In four years of exposure, more than  $10^6$  neutrino interactions have been accumulated in the emulsion target, out of which several thousands lead to the production of a charmed particle. Using its massive calorimeter as a target, CHORUS also has a potential to study other neutrino physics for which large statistics is the crucial point.

Monte-Carlo (MC) simulation is an essential part of the experiment. It includes a detailed model of the neutrino beam, generation of neutrino events, full GEANT-based simulation of the detector response and the reconstruction.

This report is organized as follows. In Section 2, a brief description of the CHORUS physics and experimental set-up is given. The MC procedure is reviewed in Section 3. Section 4 is devoted to general-purpose event generators and their verification on the existing experimental data. In Section 5, more specific generators are considered.

## 2. CHORUS: physics and set-up

The CHORUS detector [1] is a hybrid setup. A 770-kg nuclear emulsion is used as the primary target for neutrino interactions, allowing three-dimensional reconstruction of short-lived particles like the  $\tau$  lepton and any charmed hadron. The emulsion target consists of four stacks. Each stack is followed by three interface emulsion sheets and by a set of scintillating fibre tracker

planes. They provide accurate predictions of particle trajectories into the emulsion stack for the location of vertex positions. The emulsion scanning is performed by fully automatic microscopes equipped with CCD cameras and a read-out system. The electronic detectors downstream of the emulsion target include a hadron spectrometer which measures the bending of charged particles in an air-core magnet, a 100t calorimeter where the energy and direction of showers are measured and a muon spectrometer which determines charge and momentum of muons. In addition, the calorimeter was used as an active (lead) target for neutrino events.

The West Area Neutrino Facility at CERN provides a beam of 27 GeV average energy consisting mainly of  $\nu_\mu$  with a 5%  $\bar{\nu}_\mu$  contamination. During the four years of operation, emulsion target material was exposed to the beam with an integrated intensity which corresponds to  $5.06 \times 10^{19}$  protons on target. The data from the electronic detectors were analysed and the events possibly originating from the emulsion stacks were identified.

Since the CHORUS experiment was designed primarily to search for  $\nu_\mu \rightarrow \nu_\tau$  oscillation, the data selection for the first phase of the analysis was optimized for the detection of a  $\tau$  decaying into a single charged particle. It allowed to reach the limit on the  $\nu_\mu \rightarrow \nu_\tau$  oscillation probability as  $P_{\mu\tau} \leq 3.4 \times 10^{-4}$  at large  $\Delta m^2$  value [2]. CHORUS has also seen neutrino induced diffractive  $D_s^*$  production [3] and charm pair production in charged-current (CC) interactions [4]. In addition, with the calorimeter target, neutral-current (NC) production of  $J/\psi$  was observed [5] and preliminary results on differential cross-sections and

structure functions on lead were obtained [6].

Recently, the second phase of CHORUS scanning and analysis has been started. It is based on new reconstruction software and improved MC packages. The key point is the new emulsion scanning method called 'netscan'. This method, originally developed for the DONUT experiment [7], consists of recording all track segments within a large angular acceptance in a volume surrounding the located vertex position. It can improve the limit on the  $\nu_\mu \rightarrow \nu_\tau$  oscillation probability by a factor of 3 to reach the design goal. In the second phase, a search for charm decays in the emulsion is also performed. Several thousands of such events are expected to be located. Based on a small part of the statistics, the  $D^0$  production cross section has already been measured with an accuracy better than 10% [8]. The following charm physics is of interest:

- meson rates, branching ratios for different channels, extraction of CKM matrix elements  $|V_{cd}|$  and  $|V_{cs}|$ , strange sea of the nucleon and fragmentation functions;
- charmed baryon production and decays;
- diffractive production of  $D_s^*$  to measure different branching ratios and determine  $|V_{cs}|$ ;
- associated charm production;
- rare charm decays.

With the calorimeter as a target, it is possible to measure  $d^2\sigma/dx dy$  and structure functions from  $\nu_\mu$  and  $\bar{\nu}_\mu$  interactions on lead, to study dimuon production and to search for rare processes. Potentially the same tasks can be also fulfilled using the first two magnets of the iron muon spectrometer as an active target. In addition, with a set of lead, iron, marble and plastic targets<sup>1</sup> placed in the neutrino beam ratios of CC total cross-sections are being determined.

### 3. CHORUS MC simulation procedure

The procedure of MC simulation in the CHORUS experiment consists of modelling the neu-

<sup>1</sup>At the end of experiment the emulsion target was replaced by this set of 4 targets.

trino beam, the generation of physical events, the simulation of the detector response and the reconstruction.

#### 3.1. Simulation of the neutrino beam

Parent mesons for neutrinos, modelled with FLUKA [9] by NOMAD [10], are fed into the CHORUS GEANT 3.21-based [11] neutrino beam simulator called GBEAM [12]. It performs tracking of these mesons through the neutrino tunnel and models their decays into neutrinos. The output of the simulation is the flavour, the creation-vertex and the four-momentum of the neutrino.

#### 3.2. Generation of physical events

Deep-inelastic (DIS) events are simulated with the JETTA [13] package. (Quasi)-elastic (QE) processes and resonance production are modelled with the RESQUE [14] code. Information about these general-purpose packages can be found in Section 4. For specific processes, dedicated generators were developed (Section 5). All event generators use incoming neutrino information produced by GBEAM. Their output is similar to the LUND LUJETS common block [15] (particle codes, momenta, vertices and history).

#### 3.3. Simulation of the detector response

The package which simulates the detector response, called Efficass (Emulsion Fibers Calorimeter and Spectrometer Simulation), contains a very detailed description of the detector geometry in the GEANT 3.21 framework. The longitudinal vertex positioning is performed with a special geantino-based algorithm in accordance with the material density the neutrino traverses. Efficass digitizes GEANT hits in each active volume of the CHORUS detector subsystem. Its output, similar to what is produced by the data acquisition system, is sent to the reconstruction program.

### 4. General-purpose generators

#### 4.1. JETTA

JETTA (JETs in Tau Analysis) [13] was written for the CHORUS kinematical pre-selection of events by embedding into a general DIS generator (LEPTO 6.1 [16]) the formalism of Ref. [17]

to describe interactions with a massive charged lepton (5 structure functions). The code takes care of the polarization effects of the outgoing lepton also with respect to its decays by using the TAUOLA [18] package. The rest, is plain JETSET [15] code, tuned on the BEBC data [19,20] and it deals reasonably well with some charm production aspects and different interactions (NC and CC). JETTA generates DIS events ( $W^2 \geq 2 \text{ GeV}^2$ ) initiated by  $\nu_e$ ,  $\nu_\mu$  or  $\nu_\tau$  with energies in the region of  $3 \div 300 \text{ GeV}$ . Structure functions GRV94LO [21] are used by default, other choices are possible via steering cards. Nucleon composition of the target and Fermi motion are also taken into account. JETTA is able to simulate events of specific classes like open charm and dimuon production. Threshold behaviour of the cross section due to the non-zero charm quark mass ( $m_c$ ) is introduced but without slow rescaling. The Peterson longitudinal fragmentation function [22] with  $\varepsilon = 0.072$  [23] is used for charm quark hadronization.

JETTA reproduces reasonably well neutrino bubble chamber experimental data on charged track multiplicities, transverse shower development, pion energies and fragmentation functions for hadrons. It was also checked on our CC, charm and dimuon data obtained both with emulsion and calorimeter targets.

#### 4.2. RESQUE

RESQUE [14], an event generator for RESonance and (QUasi)Elastic events, has been derived from a preexisting code. Computation of cross sections, as well as the routines which describe resonance decays have been adapted from the Soudan-II RSQ generator [24]. The main changes concern:

- significant extension of the energy range for the calculation of cross-sections and for the generation of events;
- the incorporation of nuclear effects, Fermi motion [25] and Pauli suppression;
- the inclusion of  $\nu_\tau$  interactions, and  $\tau$  decays, taking into account the polarization of the lepton in the final state.<sup>2</sup>

<sup>2</sup>It is assumed that the generated  $\tau$  has always helicity -1 as obtained from an extrapolation from DIS case [17].

Three nucleon formfactors are used in the calculation of QE CC cross section [26]. The fourth formfactor which is proportional to mass squared of the outgoing lepton, is taken into account in the case of  $\nu_\tau$  interactions. For elastic NC interactions, the cross sections are taken from Ref.[27].

The original routines from RSQ code [24] are used to generate the contribution of 16 baryonic resonances ( $N^*$  and  $\Delta$ ) with invariant-mass  $W \leq 2 \text{ GeV}$ . All resonances and their decays are generated separately. The production cross-sections have been computed in Ref.[28] using the FKR [29] semirelativistic quark model. Total cross sections of QE  $\nu n$  interactions and  $\Delta^{++}$  production in  $\nu p$ - interactions are found to be in an agreement with experimental data [30–32].

#### 4.3. Verification of CHORUS MC chain

The combined performance of JETTA and RESQUE generators was checked on CHORUS data. Fig.1 shows the reconstructed neutrino and antineutrino energy of CC events in the calorimeter. The difference between detector-deconvoluted data and MC does not exceed  $10 \div 15\%$ . It is partially due to imperfections in our simulation of neutrino parent meson transportation through the decay tunnel. Charged multiplicity of tracks predicted in the emulsion is presented in Fig.2. The agreement between data and MC<sup>3</sup> is quite satisfactory.

#### 4.4. MICKEY

MICKEY [6] is used as a fast MC generator for CC interactions in the calorimeter. Instead of doing a full GEANT simulation, it applies parameterized detector resolution and inefficiencies. These parameterizations have been obtained from test-beam data and from full detector simulations. The parton distribution set used in MICKEY is that of GRV94LO [21]. Violation of the Callan-Gross relation is modelled using a parameterization of  $R(x, Q^2)$  taken from a fit to the world data [33]. Target mass effects and non-zero  $m_c$  (slow rescaling) are taken into account. The structure functions are multiplied by a nuclear correction as a function of  $x$  according to Ref.[34].

<sup>3</sup>Both data and MC were passed through the same reconstruction program.

QED radiative corrections are calculated following the scheme of Ref.[35]. The generator was tuned and validated using our calorimeter and emulsion data [6,36].

## 5. Specific generators

Four generators were developed for charm studies:

- ASTRA for diffractive  $D_s$  production [37];
- QEGEN for QE production of charmed baryons [38];
- MCDIMUON for dimuon - involving charm - production [39,40];
- CCBAR for pair production of charmed particles both in CC and NC [4].

In addition, there is a generator for detailed simulation of “white star kinks”, WSK [41].

### 5.1. ASTRA

The core of ASTRA [37] consists of a set of functions  $F_n$  describing the matrix elements for diffractive production of (vector)  $D_s^*$  and direct production of (pseudoscalar)  $D_s$ , in neutrino interactions, according to the choice of theoretical models indexed by  $n$ . It is left to the user to select her/his favourite model. By default, models from Ref.[42] (Ref.[43]) are used for  $D_s^*$  ( $D_s$ ) production. The first approach is based on generalized vector dominance while the second one uses PCAC as a fundamental ingredient. Non-zero  $m_c$  is taken into account in both.

It should be noted that a correctly selected integration algorithm and correctly computed integration limits are crucial. Ref.[44] contains a thorough study of physical and computational pitfalls to be avoided.

Fragmentation and decays are performed with JETSET [15]. Nuclear effects other than an *ad-hoc* diffractive slope are not included in ASTRA.

### 5.2. QEGEN

In the QE charm production a valence  $d$ -quark is transformed, through weak interaction, into a  $c$ -quark. The other two valence quarks in the nucleon behave as spectators, so only one hadronic state (charmed baryon  $\Lambda_c^+$ ,  $\Sigma_c^+$ ,  $\Sigma_c^{++}$  or  $\Sigma_c^{*+}$ ,  $\Sigma_c^{*++}$ ) is produced and finally each event will contain a  $\Lambda_c^+$  baryon. There are two classes of

theoretical models which try to describe the QE charm production. The first class is based on  $SU(4)$  flavour symmetry which is badly broken. A different approach is based on local duality in  $\nu N$  scattering on the basis of QCD. Although the predictions of the models for the total cross sections differ by one order of magnitude,  $Q^2$ -distributions are very similar. To simulate the dynamics of QE charmed baryon production, the differential cross sections from Ref.[45] are used. JETSET [15] is employed to perform fragmentation and charmed baryon decays. The model to generate Fermi motion in emulsion target nuclei is adopted from Ref.[25]. Note that experimental data on QE charm production are very poor.

### 5.3. MCDIMUON

The event generator MCDIMUON [39] was originally developed to simulate opposite-sign dimuon events in the CHARM-II detector [23]. CTEQ3L [46] parton distribution functions are used. The masses of the charm quark and the nucleon are not neglected in the hard-scattering cross-section (slow rescaling is included). The fragmentation of charm quarks is described by the fragmentation function from Ref.[22]. Excited charmed hadrons are not taken into consideration. The transverse momentum distribution is chosen as an exponential function of  $p_t^2$ . A correction for radiative effects is calculated for the inclusive CC cross-section using the prescription of Ref.[35]. Decays of charmed hadrons only depend on the phase space. The nucleon content of the target is also taken into account.

The code is very flexible and the user can provide many parameters through steering cards. It was tuned for simulation of dimuon events in the CHORUS calorimeter [40]. MCDIMUON was verified both on CHARM-II and CHORUS data.

### 5.4. CCBAR

The simulation of charm pair production in NC and CC interactions is performed using the general-purpose HERWIG event generator [47], version 6.1 [48]. Several features of this generator, like heavy flavour hadron production and decay via QCD coherence effects and the cluster hadronization of the jets via non-perturbative

gluon splitting, are especially relevant. The parton-shower approach is used both for initial and final states. MRS 5 (Owens) structure functions are used [49]. The Peterson's model for fragmentation functions is used with  $\varepsilon = 0.072$ . Nuclear effects such as evaporation and re-interactions are not simulated.

The process in NC is based on the  $Z^0$ -gluon fusion. A dedicated mode to produce this process is foreseen by the generator. Associated charm production in CC is based on the splitting of  $c\bar{c}$  quarks from a gluon which is radiated through bremsstrahlung of a light quark. No dedicated mode is foreseen for such a process which is therefore obtained among conventional CC interactions. It should be noted however that total cross sections predicted by HERWIG [50] and calculated in Ref.[51] differ by one order of magnitude. The CCBAR generator cannot be validated as the available experimental data for associated charm production are very poor [4,52,53].

### 5.5. WSK

A hadron-nucleus interaction which produces only one minimum ionizing particle and no heavily ionizing tracks or other signs of nuclear break up is usually called "white star kink" (WSK). Note that, this is the main background for oscillation searches in CHORUS in " $0\mu$ " mode [2], which is very difficult to estimate.

The simulation [41] is composed of two separate parts. The first is the generation of hadron interactions in emulsion, the second is the simulation of emulsion response to the different particles. The hadron-emulsion interactions have been simulated using FLUKA [9]. The emulsion response description is a very delicate point. It is based on the range in emulsion, for which the parameterization is obtained by an old experiment [54]. The generator has been tested and it reproduces the CHORUS data [2] quite well.

## 6. Conclusions

The CHORUS experiment has two general-purpose MC event generators which were validated using available experimental data. Tuning of dedicated generators, developed for charm

physics, is well advanced. Currently, a complete set of CHORUS MC generators is available.

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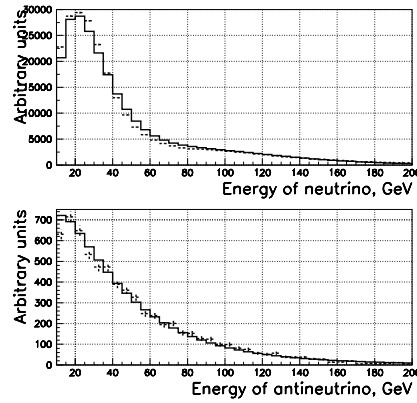


Figure 1. Neutrino (top plot) and antineutrino (bottom plot) energy spectra for CC events in the calorimeter. The solid histograms are for experimental data, the dashed histograms for MC.

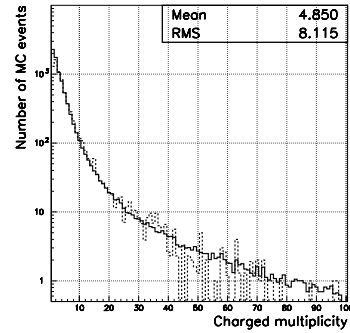


Figure 2. Charged multiplicity for events having predictions of particle trajectories into the emulsion stack for the location of the vertex positions. The solid histogram is for experimental data, the dashed histogram for MC.