Generator of neutrino-nucleon interactions for the FLUKA based simulation code

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Abstract

An event generator of neutrino-nucleon and neutrino-nucleus interactions has been developed for the general purpose Monte Carlo code **FLUKA**. The generator includes options for simulating quasi-elastic interactions, the neutrino-induced resonance production and deep inelastic scattering. Moreover, it shares the hadronization routines developed earlier in the framework of the **FLUKA** package for simulating hadron-nucleon interactions. The simulation of neutrino-nuclear interactions makes use of the well developed **PEANUT** event generator implemented in **FLUKA** for modelling of the interactions between hadrons and nuclei. The generator has been tested in the neutrino energy range from 0 to 10 TeV and it is available in the standard **FLUKA** distribution. Limitations related to some particular kinematical conditions are discussed. A number of upgrades is foreseen for the generator which will optimize its applications for simulating experiments in the CNGS beam.

Introduction

FLUKA is a general purpose Monte Carlo code currently employed in nuclear and particle physics for transport and interactions of particles and nuclei. It contains well developed nuclear models verified in a great number of different hadronic reactions.

The presented generator extends **FLUKA** possibilities by allowing simulation of interactions of electron, muon and tau neutrinos and antineutrinos with nucleons and nuclei. The dynamics of neutrino-nucleon interactions is included by using different sets of parton distribution functions (PDF), whereas the nuclear reaction dynamics is included through the **FLUKA** hadronic model called **PEANUT**.

The developed software has many urgent application including simulation of

1) events in ICARUS from the CNGS beam (E ~ 18 GeV);
2) atmospheric neutrino interactions in ICARUS (with good identification of events);
3) low energy long baseline neutrino beams;
4) search for sterile neutrinos at CERN-PS in the framework of a new project **DOUBLE-LAr** (E < 2 GeV);
5) measurements of the Theta_13 in the framework of a new project **MODULAr** in the off-axis CNGS beam;

The success of the data analyses in many cases relies heavily on good understanding of pi-0 production in the energy range below 2 GeV both on nucleons and nuclei.

In a distant future the code will be helpful for simulating reactions induced by neutrinos from beta beams or from muon factories constructed for CP violation studies.

Charged Current Reactions

			Partial Contribution	Hadronic final state symbol	FLUKA number
$\nu + p$	$\longrightarrow$	$\ell^- + X$			
$\nu + (duu)$	$\longrightarrow$	$\ell^- + (uuu)$	$\cos^2\theta_C \cdot v_d$	$p + \pi^+$	1+13
	$\longrightarrow$	$\ell^- + (cuu)$	$\sin^2\theta_C \cdot v_d$	$\Lambda_c^+ + \pi^+$	137+13
$\nu + d\bar{d}(duu)$	$\longrightarrow$	$\ell^- + u\bar{d}(duu)$	$\cos^2\theta_C \cdot s_d$	$p + \pi^+$	1+13
	$\longrightarrow$	$\ell^- + c\bar{d}(duu)$	$\sin^2\theta_C \cdot s_d$	$\Lambda_c^+ + \pi^+$	137+13
$\nu + \bar{u}u(duu)$	$\longrightarrow$	$\ell^- + \bar{d}u(duu)$	$\cos^2\theta_C$	$p + \pi^+$	1+13
	$\longrightarrow$	$\ell^- + \bar{s}u(duu)$	$\sin^2\theta_C$	$p + K^+$	1+15
$\nu + s\bar{s}(duu)$	$\longrightarrow$	$\ell^- + c\bar{s}(duu)$	$\cos^2\theta_C$	$\Lambda_c^+ + K^+$	137+15
	$\longrightarrow$	$\ell^- + u\bar{s}(duu)$	$\sin^2\theta_C$	$p + K^+$	1+15
$\nu + \bar{c}c(duu)$	$\longrightarrow$	$\ell^- + \bar{s}c(duu)$	$\cos^2\theta_C$	$\Lambda_c^+ + K^+$	137+15
	$\longrightarrow$	$\ell^- + \bar{d}c(duu)$	$\sin^2\theta_C$	$\Lambda_c^+ + \pi^+$	137+13
$\nu + n$	$\longrightarrow$	$\ell^- + X$			
$\nu + (ddu)$	$\longrightarrow$	$\ell^- + (udu)$	$\cos^2\theta_C \cdot v_d$	$p + \pi^0$	1+23
	$\longrightarrow$	$\ell^- + (cdu)$	$\sin^2\theta_C \cdot v_d$	$\Lambda_c^+ + \pi^0$	137+23
$\nu + d\bar{d}(ddu)$	$\longrightarrow$	$\ell^- + u\bar{d}(ddu)$	$\cos^2\theta_C \cdot s_d$	$p + \pi^0$	1+23
	$\longrightarrow$	$\ell^- + c\bar{d}(ddu)$	$\sin^2\theta_C \cdot s_d$	$\Lambda_c^+ + \pi^0$	137+23
$\nu + \bar{u}u(ddu)$	$\longrightarrow$	$\ell^- + \bar{d}u(ddu)$	$\cos^2\theta_C$	$p + \pi^0$	1+23
	$\longrightarrow$	$\ell^- + \bar{s}u(ddu)$	$\sin^2\theta_C$	$n + K^+$	8+15
$\nu + s\bar{s}(ddu)$	$\longrightarrow$	$\ell^- + c\bar{s}(ddu)$	$\cos^2\theta_C$	$\Lambda_c^+ + K^0$	137+24
	$\longrightarrow$	$\ell^- + u\bar{s}(ddu)$	$\sin^2\theta_C$	$n + K^+$	8+15
$\nu + \bar{c}c(ddu)$	$\longrightarrow$	$\ell^- + \bar{s}c(ddu)$	$\cos^2\theta_C$	$\Lambda_c^+ + K^0$	137+24
	$\longrightarrow$	$\ell^- + \bar{d}c(ddu)$	$\sin^2\theta_C$	$\Lambda_c^+ + \pi^0$	137+23

			Partial Contribution	Hadronic final state symbol	FLUKA number
$\bar{\nu} + p$	$\longrightarrow$	$\ell^+ + X$			
$\bar{\nu} + (uud)$	$\longrightarrow$	$\ell^+ + (dud)$	$\cos^2\theta_C \cdot v_u$	$n + \pi^0$	8+23
	$\longrightarrow$	$\ell^+ + (sud)$	$\sin^2\theta_C \cdot v_u$	$\Lambda^0 + \pi^0$	17+23
$\bar{\nu} + u\bar{u}(duu)$	$\longrightarrow$	$\ell^+ + d\bar{u}(duu)$	$\cos^2\theta_C \cdot s_u$	$n + \pi^0$	8+23
	$\longrightarrow$	$\ell^+ + s\bar{u}(duu)$	$\sin^2\theta_C \cdot s_u$	$\Lambda^0 + \pi^0$	17+23
$\bar{\nu} + \bar{d}d(duu)$	$\longrightarrow$	$\ell^+ + \bar{u}d(duu)$	$\cos^2\theta_C$	$n + \pi^0$	8+23
	$\longrightarrow$	$\ell^+ + \bar{c}d(duu)$	$\sin^2\theta_C$	$n + \bar{D}^0$	8+119
$\bar{\nu} + \bar{s}s(duu)$	$\longrightarrow$	$\ell^+ + \bar{c}s(duu)$	$\cos^2\theta_C$	$\Lambda^0 + \bar{D}^0$	17+119
	$\longrightarrow$	$\ell^+ + \bar{u}s(duu)$	$\sin^2\theta_C$	$\Lambda^0 + \pi^0$	17+23
$\bar{\nu} + c\bar{c}(duu)$	$\longrightarrow$	$\ell^+ + s\bar{c}(duu)$	$\cos^2\theta_C$	$\Lambda^0 + \bar{D}^0$	17+119
	$\longrightarrow$	$\ell^+ + d\bar{c}(duu)$	$\sin^2\theta_C$	$n + \bar{D}^0$	8+119
$\bar{\nu} + n$	$\longrightarrow$	$\ell^+ + X$			
$\bar{\nu} + (udd)$	$\longrightarrow$	$\ell^+ + (ddd)$	$\cos^2\theta_C \cdot v_u$	$n + \pi^-$	8+14
	$\longrightarrow$	$\ell^+ + (sdd)$	$\sin^2\theta_C \cdot v_u$	$\Lambda^0 + \pi^-$	17+14
$\bar{\nu} + u\bar{u}(ddu)$	$\longrightarrow$	$\ell^+ + d\bar{u}(ddu)$	$\cos^2\theta_C \cdot s_u$	$n + \pi^-$	8+14
	$\longrightarrow$	$\ell^+ + s\bar{u}(ddu)$	$\sin^2\theta_C \cdot s_u$	$\Lambda^0 + \pi^-$	17+14
$\bar{\nu} + \bar{d}d(ddu)$	$\longrightarrow$	$\ell^+ + \bar{u}d(ddu)$	$\cos^2\theta_C$	$n + \pi^-$	8+14
	$\longrightarrow$	$\ell^+ + \bar{c}d(ddu)$	$\sin^2\theta_C$	$n + D^-$	8+118
$\bar{\nu} + \bar{s}s(ddu)$	$\longrightarrow$	$\ell^+ + \bar{c}s(ddu)$	$\cos^2\theta_C$	$\Lambda^0 + D^-$	17+118
	$\longrightarrow$	$\ell^+ + \bar{u}s(ddu)$	$\sin^2\theta_C$	$\Lambda^0 + \pi^-$	17+14
$\bar{\nu} + c\bar{c}(ddu)$	$\longrightarrow$	$\ell^+ + s\bar{c}(ddu)$	$\cos^2\theta_C$	$\Lambda^0 + D^-$	17+118
	$\longrightarrow$	$\ell^+ + d\bar{c}(ddu)$	$\sin^2\theta_C$	$n + D^-$	8+118

Neutral Current Reactions

			Partial Contribution	Hadronic final state symbol	FLUKA number
$\nu/\bar{\nu} + p$	$\longrightarrow$	$\nu/\bar{\nu} + X$			
$\nu/\bar{\nu} + (uud)$	$\longrightarrow$	$\nu/\bar{\nu} + (uud)$	v_u	$p + \pi^0$	1+23
$\nu/\bar{\nu} + (duu)$	$\longrightarrow$	$\nu/\bar{\nu} + (duu)$	v_d	$p + \pi^0$	1+23
$\nu/\bar{\nu} + u\bar{u}(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + u\bar{u}(duu)$	s_u	$p + \pi^0$	1+23
$\nu/\bar{\nu} + \bar{u}u(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{u}u(duu)$		$p + \pi^0$	1+23
$\nu/\bar{\nu} + d\bar{d}(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + d\bar{d}(duu)$	s_d	$p + \pi^0$	1+23
$\nu/\bar{\nu} + \bar{d}d(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{d}d(duu)$		$p + \pi^0$	1+23
$\nu/\bar{\nu} + s\bar{s}(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + s\bar{s}(duu)$		$\Lambda^0 + K^+$	17+15
$\nu/\bar{\nu} + \bar{s}s(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{s}s(duu)$		$\Lambda^0 + K^+$	17+15
$\nu/\bar{\nu} + c\bar{c}(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + c\bar{c}(duu)$		$\Lambda_c^+ + \bar{D}^0$	137+119
$\nu/\bar{\nu} + \bar{c}c(duu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{c}c(duu)$		$\Lambda_c^+ + \bar{D}^0$	137+119
$\nu/\bar{\nu} + n$	$\longrightarrow$	$\nu/\bar{\nu} + X$			
$\nu/\bar{\nu} + (udd)$	$\longrightarrow$	$\nu/\bar{\nu} + (udd)$	v_u	$n + \pi^0$	8+23
$\nu/\bar{\nu} + (ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + (ddu)$	v_d	$n + \pi^0$	8+23
$\nu/\bar{\nu} + u\bar{u}(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + u\bar{u}(ddu)$	s_u	$n + \pi^0$	8+23
$\nu/\bar{\nu} + \bar{u}u(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{u}u(ddu)$		$n + \pi^0$	8+23
$\nu/\bar{\nu} + d\bar{d}(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + d\bar{d}(ddu)$	s_d	$n + \pi^0$	8+23
$\nu/\bar{\nu} + \bar{d}d(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{d}d(ddu)$		$n + \pi^0$	8+23
$\nu/\bar{\nu} + s\bar{s}(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + s\bar{s}(ddu)$		$\Lambda^0 + K^0$	17+24
$\nu/\bar{\nu} + \bar{s}s(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{s}s(ddu)$		$\Lambda^0 + K^0$	17+24
$\nu/\bar{\nu} + c\bar{c}(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + c\bar{c}(ddu)$		$\Lambda_c^+ + D^-$	137+118
$\nu/\bar{\nu} + \bar{c}c(ddu)$	$\longrightarrow$	$\nu/\bar{\nu} + \bar{c}c(ddu)$		$\Lambda_c^+ + D^-$	137+118

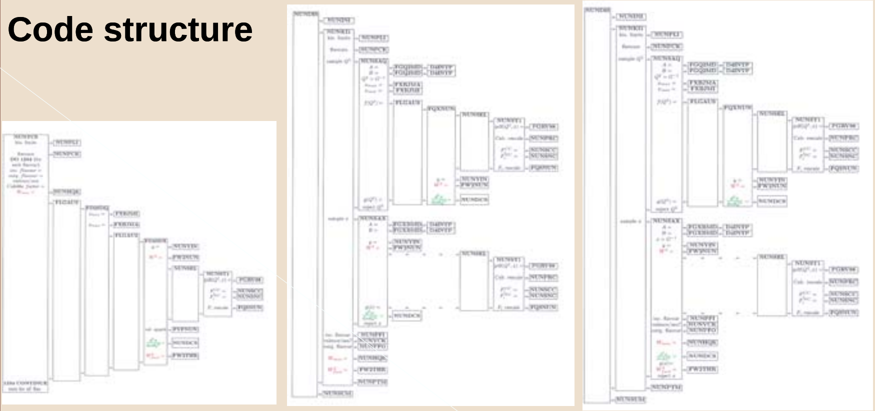
Kinematics and the PDF

Variable	Required	GRV94		GRV98		BBS	
		Default	Tested	Default	Tested	Default	Tested
E_{min} (GeV)	—	0.050					
E_{max} (GeV)	$\geq 10^4$	$70 \cdot 10^3$			10^5		
Q^2_{min} (GeV^2)	$\leq 5.5 \cdot 10^{-12}$	0.4	0.4	0.8	0.8	2	0.8
Q^2_{max} (GeV^2)	$\geq 1.9 \cdot 10^4$	10^6	10^9	10^6	10^9	10^4	$2 \cdot 10^4$
x_{min}	$\leq 1.4 \cdot 10^{-11}$	10^{-5}	10^{-30}	10^{-9}	10^{-30}	10^{-4}	10^{-30}
x_{max}	1	0.99999	0.99999	1	1	1	1

GRV94: M.Gluck, E.Reya and A. Vogt, Z. Phys. C67 (1995) 433
GRV94: M.Gluck, E.Reya and A. Vogt, Eur. J. Phys. C5 (1998) 461
BBS: C. Bourrely, J. Soffer and F. Buccella, Eur. J. Phys. C23 (2002) 487

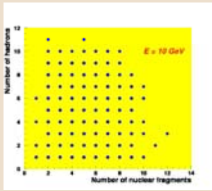
A warning is sent to the summary file if a variable is sampled (or calculated) outside the kinematic limits of the corresponding PDF set.

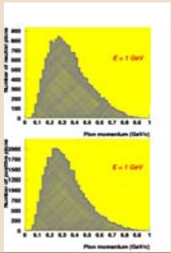
Code structure



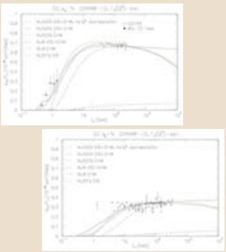
Results

Hadronic shower and nuclear fragments in ν-Ar interaction





Total CC cross sections as a function of energy



Summary

The developed generator provides a powerful tool for simulating numerous reactions of neutrino with nucleons and nuclei. It has been tested under different kinematic conditions and different PDF for the input.

Virtually complete user guide is available as “Manual Online” from the **FLUKA** home page. Work priorities are being established which include three topics: reactions induced by (1) CNGS beam, (2) atmospheric and (3) solar neutrinos.

Simulation results combined with forthcoming data from ICARUS are believed to answer questions related to the interpretation of the atmospheric neutrino data by analyzing double ratios of the neutral to charged current events.

References

1. A. Ferrari, P.R. Sala, A. Fasso, J. Ranft, CERN 2005-10 (2005); INFN/TC_0511; SLAC-R-773.
2. A. Rubbia, “NUX — neutrino generator”, Proc. NuInt01, Tsukuba, Japan, 2001.