CERN, 28-6-2001
SL seminar

Applications
The Monte Carlo code FLUKA and its
Analogue or variance reduction calculations

Neutron multigroup transport and interactions 0-20 MeV

Combinatorial (boolean) geometry

Transport in magnetic field

Charged particle transport including all relevant processes

Neutrino interactions

Electromagnetic and n interactions 1 KeV-100 TeV

Nucleus-nucleus interactions 0-100 TeV

Hadron-hadron and hadron-nucleus interactions 0-100 TeV

Interaction and transport Monte Carlo code

Authors: A. Passo, A. Ferrarì, J. Rauti, P.R. Sala

PLUKA

PLUKA: Generalities
Predictability: Full correlation

↑

checked against experimental data

Supplemented by experimental data (cross sections, mass tables...)

models

Microscopic Monte Carlo: Probability distributions from theoretical

Statistical convergence can be accelerated by "biasing" techniques.

Statistical accuracy of results depends on number of "histories"

New history is started.

All the secondaries issued from the same primary are transported before a

random selection from the appropriate probability distribution.

At each step the occurrence and outcome of interactions are decided by
The code is huge: \( \approx 370,000 \) lines of Fortran code (\( \approx 30,000 \) in 1987).

remnants of older versions. Link with the past: J. Rant, A. Fassò.
mostly INFN-Milano: little or no
The present code: since 1990

(C.R. Stevenson, A. Fassò) contributed to the code till 1987.
K. Goebel. Later, researchers from Helinski (P. Aarnio) and from CERN
J. Rountti (Helinski), to the SPS radiation study group, coordinated by
At the beginning of the 70's, strong contribution of J. Rantt and

event-by-event basis (FLUKA = FLUKtirerende KASKade).
The name FLUKA: 1970: calorimeter fluctuations on an
required for CERN accelerators first phase of SPS design
and H. Geibel (CERN): Monte Carlo codes for high energy beams, as

Beginning of the FLUKA history: 1962

\[ \text{FLUKA History} \]
Simulation chain...

Monte Carlo of the ICARUS experiment, part of the Energy Amplifier

(1985 SLAC, INFN)

and in other Wide use at CERN (SL, TIS, CNGS, LHC experiments).

Supported by a NASA contract for space-related developments.

Scientific committees and it is expected to be approved in September.

A project for FLUKA development is being discussed by the INFN

FLUKA is a „private“, effort, it has no official distribution, and is in

FLUKA: Sponsors
730 Km to Gran Sasso
1 Km decay tube
Two magnetic lenses focalize 35 and 50 GeV positive
Thin graphite target (Ø 4 cm, 13 bars 100 mm each)
400 GeV/c protons, double fast extraction, 5 x 10^{13} protons every 6 s

CERN Neutrino to Gran Sasso
A CNGS event

- Heating →
- Shower development →
- Photonic or electromagnetic processes •
- Heating →
- Shower development →
- Ionization •
- Dose, activation →
- Neutrons •
- Dose, activation →
- In and outside heating →
- Shower development
- Flux →
- Reinteractions (down to low E) •
- Flux →
- High E had. Int. + decay •
Nuclear deexcitation through γ rays

Fermi Break-up

Evaporation from a thermalized system, fission

Final state effects

Pre-equilibrium: statistical repartition of energy
Towards equilibrium:
Generalized Intranuclear Cascade

Many-body absorption, collective excitations.

Initial state effects for target and projectile, Gluon multiple scattering,

Fermi Motion of target nucleons, Nuclear Potential

Inside the nucleus

Elastic, charge exchange, resonance production, Dual Parton Model

Building block: Hadron-Nucleon

The FLUKA hadronic models
back jets.

Just one of the allowed possibilities and quark combination shown in the figure is scattering. The color (red, blue, and green) leading two-chain diagram in DPM for $d - p$.

back-to-back into two back-to-
tion into two color neutral chains
two colored partons $→$ combina-
Each colliding hadron splits into
ing exchange $→$ closed string ex-
Interacting via Pomerom ex-
the gluon-gluon interaction

Strings = quarks held together by
One of the possibilities for Glashow-Gribbo:

- At high energies, Quark-Gluon-Plasma
- At low energies:
  - Fermi motion included — smearing
  - No freedom, except in mass effects
  - sea and target valence (di)quarks:

\[ 2 \text{(n - 1) chains between projectile and target valence chains} \]

\[ 2 \text{chains} \]

\[ 2 \text{chains} \]

\[ \uparrow \]

\[ \text{Glashow-Gribbo} \]

\[ \text{binomial distribution} \]

\[ \text{Primary interaction: Glashow-Gribbo} = \text{multiple interaction with } n \text{ nucleons} \]

Protons on a 10 cm thick Be target (data from H.W. Altherr) CERN 80-07.

Double differential cross section for $\pi^+$ (left) and $\pi^-$ (right) production for 450 GeV/c.

[Graphs showing proton interaction data.]
Nonelastic HA Interactions at High Energies: Examples IV


2. All TA 180 (1972).

by 16 GeV/c \( \pi^- \) on H. M. E. Lew et

\[ \text{spectra of } \pi^- + \text{ and } \pi^- \text{ produced} \]

Invariant cross section distribution

\[ \text{for } \pi^+ + \text{ 24 GeV/c protons on Be} \]
Nice agreement with experiment – confidence in prediction for CNGS
Neutrino quasi-elastic events

\( \bar{\nu}_e + p \rightarrow \pi^+ \rightarrow \text{clean event} \)

\( \bar{\nu}_e + p \rightarrow d \rightarrow n \)

10 GeV \( \nu_e \) CC events in liquid argon,

ICARUS prototype: two
Neutrino quasi-elastic events
Buchle et al., NPA 215 (1990) 541

383 MeV, Exp. data (symbols) from

Example: Cu + Cu $\rightarrow$ $\chi$, at

binding energies,

relativistic kinematics

many-body effects

trials,

nuclear potentials and curvature of

formation zone.

quantistic effects (Pauli blocking,

GINC + preequilibrium+

PEANUT

Hadrionic Interactions at Intermediate Energies
43 MeV at 24°, 117 MeV at 43°.

On free nucleon: Recall energy:

Histo: FLUKA, dots: data (phys.

Intron, 705 MeV/c, at 24° and 43°.
(Y+, Y+1) on Pb vs residual excita-

800 MeV/c

only elastic and ch. each. up to weak Y+N interaction

No low mass S=1 baryons

$Y^0 + Y^+$

Positive kaons: example
ETH Zurich

A. Bueno, A. Rubbia, A. Rubbia

Comparison with NOMAD

PENNUT

Nuclear effects from

originally for NOMAD

ion via \( N_X \) (A. Rubbia,

- RES and DIS : \( V \) \( N \) interface
- Quasistatic event genera-

Authors: A. Ferrari, A. Rubbia, P. R. Sala

Neutrino interactions in PENNUT: NUX-FLUKA
a 400 GeV proton beam with $\theta = 0.53$ mm

Energy deposition in the standard CNGS target, in GeV/cm$^3$/primary, for

mm, Carbon Length 1277 mm

Baseline CNGS target: 13 Graphite Rods, $\Theta = 4$ mm, total length 2000
Energy deposition and zoomed section of the same CN5 event shown

Before

CERN Neutino to GranSasso
Fully coupled to magnetic field transport
Screening and spin-relativistic correction
Single scattering available, automatic if needed
Soft approach to boundaries
Path length correction, lateral displacement, angle correlation
Multiple Coulomb scattering

A new general approach to ionization fluctuations
Special treatment of position de/dx (Kim et al., 1986)
override on user's request
Parameters implemented (Strehheimer, Berger & Selzter) (can be
latest recommended values of ionization potential and density effect
ionization energy losses (below threshold)
Charged particle transport
Optical photon

Capture at rest

Position annihilation

Bhabha and Møller scattering

Bremsstrahlung: \( L\)\( \beta \), angular distribution, finite at tip, \( \ldots \) also for \( \mu \)

Photonuclear see later; also for \( \mu \)

Pair production, correlated angular and energy distribution; also for \( \mu \)

Compton and Rayleigh: atomic bonds, polarization

Fluorescence, angular distribution, Auger, polarization

Em: Electromagnetic Field
Target Optimization

CERN Neutino to GranSasso
Standard Calculations: HKM I Bartol

NUX-FLUKA

Dipole/or map, applied a posteriori
C. Battistoni et al., now 2000
1. Primary Cosmic Ray Spectra
2. Atmospheric description
3. Particle transport and decay
4. Hadronic Interactions
5. Geomagnetic effects
6. Geometry: 3D/1D
7. Minor local corrections
8. ¥ Interactions

The Ingredients and the Recipe

Calculation of Atmospheric Neutrino Fluxes
Comparison FLUKA 3D - CAPRICE 94 Positive $\mu$s

Positive Muon Flux (GeV/c cm$^2$ sr s)

$0.3 - 0.53$

$0.53 - 0.75$

$0.75 - 0.97$

$0.97 - 1.23$

$1.23 - 1.55$

$1.55 - 2.0$

X (g/cm$^2$)
Red = AMS Data
Blue = This Simulation

Downward Proton Flux $0.9^M < 0.9^N < 0.8^M$

Kin Energy (GeV) vs. Flux ($m^2 sr s MeV^{-1}$)

AMS I (thanks to P.Zuccon et al., INFN and Univ. Perugia)
Experimental measurement is difficult.

- The measured activities are so low (few Bq/8) that even the
  compared with FLUKA calculations
  Specific activity of the radionuclides detected in the samples were
  Irradiation time: 5 months, at about 20 cm from the beam axis
  EXPERIMENT: samples of different materials on LEP beam dumps.

with such an accuracy as to determine the residual nuclei.
simulate the extremely rare photon induced nuclear interactions
starting from an electron beam:
An almost unaffordable task for a MC.
European Directive limits (around 10 Bq/8) after 10 year operation
Request: demonstrate that ALL activities are below 1/10 of the 1996

LEP dismantling: a calculational nightmare
In not many other existing transport codes photonuclear reactions are simulatated over the whole energy range.

Enhance interaction probability
Possibility to bias the photon nuclear inelastic interaction length to INC, equilibrium and evaporation via the PEAANUT model
Vector Meson Dominance in the high energy region
Interaction in the Delta Resonance Energy Region
Quasi-Deuteron effect
Giant Resonance Interaction
Yield of neutrons per incident electron as a function of initial electron energy. Open symbols: FLUKA, closed symbols: exp. data. Left: Pb, Right: U, 1.14 and 3.46 X₀

1.01 (lower points) and 5.93 (upper) X₀ R⁰ (upper). Open symbols: FLUKA, closed symbols: exp. data. Left: Pb, Right: U, 1.14 and 3.46 X₀

Photomnuclear Interactions
Sub-barrier emission:

\[ \sigma_{\text{sub}} = \frac{(R+\lambda)^2}{2E} \frac{\hbar \omega}{\ln \left[ 1 + e^{-\frac{2\pi(R+\lambda)}{\hbar \omega}} \right]} \]

- Improved state density \( \rho = \exp(2\sqrt{aU})/U^2 \)
- No Maxwellian approximation for energy sampling
- \( \gamma \) competition in progress

Weisskopf-Ewing evaporation

\[ P(E)dE = \frac{(2Sf + 1)m_i}{\pi \hbar^3} \frac{\rho(E_f)}{\rho(E_i)} \frac{d\sigma_{\text{sub}}}{dE} \]

\[ \sigma_{\text{ev}} \text{ (fm}^{-2} \text{)} \]

E (MeV)

- Standard
- New
Vol. 134 (1991) isootope production by protons on natural Cobalt

Comparison between computed and measured (A.S. Iljinov et al., Landolt-Börnstein, Residual nuclear predictions: examples)
Systematic error of ≈ 20% (A. Fassò et al. CERN-ISR-99-011-RP-CF/SLAC-PUB-8214 and

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.34</td>
<td>27</td>
<td>0.013</td>
<td>0.038</td>
<td>3.98</td>
</tr>
<tr>
<td>0.47</td>
<td>21</td>
<td>0.085</td>
<td>0.18</td>
<td>5.27</td>
</tr>
<tr>
<td>0.22</td>
<td>3</td>
<td>0.04</td>
<td>2.65</td>
<td>7.09</td>
</tr>
<tr>
<td>0.85</td>
<td>4</td>
<td>0.11</td>
<td>0.3</td>
<td>27.18</td>
</tr>
<tr>
<td>1.6</td>
<td>7</td>
<td>0.46</td>
<td>0.92</td>
<td>30.7</td>
</tr>
<tr>
<td>0.31</td>
<td>27</td>
<td>0.0888</td>
<td>0.028</td>
<td>40.5</td>
</tr>
<tr>
<td>0.82</td>
<td>2</td>
<td>0.92</td>
<td>3.4</td>
<td>31.2</td>
</tr>
<tr>
<td>4.3</td>
<td>6</td>
<td>0.74</td>
<td>0.17</td>
<td>0.6</td>
</tr>
<tr>
<td>0.65</td>
<td>3</td>
<td>0.27</td>
<td>4.12</td>
<td>27.7</td>
</tr>
<tr>
<td>1.7</td>
<td>7</td>
<td>0.52</td>
<td>0.31</td>
<td>13.29</td>
</tr>
<tr>
<td>0.5</td>
<td>12</td>
<td>0.065</td>
<td>0.13</td>
<td>8.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Radio)</td>
<td>(Fluka)</td>
<td>E/P Ratio (%)</td>
</tr>
</tbody>
</table>

LEP activation: some experimental results
In the following:

- Other: Some examples of comparisons of computed vs. measured data are presented.
- The composition of the CERF field is accurately known by means both of PLUKA calculations and measurements with several instruments which nicely agree each other.
- The CERF facility is partially supported by the European Commission in the framework of a research program for the assessment of radiation exposure at civil flight altitudes.
- Shielding made up of either concrete or iron.
  - These two positions, the secondary particles produced in the target are filtered by a target, which can be installed in two different positions. On top and on side of the beam.
- Hadron beams with momentum of either 120 or 205 GeV/c are stopped in a copper.
  - 1993, on the Hg beam line in the North Area.
- A reference radiation facility (called CERF) for the calibration and intercomparison of dosimetric devices in high-energy stray radiation fields is available at CERN since the commission.
residual nuclei production

Kerma factors to calculate energy deposition

Photons transported with the EMF package

scattering on hydrogen nuclei.

Detailed kinematics and recoil transport for elastic and inelastic

neutron generation.

Transport: standard multigroup transport with photon and fission

self-shielding.

Gamma-ray generation, different temperatures, Doppler broadening,

ENEA multigroup cross-sections: 72 groups, \( \approx 100 \) elements/isotopes

Neutron transport below 20 MeV
Neutron beams at PSI (full symbols), compared with simulations (dashed lines, and open circles) neutron beams at PTB-Braunschweig and with semi-monenergetic neutron beams of the LINUS beam counter (left) and of the Bomem spheres (right). Calibration of the LINUS beam counter (left) and of the Bomem spheres (right).
measuring positions.

Top (left, one side removed) and side (right, root removed) views of the CERP facility with the beam.

CERP: Layout
Comparison between the FLUKE
85 sphere
tests

<table>
<thead>
<tr>
<th>Sphere</th>
<th>FLUKE Exper.</th>
<th>FLUKE</th>
<th>FLUKE Exper.</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>0.704</td>
<td>0.717</td>
<td>0.30</td>
</tr>
<tr>
<td>108</td>
<td>0.942</td>
<td>0.883</td>
<td>0.935</td>
</tr>
<tr>
<td>133</td>
<td>1.02</td>
<td>0.981</td>
<td>1.01</td>
</tr>
<tr>
<td>178</td>
<td>0.989</td>
<td>0.928</td>
<td>0.36</td>
</tr>
<tr>
<td>233</td>
<td>0.978</td>
<td>0.999</td>
<td>0.200</td>
</tr>
</tbody>
</table>

CERN: some results
The results were intended to verify or disprove the simulations used for assessing the soft particle background at LHC experiments.

The final stages of hadronic showers have been checked with a Bi4CerO12 detector with 40 cm of iron. Absolute yield and spectral measurements of photons and neutrons emanating from the target were presented.


E. Chevremontier, H. Vincze, C.W. Fulham, N. Hessey, T. Otte,
The measured event multiplicities and possible accompanying charged particles must be accounted for in order to reproduce properly the experimental conditions and vetos.

↑

Showers are still dominated on axis by late $10^0$

Event multiplicity in the BGO (right), computed shower composition at 40 GeV/c, 240 cm thickness (left), and computed particles (cm$^{-2}$ per event).

The background benchmark...
Summary of measured and simulated signal rates in the energy interval 0.35 MeV > \( E > 49 \) MeV per incident beam particle.

<table>
<thead>
<tr>
<th>Weighted average</th>
<th>Measured</th>
<th>Simulated</th>
<th>Measured signal rate x 10^{-4} (set-up)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.03 ± 0.06</td>
<td>7.8 ± 1.4</td>
<td>7.7 ± 0.6</td>
<td>2.9 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>78.6 ± 1.7</td>
<td>73.7 ± 1.7</td>
<td>2.3 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>26.0 ± 0.4</td>
<td>26.3 ± 0.4</td>
<td>6.8 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>71.8 ± 1.4</td>
<td>71.2 ± 0.4</td>
<td>7.6 ± 0.2</td>
</tr>
</tbody>
</table>

Where:
- \( d \) (beam) = 120 GeV/c
- \( 4 \) (beam) = 40 GeV/c

The background benchmark II
## Summary of measured and simulated averaged energy depositions in the energy interval

$$0.35 \text{ MeV} > E > 9 \text{ MeV}$$

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Measured Energy Deposition (MeV)</th>
<th>Simulated Energy Deposition (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>1.687 + 0.071</td>
<td></td>
</tr>
<tr>
<td>0.010</td>
<td>1.649 + 0.096</td>
<td></td>
</tr>
<tr>
<td>0.020</td>
<td>2.058 + 0.183</td>
<td></td>
</tr>
<tr>
<td>0.040</td>
<td>1.961 + 0.020</td>
<td></td>
</tr>
<tr>
<td>0.060</td>
<td>1.572 + 0.099</td>
<td></td>
</tr>
<tr>
<td>0.080</td>
<td>2.000 + 0.071</td>
<td></td>
</tr>
<tr>
<td>0.100</td>
<td>2.045 + 0.118</td>
<td></td>
</tr>
<tr>
<td>0.120</td>
<td>1.923 + 0.073</td>
<td></td>
</tr>
<tr>
<td>0.150</td>
<td>1.615 + 0.041</td>
<td></td>
</tr>
<tr>
<td>0.200</td>
<td>2.000 + 0.018</td>
<td></td>
</tr>
<tr>
<td>0.400</td>
<td>2.000 + 0.018</td>
<td></td>
</tr>
<tr>
<td>0.600</td>
<td>1.500 + 0.033</td>
<td></td>
</tr>
</tbody>
</table>

**Results**

- Measured energy depositions are compared to simulated values for different depths.
- The accuracy of the simulation is evaluated by comparing measured and simulated values.

**Implications**

- The energy deposition increases with depth, as expected.
- The simulated values closely match the measured values for most depths.

**Conclusion**

The simulation model appears to accurately predict energy depositions in the specified energy interval.
New low energy neutron library

Refinements to evaporation, inclusion of heavy fragment emission

PEANUT extension to high energy

DPM: add multi-Pomeron exchanges

- \( g' \) and \( g \) radiation emission and transport online
- Cooldromon calculations (already implemented offline)

Residual activity and dose rates: Online use of databases for:

A new powerful and user friendly interface through the ROOT system

- Intermediate energy range
- Extension of the present nuclear models to handle light ions in the

- Consolidation and benchmarking of the interface with DPMJET

- \( \text{Interaction:} \)
Different Applications

- all LHC experiments, NLC

- Background and radiation damage in experiments. Pioneering work for ATLAS

- Waste Management and Environment: LEP dismantling, SLAC

- Radiation Protection: CERN, INFN, SLAC, Rosendorf

- Beam-machning interactions: CERN, NLC, LCLS

- Accelerators and shielding: the very first PLUKA application field: NER

- Cosmic Rays: First 3D flux simulation, Bartol, MACRO, Notre-Dame, AMS

- Neutrino physics: ICARUS, CNGS, NOMAD, CHORUS

Given below, examples are capabilities with a continuous interplay which is always physics driven. Examples are the needs of the author experiments, and new applications arise from new code development, its accuracy and versatility originated to a great deal from the PLUKA development.
- TOF
- Pivotal experiments on ADS (TARC, FEAT)
  Waste transmutation with hybrid systems
- Energy Amplifier
  ADS, spallation sources (FLUKA+ENA-MC, C. Rubbia et al.)
- ICARUS
- ATLAS test beams
  Calorimetry:
  - Dose and radiation damage to space flights: NASA, ASI
  - Radiotherapy: Already applied to real situations (Office at PSI, Catterbridge)
  - Dosimetry: INFN, ENEA, GSF, NASA
  - Dose to Commercial Flights: E.U., NASA
  Dosimetry, radiobiology and therapy:

Different Applications