FLUKA

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Interaction and transport MonteCarlo code

- Hadron-hadron, hadron-nucleus and nucleus-nucleus interactions 0-10000 TeV/n
- Electromagnetic and μ interactions 1 keV-1000 TeV
- Neutrino interactions
- Charged particle transport including all relevant processes
- Transport in magnetic field
- Combinatorial (boolean) geometry
- Neutron multigroup transport and interactions 0-20 MeV
- Analogue or variance reduction calculations

FLUKA: a long history

The beginning of the FLUKA *history is back to 1964 when Johannes Ranft started to develop MonteCarlo codes for high energy beams, as required at CERN for many accelerator related tasks.*

The name FLUKA *came around 1970, when first attempts were made to predict calorimeter fluctuations on an event-by-event basis (*FLUKA = FLU*ktuierende* KA*skade). At the beginning of the 70's J. Routti from Helsinki was collaborating with J. Ranft. In the following years researchers from Helsinki (P. Aarnio) and from CERN (G.R. Stevenson) contributed to the code till ≈ 1987.*

The modern FLUKA *code is mostly an effort of researchers of INFN-Milan started at the end of the 80's, and has little or no remnants of older versions. The main links with the past are Johannes Ranft, in the development of the high energy generator part, and Alberto Fassò, mostly for the electromagnetic sector.*

The code contains $\approx 400,000$ *lines of Fortran code and has amply demonstrated its ability to treat with good accuracy a variety of problems.*

Up to a couple of years ago FLUKA *was a "private" effort carried out completely within INFN. It had no official distribution and it was (is) in continuous evolution. It has been always meant as a tool where new ideas and models for radiation interactions and transport can be developed and tested rather than as general user tool*

Different Applications

The FLUKA development, its accuracy and versatility originated to a great deal from the needs of the author experiments, and new applications arise from new code capabilities, with a continuous interplay which is always physics driven. Examples are given below.

- Neutrino physics and Cosmic Ray studies: initiated within ICARUS
  - Neutrino physics: ICARUS, CNGS, NOMAD, CHORUS
  - Cosmic Rays: First 3D ν flux simulation, Bartol, MACRO, Notre-Dame, AMS
- Accelerators and shielding : the very first FLUKA application field
  - Beam-machine interactions: CERN, NLC, LCLS
  - Radiation Protection: CERN, INFN, SLAC, Rossendorf
  - Waste Management and environment: LEP dismantling, SLAC
- Background and radiation damage in experiments: Pioneering work for ATLAS
  - LHC experiments, NLC

Different Applications

- Dosimetry, radiobiology and therapy :
  - Dose to Commercial Flights: E.U., NASA
  - Dosimetry: INFN, ENEA, GSF, NASA
  - Radiotherapy: Already applied to real situations (Optis at PSI, Clatterbridge)
  - Dose and radiation damage to Space flights: NASA, ASI
- Calorimetry:
  - ATLAS test beams
  - ICARUS
- ADS, spallation sources (FLUKA+EA-MC, C.Rubbia et al.)
  - Energy Amplifier
  - Waste trasmutation with hybrid systems
  - Pivotal experiments on ADS (TARC, FEAT)
  - nTOF

FLUKA approach

The approach to hadronic interaction modelling adopted in FLUKA *is the one used by most state-of-the-art codes*

In this "microscopic" approach, each step has sound physical bases. The performances are optimized comparing with particle production data at single interaction level. No tuning whatsoever on "integral" data, like calorimeter resolutions, thick target yields etc, is performed

The final predictions are obtained with minimal free parameters, fixed for all energies and target/projectile combinations

Results in complex cases as well as scaling laws and properties come out naturally from the underlying physical models. The basic conservation laws are fulfilled "a priori"

All results/benchmarks published so far have been obtained with the same standard FLUKA*, of course with possibly improved models along the years*

The FLUKA project (http://www.fluka.org):

A.Fassò (→SLAC), A.Ferrari (on leave from INFN), S.Roesler
CERN

J. Ranft
Leipzig

P.R.Sala (on leave from INFN)
ETH Zürich

F.Ballarini, G.Battistoni, M. Campanella, A. Coppola, M.Carboni, F.Cerutti, L.DeBiaggi, R. Di Liberto, E.Gadioli, M.V.Garzelli, A.Ottolenghi, M.Pelliccioni, T.Rancati, D.Scannicchio, R.Villari
INFN-Milan & Frascati, University of Milan and University of Pavia

V.Anderson, A.Empl, K.Lee, L.Pinsky
University of Houston

T.N. Wilson, N. Zapp
NASA/JSC

FLUKA: sponsors

Since two years ago the long dating ($>$ 14 years) INFN support became official. A "FLUKA" project has been established and funded in the framework of the INFN Commissione V

It is the official MonteCarlo of the ICARUS experiment, as well as for the spallation part of the Energy Amplifier and related studies (all activities chaired by C. Rubbia).

Strong support is coming from the University of Houston and NASA. A three-year (2000-2003) development program for FLUKA has been funded, and recently a new four-year grant has been approved. The final goal is to produce a state-of-the-art tool for space radiation calculations, which will also exploit the ROOT capabilities for the user interface and output analysis (F. Carminati and R. Brun are members of this collaboration).

The INFN FLUKA project

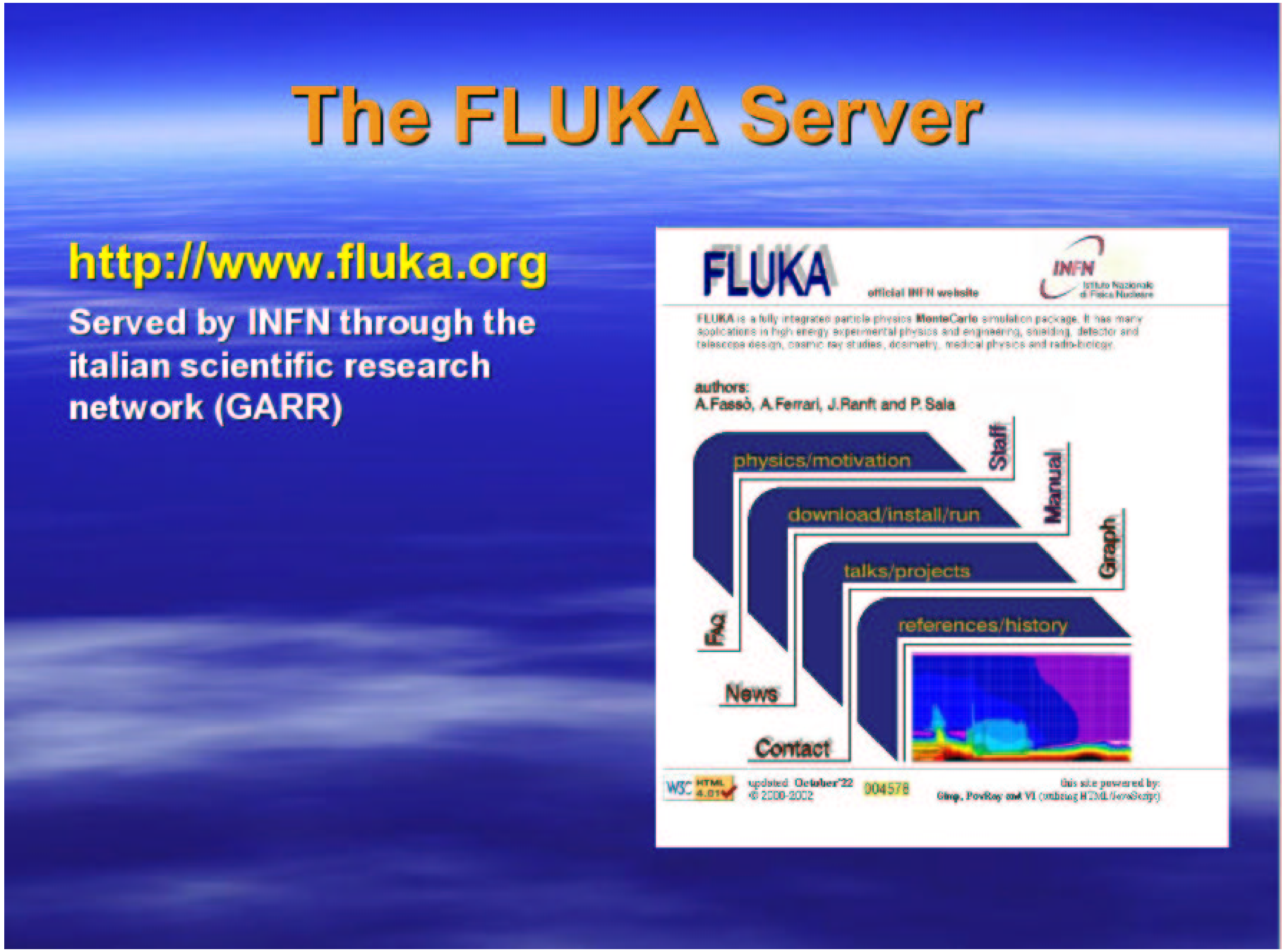
FLUKA approved as official INFN project in Sept. 2001
(presently 6.35 FTE from Milan, Pavia, Frascati)

INFN project milestones for 2002 and 2003:

- 31/12/2002 Ion (nuclear) interaction model ($E > 5$ GeV/u)
- 31/12/2002 First (preliminary) integration with radiobiological databases
- 30/06/2002 Preliminary “module” for cosmic ray applications
- 30/06/2002 Official WWW server for the code distribution
- 31/12/2002 Improvements of the user-friendliness of the code
- 31/12/2002 Release of an interface to the GEANT4 geometry (FLUGG)
- 30/03/2003 FAQ and mailing list services on www.fluka.org
- 31/12/2003 Documented examples to be consulted via web
- 31/12/2003 Documentation about the new geometry (incl. CT Voxel scans)
- 31/12/2003 New radiobiology results about the 3D voxel phantom
- 31/12/2003 Upgrade of the DPMJET interface to DPMJET-III

Proposed INFN project milestones for 2004

- Web site mirrors (SLAC, CERN ?)
- New manual (already $>$ 300 pages) and new web examples
- Setting up of regular FLUKA courses
- CVS server
- Elimination of the preprocessor for EM cross section calculations
- New geometry abstraction level (names instead of numbers and infinite number of parentheses in the Boolean operations)
- Heavy (A>4) fragment evaporation and fragmentation
- Residual dose rate temporal evolution, including γ, and $\beta^{+/-}$ emission from calculated residuals
- Extension up to 100 MeV/u of the BME model for low energy ion interactions
- Further developments of the FLUKA cosmic ray special package
- Solar particle event simulation (August 1972 particularly)
- Organ doses due to 1 GeV/n alpha and heavier ions beams


The FLUKA Server
http://www.fluka.org
Served by INFN through the italian scientific research network (GARR)
FLUKA
official INFN website
INFN
authors:
A.Fassò, A.Ferrari, J.Ranft and P.Sala
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Present Availability and Documentation

Free download from the web server of:

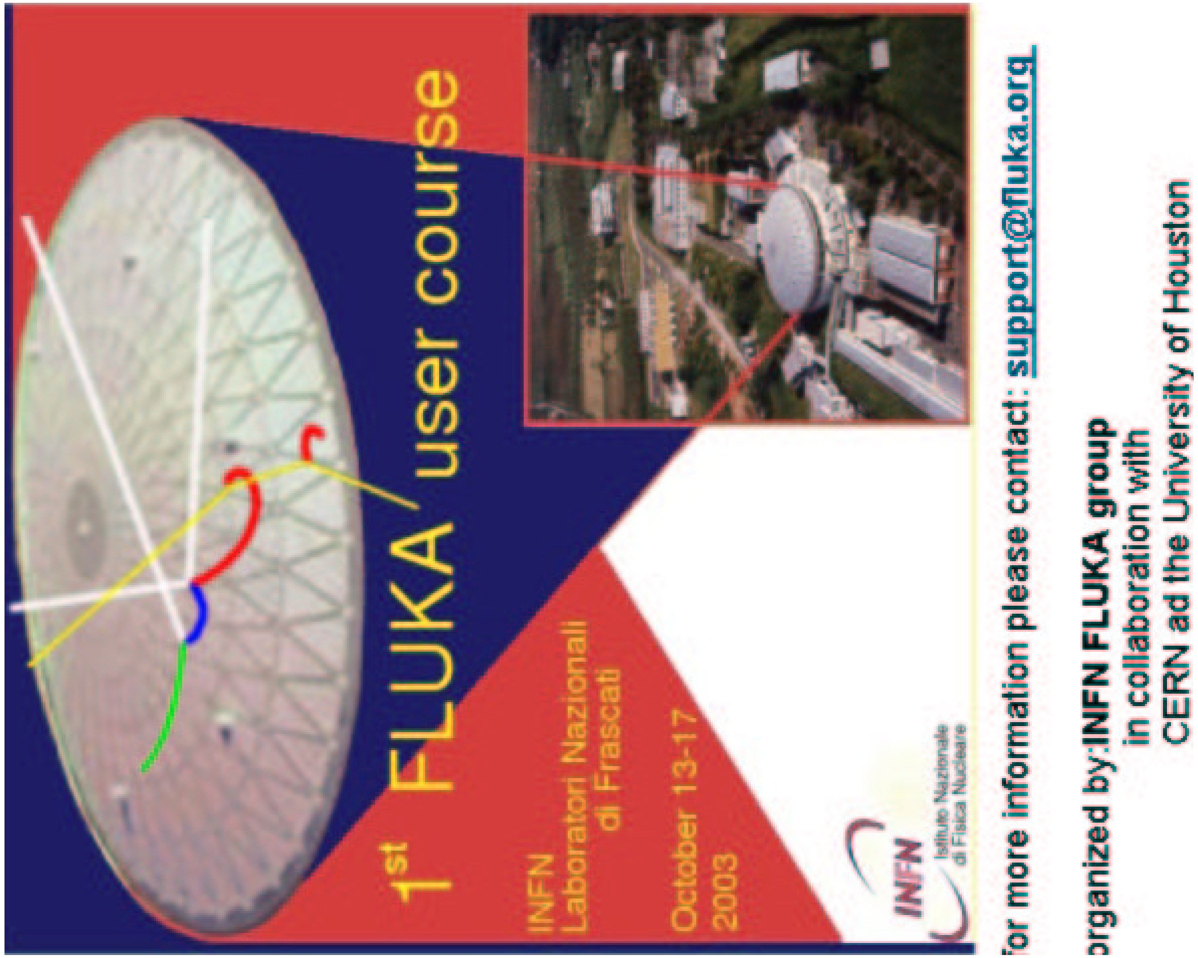
- Libraries, data files, user interface routines, utility scripts and programs for
  1. Linux (RH 8.0, 7.3 and 7.x x<3)
  2. Digital Unix
  3. Sun
  4. HP-UX 10
  5. VMS (on request)
- User manual: included in the distribution, + browsable version

Publications: list on the www server

User Support: mailing list

Latest release: FLUKA2002.4 on may 23rd 2003

course


1st FLUKA user course
INFN
Laboratori Nazionali
di Frascati
October 13-17
2003
INFN
Istituto Nazionale
di Fisica Nucleare
for more information please contact: support@fluka.org
organized by: INFN FLUKA group
in collaboration with
CERN ad the University of Houston

FLUka with Geant4 Geometry [1]

An extension of FLUKA FORTRAN
that uses the GEANT4 geometry package C++
to build the geometrical model, compute particle steps and location.
Provides to FLUKA a geometry more flexible than the default one
Allows to run FLUKA using a geometry input in the GEANT4 format
(or GEANT3 via the ALICE translator (with some limitations))

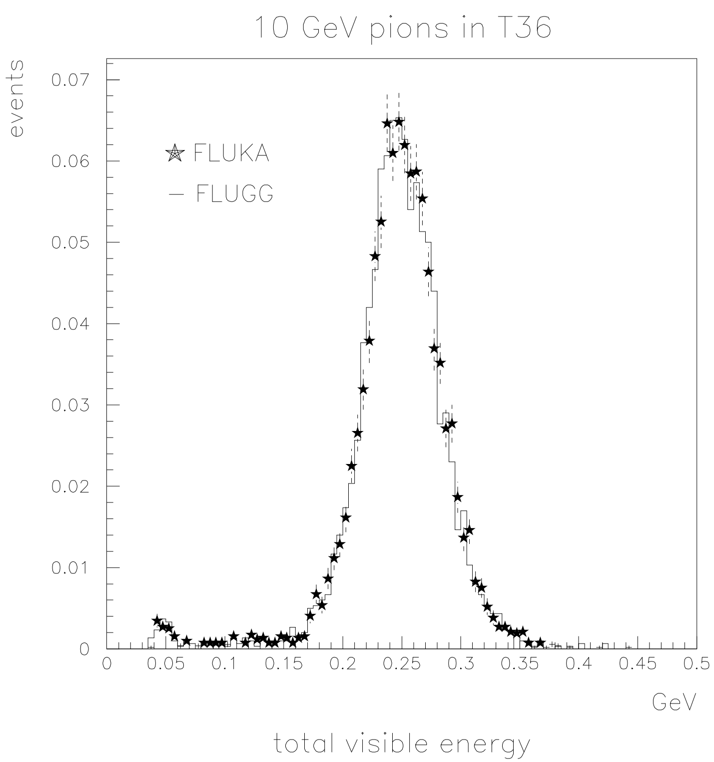
Present Status

- particle transport in single level and multi-level geometries
- input user interface , output in FLUKA format
- tested on HP and Linux

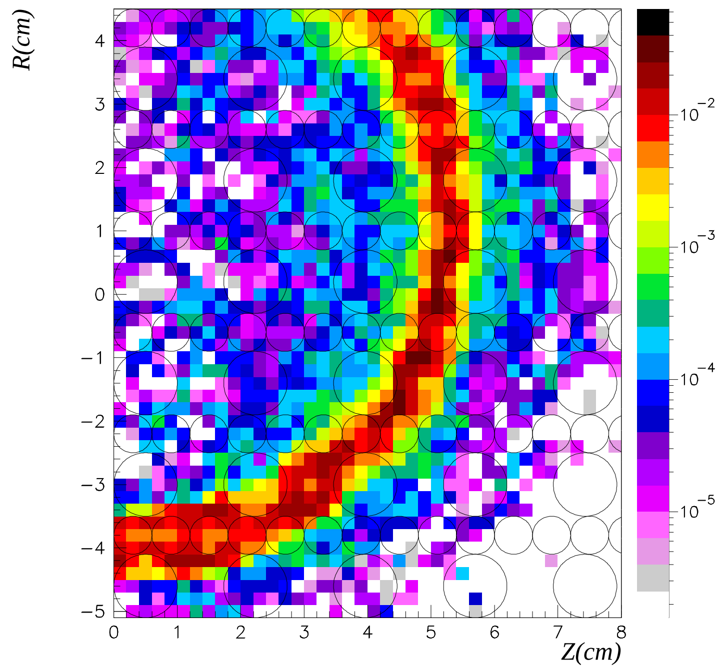
[1] ATL-SOFT-98-039,ATL-SOFT-99-004

The FLUGG project: tests

A simple calorimeter :T36



Toy geometry with magnetic field



The INFN-CERN FLUKA Agreement

February 2003 *Scientific Agreement* signed by CERN EP and AB - INFN - FLUKA Authors

The purpose of this agreement is to make the FLUKA *Monte Carlo code, fully available to the scientific community, while protecting the scientific rights of the authors and the integrity of the code*

- A (5 member) Coordinating Committee supervises the project
- A full release including source and documentation is foreseen within 12-18 months, starting from the availability of 1 FTE Scientific Associate from EP and 1 FTE Staff from AB
- The Coordinating Committee has also the task of drafting a proper licensing scheme

Benchmarking

Benchmarking is an essential part of the development. Single interaction data, when available, are always used to check any FLUKA *development*

FLUKA hadronic benchmarks (double differential yields, particle multiplicity, invariant cross sections...) cover (see www.fluka.org for some examples):

- High Energy h-N (test of DPM)
- High Energy h-A (DPM, Glauber-Gribov, (G)INC)
- Intermediate Energy h-A (Resonance model, (G)INC)
- Medium-low energy (PEANUT: (G)INC + preequilibrium + evap/fission/break-up)
- Residual nuclei production (whole chain + evaporation)
- Intermediate energy Pion induced reactions
- Photonuclear interactions
- Neutrino nuclear interactions
- Muon photonuclear
- ...

Complex benchmarks

- The TIARA neutron propagation experiment: Y.Nakane et al., Proc. SATIF-3 KEK 1997
- The TARC exp. at CERN, the ultimate neutronic benchmark: **PLB458** (1999) 167
- The Rösti experiments at CERN: A. Fassò et al., NIM **A332** (1993) 459
- The CERF dosimetry facility at CERN: A. Esposito et al, Rad. Prot. Dos. **76**,(1998) 135
- The OPTIS beam at PSI, an attempt of merging biophysical and physical models: M. Biaggi et al., NIM, **B159**, (1999) 89
- Muon and hadron fluxes in the atmosphere: CAPRICE and AMS data, G. Battistoni et al., Astropart. Phys. **17**,(2002) 477 P. Zuccon et al. CERN-OPEN-2001-068
- LHC background benchmarking: E. Gschwendtner et al., NIM **A476**, 222 (2002)
- ATLAS Calorimeters: NIM **A387** (1997), 333 ; NIM **A449** (2000), 461
- LEP activation: CERN-TIS-99-011-RP-CF/SLAC-PUB-8214 , CERN-TIS-99-012-RP-CF/SLAC-PUB-8215
- Dose to commercial flights A. Ferrari et al., Rad. Prot. Dos. **3**, 101 (2001), S. Roesler et al., Rad. Prot. Dos. **98**, 367 (2002)

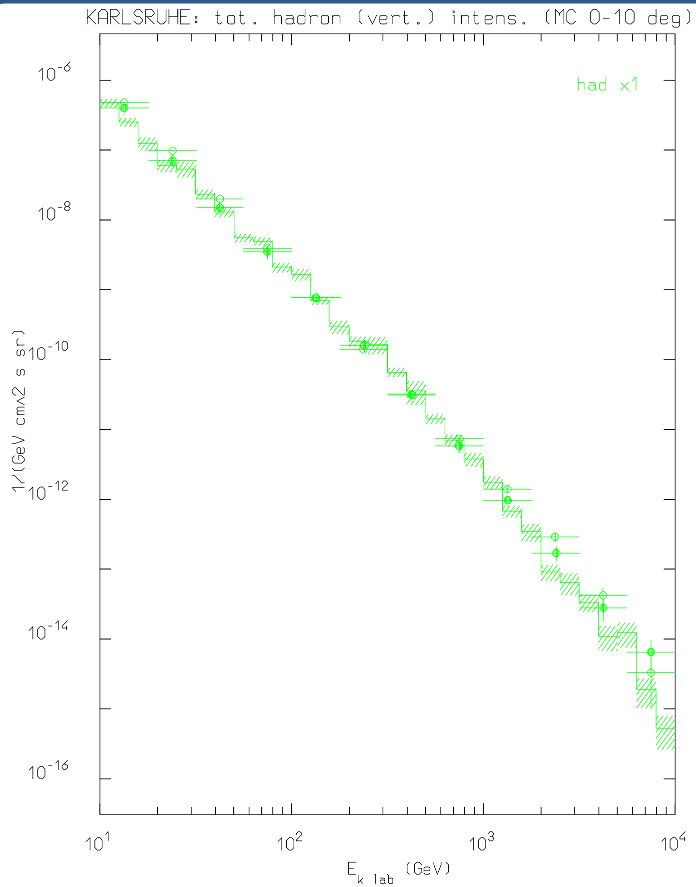
Original motivations: Atmospheric ν fluxes (Astropart.Phys.**12** (2000) 315) (Milan)
Aircraft doses (Frascati, Siegen and GSF)

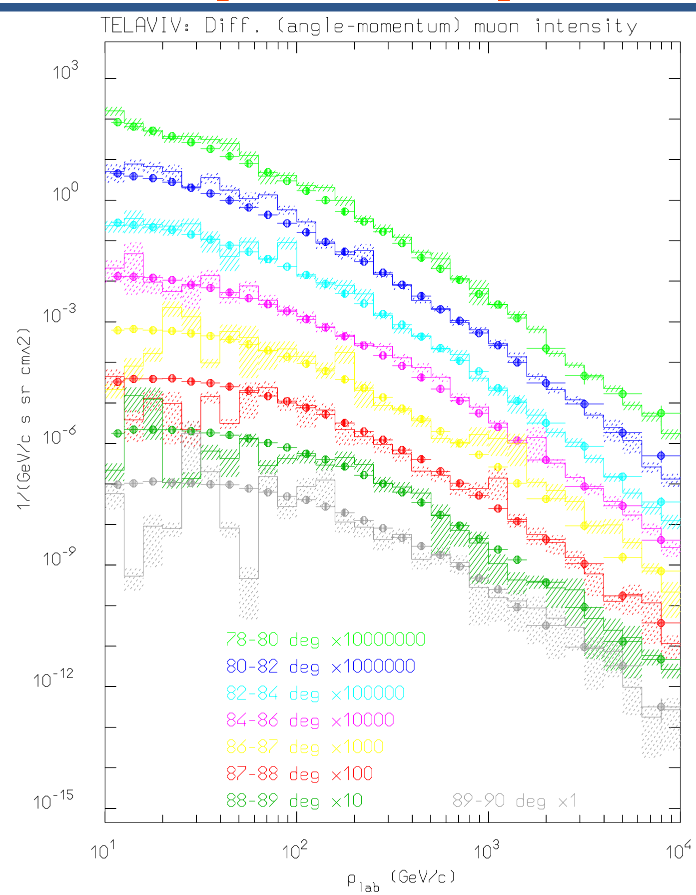
$\rightarrow$ Exploiting the reliability of FLUKA Hadronic interaction models

Results

- The first 3Dimensional MC simulation of ν production due to atmospheric showers
- Extensive benchmarking with muon and hadron data in atmosphere
- Photomuon production by cosmic rays
- Widespread applications to aircraft exposure evaluation
- Space radiation applications (NASA, ASI)

Hadron/muon fluxes in the atmosphere: examples

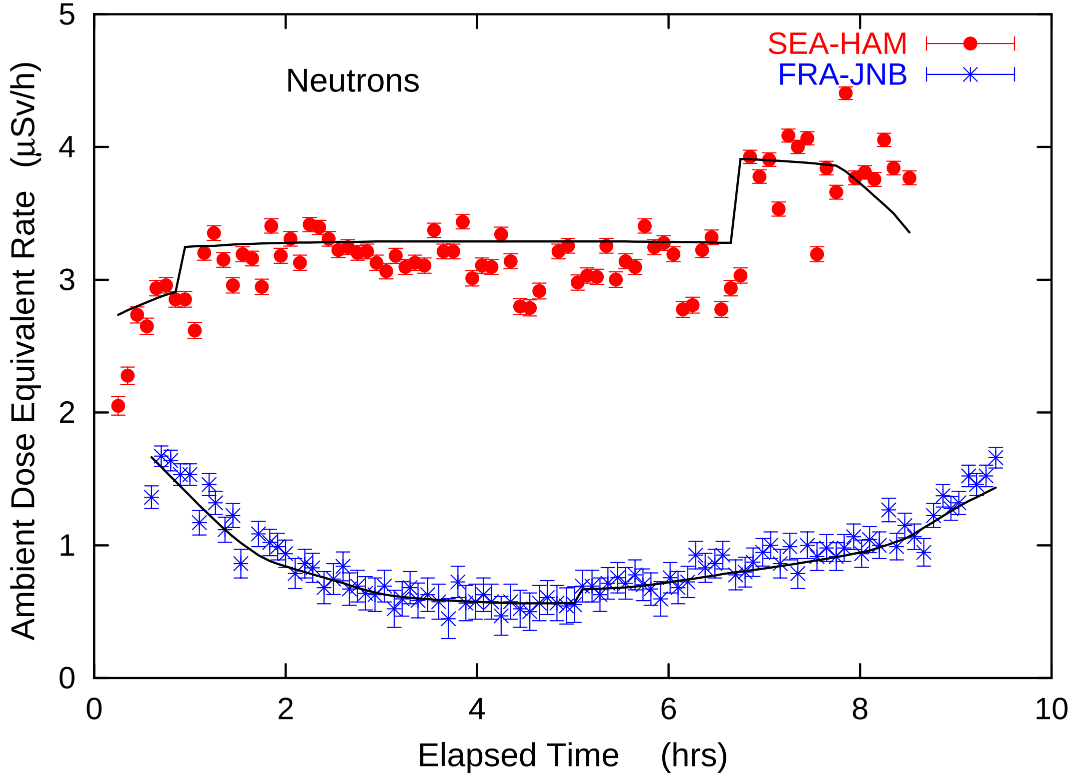




Hadron flux at sea level, KASKADE data from H. Kornmayer et al, JPG 21, 439 (1995).

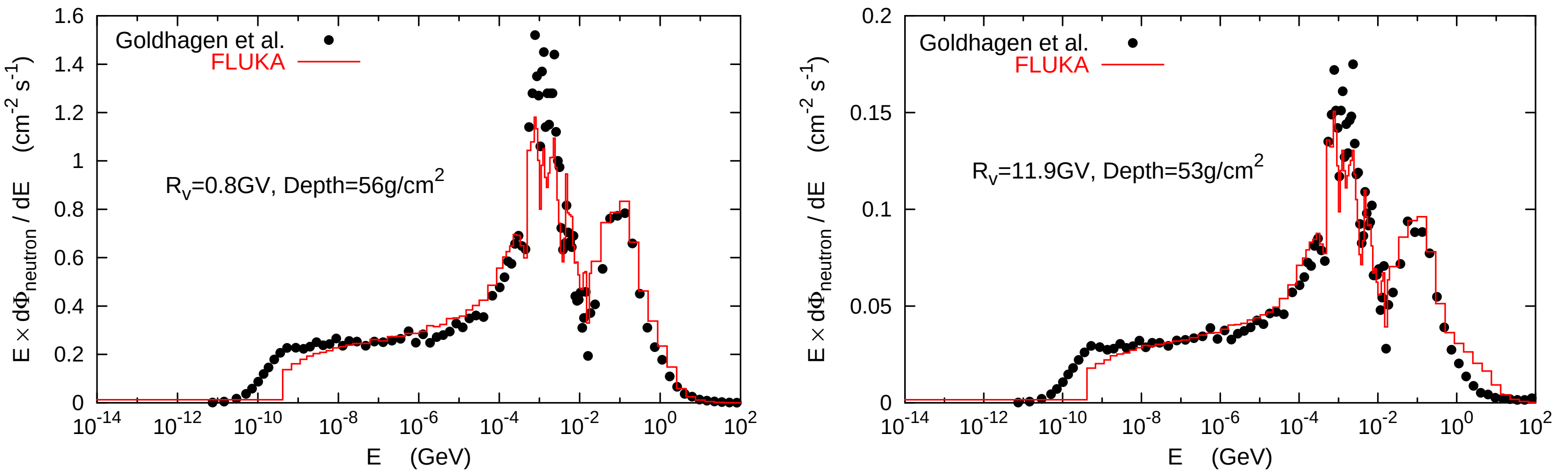
Double differential muon fluxes in Tel Aviv. Data: O.C. Allkofer et al. NPB 259, 1, (1985).

Hadron/muon fluxes in the atmosphere: examples II (Rad.Prot.Dosim.98 (2002) 367)



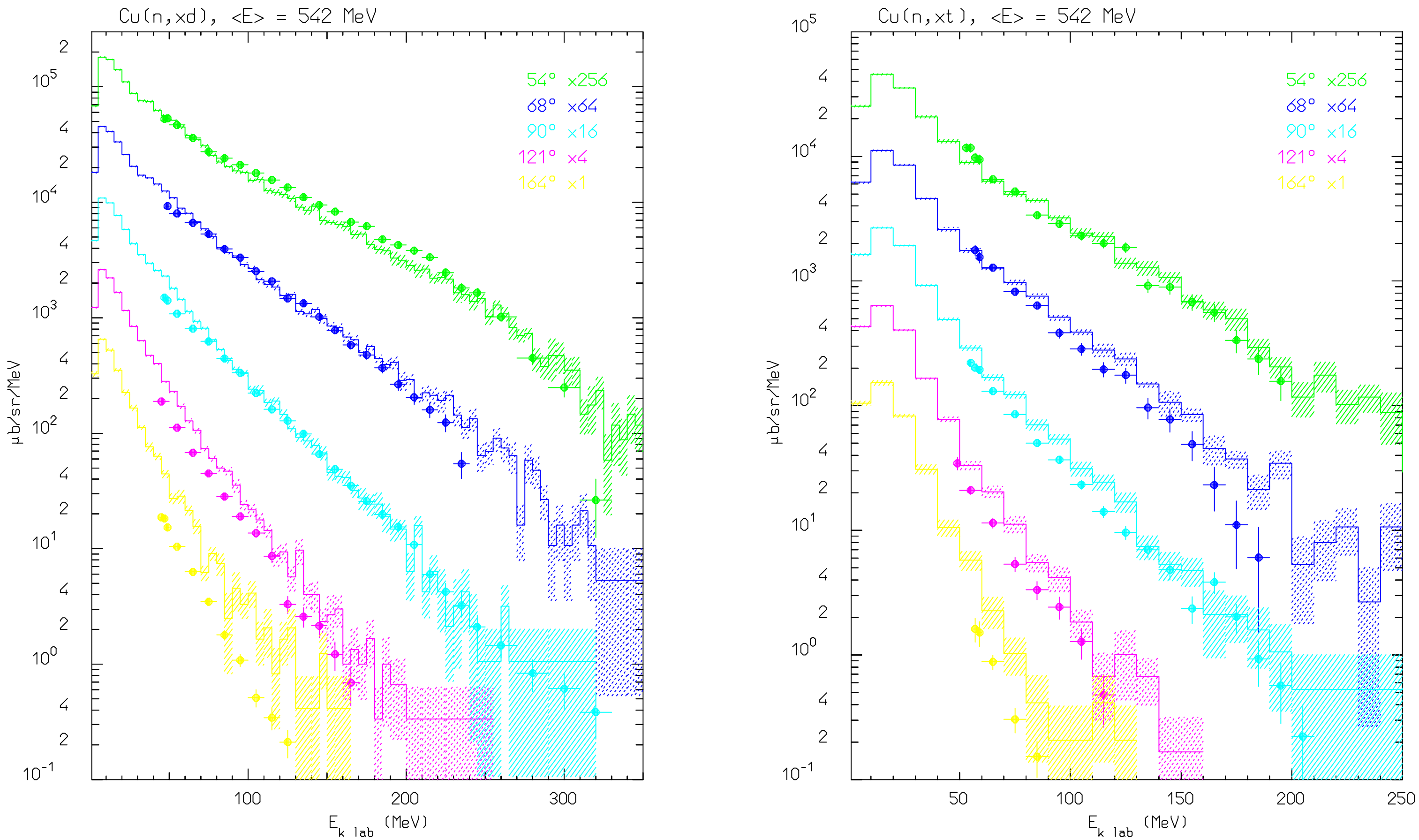
Ambient dose equivalent from neutrons measured during solar maximum on commercial flights from Seattle to Hamburg and from Frankfurt to Johannesburg, as function of time after take-off (symbols, exp. data, Lines: FLUKA).

Hadron/muon fluxes in the atmosphere: examples III (Rad.Prot.Dosim.98 (2002) 367)



Atmospheric neutron spectra measured aboard of an ER-2 high-altitude airplane (NIM A476, 42 (2002)) (symbols) and calculated with FLUKA (histograms), at two different geographic locations and altitudes.

Coalescence : examples



Deuteron (left) and triton (right) emission from 542 MeV neutrons on Cu. Data (symbols): J. Franz et al.,Nucl. Phys. **A510**, 774 (1990)

Heavy ion Interactions

High energy A-A interactions ($E > 5 - 10\ GeV/u$):

- Interface to DPMJET

Present

Intermediate energy A-A interactions

- Medium-heavy nuclei: interface to RQMD-2.4 code (as obtained from H.Sorge web page)

- Medium-heavy nuclei: Internally developed QMD
- Light nuclei ($\leq$C): extension of PEANUT, (the FLUKA cascade+preequilibrium model)

Near Future

Low energy A-A interactions ($E < 100 MeV/amu$):

- Interface to Monte-Carlo Boltzmann Master Equation code developed at Milan University. (NPA 679 (2001) 753)

Heavy ions at relativistic energies: DPMJET(-2.5/III)

DPMJET [2] : *(R. Engel, J. Ranft, and S. Roesler)*

Nucleus-Nucleus interaction code for collisions from ≈5-10 GeV/n up to the highest cosmic ray energies ($10^{18} - 10^{20}$ eV) used in many CR shower codes

DPMJET *is based on the Dual Parton Model and the Glauber model, like the high energy* FLUKA *hadron-nucleus generator*

FLUKA-DPMJET (DPMJET-II.53 , upgrading to DPMJET-III):

Cross sections pre-computed by DPMJET, tabulation is used by FLUKA

Glauber impact parameter pre-computed over complete A and E range

Interface call at begin and end of single interactions

Reaction products given back to be transported by FLUKA

Evaporation and deexcitation of residual nuclei performed in FLUKA

[2] PRD 51 (1995) 64; Gran Sasso INFN/AE-97/45 (1997); hep-ph/9911232; hep-ph/9911213; hep-ph/0002137, "The Monte Carlo Event Generator DPMJET-III" Proc. MC2000, Springer-Verlag Berlin, Heidelberg, pp. 1033-1038.

The FLUKA - RQMD-2.4 interface

Refs: H. Sorge PRC52 3291 (1995), H.Sorge, H.Stocker, W.Greiner, Ann. Phys. 192 266 (1989), NPA498 567c (1989)

Relativistic QMD model applicable from $\approx$ 0.1 GeV/n up to several hundreds of GeV/n, successfully applied to relativistic A-A particle production over a wide energy range

Limitations:

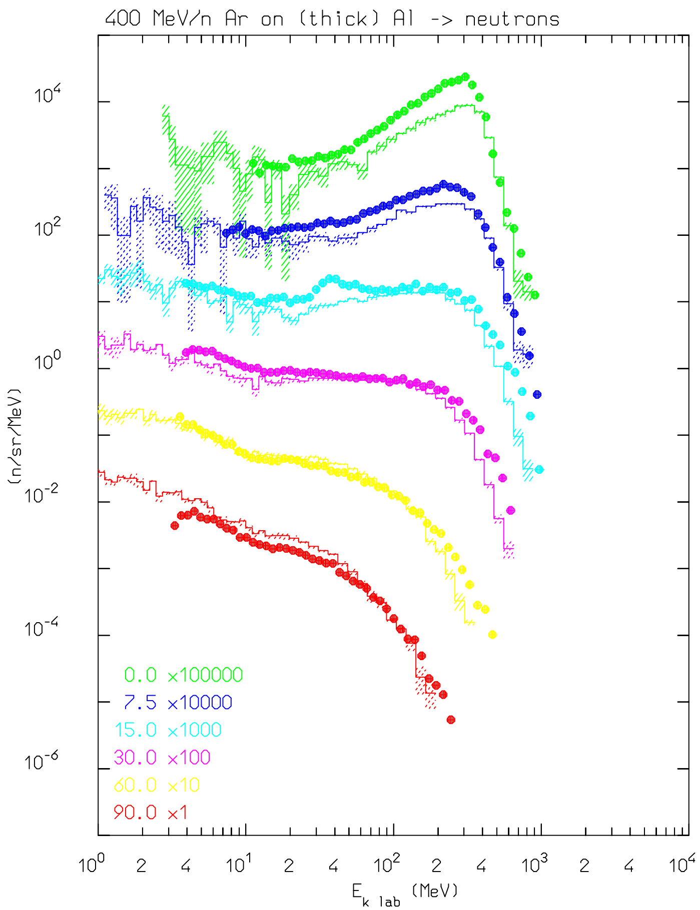
- No evaporation/fragmentation/fission/deexcitation of residuals and fragments
- Energy non-conservation issues, particularly when run in full QMD mode
- No meaningful excitation energy calculation implemented or possible
- Apparently no longer maintained

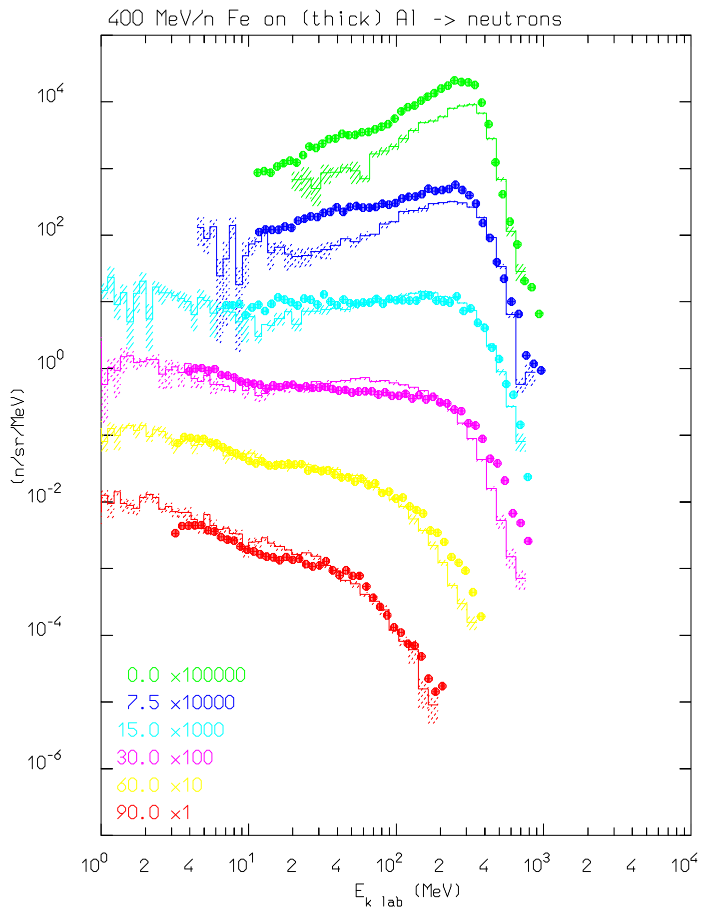
Solutions: *ALREADY IMPLEMENTED IN FLUKA-RQMD*

- Rework from scratch the nuclear final state out of the available info on spectators, correlating the excitation energy to the actual hole depth of hit nucleons
- Fix the remaining energy-momentum conservation issues taking into account exp. binding energies as well
- Use the FLUKA evaporation/fragmentation/fission/deexcitation module

Current solution for A-A interactions below few GeV/n, waiting for an in-house developed model

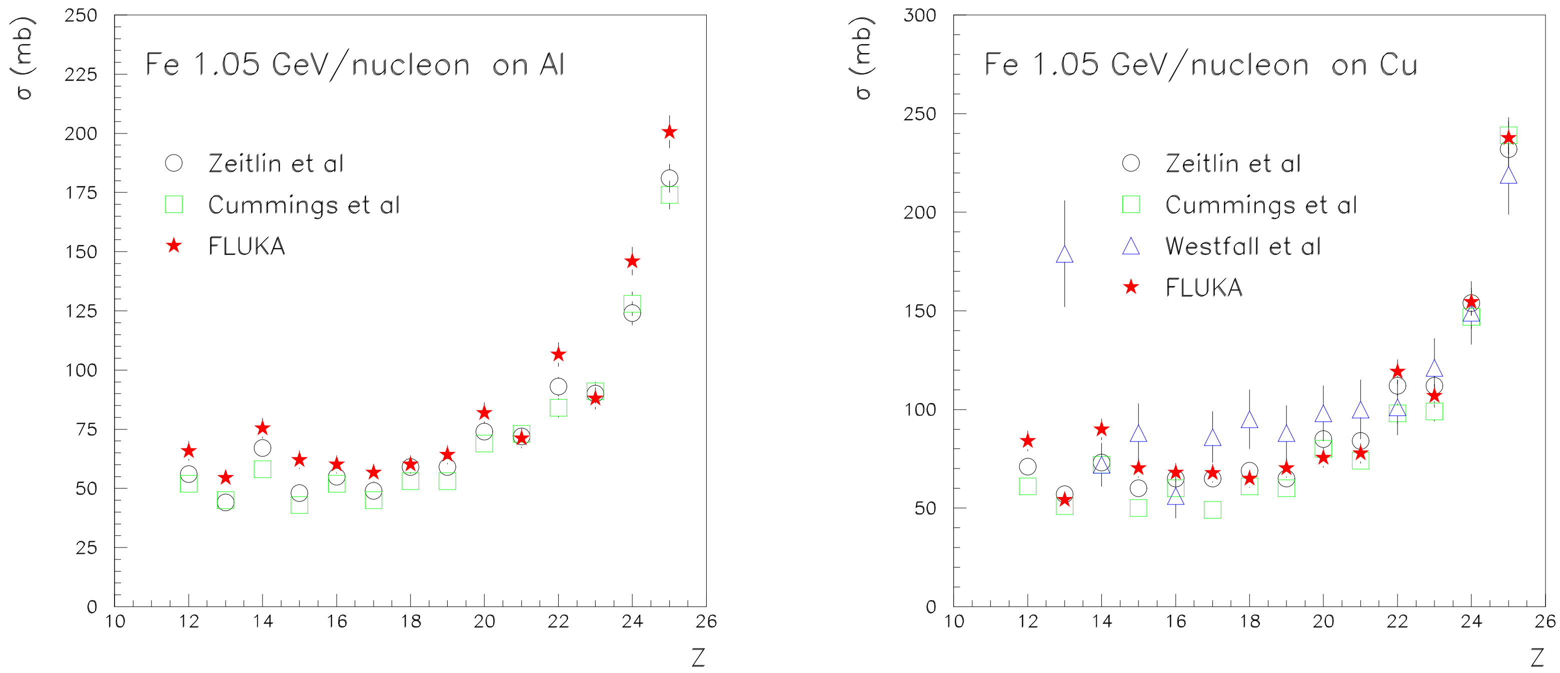
FLUKA with modified RQMD-2.4 (cascade mode)- results





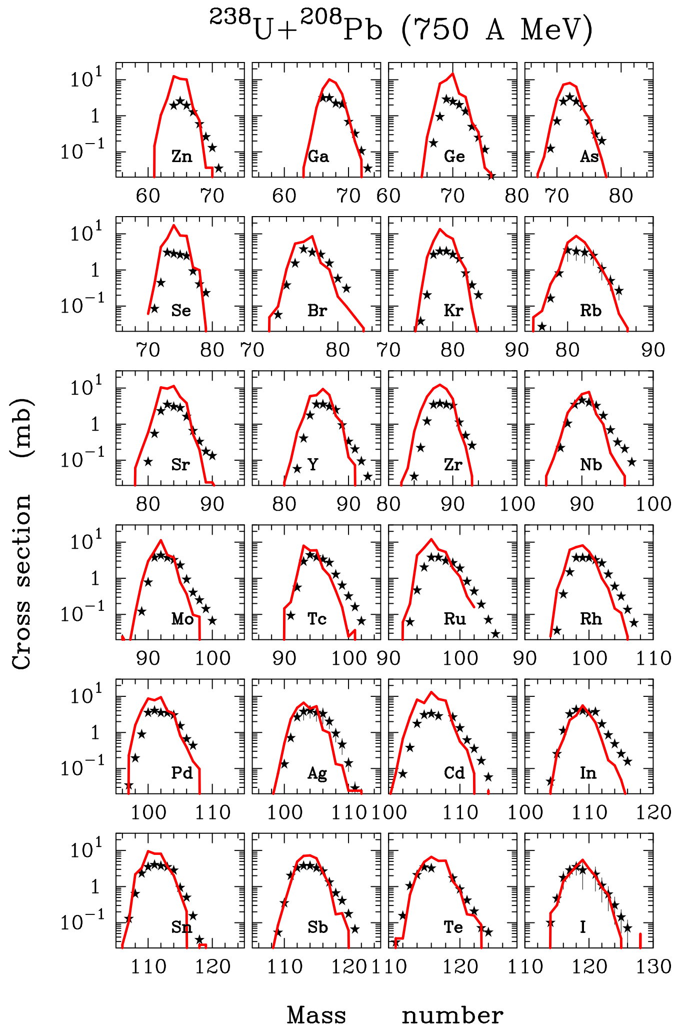
Double differential neutron yield by 400 MeV/n Ar (left) and Fe (right) ions on thick Al targets, histo FLUKA, dots exp. data (PRC62 044615 (2000)).

FLUKA with modified RQMD-2.4 (cascade mode) - results II



Fragment charge cross sections for 1.05 GeV/n Fe ions on Al (left) and Cu (right). stars FLUKA, circles PRC56 (1997) 388, squares PRC42 (1990) 5208 (at 1.5 GeV/n), triangles PRC19 (1979) 1309 (at 1.88 GeV/n).

FLUKA with modified RQMD-2.4 (cascade mode) - results III



Fragment charge cross sections for 750 MeV/n U ions on Pb. Data (stars) from J. Benlliure, P. Armbruster et al. Eur. Phys. J A 2, 193-198 (1998)). Fission products have been excluded like in the experimental analysis.

Conclusions

- FLUKA: proven capabilities in accelerator shielding and design problems, as well as the primary tool for pivotal ADS related studies and experiments, over a very wide energy range
- In the last years well established capabilities in atmospheric and cosmic ray problems besides the original accelerator ones. It is the "de facto" standard tool for all aircraft dosimetry studies in Europe
- The MonteCarlo of ICARUS as well as for all CNGS calculations
- Recently: ability to follow the whole shower induced by whichever ion on whichever target, with sound interaction physics above 100 MeV/n
- Rich physics development program for the future, in particular:
  - PEANUT and new QMD in place of the RQMD-2.4 "temporary" solution
  - BME model covering the low energy side

The FLUKA development is partially supported under:

- NASA Grants NAG8-1658 and 01-OBPR-05, ASI Contract 1R/090/00