The FLUKA code for space applications: recent developments

COSPAR2002 ,

October 10-19, 2002 Houston, Texas

V. Andersen[1], F. Ballarini[0], G. Battistoni[0], F. Cerutti[0], A. Empl[1], A. Fassò[2], A. Ferrari[3], E. Gadioli[0], M.V. Garzelli[0], K. Lee[1], A. Ottolenghi[4], M. Pelliccioni[5], L.S. Pinsky[1], J. Ranft[6], S. Roesler[7], P.R. Sala[8], T.L. Wilson[9]

[0] University of Milan and INFN, Italy
[1] Houston University, Texas, USA
[2] CERN (on leave from GSI Darmstadt)
[3] CERN (on leave from INFN-Milan)
[4] University of Pavia and INFN, Italy
[5] INFN Frascati, Italy
[6] Siegen University, Germany
[7] CERN
[8] ETH Zurich, Switzerland (on leave from INFN-Milan)
[9] NASA/JSC, USA

FLUKA

Authors: **A. Fassò[†], A. Ferrari[&], J. Ranft[*], P.R. Sala[#]**

[†] GSI Darmstadt and CERN, [&] INFN Milan and CERN, [*] Siegen University,

[#] INFN Milan and ETH Zurich

Interaction and Transport MonteCarlo code

Hadrons, leptons, (incl. ν), photons, heavy ions, low energy neutrons from thermal or few keV to cosmic

- Each component is treated as far as possible with the same accuracy
- All components in a single run, without intermediate steps. All the secondaries are transported before a new history is started.
- FLUKA can be run in fully analog mode. Its *microscopic* interaction models reproduce internal correlations.
- It can also be run in biased mode

http://www.fluka.org

FLUKA Topics

Descriptions of FLUKA models and extensive benchmarking can be found in the literature (see the web page)

A few recent, space-related developments will be presented here

- The Past: Cosmic ray shower calculations, Benchmarks and applications
- The Present: integration of Ion interaction codes, Cross section parametrizations, (details in modulations/geomagnetic field, new primary spectra)
- The future: new intermediate energy nucleus-nucleus generators (extended PEANUT, new QMD) development, BME at low energies...)

Cosmic Ray Showers

Motivations: Atmospheric neutrino fluxes (Astropart.Phys.**12** (2000) 315) (Milan)

Aircraft doses (Frascati, Siegen and GSF)

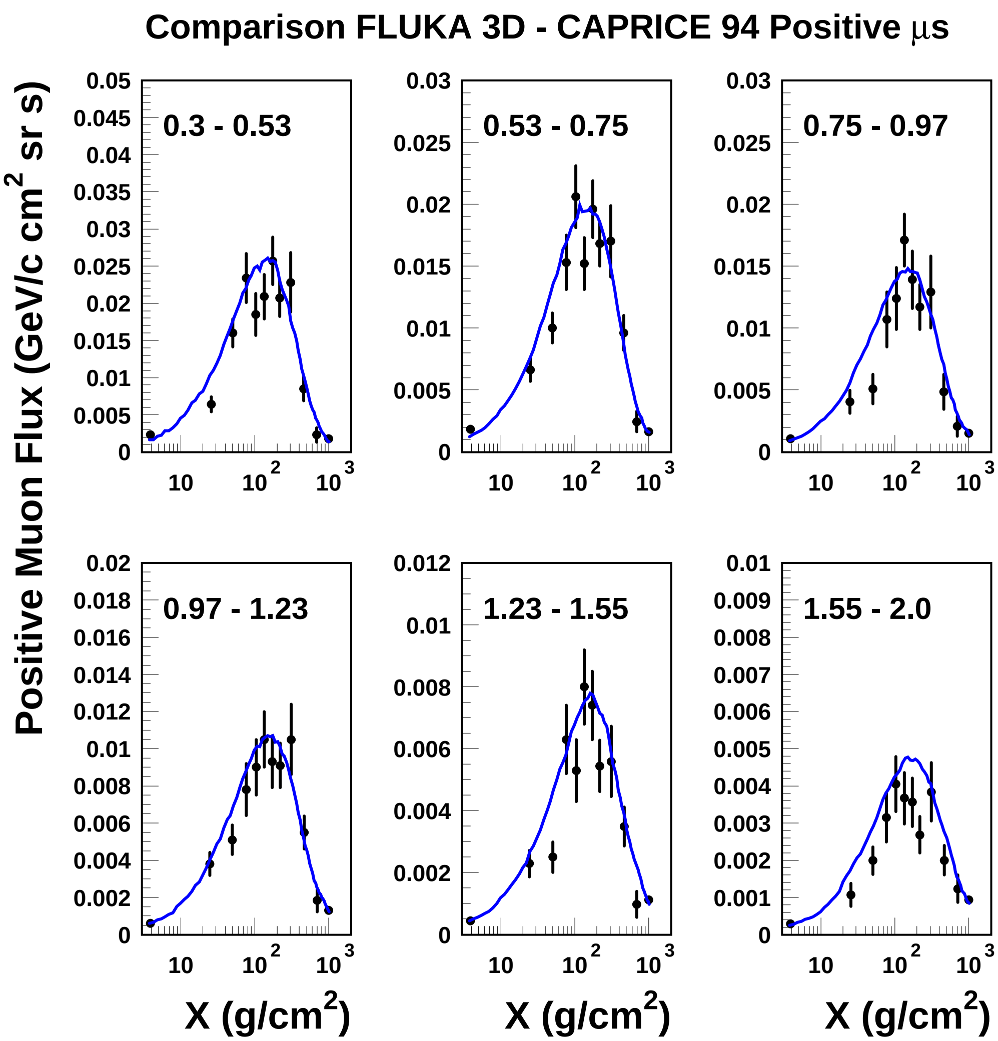
$\rightarrow$ Exploiting the reliability of FLUKA Hadronic interaction models

Results

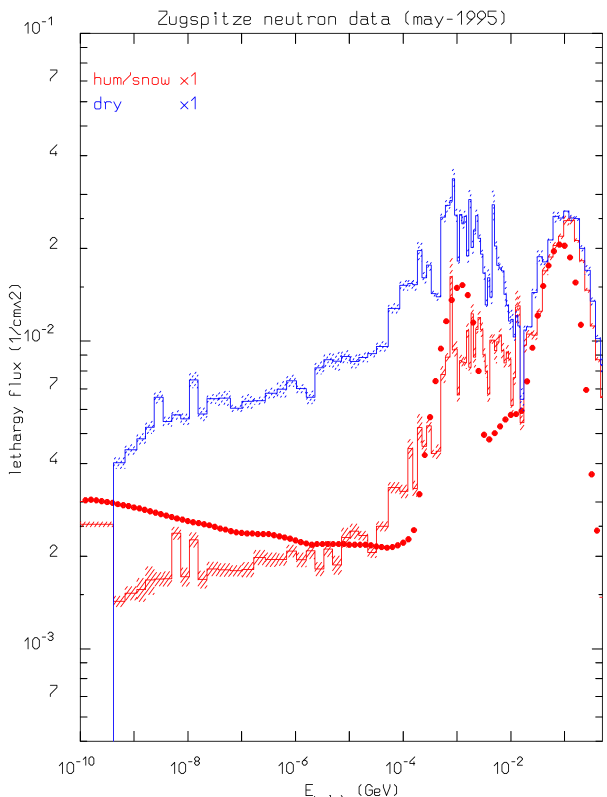
- The first 3Dimensional MC simulation of ν production due to atmospheric showers
- Extensive benchmarking with muon and hadron data in atmosphere
- Photomuon production by cosmic rays
- Widespread applications to aircraft exposure evaluation

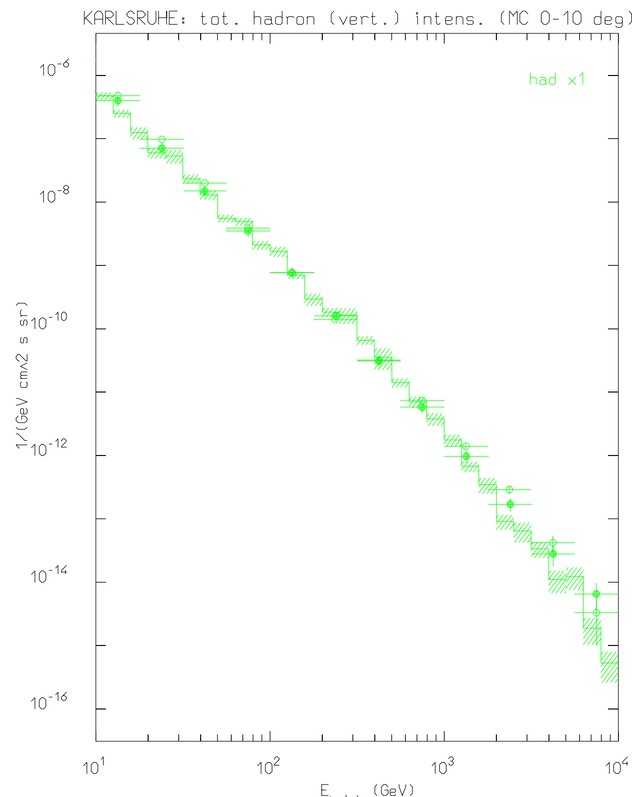
Past results obtained in the superposition model: primary nuclei are split into nucleons before interacting

Hadron/muon fluxes (Astropart. Phys. 17 (2002) 477), FLUKA and CAPRICE94 data



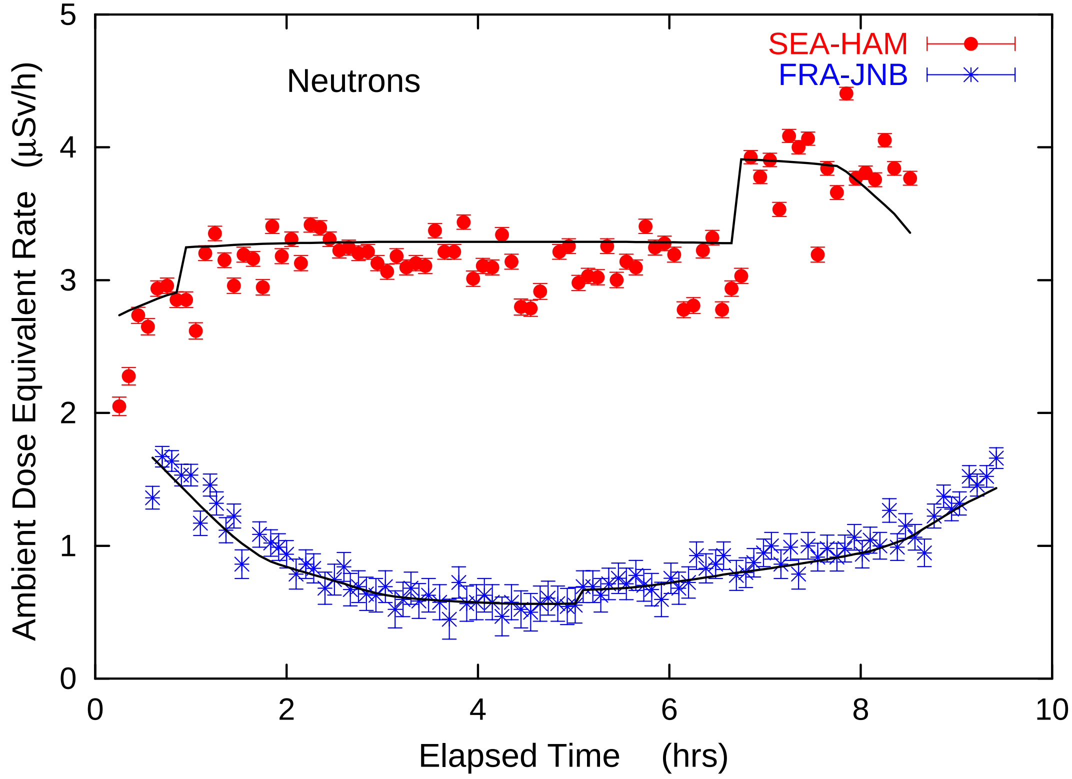
Hadron/muon fluxes in the atmosphere: examples III





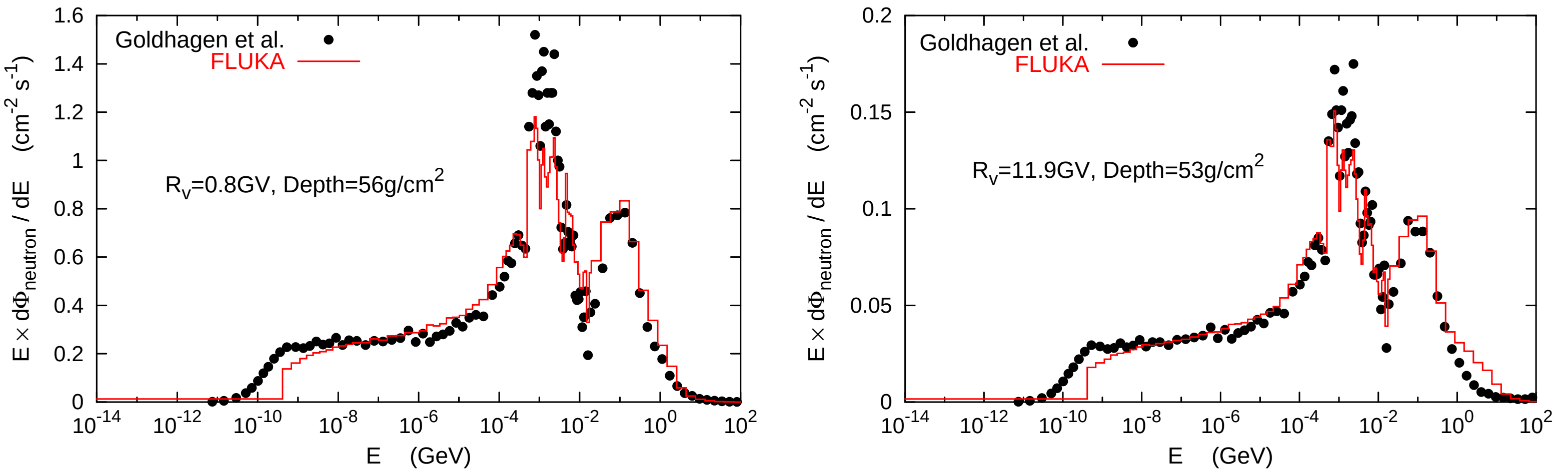
Computed neutron flux (histo) at top of the Zugspitze (left) for dry and wet conditions, and hadron flux (right) measured with the KASKADE experiment. Data (symbols) from JPG 20, 637 (1994), JPG 21, 439 (1995).

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



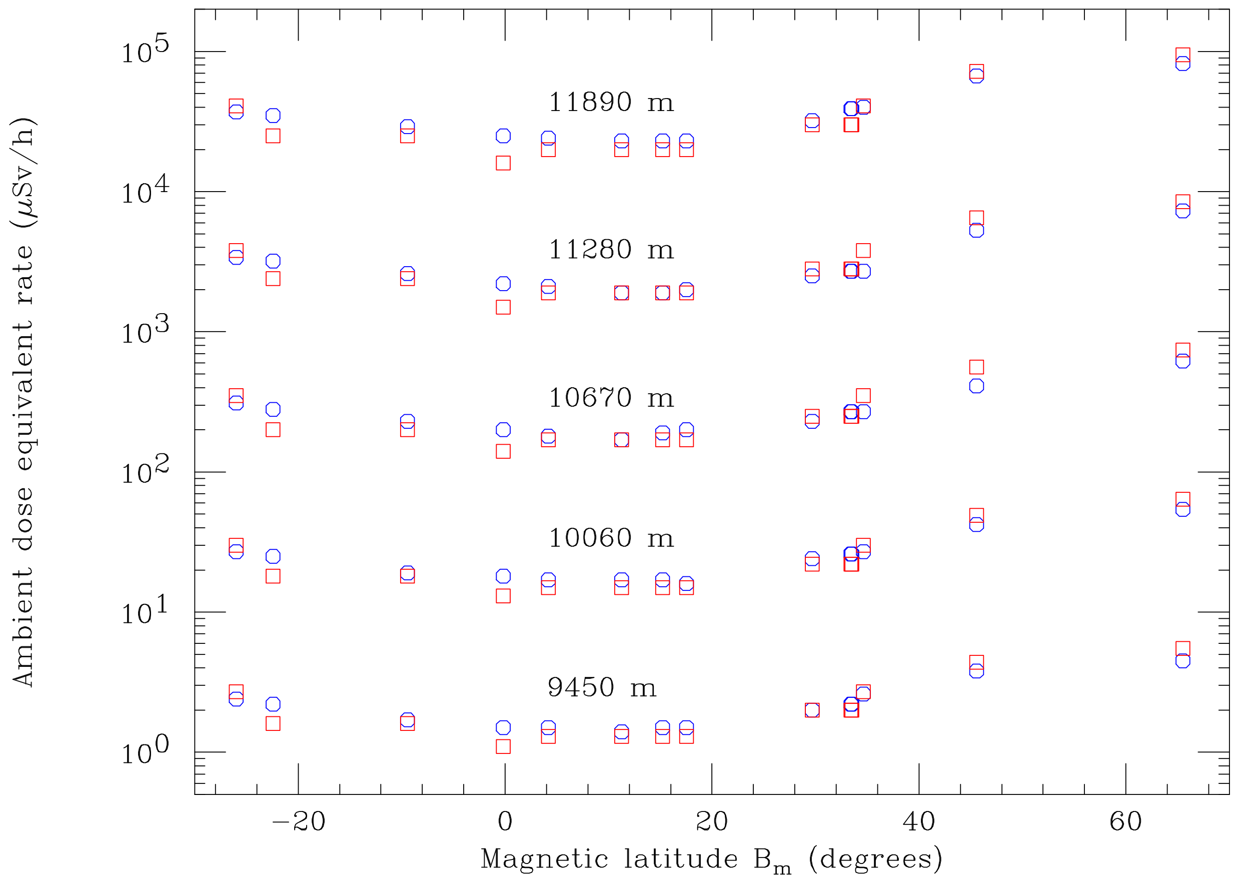
Ambient dose equivalent from neutrons measured during solar maximum on commercial flights from Seattle to Hamburg and from Frankfurt to Johannesburg, as function of time after take-off (symbols, exp. data, Lines: FLUKA).

Hadron/muon fluxes in the atmosphere: examples V
(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.

Doses to aircraft crews (Pelliccioni et al., Rad.Prot.Dosim. 93 101 and 96 219 (2001))



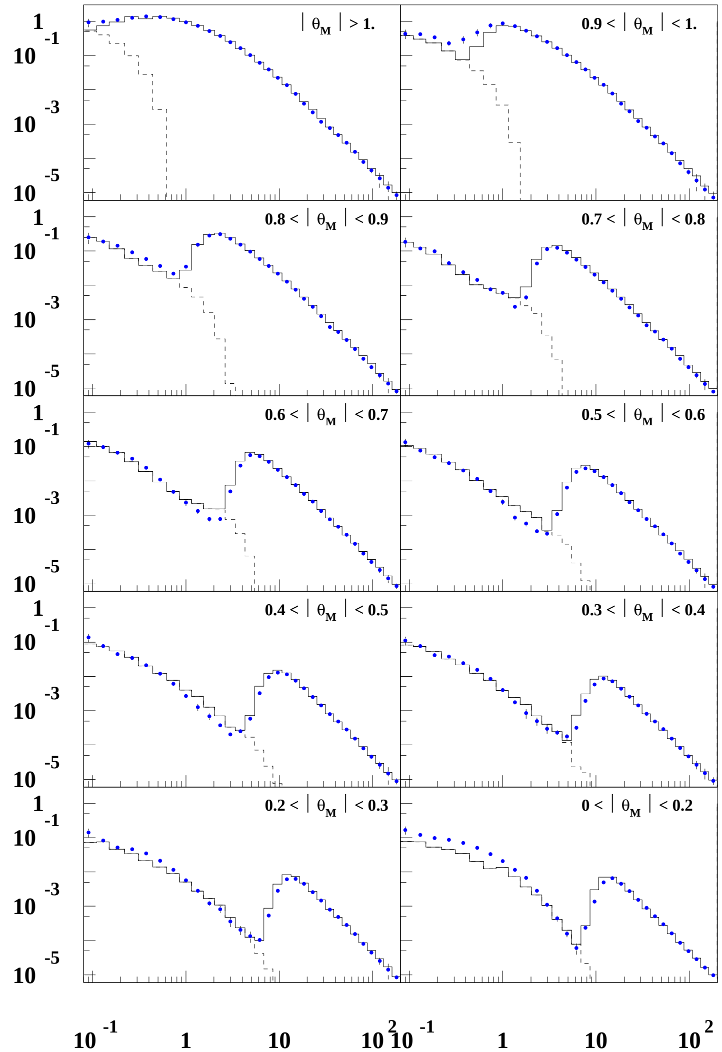
FLUKA (red) H*(10) rates vs in-flight measurements (blue, U.J.Schrewe, NIMA422 (1999) 621) for various altitudes (scaled by one decade) and geomagnetic latitudes.

Differences < 20% for 78% of data, < 34% for all.

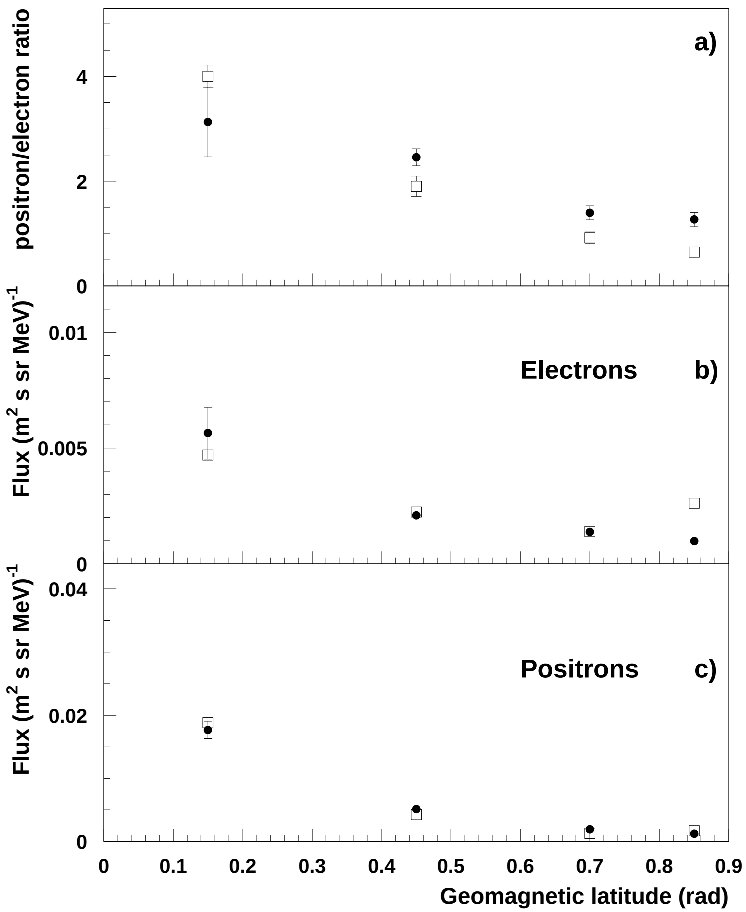
AMS (AMS-Perugia, astro-ph/0111111 and P.Zuccon PhD Thesis)

Protons and leptons
below the geomagnetic cutoff
have been measured by the AMS experiment
at altitudes 370-390 Km,
latitude $\pm 51.7^o$.

Shown: downgoing proton flux,
at different latitudes Θ_M
Dots: Data
Histogram: FLUKA simulations

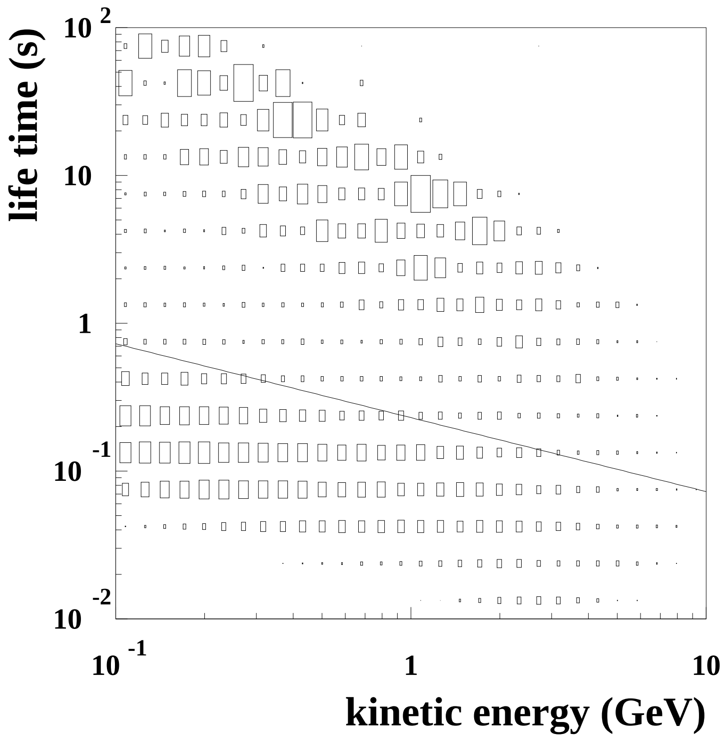


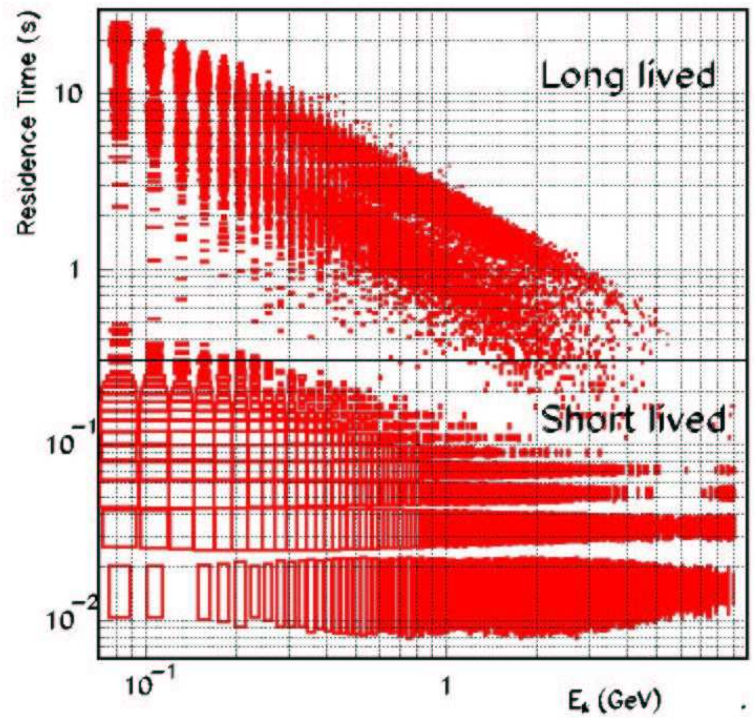
AMS (courtesy of AMS-INFN Perugia)



Electron (b) and positron (c) fluxes and their ratio (a) integrated in the kinetic energy range $0.2-1.5\ GeV$, as function of geomagnetic latitude. Open squares (AMS data), black points (FLUKA simulation).

AMS (courtesy of AMS-INFN Perugia)





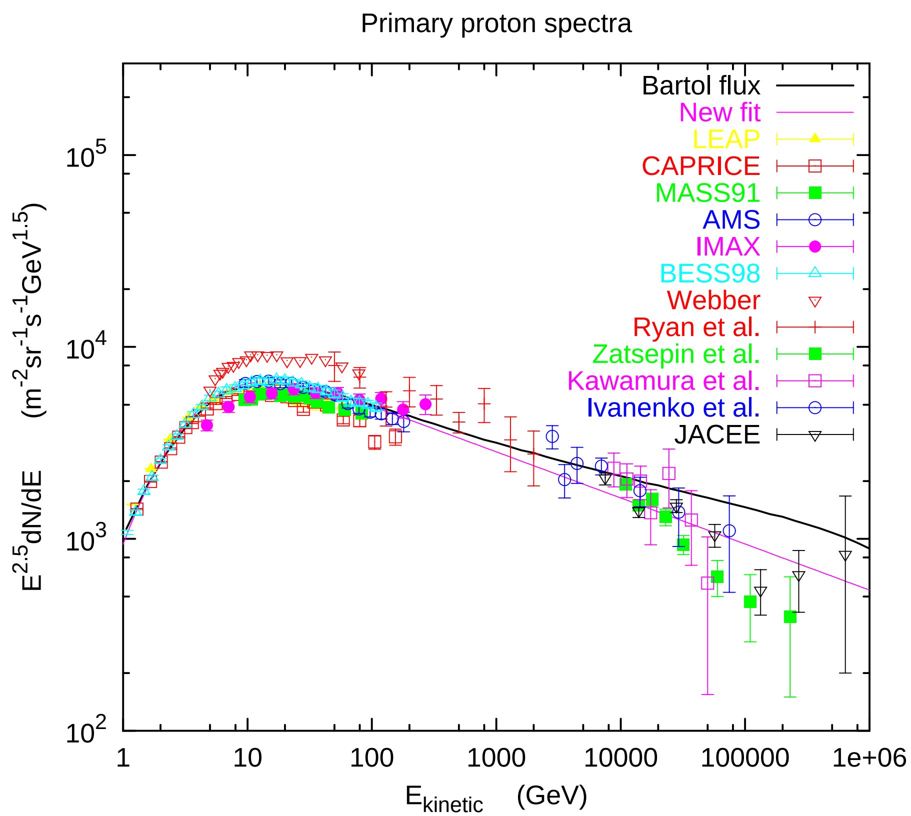
Proton flight time calculated with FLUKA (left) and evaluated from AMS data (right). Cut at $\Theta_M < 0.6$ rad

New Primary spectra

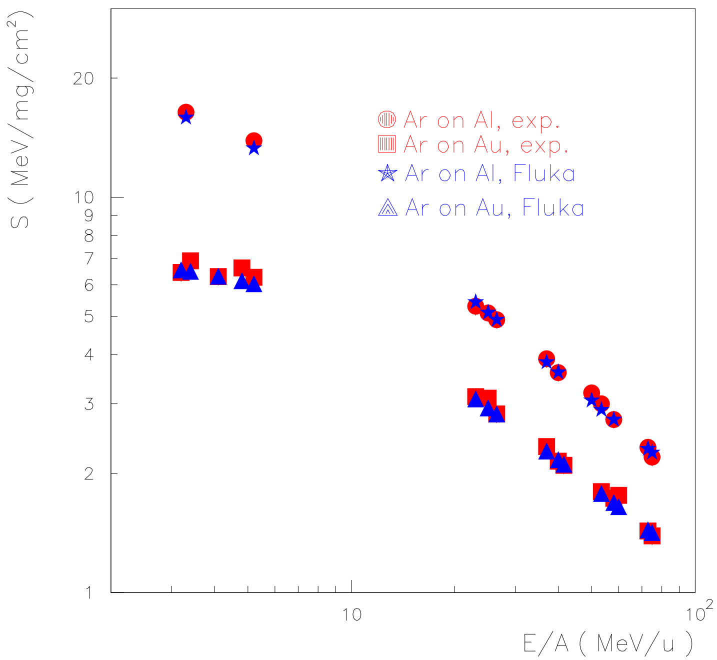
New measurements

Stringent accuracy needed for ν fluxes

New *Bartol* fit to primary spectra



Heavy Ion TRANSPORT



Experimental (red) (R.Bimbot, NIM**B69** (1992) 1) and FLUKA (blue) stopping powers of Argon ions in different materials and at different energies.

Heavy ion transport is already in FLUKA:

- Ionization energy losses
  - Up-to date effective charge parametrizations
  - Energy loss straggling
- Multiple scattering

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 (H.Sorge)

- 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 [1] : *(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

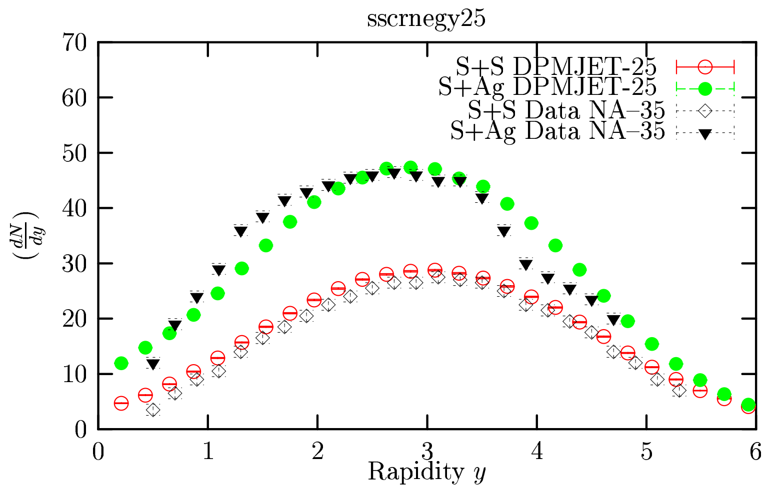
Interface call at begin and end of single interactions

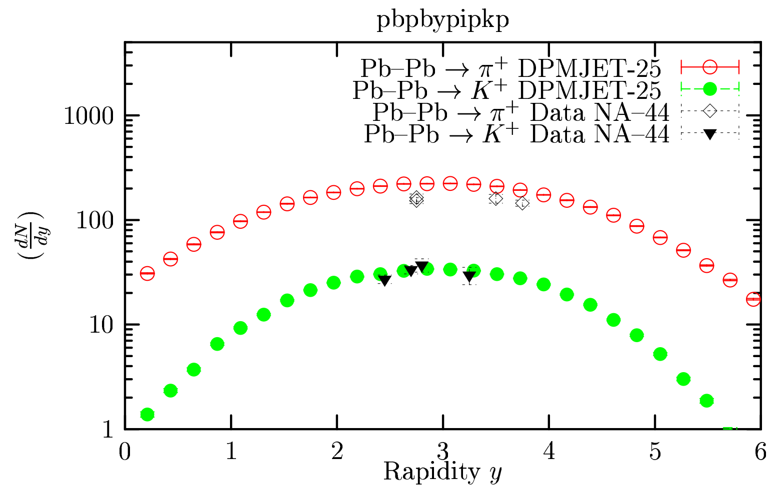
Reaction products given back to be transported by FLUKA

Evaporation and deexcitation of residual nuclei performed in FLUKA

[1] 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.

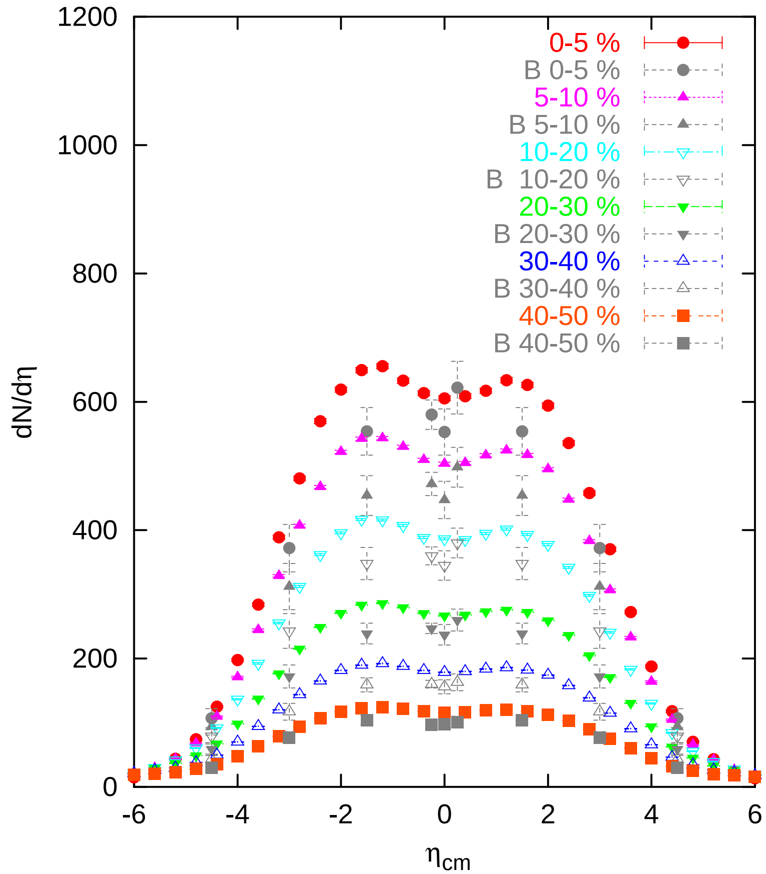
DPMJET(-2.5): examples of performances





Rapidity distribution of negative particles for 158 AGeV/c S-S and S-Ag collisions (left) and of positive pions and kaons for 158 AGeV/c Pb-Pb collisions (right). Experimental data from the NA-35 and NA-44 collaborations are compared with DPMJET predictions.

DPMJET(-III): examples of performances II

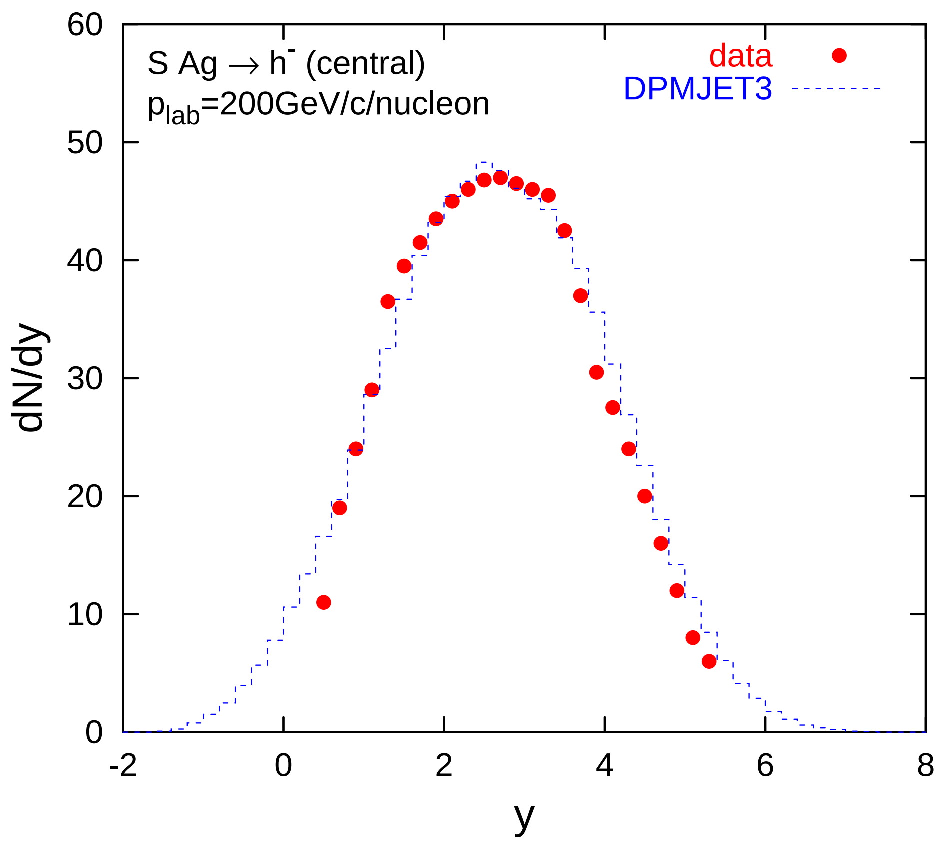


Pseudorapidity distributions of charged hadrons in Au–Au collisions at $\sqrt{(s)}=$ 130 GeV for centralities 0–5 % up to 40–50 %.

Coloured points are from the DPMJET–III Monte Carlo with chain fusion.

The data points (with a B in the label) are from the BRAHMS Collaboration, except the points at η=0.25 , which are from PHENIX for η=0.0, and the points at η=-0.25, which are from PHOBOS for η=0.0.

DPMJET(-III): examples of performances III



Pseudorapidity distribution of negative hadrons in S–Ag collisions at p_{lab}= 200 GeV/nucleon.

The ATIC detector

Balloon experiment to measure cosmic ray composition

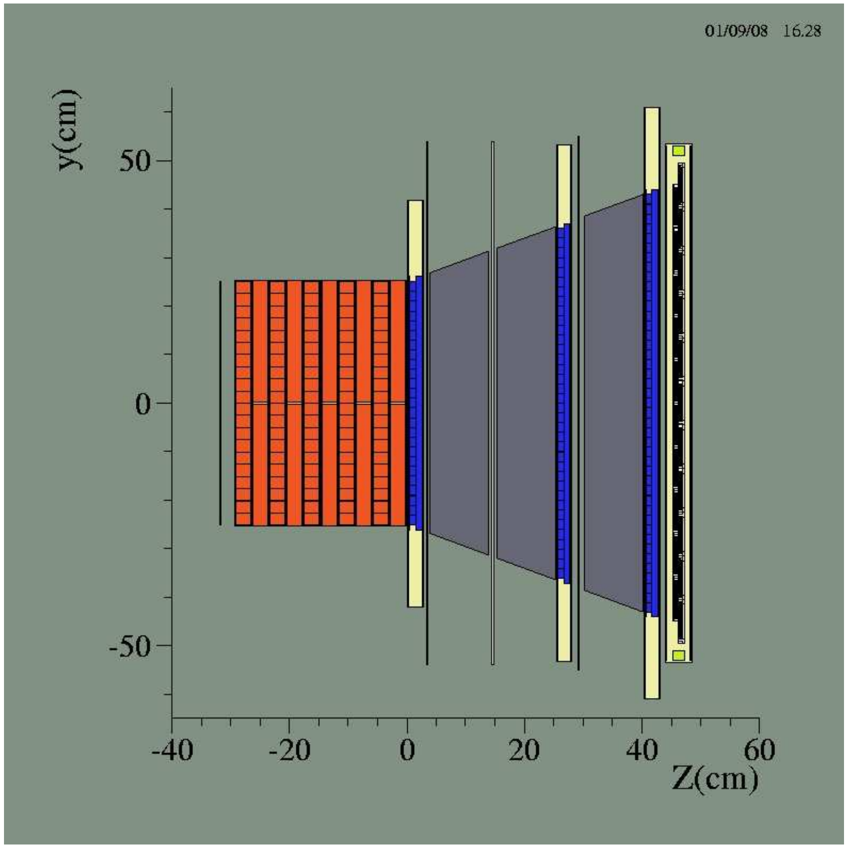
Flew 2001 over Antarctica, more flights planned

BGO calorimeter

scintillator hodoscopes

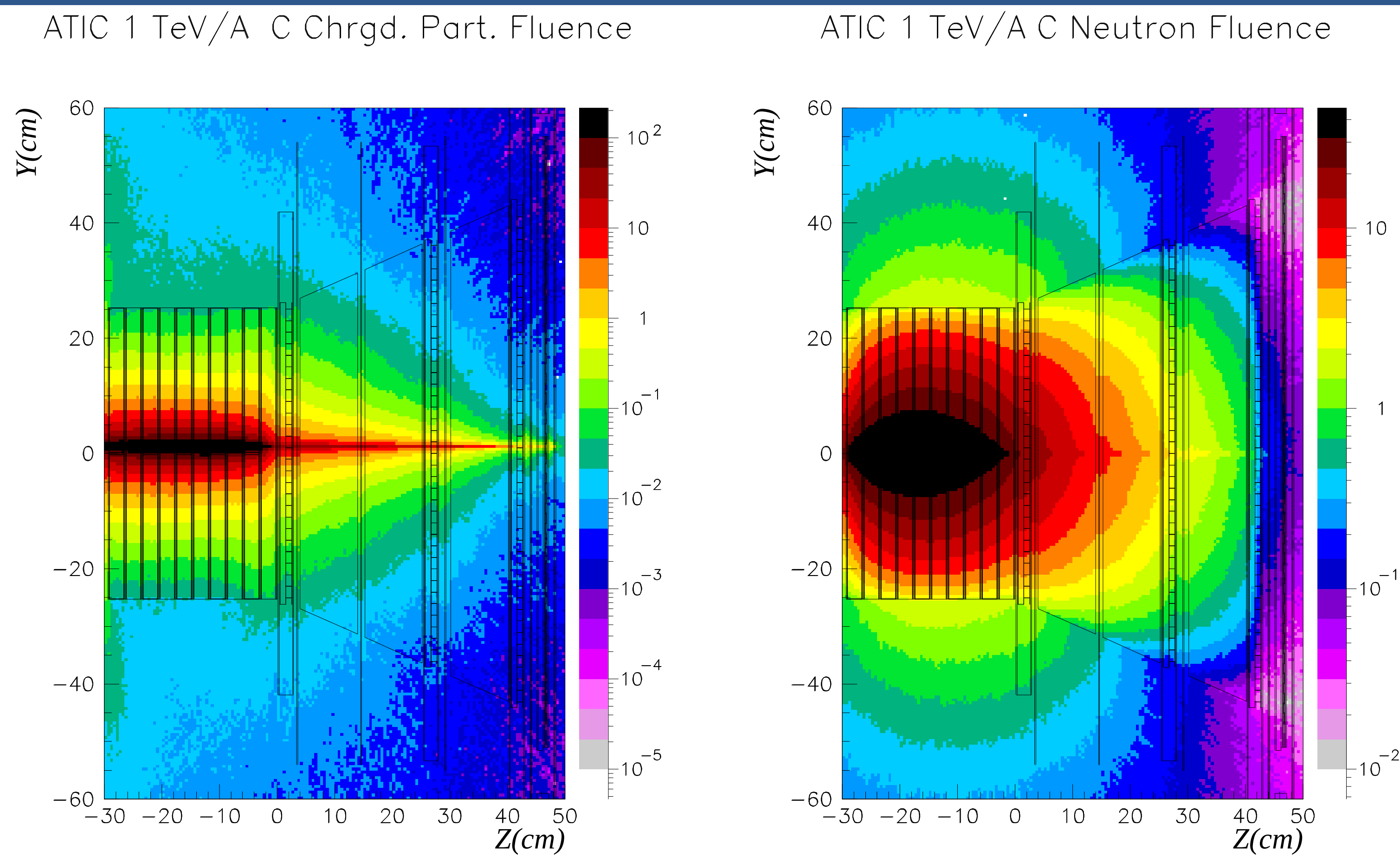
Carbon targets

silicon strip detectors



BOTTOM TOP

ATIC (preliminary)



Simulated particle fluences (particles/cm^2) for 1 TeV/A ^{12}C ions on axis

(r)QMD approach:

Features of a generic QMD:

Nucleons = wave packets

Classical Hamilton equations of motion

Mean field potential given by sum of two-body + three-body + surface + Coulomb + Fermi

⇒**the mean field evolves during the interaction**

Introduce (Monte Carlo) two–body scattering/interactions to model the reaction

Initialization is critical (very unstable configurations possible)

Relativistic extension problematic.

... RQMD-2.4 (next slide) is a (relativistic) QMD model with some of these features

The FLUKA - RQMD-2.4 interface

Author: H. Sorge (PRC52 3291 (1995), Ann. Phys. 192 266 (1989))

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

Problems:

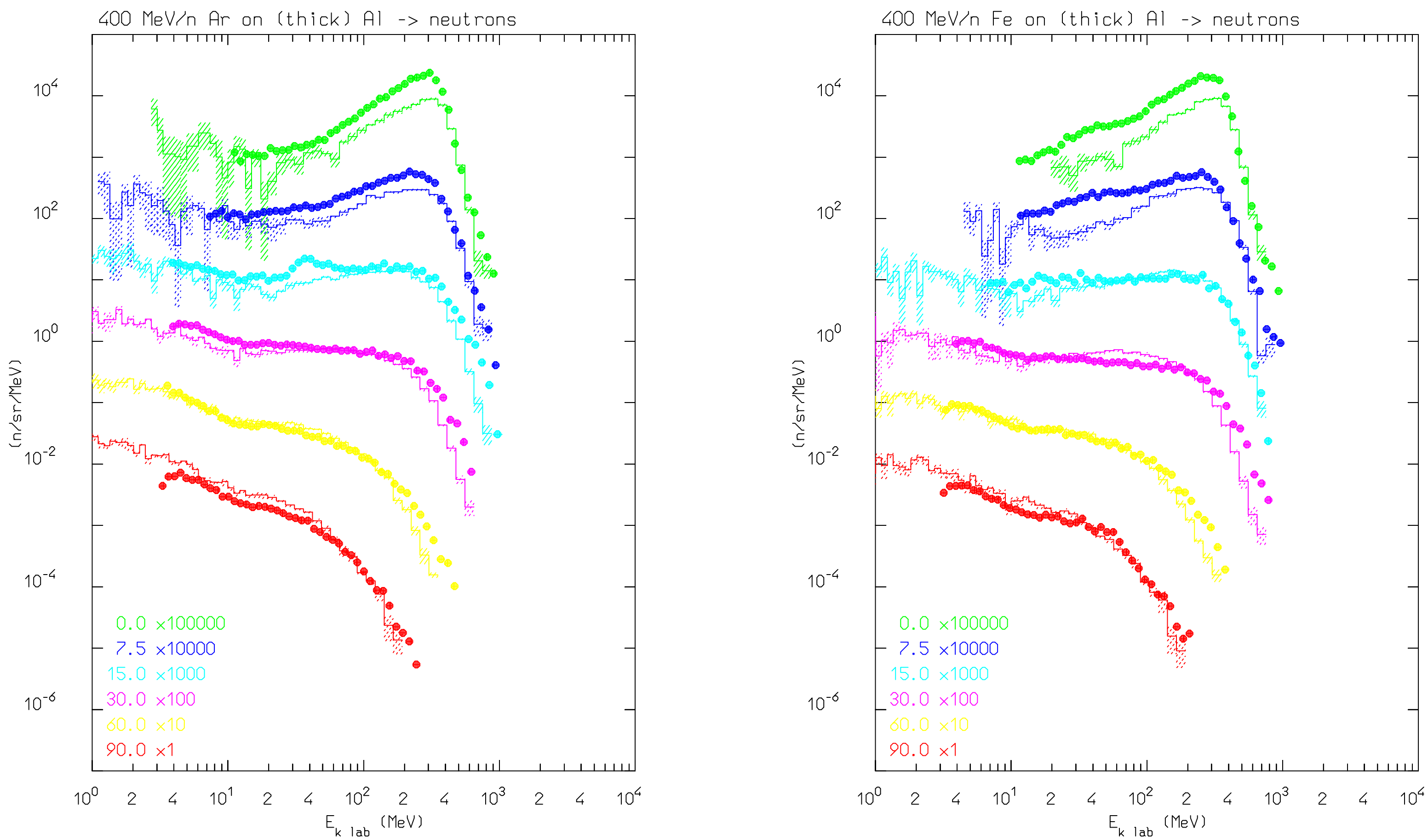
- No evaporation/fragmentation/fission/deexcitation of residuals and fragments
- Serious energy non-conservation issues, particularly when run in full QMD mode
- No meaningful excitation energy calculation implemented or possible
- No longer maintained

Solutions:

- 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

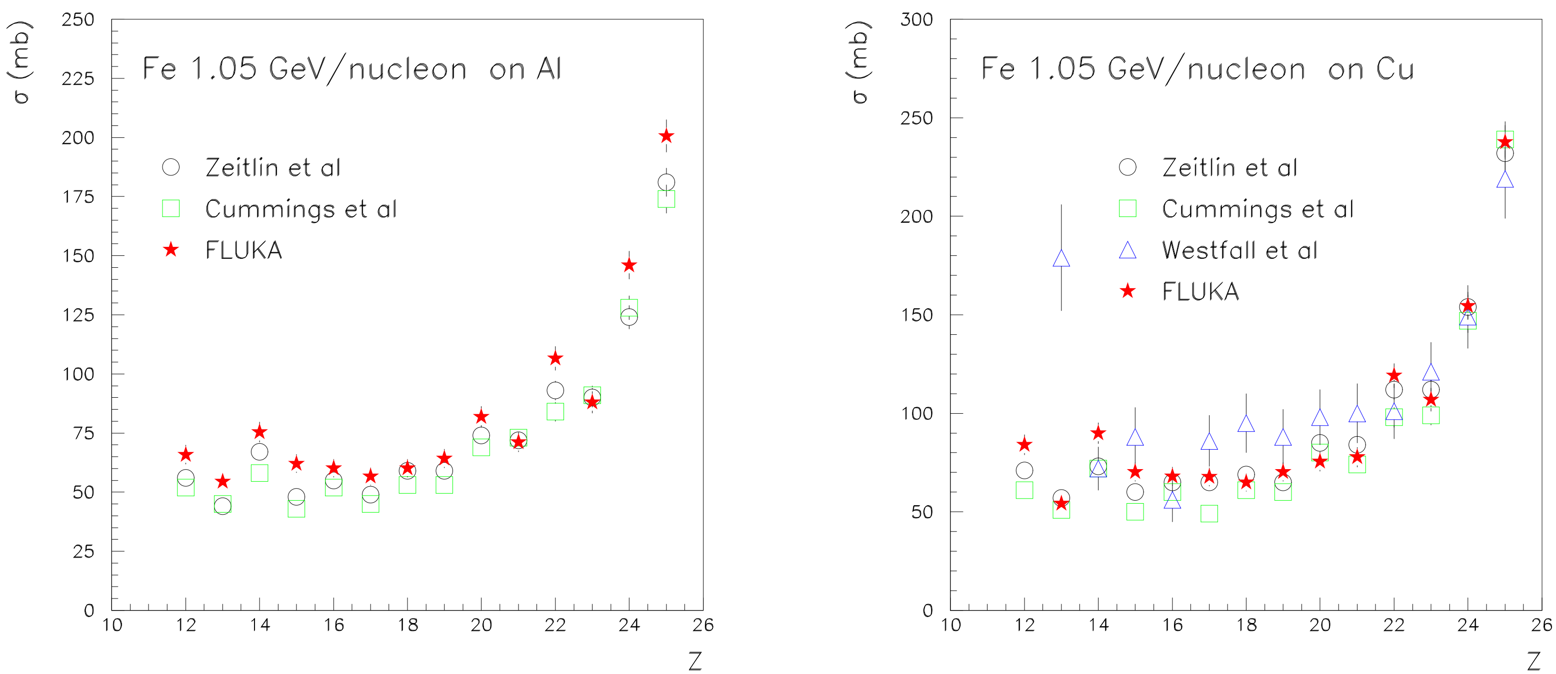
Temporary solution for A-A interactions below few GeV/n

FLUKA with modified RQMD-2.4 - 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 - results II



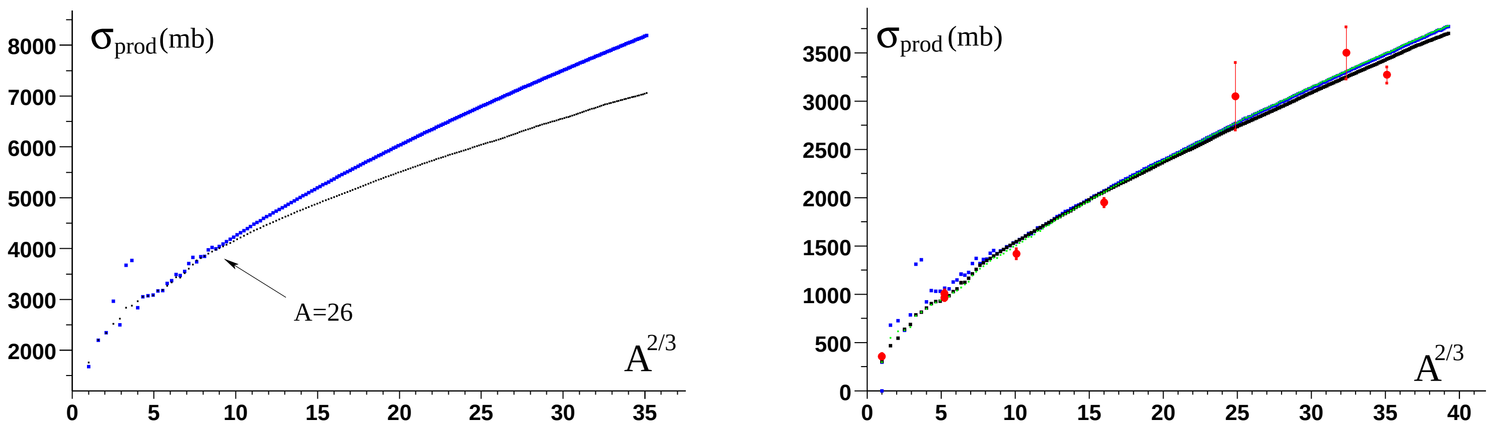
Fragment charge cross sections for 1.05 GeV/n Fe ions on Al (left) and Cu (right). stars FLUKA, circles PRC56 (1997) 388, squares PRC42 (1990) 5208 (at 1.5 GeV/n), triangles PRC19 (1979) 1309 (at 1.88 GeV/n).

A-A cross sections

At high energies, down to ≈ 3 GeV/nucleon: Glauber σ (DPMJET)

At lower energies, from few AMeV to few AGeV, NASA parametrization (R.K. Tripathi et al., NIM B117,347(1996))

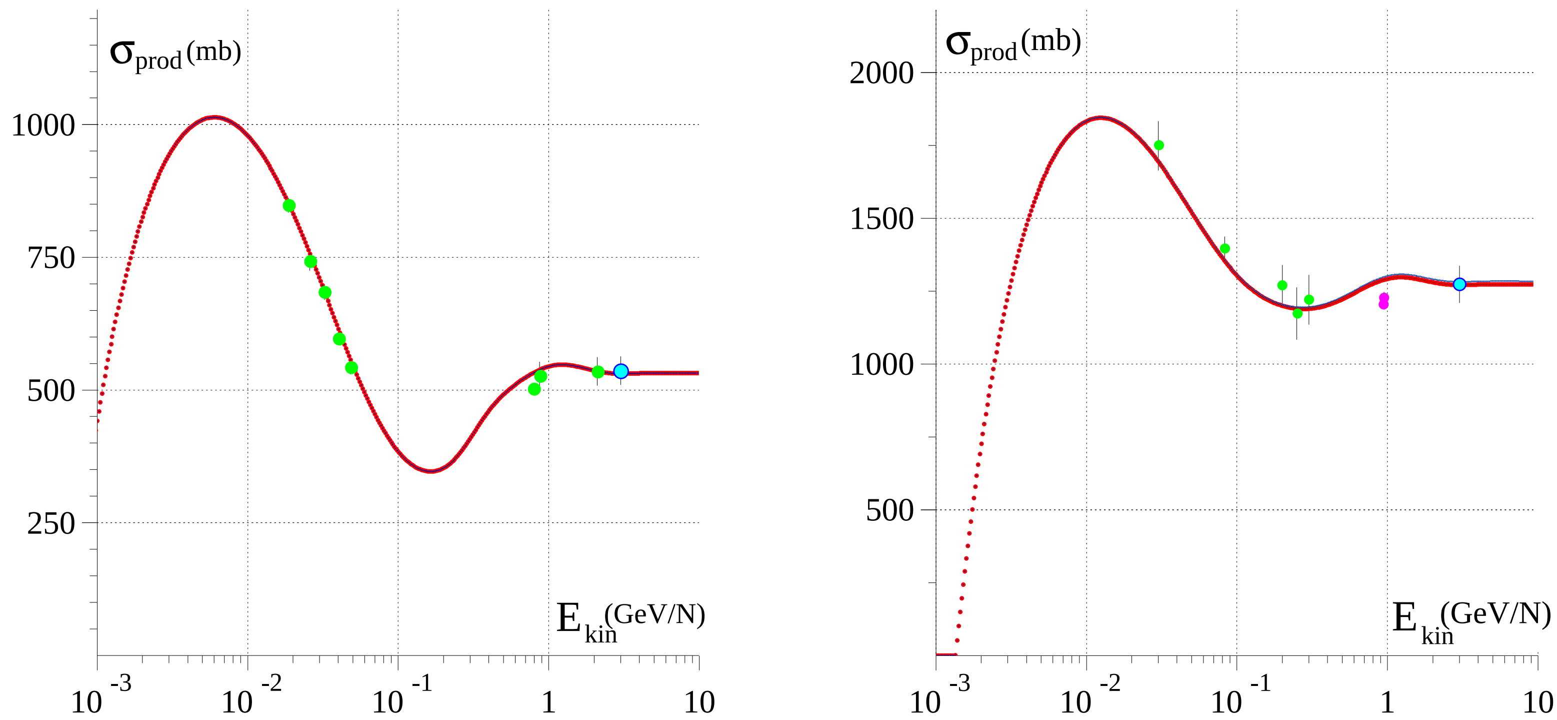
Good matching for light systems, small modification to NASA σ needed for heavy systems (and for Li)



Pb-A (left) and ^{16}O-A (right), σ at $\sqrt{s_{NN}} = 3$ GeV

black: Glauber; blue: NASA; green: modified NASA; red: data

A-A cross sections



Reaction cross sections for α's on Carbon (left) and ^{12}C on Aluminium as obtained from our approach compared with exp. data (green and purple symbols) from various sources. The light blue point is the Glauber computed DPMJET cross section at the joining point. The original NASA parametrization is not distinguishable in this case.

A-A cross sections

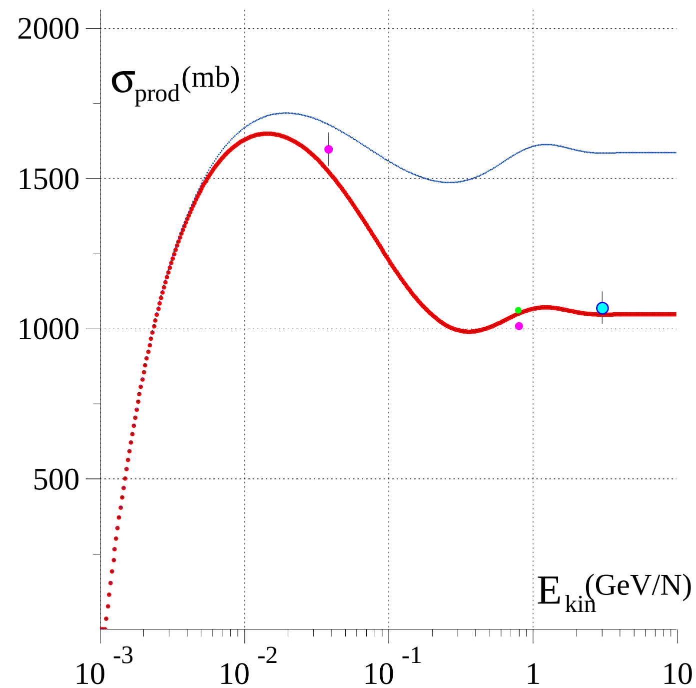
NASA σ parametrization seems to have problems for Li ions: ^{6}Li on ^{27}Al vs. Energy

green: Original NASA

red: revised parametrization

light blue point: DPMJET

green and purple points: exp. data



New QMD

Presently working on the initialization stage

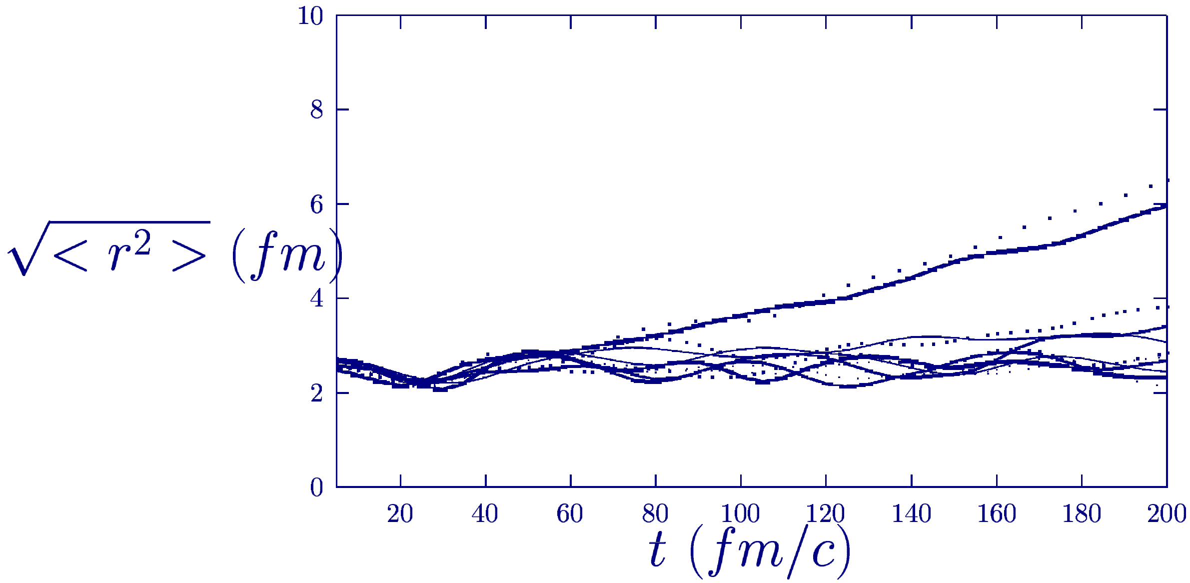
Key issues are

- *selection of potentials and of the potential parameters*
- *Pauli blocking constraint*.

Goal: MonteCarlo creation of initial nuclear configurations with

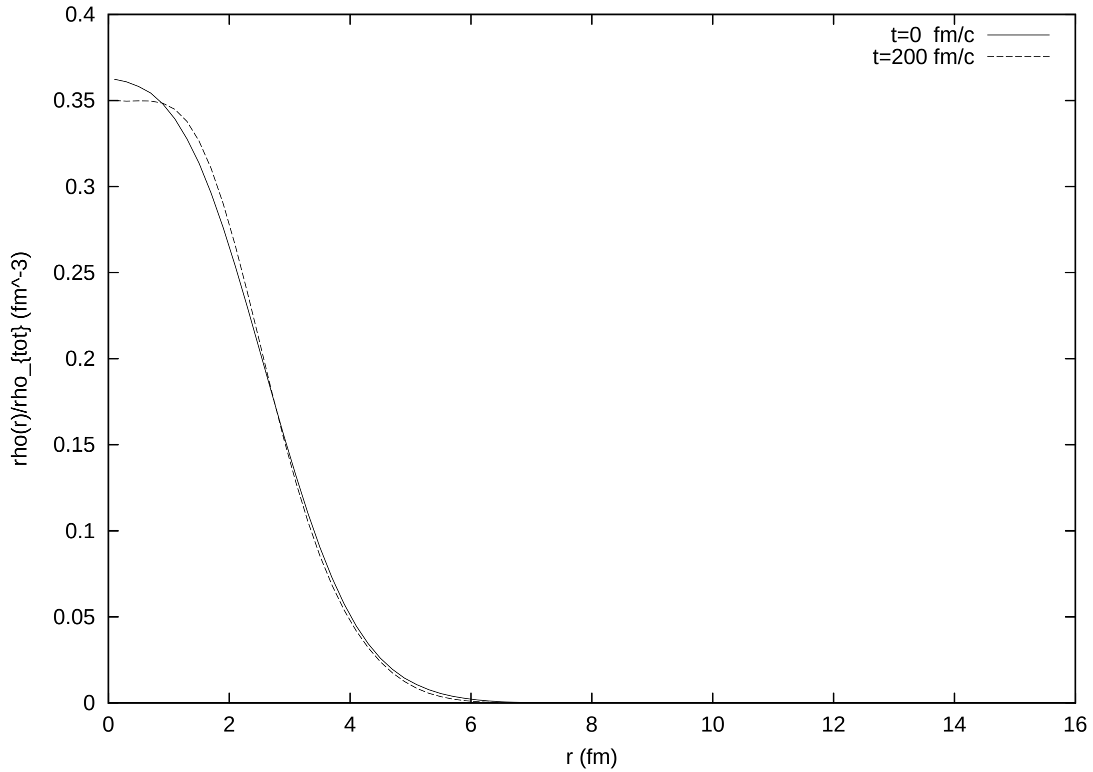
- properties close to experimental ground state ones
- stability for a time $\mathcal{O}$ nuclear collision

New QMD



Root mean square radii of ^{16}O nuclei (fm) versus time (fm/c) for eleven initial "random" configurations: about 1/2 of them can be stored as "stable" configurations.

New QMD



Normalized radial density distribution of a "stable" $^{40}\mathrm{Ca}$ nuclear configuration at t=0 (solid line) and at t=200 fm/c (dotted line)

Monte Carlo BME

Monte Carlo approach based on the **B**oltzmann **M**aster **E**quation theory

Heavy ion reactions at incident energies of a few tens of MeV/amu

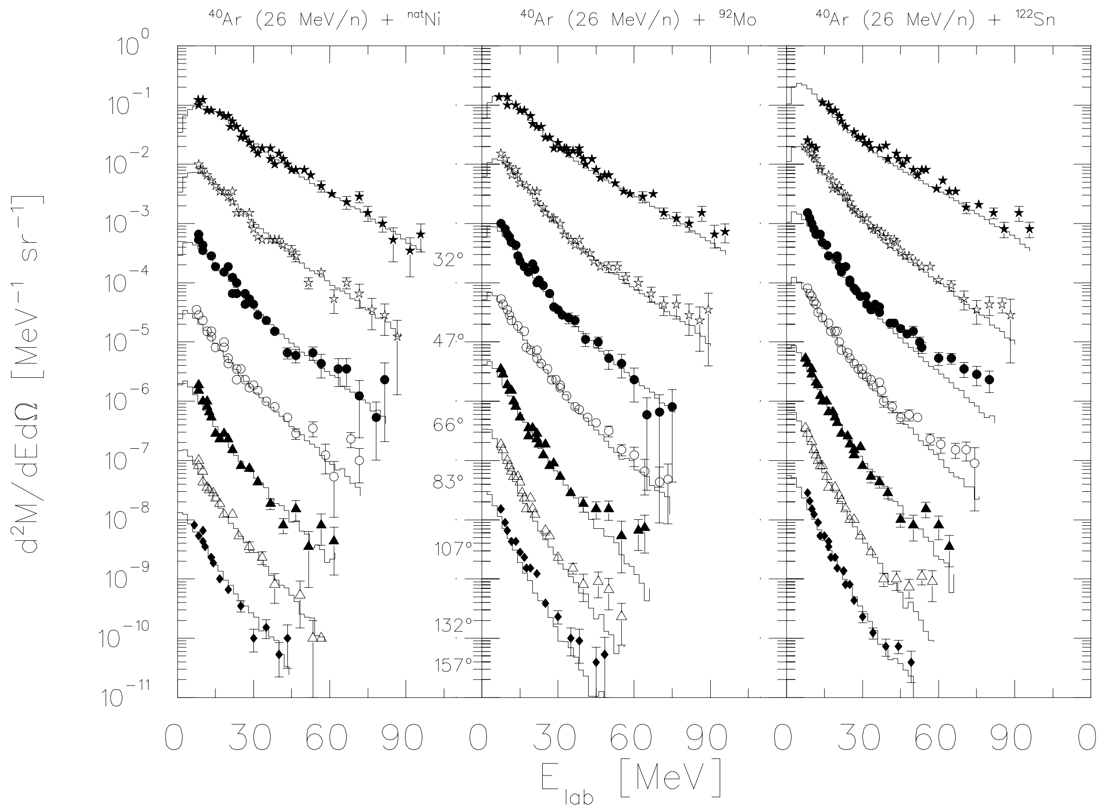
BME: statistical evolution of the composite nucleus through a sequence of two body interactions and emission of unbound particles, also in the form of light clusters. Mean field effects are taken into account

BME is inclusive, but:

Milan: Monte Carlo code (exclusive) evaluates the probability of any complex event as the joint probability of a sequence of elementary emissions, whose probabilities are assumed to be equal to corresponding multiplicities (given by BME) in very short time intervals. Up to ^{16}O, incomplete fusion processes following the projectile break-up are included.

M. Cavinato et al., Nucl. Phys. A 679 (2001) 753, Phys. Lett. B 382 (1996) 1
E. Gadioli et al., Nucl. Phys. A 708 (2002) 391

Monte Carlo BME: examples I, from Nucl. Phys. A 679 (2001) 753

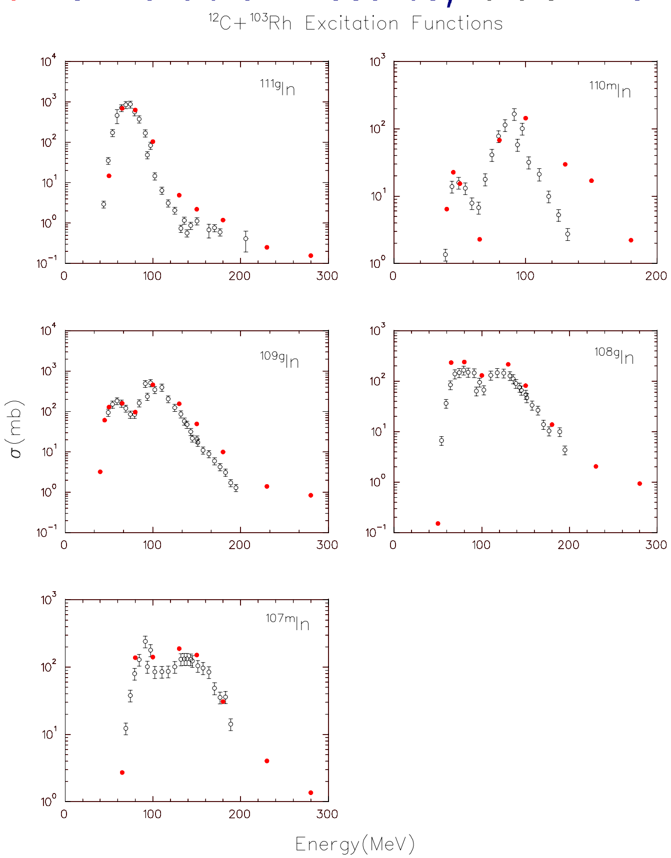


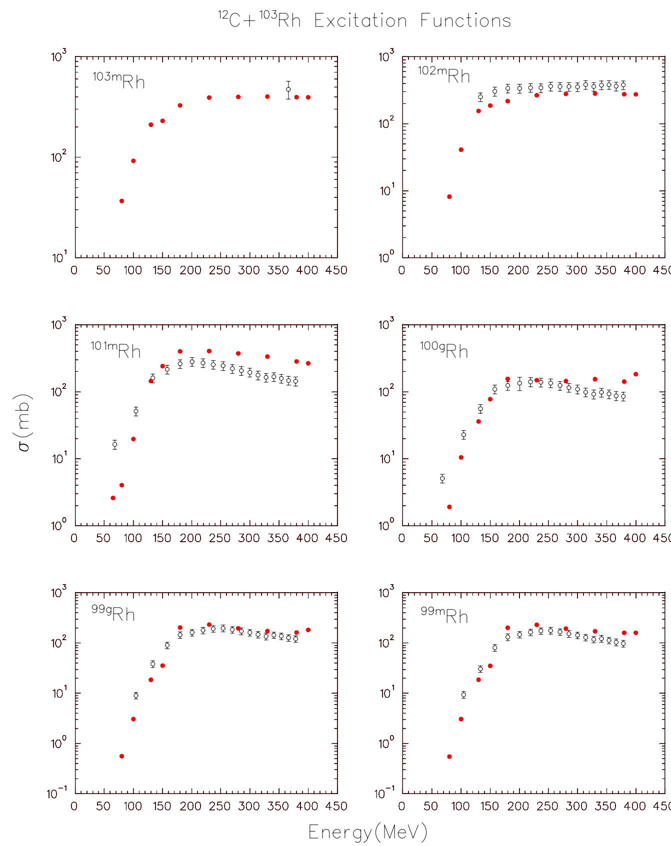
Spectra of neutrons emitted in central collisions of ^{40} Ar with Ni, ^{92}Mo and ^{122}Sn at 26 MeV/amu. Symbols are exp. data, histograms are simulation results. Starting from top the spectra are progressively scaled down by a factor ten

Monte Carlo BME: examples II, unpublished

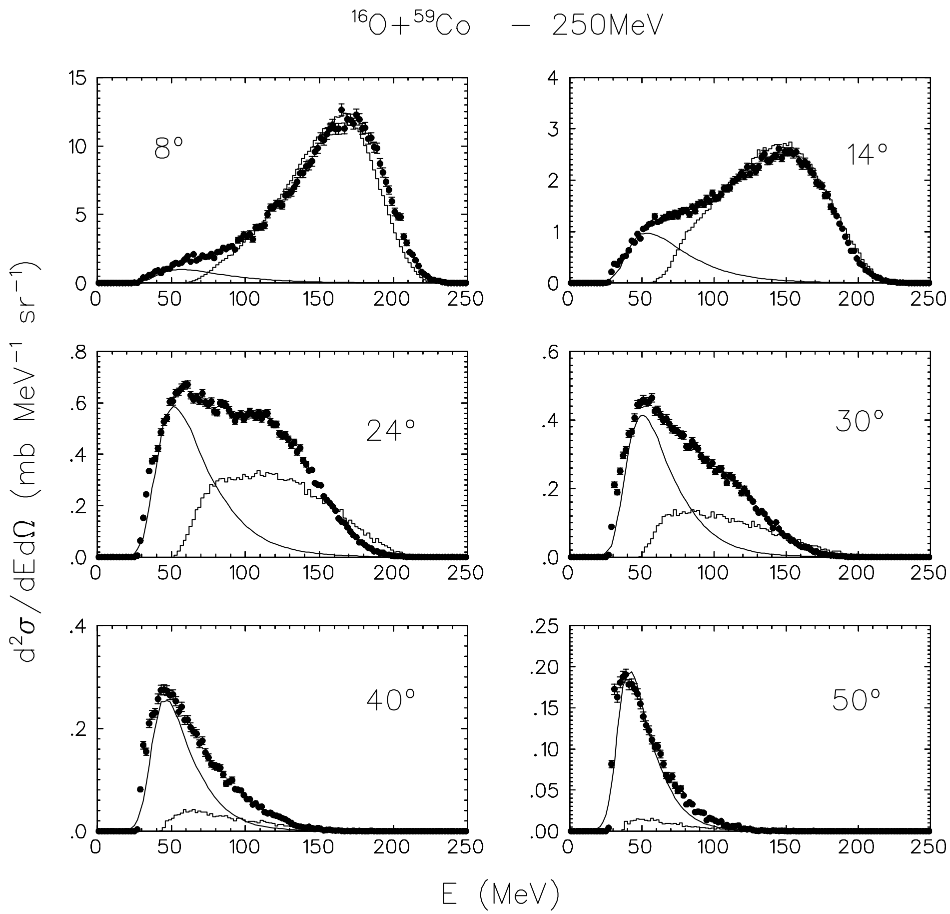
Residual In and Rh excitation functions following ^{12}C+^{103}Rh.

Red: simulation results, black: exp. data





Monte Carlo BME: examples III (NPA 708 (2002) 391)



Spectra of carbon fragments emitted in ^{16}O on ^{59}Co at 250 MeV.

Exp. spectra: solid points

Theoretical predictions by BME (lines)

projectile break-up (histo)

Conclusions

- FLUKA: proven capabilities in atmospheric and cosmic ray problems besides the original accelerator ones
- Complex 3D geometries with magnetic field transport, up-to-date CR primary spectra, solar modulation, multipole expansion of the earth magnetic field implemented and available
- *Ability to follow the whole shower induced by whichever ion on whichever target, with sound interaction physics above 100 MeV/n now achieved*
- Rich development program for the future: performances will improve with
  - PEANUT and new QMD in place of the RQMD-2.4 “temporary” solution
  - BME model covering the low energy side

This work was partially supported under:

- NASA Grant NAG8-1658
- ASI Contract 1R/090/00