THE **FLUKA** RADIATION TRANSPORT CODE AND ITS USE FOR SPACE PROBLEMS

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Topics

- Generalities about FLUKA
- Reliability of calculation of particle production and transport in FLUKA:
  - Thin target benchmarks
  - Thick target benchmarks
  - More complex shielding benchmarks
- The production of fragments nuclei: the ultimate problem of hadron reaction modelling
- Cosmic rays and FLUKA: the atmospheric neutrino calculations:
  - The primary fluxes and the geomagnetic effects
  - Benchmarking FLUKA against measured data in the atmosphere
- Extending FLUKA to ions transport and interactions
- Conclusions
**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 = FLUctuating KASkades).

The present code is mostly an effort of researchers of INFN-Milan (now at CERN) started in 1990, and has little or no remnants of older versions. The main link with the past is Johannes Ranft, mostly in the development of the high energy generator part.

The code is huge (≈ 350,000 lines of fortran code) and has the ability to treat with good accuracy a variety of problems.

It is a “private” effort, it has no official distribution and 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. There is no “official” CERN support for it, even though presently A. Ferrari and P.R. Sala are CERN staff. The only “official” status is that it is the MonteCarlo of the ICARUS/ICARNOE experiments, as well as for the spallation part of the Energy Amplifier studies (all activities chaired by C. Rubbia).

The code is in wide use at CERN and in other labs, and is THE tool used for all radiation calculations and for the neutrino beam studies at CERN.
FLUKA: generalities

FLUKA

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Interaction and transport Monte Carlo code

- Hadron-hadron and hadron-nucleus interactions 0-100 TeV
- Nucleus-nucleus interactions 0-10000 TeV/n: under development !!!
- Electromagnetic and $\mu$ interactions 1 keV-100 TeV
- Charged particle transport - ionization energy loss
- Neutron multigroup transport and interactions 0-20 MeV
- Analogue or biased calculations
Structure: a fully integrated code

Four major radiation components:

- Hadrons (and now ions!)
- Muons
- Electrons and photons
- Low energy neutrons

FLUKA can deal with all components in a single run without any interface between components.

It is not an assembly of different codes. All the secondaries issued from the same primary are transported before a new history is started. Correlations are preserved as far as possible, also between different radiation components.

Memory for geometry, tables, etc. is dynamically allocated.
A multipurpose code

The program has been used successfully in different fields such as shielding, dosimetry, high energy experimental physics and engineering, cosmic ray studies, medical physics, etc.

- Each radiation component is treated as far as possible with the same level of accuracy (it’s like having 4 different programs in one, for pure neutron, electron-photon or muon problems – and hadrons, of course!)
- FLUKA can be run in fully analog mode, for calorimetry. It can calculate coincidences and anticoincidences
- It can also be run in biased mode, for shielding design

But also experimental high energy physicists need sometimes to make studies of deep penetration or rare events: hadron punchthrough, radiation background in underground experiments, muon production over short decay lengths
## Energy limits

**Approximate values**

<table>
<thead>
<tr>
<th>PARTICLES</th>
<th>transport limits</th>
<th>limits for primary particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>charged hadrons</td>
<td>1 keV - 20 TeV</td>
<td>100 keV - 20 TeV</td>
</tr>
<tr>
<td>neutrons</td>
<td>thermal - 20 TeV</td>
<td>thermal - 20 TeV</td>
</tr>
<tr>
<td>antineutrons</td>
<td>50 MeV - 20 TeV</td>
<td>100 MeV - 20 TeV</td>
</tr>
<tr>
<td>muons</td>
<td>1 keV - 1000 TeV</td>
<td>100 keV - 1000 TeV</td>
</tr>
<tr>
<td>electrons</td>
<td>1 keV - 1000 TeV</td>
<td>70 keV - 1000 TeV (low-Z)</td>
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<tr>
<td></td>
<td></td>
<td>150 keV - 1000 TeV (high-Z)</td>
</tr>
<tr>
<td>photons</td>
<td>1 keV - 1000 TeV</td>
<td>7 keV - 1000 TeV</td>
</tr>
<tr>
<td>neutrinos (with NUX)</td>
<td>100 keV - 1 TeV</td>
<td>1 MeV - 400 GeV</td>
</tr>
</tbody>
</table>
**The FLUKA hadron interaction models**

Two models are used inside FLUKA to describe nonelastic interactions:

- The “low-intermediate” energy one, **PEANUT**, which covers the energy range up to 5 GeV
- The high energy one which can be used up to several tens of TeV

The nuclear physics embedded in the two models is very much the same. The main differences are a coarser nuclear description (and no preequilibrium stage) for the high energy one, and the Gribov-Glauber cascade for the high energy one.

In the following the description will mostly concentrate on **PEANUT**. **PEANUT** is a three step model:

1. (Generalized) IntraNuclear Cascade
2. Preequilibrium
3. Evaporation/Fission or Fermi break-up
(Generalized) IntraNuclear Cascade basic assumptions

1. Interaction probability from $\sigma_{free} + $ Fermi motion $\times \rho(r)$
2. Classical trajectories (+) nuclear mean potential (resonant for $\pi$’s!!)
3. Curvature from nuclear potential $\rightarrow$ refraction and reflection.
4. Interactions in projectile-target nucleon CMS $\rightarrow$ Lorentz boosts
5. Interactions are incoherent and uncorrelated
6. Multibody absorption for $\pi, \mu^-, K^-$
7. Quantum effects
8. Glauber cascade at high energies
9. Secondaries treated $=$ primary
10. Exact conservation of energy, momenta and all additive quantum numbers, including nuclear recoil
Quantistic effects in (G)INC

1. Pauli blocking,
2. Formation time (inelastic),
3. Coherence length ((quasi)-elastic and charge exchange),
4. Nucleon antisymmetrization,
5. Hard core nucleon correlations
Coherence length \( \equiv \) formation time for elastic or quasielastic interactions.

Given a two body interaction between with four-momentum transfer

\[
q = p_{1i} - p_{1f}
\]

the energy transfer seen in a frame where the particle 2 is at rest is given by

\[
\Delta E_2 = \nu_2 = \frac{q \cdot p_{2i}}{m_2}
\]

(1)

From the uncertainty principle this \( \Delta E \) corresponds to a indetermination in proper time given by \( \Delta \tau \cdot \Delta E_2 = \hat{n} \), that boosted to the lab frames gives a coherence length

\[
\Delta x_{lab} = \frac{p_{2lab}}{m_2} \cdot \Delta \tau = \frac{p_{2lab}}{m_2} \frac{\hat{n}}{\nu_2}
\]

(2)

And analogue for particle 1

Applied also to \( \nu - h \) interactions
Naively: “materialization” time. Qualitative estimate: in the frame where $p_\parallel = 0$

$$\bar{t} = \Delta t \approx \frac{\hat{t}}{E_T} = \frac{\hat{t}}{\sqrt{p_T^2 + M^2}}$$  \hspace{1cm} (3)

particle proper time

$$\tau = \frac{M}{E_T} \bar{t} = \frac{\hat{t}M}{\sqrt{p_T^2 + M^2}}$$  \hspace{1cm} (4)

Going to lab system

$$t_{lab} = \frac{E_{lab}}{E_T} \bar{t} = \frac{E_{lab}}{M} \tau = \frac{\hat{t}E_{lab}}{\sqrt{p_T^2 + M^2}}$$

As a function of particle rapidity $y$

$$t_{lab} = \bar{t} \cosh y = \frac{\hat{t}}{\sqrt{p_T^2 + M^2}} \cosh y$$

Condition for possible reinteraction inside a nucleus:

$$v \cdot t \leq R_A \approx r_0 A^{\frac{1}{3}}$$
Preequilibrium : GDH

Preequilibrium emission probability:

\[ P_{x,n}(\epsilon)d\epsilon = \sum n_{px} \frac{\rho_n(U, \epsilon)gd\epsilon}{\rho_n(E)} \frac{r_c(\epsilon)}{r_c(\epsilon) + r_+(\epsilon)} \]

where the density (MeV\(^{-1}\)) of exciton states is given by:

\[ \rho_n(E) = \frac{g(gE)^{n-1}}{n!(n-1)!} \]

the emission rate in the continuum:

\[ r_c = \sigma_{inv} \frac{\epsilon}{g_x} \frac{(2s+1)8\pi m}{h^3} \]

and the reinteraction rate:

\[ r_+(\epsilon) = f_{Pauli}(\epsilon, E_F) \left[ \rho_p \sigma_{xp} + \rho_n \sigma_{xn} \right] \frac{2(\epsilon + V)}{m} \left[ \frac{2(\epsilon + V)}{m} \right]^{1/2} \]

(or from optical potential)

GDH: \( \rho, E_F \) are “local” averages on the trajectory and constrained exciton state densities are used for the lowest lying exciton configurations.
Preequilibrium: modified GDH in PEANUT

- $\sigma_{inv}$ from systematics

- Correlation/formation zone / hardcore effect on reinteractions:

\[
\frac{r_c(\epsilon)}{r_c(\epsilon) + r_+(\epsilon)} \rightarrow P_c^{(h\tau)} + P_c^{(co)} + P_c^{(std)}
\]

- $P_c^{(h\tau)} = \text{escape prob. in zone} = \max(\tau, \text{hardcore}) \equiv h\tau$
- $P_c^{(co)} = \text{escape/total prob. in zone} = (\text{correlation} - h\tau)$
  (here reinteraction only on non-correlated nucleon species)
- $P_c^{(std)} = \text{”standard” escape/total in remaining zone.}$

- Constrained exciton state densities configurations 1p-1h, 2p-1h, 1p-2h, 2p-2h, 3p-1h and 3p-2h
Preequilibrium: modified GDH in PEANUT

- Energy dependent form for $g_x$
- Position dependent parameters = point like values:
  - first step: $n_h$ holes generated in the INC step at positions $\vec{x}_i$:
    \[
    \rho_{n_h}^{loc} = \frac{\sum_{i=1}^{n_h} \rho(\vec{x}_i)}{n_h} \quad E_{F}^{loc}_{n_h} = \frac{\sum_{i=1}^{n_h} E_F(\vec{x}_i)}{n_h}
    \]
  - When looking at reinteraction: consider neighborhood:
    \[
    \rho_{n_h}^{nei} = \frac{n_h \rho_{n_h}^{loc} + \rho^{ave}}{n_h + 1} \quad E_{F}^{nei}_{n_h} = \frac{n_h E_{F}^{loc}_{n_h} + E^{ave}}{n_h + 1}
    \]
  - Subsequent steps: go towards average quantities
    \[
    \rho_{n_h+1}^{loc} = \rho_{n_h}^{nei} \quad E_{F}^{loc}_{n_h+1} = E_{F}^{nei}_{n_h}
    \]
Preequilibrium/(G)INC transition

Example of angle integrated $^{90}$Zr(p,xn) at 80.5 MeV calculations with the full algorithm (right), and without the INC stage (left). The various lines show the total, INC, preeq. and evaporation contributions, the exp. data have been taken from M. Trabandt et al. PRC39 (1989) 452
Nucleon emission: thin target examples I

Computed (light symbols) and experimental (symbols with lines) double differential distributions for $^{90}$Zr(p,xn) (left) and $^{90}$Zr(p,xp) at 80.5 MeV. The exp. data have been taken from M. Traban et al. PRC39 (1989) 452 and A.A. Cowley et al., PRC43, (1991) 678.
Nucleon emission: thin target examples II

Computed (histograms) and experimental (symbols) double differential neutron distributions for Al\(p,\text{xn}\) (left) at 597 MeV and Pb\(p,\text{xn}\) at 3 GeV. The exp. data have been taken from W.B. Amian et al., Nucl. Sci. Eng. 115, (1993) 1, and K. Ishibashi et al, Nucl. Sci. Technol. 32 (1995) 827.
Pion interactions in nuclei

The description of pion interactions on nuclei in the sub-GeV energy range must take into account:

- The resonant nature of the $\pi - N$ interaction, mostly dominated by the $\Delta(1232)$.
- The effect of the nuclear medium on the $\pi - N$ interaction
- The possibility of absorption (both s-wave and p-wave) on two or more nucleons
- The resonant nature of the pion-nucleus potential, which is rapidly varying with the pion energy
Microscopic pion absorption cross sections

Charged pion absorption cross section for infinite symmetric nuclear matter at two different density values ($\lambda_{abs}^{-1} = \sigma_{abs} \cdot \frac{1}{2} \rho = \sigma_{abs} \cdot \rho_{pro} = \sigma_{abs} \cdot \rho_{neu}$)
Pion absorption cross sections: examples

Computed and exp. pion absorption cross section on Aluminum as a function of energy

Computed and exp. pion absorption cross section on Gold or Bismuth as a function of energy
Pion interactions: examples

Computed and exp. pion charge exchange angular distribution for $^{58}\text{Ni}(\pi^+,\pi^0)$ at 160 MeV

(Exp. data: W.J. Burger et al., PRC41, (1990) 2215, R.D. McKeown et al., PRC24, (1981) 211)
Nonelastic hN interactions at intermediate energies

For energies in excess of few hundreds MeV the inelastic channels (pion production channels) start to play a major role.

- $N_1 + N_2 \rightarrow N'_1 + N'_2 + \pi$ has its threshold around 290 MeV, and it starts to be important around 700,

- $\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV.

- Dominance of the $\Delta$ resonance and of the $N^*$ resonances at higher energies, in the $\pi N$ channel $\rightarrow$ reactions treated in the framework of the isobar model $\rightarrow$ all reactions proceed through an intermediate state containing at least one resonance.
N-N nonelastic interactions at intermediate energies

Examples of N-N nonelastic interactions:

\[ N_1 + N_2 \rightarrow N'_1 + \Delta(1232) \rightarrow N'_1 + N'_2 + \pi \]
\[ N_1 + N_2 \rightarrow N'_1 + N^*(1440) \rightarrow N'_1 + N'_2 + \pi \]

where the \( N^*(1440) \) is a \( T(J^P)=\frac{1}{2} \left( \frac{1}{2}^+ \right) \) baryon resonance with sizeable decay channels into one or two pions plus one nucleon.
**π-N Nonelastic interactions at intermediate energies**

Possibility of direct production of \( s \)-channel resonances (that is \( \pi N \) going into one resonance, like the \( \Delta \)), which are not possible in the \( NN \) system since no dibaryon resonance has ever been discovered.

Examples:

\[
\begin{align*}
\pi + N & \rightarrow N^*(1440) \rightarrow \rho(770) + N' \rightarrow \pi' + \pi'' + N' \\
\pi + N & \rightarrow \Delta(1600) \rightarrow \pi' + \Delta(1232) \rightarrow \pi' + \pi'' + N' \\
\pi + N & \rightarrow \rho(770) + N' \rightarrow \pi' + \pi'' + N' \\
\pi + N & \rightarrow \pi' + \Delta(1232) \rightarrow \pi' + \pi'' + N' 
\end{align*}
\]

where the first two reactions are examples of \( s \)-channel direct resonance production. \( \rho(770) \) is a \( T(J^P)=1 \) \( (1^+) \) meson resonance with 100% decay branching into \( \pi \pi \).
Multiple pion production at intermediate energies

The isobar model easily accommodates multiple pion production, for example allowing the presence of more than one resonance in the intermediate state (double pion production opens already at 600 MeV in nucleon-nucleon reactions, and at about 350 MeV in pion-nucleon ones).

Examples of two pion production for $N - N$:

\[
N_1 + N_2 \rightarrow \Delta_1(1232) + \Delta_2(1232) \rightarrow N'_1 + \pi_1 + N'_2 + \pi_2 \\
N_1 + N_2 \rightarrow N'_1 + N^*(1440) \rightarrow N'_1 + \pi_1 + \Delta(1232) \rightarrow N'_1 + \pi_1 + N'_2 + \pi_2 \\
N_1 + N_2 \rightarrow N'_1 + \Delta(1600) \rightarrow N'_1 + \pi_1 + N^*(1440) \rightarrow N'_1 + \pi_1 + N'_2 + \pi_2
\]

and for pion-nucleon:

\[
\pi + N \rightarrow \Delta(1600) \rightarrow \pi' + N^*(1440) \rightarrow \pi' + \pi'' + \Delta(1232) \\
\rightarrow \pi' + \pi'' + \pi''' + N' \\
\pi + N \rightarrow \omega(782) + N' \rightarrow \pi' + \pi'' + \pi''' + N' \\
\pi + N \rightarrow \rho(770) + \Delta(1232) \rightarrow \pi' + \pi''' + \pi'' + N'
\]
Pion production at intermediate energies: summary

Summarizing, all reactions can be thought to proceed through channels like:

\[ h + N \rightarrow X \rightarrow x_1 + \cdots + x_n \]  
(6)

\[ h + N \rightarrow X + Y \rightarrow x_1 + \cdots + x_n + y_1 + \cdots + y_m \]  
(7)

where \( X \) and \( Y \) can be real resonances, or stable particles \((n, p, \pi)\) directly.

*Resonances which appear in the intermediate states can be treated as real particles, that is, in a MonteCarlo code they can be transported and then transformed into secondaries according to their lifetimes and decay branching ratios.*

Reactions described by eq. 6 are examples of \( s \)-channel direct resonance production → **bumps** in the corresponding isospin cross section around the centre-of-mass energy corresponding to the resonance mass.

The reactions proceeding like in 7, due to the presence of two particles in the intermediate state with the associated extra degree of freedom of their relative motion, do not exhibit a resonant behaviour, but rather a relatively fast increase starting from a centre-of-mass energy, \( \sqrt{s} \approx M_X + M_Y \), followed by a smooth behaviour. \( N \, N \) reactions are all of this latter type and therefore no resonant structure can be find in \( N \, N \) cross sections.
Nonelastic interactions at intermediate energies: $\Delta$ mass distribution

The actual $\Delta$ mass distribution can be represented by:

$$P(M_\Delta^2)dM_\Delta^2 \propto \frac{\Gamma(k_\pi)M_0}{(M_\Delta^2 - M_0^2)} \frac{k_{\Delta \text{ cms}}}{\Gamma^2(k_\pi)M_0^2 k_{\Delta \text{ max}}} dM_\Delta^2$$

$$\Gamma(k_\pi) = \Gamma_0 \left( \frac{k_\pi k_\Delta}{k_\pi_0} \right)^3 \frac{1 + (0.83k_\pi k_\Delta)^2 + (0.62k_\pi k_\Delta)^4}{1 + (0.83k_\pi_0)^2 + (0.62k_\pi_0)^4}$$

Suitable momentum dependent widths have been implemented also for all other baryon and meson resonances, following general rules.
Nonelastic interactions at intermediate energies: examples

Double differential distributions of charged pions produced by neutrons of $<E_n> = 383$ MeV (left) and 542 MeV (right).

Exp. data have been taken from Buchle et al. NPA515, (1990) 541
Nonelastic interactions at intermediate energies: examples II

Double differential distributions of pions produced by 730 MeV protons. $\pi^-$ from Be (left) and $\pi^+$ from Pb (right). Exp. data (symbols) have been taken from D.R.F. Cochran et al., PRD6, (1972)
Nonelastic interactions at intermediate energies: examples III

Double differential distributions of $\pi^+$'s produced by 1.6 GeV protons on Pb (left, exp. data from M.C. Lemaire et. al., CEA-N-2670) and $\pi$ produced by 4 GeV/c protons on Al (right, exp. data from H. En’yo et al, PL 159B, 1 (1985)).
Nonelastic hN interactions at high energies

Above a few GeV a DPM based model is used for the description of individual hN interactions. The model includes:

- main chain diagrams for all combinations of h-h. Well tested up to strange meson/(anti)baryons, not really for charm
- Diffraction including low mass diffraction to individual resonances
- Chain hadronization with $p_t$ and mass effects particularly tuned for (relatively) low mass quark chains
Nonelastic hN interactions at high energies: examples

Invariant cross section spectra, as a function of Feynman $x_F$ of negative (left), and positive (right) pions emitted for $\pi^+$ on protons at various momenta. Data from M.E Law et al. LBL80 (1972).
Nonelastic hN interactions at high energies: examples II

Double differential cross section for $K^- p \to \Lambda X$ at 10 GeV/c (left), $p_T$ spectra of $\pi^+$ and $\pi^-$ produced by 16 GeV/c $\pi$ incident on an hydrogen target. Data from M.E Law et al. LBL80 (1972).
Nonelastic hN interactions at high energies: examples III

Feynman $x_F$ (left) and $p_t$ (right) spectra of positive particles and $\pi^-$ produced by 250 GeV/c $\pi^+$ incident on an hydrogen target. Exp. data (symbols) have been taken from M. Adamus et al. ZPC39, 311 (1988).
Nonelastic $\pi A$ interactions at high energies: examples

Shower, grey, and black tracks multiplicities for $\pi^-$ (left) and protons (right) incident on emulsion, as a function of the projectile momentum. Open symbols are experimental data from various sources, full symbols are FLUKA results.
Nonelastic hA interactions at high energies: examples II

Correlation between the number of heavy prongs and fast particle multiplicity for protons on emulsion at various momenta, and mutual correlations ($<n_g>$ vs $n_b$ and $<n_b>$ vs $n_g$) between black and grey charged tracks for 400 GeV/c p on emulsion. Open symbols are experimental data from various sources, full symbols are FLUKA results.
Rapidity distribution of $p^+/-$, $K^+/-$, protons and deuterons for 14.6 GeV/c protons on Be (left, data from T.Abbott et al PRD45(11), 3906 1992), and $X_{lab}$ distribution for $p^+/-$ for 24 GeV/c protons on Be (right, symbols extrapolated from the DDCS reported in T.Eichten et al. NPB 44, 333 (1972)).
Nonelastic hA interactions at high energies: examples IV

Invariant cross section distribution for $p\pi^+$ (left) and $\pi^-$ for 24 GeV/c protons on Be (data from T.Eichten et al. NPB 44, 333 (1972)).
Nonelastic hA interactions at high energies: examples V

Rapidity distribution of charged particles produced in 200 GeV proton collisions on Hydrogen, Argon, and Xenon target (left) and ratio of rapidity distribution of charged, positive, and negative particles produced in 200 GeV proton collisions on Xenon and Hydrogen (right). Data from C. De Marzo et al., PRD26, 1019 (1982).
Nonelastic hA interactions at high energies: examples VI

Multiplicity distribution of negative shower particles for 250 GeV/c K⁺ on Aluminium and Gold targets (left), and rapidity distribution of positive, negative, and “π⁺” particle for 250 GeV/c π⁺ on Aluminium (right). Data from I.V. Ajinenko et al. ZPC42 377 (1989) and N.M. Agababyan et al. ZPC50 361 (1991).
Nonelastic hA interactions at high energies: examples VII

Invariant cross section for Λ production from 300 GeV protons on Be (left, data from P. Skubic et al. PRD 18 3115 (1978)), and double differential cross section for proton production (right) for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80 07, G. Ambrosini et al. PL B425 208 (1988)).
Nonelastic hA interactions at high energies: examples VIII

Double differential cross section for $p\pi^+$ (left) and $\pi^-$ (right) production for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80 07, G. Ambrosini et al. PL B425 208 (1988)).
Nonelastic hA interactions at high energies: examples IX

Double differential cross section for K⁺ (left) and K⁻ (right) production for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80 07, G. Ambrosini et al. PL B425 208 (1988)).
Thick target neutron production: examples

Simulated (dashed histogram) and experimental (symbols) neutron double differential distributions out of stopping length targets for 19.08 MeV protons on beryllium (left, H.J. Brede et. al., NIMA274 (1989) 332) and 68 MeV protons on gold (right, S. Meigo et al., NDST97)
Thick target neutron production: examples II

Simulated (dashed histogram) and experimental (symbols) neutron double differential distributions out of stopping length targets for 113 MeV protons on uranium (left, M.M. Meier et al., Nucl. Sci. Eng. 110, (1992) 299) and 256 MeV protons on uranium (right, M.M. Meier et al., Nucl. Sci. Eng. 102, (1989) 310)
Simulated (dashed histogram) and experimental (symbols) neutron double differential distributions out of (semi)stopping length targets for 500 (left) and 1500 MeV protons on lead (right). Exp. data from S. Meigo et al., JAERI-Conf 95-008, (1995), 213
Residual nuclei predictions: the ultimate problem

Many problems require a reasonable knowledge of the identity and energy of the heavy fragments (residuals) produced in $h-A$ and $A-A$ interactions, both on the target and the projectile side. In particular, reliable estimates are important for

- Activation of irradiated components
- Environmental impact (activation of ground, water etc.)
- Radiation damage to sensitive components (SEU etc.)
- Radiobiological effects due to highly ionizing fragments
Evaporation/Fission and Fermi break-up

Main features of the FLUKA evaporation/fission/break-up model: Weisskopf-Ewing evaporation including

- Level densities from Gilbert-Cameron + Ignatyuk energy dependence
- Competition with fission
- Competition with $\gamma$ ray emission
- Fermi Break-up for $A \leq 17$ nuclei, with optional spin-parity effects
- Sampling from emission widths without Maxwellian approximation
- Rough sub-barrier emission
- Rough spin-parity effects for low excitations
Residual nuclei predictions: generalities

The predictions about production of specific isotopes have additional problems wrt the calculation of emission spectra (this applies to both target and projectile ions):

- Small changes in the final evaporation steps can lead to fairly different residuals with little or no impact on the emitted spectra
- Nuclear structure effects play a major role which cannot be easily accounted for
- The lack of spin-parity dependent calculations in most MonteCarlo models limits their accuracy
- Fragmentation processes are known to populate the mass range $A < 20-30$ for medium/heavy target nuclei. These processes are difficult to model in MonteCarlo codes.
- Isomer production: an open question
- The range of interesting cross section values typically spans four order of magnitudes
Residual nuclei: the mass distribution at high energies

Experimental and computed residual nuclei mass distribution following for Ag(p,x)X at 300 GeV (top) and Au(p,x)X at 800 GeV (bottom).
Mass distribution for Gold at 300 MeV

Computed mass yield distributions for 300 MeV protons on Gold using the old “a la EVAP” evaporation (purple) and the new FLUKA evaporation model (green)
Residual nuclei predictions: a look at the isotope table
Residual nuclei predictions: examples

Comparison between computed and measured (A.S. Iljinov et al., Landolt-Börnstein, Vol. 13a (1991)) isotope production by protons on natural Cobalt
Residual nuclei predictions: “new” vs “old” evap.

Comparison between isotope yields computed with the new (left) and (right) evaporation model in FLUKA
Residual nuclei predictions: examples II

Comparison between computed and measured (A.S. Iljinov et al., Landolt-Börnstein, Vol. 13a (1991)) isotope production by protons on natural carbon (left) and by negative pions on Iodine (right)
Residual nuclei predictions: the example of Gold

In the following a few examples of $^{197}$Au(p,x)X reactions will be shown comparing the experimental data and several model predictions.

The model predictions but the one of FLUKA, have been taken from

*International Codes and Model Intercomparison for Intermediate Energy Activation Yields, NSC/DOC(97)-1 NEA/P&I T No 14 (1997)*

The references for the experimental data can be found in the same report
Residual nuclei predictions: the example of Gold I

Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}$Au(p,x)$^{195}$Au (left) and $^{197}$Au(p,x)$^{194}$Hg (right) as a function of the proton energy.
Residual nuclei predictions: the example of Gold II

Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}\text{Au}(p,x)^{191}\text{Pt}$ (left) and $^{197}\text{Au}(p,x)^{187}\text{Ir}$ (right) as a function of the proton energy.
Residual nuclei predictions: the example of Gold III

Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}\text{Au}(p,x)^{185}\text{Os}$ (left) and $^{197}\text{Au}(p,x)^{181}\text{Re}$ (right) as a function of the proton energy
Residual nuclei predictions: the example of Gold IV

Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}$Au(p,x)$^{149}$Tb (left) and $^{197}$Au(p,x)$^{148}$Eu (right) as a function of the proton energy.
Residual nuclei predictions: the example of Gold V

Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}$Au(p,x)$^{105}$Ag (left) and $^{197}$Au(p,x)$^{96}$Tc (right) as a function of the proton energy.
Residual nuclei predictions: the example of Gold VI

Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}$Au(p,x)$^{85}$Sr (left) and $^{197}$Au(p,x)$^{75}$Se (right) as a function of the proton energy.
Comparison between computed (symbols with lines, FLUKA red line with stars) and measured cross sections (black symbols) for $^{197}$Au(p,x)$^{60}$Co (left) and $^{197}$Au(p,x)$^{54}$Mn (right) as a function of the proton energy.
Residual nuclei predictions: summary

The present status of the residual nuclei predictions can be summarized as follows:

- Isotopes in the spallation peak can be predicted reasonably well (within a factor 2-3)
- Isotopes in the fission region can be predicted within a factor of a few
- Isotopes in between the spallation peak and the fission region are subject to large errors (heavy nuclei only)
- Isotopes in the fragmentation region (left of the fission region) are difficult to predict when the fragmenting target is a medium/heavy mass one
- The split between ground state and isomer production is still missing

The uncertainties in the predicted isotope production can be greatly mitigated in all practical situations when the production is dominated by interactions of neutrons below 20 MeV, where extensive and reasonably precise collections of evaluated data exist, i.e. for bulky fissionable targets
LEP dismantling: a calculational nightmare

Request: demonstrate that ALL activities are below 1/10 of the 1996 European Directive limits (around 10 Bq/g) after 10 year operation

An almost unaffordable task for a MC:
Starting from an electron beam,
simulate the extremely rare photon induced nuclear interactions
with such an accuracy as to determine the residual nuclei.

EXPERIMENT: samples of different materials (Al, Cu, stainless steel, Pb and iron-laminated concrete) were irradiated on LEP beam dumps.
- Irradiation time: 5 months, at about 20 cm from the beam axis
- Saturated specific activity of the radionuclides detected in the samples were compared with FLUKA calculations
- The measured activities are so low (few Bq/g) that even the experimental measurement is difficult
**LEP activation: some experimental results**

<table>
<thead>
<tr>
<th>Radio nuclide</th>
<th>T(_{1/2}) (d)</th>
<th>Specific Activity (Bq/g)</th>
<th>Ratio (F/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{46}\text{Sc})</td>
<td>83.8</td>
<td>0.13</td>
<td>0.065</td>
</tr>
<tr>
<td>(^{48}\text{V})</td>
<td>15.97</td>
<td>0.31</td>
<td>0.52</td>
</tr>
<tr>
<td>(^{51}\text{Cr})</td>
<td>27.7</td>
<td>4.12</td>
<td>2.7</td>
</tr>
<tr>
<td>(^{52}\text{Mn})</td>
<td>5.6</td>
<td>0.17</td>
<td>0.74</td>
</tr>
<tr>
<td>(^{54}\text{Mn})</td>
<td>312.2</td>
<td>3.54</td>
<td>2.9</td>
</tr>
<tr>
<td>(^{59}\text{Fe})</td>
<td>44.5</td>
<td>0.028</td>
<td>0.0088</td>
</tr>
<tr>
<td>(^{56}\text{Co})</td>
<td>77.7</td>
<td>0.29</td>
<td>0.46</td>
</tr>
<tr>
<td>(^{57}\text{Co})</td>
<td>271.8</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>(^{58}\text{Co})</td>
<td>70.9</td>
<td>2.65</td>
<td>1.4</td>
</tr>
<tr>
<td>(^{60}\text{Co})</td>
<td>5.27</td>
<td>0.18</td>
<td>0.085</td>
</tr>
<tr>
<td>(^{95}\text{Nb})</td>
<td>34.9</td>
<td>0.038</td>
<td>0.013</td>
</tr>
</tbody>
</table>

MonteCarlo (FLUKA) and experimental cross sections for neutrons on copper (left) and negative pions on carbon (right)
Cross sections: examples II

![Graphs showing cross sections for different elements and energies.](image)
Complex benchmarks

Full cascade or neutron propagation benchmarks:

- The TIARA $^1$ neutron propagation experiment
- The TARC $^2$ experiment at CERN: the ultimate neutronic benchmark
- The Rösti $^3$ experiments at CERN
- The CERF $^4$ dosimetry facility at CERN
- The OPTIS beam at PSI: an attempt of merging biophysical and physical models $^5$

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$^2$H. Arnould et al., PLB458 (1999) 167
$^5$M. Biaggi et al., Nucl. Instr. Meth, B159, (199) 89
The TIARA neutron propagation experiment

Main features:\n
- Source term: semi-monoenergetic neutron spectra generated by 43 and 68 MeV protons on a $^7$Li target, carefully measured with TOF techniques.

- Attenuation of the neutron beam at different depths in concrete and iron shields, both on axis and off-axis (*critical for elastic scattering!!*)

- Emerging neutron spectra measured with liquid scintillator detectors (the high energy component) and Bonner spheres (the low energy component)

---

The TIARA exp.: FLUKA vs exp. data (concrete on axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra after different concrete thicknesses (from 25 to 150 cm), on axis. The neutrons are generated by $^7$Li(p,n) at 43 (left) and 68 MeV (right).
The TIARA exp.: FLUKA vs exp. data (iron on axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra after different iron thicknesses (from 20 to 100 cm), on axis. The neutrons are generated by $^7$Li(p,n) at 43 (left) and 68 MeV (right)
The TIARA exp.: FLUKA vs exp. data (concrete off axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra off axis (from 0 to 40 cm) after 25 (left) and 50 cm thick concrete shields. The neutrons are generated by $^7$Li(p,n) at 43 (left) and 68 MeV (right)
The TIARA exp.: FLUKA vs exp. data (iron off axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra off axis (from 0 to 40 cm) after 20 (left) and 40 cm thick iron shields. The neutrons are generated by $^7\text{Li}(\text{p},\text{n})$ at 43 (left) and 68 MeV (right)
The CERN reference radiation facility – CERF

- 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 1993, on the H6 beam line in the North Area.

- Hadron beams with momentum of either 120 or 205 GeV/c are stopped in a copper target, which can be installed in two different positions. On top and on side of these two positions, the secondary particles produced in the target are filtered by a shielding made up of either concrete or iron.

- The 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.

- The composition of the CERF field is accurately known by means both of FLUKA calculations and measurements with several instruments which nicely agree each other. Some examples of comparisons of computed vs measured data are presented in the following.
Neutron detector calibration

Calibration of the LINUS rem counter (left) and of three Bonner spheres (right) with monoenergetic neutron beams at PTB–Braunschweig and with semi–monoenergetic neutron beams at PSI (full symbols), compared with simulations (dashed histos and open circles)
CERF: layout

Top (left, one side removed) and side (right, roof removed) views of the CERF facility with the measuring positions.
**CERF: some results**

<table>
<thead>
<tr>
<th></th>
<th>experimental cts/PIC</th>
<th>FLUKA cts/PIC</th>
<th>experimental cts/PIC</th>
<th>FLUKA cts/PIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>CONCRETE TOP “E”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LINUS rem counter*</td>
<td>0.364</td>
<td>0.36</td>
<td>0.409</td>
<td>2.2</td>
</tr>
<tr>
<td>SNOOPY rem counter*</td>
<td>0.200</td>
<td>0.59</td>
<td>0.207</td>
<td>3.3</td>
</tr>
<tr>
<td>233 sphere</td>
<td>0.788</td>
<td>0.33</td>
<td>0.899</td>
<td>3.7</td>
</tr>
<tr>
<td>178 sphere</td>
<td>0.989</td>
<td>0.36</td>
<td>1.01</td>
<td>3.4</td>
</tr>
<tr>
<td>133 sphere</td>
<td>1.02</td>
<td>0.30</td>
<td>0.981</td>
<td>3.2</td>
</tr>
<tr>
<td>108 sphere</td>
<td>0.942</td>
<td>0.35</td>
<td>0.883</td>
<td>3.1</td>
</tr>
<tr>
<td>83 sphere</td>
<td>0.704</td>
<td>0.30</td>
<td>0.717</td>
<td>3.1</td>
</tr>
<tr>
<td>IRON TOP “C”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN. The percent statistical uncertainty (%) is indicated.

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From atmospheric neutrinos to aircrew doses

Ultimate goal: exploit the FLUKA interaction models to compute atmospheric neutrino fluxes for ICARUS with unprecedented accuracy within a full 3D calculation

- Primary cosmic ray spectra and interplanetary modulation according to measured solar activity on a day-to-day basis have been implemented
- Geomagnetic effects implemented with full multipole expansion of the field or with a simplified offset dipole model (much faster...)
- Extensive benchmarking against available experimental muon and hadron

A natural byproduct: a powerful tool for computing radiation fluxes in the earth (and Mars...) atmosphere as well as for spacecrafts or satellites

The code is now used in several labs (Frascati, Siegen, Bartol, Houston, GSF...) for simulating the radiation fields generated by cosmic rays in the atmosphere and/or inside spacecrafts.
Hadron/muon fluxes in the atmosphere: examples

Angle integrated (78-90 deg, left) and double differential muon fluxes, measured close to the horizontal in Tel Aviv. Data from O.C. Allkofer et al. NPB 259, 1, (1985).
Neutron flux at top of the Zugspitze (left) for dry and wet conditions, and hadron flux (right) measured with the KASKADE experiment. Data from and from H.H Mielke et al. JPG 20, 637 (1994), H. Kornmayer et al, JPG 21, 439 (1995).
Hadron/muon fluxes in the atmosphere: examples III

Muon fluxes at ground level (left) at 53N 106W on 8-aug-94 compared with data from Mass89 (open symbols, 1989) and from Caprice94 (full symbols). Muon fluxes at various atmospheric depths (right) on 9-aug-94, compared with Caprice94 measurements.
## Hadron/muon fluxes in the atmosphere: examples IV

<table>
<thead>
<tr>
<th>Poly radius (cm)</th>
<th>Altitude</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 m</td>
<td>4880 m</td>
<td>11280 m</td>
</tr>
<tr>
<td></td>
<td>EXP ($s^{-1} \pm %$)</td>
<td>FLUKA ($s^{-1} \pm %$)</td>
<td>EXP ($s^{-1} \pm %$)</td>
</tr>
<tr>
<td>0</td>
<td>2.40 $\cdot 10^{-2}$ ± 12</td>
<td>4.15 $\cdot 10^{-2}$ ± 5</td>
<td>0.43 ± 9</td>
</tr>
<tr>
<td>4.1</td>
<td>2.30 $\cdot 10^{-2}$ ± 12</td>
<td>2.74 $\cdot 10^{-2}$ ± 4</td>
<td>0.570 ± 4</td>
</tr>
<tr>
<td>5.6</td>
<td>2.90 $\cdot 10^{-2}$ ± 11</td>
<td>3.27 $\cdot 10^{-2}$ ± 3</td>
<td>0.753 ± 7</td>
</tr>
<tr>
<td>7.6</td>
<td>3.53 $\cdot 10^{-2}$ ± 10</td>
<td>3.51 $\cdot 10^{-2}$ ± 3</td>
<td>0.860 ± 6</td>
</tr>
<tr>
<td>11.6</td>
<td>2.03 $\cdot 10^{-2}$ ± 13</td>
<td>2.71 $\cdot 10^{-2}$ ± 3</td>
<td>0.620 ± 7</td>
</tr>
<tr>
<td>22.6</td>
<td>8.14 $\cdot 10^{-3}$ ± 13</td>
<td>1.20 $\cdot 10^{-2}$ ± 3</td>
<td>0.177 ± 10</td>
</tr>
</tbody>
</table>

**Altitude variation of multi-sphere neutron spectrometer rates above the Narita airport (1985): comparison between experimental \(^8\) and FLUKA results.**

\(^8\)T. Nakamura et al., Health Phys. 53 509 (1987)
Hadron/muon fluxes in the atmosphere: examples IVbis
Hadron/muon fluxes in the atmosphere: examples IVtris

Variation with altitude of neutron dose equivalent above the Narita airport (1985). Experimental results (blue symbols) obtained with a commercial Rem Counter and the Bonner spectrometer are compared with FLUKA calculations for the overall neutron dose equivalent (green symbols) and for the response of a standard rem counter (“SNOOPY”, purple) and an extended range one (“LINUS”, red).
Doses to commercial flight crews (M. Pelliccioni et al, work in progress)

Calculated effective dose as a function of altitude for a vertical rigidity cutoff of 0.4 GV at solar minimum (open circles), and at solar maximum (open squares), and for a cutoff of 17.6 GV (black circles)
GCR radiation fields on the Mars surface: a first attempt

A simple model of the Mars atmosphere has been setup ($\approx 10 \, g/cm^2$ of CO$_2$), with a terrestrial rock composition for the Mars surface (to be improved in future calculations)

Individual energy losses have been weighted with proper factors depending on the LET, according to the most recent recommendations for quality factors issued in ICRP60, with the same procedure used in $^9$ when computing fluence to dose equivalent conversion data and effective quality factors for high energy neutrons.

A 30 cm thick water layer has been used as scoring phantom. For obvious statistical reasons it had to be quite large, therefore introducing a bias in the low energy neutron spectrum. Future calculations will be done in two stages

- computing the radiation environment on the Mars surface,
- simulating on a local scale a suitable phantom into such an environment.

GCR radiation fields on the Mars surface: a first attempt II

Computed Dose and Dose equivalent rates at Mars surface

Particle fluences as a function of depth in the Mars atmosphere
GCR radiation fields on the Mars surface: a first attempt III

Hadron/muon (left) and neutron (right) spectra at ground level
GCR radiation fields on the Mars surface: a first attempt IV

Electron/positron (left) and photon (right) spectra at ground level
The background in the ATLAS hall

Computed neutron background in the ATLAS experiment at LHC for two different shielding configurations, one with the “shielding cone” made out of high density “pure” iron (left) and the other with a lower density, carbon rich (5% by weight) iron (right)
The background in the ATLAS hall II

A magnification of the "shielding cone" area showing the different effectiveness of the two "iron" shielding
Shielding in the ATLAS hall
**Heavy ions**

Heavy ion transport and interactions are presently under development in FLUKA:

- Ionization energy losses already implemented
  - Up-to-date effective charge parametrizations
  - Energy loss straggling according to:
    * “normal” first Born approximation
    * Charge exchange effects (dominant at low energies, ad-hoc model developed for FLUKA)
    * Mott cross section and nuclear form factors (high energies)(in progress)
- Multiple scattering already implemented

- High energy A-A interactions \( E > 5 - 10 \text{ GeV}/u \): interface to DPMJET coming soon

- Low energy A-A interactions: extension of the PEANUT model almost ready for tests with \( \alpha' \)’s

The availability of exp. data on particle production in A-A collisions in the intermediate energy range will be a crucial issue in the next future
dE/dx and straggling of heavy ions

Comparison of experimental (R. Bimbot, *NIMB* 69 (1992) 1) (red) and FLUKA (blue) stopping powers of Argon and Uranium ions in different materials and at different energies.
dE/dx and straggling of heavy ions

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Target</th>
<th>thickness (mg/cm²)</th>
<th>FWHM (keV)</th>
<th>Exp</th>
<th>FLUKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>Al</td>
<td>0.217</td>
<td>74.5 ± 3</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Al</td>
<td>0.110</td>
<td>92 ± 2</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Al</td>
<td>0.246</td>
<td>147 ± 3</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Al</td>
<td>0.457</td>
<td>202 ± 2</td>
<td>198</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Al</td>
<td>0.315</td>
<td>290 ± 30</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Al</td>
<td>0.990</td>
<td>521 ± 20</td>
<td>638</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Au</td>
<td>0.053</td>
<td>98 ± 20</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Au</td>
<td>3.492</td>
<td>820 ± 20</td>
<td>1092</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Al</td>
<td>0.321</td>
<td>780 ± 40</td>
<td>735</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Al</td>
<td>0.530</td>
<td>1000 ± 35</td>
<td>949</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Al</td>
<td>0.990</td>
<td>1375 ± 50</td>
<td>1297</td>
<td></td>
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<tr>
<td>$^{127}$I</td>
<td>Au</td>
<td>0.053</td>
<td>250 ± 10</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Au</td>
<td>1.186</td>
<td>1200 ± 50</td>
<td>1255</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Au</td>
<td>3.800</td>
<td>2250 ± 90</td>
<td>1932</td>
<td></td>
</tr>
</tbody>
</table>

Measured (S. Ouichaoui et al. NIM B164-165 (2000) 259) and computed (FLUKA) straggling for 2 MeV/amu $^{12}$C, $^{16}$O, $^{32}$S ions and 1.467 MeV/amu $^{127}$I ions
Heavy ions at relativistic energies: DPMJET

DPMJET

Authors: R. Engel†, J. Ranft*, and S. Roesler&
† Bartol, * Siegen University, & SLAC

Nucleus-Nucleus interaction code ¹⁰ for collisions from ≈5-10 GeV/n till the highest cosmic ray energies (10¹⁸ – 10²⁰ eV)

Applications of DPMJET

- Predictions for heavy ion experiments at present and future accelerators (i.e. ALICE at LHC)
- Simulations of Cosmic Ray cascades in the HEMAS-DPM code used by the MACRO Collaboration
- Simulations of Cosmic Ray cascades in the CORSIKA code (Karlsruhe)

**DPMJET: 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.
Conclusions

- The physical models embedded in **FLUKA** have proven to be enough advanced to provide reliable estimates of particle production and propagation in a wide range of energies and problems
- The code has been already successfully used for a variety of problems related to cosmic ray propagation and interactions in the atmosphere
- Space radiation applications will benefit from the robust physics modelling and of course from the almost unlimited capabilities in geometrical description, magnetic field transport and biasing of the code
- The development of capabilities for A-A interactions comparable to those for h-A is now under progress