# Nuclear models in FLUKA: a review

10th INTERNATIONAL CONFERENCE ON NUCLEAR REACTION MECHANISMS

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Varenna

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# FLUKA

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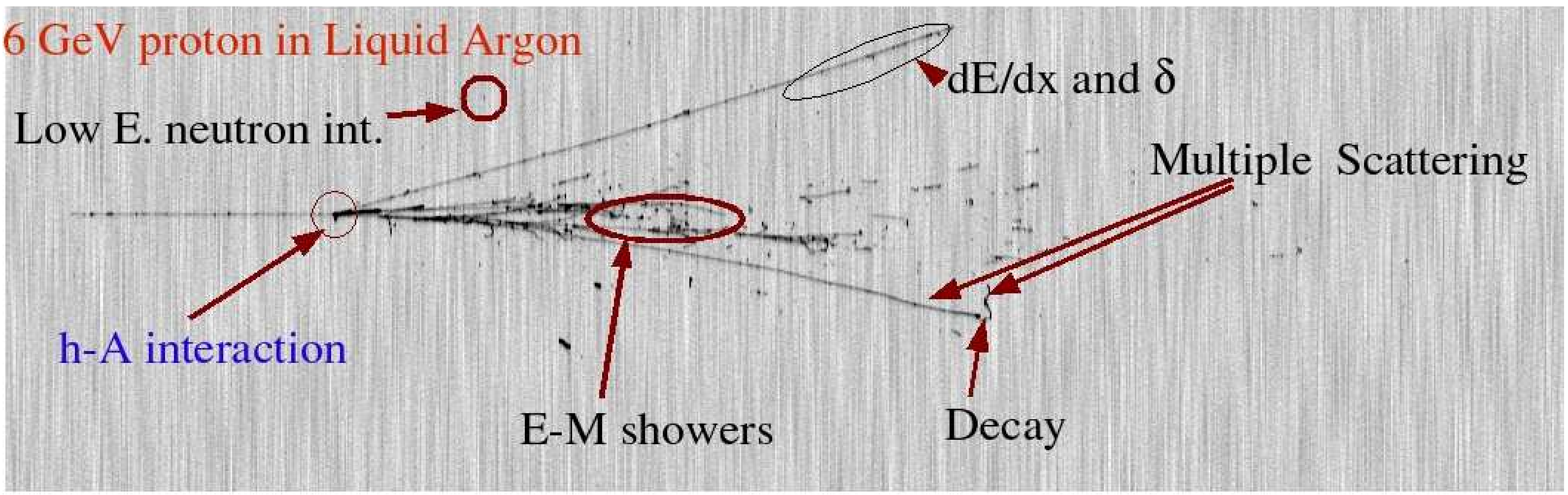
Interaction and Transport MonteCarlo code




http://www.fluka.org

# FLUKA Topics

- The FLUKA High energy hadronic models
  - Short description and (few) thin target benchmarks
- The FLUKA Low-intermediate energy hadronic models
  - Short summary and thin target benchmarks
  - Applications to neutrino physics and nucleon decay
- Nucleus-nucleus interactions in FLUKA
  - Status and Benchmarks
- Examples of complex applications
  - Cosmic ray showers and aircraft doses
  - Neutronics: the TARC experiment

## The FLUKA hadronic models

**Hadron-Nucleon**

| Elastic, exchange | P<3-5GeV/c | low E $\pi$,$K$ | High Energy |
|---|---|---|---|
| Phase shifts, data,eikonal | Resonance prod. and decay | Special | DPM hadronization |

**Hadron-Nucleus**

| P<4-5GeV/c | High Energy |
|---|---|
| PEANUT: | Glauber-Gribov |
| Sophisticated GINC | multiple interactions |
| preequilibrium | Coarser GINC |
| Coalescence | Coalescence |

**Nucleus-Nucleus**

E> 5 GeV/$u$
DPMJET
0.1< E < 5 GeV/$u$
(modified) rQMD-2.4

Evaporation/Fission/Fermi break-up
$\gamma$ deexcitation

## Inelastic hN at high energies: (DPM, QGSM, ...)

- Problem: "soft" interactions $\rightarrow$ no perturbation theory
- Solution: Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
- Interactions treated in the Reggeon-Pomeron framework
- At sufficiently high energies the leading term corresponds to a Pomeron ($I\!P$) exchange (a closed string exchange)

- Each of the two colliding hadrons splits into two colored partons $\rightarrow$ combination into two color neutral chains $\rightarrow$ two back-to-back jets
- Physical particle exchange produce single chains at low energies
- Higher order contributions with multi-Pomeron exchanges important at $E_{lab} \geq 1$ TeV

# Dual Parton Model (DPM)

★ DPM provides recipes for:

- determining the number of cut $I\!P$omerons, and therefore the number of chains contributing to the reaction
- forming the chains using the valence and possibly sea quarks of the two colliding hadrons
- determining the energy and momentum carried by each chain, according to the momentum distribution functions of the two colliding hadrons
- hadronizing each chain producing the final hadrons, stable ones or resonances

★ Hadronization: not exactly a part of DPM, but DPM is factorized so that it can admit any suitable hadronization scheme (hard processes, $e^+e^- \ldots$)

- Hadronization properties assumed to be independent of the physical process originating the chain (chain universality)
- Excluding hadronization, little or no freedom in each individual step
  $\Rightarrow$ high predictive power of the model
- Diffractive scattering in h–h, h–N and N–N collisions can also be described in the DPM framework

## Nonelastic hN interactions at intermediate energies

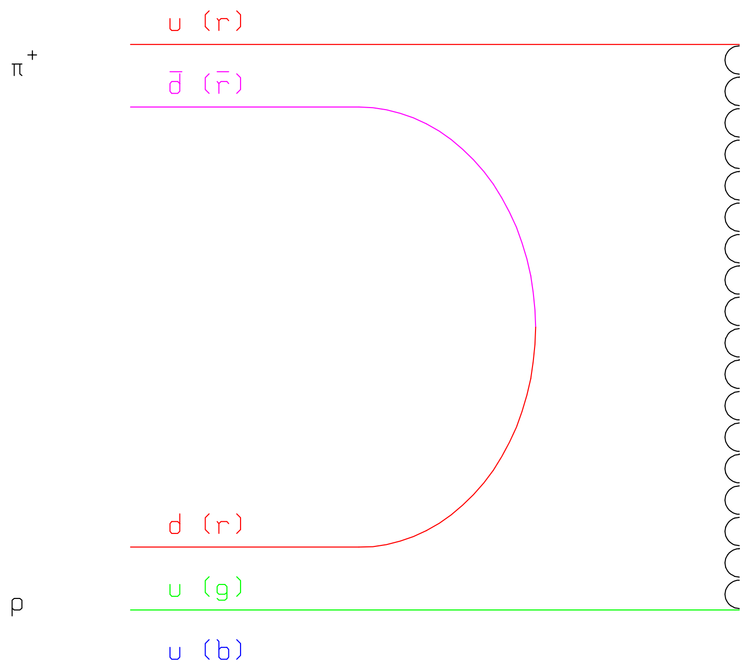
- $N_1 + N_2 \to N_1' + N_2' + \pi$ threshold around 290 MeV, important above 700 MeV,
- $\pi + N \to \pi' + \pi'' + N'$ opens at 170 MeV.

Dominance of the $\Delta$ resonance and of the $N^*$ resonances $\to$ reactions treated in the framework of the isobar model $\to$ all reactions proceed through an intermediate state containing at least one resonance.

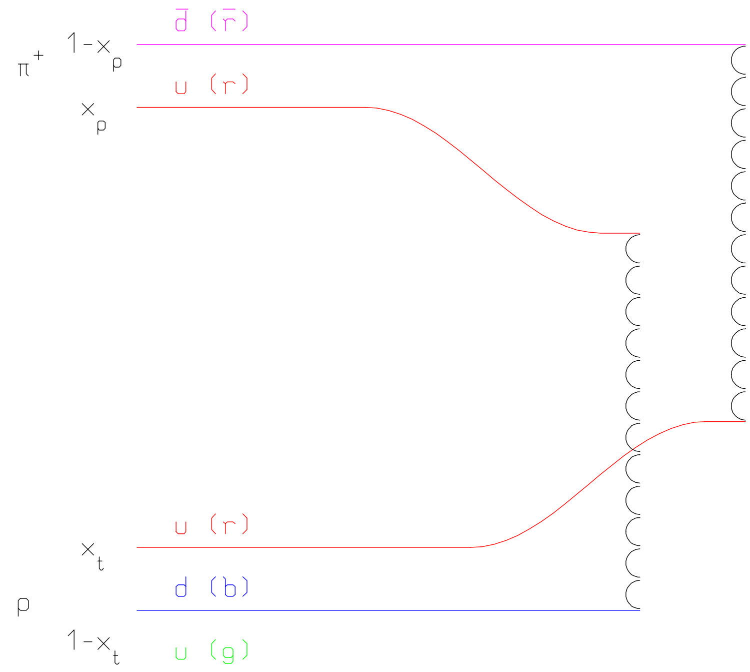
$$
\begin{aligned}
N_1 + N_2 &\to N_1' + \Delta(1232) \to N_1' + N_2' + \pi \\
\pi + N &\to \Delta(1600) \to \pi' + \Delta(1232) \to \pi' + \pi'' + N' \\
N_1 + N_2 &\to \Delta_1(1232) + \Delta_2(1232) \to N_1' + \pi_1 + N_2' + \pi_2
\end{aligned}
$$

Resonance energies, widths, cross sections, branching ratios from data and conservation laws, whenever possible. Inferred from inclusive cross sections when needed

# From resonance production to DPM

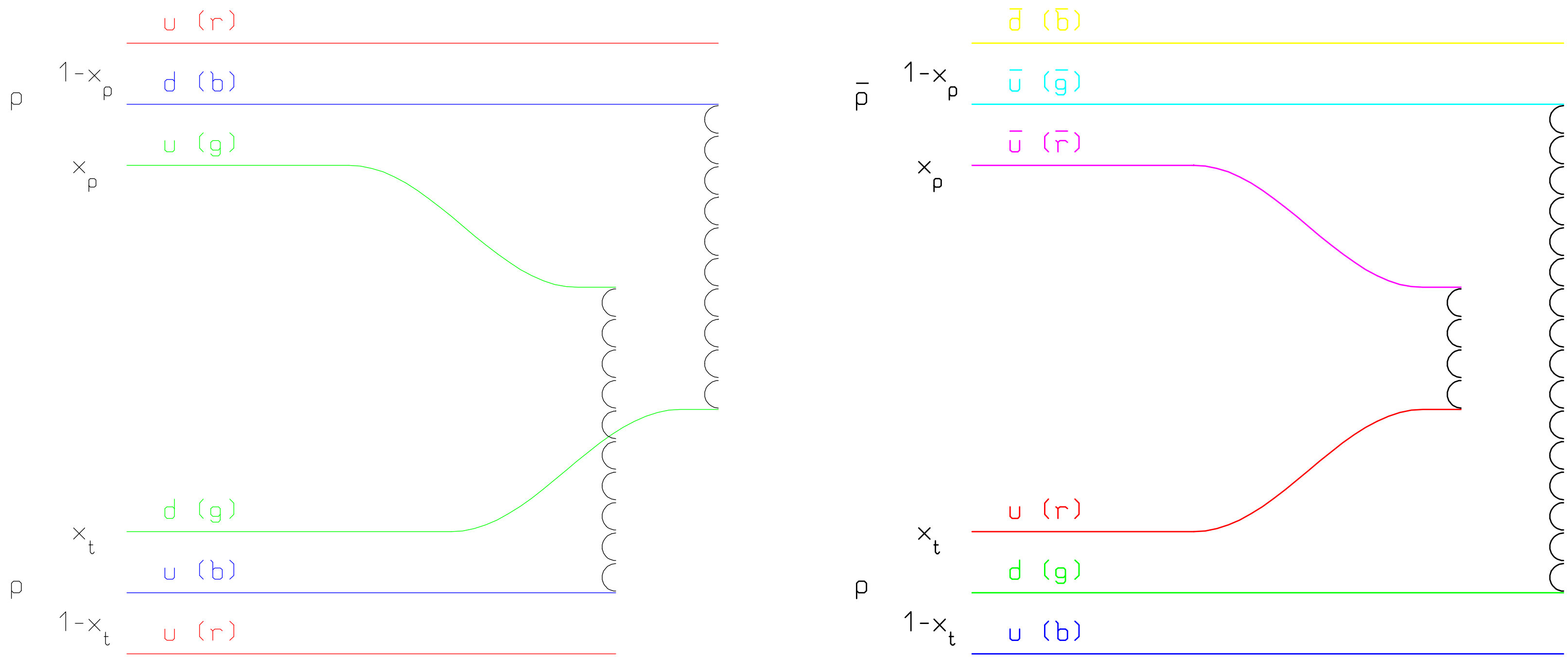



Single chain diagram for $\pi^+ - p$ scattering, corresponding to a physical particle exchange. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities



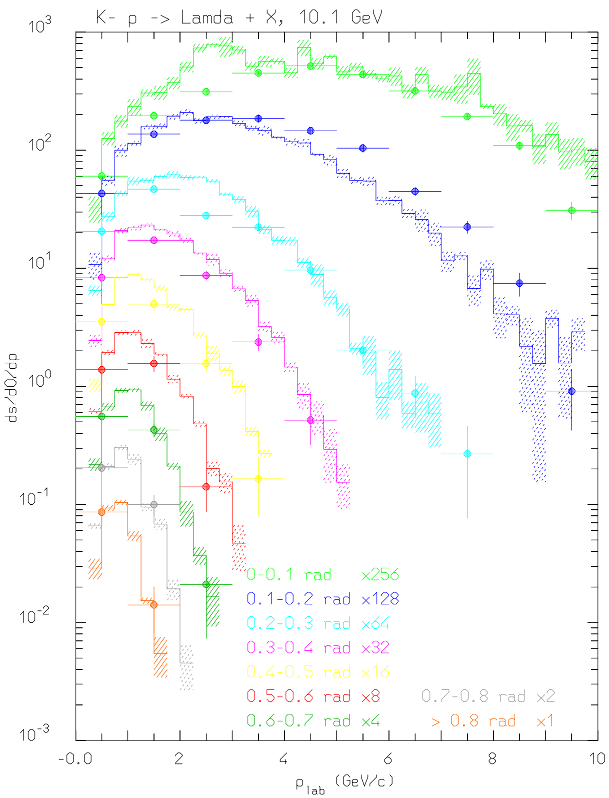

Leading two-chain diagram in DPM for $pi^+ - p$ scattering. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities

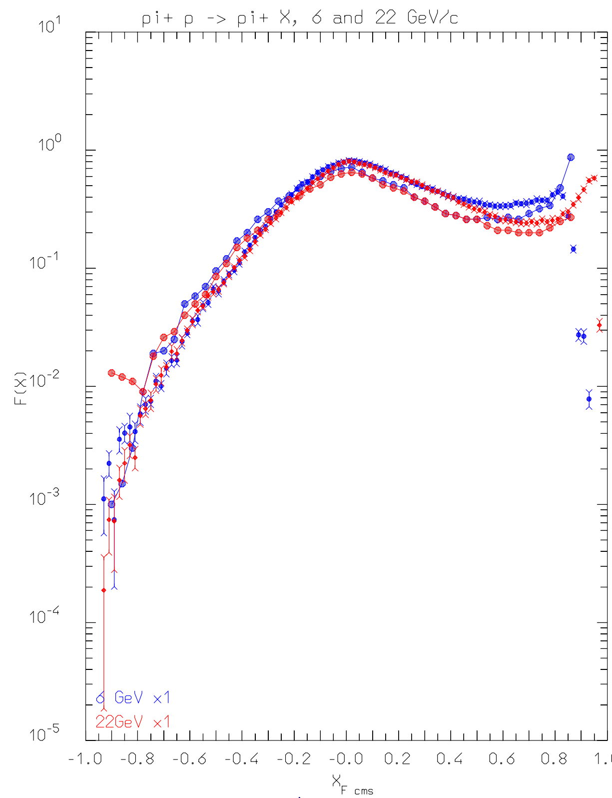
# DPM: chain examples




Leading two-chain diagrams in DPM for $p - p$ (left) and $\bar{p} - p$ (right) scattering. The color (red, blue, and green) and quark combinations shown in the figure are just one of the allowed possibilities

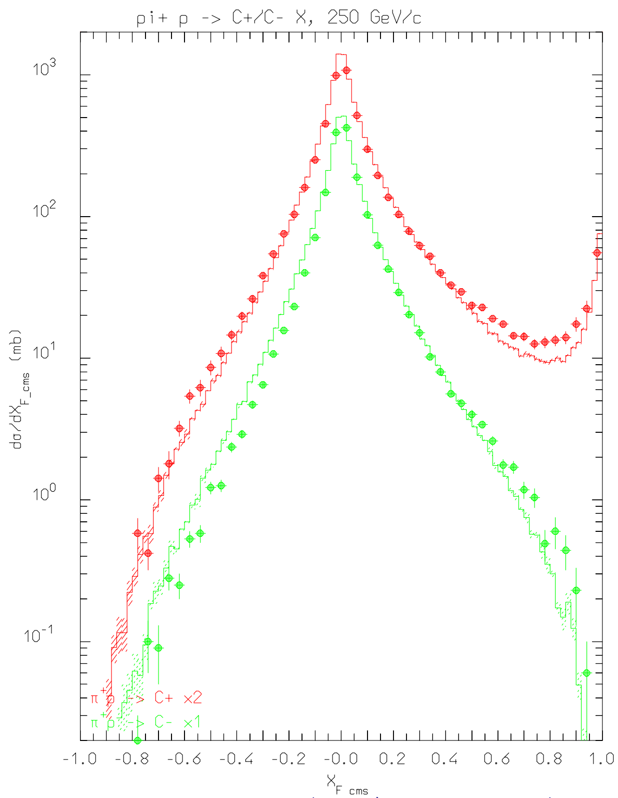
# Nonelastic hN high E: ($K^-p$) , ($\pi^-p$) 10-16 GeV, $p_T$

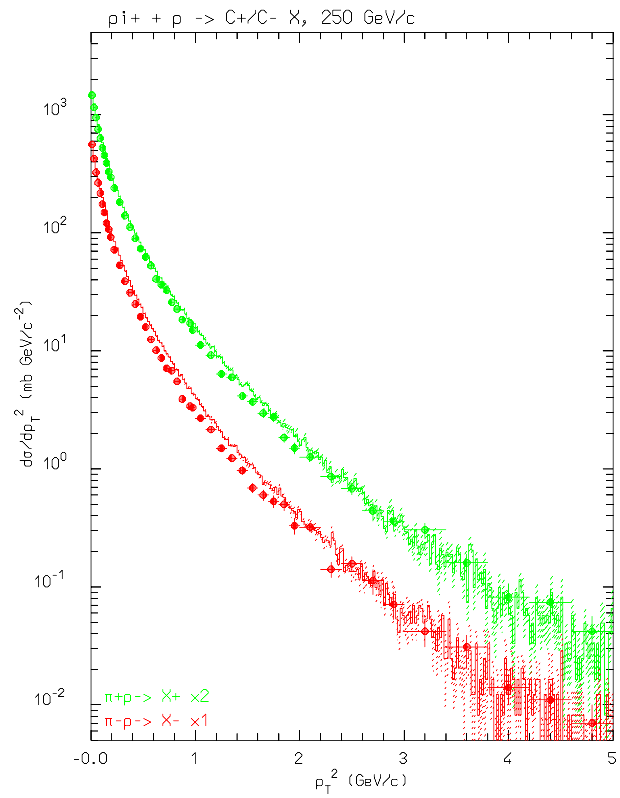



Left: Double differential cross section for $K^-p \to \Lambda X$ at 10 GeV/c. Right: Invariant $\sigma$ spectra, as a function of Feynman $x_F^*$, for $\pi^+$ emitted from ($\pi^+$,p) at various momenta. Data from M.E Law et al. LBL80 (1972).

## Nonelastic hN high E: ($\pi^+$ p) 250GeV, $x_F$ and $p_t$




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).

## hA at high energies: Glauber-Gribov cascade with formation zone

★ Glauber cascade

- Quantum mechanical method to compute all relevant cross sections from hadron–nucleon scattering and nuclear ground state wave function
- Elastic, Quasi-elastic and Absorption hA cross sections derived from Free hadron-Nucleon cross section + Nuclear ground state ONLY

★ Glauber-Gribov

- Field theory formulation of Glauber model
- Multiple collision terms ⇔ Feynman graphs
- High energies: exchange of one or more Pomerons ($I\!P$) with one or more ($=\nu$) target nucleons (a closed string exchange)

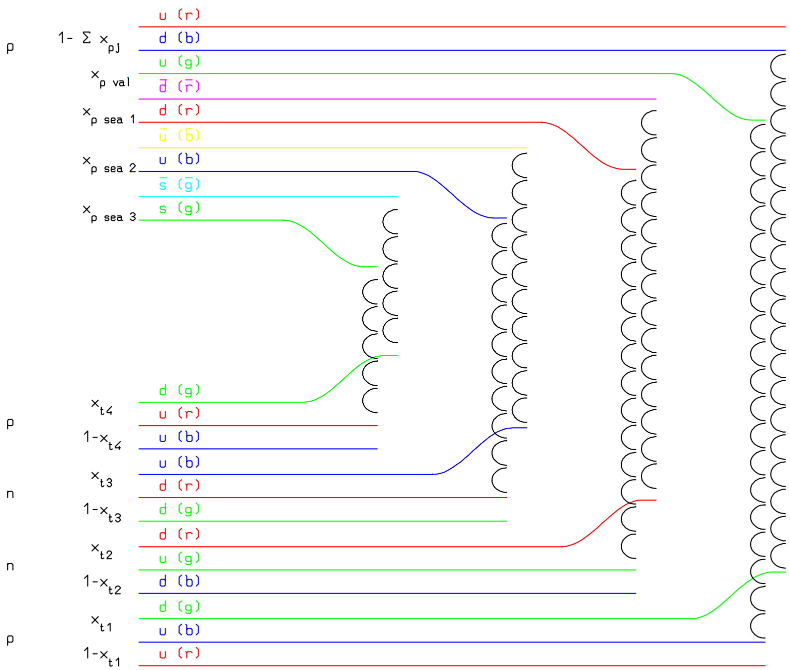
$$P_{r\ \nu}(b) \ \equiv \ \binom{A}{\nu} P_r^{\nu}(b)\left[1 - P_r(b)\right]^{A-\nu}$$

$P_r(b) \equiv \sigma_{hN\ r} T_r(b)$, $T_r(b)=$ nuclear density and scattering profile folding

$$<\nu>= \frac{Z\sigma_{hp\ r} + N\sigma_{hn\ r}}{\sigma_{hA\ abs}} \qquad \sigma_{hA\ abs}(s) = \int \mathrm{d}^2\vec{b}\left[1 - (1 - \sigma_{hN\ r}(s)T_r(b))^A\right]$$

★ Formation zone (= materialization time)

# h-A at high energies: Glauber-Gribov




One of the possibilities for Glauber-Gribov scattering with 4 collisions

Gribov

⇓

$2\nu$ chains

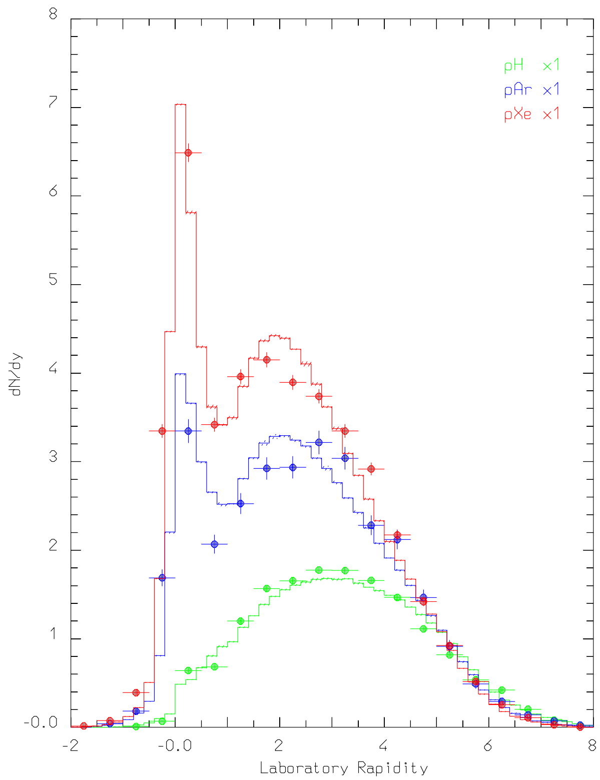
2 valence-valence chains

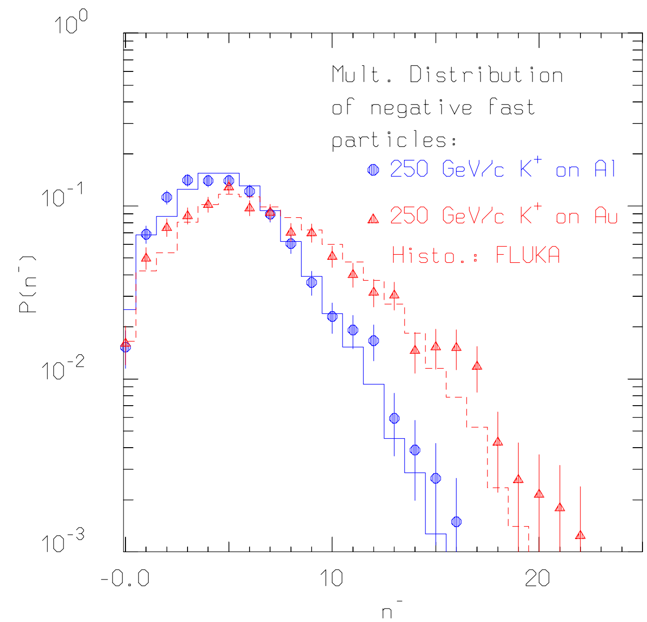
$2(\nu - 1)$ chains between projectile sea and target valence (di)quarks.

No freedom, except in mass effects at low energies.

Fermi motion included → smearing of E and $p_T$ distributions

# Nonelastic hA interactions at high energies: examples




Rapidity distribution of charged particles produced in 200 GeV proton collisions on Hydrogen, Argon, and Xenon target (left), and multiplicity distribution of negative shower particles for 250 GeV/c $K^+$ on Aluminium and Gold targets (right). Data from C. De Marzo et al., PRD26, 1019 (1982), I.V. Ajinenko et al. ZPC42 377 (1989).

## Generalized Intra-Nuclear Cascade: PEANUT

★ Main assets of the full GINC as implemented in FLUKA below 5 GeV:

- PEANUT (PreEquilibrium Approach to NUclear Thermalization): GINC + preequilibrium stage handling nucleons, pions, kaons, $\gamma$, stopping $\mu^-$ and $\nu$'s
- Nucleus divided into 16 radial zones of different density, plus 6 outside the nucleus to account for nuclear potential, plus 10 for charged particles
- Different nuclear densities for neutrons and protons
- Nuclear (complex) optical potential $\Longrightarrow$ curved trajectories in the mean nuclear+Coulomb field (reflection, refraction)
- Updating binding energy (from mass tables) after each particle emission
- Multibody absorption for $\pi^{+/0/-}$, $K^{-/0}$, $\mu^-$
- Energy-momentum conservation including the recoil of the residual nucleus
- Nucleon Fermi motion including wave packet-like uncertainty smearing
- Quantum effects (mostly suppressing): Pauli blocking, Formation zone, Nucleon antisymmetrization, Nucleon-nucleon hard-core correlations, Coherence length

## Neutrino interactions in PEANUT: the *NUX-FLUKA* event generator

Authors: A. Ferrari (CERN/INFN), A. Rubbia (ETH Zurich), P.R. Sala (ETH/INFN)

Features:

- Full use of all sophisticated nuclear physics of PEANUT
- Quasielastic event generator built-in
- RES and DIS: nucleon density, position and Fermi motion via PEANUT $\rightarrow$ $\nu$N interaction via *NUX* (A.Rubbia, originally developed for NOMAD), $\rightarrow$ all secondaries propagated with PEANUT. Fully integrated one in the other in a single code $\rightarrow$ "correct" account for kinematical effects on cross section due to Fermi motion and for Pauli blocking

The comparison with NOMAD data are due to A. Bueno, A. Rubbia, ETH Zurich

## Formation zone

Naively: "materialization" time. Qualitative estimate: in the frame where $p_{\parallel} = 0$

$$\bar{t} = \Delta t \approx \frac{\hbar}{E_T} = \frac{\hbar}{\sqrt{p_T^2 + M^2}}$$

particle proper time

$$\tau = \frac{M}{E_T}\bar{t} = \frac{\hbar M}{p_T^2 + M^2}$$

Going to lab system

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

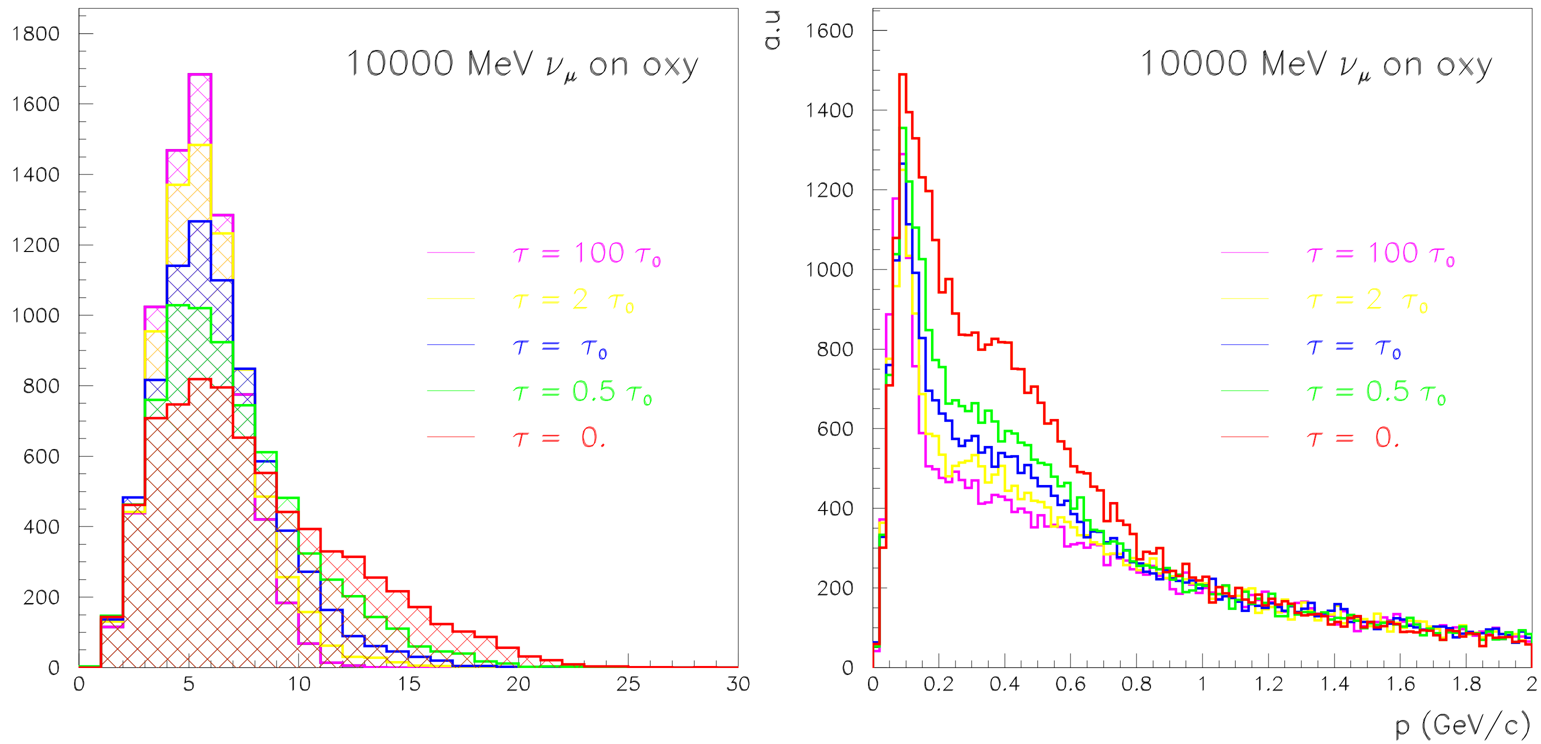
Condition for possible reinteraction inside a nucleus:

$$v \cdot t_{lab} \leq R_A \approx r_0 A^{\frac{1}{3}}$$

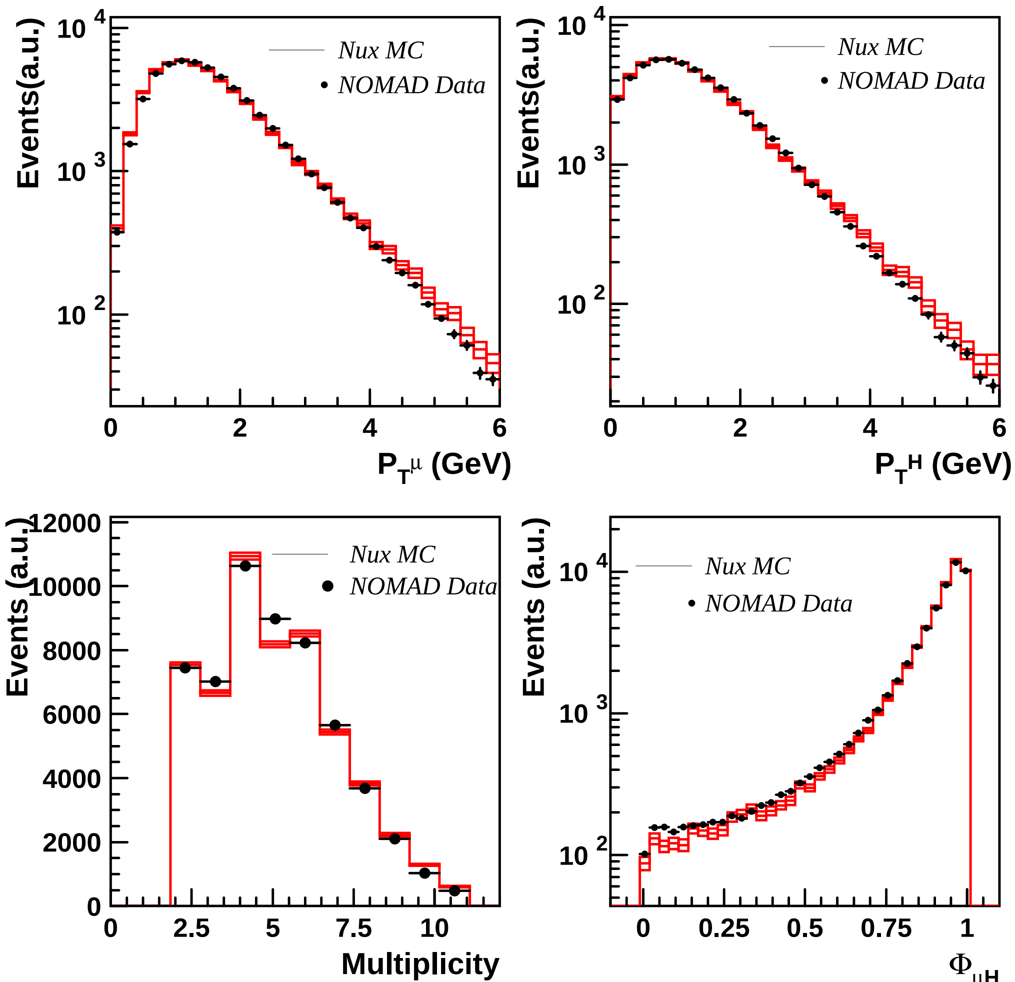
*Coherence length ≡ formation time for elastic or quasielastic hN interactions (not discussed here)*

## Formation zone+ coherence length in $\nu$ interactions

Effect of different formation time ($\tau$) values on the total hadron multiplicity and on hadron spectra in $\nu_\mu$ CC interactions.



## The *NUX-FLUKA* event generator: comparison with NOMAD




CC $\nu_\mu$ interactions in the NOMAD detector, from the CERN $\nu$ beam.

Top: Transverse mom. of $\mu$ (left) and hadrons (right)

Bottom left: Hadron multiplicity distribution

Bottom right: Azimuthal angle (rad/$\pi$) between $\mu$ and "all hadrons"

## Pions: nuclear medium effects

*Pion-nucleon interactions: non-resonant + p-wave resonant $\Delta$'s.*

$\Delta$ in nuclear medium

decay — elastic scattering or charge exchange

reinteraction — pion absorption

$\rightarrow$ $\Delta$ width different from the free one

*Assuming a Breit-Wigner for the free resonant cross section with width* $\Gamma_F$

$$\sigma_{res}^{Free} = \frac{8\pi}{p_{cm}^2} \frac{M_\Delta^2 \Gamma_F(p_{cm})^2}{(s - M_\Delta^2)^2 + M_\Delta^2 \Gamma_F(p_{cm})^2}$$

*Add "in medium" width* (Oset et.al ,NPA 468, 631)

$$\frac{1}{2}\Gamma_T = \frac{1}{2}\Gamma_F - \mathrm{Im}\Sigma_\Delta, \quad \Sigma_\Delta = \Sigma_{qe} + \Sigma_2 + \Sigma_3$$

*($\Sigma_{qe}$, $\Sigma_2$, $\Sigma_3$ = widths for quasielastic scattering, two and three body absorption)*

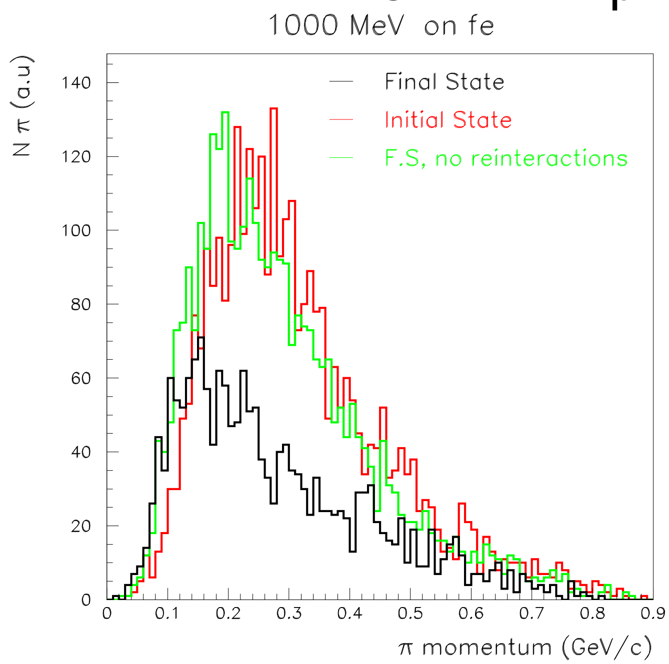
*Add two-body s-wave absorption cross section from optical model*

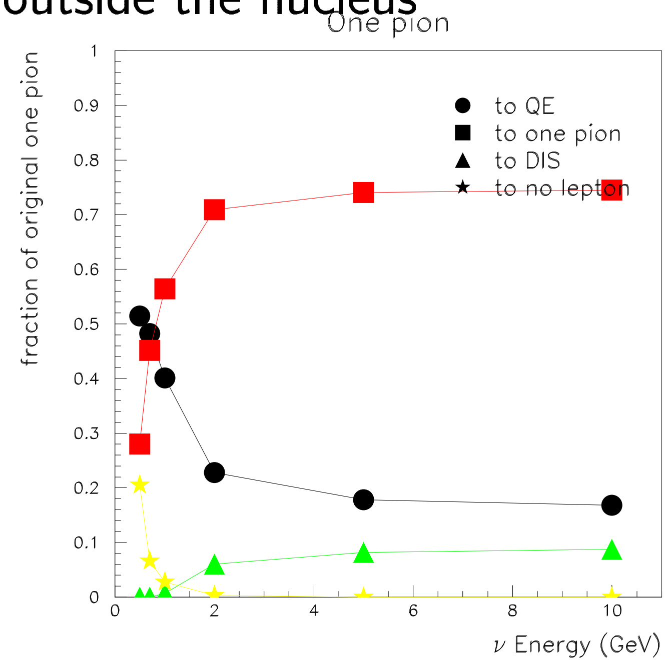
Nuclear potential for $\pi$: Energy dependent, resonant shape (+ Coulomb)

Charged pion spectra and reaction identification after $\nu_\mu$ interaction.

Initial State == particles still inside the nucleus

Final State == particles outside the nucleus

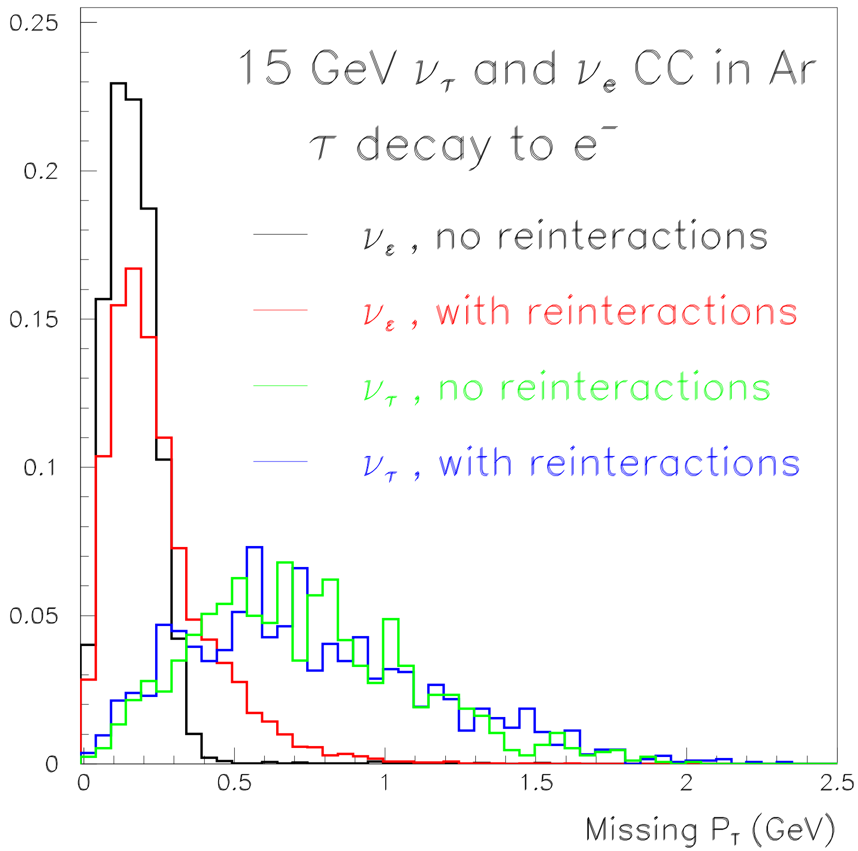



Only 55% escape at 1 GeV on Fe, 75% on Oxygen

$\nu_\mu$ on O, Water Cerenkov detector: mis- identification of "Resonant" reactions

# Missing Transverse Momentum




$\nu_\tau$ identification vs $\nu_e$

(i.e. CNGS $\nu$ beam)

One of the possible "cuts" :

missing $P_T$

$$\nu_\tau + A \rightarrow \tau^- + X \rightarrow e^- + \bar{\nu}_e + \nu_\tau + X$$

Intrinsic Missing $P_T$ due to $\tau$ decay

$$\nu_e + A \rightarrow e^- + X$$

No Missing $P_T$ *on free nucleon*

Deeply changed by nuclear effects

# Preequilibrium in FLUKA

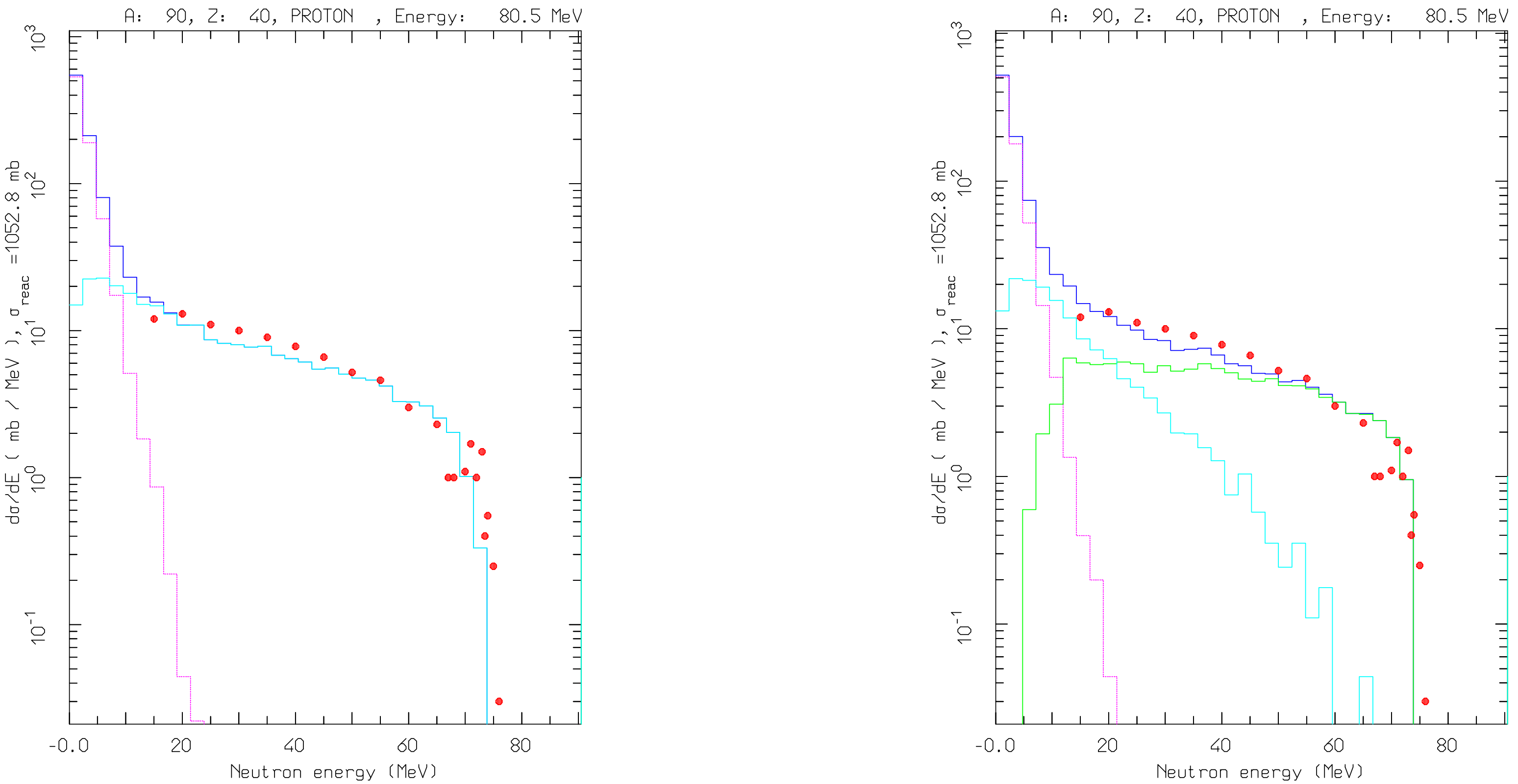
FLUKA preequilibrium is based on GDH (*M. Blann et al.*) cast in a MonteCarlo form

GDH: Exciton model, $\rho$,$E_F$ are "local" averages on the trajectory and constrained state densities are used for the lowest lying configurations.

Modifications of GDH in FLUKA:

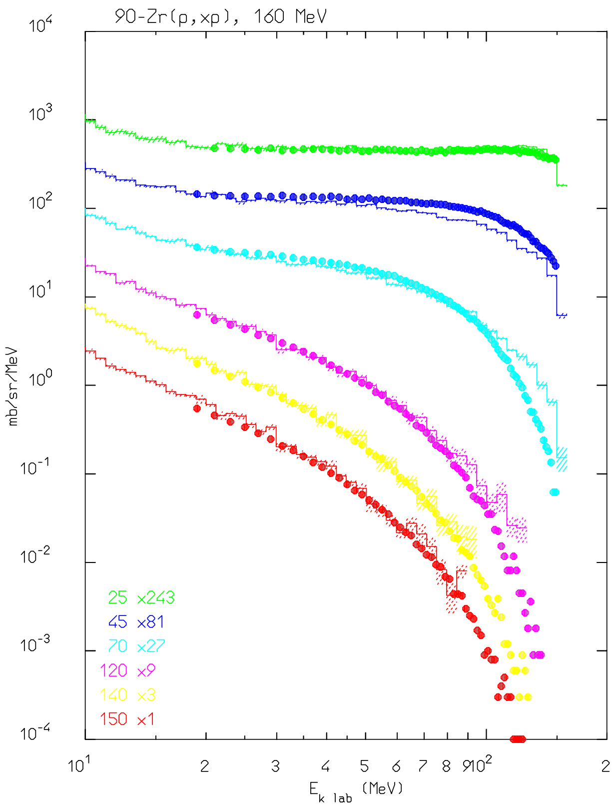
- $\sigma_{inv}$ from systematics
- Correlation/coherence length/ hardcore effect on reinteractions
- Constrained exciton state densities configurations 1p-1h, 2p-1h, 1p-2h, 2p-2h, 3p-1h and 3p-2h
- True local $\rho$,$E_F$ for the initial configuration, evolving into average
- Non-isotropic angular distribution (fast particle approximation)

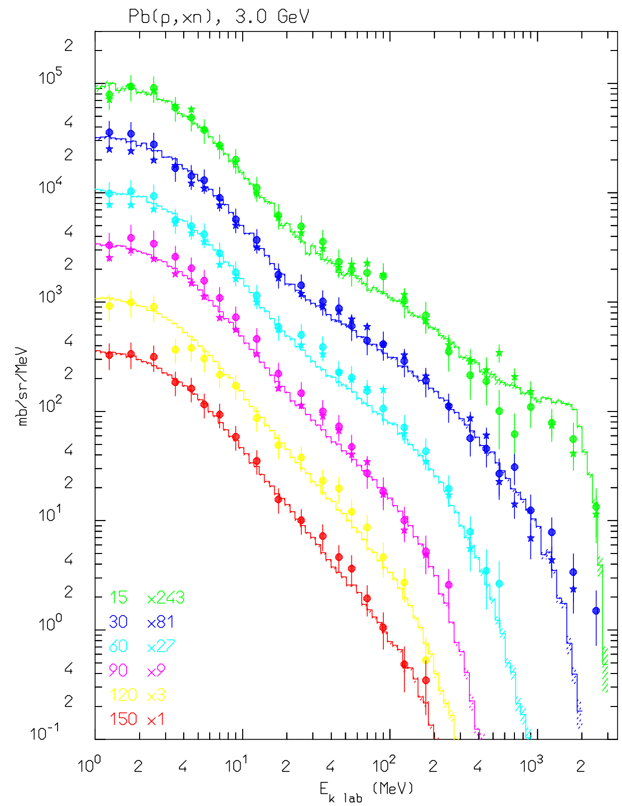
# Preequilibrium/(G)INC transition




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



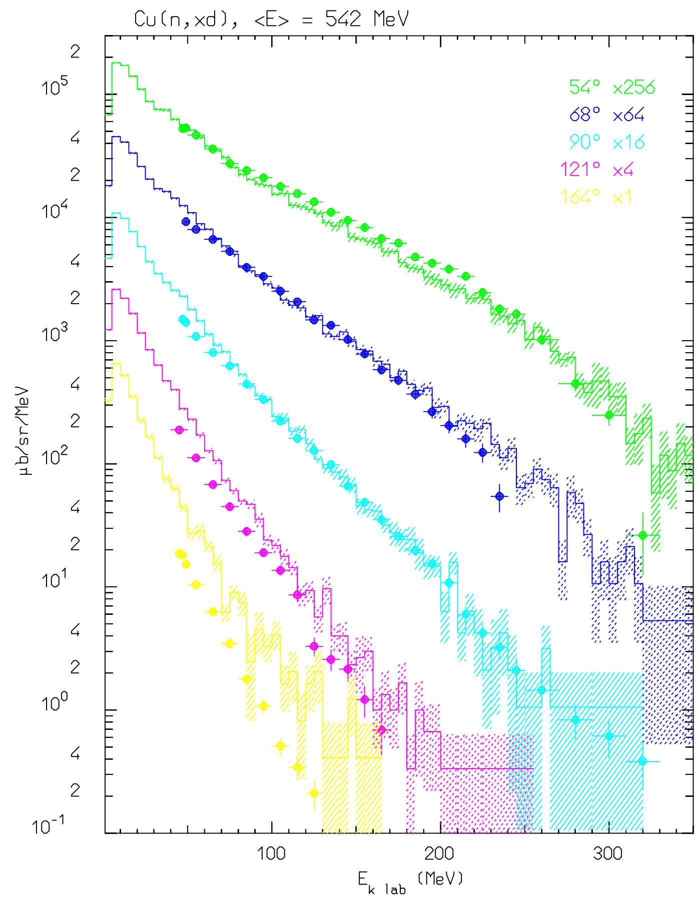



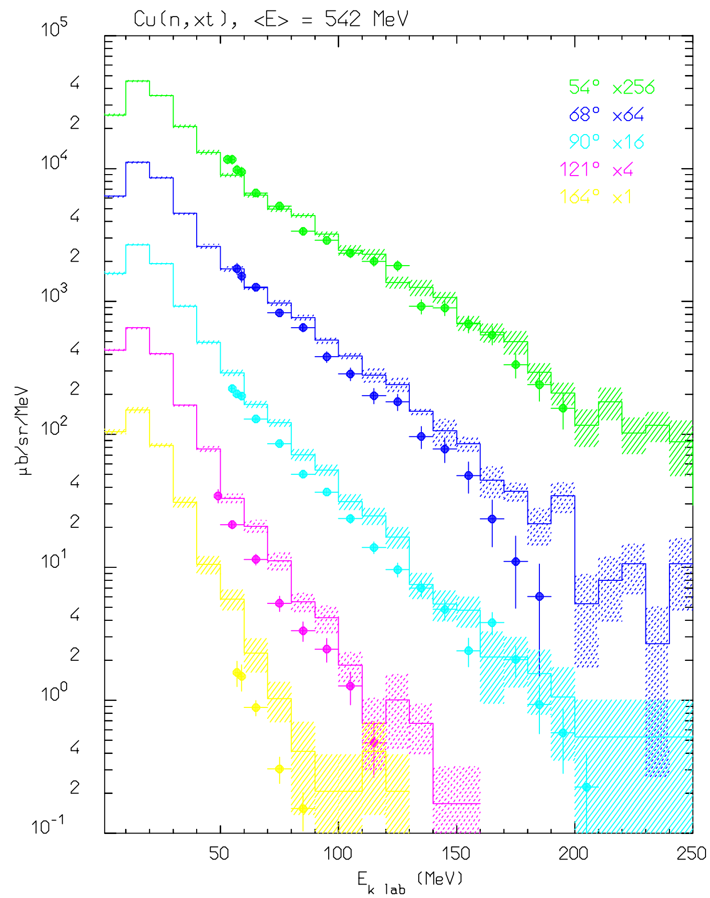

Double differential neutron distributions for Zr(p,xp) at 160 MeV (left) and Pb(p,xn) at 3 GeV (right)

Histograms: computed with FLUKA; symbols: experimental data from

Richter et al, *NAC Annual report*, 92-01 (1992), Ishibashi et al., Nucl. Sci. Technol. **32** (1995) 827

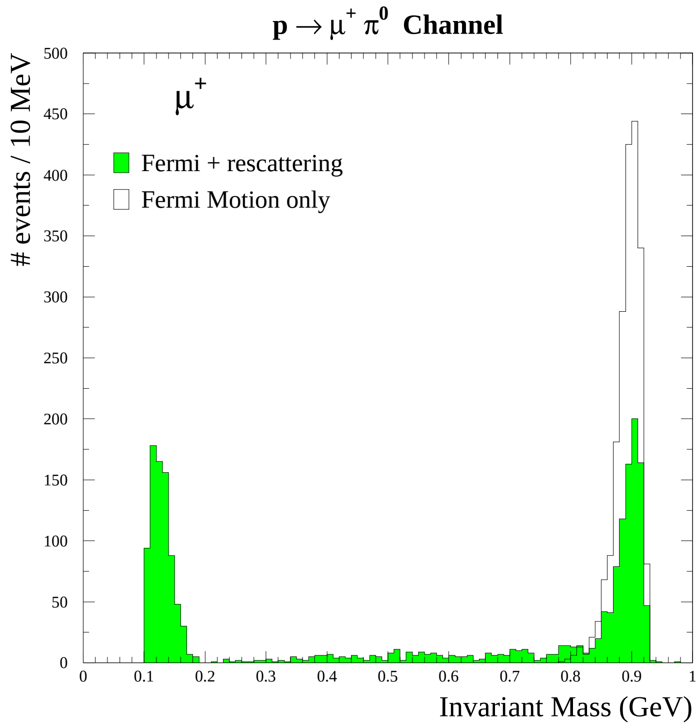
# Coalescence : examples (!!! Available in FLUKA since '96!!!)




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

# Proton decay




An "Exotic" application, highly sensitive to the nuclear model

Reconstructed invariant mass: no recoils, no low energy hadrons

(Figure: proton decay in Ar nuclei, ICARUS experiment)

## Equilibrium particle emission

- ⋆ Evaporation: Weisspokf-Ewing approach
  - ≈ 600 (in test!) possible evaporated particles/states (A≤24)
  - Full level density formula with level density parameter A,Z and excitation dependent
  - Inverse cross-sections with proper sub-barrier
  - Analytic solution for the emission widths (neglecting the $a$ dependence on $U$, taken into account by rejection)
  - Emission energies from the width expression with no approx.
- ⋆ Fission: improved version of the Atchison algorithm
  - Improved mass and charge widths
  - Full competition with evaporation
- ⋆ Fermi Break-up for A≤17 nuclei
  - ≈ 50,000 combinations included with up to 6 ejectiles
- ⋆ $\gamma$ de-excitation: statistical + rotational + tabulated levels

## 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)

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- 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.

## 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 ≈ 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:

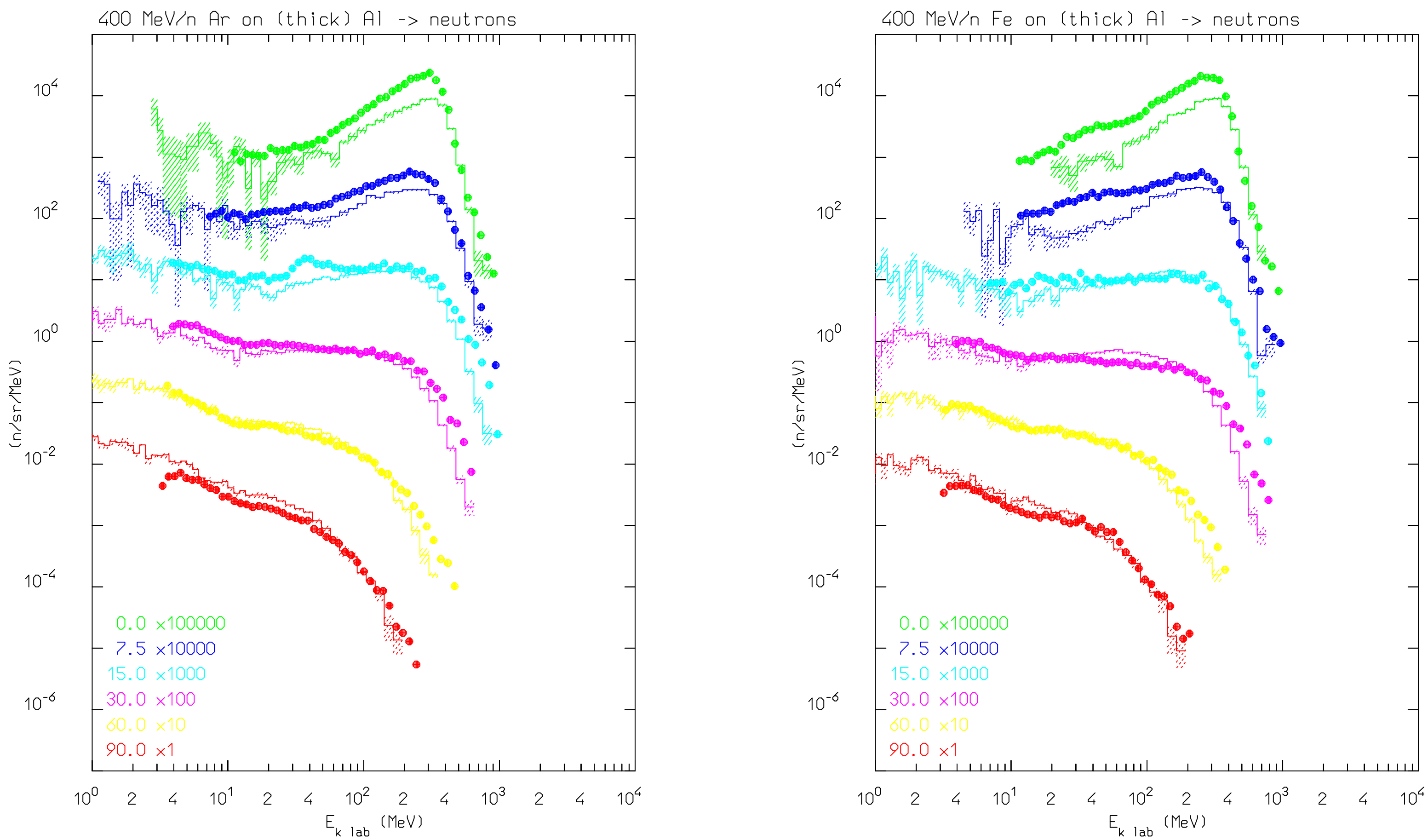
- No evaporation/fragmentation/fission/deexcitation of residuals and fragments
- Energy non-conservation issues, particularly when run in full QMD mode
- No meaningful excitation energy calculation implemented or possible
- Apparently no longer maintained

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

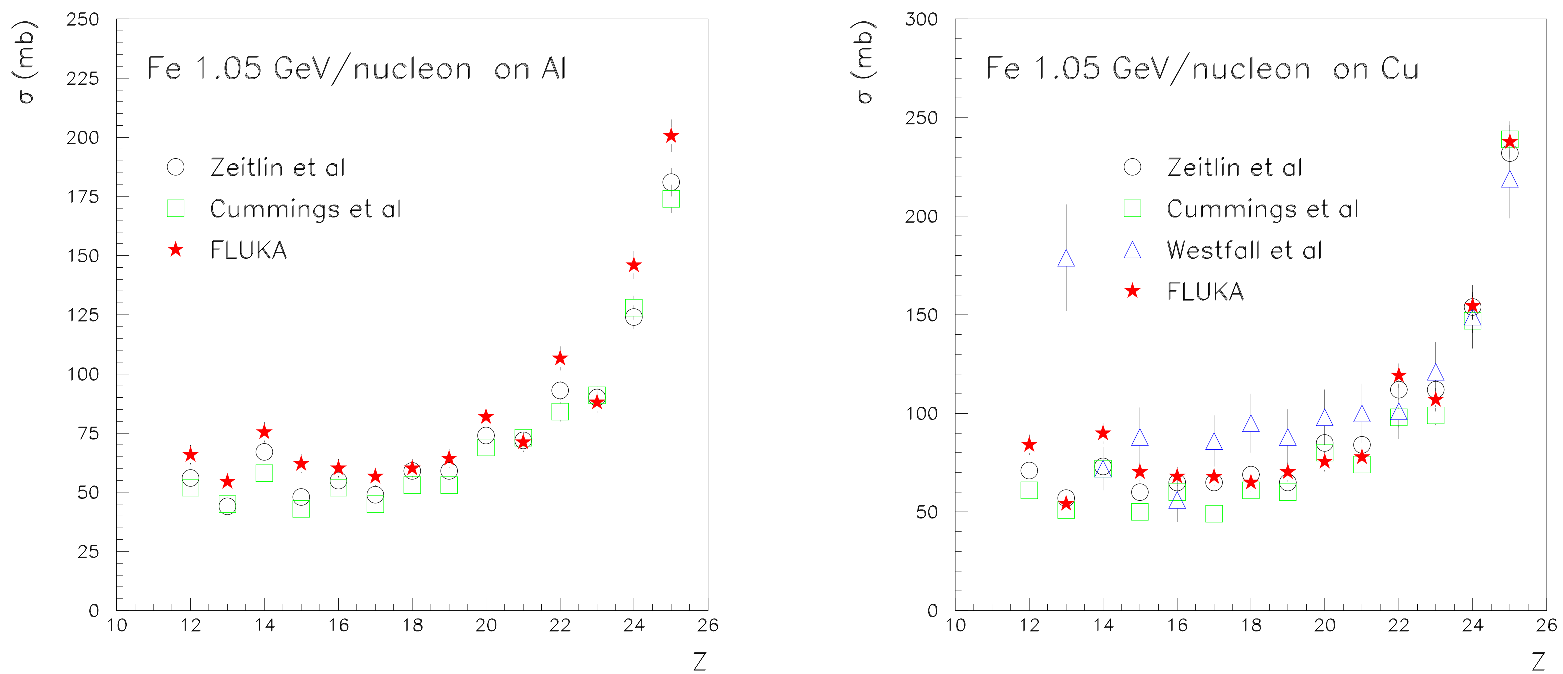
*Current solution for A-A interactions below few GeV/n, waiting for an in-house developed model*

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



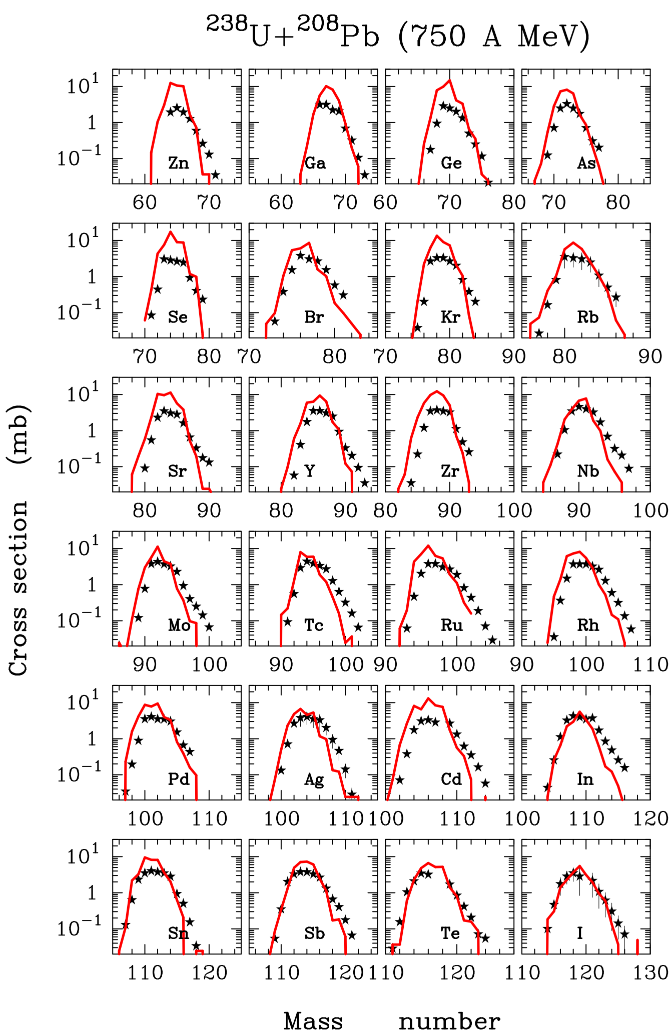

Double differential neutron yield by 400 MeV/n Ar (left) and Fe (right) ions on thick Al targets, histo FLUKA, dots exp. data (PRC62 044615 (2000)).

# 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.

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

Aircraft doses (Frascati, Siegen and GSF)

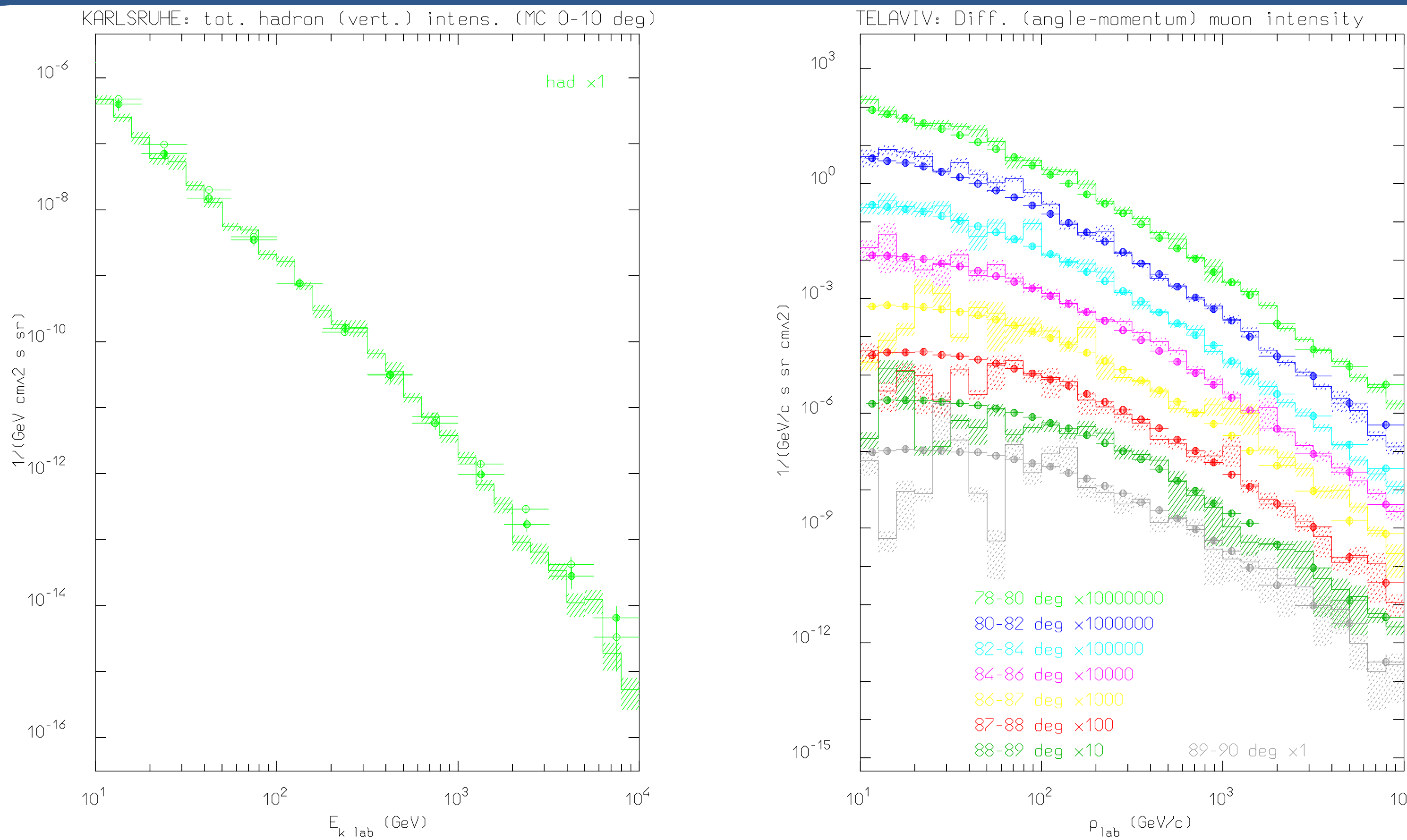
→ Exploiting the reliability of FLUKA Hadronic interaction models

Results

- The first 3Dimensional MC simulation of $\nu$ 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*

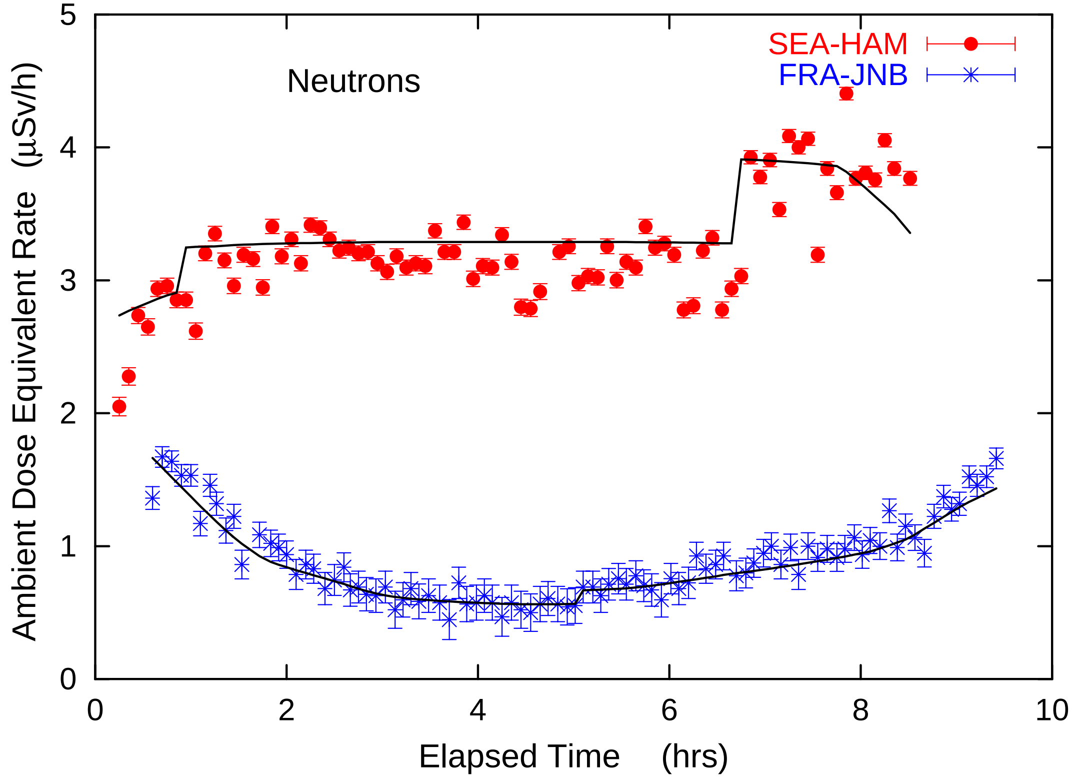
# Hadron/muon fluxes in the atmosphere: examples




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

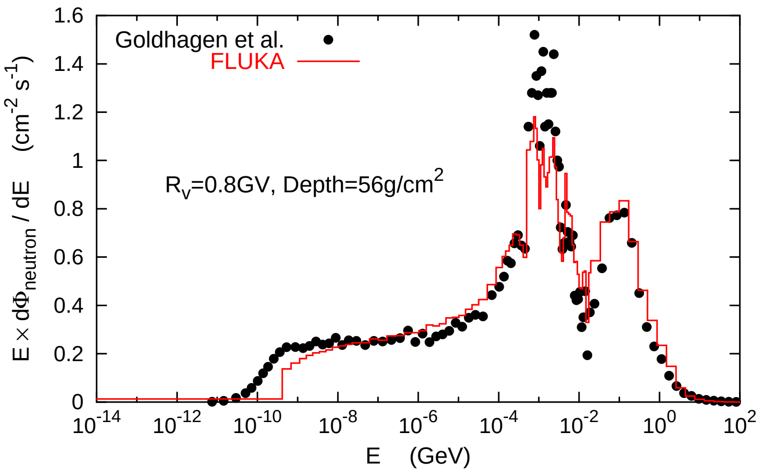
Double differential muon fluxes in Tel Aviv. Data: O.C. Allkofer et al. NPB 259, 1, (1985).

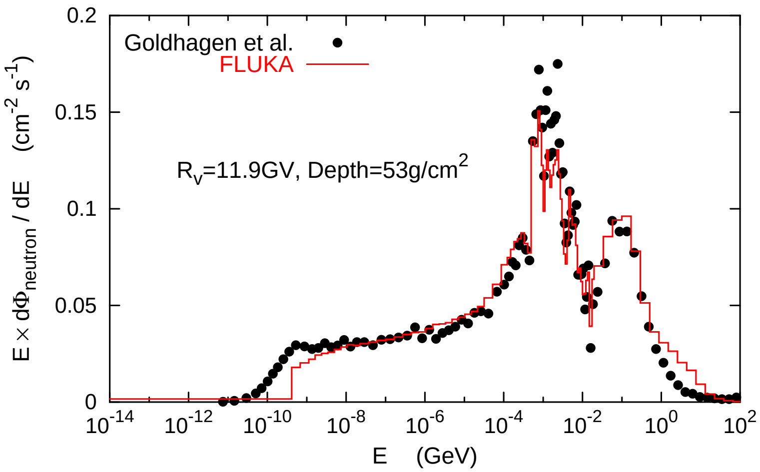
# Hadron/muon fluxes in the atmosphere: examples II (Rad.Prot.Dosim.98 (2002) 367)




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.

## Neutron production: TARC

Experiment

Protons from the CERN PS , 2.5 or 3.57 GeV/c

Lead target , 334 ton , 99.99% purity

64 Instrumentation holes, different detectors to measure neutrons from thermal to MeV

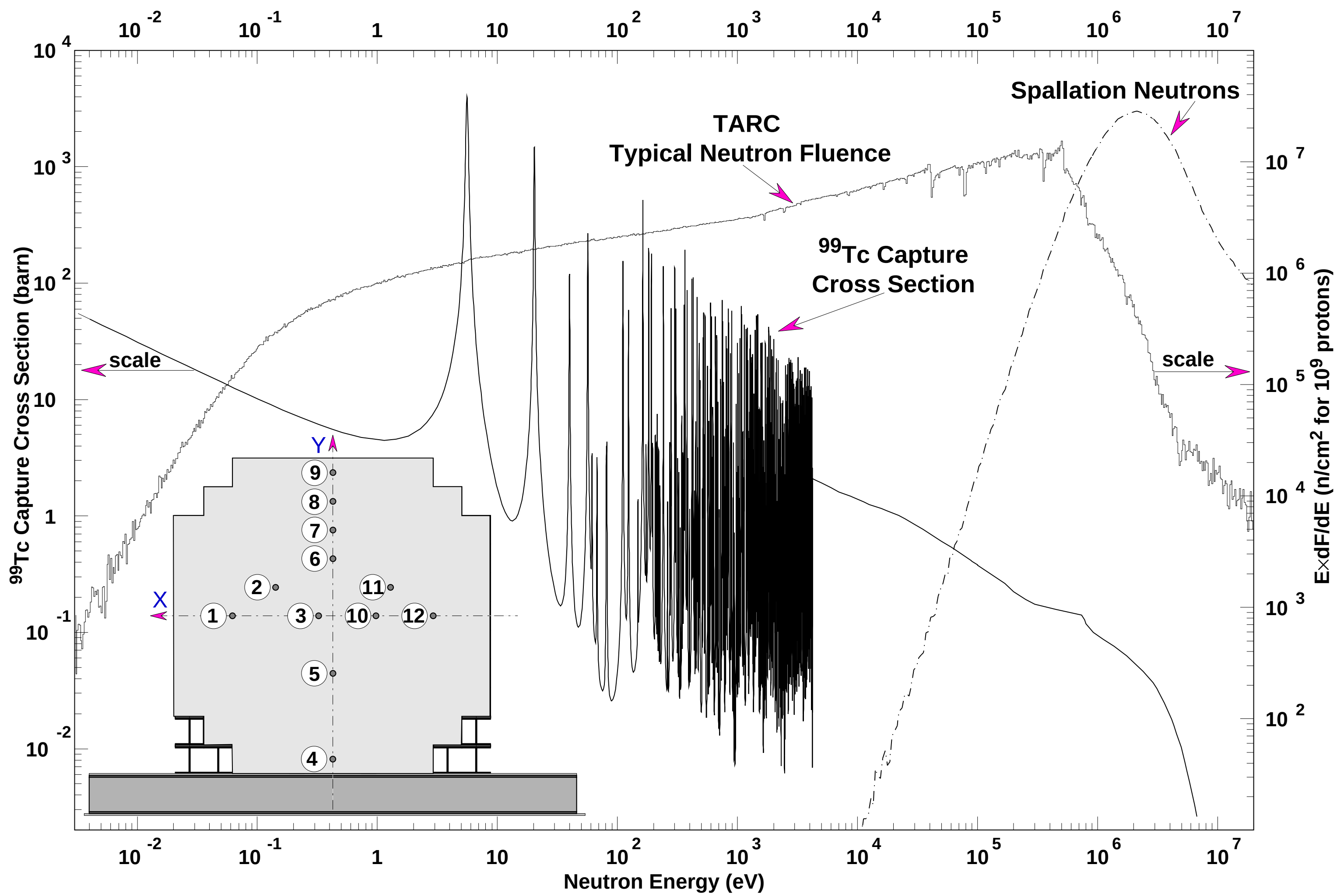
Simulations: EA MC

Spallation production, transport down to 20 MeV : FLUKA

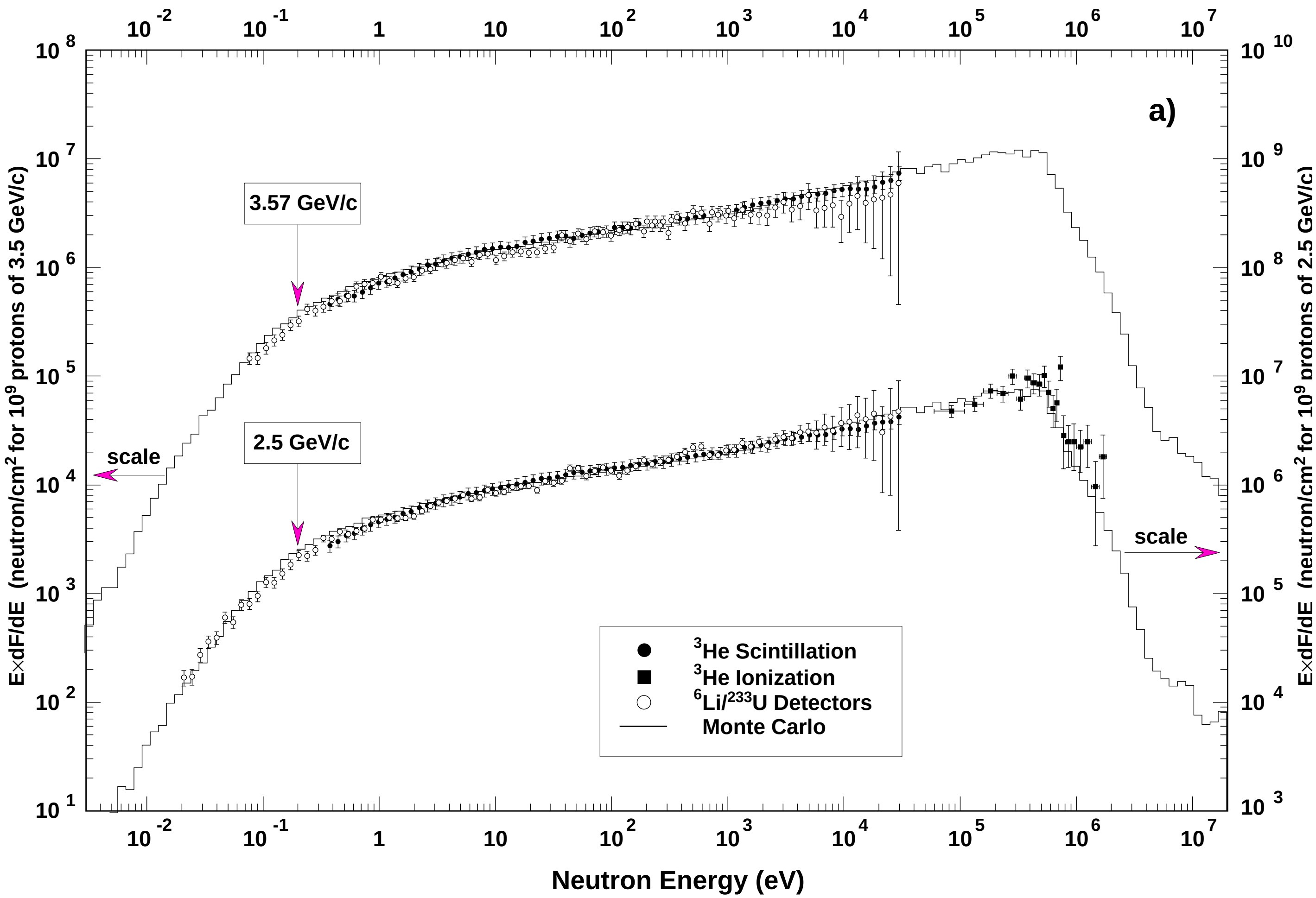
Neutron transport and interactions below 20 MeV and target evolution: new code EA-MC (C.Rubbia et al)

Refs.: PLB458 (1999) 167, NIMA478 (2002) 577

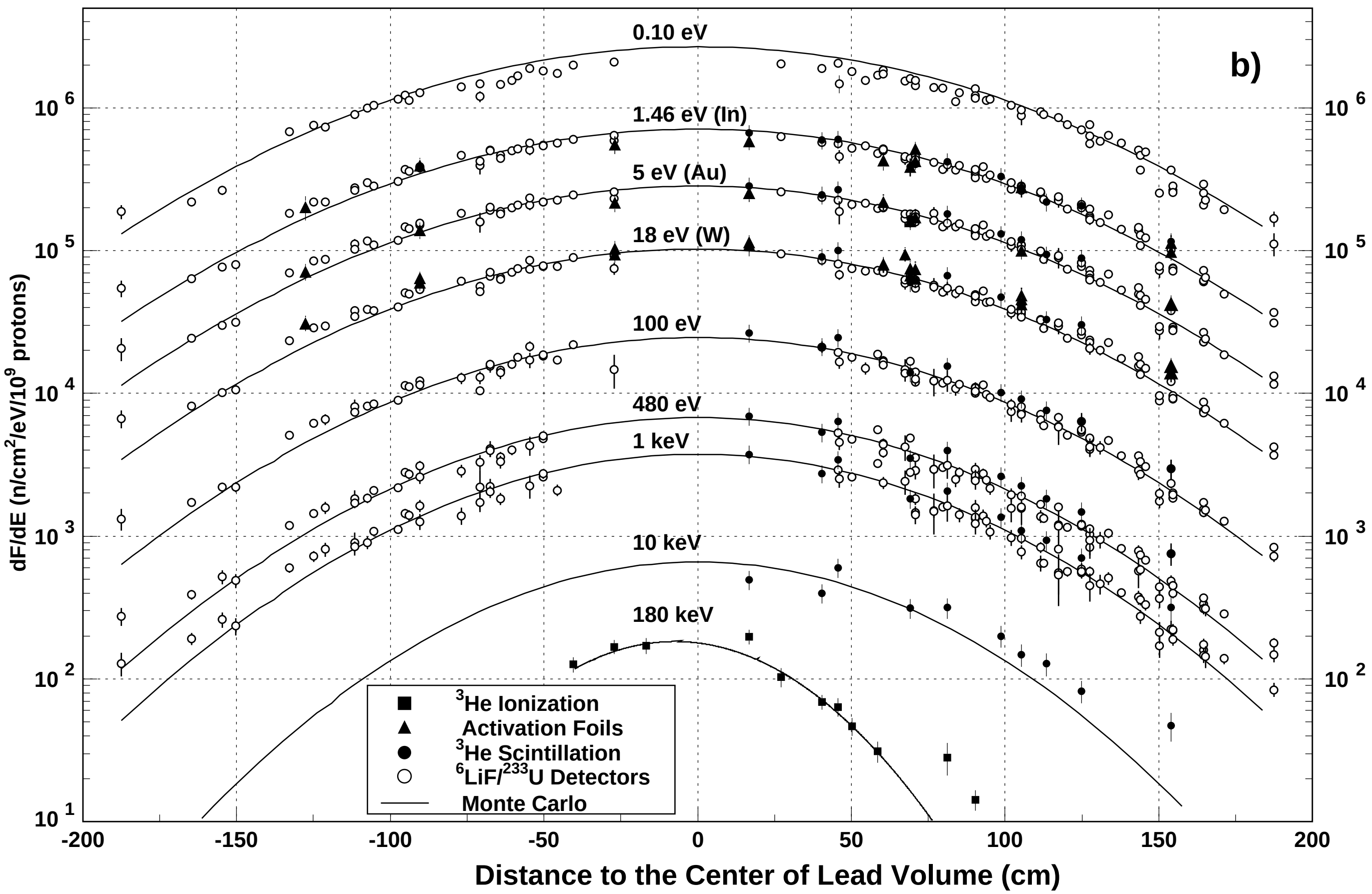
# Neutron production examples: TARC (PLB458 167, NIMA478 577)



# Neutron production examples: TARC (PLB458 167, NIMA478 577)



# Neutron production examples: TARC (PLB458 167, NIMA478 577)



## 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
- Recently: ability to follow the whole shower induced by whichever ion on whichever target, with sound interaction physics above 100 MeV/n
- Rich development program for the future:
  - PEANUT and new QMD in place of the RQMD-2.4 "temporary" solution
  - BME model covering the low energy side

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