FLUKA: status and prospective for Hadronic Applications

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Topics

- General description of FLUKA
- Recent developments
  - Improvements to hadronization — Comparison with SPY; the WANF neutrino beam; the CNGS neutrino beam
  - Charm production
  - Kaon interactions
  - Improvements to evaporation — effects on residual nuclei production
  - Neutrino interactions — Neutrino-nucleus interactions and NOMAD
- The atmospheric neutrino calculations
- The G4 geometry interface
- Heavy ion interactions: work in progress

FLUKA

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Interaction and transport MonteCarlo code.

- Hadron-hadron and hadron-nucleus interactions 0-20 TeV
- Nucleus-nucleus interactions 0-10000 TeV/n: *under development !!!*
- Electromagnetic and μ interactions 0-100 TeV
- Charged particle transport - ionization energy loss
- Neutron multigroup transport and interactions 0-20 MeV
- Analogue or biased calculations

The FLUKA hadronic models

Hadron-Nucleon

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

Hadron-Nucleus

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

Evaporation/Fission/Fermi break-up

γ deexcitation

from DPM:

- Number of chains
- Chain composition
- Chain energies and momenta
- Diffractive events

Almost No Freedom

Chain hadronization

- Assumes chain universality
- Fragmentation functions from hard processes and e^+e^-
- Transverse momentum from e^{-bm_T} behaviour
- Mass effects at low energies

The same functions and (few) parameters for all reactions and energies

Recent improvements in the high energy model

G. Collazuol, A. Ferrari, A. Guglielmi and P.R. Sala, NIM A 449 (2000), 609

The DPM + Glauber model embedded into old FLUKA versions (and in *GEANT-FLUKA*) had important limitations:

- Glauber cascade described at an elementary level;
- all resonances assumed on mass shell;
- coarse chain hadronization, and no particular attention to threshold and finite mass effects;
- isospin conservation not enforced at each individual hadron production step;
- transverse motion reasonable but still far from satisfactory;
- simplified description of diffractive processes.

Recent improvements in the high energy model

All improved along the years:

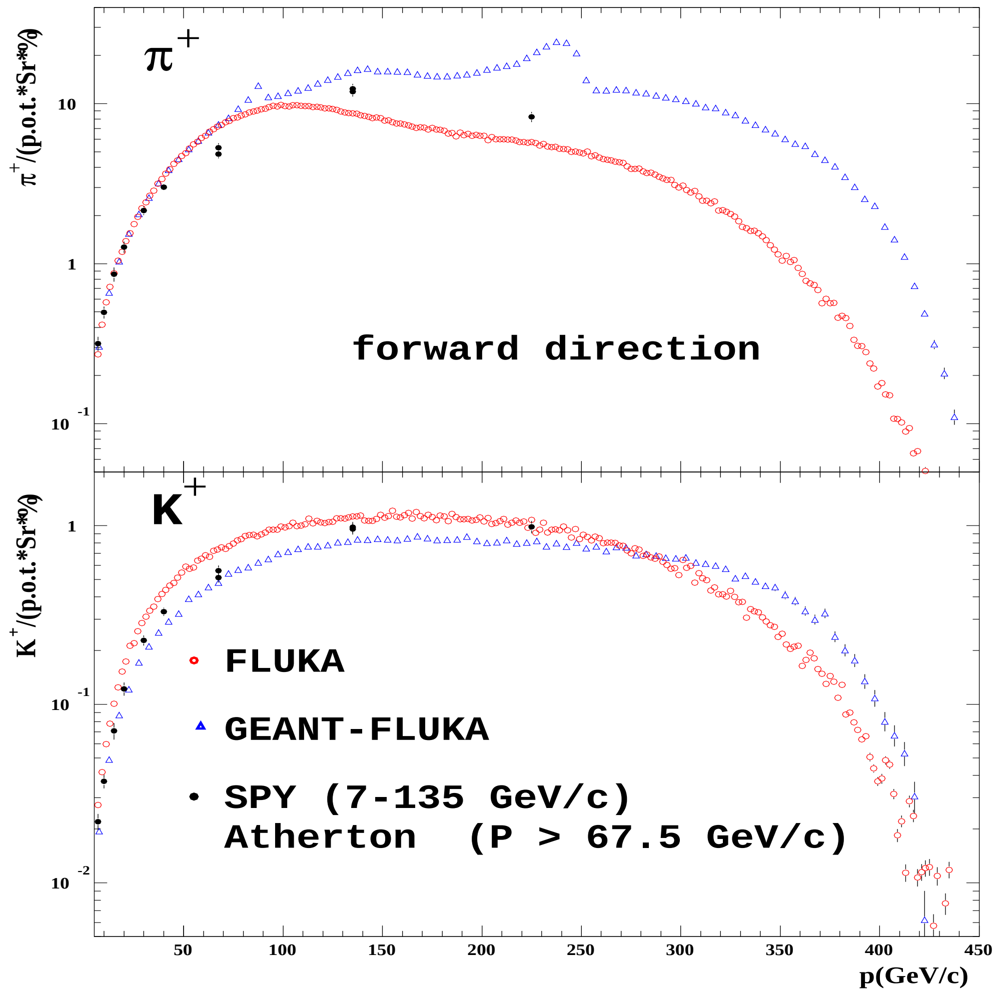
Very old reference : FLUKA92 and GEANT-FLUKA

Many versions in between: most already done in 1995

Latest optimization: chain hadronization

- Threshold and finite mass effects checked against low energy data (chains with few had.)
- Fragmentation functions checked vs. 16-450 GeV h-N and h-A data
- Constraint: hadron multiplicity at 200 GeV.
- Balanced optimization: better SPY agreement could be achieved, spoiling low energy data.

Improvements: SPY I : forward yield



π^+ and K^+

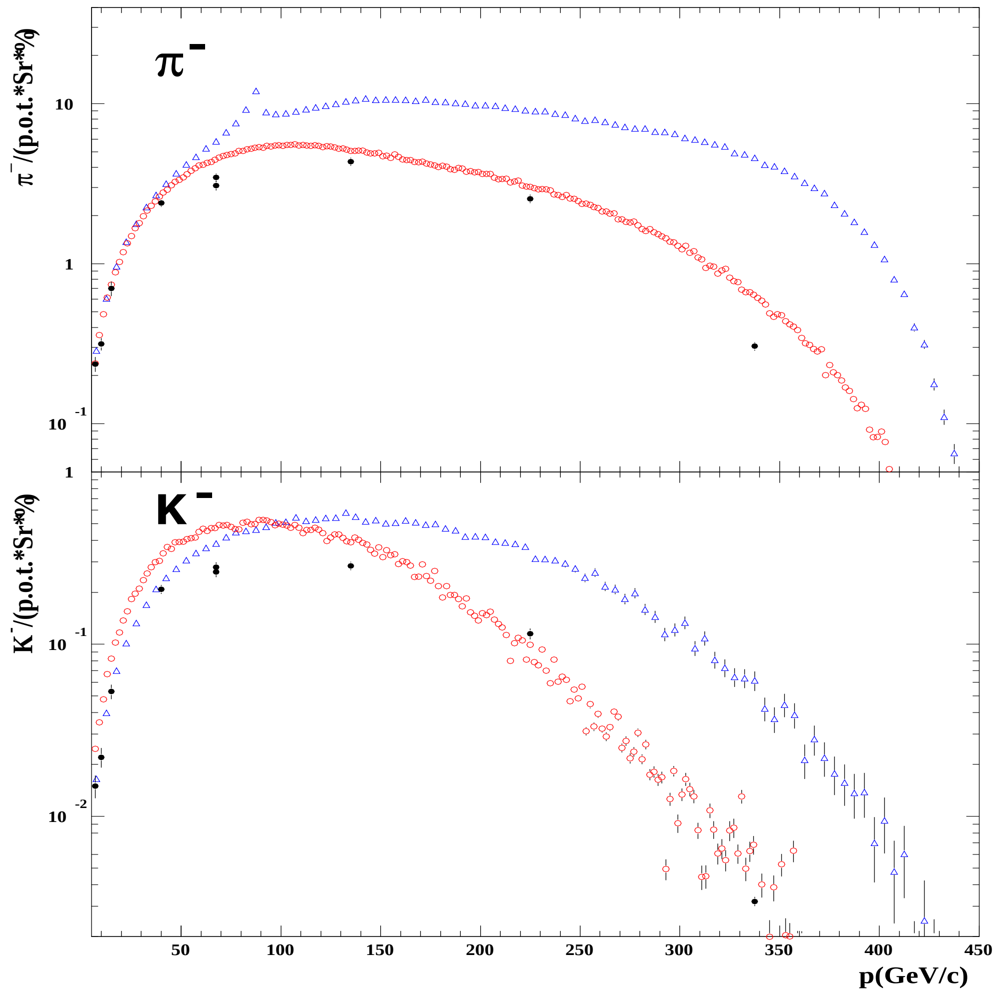
$d^2N\,/\,(dp/p\,d\Omega)$

100 mm Be target,

$\theta \leq 0.2$ mrad

SPY ($P \leq 135$ GeV/c, •) and Atherton et al. ($P \geq 67.5$ GeV/c,) compared with the *FLUKA* and the *GEANT-FLUKA* predictions.

Improvements: SPY II : forward yield



π^- and K^-

$d^2N\,/\,(dp/p\,d\Omega)$

100 mm Be target,

$\theta \leq 0.2$ mrad

SPY ($P \leq 135$ GeV/c, ●)

and Atherton et al.

($P \geq 67.5$ GeV/c,)

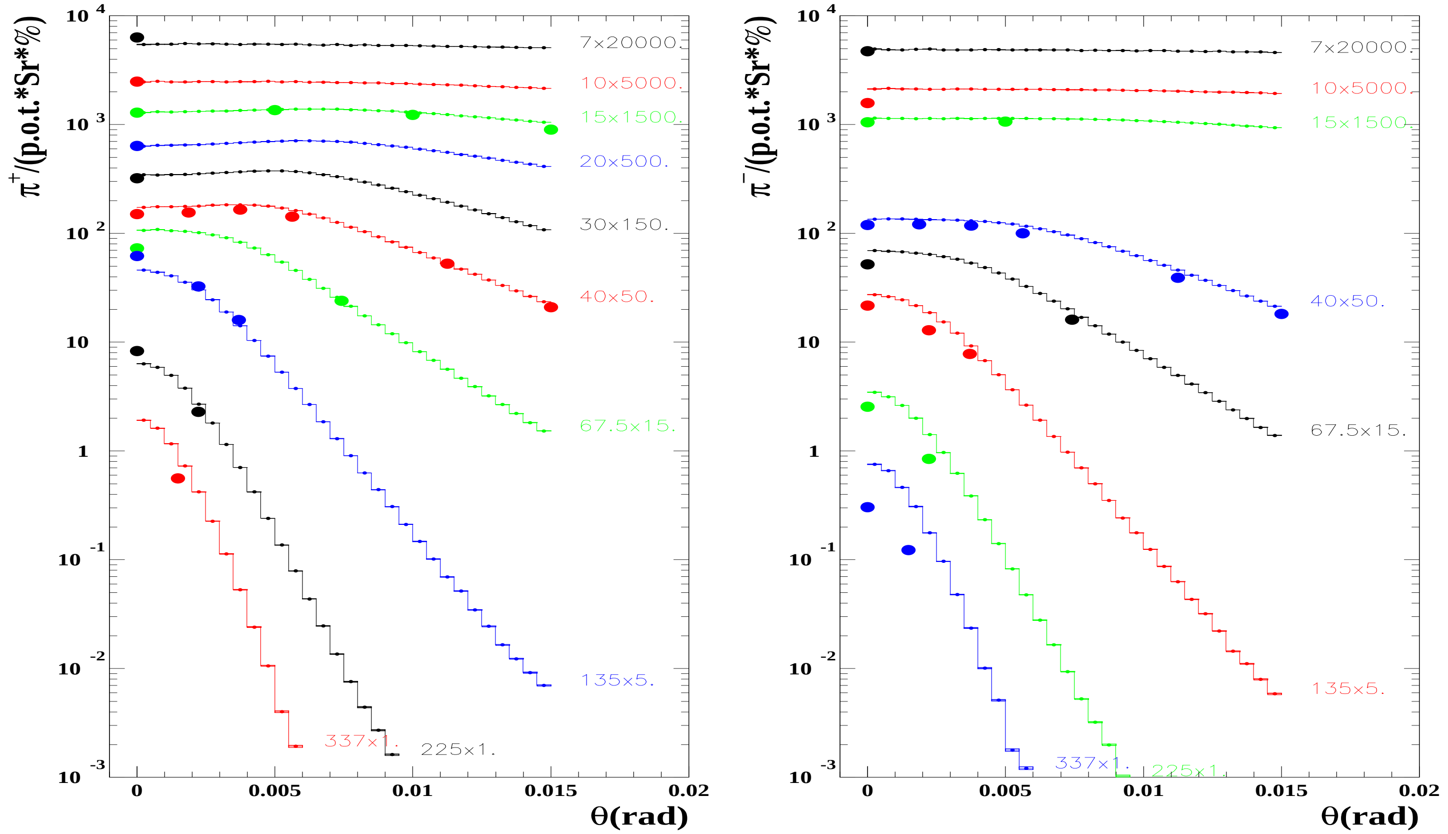
compared with the

FLUKA and the

GEANT-FLUKA

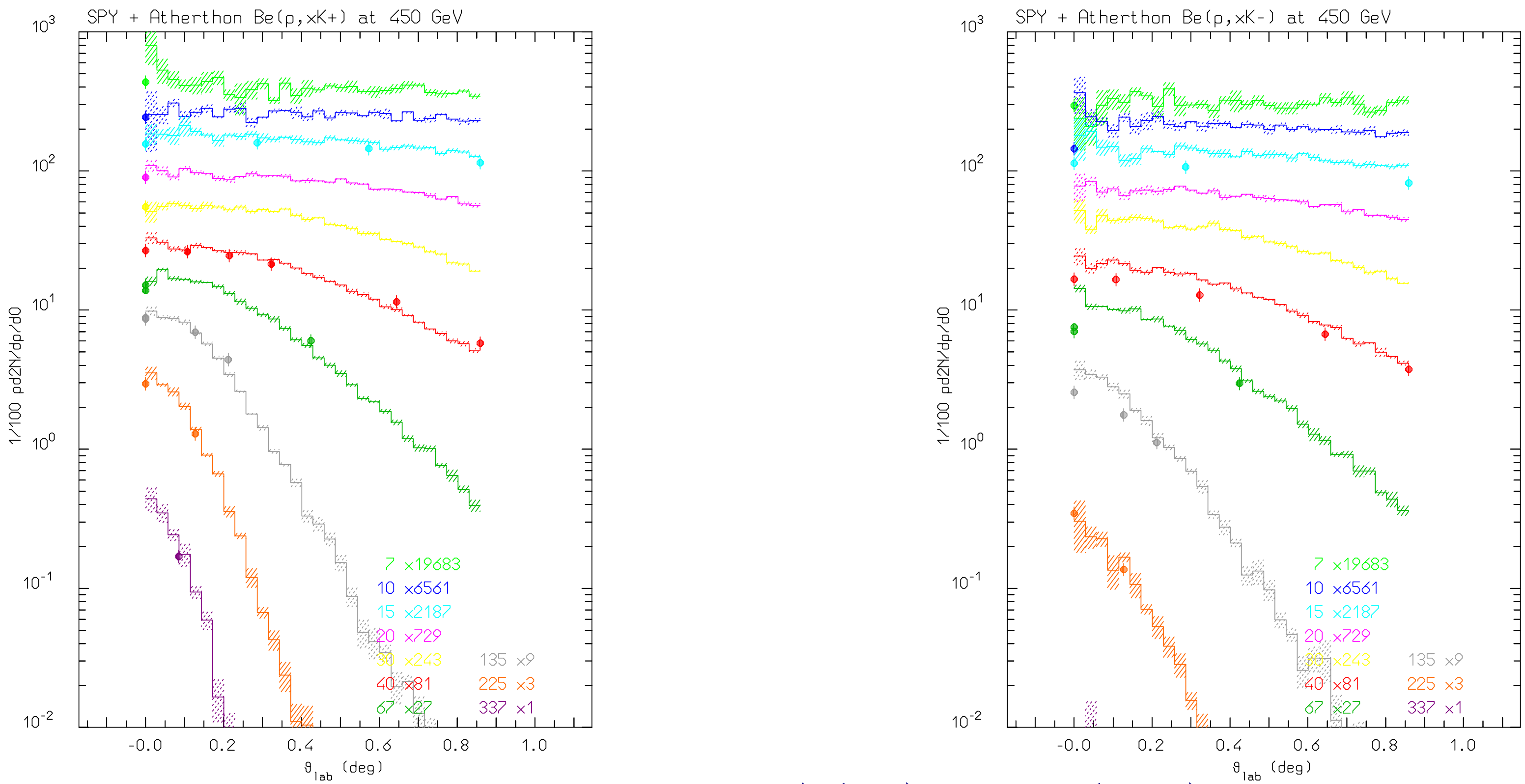
predictions.

Comparison with SPY I



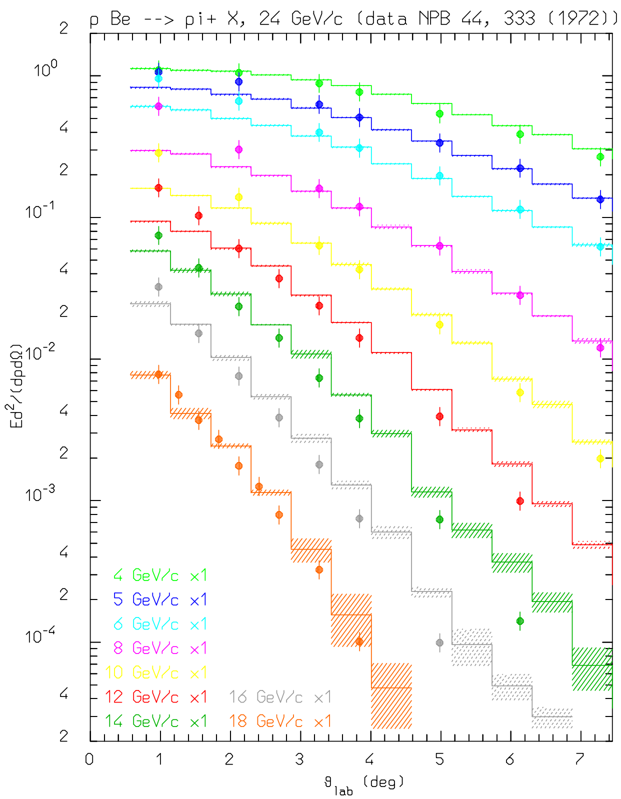
Double differential cross section for π^+ (left) and π^- (right) production for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80–07, G. Ambrosini et al. PL B425 208 (1988)).

Comparison with SPY II

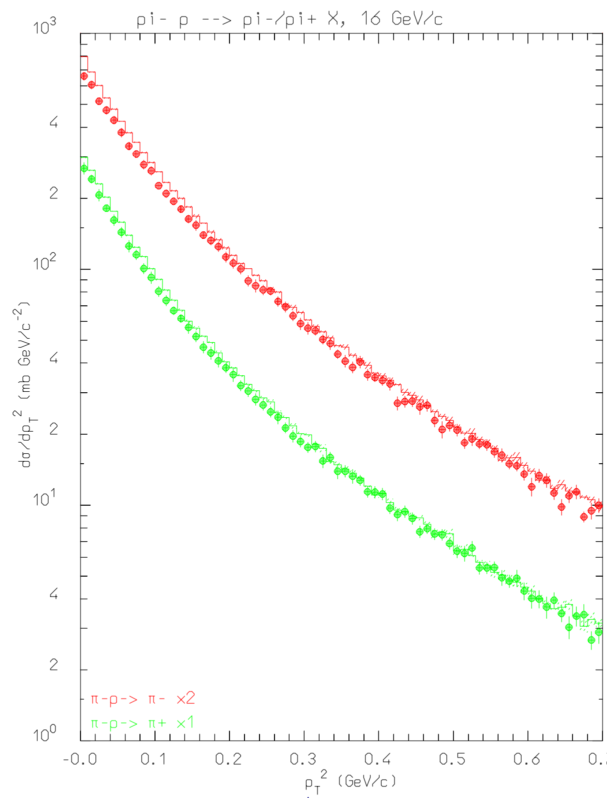


Double differential cross section for K^+ (left) and K^- (right) production for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80–07, G. Ambrosini et al. PL B425 208 (1988)).

Nonelastic hA interactions at high energies: examples IV



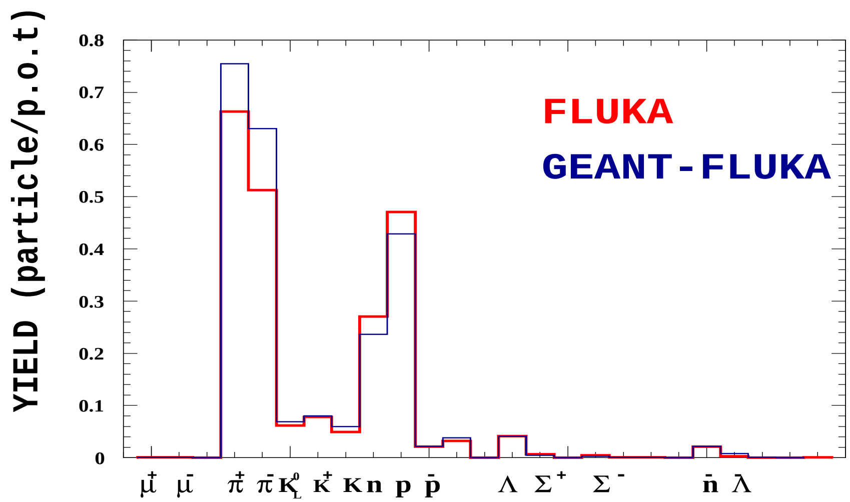
Invariant cross section distribution for π^+, 24 GeV/c protons on Be (T.Eichten et al. NPB 44, 333 (1972)).



p_T spectra of π^+ and π^- produced by 16 GeV/c π^- on H. (M.E Law et al. LBL80 (1972)).

Particle production in T9 Be target

($\Delta\Omega < 0.1$ **mSr E > 5 GeV)**



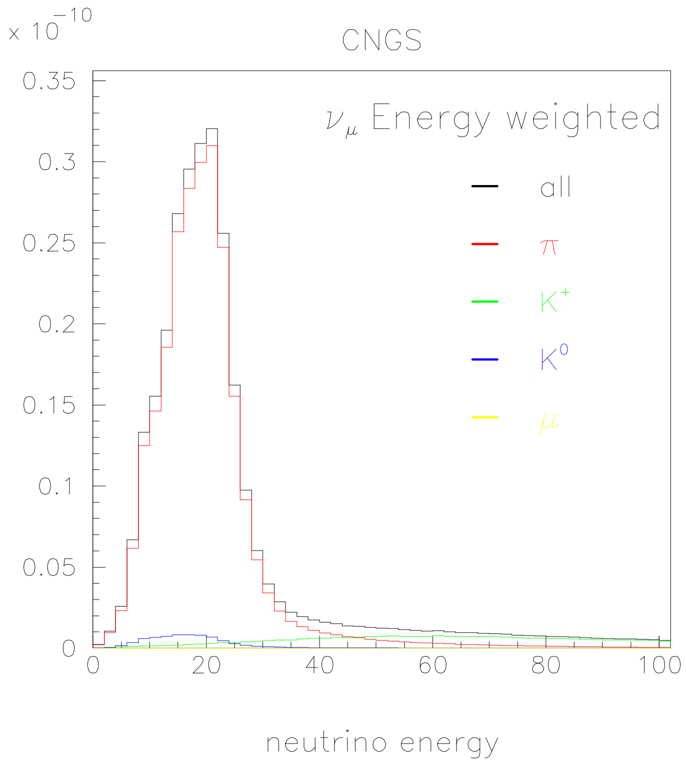
The particle spectrum at the end of T9 by FLUKA (full line) and GEANT-FLUKA (dashed line) with $P \geq 5$ GeV/c and $\theta \leq$ 10 mrad; neutrinos are not quoted.

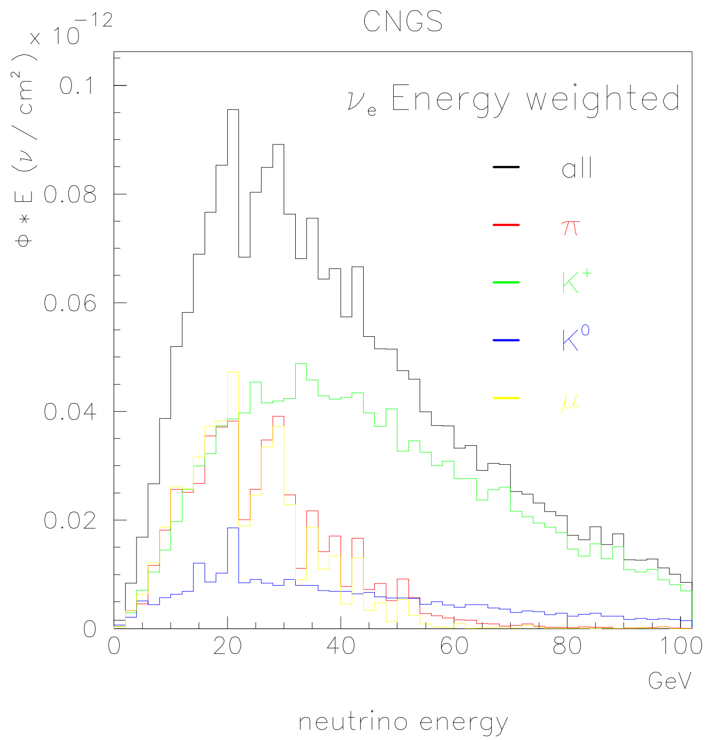
Improvements: effect on WANF

Intensity, mean energy and relative abundances for ν fluxes at NOMAD fiducial area as calculated with the $FLUKA$ and $GEANT$-$FLUKA$ generator.

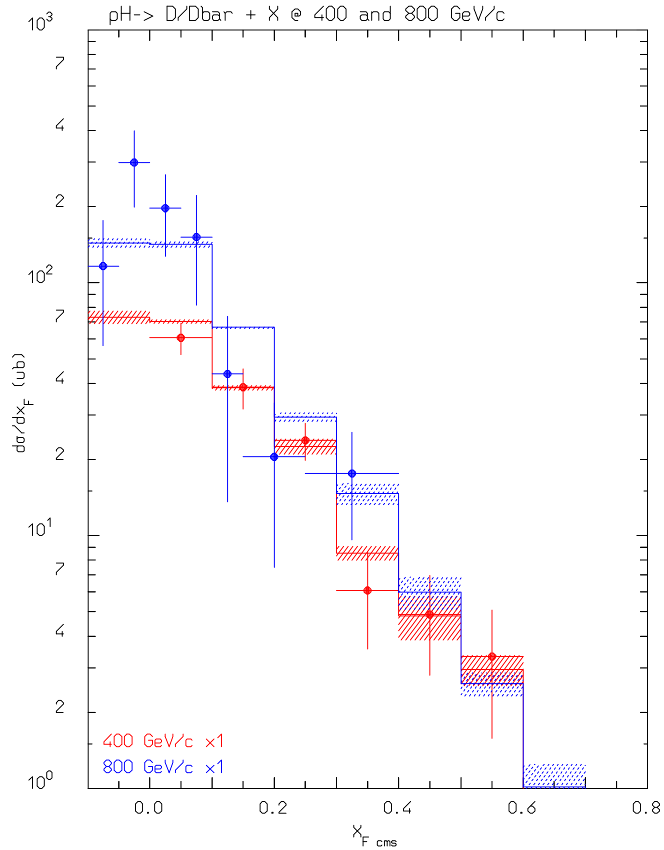
	Neutrino	intensity $[\nu/pot]$	$< E_\nu >$ $[GeV]$	relative abb.
$FLUKA$	ν_μ	1.11×10^{-2}	23.5	1.0
	$\overline{\nu}_\mu$		19.2	0.0627
	ν_e		37.1	0.0094
	$\overline{\nu}_e$		31.3	0.0024
$GEANT$-$FLUKA$	ν_μ	1.25×10^{-2}	23.5	1.0
	$\overline{\nu}_\mu$		23.1	0.0702
	ν_e		36.7	0.0092
	$\overline{\nu}_e$		34.2	0.0025

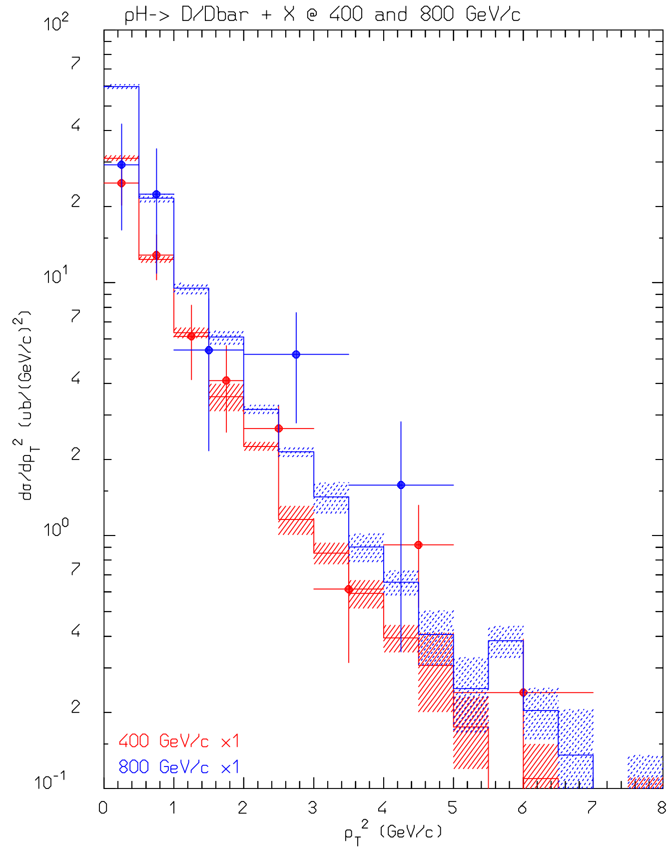
Nice agreement with experiment → confidence in prediction for CNGS





Charm production





Charm x_F (left) and p_T (right) distributions in p-p at 400(red) and 800(blue) GeV/c.
Dots: data from Phys. Rev.Lett. 61(1988)2185 and Z.Phys.C41(1988)191

Kaon-nucleus interactions at medium-low energies

ICARUS : proton decay
LHC: penetrating background
LHC: B physics

Treated in the PEANUT framework

Full exploitment of all nuclear effects
Possibility to rise the PEANUT upper energy limit $\rightarrow$ future coverage of the whole energy range

scarce exp. data

Kaon-nucleon interactions at medium-low energies

$K^+ \quad K^0$

No low mass S=1 baryons → weak K^+N interaction

only elastic and charge exchange up to ≈ 800 MeV/c (π prod. threshold)

Easy description in terms of phase shift analisys

Good probe for nuclear medium

In PEANUT:

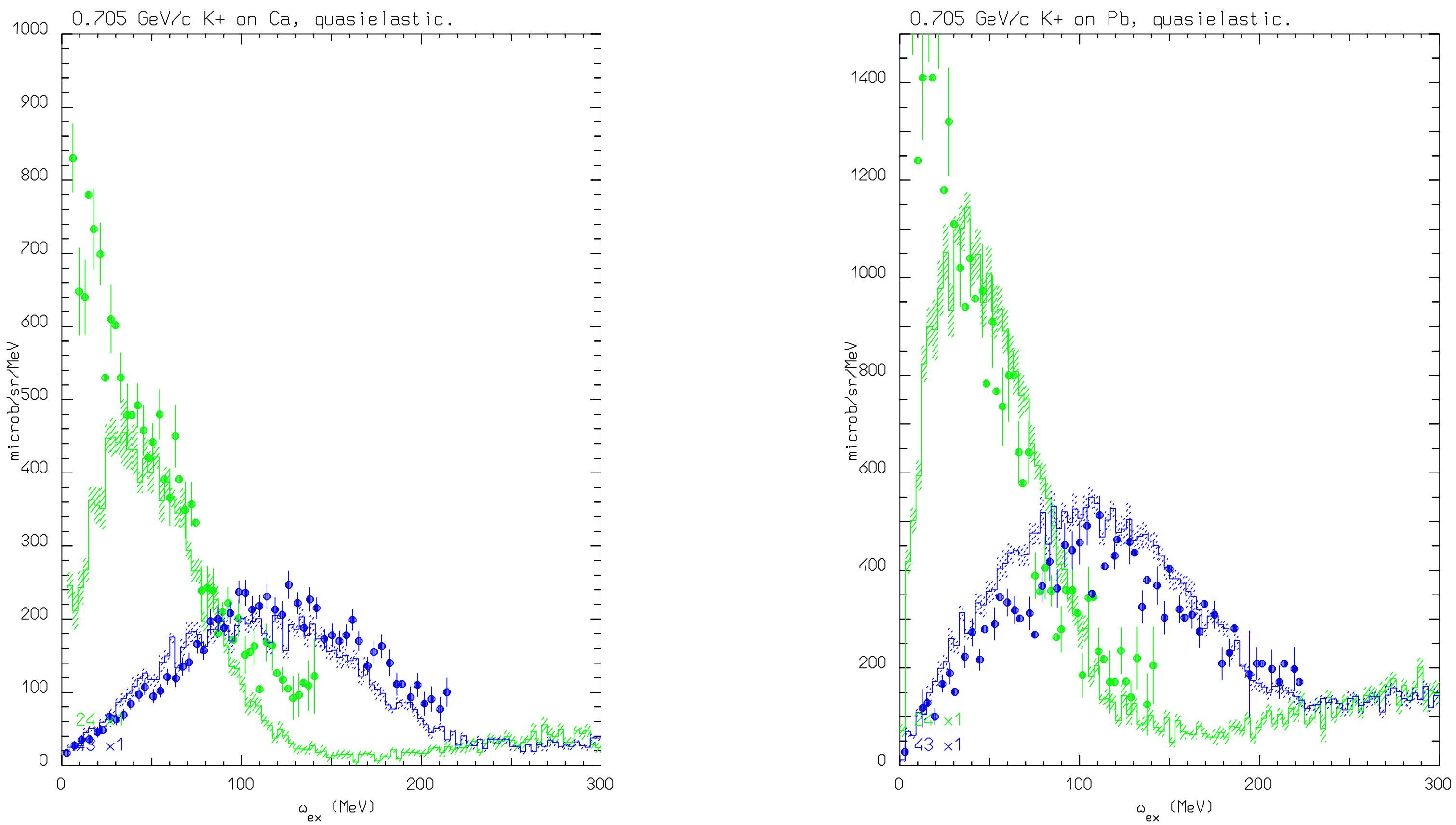
Standard partial wave expansion, parameters from the BGRT analisys: up to 1.5 GeV/c, s,p and d partial waves. [1].

Isospin relations to link different charge states

Mass differences taken into account (charge exchange)

[1] G. Giacomelli et al., NPB 71 (1974) 138

Positive Kaons : example



$(K^+, K^{+\prime})$ on Ca(left) and Pb(right) vs residual excitation, 705 MeV/c, at 24° and 43°. Histo:FLUKA, dots: C.M.Kormanyos et al,Phys. Rev. C51, 669 (1995)

K^- $\bar{K}^0$ -nucleon interactions at medium-low energies

Plenty of S=1 baryonic resonances at low energies

$\Lambda\pi$ and $\Sigma\pi$ channels already open at rest

$\rightarrow$ Strong K^-N interaction

Multichannel analisys needed

Many partial waves contribute

Kaon nuclear potential non-negligible

Hyperons can be bound in nuclei

In PEANUT: in progress

Multichannel partial wave expansion

s wave at low momenta [2];

$0 < l < 5$ up to 1.8 GeV/c [3]

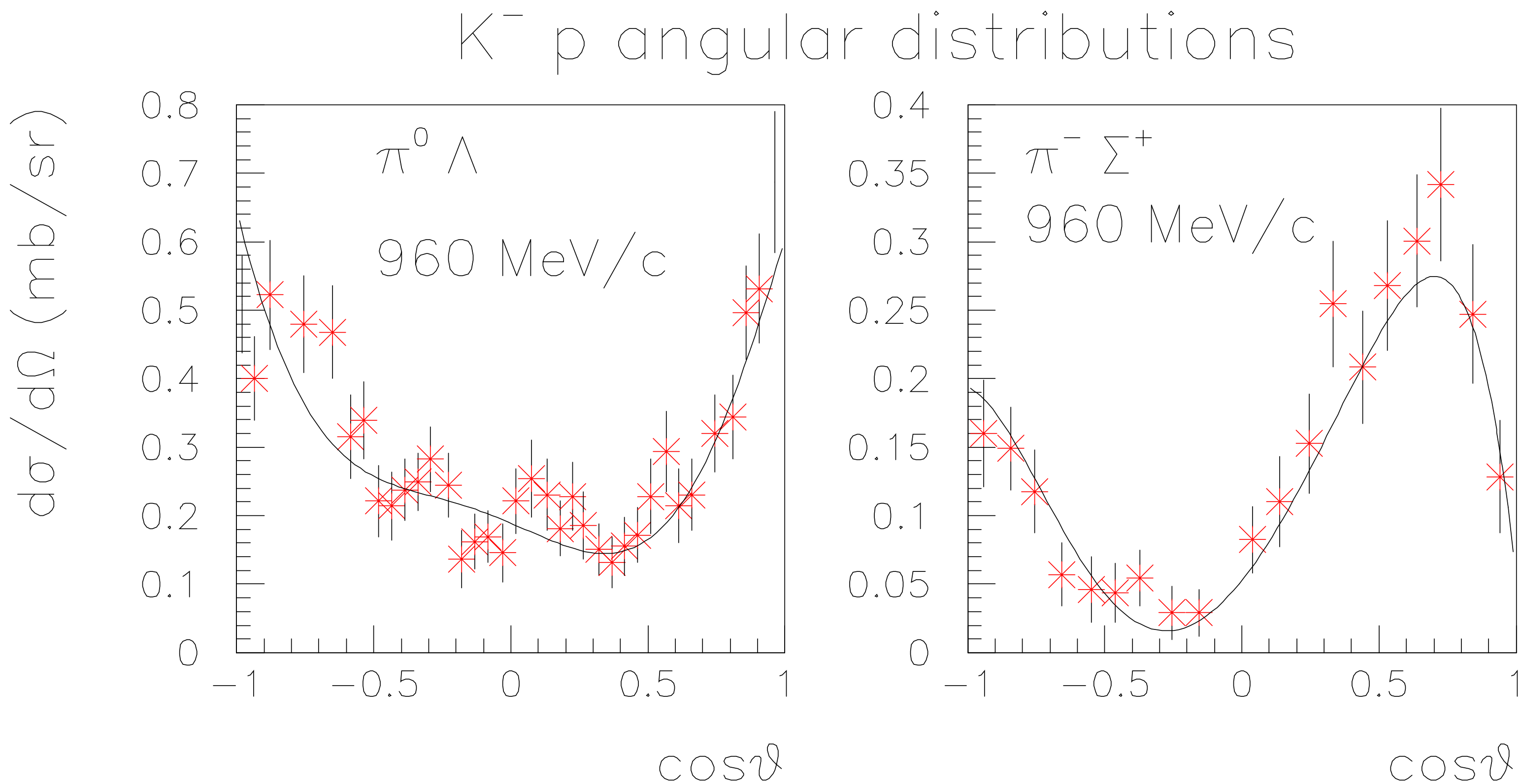
Isospin relations to link different charge states

Mass differences taken into account (charge exchange)

[2] A.D. Martin, Nuc.Phys. B179 (1981) 33

[3] G.P. Gopal et al., Nuc. Phys. B119(1977),362

Kaon-nucleon interactions examples



Line: FLUKA, partial wave expansion, symbols: exp. data from B.R. Martin and M.K. Pidkok, Nucl. Phys. B126 (1977) 266

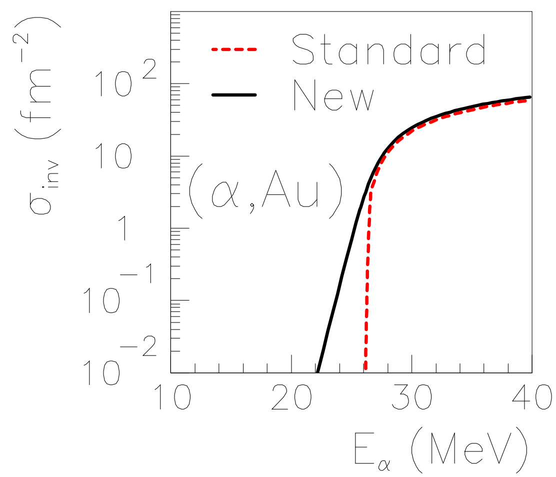
Weisskopf-Ewing evaporation

$$P_j(E)dE = \frac{(2S_j+1)m_j}{\pi^2\hbar^3}\sigma_{\text{inv}}\frac{\rho_f(U_f)}{\rho_i(U_i)}EdE \qquad (1)$$

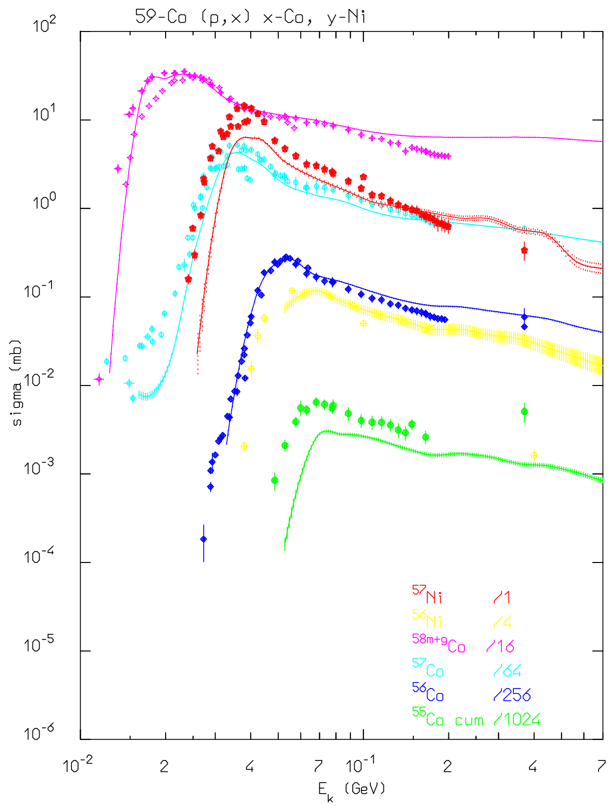
- Improved state density $\rho = \exp(2\sqrt{aU})/U^{\frac{5}{4}}$
- No Maxwellian approximation for energy sampling
- γ competition in progress

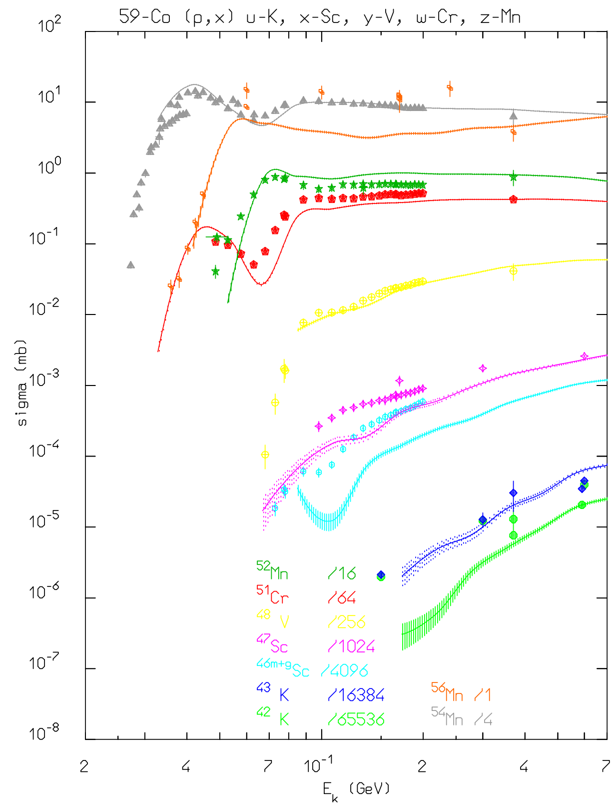
- Sub-barrier emission:

$$\sigma^x_{inv} = (R+\bar{\lambda})^2\frac{\hbar\omega_x}{2E}\ln\left[1+e^{\frac{2\pi(E-V_c)}{\hbar\omega_x}}\right]$$



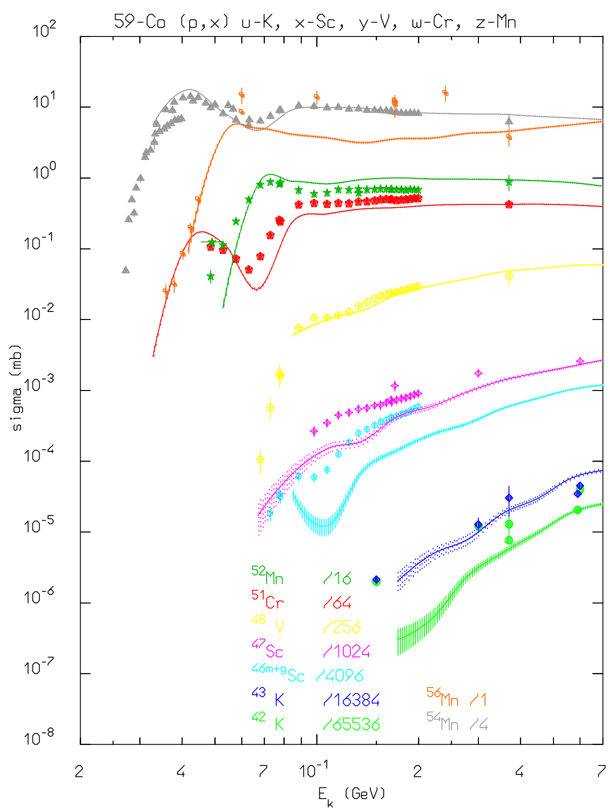
Residual nuclei predictions: examples

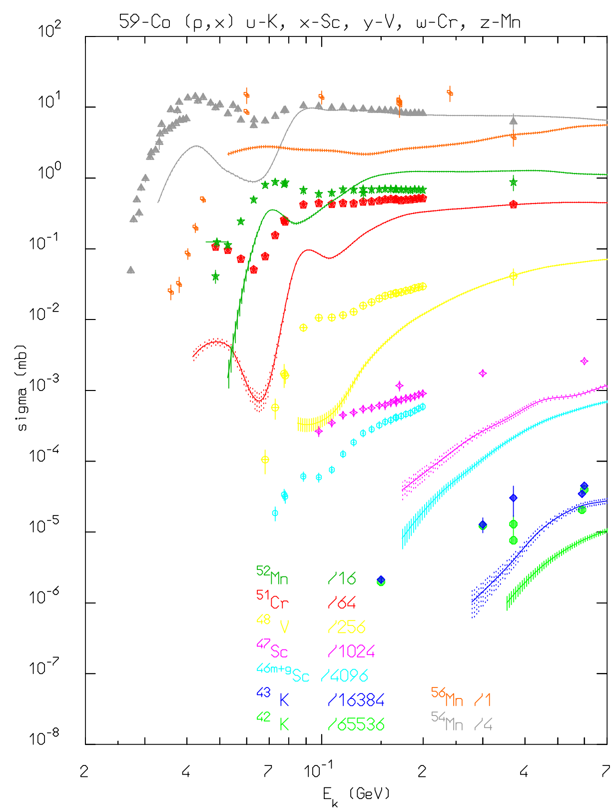




Comparison between computed and measured (A.S. Iljinov et al., Landolt-Börnstein, **Vol. 13a** (1991)) isotope production by protons on natural Cobalt

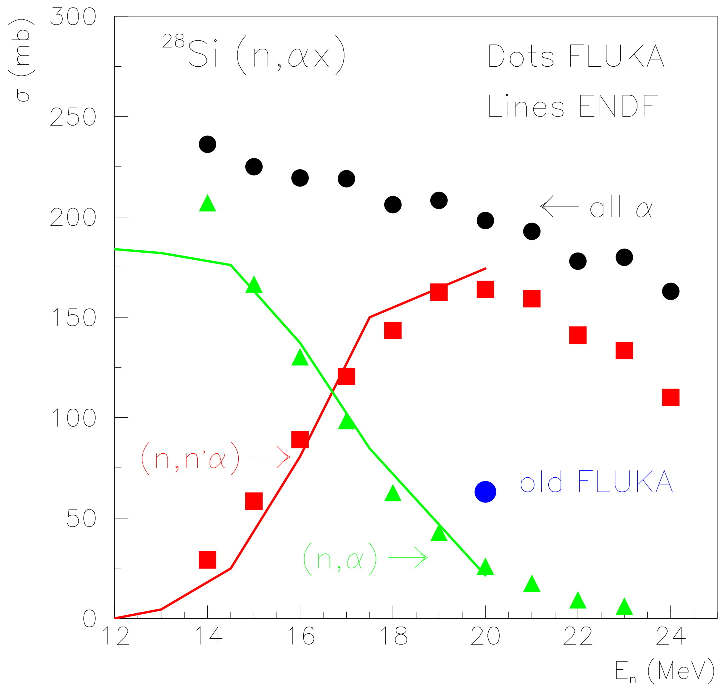
Residual nuclei predictions: "new" vs "old" evap.





Comparison between isotope yields computed with the new (left) and (right) evaporation model in FLUKA

Residual nuclei predictions: "new" vs "old" evap.



A practical case:
Si damage
(a pity that CMS [a] still uses
a very old version)
Message to users:
Always use updated versions

[a]M. Huhtinen and Faccio, NIM A450 (2000)

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

Radio nuclide	$T_{1/2}$	Specific Activity (Bq/g) Exp.	FLUKA	(%)	Ratio F/E
^{46}Sc	83.8 d	0.13	0.065	12	0.5
^{48}V	15.97 d	0.31	0.52	7	1.7
^{51}Cr	27.7 d	4.12	2.7	5	0.65
^{52}Mn	5.6 d	0.17	0.74	6	4.3
^{54}Mn	312.2 d	3.54	2.9	2	0.82
^{59}Fe	44.5 d	0.028	0.0088	27	0.31
^{56}Co	77.7 d	0.29	0.46	7	1.6
^{57}Co	271.8 d	1.3	1.1	4	0.85
^{58}Co	70.9 d	2.65	1.4	3	0.52
^{60}Co	5.27 y	0.18	0.085	21	0.47
^{95}Nb	34.9 d	0.038	0.013	27	0.34

Stainless Steel sample on the LEP electron dump. The exp. points have a systematic error of ≈20%(A.Fassò et al. CERN-TIS-99-011-RP-CF/SLAC-PUB-8214 and CERN-TIS-99-012-RP-CF/SLAC-PUB-8215)

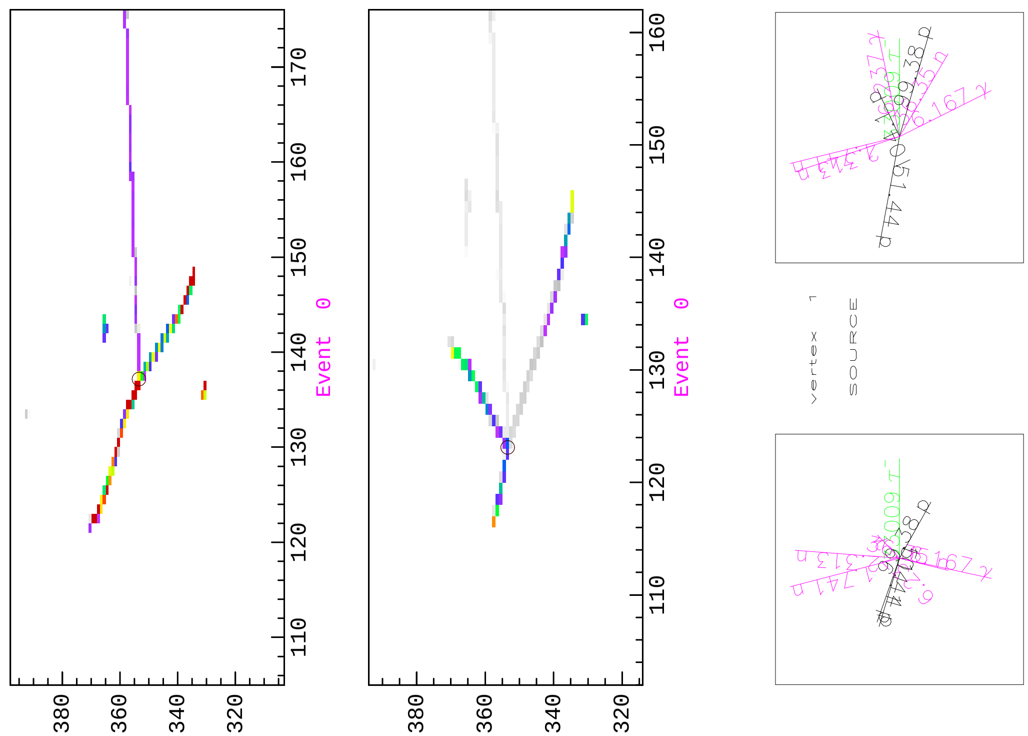
Neutrino interactions in PEANUT: the *NUX-FLUKA* event generator

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

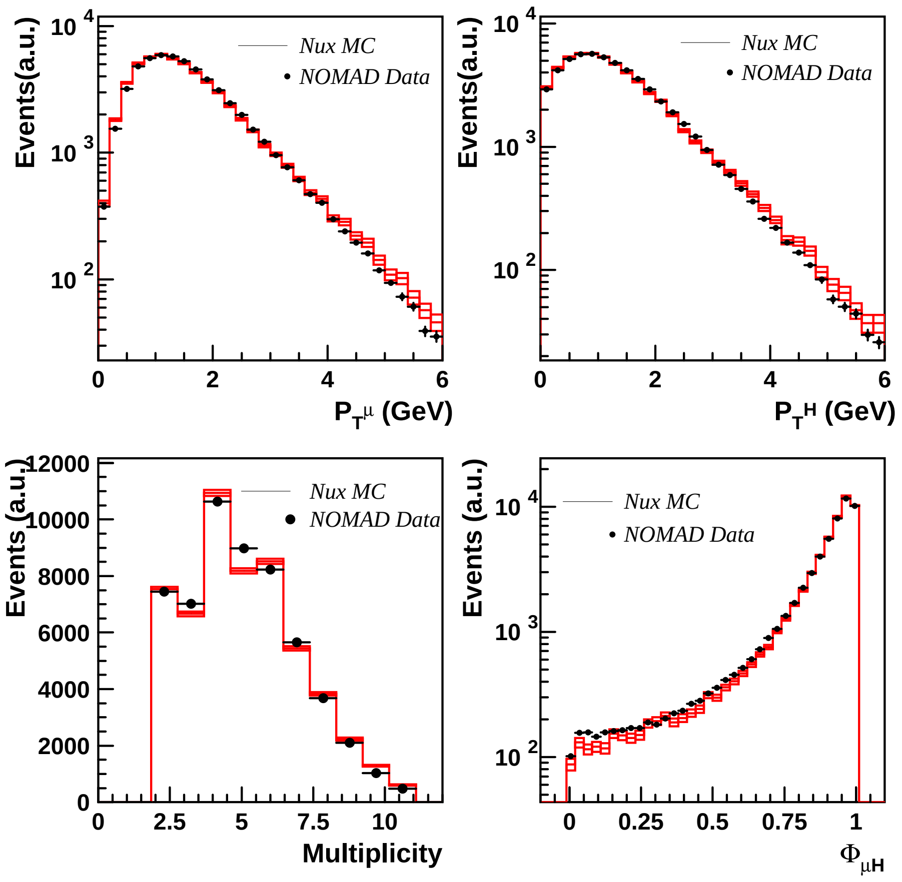
The comparison with NOMAD data are due to A. Bueno, A. Rubbia, ETH Zurich

The *NUX-FLUKA* event generator



ν_τ resonance interaction on Ar

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



Calculation of Atmospheric Neutrino Fluxes

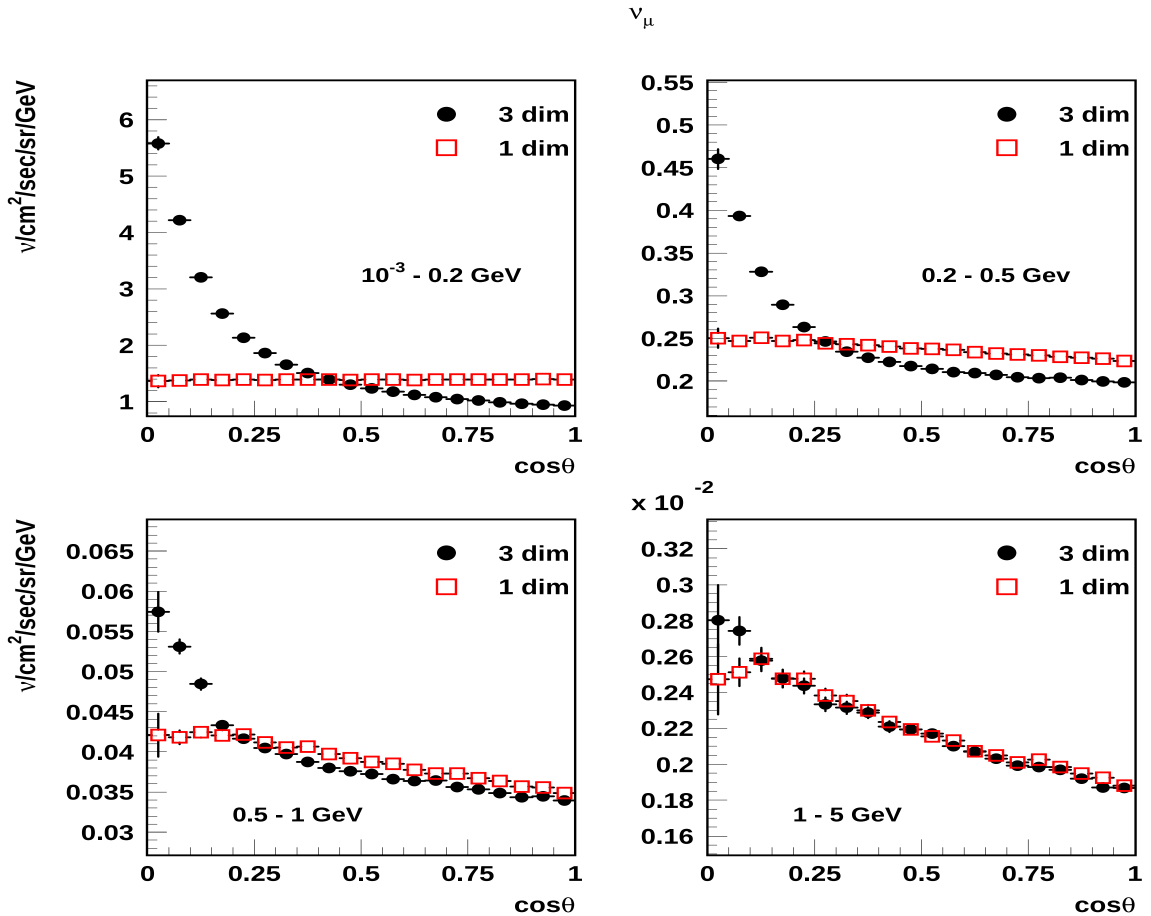
The ingredients and the recipe

1. Primary Spectra
2. Atmosphere description — 51 concentric shells of a mixture of N,O,Ar
3. Particle transport and decay
4. Geometry :3D/1D — G. Battistoni et al.,Astropart. Phys 12 (2000) 315
5. Geomagnetic effects — Dipole or map, applied a posteriori
6. Minor local corrections
7. Hadronic interactions — G. Battistoni et al now2000
8. ν interactions — NUX-FLUKA

Standard Calculations: HKKM [4] Bartol [5]

[4] M.Honda et al. , Phys Rev.D52 (1995) 4985
[5] V. Agrawal et al., Phys Rev.D53 (1996) 1314

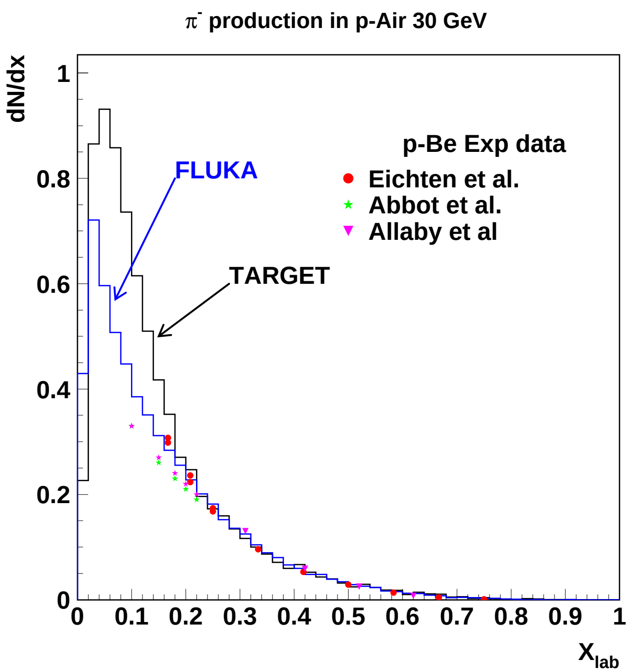
Comparison 3D/1D: angular distribution

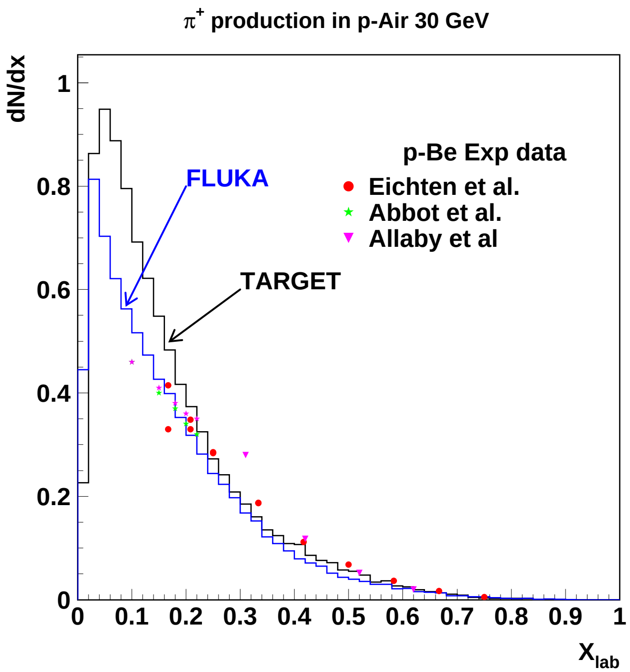


$\cos\theta$ distributions of ν_μ for 4 energy ranges for 1D/3D

Comparison of the hadronic interaction models in FLUKA and TARGET (Bartol)

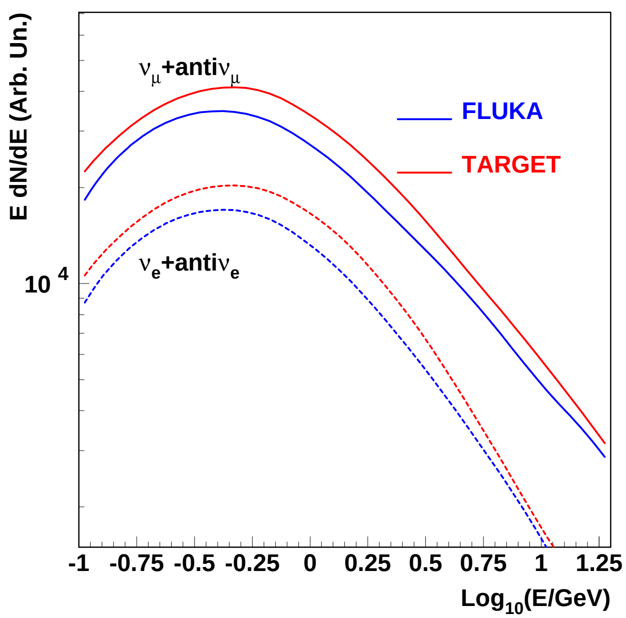
TARGET: parametrizations of accelerator data

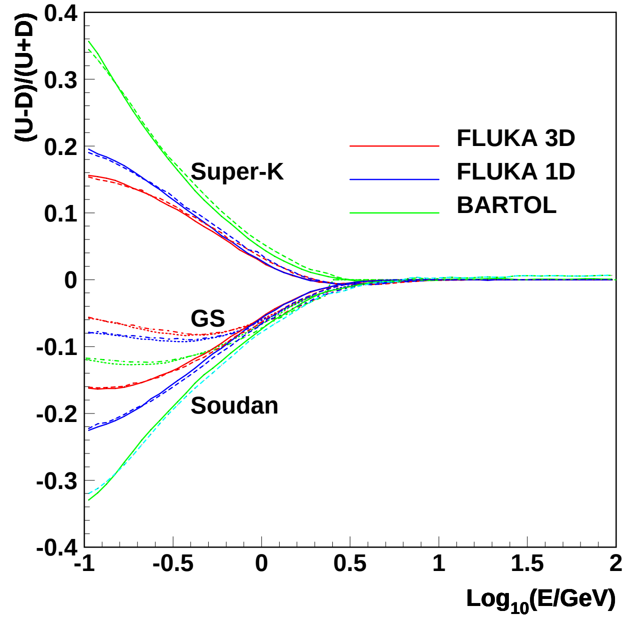




The Role of Hadronic interactions

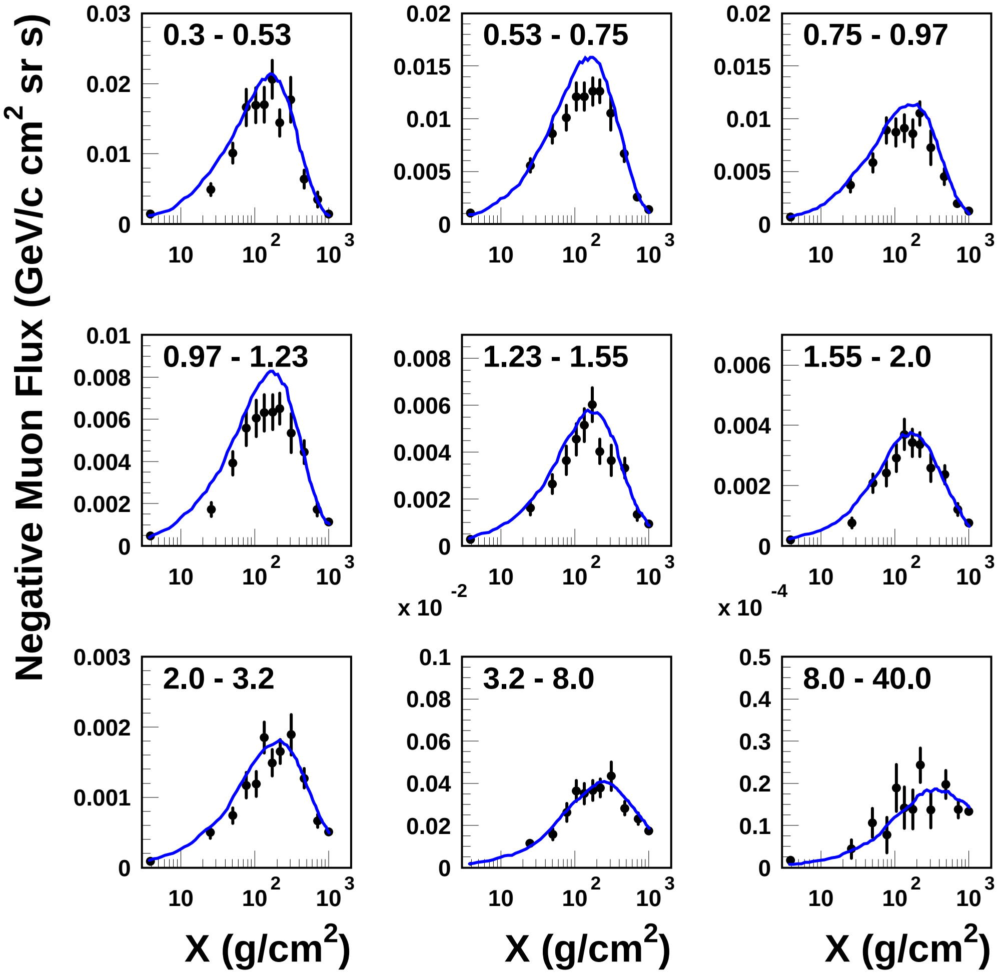
Different hadronic models in the same transport $\rightarrow$ Different ν fluxes





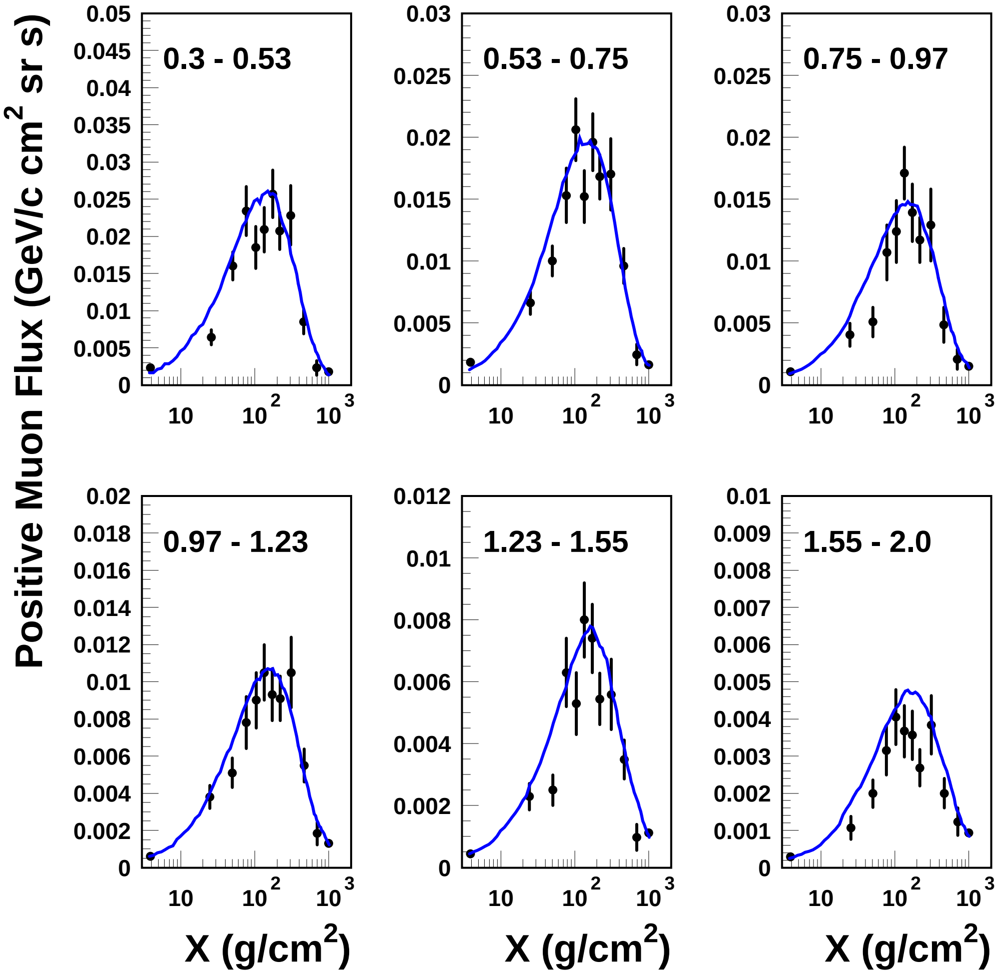
Effects are smeared by detectors
No effect on ν_μ/ν_e

Comparison FLUKA 3D - CAPRICE 94 Negative μs



Hadron/muon fluxes

Comparison FLUKA 3D - CAPRICE 94 Positive μs



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 ($E > 5 - 10\ GeV/u$): 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

FLUka with Geant4 Geometry [6]

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))

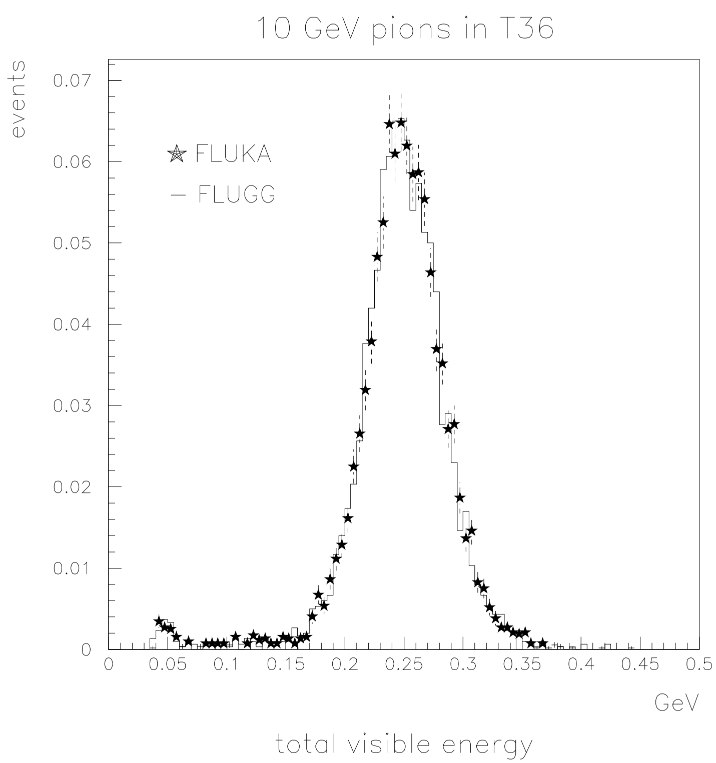
Present Status

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

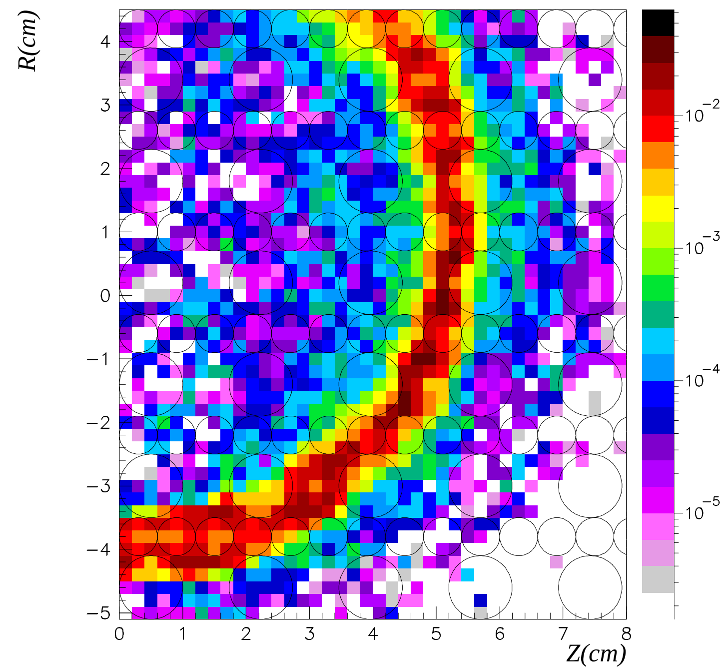
[6] ATL-SOFT-98-039,ATL-SOFT-99-004

The FLUGG project: tests

A simple calorimeter :T36



Toy geometry with magnetic field



Future Developments

- Heavy Ions In collaboration with the Huston University, under a NASA contract
- input/output interface to ROOT in collaboration with NASA, R.Brun, F.Carminati
- PEANUT extension to high energy
- Neutron new low energy library....never find the time to do it
- Residual dose rate almost implemented, from decay database
- A.O.B ??