FLUKA

GDR neutrino meeting,
Paris 20 October 2005

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FLUKA

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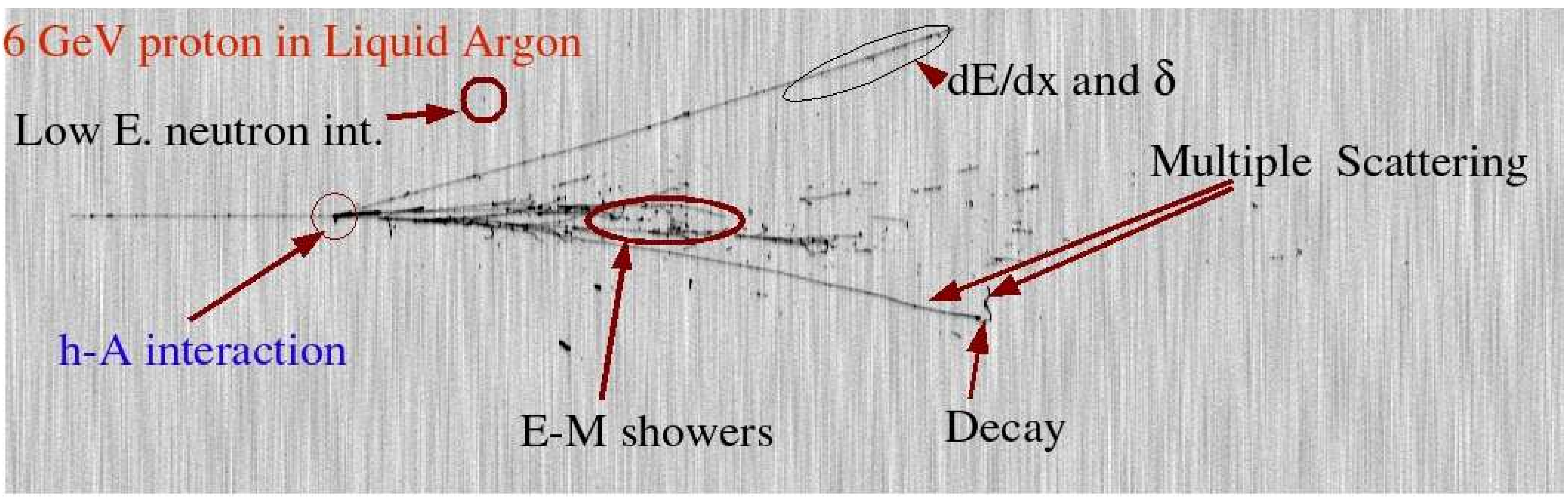
Interaction and Transport MonteCarlo code



INFN-CERN joint project

http://www.fluka.org

The FLUKA hadronic models

Hadron-Nucleon

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

Inelastic hN at high energies: DPM

Inelastic hadron-nucleon interactions at high energies ($> \approx 5 GeV/c$):

- Problem: "soft" interactions $\longrightarrow$ no perturbation theory.
- Solution : Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
- Each colliding hadron splits into two colored partons $\longrightarrow$ combination into two color neutral chains

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

  - Hadronization properties assumed to be independent of the physical process originating the chain (chain universality)

Glauber

★ Hadron-NUCLEUS interactions at high energies: Glauber cascade

• Quantum mechanical method to compute Elastic, Quasi-elastic and Absorption hA cross sections from Free hadron-Nucleon cross section + Nuclear ground state ONLY

• Primary interaction == multiple collisions with one or more target nucleons

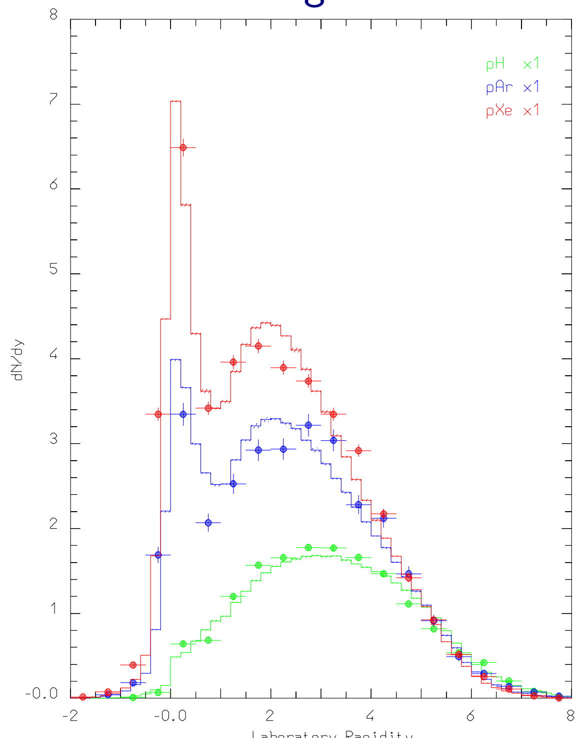
★Glauber-Gribov

Multiple collisions == exchange of one or more Pomerons (IP) with one or more target nucleons == 2 or more chains, with valence and sea quarks

No freedom, except in the treatment of mass effects at low energies.

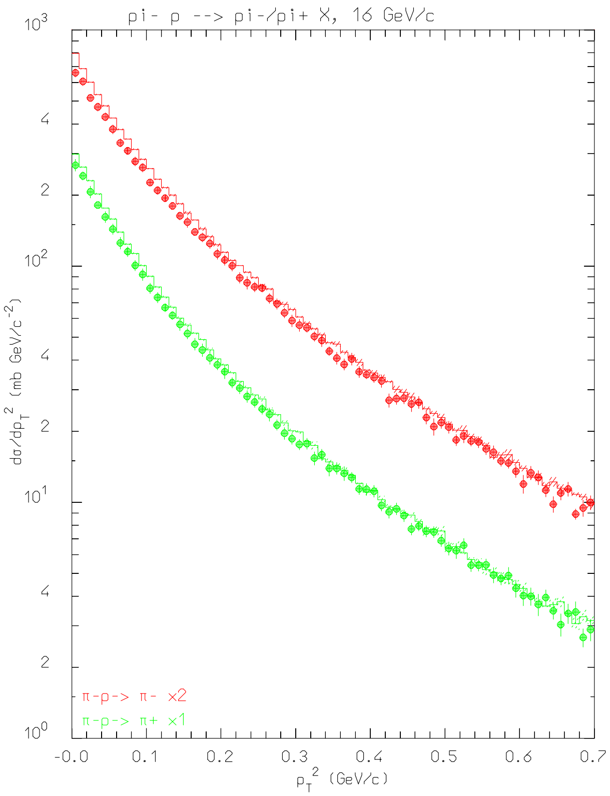
Fermi motion included $\longrightarrow$ smearing of p_T distributions

(G)INC follows

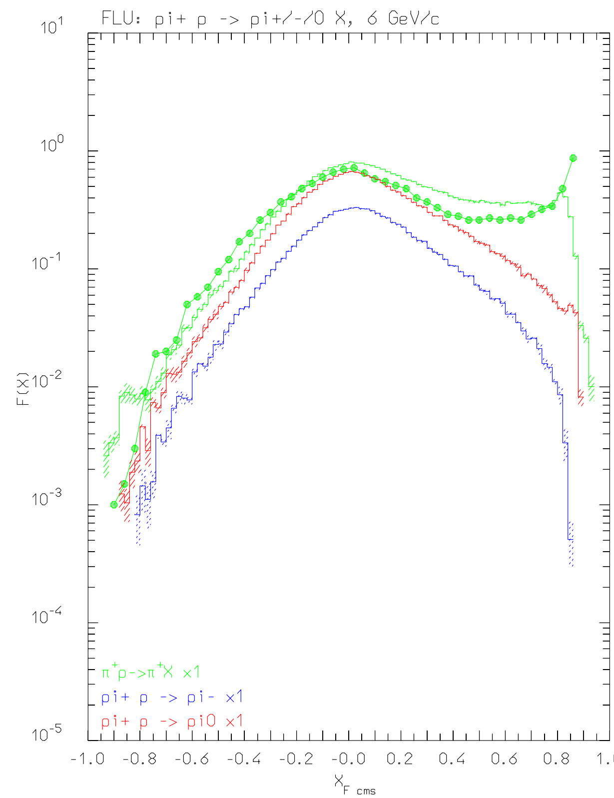


Charged Particle rapidity, 200 GeV p on H, Ar, Xe PRD26, 1019 (1982)

Examples

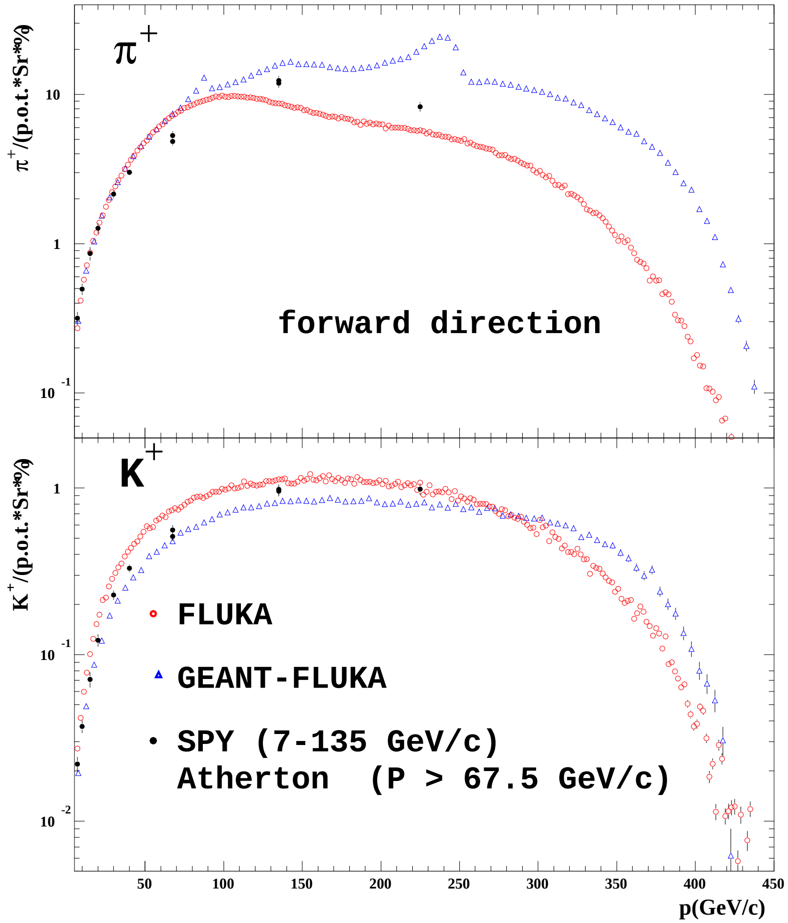


p_T spectra of π^+ and π^- from 16 GeV/c π^- on H. (M.E Law et al. LBL80 (1972)).



Invariant cross section spectra, vs Feynman x_F^* of π^-, π^0, π^+ for π^+ on protons at 6 GeV/c.

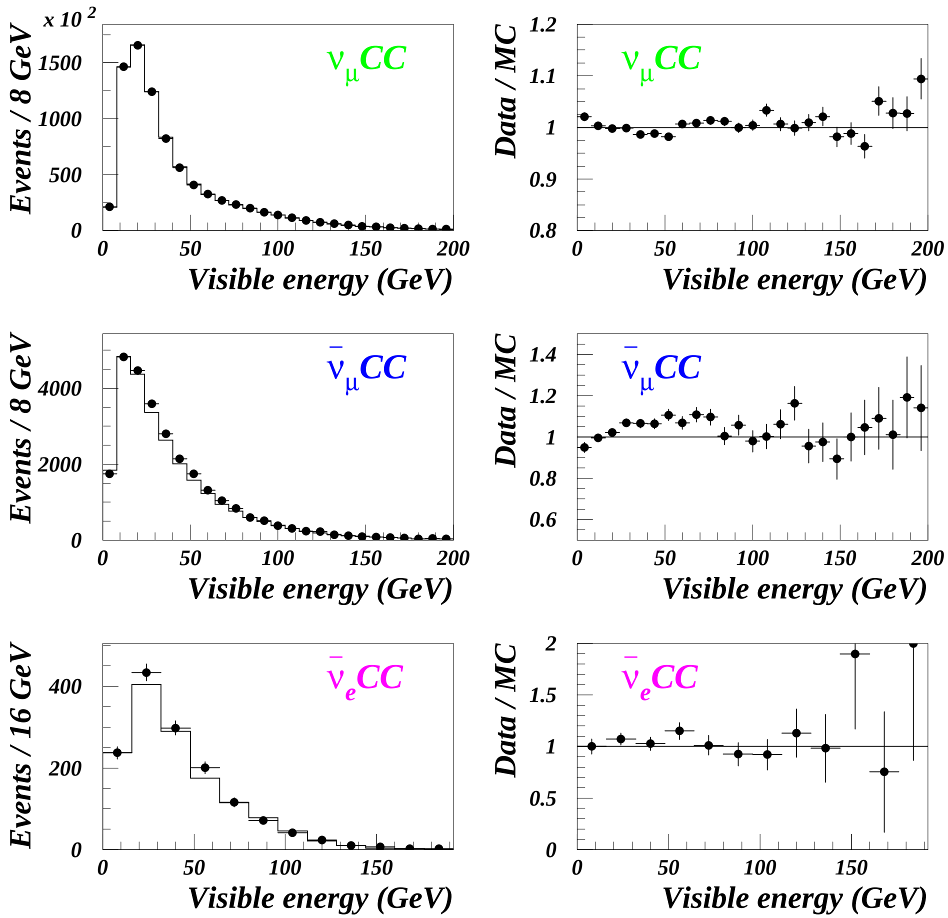
Improvements: SPY : forward yield



CNGS-oriented work on chain hadronization: fragmentation functions, threshold effects, transverse momentum.
Global optimization on 16-450 h-N and h-A data

π^+ and K^+
$d^2N \,/\, (dp/p\, d\Omega)$
100 mm Be target,
$\theta \leq 0.2$ mrad
SPY ($P \leq 135$ GeV/c, $\bullet$)
and Atherton et al. ($P \geq 67.5$ GeV/c,)
compared with *FLUKA* and *GEANT-FLUKA*

WANF and NOMAD

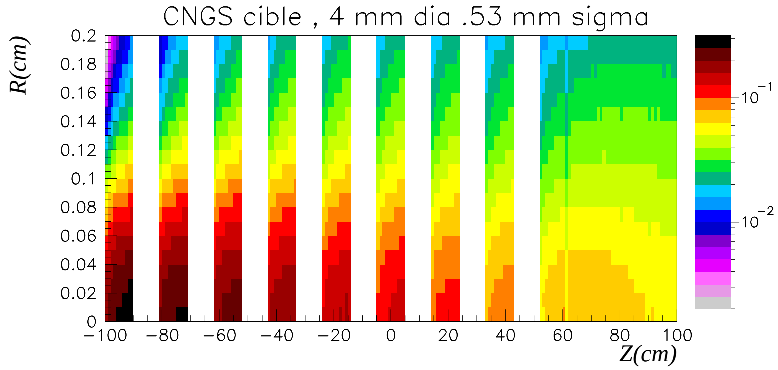


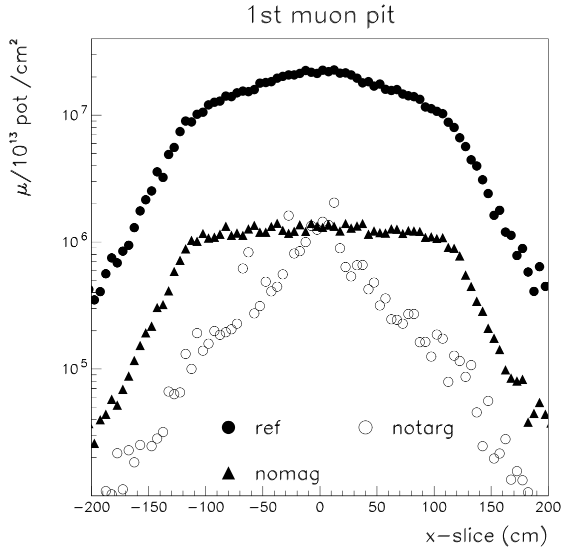
NOMAD , NIM A 515 (2003) 800

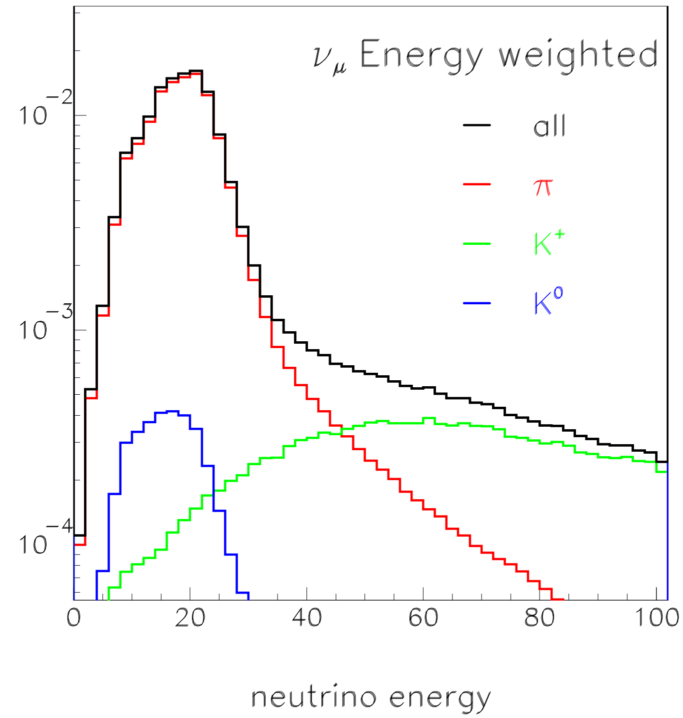
FLUKA + NUBEAM + corrections

Neutrino energy spectra (left) for the data (points) and the Monte Carlo (histogram) for ν_μ CC, $\overline{\nu}_\mu$ CC and $\overline{\nu}_e$ CC interactions and their corresponding ratios (right) in NOMAD

CNGS simulations:







Target heating, muon flux at pits, neutrino spectra, neutrino interactions http://www.mi.infn.it/p̃sala/Icarus/cngs.html

Cosmic Ray Showers

Motivation: Atmospheric neutrino fluxes (Astr.Phys. **12**, 315 (2000); **19**, 269 (2003))

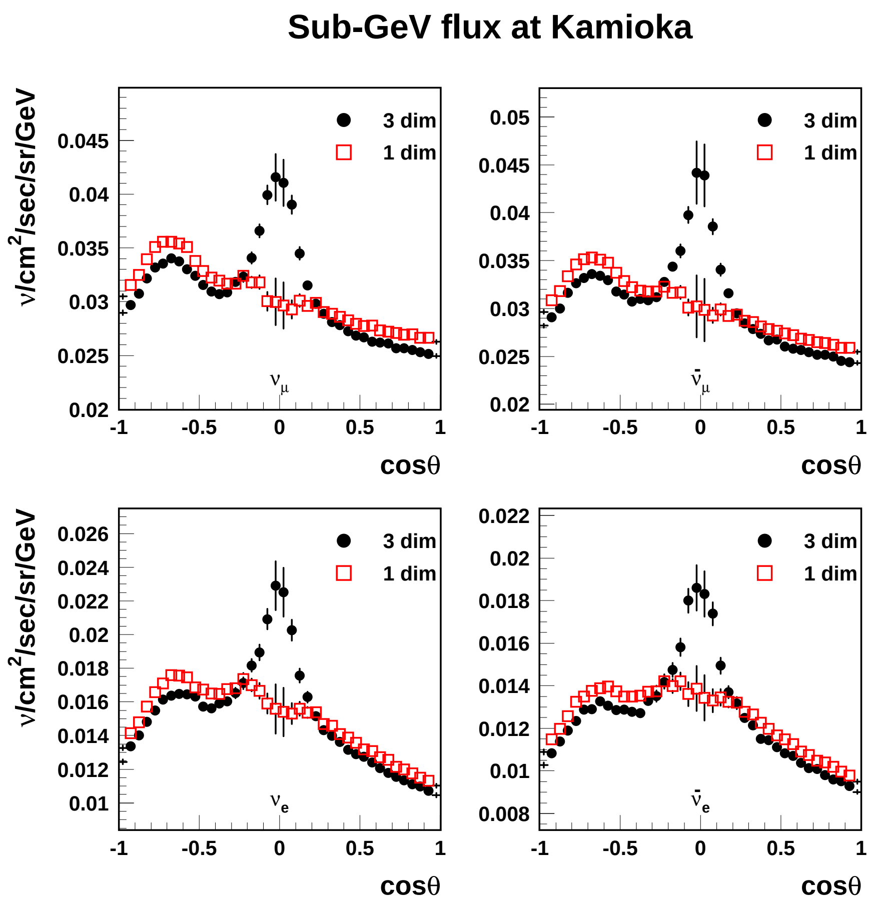
Benchmarks and Applications: Muon and hadron fluxes, Aircraft exposure

Ingredients

- Primary ray spectrum and composition, solar modulation
- Atmosphere description (3 Dimensional)
- Particle transport and decay (3-D, μ and ν polarization included)
- Hadronic interactions
- Geomagnetic effects

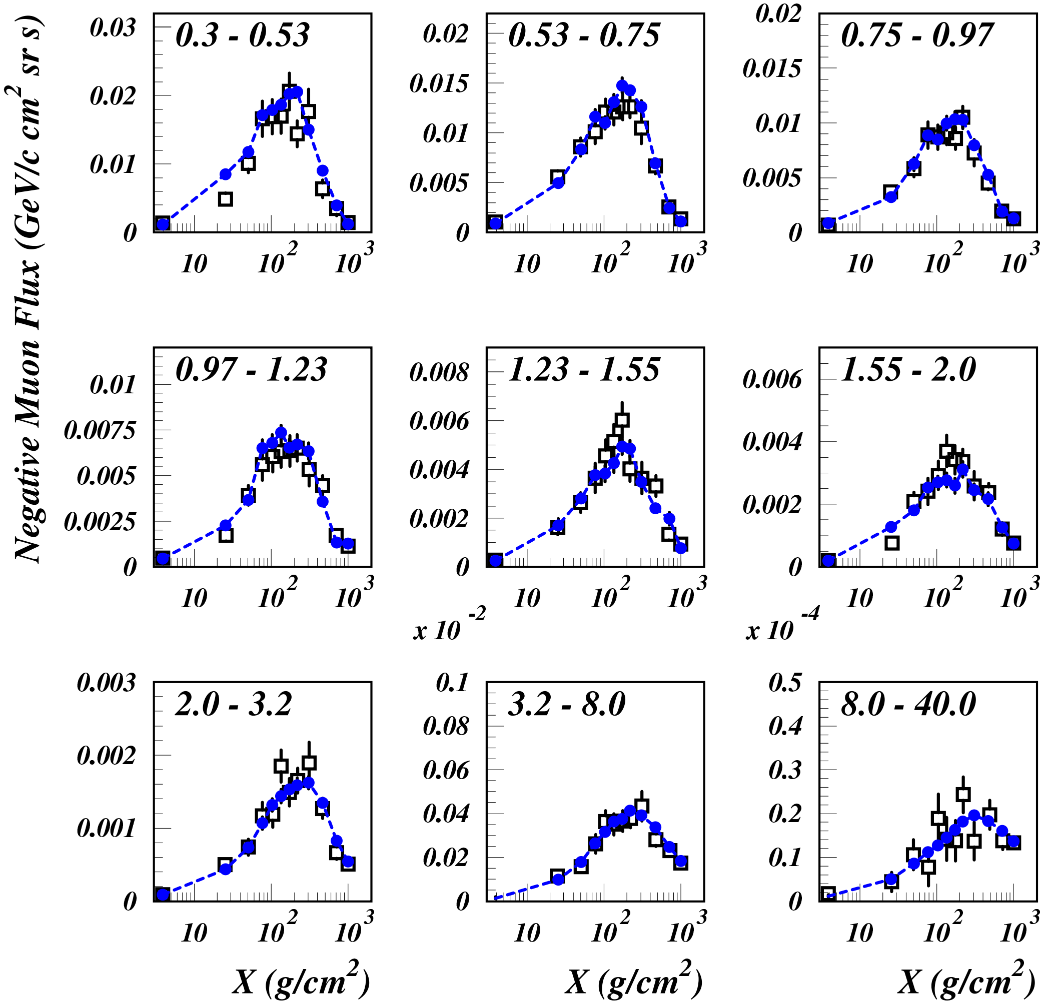
Nucleus-Nucleus interactions are treated by the DPMJET code interfaced to FLUKA

3D effects in ν angular distributions



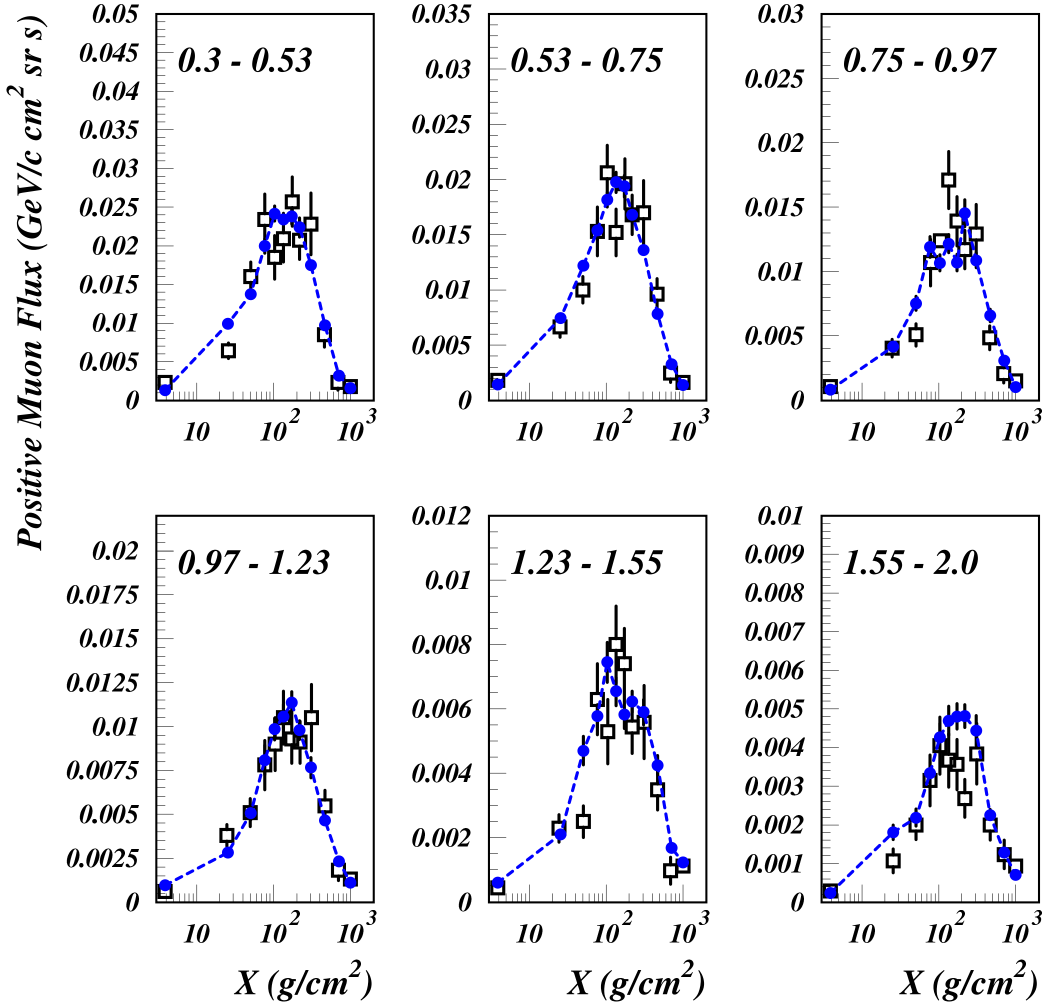
Hadron/muon fluxes in the atmosphere: μ^-

Negative muon flux measured by Caprice94 (PRD62 (2000) 032007; PRL83 (1999) 4241) for various momentum bins (GeV/c) as a function of the atmospheric depth (black symbols) compared with FLUKA simulations (blue symbols) (Astropart. Phys. **17** 477 (2002))

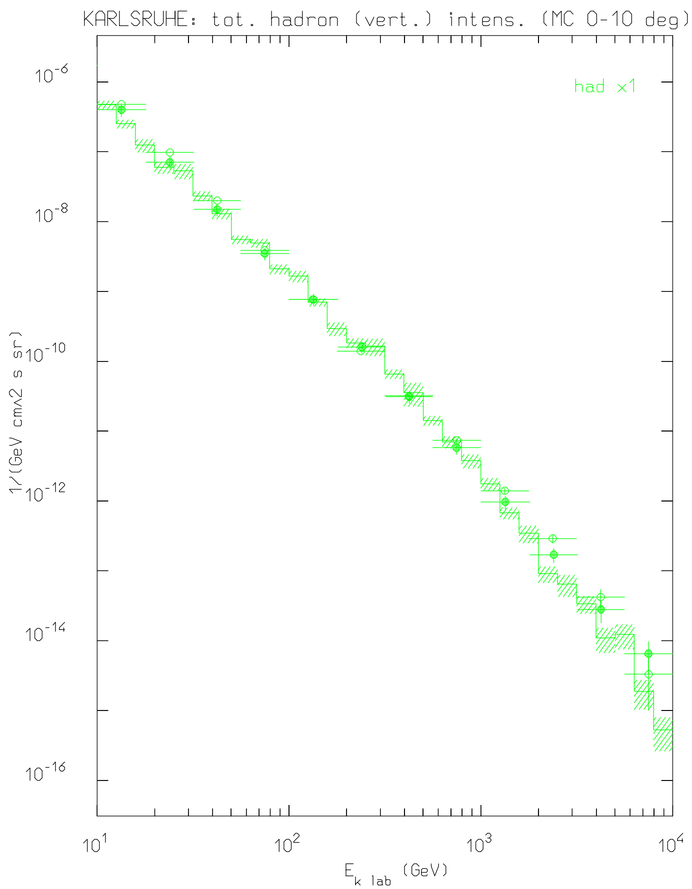


Hadron/muon fluxes in the atmosphere: μ^+

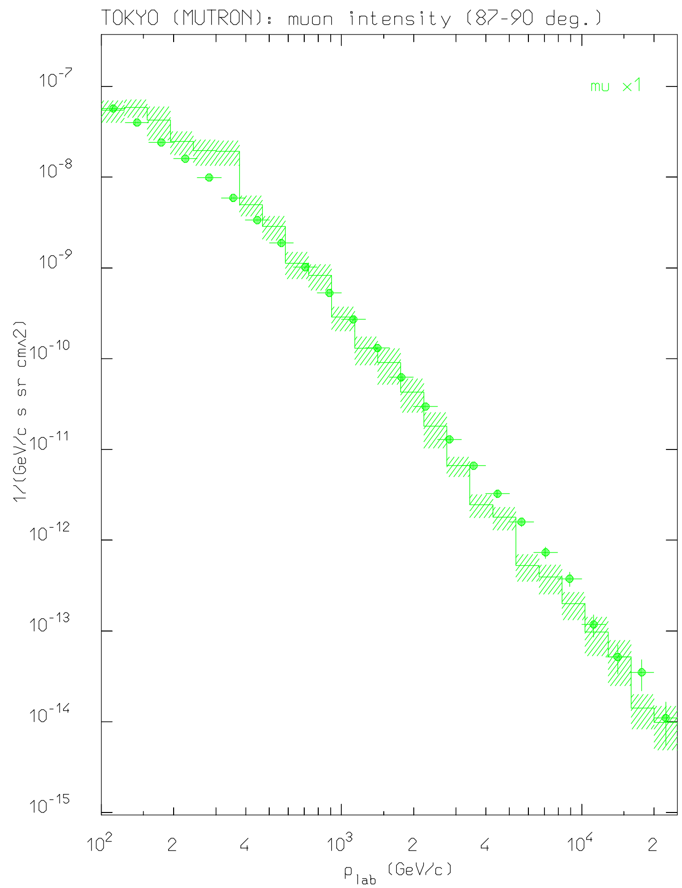
Positive muon flux measured by Caprice94 (PRD62 (2000) 032007; PRL83 (1999) 4241) for various momentum bins (GeV/c) as a function of the atmospheric depth (black symbols) compared with FLUKA simulations (blue symbols) (Astropart. Phys. **17** 477 (2002))



Hadron/muon fluxes in the atmosphere:

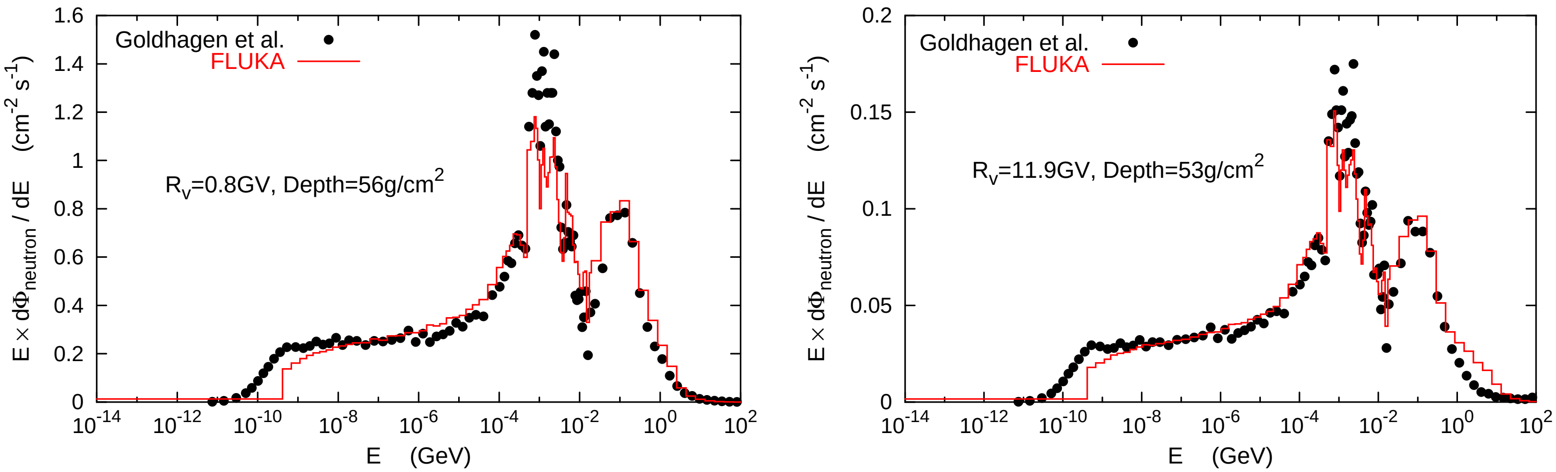


Hadron flux at sea level, KASKADE data from H. Kornmayer et al, JPG 21, 439 (1995).



MUTRON horizontal muon flux: up to 20 TeV

Radiation Field at Aircraft altitudes: (Rad.Prot.Dosim.98 (2002) 367)

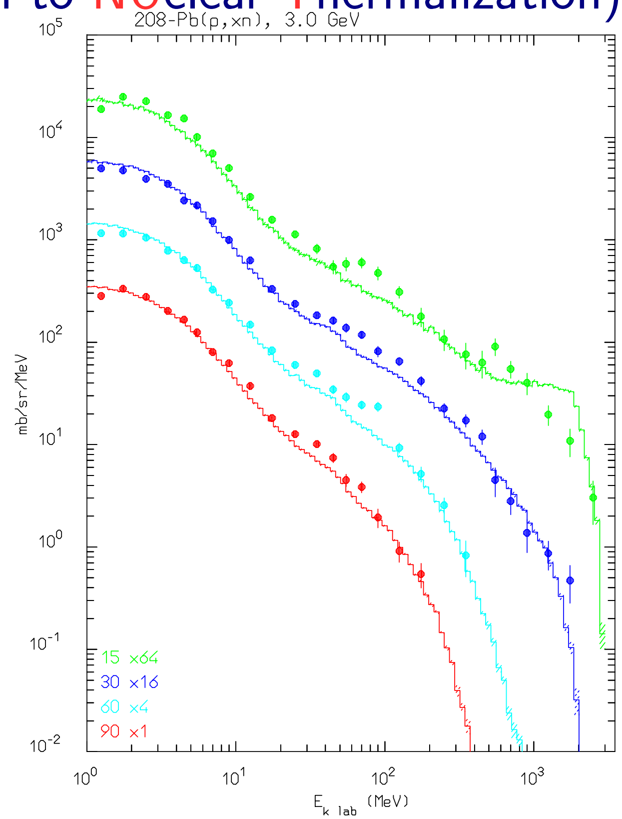


Atmospheric neutron spectra measured aboard of an ER-2 high-altitude airplane (NIM A476, 42 (2002)) (symbols) and calculated with FLUKA (histograms), at two different geographic locations and altitudes.

PEANUT (PreEquilibrium Approach to NUclear Thermalization):

Generalized IntraNuclearCascade
+ preequilibrium stage
+ Equilibrium stage

- Nucleon, pion and kaon induced reactions
- Photonuclear reactions
- Stopping μ^- absorption
- Proton decay
- Neutrino interactions

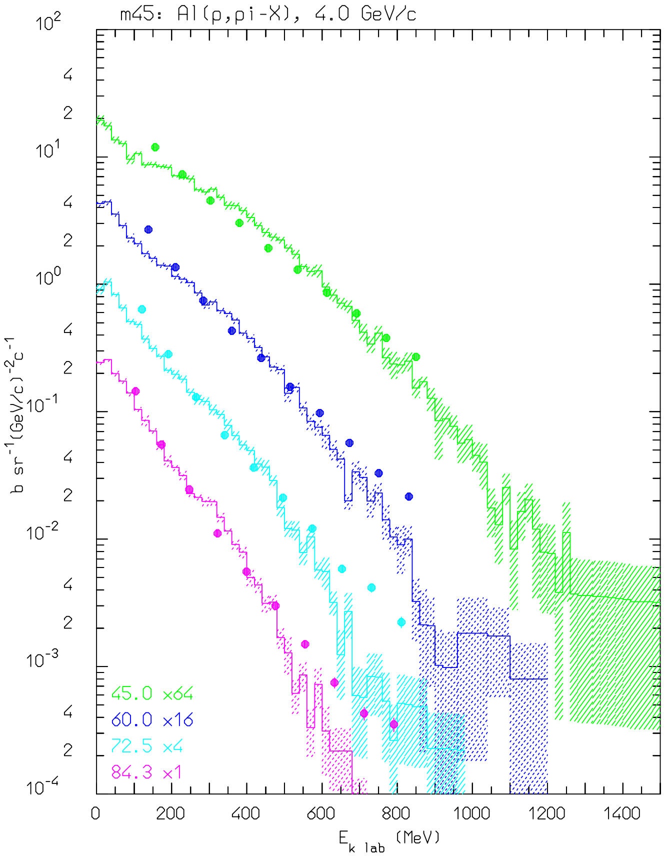


PEANUT(histo) and exp.(symbols), Pb(p,xn) at 3 GeV

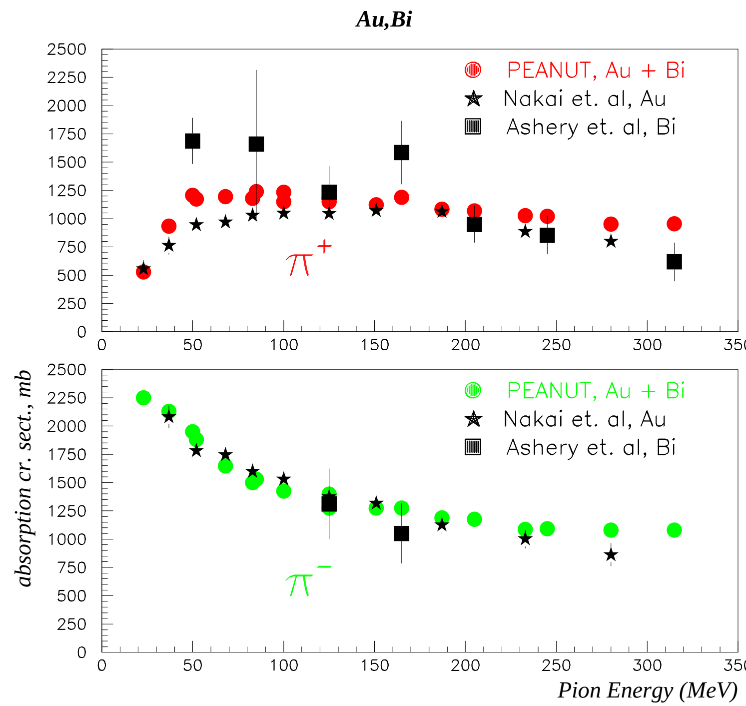
(Generalized) IntraNuclear Cascade basic assumptions

1. Primary and secondary particles moving in the nuclear medium
2. *Target nucleons motion and nuclear well according to the Fermi gas model*
3. Interaction probability from σ_{free} + Fermi motion $\times\ \rho(r)$ + exceptions (ex. π)
4. *Glauber cascade at high energies*
5. Classical trajectories $(+)$ nuclear mean potential (*resonant for π's!!*)
6. Curvature from nuclear potential $\longrightarrow$ refraction and reflection.
7. Interactions are incoherent and uncorrelated
8. Interactions in projectile–target nucleon CMS $\longrightarrow$ Lorentz boosts
9. *Multibody absorption for π, μ^-, K^-*
10. *Quantum effects (Pauli blocking, Formation zone, antisymmetrization, Nucleon-nucleon hard-core correlations, Coherence lengt)*
11. *Exact conservation of energy, momenta and all additive quantum numbers,including nuclear recoil*

The FLUKA nuclear module , examples

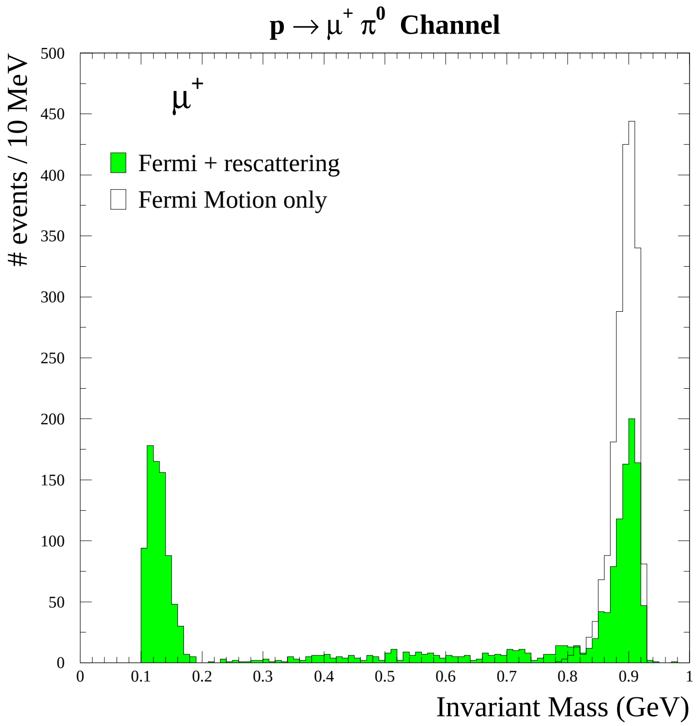


Al($p,\pi^- x$) at 4 GeV/c, double differential



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

Proton decay



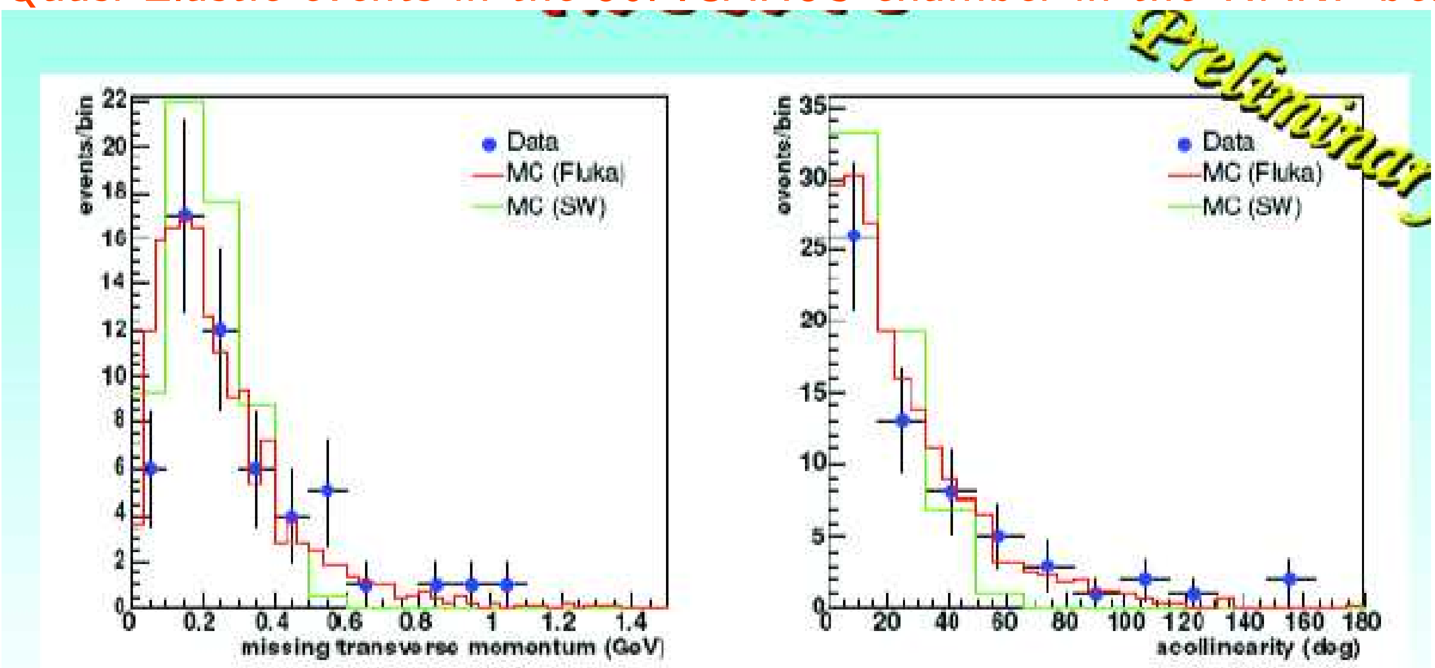
Simulation of nucleon decay is highly sensitive to the nuclear model
Reconstructed invariant mass: no recoils, no low energy hadrons
(Figure: proton decay in Ar nuclei, ICARUS experiment)

Quasi Elastic ν interactions directly simulated in PEANUT

For ICARUS : NUX-FLUKA (NUX from A.Rubbia) interface

Next future : direct implementation of DIS and Res. in FLUKA

Quasi Elastic events in the 50l ICARUS chamber in the WANF beam

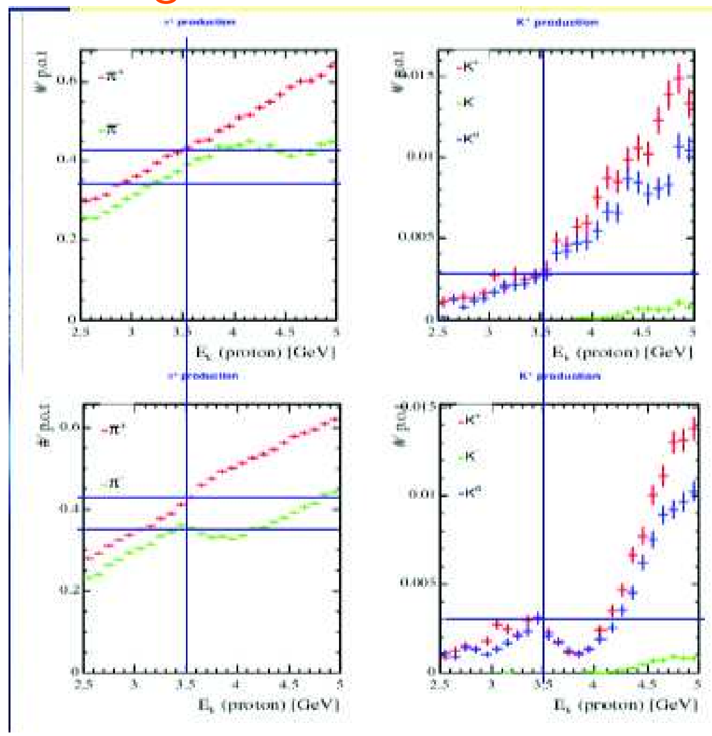


Peanut extension

In the last FLUKA release: PEANUT extended up to 5 GeV/c for nucleons/pions
Before : OLD "Nucriv" nuclear event generator 3.5-5 GeV/c
See the difference in plot:
TOP: FLUKA 2005.6
Bottom: FLUKA2003.4

However: too low π^- yield a 4-5 GeV
Small dicontinuity in π production
Work is in progress to extend PEANUT to the whole energy range and to have a consistent description of quasi-elastic interactions

From J.E. Campagne's talk , ISS meeting at CERN



EMF : ElectroMagnetic Fluka. Physical interactions

Photoelectric : fluorescence,angular distribution,Auger , polarization

Compton and Rayleigh: atomic bonds,polarization

Pair production correlated angular and energy distribution; also for μ

Photonuclear ; also for μ

Bremsstrahlung : LPM, angular distribution, finite at tip, ... also for μ

Bhabha and Møller scattering

Positron annihilation at rest and in flight

μ^- capture at rest

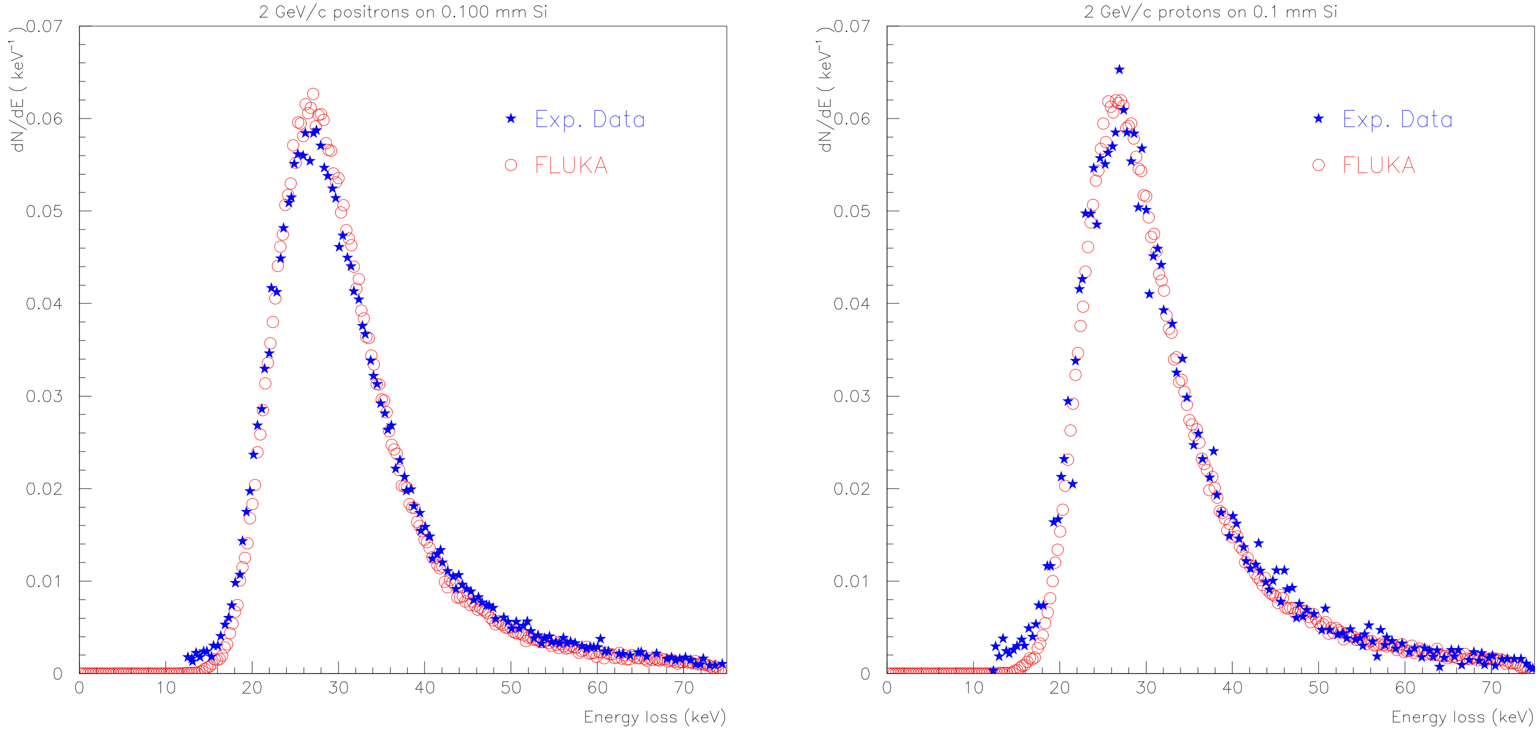
Optical photon (Cherenkov) production and transport

PEMF preprocessor eliminated in FLUKA2005.6

Charged particle transport

- δ-ray production. Below δ threshold: Ionization energy losses with fluctuations
- Ionization fluctuations: new general approach based on the cumulants of a distribution
- Ionization potential and density effect parameters: latest recommended values, can be overridden by user
- Heavy ions:
  - Effective charge with fluctuations
  - Charge exchange effets (dominant at low energies, ad-hoc FLUKA model)
- Positron dE/dx: radiation integral scaled according to Kim et al., differential cross sections fitted to numerical results of Feng et al.
- Multiple Coulomb scattering: path length correction, lateral displacement, angle correlation, soft approach to boundaries, screening and spin-relativistic corrections, fully coupled to magnetic field transport
- Single scattering at boundaries and when Molière theory conditions are not satisfied. Also systematic if requested

Ionization Energy losses

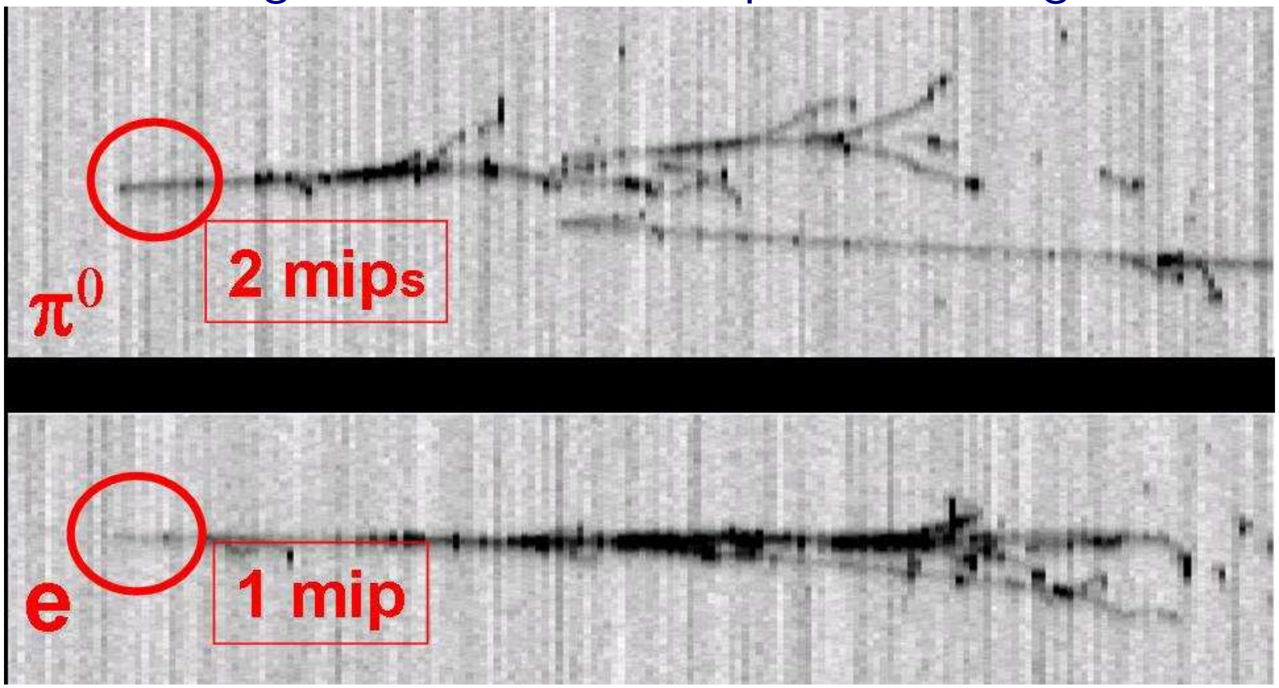


Experimental [1] and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100μm of Si

[1] J.Bak et al. NPB288, 681 (1987)

Particle ID in ICARUS

e/π^0 discrimination based on dE/dx in the first ≈2.5 cm of track:
$< 3\%\pi^0$ with 90% efficiency on e at 1 GeV, improving with energy due to decreasing contribution of Compton scattering

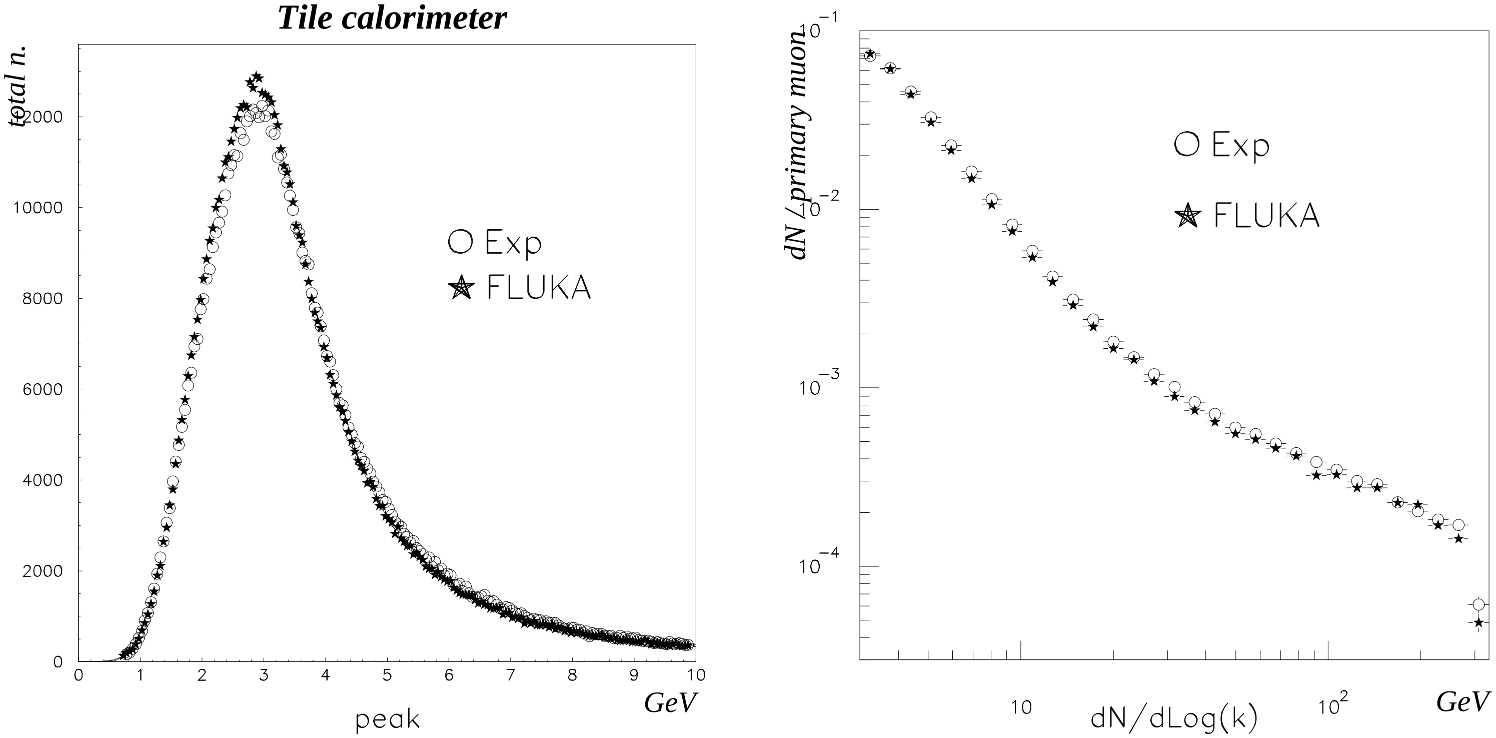


Charged hadrons and muons experience also other atomic processes (important at very high energy, above several tens of GeV):

- Bremsstrahlung: implemented in FLUKA including the effect of nuclear form factors which are critical for "heavy" bremsstrahlung for all charged hadrons and muons
- Direct e^+/e^- pair production: implemented in FLUKA for all charged hadrons and muons

photonuclear interactions mediated by virtual photons are also important for high energy muon propagation and they are implemented making use of the standard FLUKA nuclear models

300 GeV μ in ATLAS combined calo



300 GeV μ comparison between calculated and experimental spectra in the ATLAS tile calorimeter prototype, ionization peak (left) and $\Delta E/E > 0.01$ (right). Absolute calibration.

Neutrons from muons underground (PRD64 (2001) 013012)

Neutron production rate as a function of muon energy Stars: FLUKA simulation with a fit to a power law. Exp. points: abscissa → average μ energy at the experiment's depth:

A) 20 m.w.e.

B) 25 m.w.e.

C) 32 m.w.e. (Palo Verde)

D) 316 m.w.e.

E) 750 m.w.e.

F) 3650 m.w.e.(LVD)

G) 5200 m.w.e. (LSD)