The Monte Carlo code FLUKA and its applications

SL seminar

CERN, 28-6-2001

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[2] CERN SL/BT/TA (on leave from INFN-Milan)

FLUKA

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Interaction and transport MonteCarlo code

- Hadron-hadron and hadron-nucleus interactions 0-100 TeV
- Nucleus-nucleus interactions 0-10000 TeV/n: *under development*
- Electromagnetic and μ interactions 1 keV-100 TeV
- Neutrino interactions
- Charged particle transport including all relevant processes
- Transport in magnetic field
- Combinatorial (boolean) geometry
- Neutron multigroup transport and interactions 0-20 MeV
- Analogue or variance reduction calculations

FLUKA: generalities

At each step the occurrence and outcome of interactions are decided by random selection from the appropriate probability distribution.

All the secondaries issued from the same primary are transported before a new history is started.

Statistical accuracy of results depends on number of “histories”

Statistical convergence can be accelerated by “biasing” techniques.

Microscopic MonteCarlo: Probability distributions from theoretical models

Supplemented by experimental data (cross sections, mass tables...)

Checked against experimental data

$\Downarrow$

Predictivity , full correlation

FLUKA **History**

Beginning of the FLUKA *history : 1962* Johannes Ranft (Leipzig) and H. Geibel (CERN): MonteCarlo codes for high energy beams, as required for CERN accelerators *first phase of SPS design*

The name FLUKA *: 1970*: calorimeter fluctuations on an event-by-event basis (FLUKA = FLUktuierende KASkade).

At the beginning of the 70's, strong contribution of J. Ranft and J. Routti (Helsinki), to the SPS radiation study group, coordinated by K. Goebel. Later, researchers from Helsinki (P. Aarnio) and from CERN (G.R. Stevenson, A. Fassò) contributed to the code till $\approx$ 1987.

The present code : since 1990 mostly INFN-Milan : little or no remnants of older versions. Link with the past: J. Ranft, A. Fassò

The code is huge: $\approx 350,000$ lines of fortran code (vs $\approx 30,000$ in 1987)

FLUKA **History**

FLUKA: sponsors

FLUKA is a “private” effort, it has no official distribution, and is in continuos evolution. Developments are always driven by the concrete needs of the authors experiments/collaborations.

There is no “official” CERN support for FLUKA, even though presently A. Ferrari , A. Fassò and P.R. Sala are working at CERN.

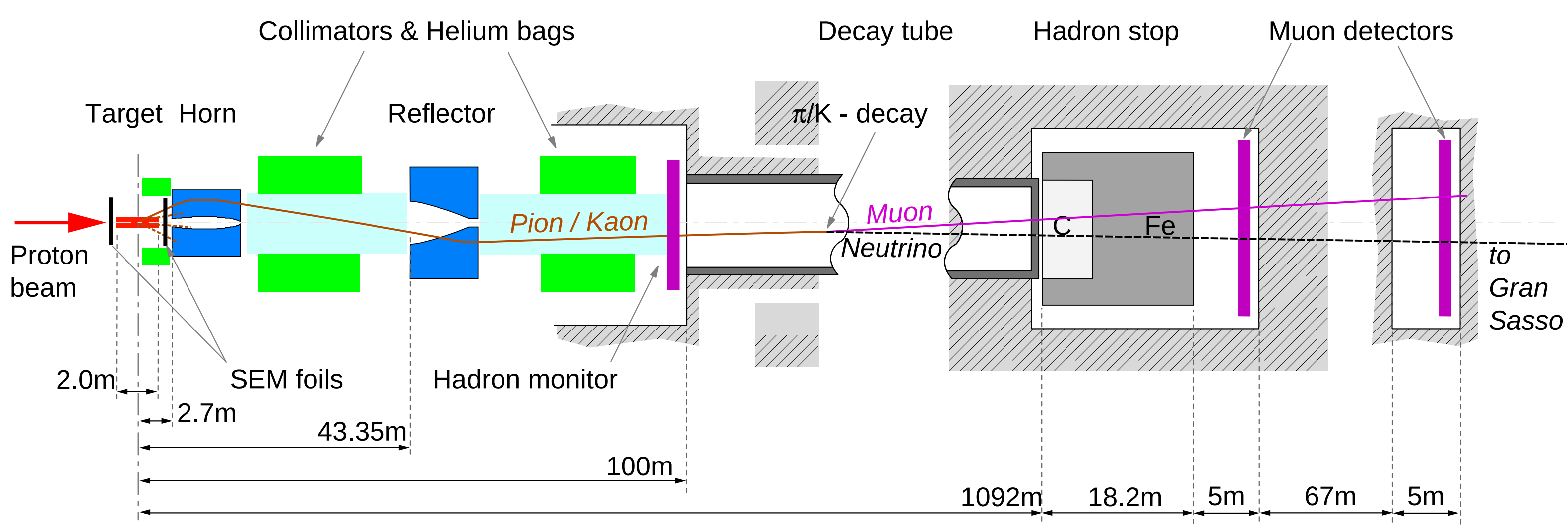
A project for FLUKA development is being discussed by the INFN scientific committees and it is expected to be approved in September.

Supported by a NASA contract for space-related developments.

Wide use at CERN (SL, TIS, CNGS, LHC experiments..) and in other labs (SLAC, INFN..)

MonteCarlo of the ICARUS experiment, part of the Energy Amplifier simulation chain...

CERN Neutrino to GranSasso



400 GeV/c protons, double fast extraction, $5\ 10^{13}$ protons every 6 s

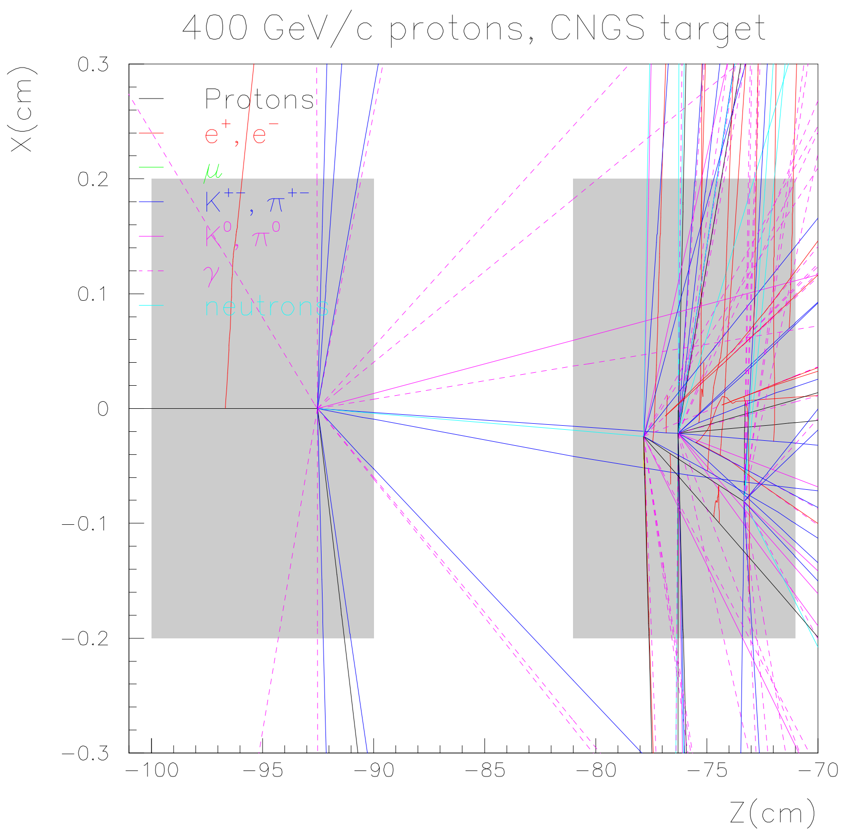
Thin graphite target (⊘4 mm, 13 bars 100 mm each)

Two magnetic lenses focalize 35 and 50 GeV positive

1 Km decay tube

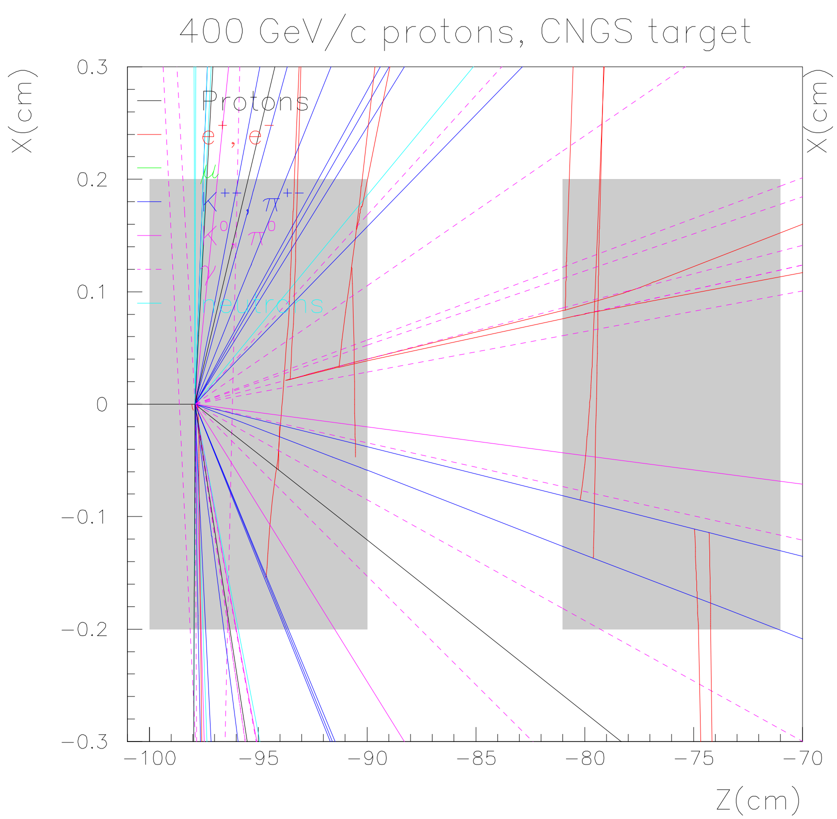
730 Km to Gran Sasso

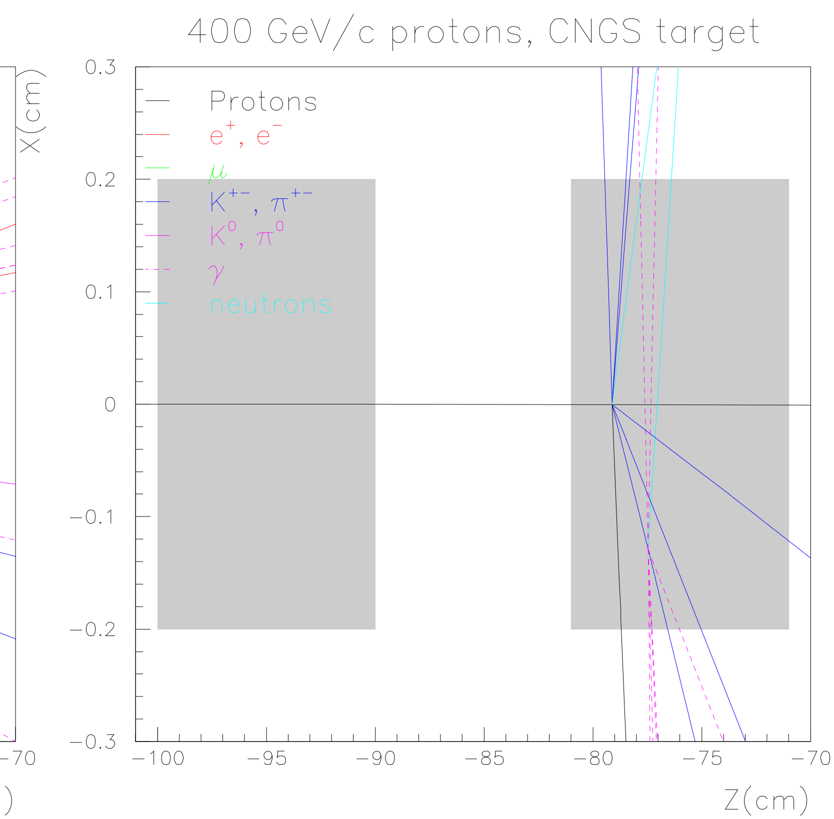
A CNGS event



- High E had. int +decay
  $\rightarrow \nu$ flux
- Reinteractions (down to low E)
  $\rightarrow \nu$ flux
  $\rightarrow$ shower development
  $\rightarrow$ in and outside heating
  $\rightarrow$ dose, activation
- Neutronics
  $\rightarrow$ dose, activation
- Ionization
  $\rightarrow$ shower development
  $\rightarrow$ heating
- ElectroMagnetic processes
  $\rightarrow$ shower development
  $\rightarrow$ heating

Other CNGS events





The FLUKA hadronic models

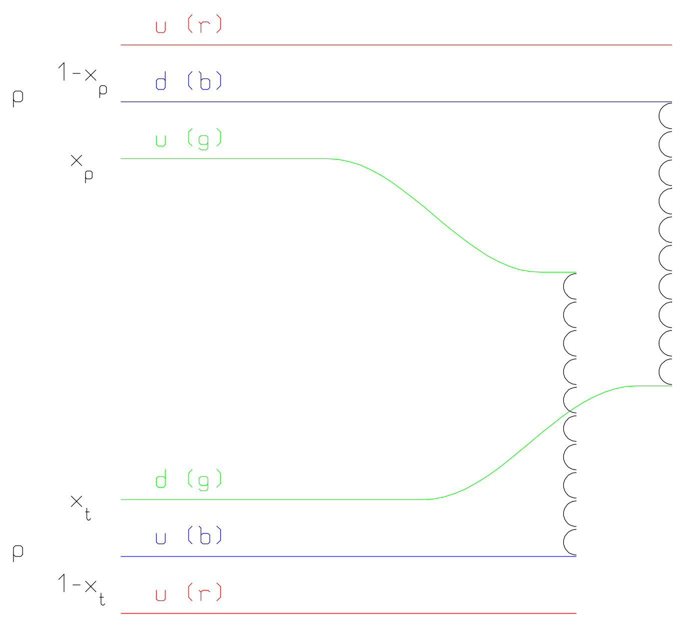
Building block: Hadron-Nucleon

Elastic, charge exchange, resonance production, Dual Parton Model

Inside the nucleus

Initial state effects	Fermi Motion of target nucleons, Nuclear Potential for target and projectile, Glauber multiple scattering, many-body absorption, collective excitations..
Final state effects	Generalized Intranuclear Cascade Towards equilibrium : • Preequilibrium: statistical repartition of energy • Evaporation from a thermalized system, fission, Fermi Break-up • Nuclear deexcitation through γ rays

Inelastic hN at high energies: DPM



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

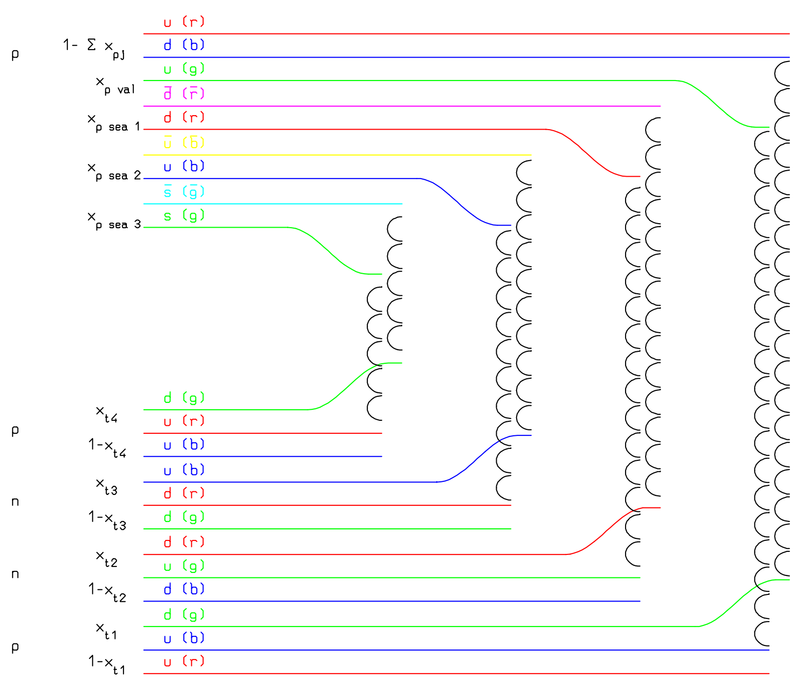
Strings = quarks held together by the gluon-gluon interaction

Interacting via Pomeron exchange = closed string exchange

Each colliding hadron splits into two colored partons → combination into two color neutral chains → hadronize into two back-to-back jets.

h-A at high energies: Glauber-Gribov

Primary interaction: Glauber = multiple interaction with ν nucleons, binomial distribution



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

Gribov

$\Downarrow$

2ν chains

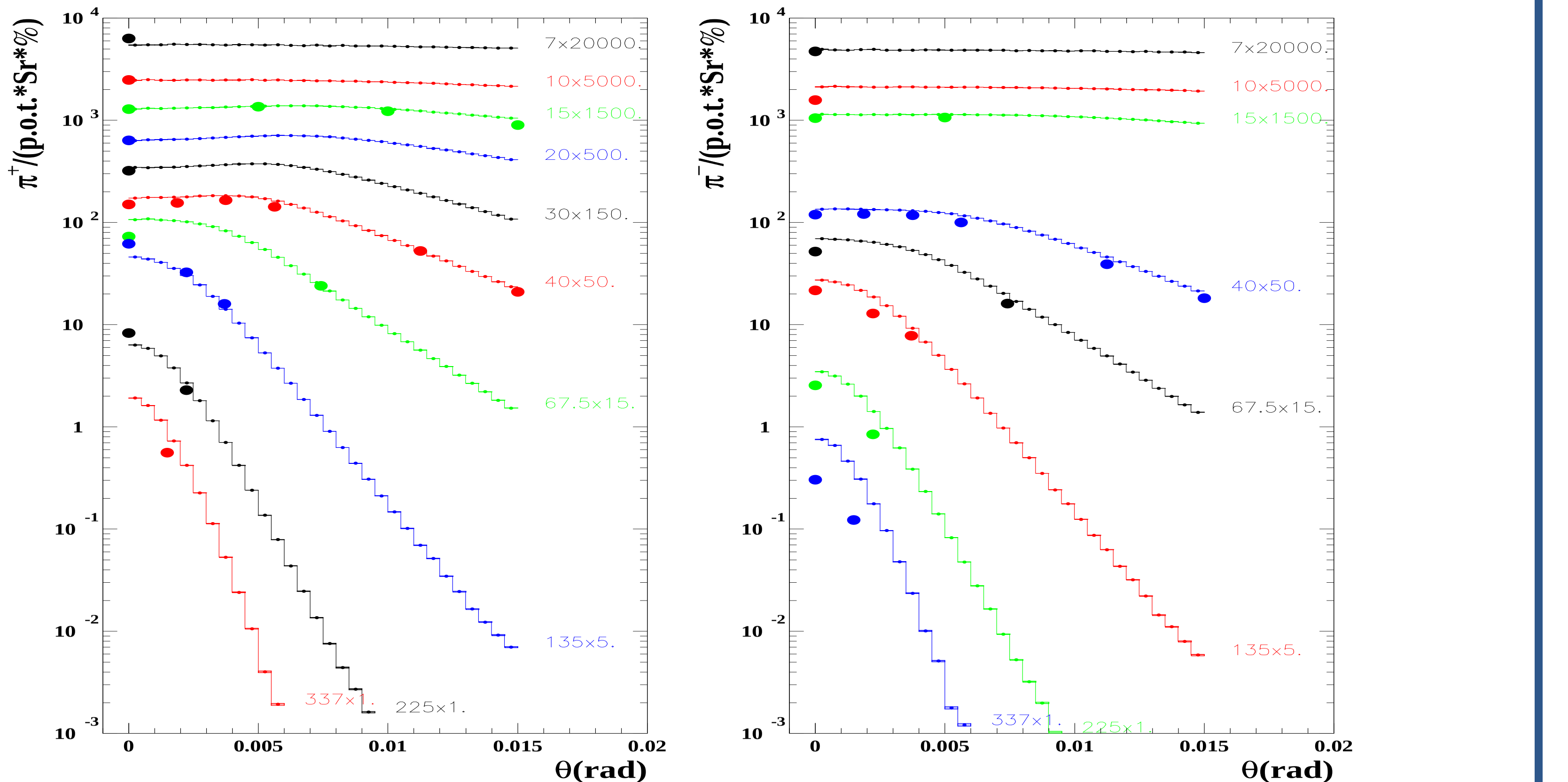
2 valence-valence chains

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

No freedom, except in mass effects at low energies.

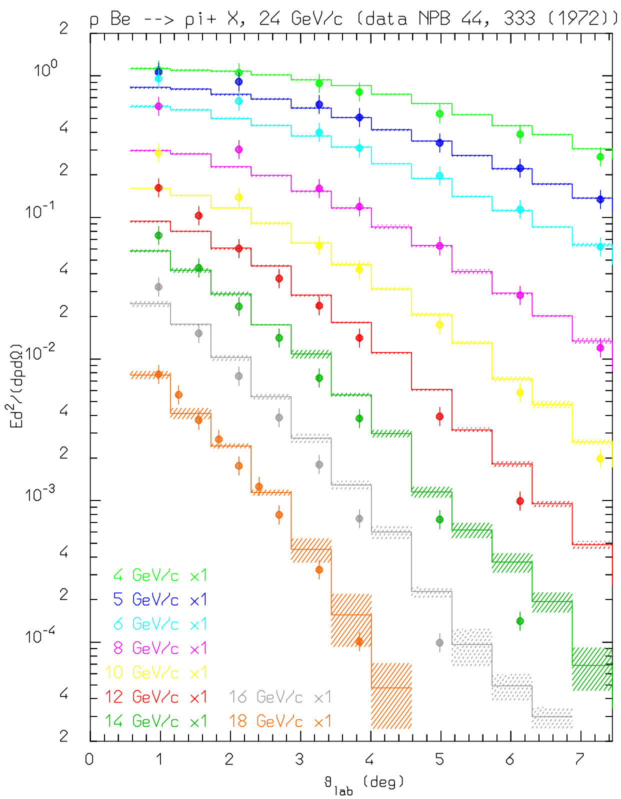
Fermi motion included $\rightarrow$ smearing of E and p_T distributions

Comparison with SPY I

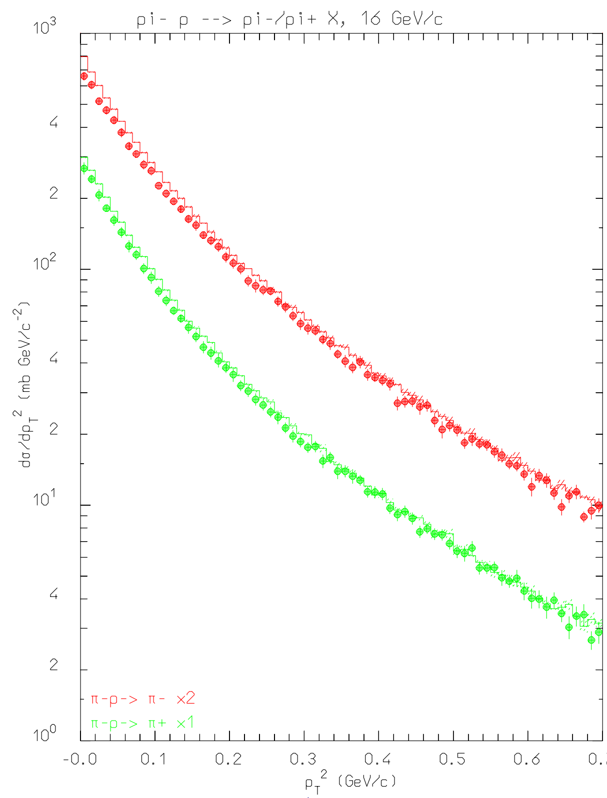


Double differential cross section for π^+ (left) and π^- (right) production for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80–07, G. Ambrosini et al. PL B425 208 (1988)).

Nonelastic hA interactions at high energies: examples IV

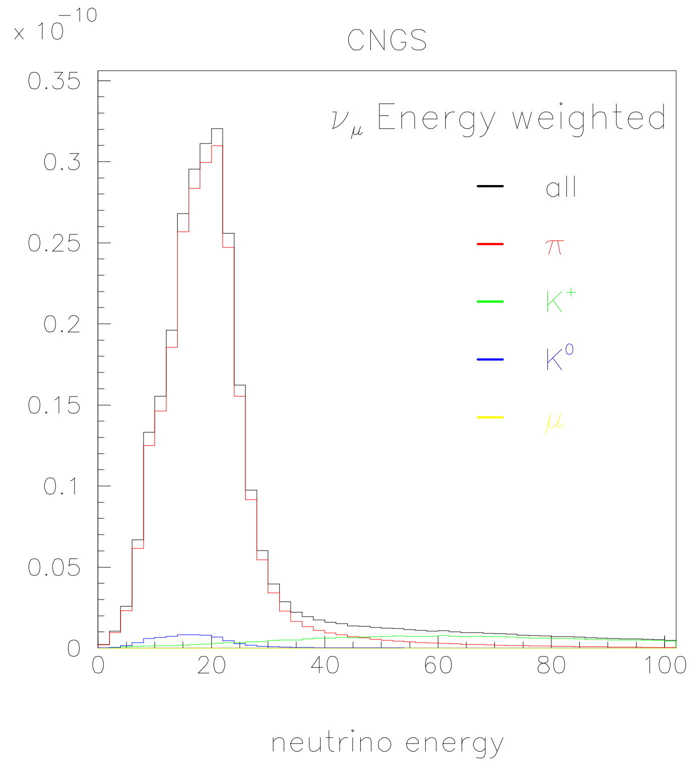


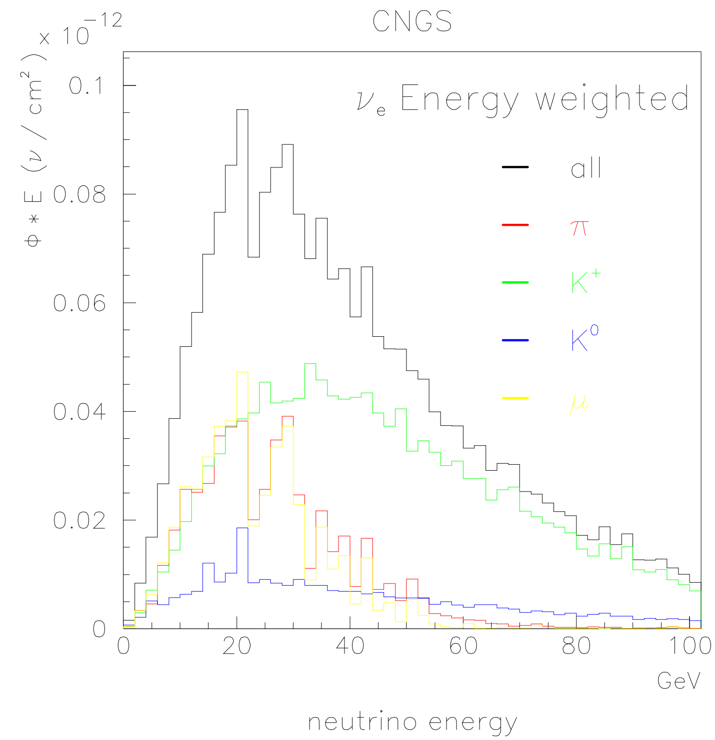
Invariant cross section distribution for π^+, 24 GeV/c protons on Be (T.Eichten et al. NPB 44, 333 (1972)).



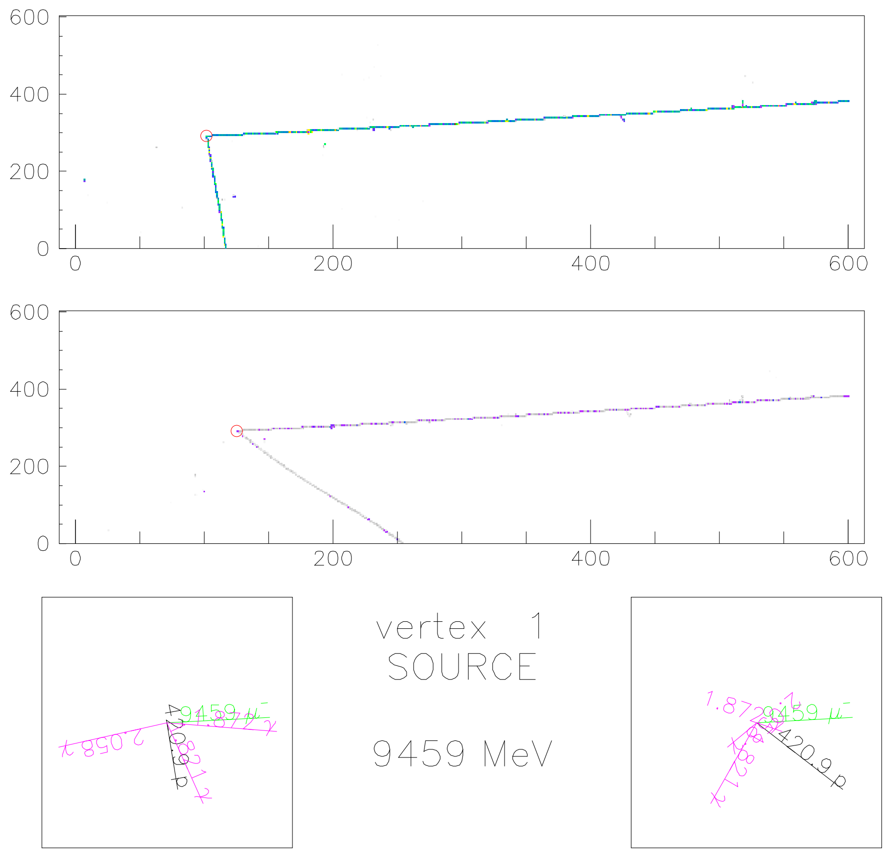
p_T spectra of π^+ and π^- produced by 16 GeV/c π^- on H. (M.E Law et al. LBL80 (1972)).

Nice agreement with experiment → confidence in prediction for CNGS





Neutrino quasi-elestic events



ICARUS prototype: two views in Liqid Argon, 10 GeV ν_μ CC

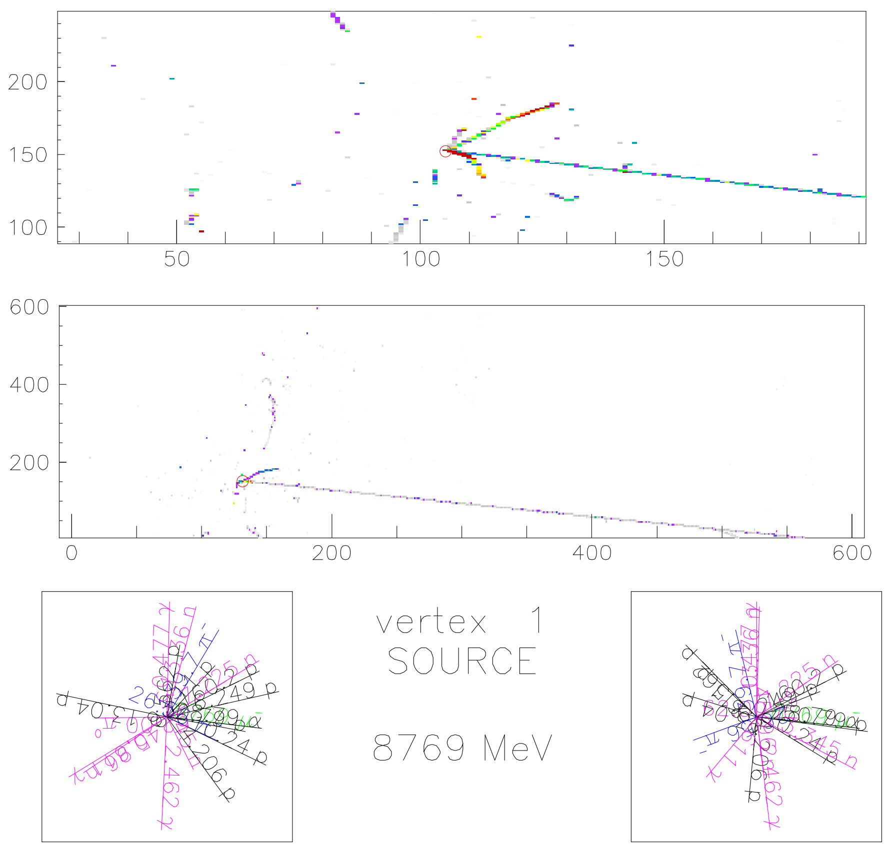
"Clean" event :

$$\nu_\mu\, n \rightarrow \mu^-\, p$$

$$\downarrow$$

$$\mu^- \;\; \mathrm{p}\; \gamma$$

Neutrino quasi-elestic events



ICARUS prototype: two views in Liqid Argon, 10 GeV ν_μ CC

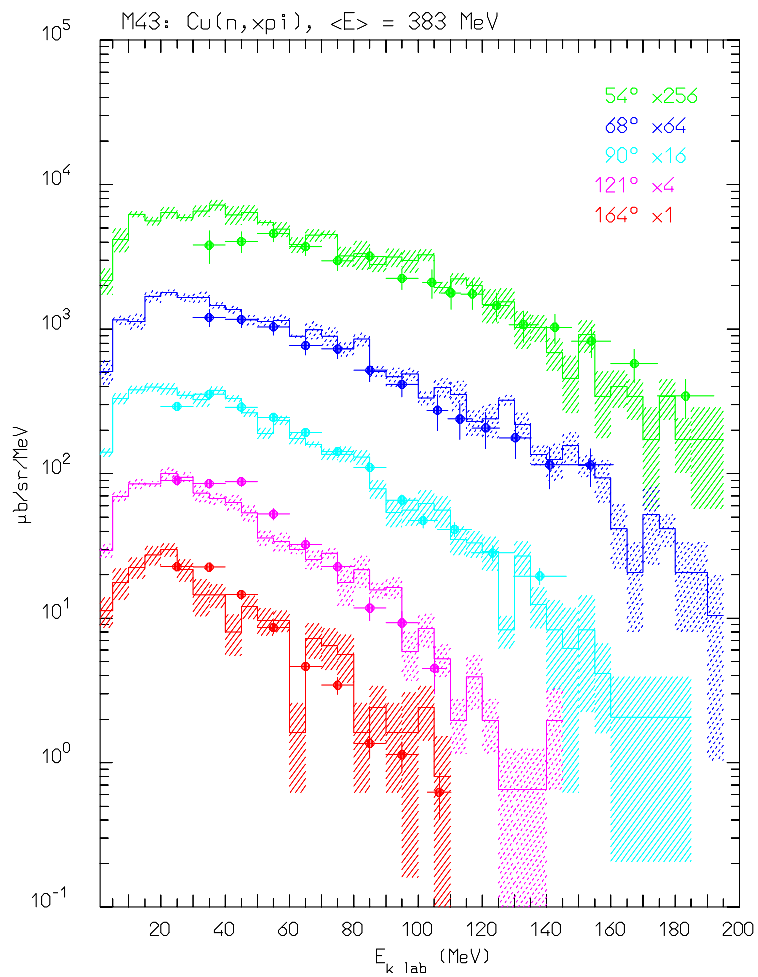
Complex event :

$$\nu_\mu \, n \rightarrow \mu^- \, p$$

$$\downarrow$$

1 μ^-, 8 p, 2 π^-, 1 π^0, 4 n, 1 α, 3 γ

Hadronic interactions at intermediate energies



PEANUT

GINC + preequilibrium+..

quantistic effects (Pauli blocking, formation zone..)

nuclear potentials and curvature of trajectories,

many-body effects

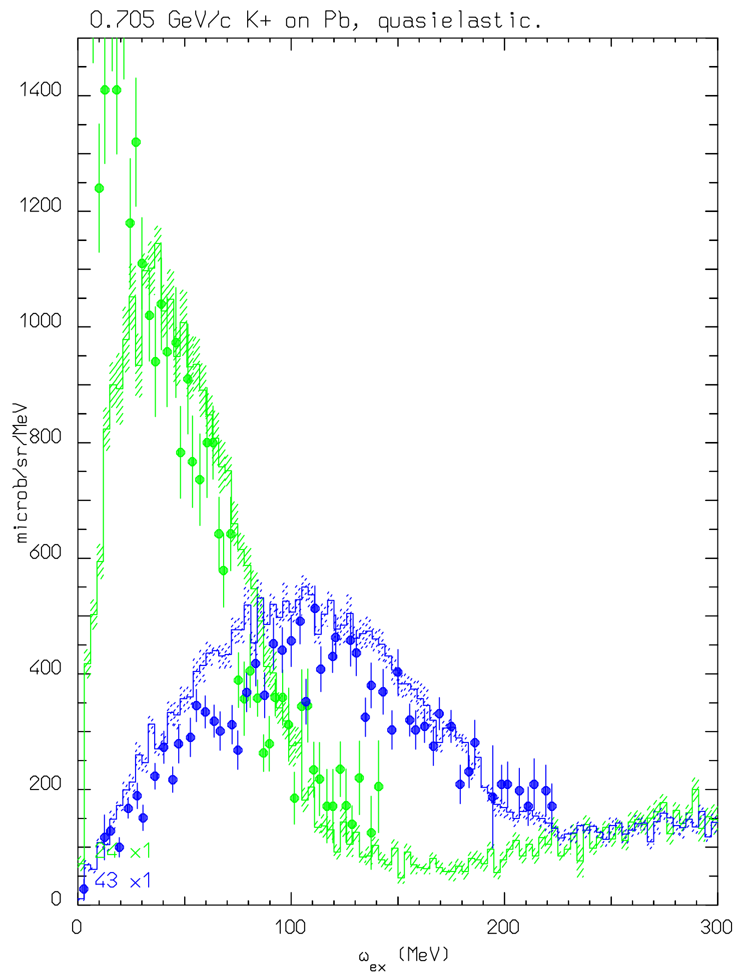
relativistic kinematics

binding energies, ..

Example: n+Cu→ πX, at 383 MeV. Exp. data (symbols) from

Buchle et al. **NPA515**, (1990) 541

Positive Kaons : example



K^+ K^0

No low mass S=1 baryons $\rightarrow$
weak K^+N interaction
only elastic and ch. exch. up to ≈ 800 MeV/c

$(K^+, K^{+\prime})$ on Pb vs residual excitation, 705 MeV/c, at 24° and 43°.
Histo: FLUKA, dots: data (Phys. Rev. C51, 669 (1995))

On free nucleon: recoil energy :
43 MeV at 24° , 117 MeV at 43°.

Neutrino interactions in PEANUT: *NUX-FLUKA*

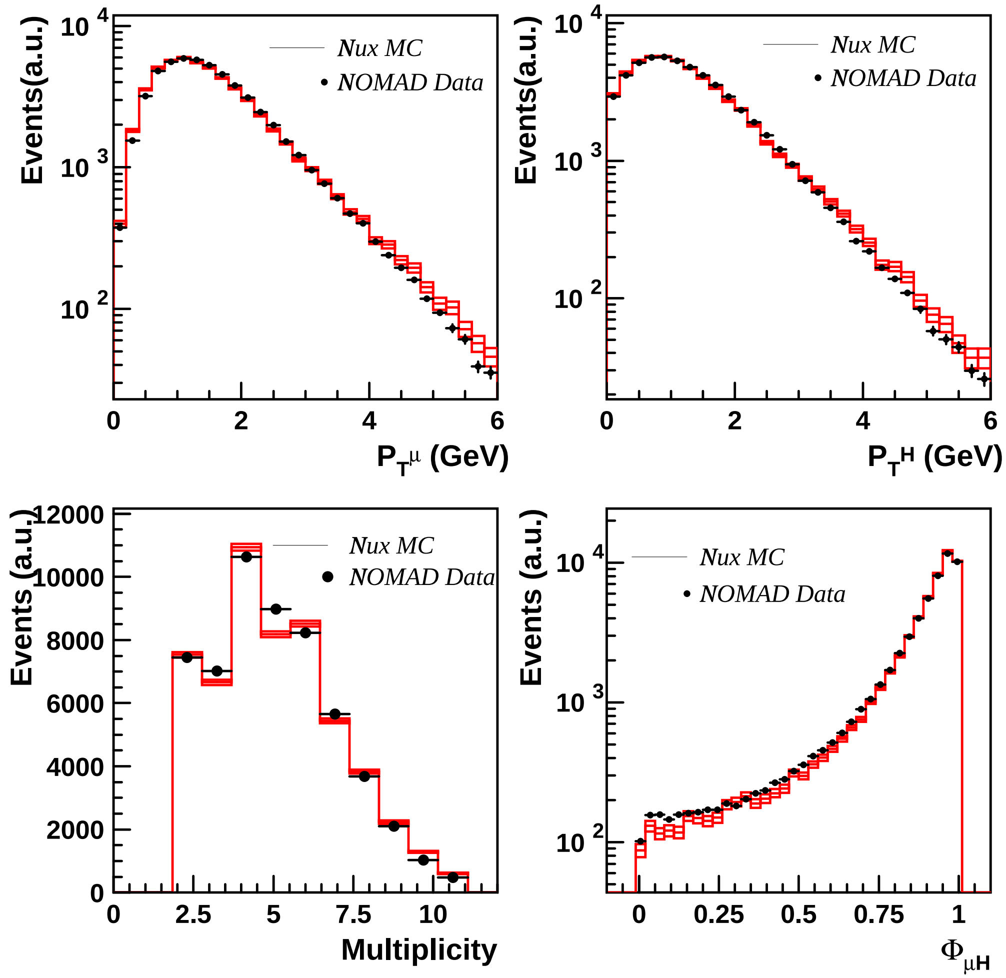
Authors: A. Ferrari , A. Rubbia, P.R. Sala

Quasielastic event generator built-in

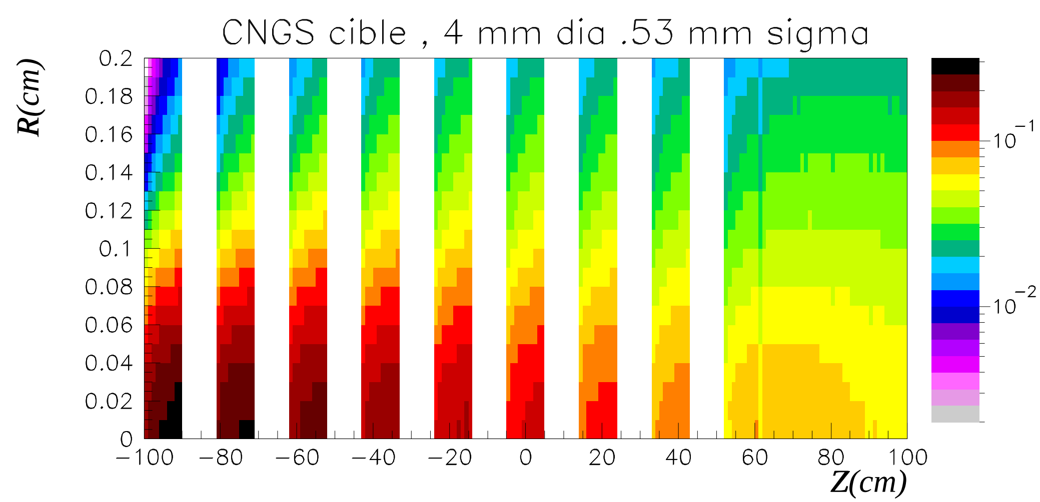
RES and DIS: νN interaction via *NUX* (A.Rubbia, originally for NOMAD)

Nuclear effects from PEANUT

Comparison with NOMAD data A. Bueno, A. Rubbia, ETH Zurich

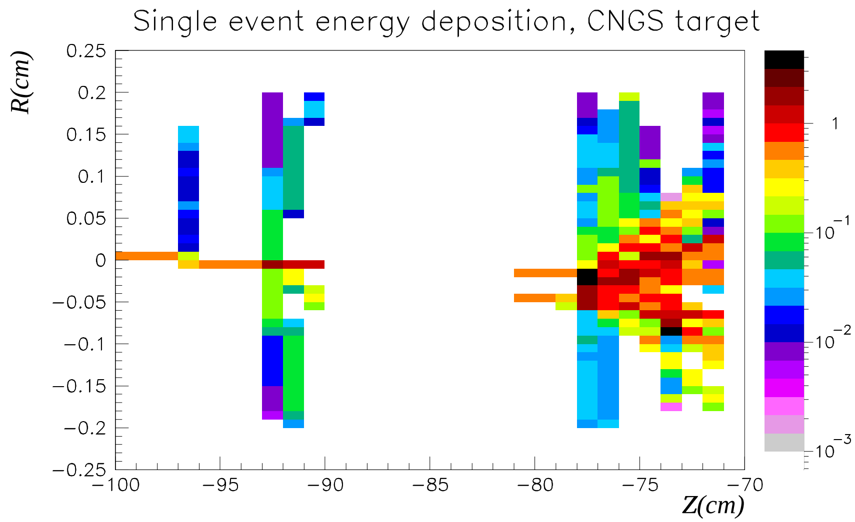


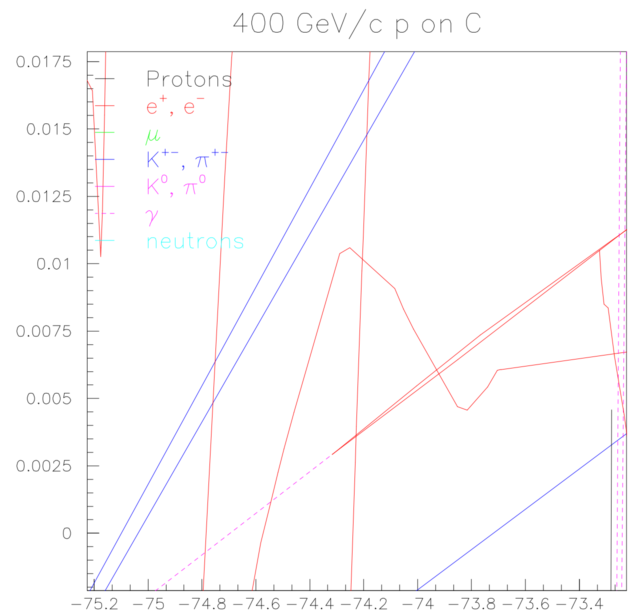
Baseline CNGS target : 13 Graphite rods, ⊘=4 mm, total length 2000 mm, Carbon length 1277 mm



Energy depostion in the standard CNGS target, in GeV/cm^3/primary, for a 400 GeV proton beam with σ=0.53mm

Energy deposition and zoomed section of the same CNGS event shown before





Charged particle transport

Ionization energy losses (below δ threshold)

Latest recommended values of ionization potential and density effect parameters implemented (Sternheimer, Berger & Seltzer) (can be overridden on user's request)
Special treatment of positron dE/dx (Kim et al. 1986)
A new general approach to ionization fluctuations

Multiple coulomb scattering

path length correction, lateral displacement, angle correlation
Soft approach to boundaries
Single scattering available, automatic if needed
Screening and spin-relativistic correction
Fully coupled to magnetic field transport

EMF : ElectroMagnetic Fluka

Photoelectric : fluorescence,angular distribution,Auger , polarization

Compton and Rayleigh: atomic bonds,polarization

Pair production correlated angular and energy distribution; also for μ

Photonuclear see later; also for μ

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

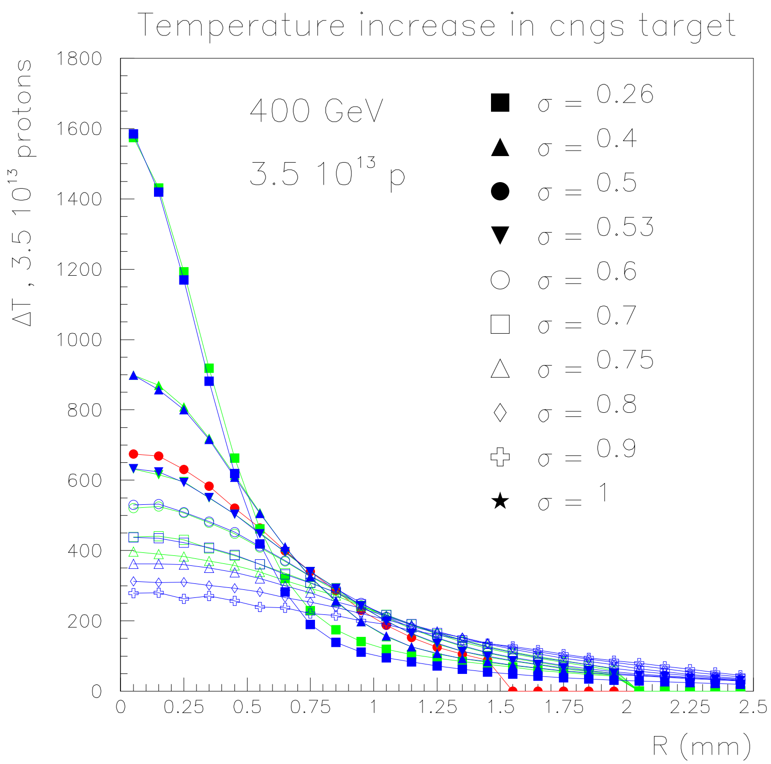
Bhabha and Møller scattering

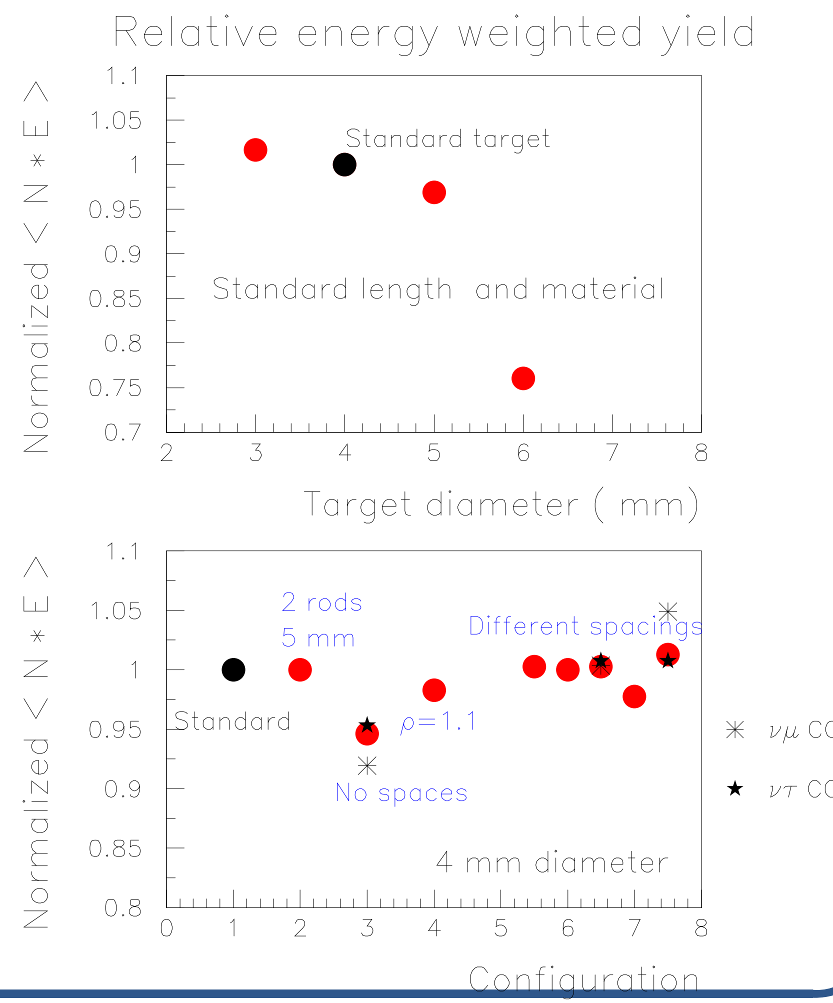
Positron annihilation at rest and in flight

μ^- capture at rest

Optical photon (Čerenkov) production and transport

Target optimization





LHC beam dump

LHC beam dump

LHC beam dump

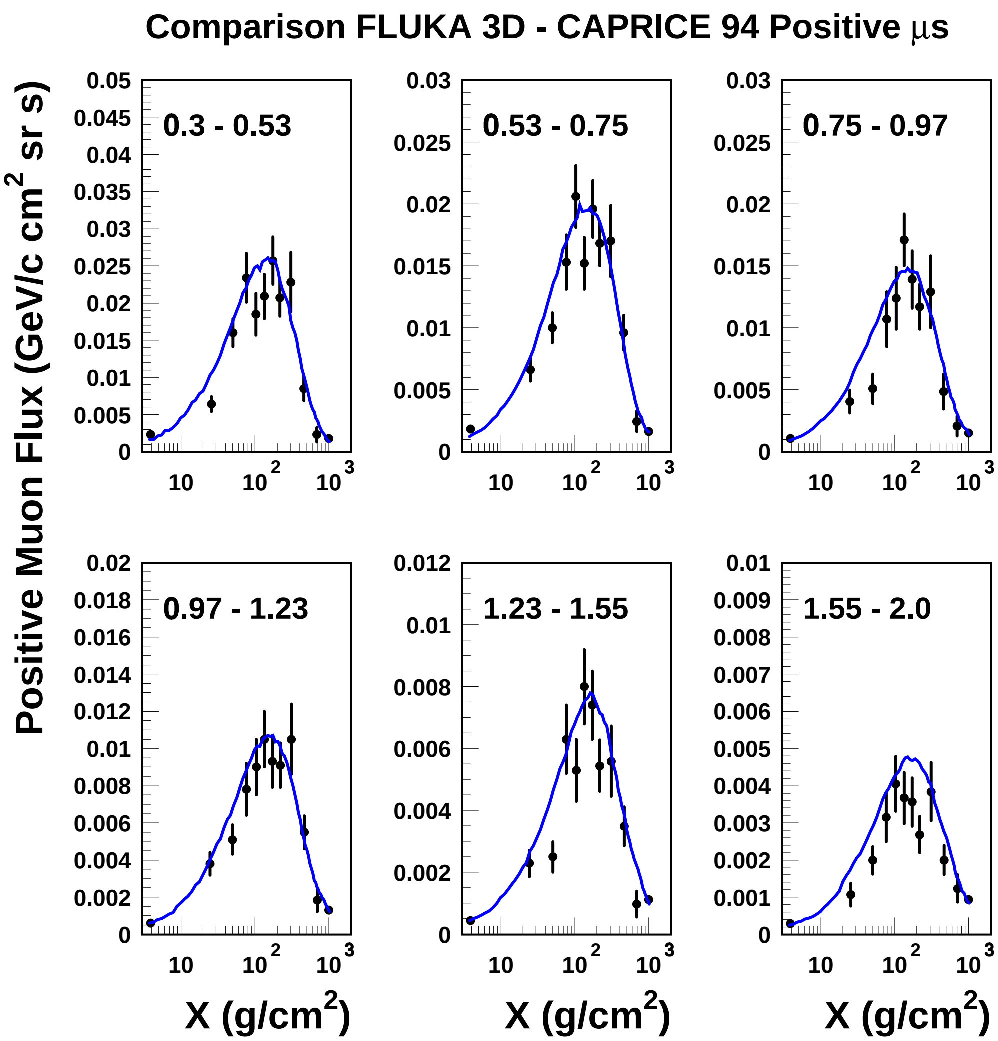
The ingredients and the recipe

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

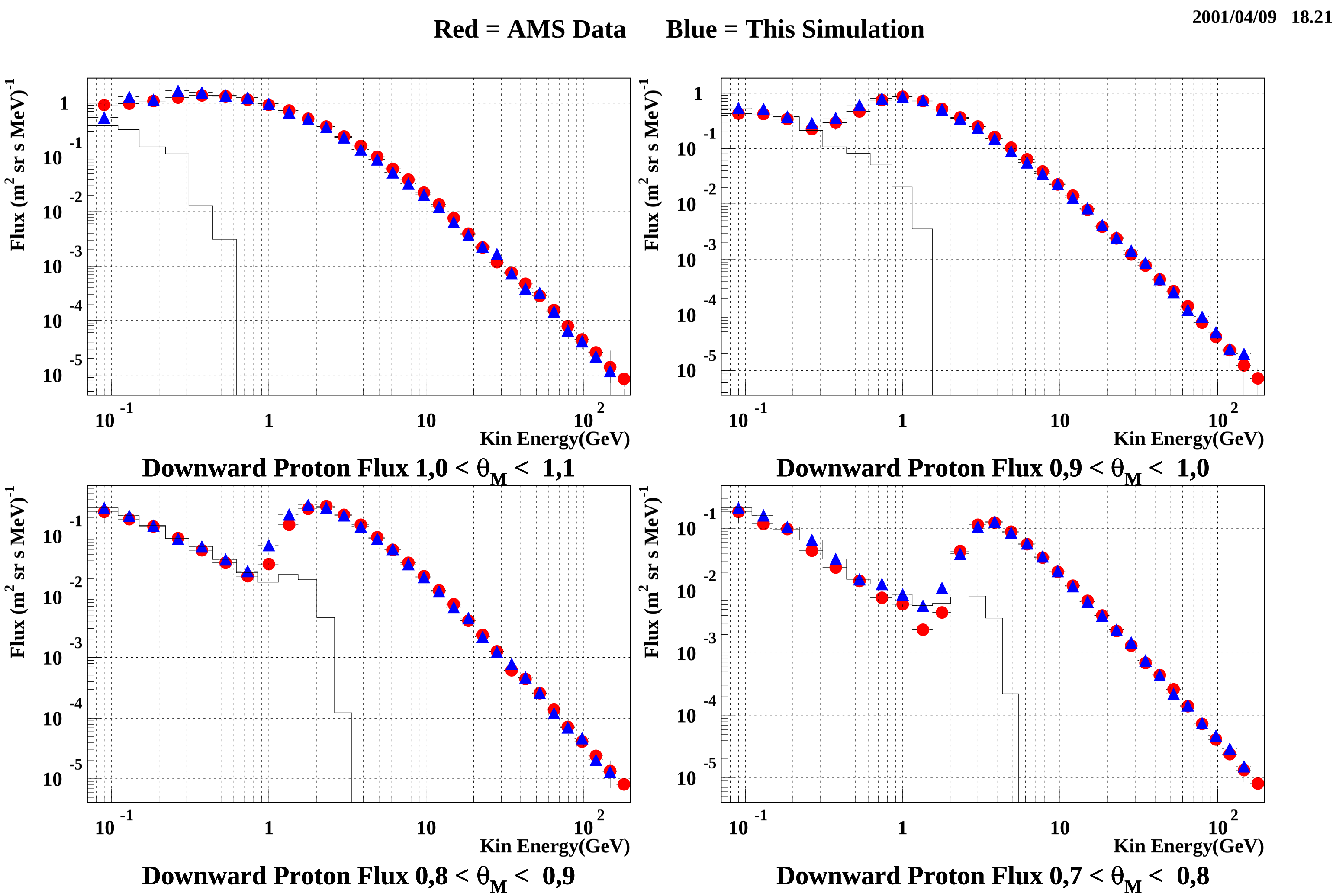
Standard Calculations: HKKM [1] Bartol [2]

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

Hadron/muon fluxes



AMS I (thanks to P.Zuccon et al., INFN and Univ. Perugia)



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 on LEP beam dumps.

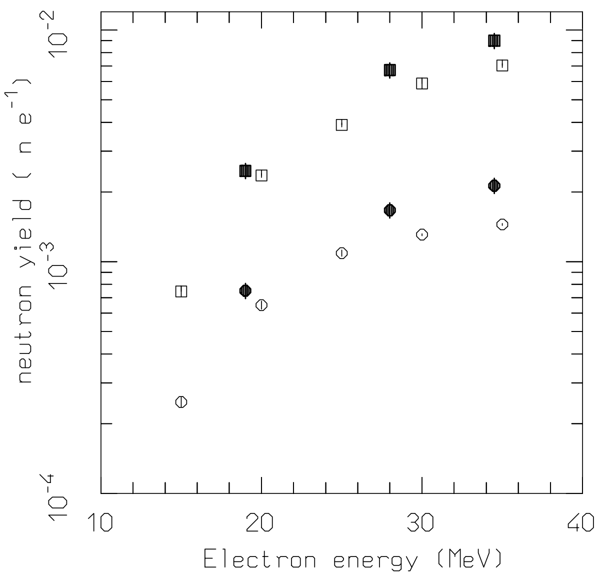
- Irradiation time: 5 months, at about 20 cm from the beam axis
- Specific activity of the radionuclides detected in the samples were compared with FLUKA calculations
- The measured activities are so low (few Bq/g) that even the experimental measurement is difficult

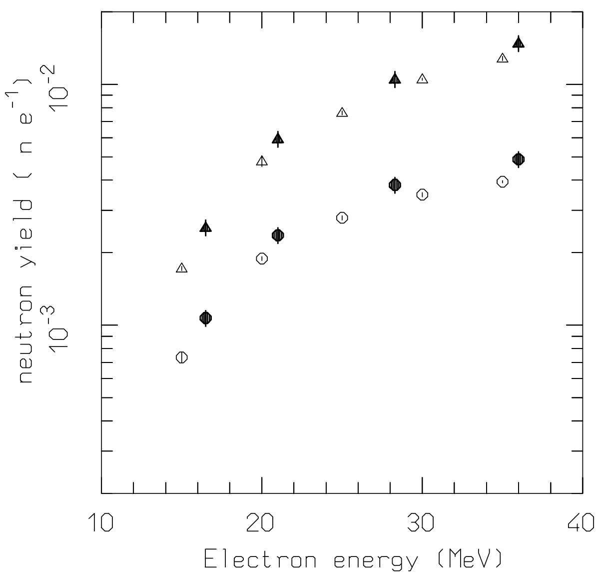
Photonuclear Interactions

- Giant Resonance interaction
- Quasi-Deuteron effect
- interaction in the Delta Resonance energy region
- Vector Meson Dominance in the high energy region
- INC, preequilibrium and evaporation via the PEANUT model
- Possibility to bias the photon nuclear inelastic interaction length to enhance interaction probability

In not many other existing transport codes photonuclear reactions are simulated over the whole energy range

Photonuclear Interactions





Yield of neutrons per incident electron as a function of initial electron energy. Open symbols: FLUKA, closed symbols: exp. data. Left: Pb, 1.01 (lower points) and 5.93 (upper) X_0 Right: U, 1.14 and 3.46 X_0

Evaporation

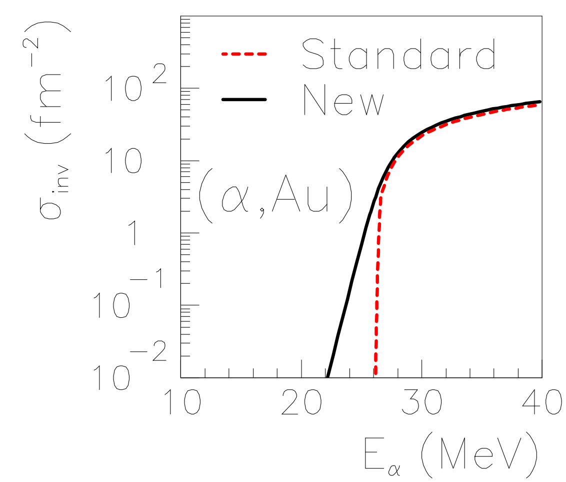
Weisskopf-Ewing evaporation

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

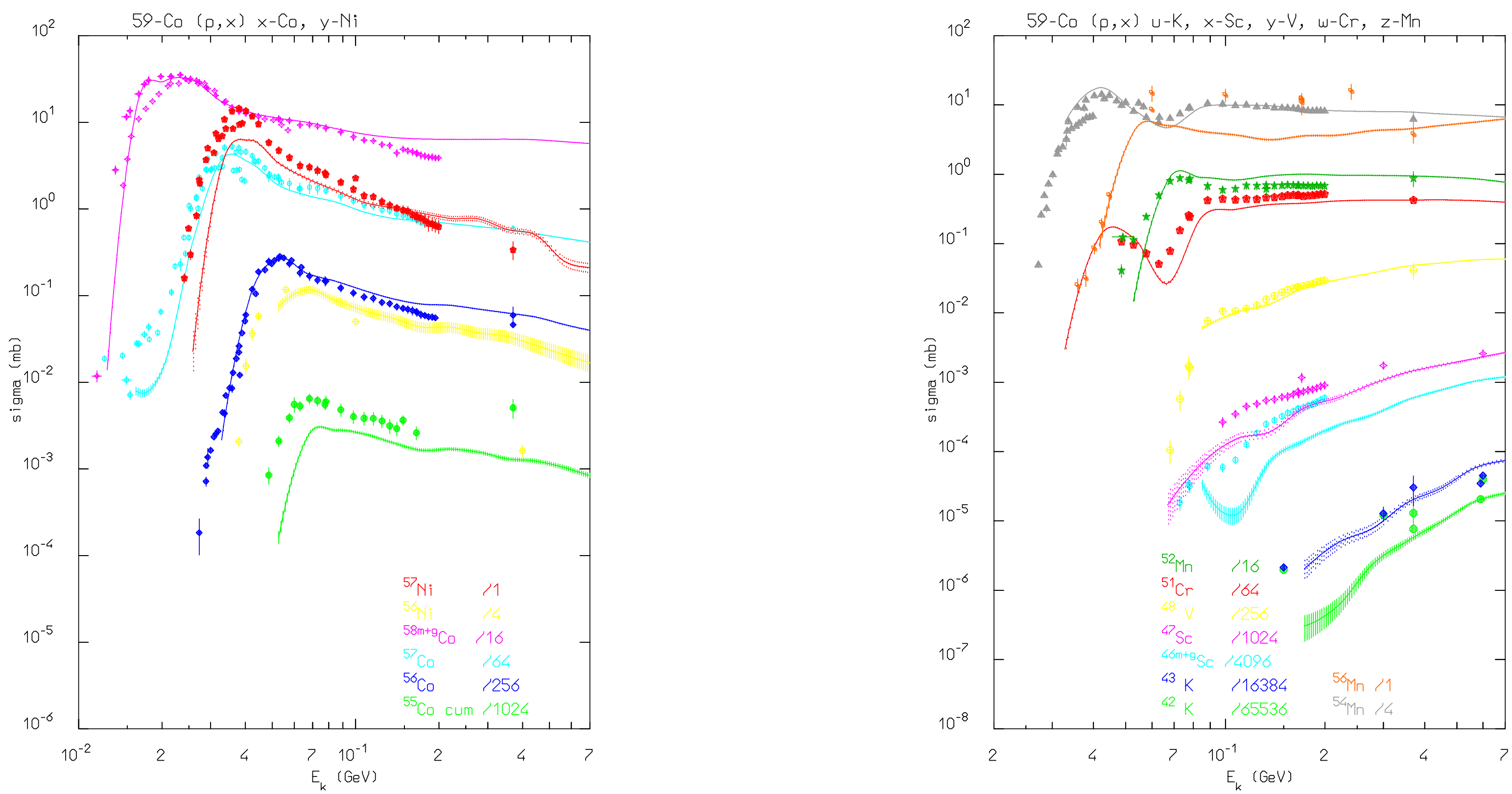
- Improved state density $\rho = \exp(2\sqrt{aU})/U^{\frac{5}{4}}$
- No Maxwellian approximation for energy sampling
- γ competition in progress

•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

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)

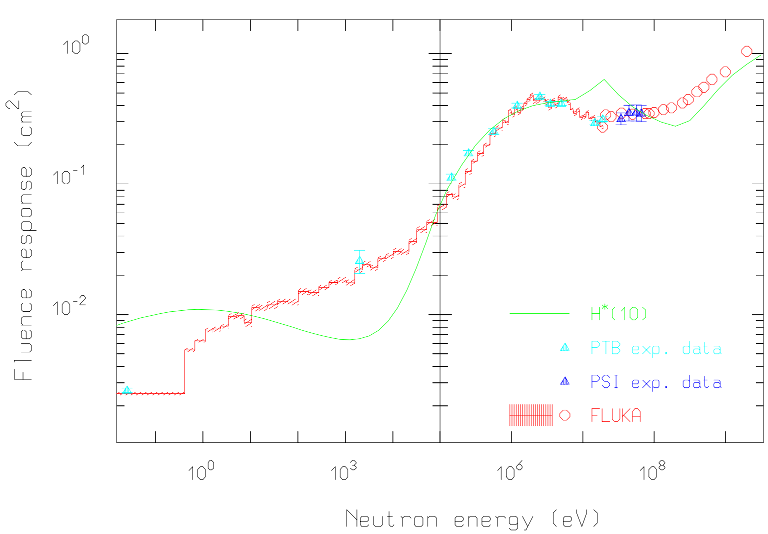
The CERN reference radiation facility – CERF

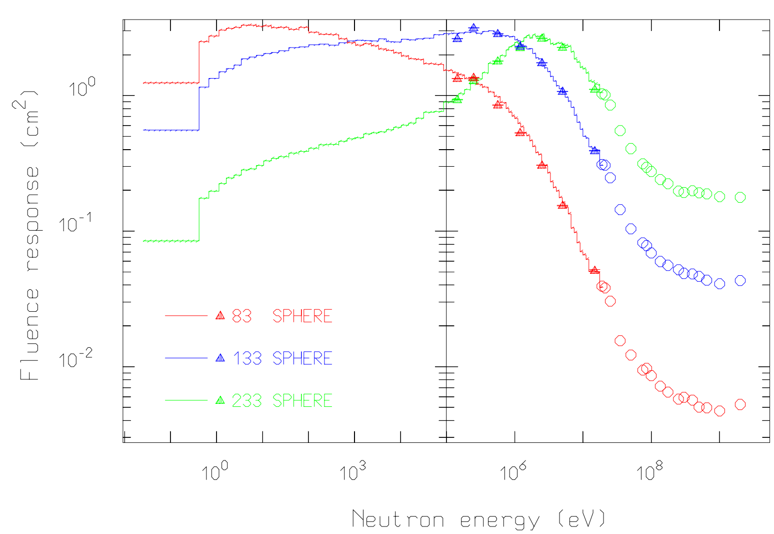
- A reference radiation facility (called CERF) for the calibration and intercomparison of dosimetric devices in high energy stray radiation fields is available at CERN since 1993, on the H6 beam line in the North Area.
- Hadron beams with momentum of either 120 or 205 GeV/c are stopped in a copper target, 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 transport below 20 MeV

- ENEA multigroup cross-sections: 72 groups, $\approx$100 elements/isotopes
- gamma-ray generation,different temperatures, Doppler broadening, self-shielding.
- Transport: standard multigroup transport with photon and fission neutron generation.
- Detailed kinematics and recoil transport for elastic and inelastic scattering on hydrogen nuclei.
- Photons transported with the EMF package
- Kerma factors to calculate energy deposition
- residual nuclei production

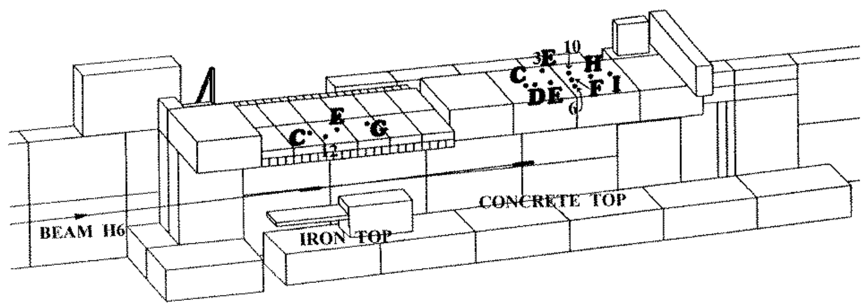
Neutron detector calibration

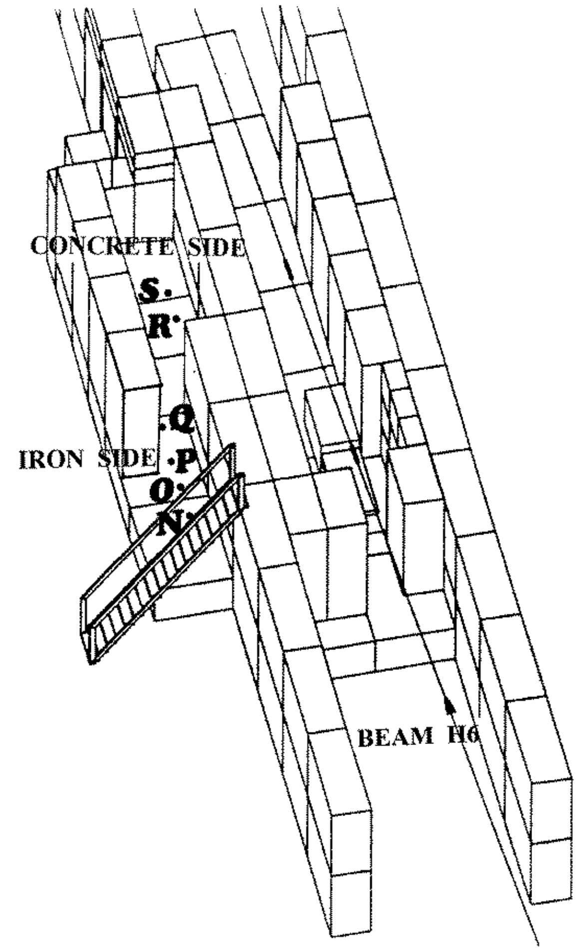




Calibration of the LINUS rem counter (left) and of three Bonner spheres (right) with monoenergetic neutron beams at PTB–Braunschweig and with semi–monoergetic neutron beams at PSI (full symbols), compared with simulations (dashed histos and open circles)

CERF: layout





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

CERF: some results

	experimental		FLUKA		experimental		FLUKA	
	cts/PIC	%	cts/PIC	%	cts/PIC	%	cts/PIC	%
	CONCRETE TOP “E”				IRON TOP “C”			
LINUS rem counter*	0.364	0.36	0.409	2.2	1.78	0.30	1.68	2.1
SNOOPY rem counter*	0.200	0.59	0.207	3.3	1.83	0.75	1.71	2.0
233 sphere	0.788	0.33	0.899	3.7	9.28	0.28	9.23	2.0
178 sphere	0.989	0.36	1.01	3.4	16.1	0.24	16.9	1.9
133 sphere	1.02	0.30	0.981	3.2	19.2	0.19	21.2	1.9
108 sphere	0.942	0.35	0.883	3.1	17.7	0.20	19.2	1.9
83 sphere	0.704	0.30	0.717	3.1	11.2	0.26	12.1	1.9

Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN [3]. The percent statistical uncertainty (%) is indicated.

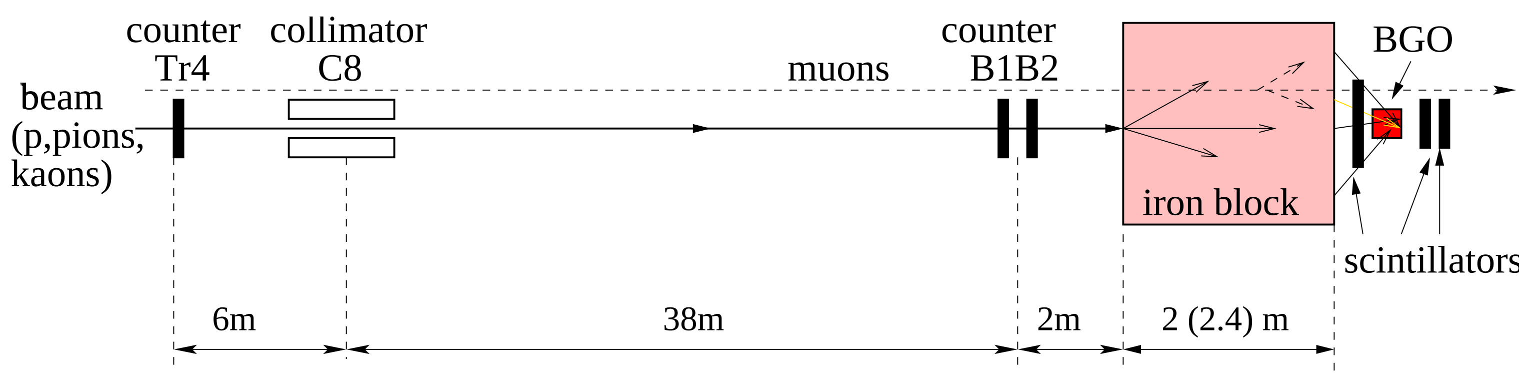
[3] C.Birattari et al., Rad.Prot.Dos.**76** (1998) 135

LHC background benchmarking

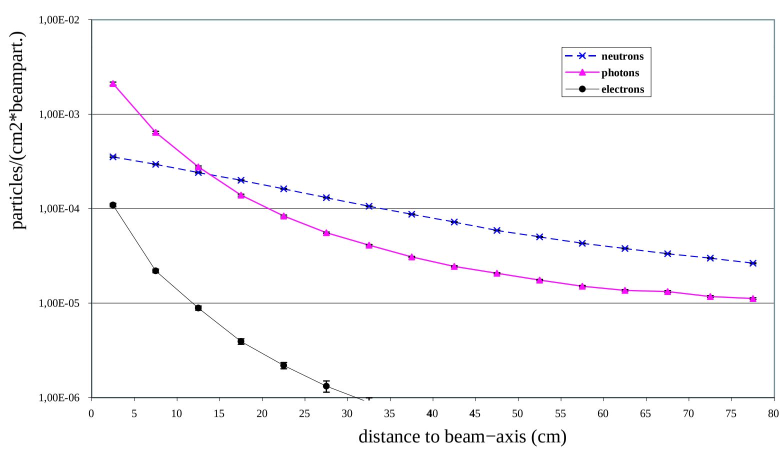
Absolute yield and spectral measurements of photons and neutrons emanating from the final stages of hadronic showers have been checked with a $Bi_4Ge_3O_{12}$ detector with 40 and 120 GeV/c beams on 11 λ (200 cm) and 14 λ (240 cm) thick cast iron targets

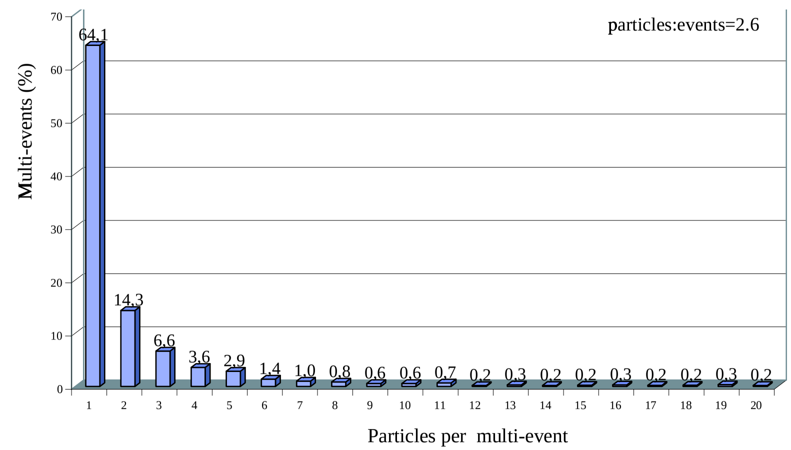
The results were intended to verify or disproof the simulations used for assessing the soft particle background at LHC experiments

(E. Gschwendtner, H. Vincke, C.W. Fabjan, N. Hessey, T. Otto, CERN-EP/2001-025, submitted to NIMA)



LHC background benchmarking





Computed shower composition at 40 GeV/c, 240 cm thickness (left), and computed event multiplicity in the BGO (right)

Showers are still dominated on axis by late π^0

$\Downarrow$

The event multiplicity and possible accompanying charged particles must be accounted for in order to repoduce properly the experimental conditions and vetos

LHC background benchmarking II

Measurement set-up	Signal rate $\times 10^{-4}$ Measured	Signal rate $\times 10^{-4}$ Simulated	Ratio meas./sim.
$p_{\mathrm{beam}} = 40\,\mathrm{GeV}/c$			
200 cm on-axis	76.2 ± 0.4	$71.8^{+6.7}_{-14.9}$	$1.06^{+0.10}_{-0.22}$
200 cm off-axis	6.8 ± 0.2	$6.1^{+0.8}_{-0.7}$	$1.12^{+0.14}_{-0.13}$
240 cm on-axis	23.0 ± 0.4	$15.8^{+2.7}_{-3.6}$	$1.46^{+0.25}_{-0.33}$
240 cm off-axis	2.3 ± 0.1	$1.9^{+0.3}_{-0.2}$	$1.24^{+0.19}_{-0.15}$
$p_{\mathrm{beam}} = 120\,\mathrm{GeV}/c$			
200 cm off-axis	26.3 ± 0.4	$26.0^{+3.0}_{-2.9}$	$1.01^{+0.12}_{-0.12}$
240 cm on-axis	93.5 ± 1.7	$78.6^{+9.6}_{-11.1}$	$1.19^{+0.15}_{-0.17}$
240 cm off-axis	9.7 ± 0.6	$7.8^{+1.4}_{-1.3}$	$1.24^{+0.24}_{-0.21}$
		Weighted average	1.13 ± 0.06

Summary of measured and simulated signal rates in the energy interval $0.35\,\mathrm{MeV} < E < 9\,\mathrm{MeV}$ per incident beam particle

LHC background benchmarking III

Measurement set-up	$\langle E$-deposition$\rangle$ [MeV]	
	Measured	Simulated
$p_{\mathrm{beam}} = 40\,\mathrm{GeV}/c$		
200 cm on-axis	2.045 ± 0.018	2.057 ± 0.174
200 cm off-axis	1.615 ± 0.004	1.618 ± 0.041
240 cm on-axis	1.923 ± 0.009	1.824 ± 0.073
240 cm off-axis	1.666 ± 0.003	1.530 ± 0.021
$p_{\mathrm{beam}} = 120\,\mathrm{GeV}/c$		
200 cm off-axis	1.572 ± 0.009	1.805 ± 0.091
240 cm on-axis	2.051 ± 0.020	2.058 ± 0.183
240 cm off-axis	1.649 ± 0.006	1.687 ± 0.051

Summary of measured and simulated averaged energy depositions in the energy interval $0.35\,\mathrm{MeV} < E < 9\,\mathrm{MeV}$

Future developments:

- Ion interactions:
  - Consolidation and benchmarking of the interface with DPMJET
  - Extension of the present nuclear models to handle light ions in the intermediate energy range
- A new powerful and user friendly interface through the ROOT system
- Residual activity and dose rates: *Online use of databases for:*
  - *Cooldown* calculations (already implemented offline)
  - γ, β *and* α radiation emission and transport online.
- DPM: add multi-Pomeron exchanges
- PEANUT extension to high energy
- Refinements to evaporation, inclusion of heavy fragment emission
- New low energy neutron library

Different Applications

The FLUKA development, its accuracy and versatility originated to a great deal from the needs of the author experiments, and new applications arise from new code capabilities, with a continuous interplay which is always physics driven. Examples are given below.

- Neutrino physics and Cosmic Ray studies: initiated within ICARUS
  - Neutrino physics: ICARUS, CNGS, NOMAD, CHORUS
  - Cosmic Rays: First 3D ν flux simulation, Bartol, MACRO, Notre-Dame, AMS
- Accelerators and shielding : the very first FLUKA application field
  - Beam-machine interactions: CERN, NLC, LCLS
  - Radiation Protection: CERN, INFN, SLAC, Rossendorf
  - Waste Management and environment: LEP dismantling, SLAC
- Background and radiation damage in experiments: Pioneering work for ATLAS
  - all LHC experiments, NLC

Different Applications

- Dosimetry, radiobiology and therapy :
  - Dose to Commercial Flights: E.U., NASA
  - Dosimetry: INFN, ENEA, GSF, NASA
  - Radiotherapy: Already applied to real situations (Optis at PSI, Clatterbridge)
  - Dose and radiation damage to Space flights: NASA, ASI
- Calorimetry:
  - ATLAS test beams
  - ICARUS
- ADS, spallation sources (FLUKA+EA-MC, C.Rubbia et al.)
  - Energy Amplifier
  - Waste trasmutation with hybrid systems
  - Pivotal experiments on ADS (TARC, FEAT)
  - nTOF