Review of Recent Applications of the FLUKA MC in High Energy and Accelerator Physics

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Example of recent applications of FLUKA

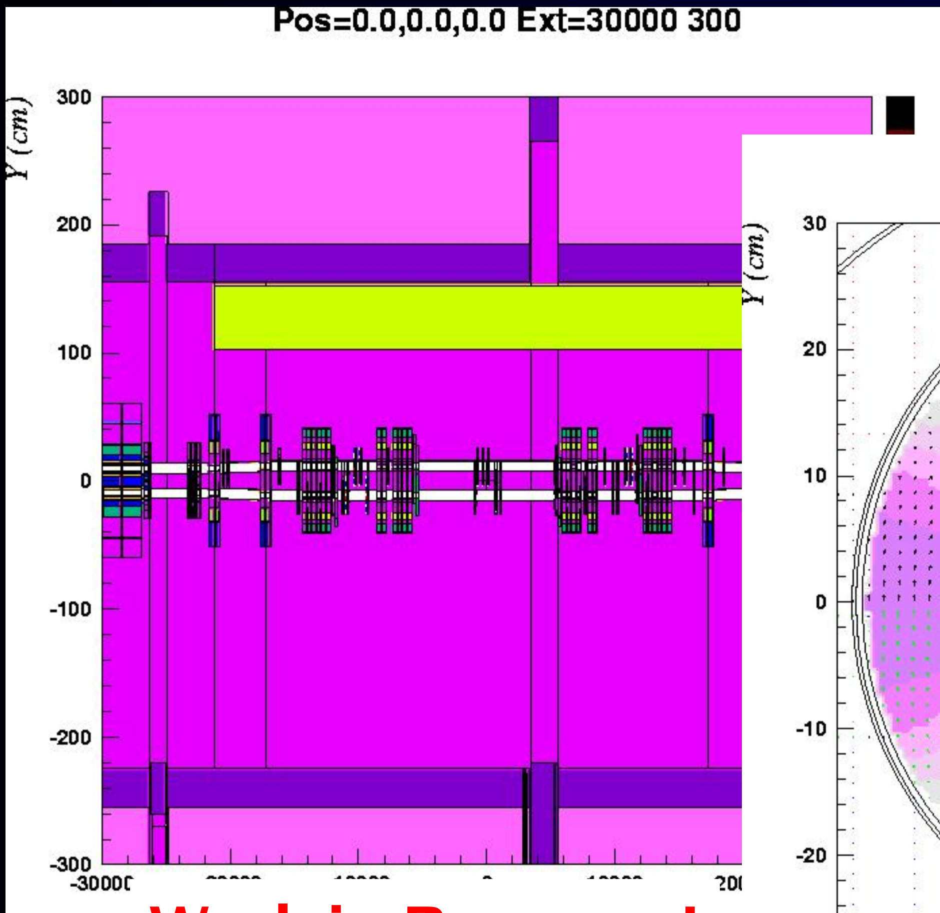
- **LHC**: collimation system design, beam-gas collision, study of targets, dumps and other critical points for the machine operation
- **Underground Physics**: HE cosmic ray physics
- **Space Physics**: cosmic rays and radiation effects

All applications demanding a high reliability in the whole processes from TeV to MeV physics

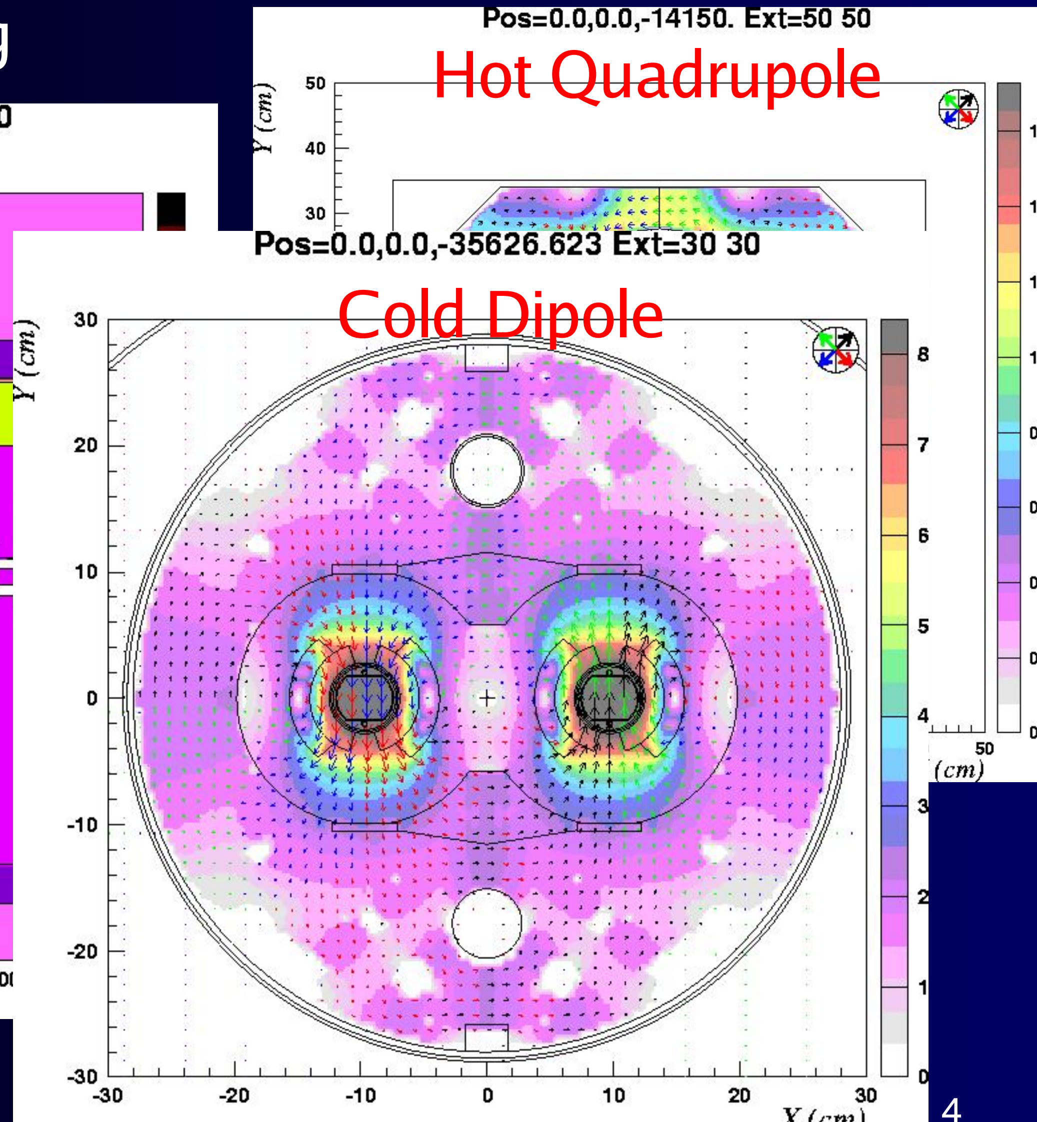
LHC

Simulations carried on by the CERN FLUKA group

Point 7: Beam Cleaning



Work in Progress!



Estimate of radiation damage to low-level electronics of the RF system in the LHC cavities, produced from beam gas collisions.

A. Ferrari, K. Tsoulou, V. Vlachoudis
CERN

- **16 superconducting radiofrequency cavities**
  - **accelerate and control the beams**
  - **many feedback loops for beam control**

- **Radiation Effects to RF electronics will result in the proton beam becoming unstable and being dumped**
  - **several hours of recovery time**
  - **high risk of damage due to stored energy**

Possible Radiation Effects

Cumulative Effects

Total Ionising Dose (TID)

✓ Energy deposition (dose)

Displacement Damage (DD)
or Non-Ionising Energy Loss (NIEL)

Bulk effects in semi-conductor electronics

✓

Statistical Effects

Measurable effects to a circuit due to an ion strike

Single Event Errors (SEE) – a variety of hard (destructive: Latch-Up, Burn-Out) or soft (data corruption: Upset) errors

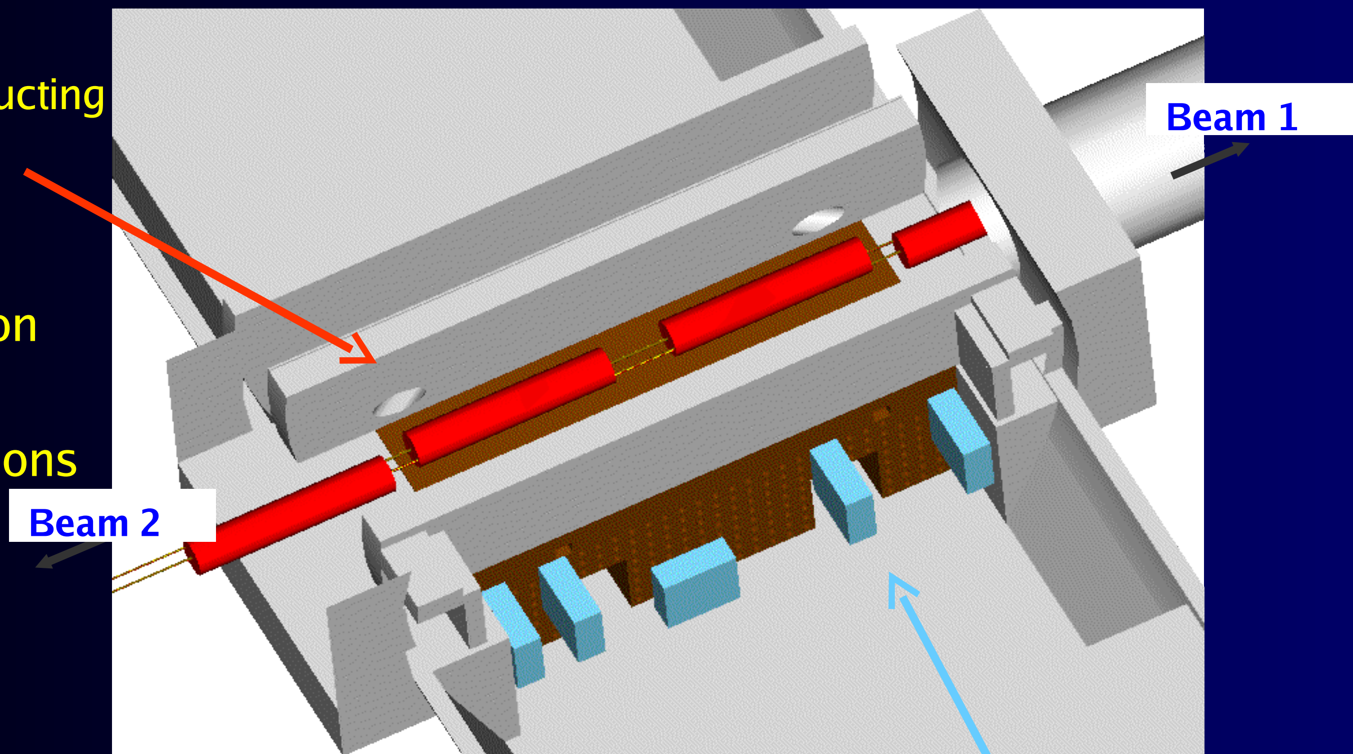
✓ Hadron fluence for E > 20MeV

Simulation with FLUKA

Conditions

FLUKA Geometry by AutoCAD

accelerating superconducting cavities (ACS)

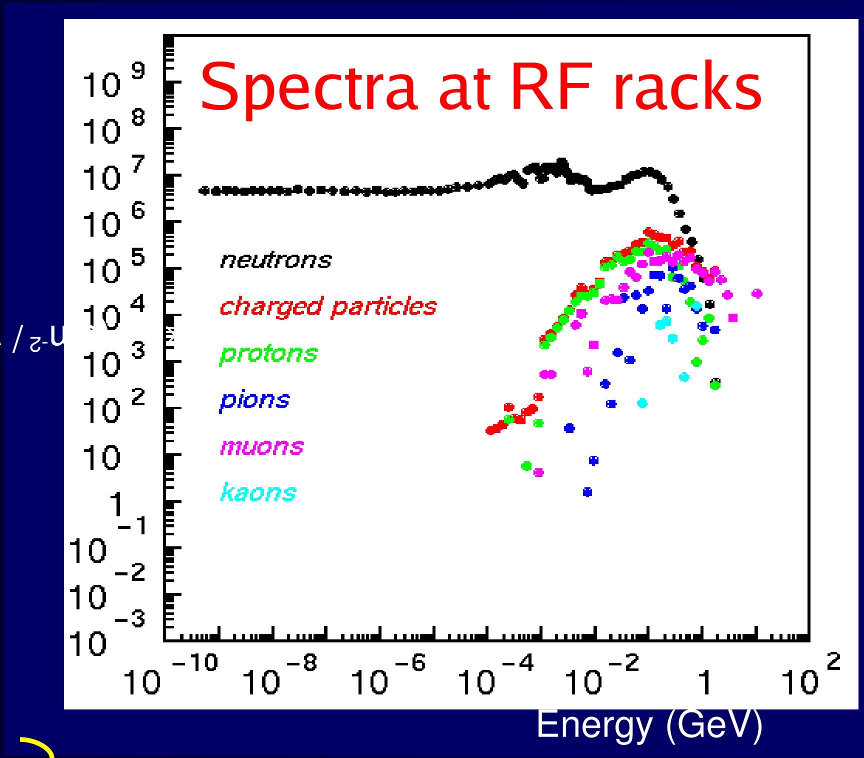


racks for RF electronics (scoring in air)

- ➔ Hadrons > 1 MeV
- ➔ No e^-/γ transportation (No dose calculation)
- ➔ Geometry Simplifications (ACS,APW)
- ➔ Specific residual gas compositions
- ➔ Re-scaling if different residual gas densities

Results

Neutrons (90%) and charged particles up to a few GeV



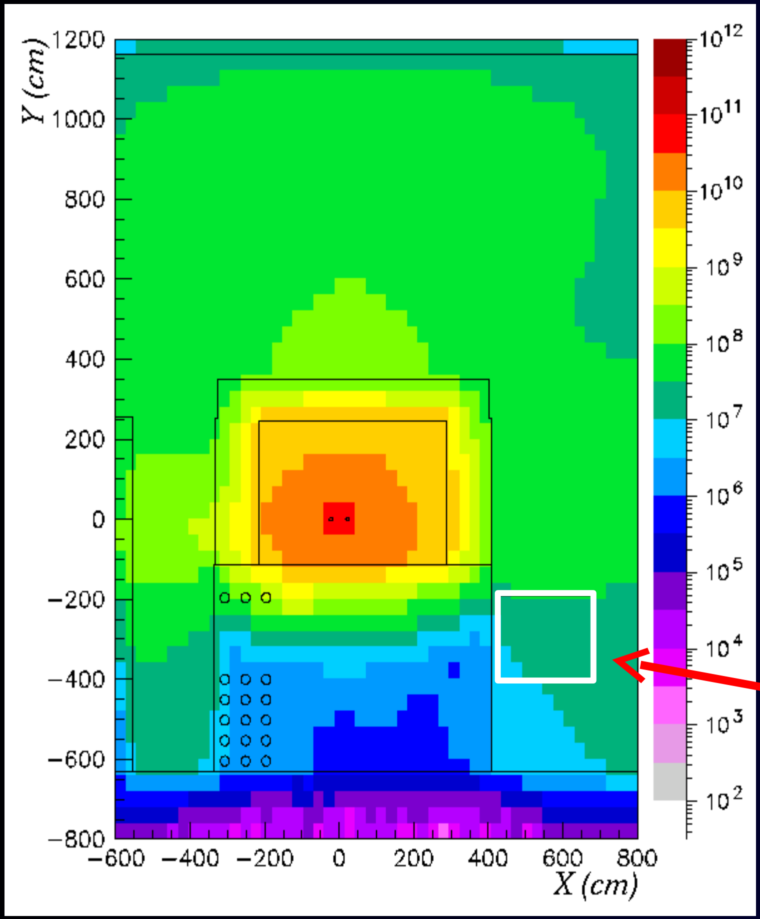
Energy thresholds	Hadrons (cm^{-2} / year)
> 1 MeV	1.1×10^7
> 20 MeV	5.0×10^6
> 250 MeV	2.5×10^5

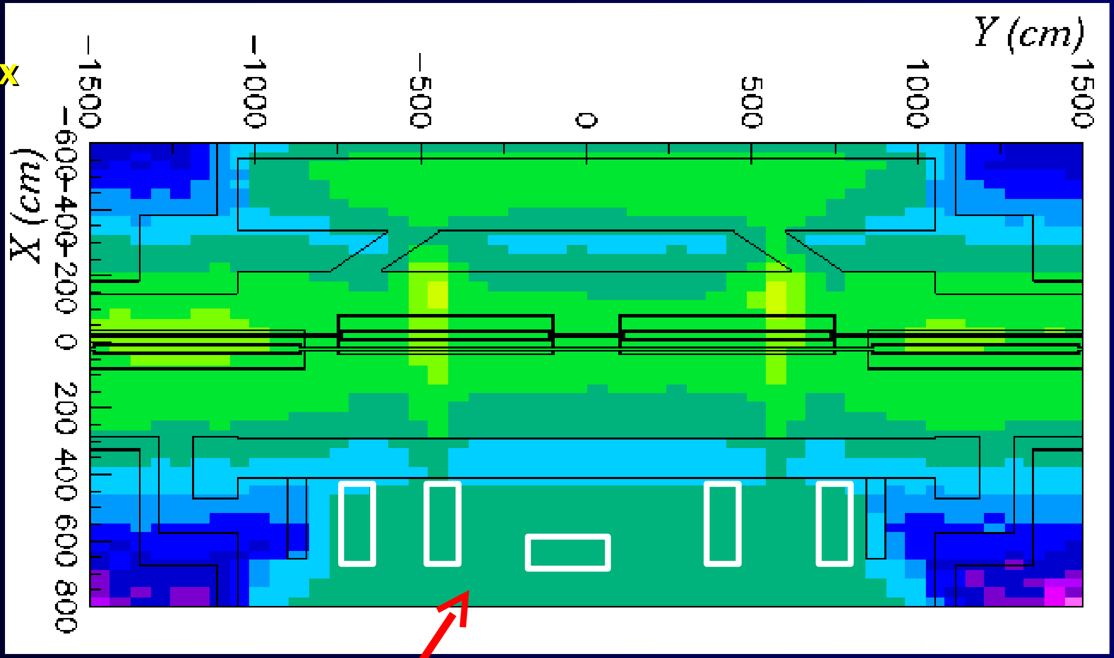
95 % from the beam lines

Results

1 MeV n eq. flux

1MeVneq. flux (cm^{-2} / year)





1 MeV n eq. flux: ~ 1.5 × 10^{7} cm^{-2} / year

LHC: Conclusions on RF damage

Displacement Damage

1 MeV n eq. flux: $4 \times 10^{7} \rightarrow 4 \times 10^{8}$ cm^{-2} / year

- ✓ Displacement Damage is not threatening for the near future.
- ✓ DD will become important for fluences > 10^{10} cm^{-2}, no serious problems expected in the first 25 years…

Single Event Effects

Hadrons > 20 MeV flux: $5 \times 10^{6} \rightarrow 5 \times 10^{7}$ cm^{-2} / year

- ✓ Single Event Effects have an annual probability to affect the RF system around 20 –200 failures/year.

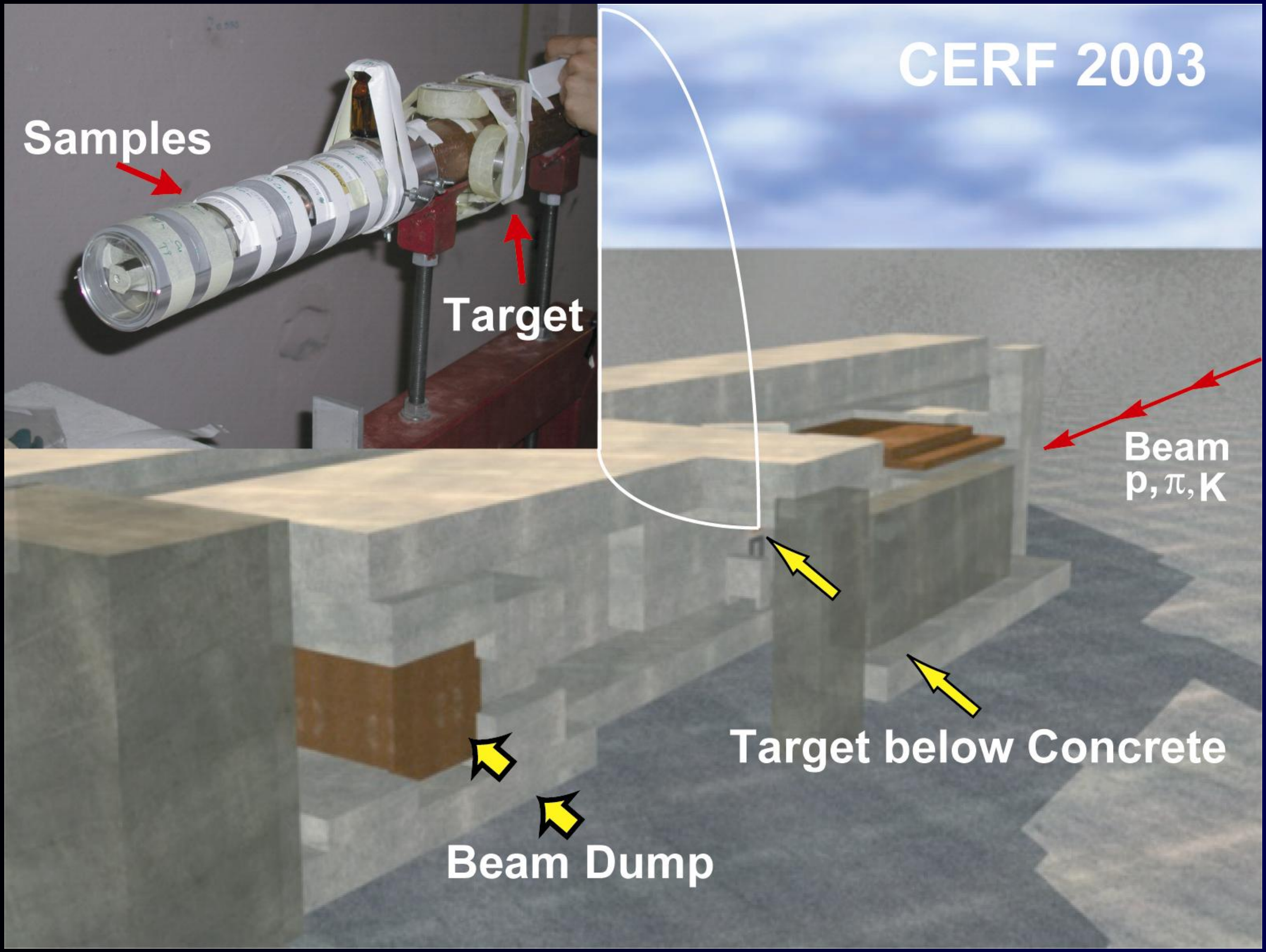
Benchmark Studies of Induced Radioactivity Produced in LHC Materials

From S. Roesler et al. (CERN)
presented at ICRS Madeira (2004)

- **Part 1: Specific Activities**
- **Part 2: Remanent Dose Rates**

- Beamline components at high-energy hadron colliders can become highly activated due to various beam loss mechanisms: it is an important radiation safety concern
- It is required to perform calculations of the radionuclide inventory rather accurately
- Modern computing techniques allow a detailed assessment of isotope production by high-energy particle beams

CERN-EU High-Energy Reference Field (CERF) facility



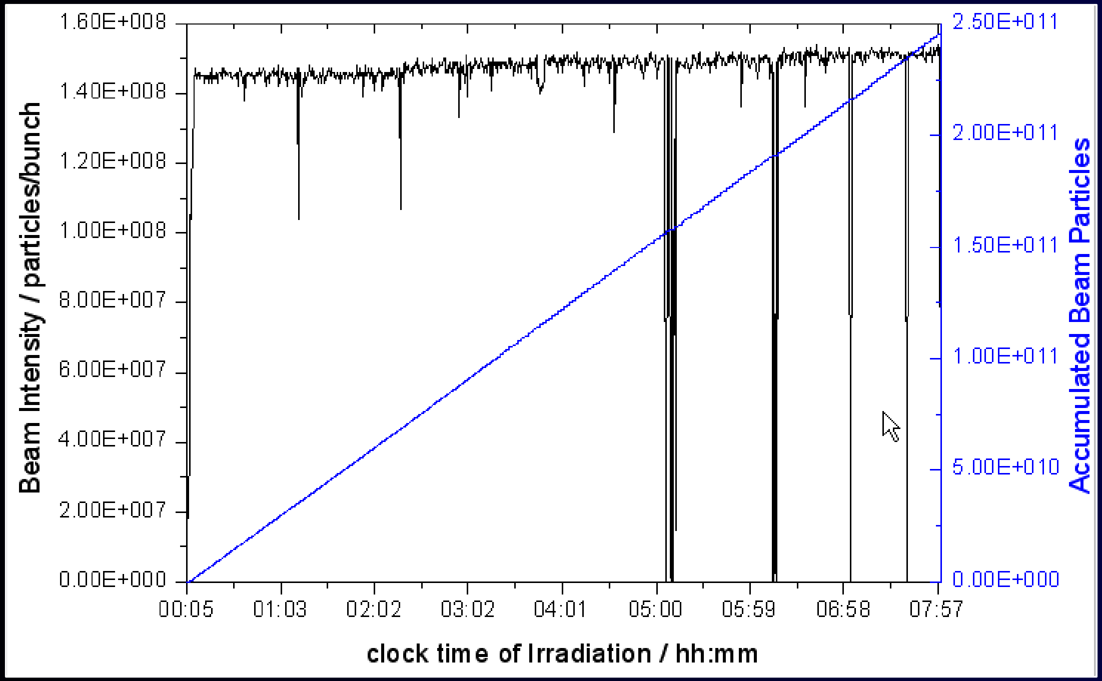
Location of Samples:

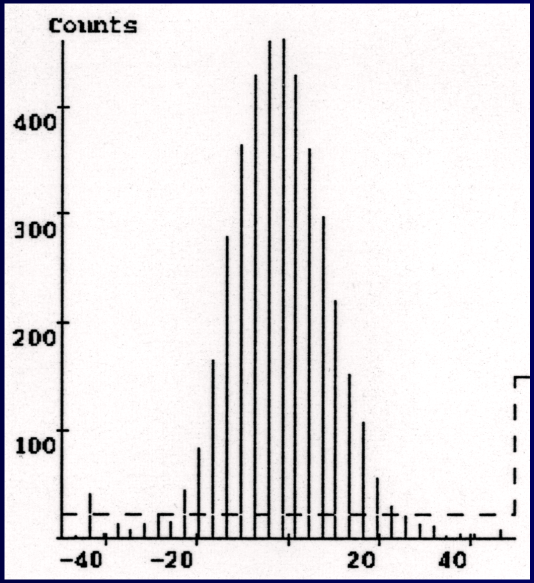
Behind a 50 cm long, 7 cm diameter copper target, centred with the beam axis

Beam Conditions

- 120 GeV secondary SPS mixed hadron beam
(p 34.8%, π 60.7% and K 4.5%)
- 16.8s spill cycle, 4s burst
- ~ 5×10^{10} (short) - 1×10^{12} (long) particles hit the target during irradiation

- Beam Profile (approx. Gaussian): measured with multi-wire prop. Chamber, $\sigma \sim 10$ mm





Details of Samples

Elemental composition in percent by weight											
Steel $\rho = 7.25$ g/cm³		Copper $\rho = 8.89$ g/cm³		Aluminium $\rho = 2.72$ g/cm³		Concrete $\rho = 1.70$ g/cm³		Titanium $\rho = 4.42$ g/cm³		Resin $\rho = 1.24$ g/cm³	
Fe	63.088	Cu	99.328	Al	96.4589	O	47.87	Ti	88.036	C	66.77
Cr	17.79	Al	0.4745	Si	1.08	Ca	35.4	Al	6.5	O	27.64
Mn	11.43	Si	0.13	Mg	0.83	C	9.24	V	5.28	H	5.59
Ni	6.5	Fe	0.0261	Mn	0.696	Si	4.0	Fe	0.093		
Si	0.38	S	0.0137	Fe	0.5	Al	0.97	Cr	0.05		
N	0.31	Cd	0.004	Cu	0.115	Fe	0.69	Ni	0.0116		
Co	0.11	Sb	0.004	Zn	0.1044	Mg	0.64	Cl	0.0102		
P	0.019	Cr	0.0021	Cr	0.033	H	0.6	Mn	0.0071		
C	0.095	Te	0.002	Ti	0.0302	K	0.26	Cu	0.0043		
Mo	0.09	Pb	0.002	Pb	0.0287	S	0.15	Zn	0.004		
Cu	0.085	Sn	0.002	Sn	0.0278	Ti	0.06	P	0.0038		
V	0.07	As	0.002	Ca	0.0201	Sr	0.05				
Ti	0.01	Ag	0.002	Bi	0.0161	P	0.03				
Nb	0.01	Zn	0.002	Ni	0.0128	Na	0.03				
W	0.01	Mn	0.0016	P	0.0126	Mn	0.01				
O	0.002	Se	0.0011	Ga	0.0102						
S	0.001	Bi	0.001	Cl	0.0087						
		Ni	0.001	S	0.0076						
		P	0.0004	V	0.0041						
		Co	0.0002	Zr	0.0024						
				Am	0.0014						

Calculation of Induced Activity with FLUKA

- **Simulation of particle interactions and transport in the target, the samples, as well as the tunnel/cavern walls**
- **Separate simulations for proton and pion beam**
- **Simulations of isotope production via**
  - **High-energy processes**
  - **Low-energy neutron interactions**
- **Transport thresholds**
  - **Neutrons: down to thermal energies**
  - **Other hadrons: until stopped or captured**
  - **No electromagnetic cascade was simulated**
- **Calculated quantities**
  - **Radioactive isotope production per primary particle**
  - **(Star density and particle energy spectra in the samples)**
- **Calculation of build-up and decay of radioactive isotopes for specific irradiation and cooling patterns including radioactive daughter products**

Example of results: Titanium

Cooling Times: (1) 2h 49m, (2) 4d 1h 30m and (3) 20d 4h 3m.

Cooling time	Isotope	$t_{1/2}$	FLUKA (Bq/g) ± (%)	Experiment (Bq/g) ± (%)	Exp/MDA	FLUKA/Exp
2	^{22}Na	2.60y	0.061 ± 6.8	0.056 ± 10.7	3.9	1.08 ± 0.19
1	^{24}Na	14.96h	15.1 ± 2.6	25.1 ± 3.6	546.8	0.60 ± 0.04
1	^{28}Mg	20.91h	0.524 ± 13.6	2.35 ± 5.5	13.0	0.22 ± 0.04
1	^{42}K	12.36h	41.5 ± 1.8	46.9 ± 5.2	134.0	0.89 ± 0.06
1	^{43}K	22.30h	16.2 ± 2.6	20.4 ± 3.7	124.4	0.79 ± 0.05
2	^{47}Ca	4.54d	0.42 ± 9.7	0.58 ± 15.7	43.3	0.73 ± 0.18
1	^{43}Sc	3.89h	31.5 ± 1.9	19.6 ± 56.7	21.3	1.61 ± 0.94
1	^{44}Sc	3.93h	118. ± 1	97.6 ± 4.2	503.1	1.21 ± 0.06
2	^{m44}Sc	58.60h	16.8 ± 1.1	7.61 ± 5.5	272.8	2.20 ± 0.14
3	^{46}Sc	83.79d	4.86 ± 0.7	5.82 ± 8.2	559.6	0.84 ± 0.07
2	^{47}Sc	80.28h	52.7 ± 1	61.6 ± 8.2	1422.6	0.86 ± 0.08
2	^{48}Sc	43.67h	5.23 ± 2.1	4.79 ± 3.7	281.8	1.09 ± 0.06
2	^{48}V	15.97d	2.73 ± 2.3	2.16 ± 6.1	213.9	1.27 ± 0.11
3	^{51}Cr	27.70d	0.078 ± 9	0.094 ± 36.3	1.4	0.82 ± 0.37

Example of results: Concrete

Cooling Times: (1) 11h 41m, (2) 12d 6h 40m and (3) 55d 2h 31m.

Cooling time	Isotope	$t_{1/2}$	FLUKA (Bq/g) ± (%)	Experiment (Bq/g) ± (%)	Exp/MDA	FLUKA/Exp
3	^{7}Be	53.29d	2.63 ± 1.0	2.95 ±11.9	263.4	0.89 ± 0.11
3	^{22}Na	2.60y	0.060 ± 1.4	0.061 ± 9.9	101.5	0.98 ± 0.11
1	^{42}K	12.36h	1.34 ± 8.8	1.03 ± 6.1	20.3	1.30 ± 0.19
1	^{43}K	22.30h	1.58 ± 3.7	1.52 ± 3.4	157.7	1.04 ± 0.07
1	^{47}Ca	4.54d	0.239 ± 6.8	0.343 ± 14.5	29.6	0.70 ± 0.15
1	^{44}Sc	3.93h	0.304 ± 5.2	0.315 ± 6.3	12.0	0.97 ± 0.11
1	^{m44}Sc	58.60h	0.242 ± 5.7	0.127 ± 9.1	15.5	1.91 ± 0.28
1	^{47}Sc	80.28h	0.296 ± 6.4	0.325 ± 8.3	35.0	0.91 ± 0.13
2	^{48}V	15.97d	0.086 ± 7.7	0.045 ± 8.8	36.4	1.90 ± 0.31
2	^{51}Cr	27.70d	0.111 ± 5.0	0.085 ± 15.8	4.8	1.30 ± 0.27
1	^{52}Mn	5.59d	0.19 ± 7.2	0.11 ± 4.1	15.1	1.74 ± 0.20
3	^{54}Mn	312.12d	0.016 ± 5.5	0.015 ±11.9	9.5	1.06 ± 0.18
2	^{56}Co	77.27d	0.0024 ± 19.8	0.003 ± 21.8	2.2	0.80 ± 0.33

LHC: Conclusions on activation study

- Good agreement was found between the measured and calculated values for most of the isotopes and samples
- The large number of samples and variety of different materials offers a extensive possibility to study isotope production
- General discrepancies were only observed for intermediate and small-mass isotopes (relative to the target mass) which can most likely be attributed to parts still missing in the FLUKA models (example: multifragmentation): **NOW DEVELOPED AND PRESENTED AT INT. CONF. ON NUCLEAR DATA FOR SCIENCE AND TECHN. (Santa Fe 2004)**
- As a consequence, the calculation of remanent dose rates based on an explicit simulation of isotope production and transport of radiation from radioactive decay with FLUKA should also give reliable results $\rightarrow$ Part 2

Part 2: Radioactivity Produced in LHC Materials: Remanent Dose Rates

- Levels of remanent dose rates are an important design criterion for any high energy facility

- Residual dose rates for arbitrary locations and cooling times are so far predicted with a rather poor accuracy
  - typically based on the concept of so-called ω-factors and comprising several severe restrictions
  - layouts and material composition of beam-line components and surrounding equipment are often very complex

- A proper two-step approach based on the explicit generation and transport of gamma and beta radiation from radioactive decay should result in much more accurate results

FLUKA Simulations

First Step

- **Geometry:**

  target, the samples, as well as the tunnel/cavern walls

- **Beam & Source:**

  Separate simulations for proton and pion beam

- **Transport thresholds:**
  - Neutrons: down to thermal energies
  - Other hadrons: until stopped or captured
  - No electromagnetic cascade was simulated
- **Calculated quantities:**
  - **Complete information on radioactive isotopes for 12 cooling times written into external file (6' to 1000h)**

Second Step

- **Geometry:**

  Irradiated sample surrounded by air

- **Beam & Source:**

  Photons, positions, and electrons sampled according to the spatial distribution of the radioactive isotopes at a certain cooling time

- **Transport thresholds:**
  - Photons: 10 keV
  - Electrons, positrons: 100 keV
- **Calculated quantities:**
  - **Ambient dose equivalent rate from photons , $beta^{+}$, and $beta^{-}$ around the sample up to 50 cm from the centre of the sample**

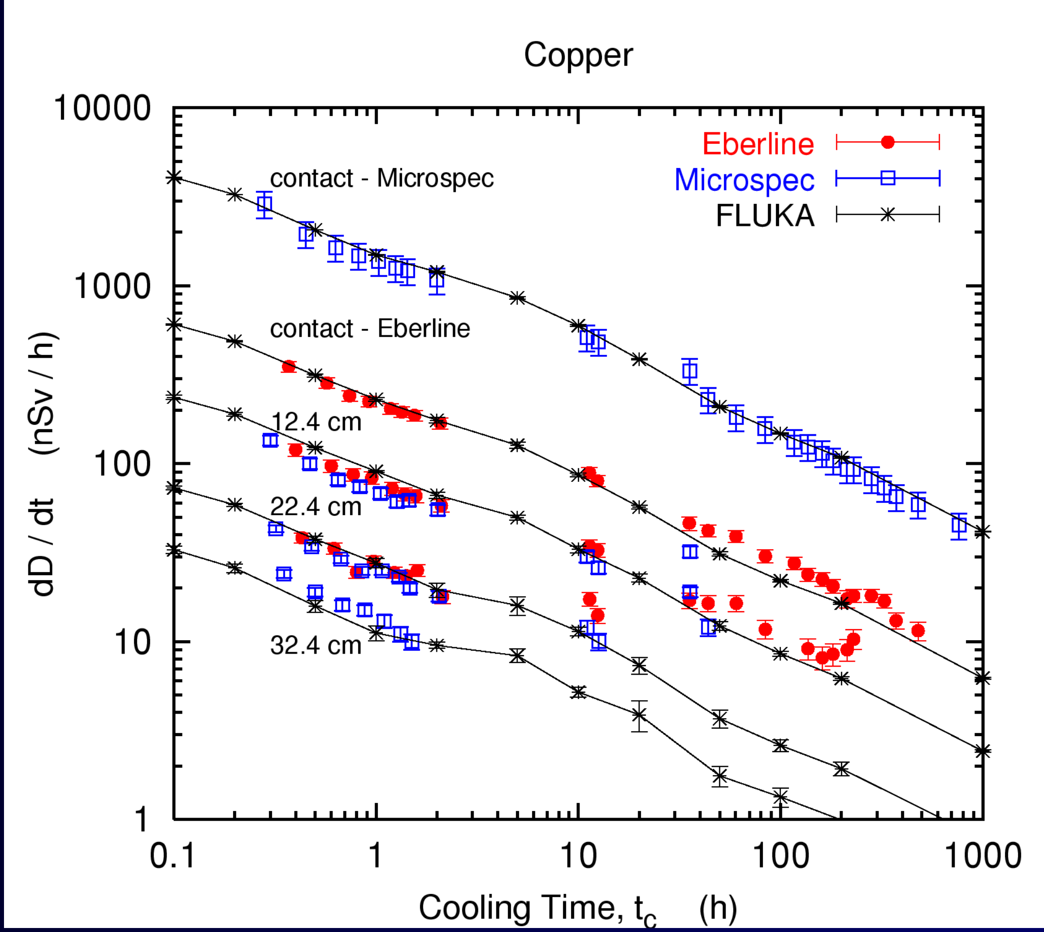
Results: Dose Rates in Copper

Very good agreement for both instruments

Positron emitter (mainly copper isotopes) dominate the dose rate up to cooling time of 20 hours!

Errors of Measurements include the following:

- **±2 mm of the effective centre of the detector as well as the positioning of the samples**
- **Eberline: a statistical error obtained from repetitive measurements**
- **Microspec: 5% general uncertainty as specified in the manual**
- **a systematic instrument uncertainty of 1 nSv/h**



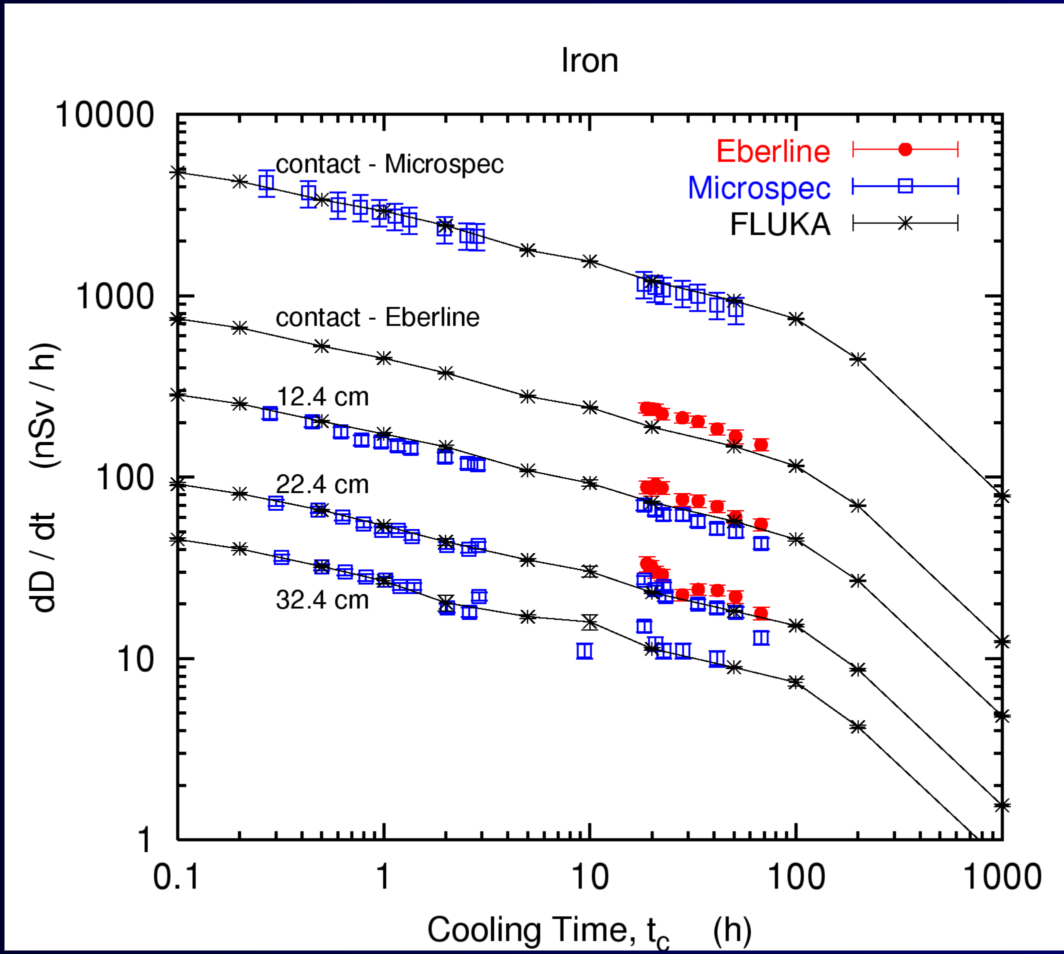
Results in Iron and Conclusions

- Again very good agreement

▪The explicit method to calculate remanent dose rates with FLUKA has been successfully benchmarked for a large number of different materials and samples

▪The approach can be applied to arbitrary situations, locations and cooling times and is thus superior to the classical omega-factor method

▪The largest uncertainties in this method arise from possible deficiencies in the models for isotope production



Underground Physics

Experiments at LNGS

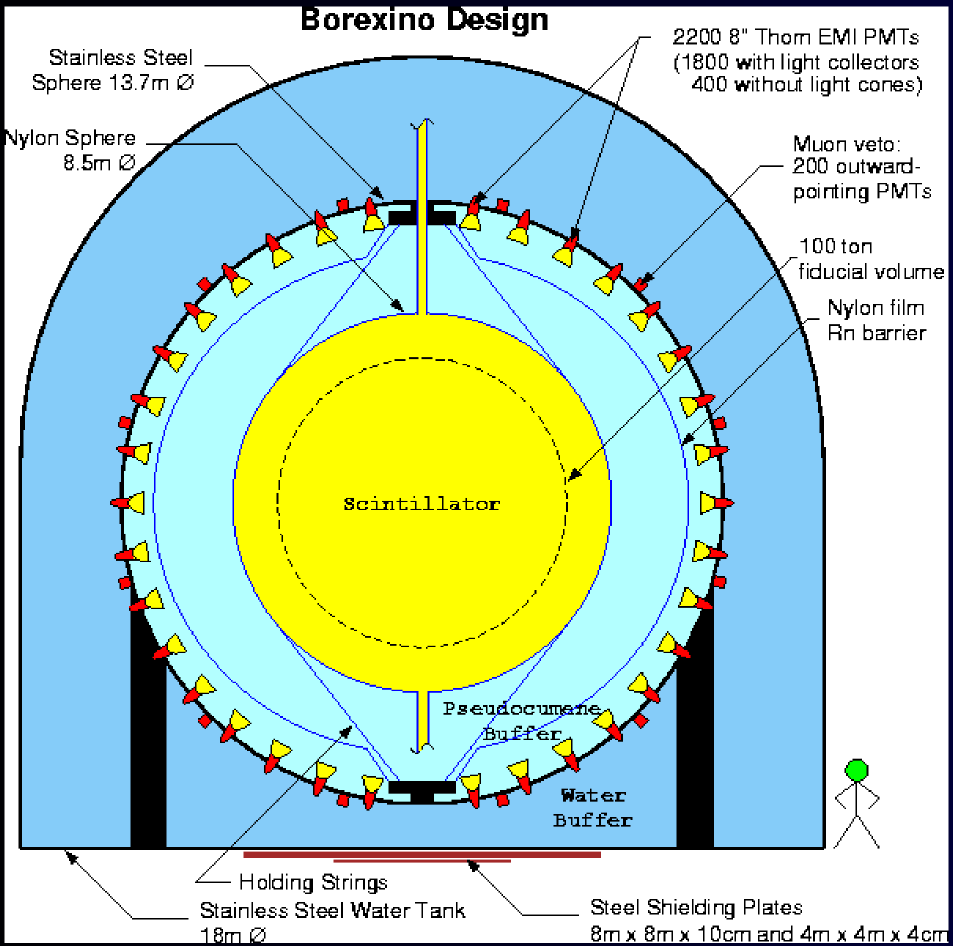
Production of TeV Muons from C.R.

Muon transport in rock

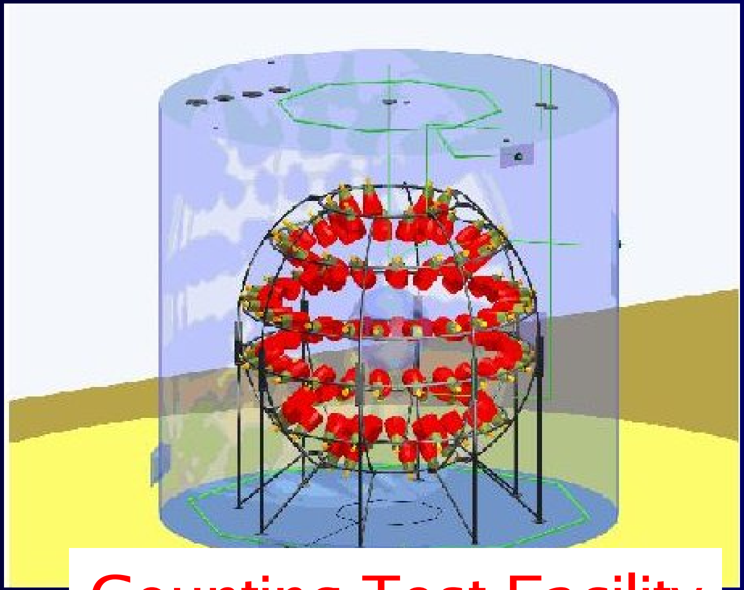
HE Muon interactions

An application of FLUKA in Borexino@LNGS

by D. Franco (Milano, Heidelberg) for the Borexino Collaboration



- Real time observation of low energy neutrinos
- ^{7}Be measurement



Counting Test Facility (background study)

Among the goals of CTF:

learn how to reduce the cosmogenic background: the ^{11}C problem

In situ production muon-induced ^{11}C: 7.5 c/d in the range [0.8 – 1.4] MeV

$\langle E_\mu \rangle \sim 300$ GeV required reduction factor > 10

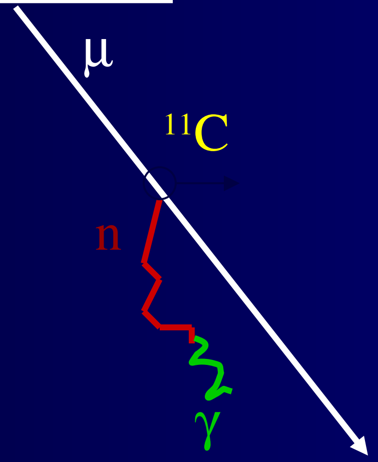
Goal: tagging and removing ^{11}C <u>event by event</u>!!!

$$\mu + {}^{12}C \rightarrow {}^{11}C + n$$

$$n + p \rightarrow d + \gamma$$

$\tau \sim 200\ \mu s$

$E = 2.2$ MeV

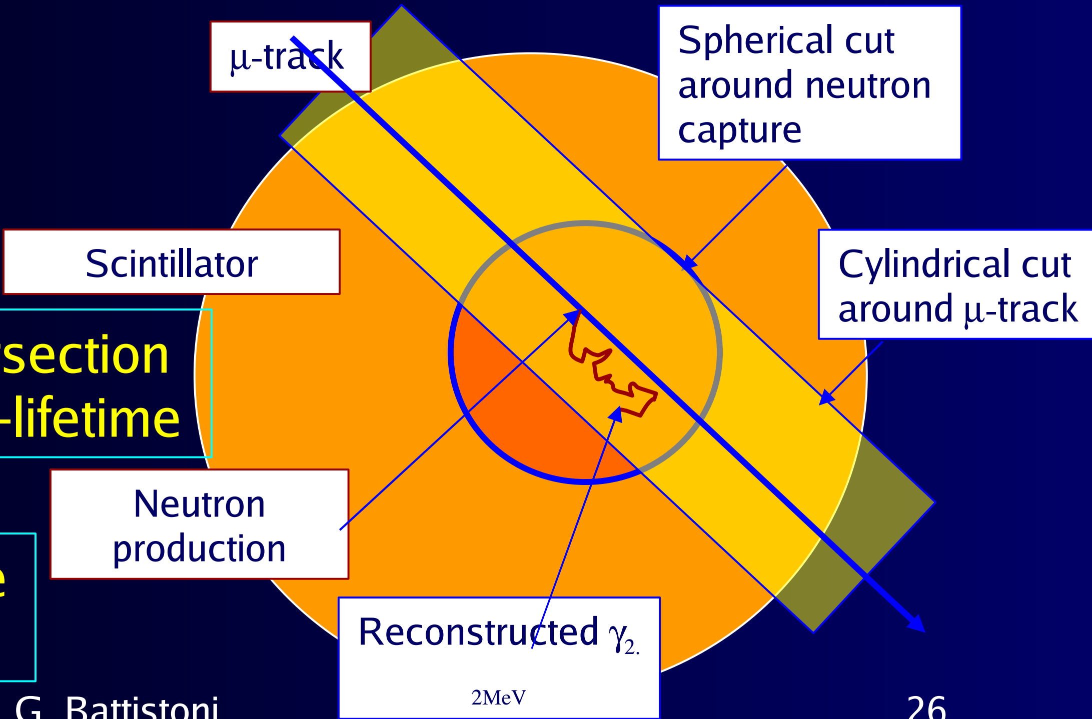


Simulation Plan

FLUKA has been already tested succesfully in muon-induced neutron production (LVD, etc)

Simulation strategy: **detector geometry, vertical muon beam spread over the whole detector surface, neutron tracking in scintillator and water**

<u>Eventual goal:</u>
Define the proper volume around neutron production

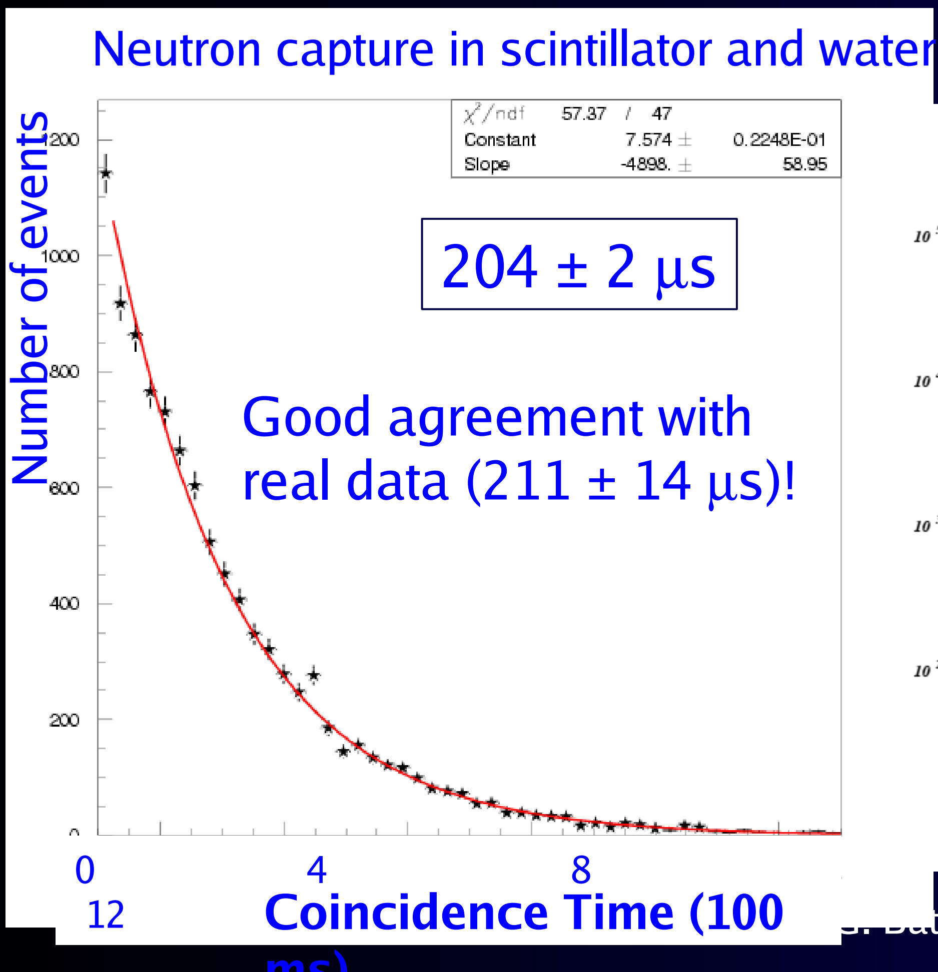


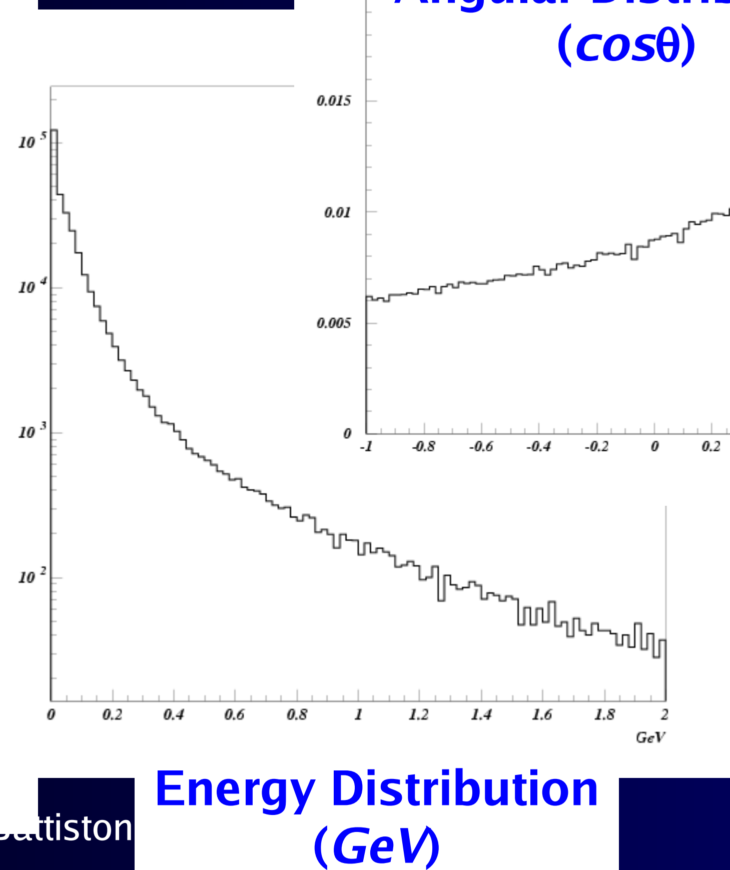
^{11}C is removed <u>blinding</u> the intersection of the two volumes for 5-10 ^{11}C-lifetime

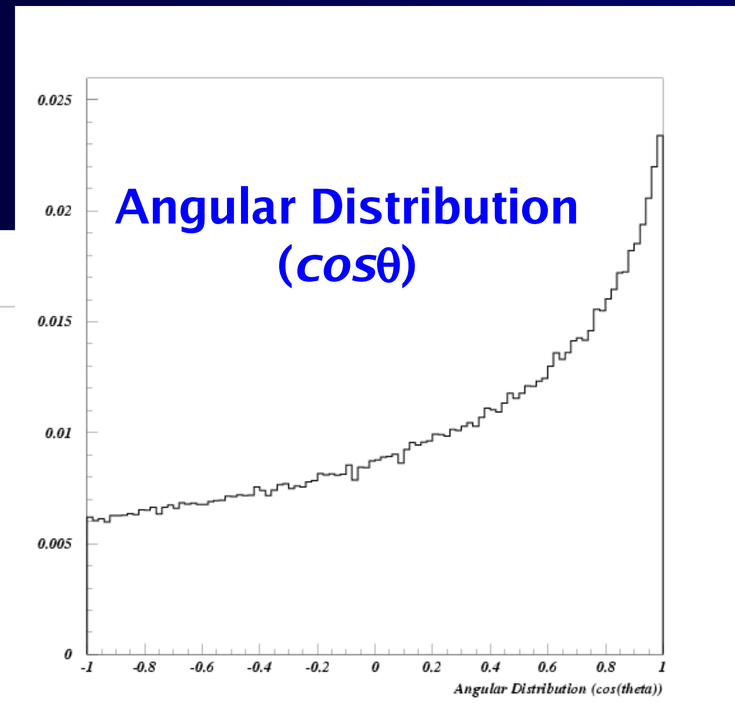
Main challenge: keeping low the total <u>dead volume x time</u>

Results from the MC (1)

Events in water and in scintillator







Results from the MC (2)

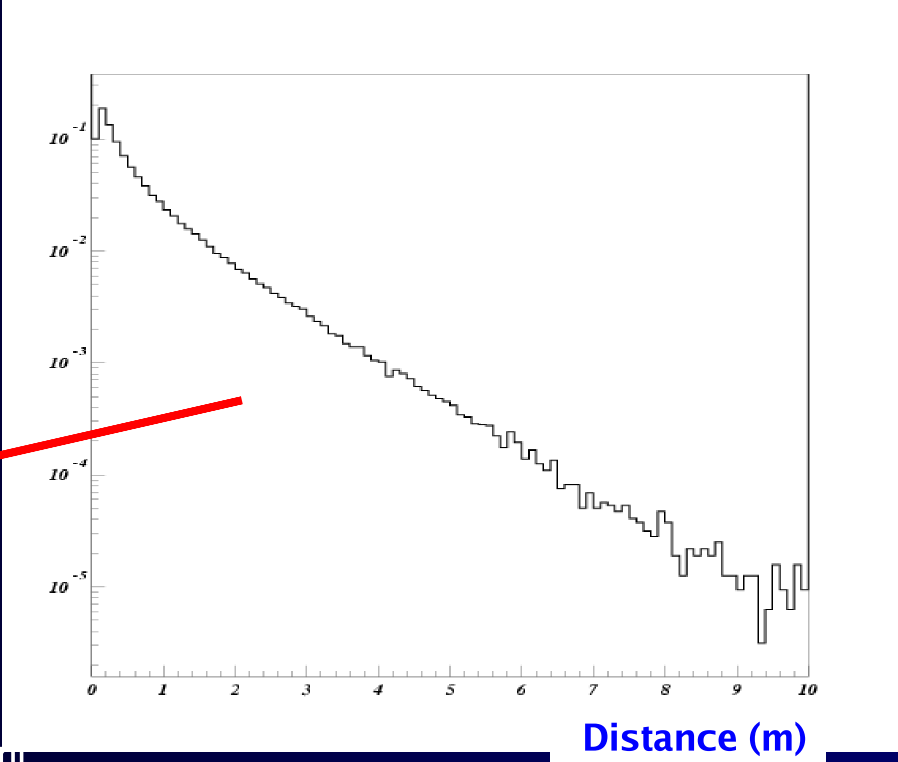
$$R(r < 0.7m) = \frac{(0.17 \quad 0.04)}{e_r ?e_n ?e_g} c/d$$

From MC:
$e_r ?e_n ?e_g = 0.29$

$$R_{measured} = 0.60 \quad 0.14(stat.)^{+0.06}_{-0.04}(syst.)\ c/d$$

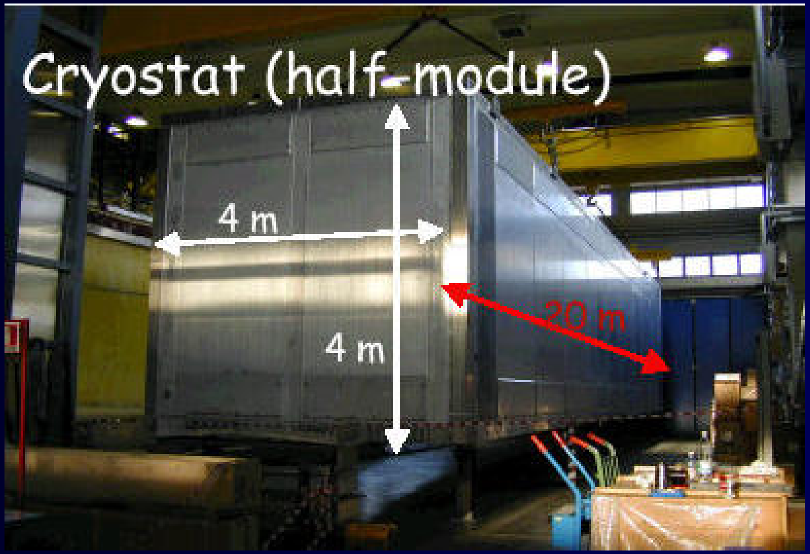
$$R_{expected} = 0.54 \pm 0.06\ c/d$$

The distance distribution
allows to define the cut volume



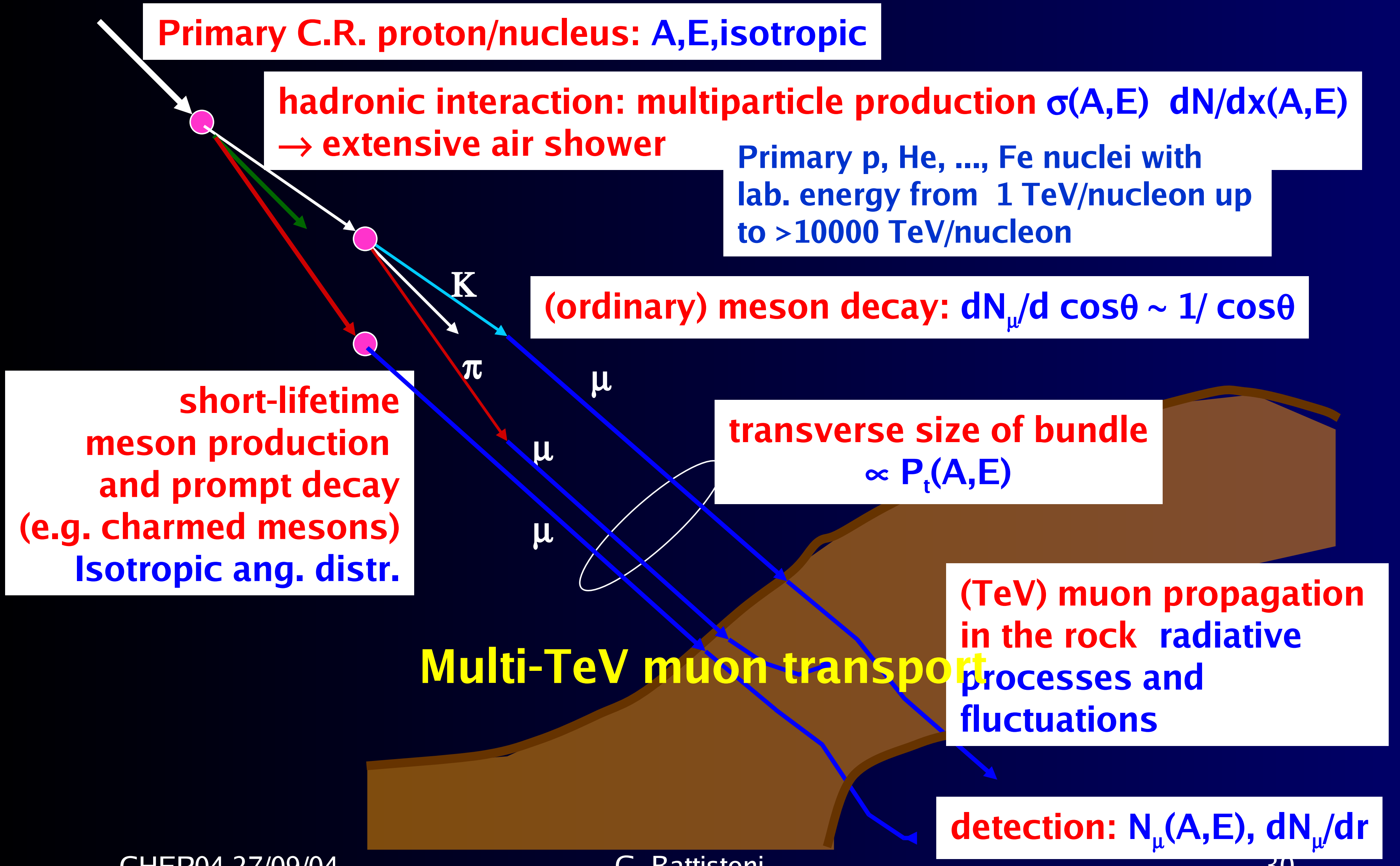
High Energy Cosmic Ray Physics

with S. Muraro, T. Rancati and P. Sala (Milano) for the ICARUS Collaboration



One of the FLUKA applications inside ICARUS concerns the calculation the expected rate vs multiplicty of underground muon events in the ICARUS module to be installed now in underground Gran Sasso Laboratory

Underground Muons: the physics involved



Our simulation approach

The aim is to produce the prediction for multiple muon rates in ICARUS-T600 for different primary mass and energy within the framework of a unique simulation model

Steps:

- **atmospheric shower generation**
- **transport in Gran Sasso rock**
- **folding with the detector (spatial randomization of event)**
- **full simulation in ICARUS T600**

Step 1: Atmospheric Shower Generation

Interaction model:

FLUKA (superposition model) DPMJET-2 or DPMJET-3 for nucleus-nucleus collisions

secondary threshold normally kept @1 TeV

3D earth+atmosphere layered in 100 shells

Input: primary spectra or fixed energies for individual nuclear species of primary flux.

Output: muons (E > 1 TeV) event by event, carrying together the kinematics of primary

Our input choice:

- 5 Mass Groups: Z = 1, 2, 7, 13, 26 (spectra from NASA)

Step 2: Transport in GS rock

Transport model:

FLUKA *(all processes switched on but no production of secondaries)*

GS geometry *(as taken from the map used in MACRO experiment)*

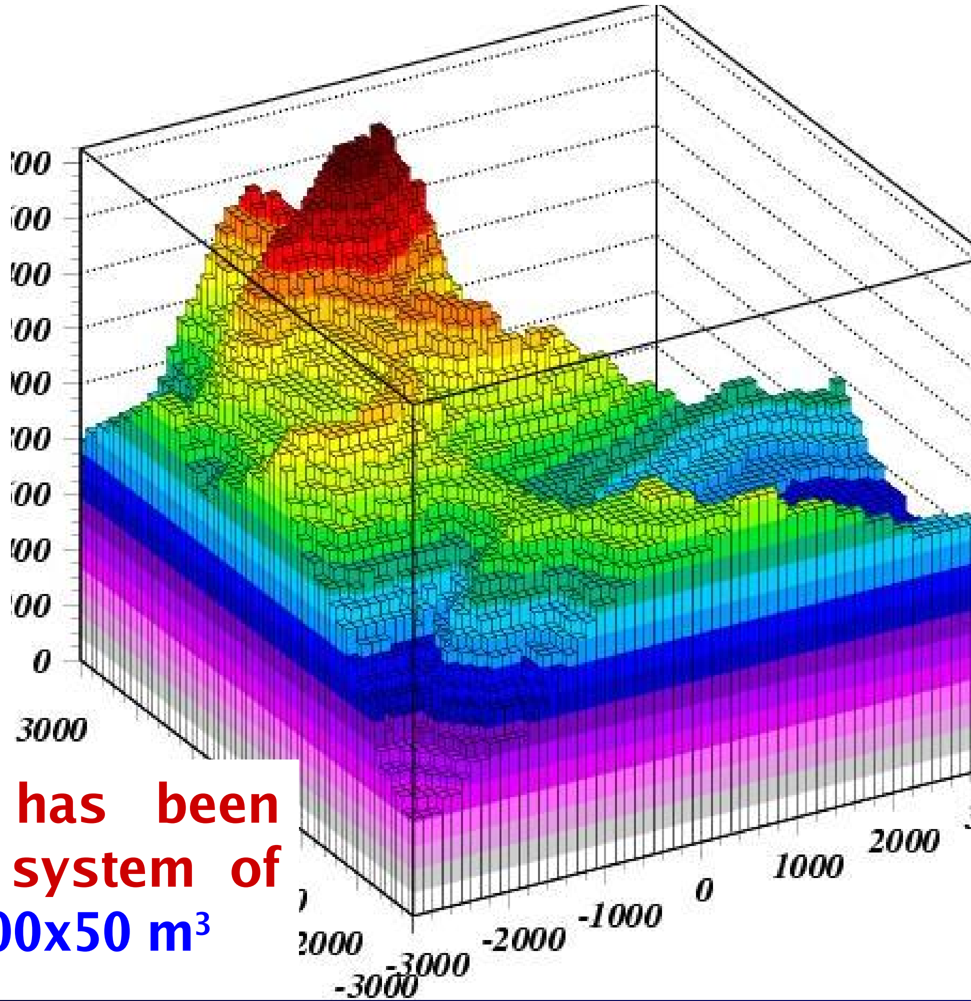
Input:

output event by event from atm. shower generation

Output:

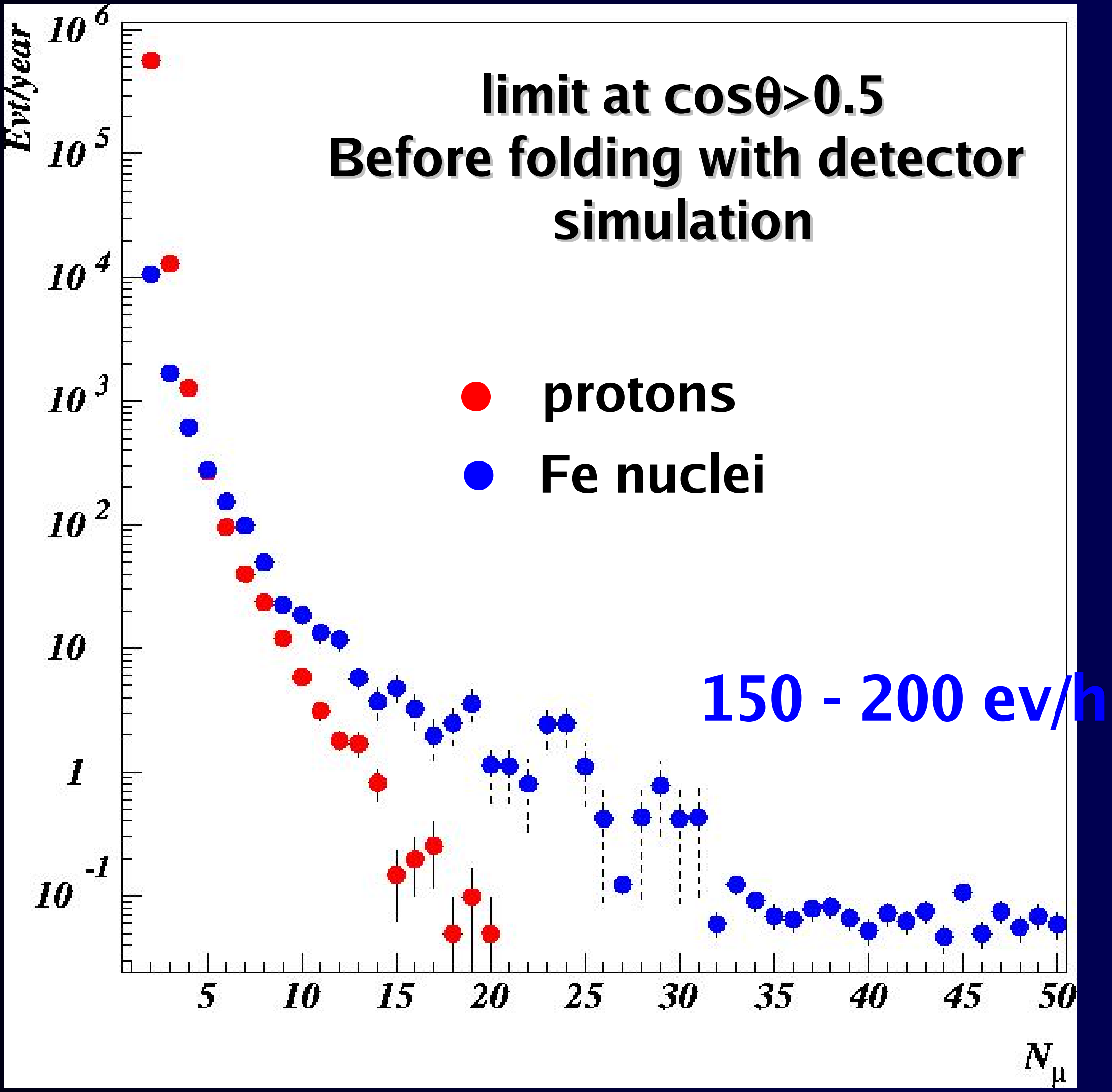
event by event the muons survived at the depth of underground GS lab: 963 m a.s.l.

The layered geological structure has been reproduced (5 different materials)

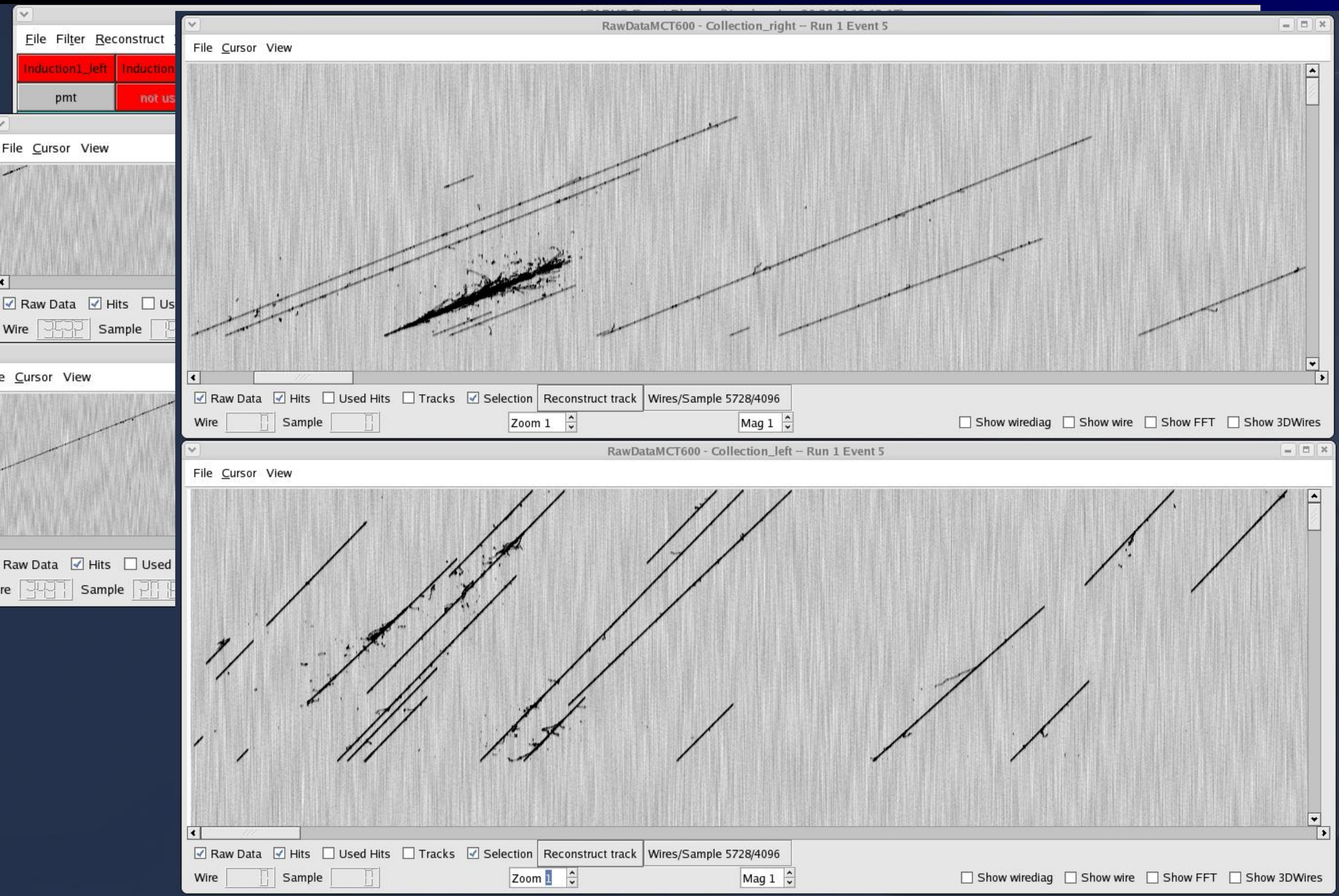


The geometry of the mountain has been described using the new <u>“voxel”</u> system of FLUKA. Our choice: 1 voxel = 100x100x50 m^3

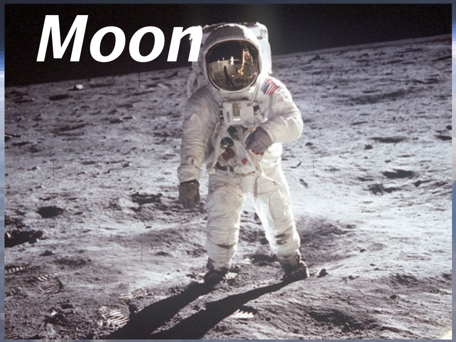
First results: 1) expected event multiplicity distribution from extreme components

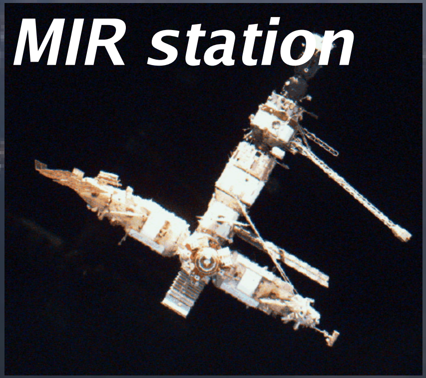


First results: 2) folding with full simulation



Applications to Space Radiation Protection





- FLUKA ⇒ spatial distribution of absorbed dose delivered by the different components of the radiation field
- “event-by-event” track structure codes ⇒ yields of CL/(Gy cell) induced by different radiation types
- integration ⇒ spatial distribution of CL/cell *(“biological” dose)*

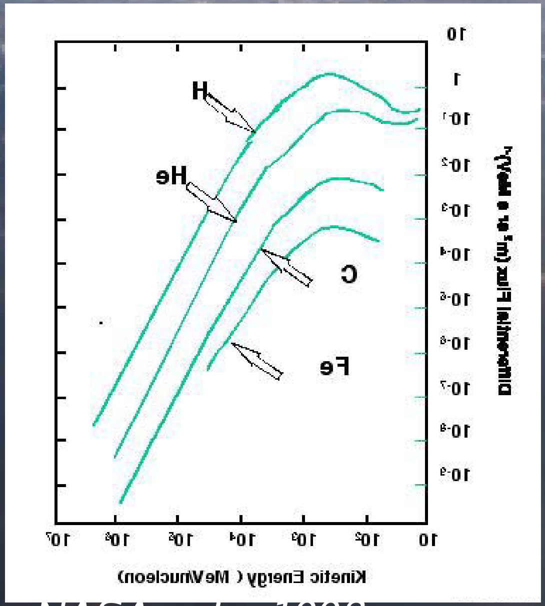
ISS007E10807

Galactic Cosmic Rays

spectrum: 87% protons, 12% He ions, 1% heavier ions (in fluence) with peak at 1 GeV/n

flux: ~4 particles/(cm^2 s) at solar min.

dose: ~1 mSv/day



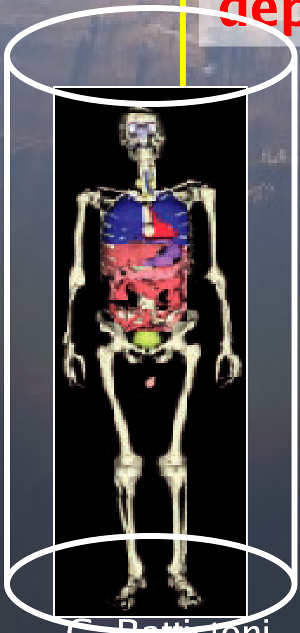
NASA pub. 1998

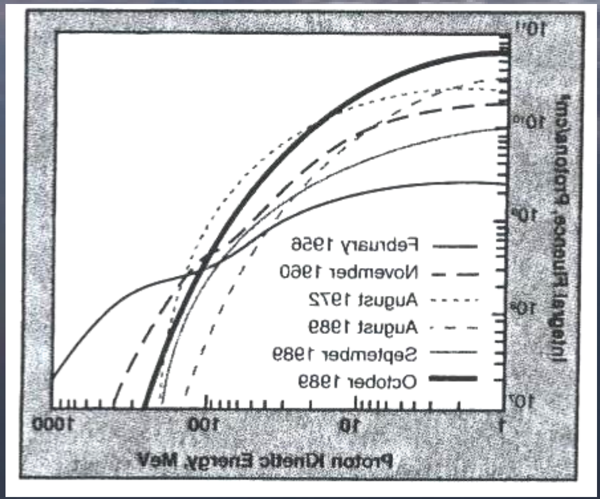
Solar Particle Events

spectrum: 90% protons, 10% heavier ions with energy mainly below ~200 MeV

flux: up to ~10^{10} particles/cm^2 in some hrs.

dose: order of Sv, strongly dependent on shielding and organ



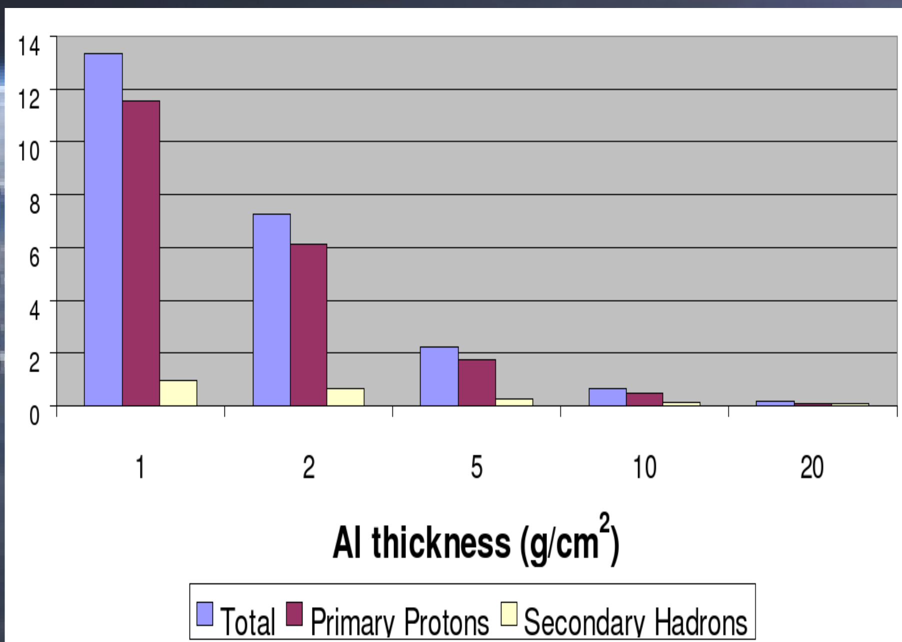


NASA pub. 1998

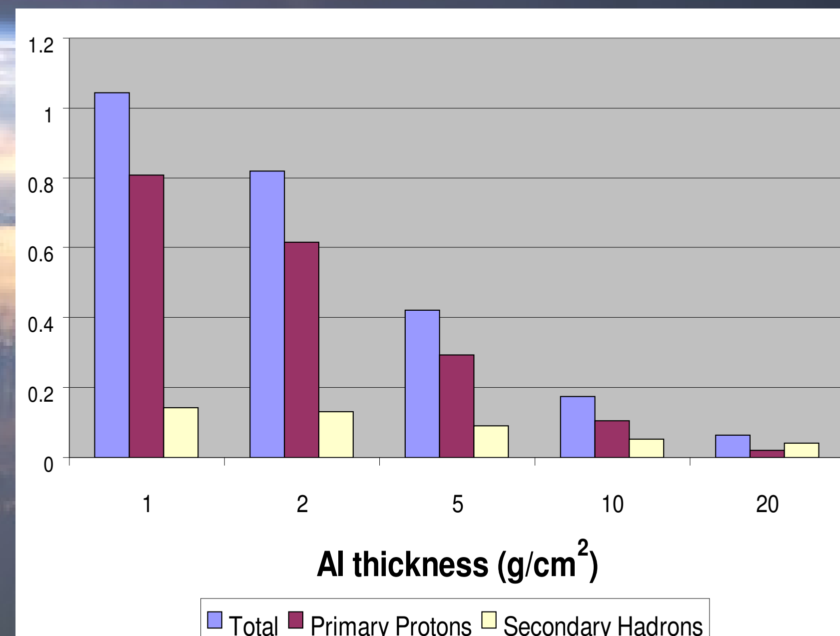
ISS007E10807

August 1972 SPE - skin vs. internal organs

Equivalent dose to skin (Sv)



Equivalent dose to liver (Sv)



- much lower doses to liver than to skin (e.g. 1.0 vs. 13.3 Sv behind 1 g/cm^2 Al)
- larger relative contribution of nuclear reaction products for liver than for skin (e.g. 14% vs. 7% behind 1 g/cm^2 Al)

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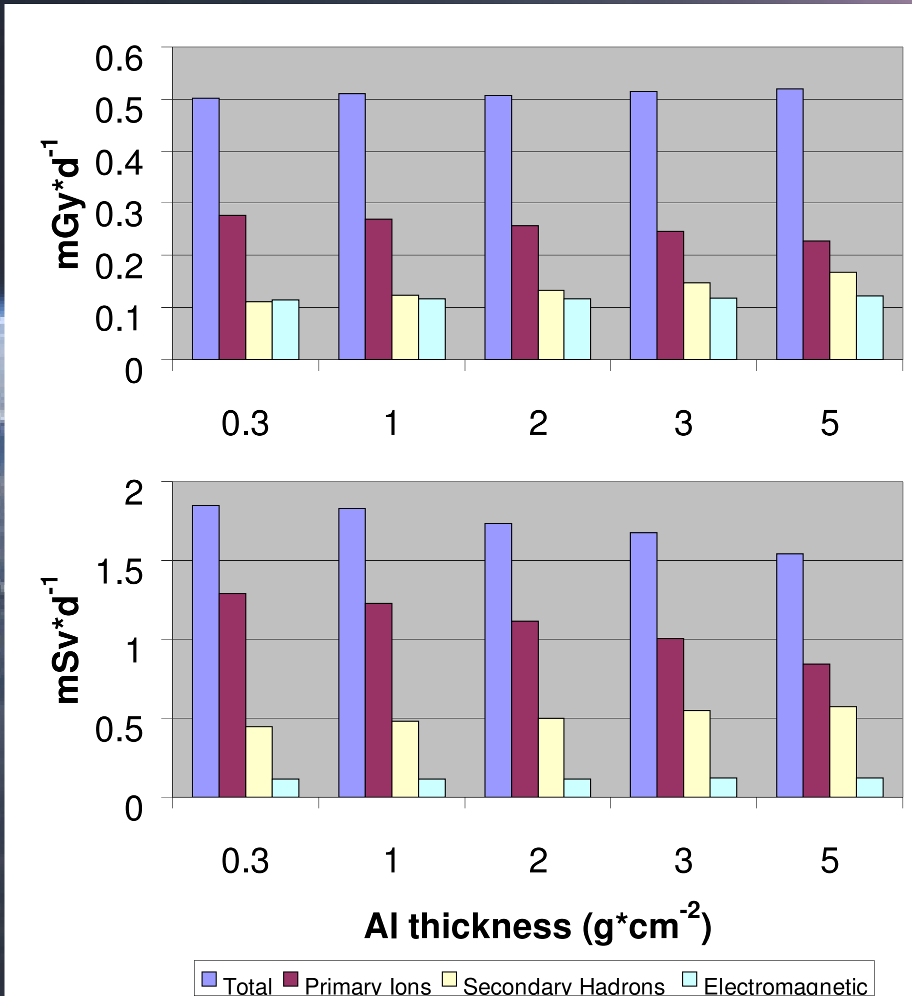
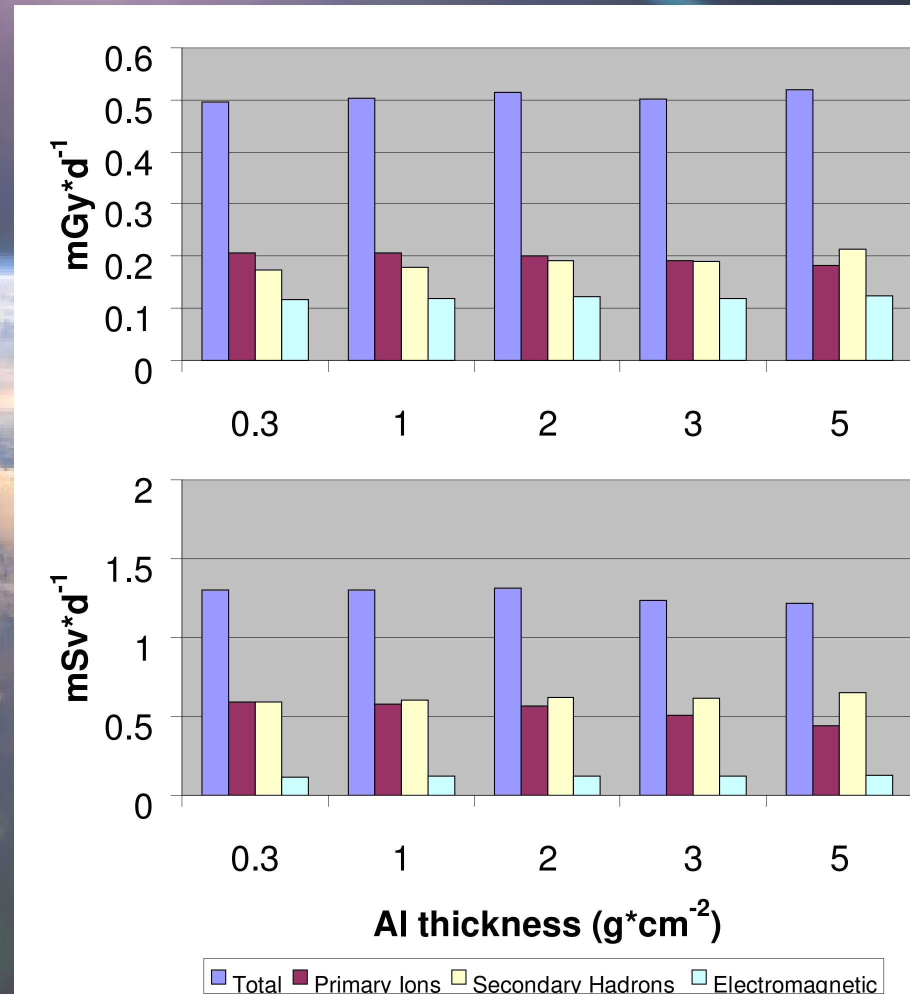
Galactic Cosmic Rays - skin vs. internal organs

skin



liver



With respect to skin, internal organs have 1) similar dose (~0.5 mGy/day) but smaller equivalent dose (~ 1.3 vs. 1.7 mSv/day); 2) larger relative contributions from nuclear interaction products

ISS007E10807

General Conclusions

- FLUKA is being successfully employed in many HE applications connected to accelerator and non-accelerator physics
- The common elements among the example shown here is the capability to treat problems where different scales of energy are connected.
- The comparison with data is guiding the refining of some models in order to achieve better and better perfomances
- The recent additions for Nucleus-Nucleus collisions have increased the range of FLUKA applications, in particular in the cosmic-ray sector, radiation protection, hadrotherapy, etc.
- The increased number of users is allowing the development of advanced FLUKA software tools for user interface (plotting results, building geometries, etc.)