Detector simulation

with FLUKA:

a multipurpose Interaction and Transport MC code

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snri12

FLUKA

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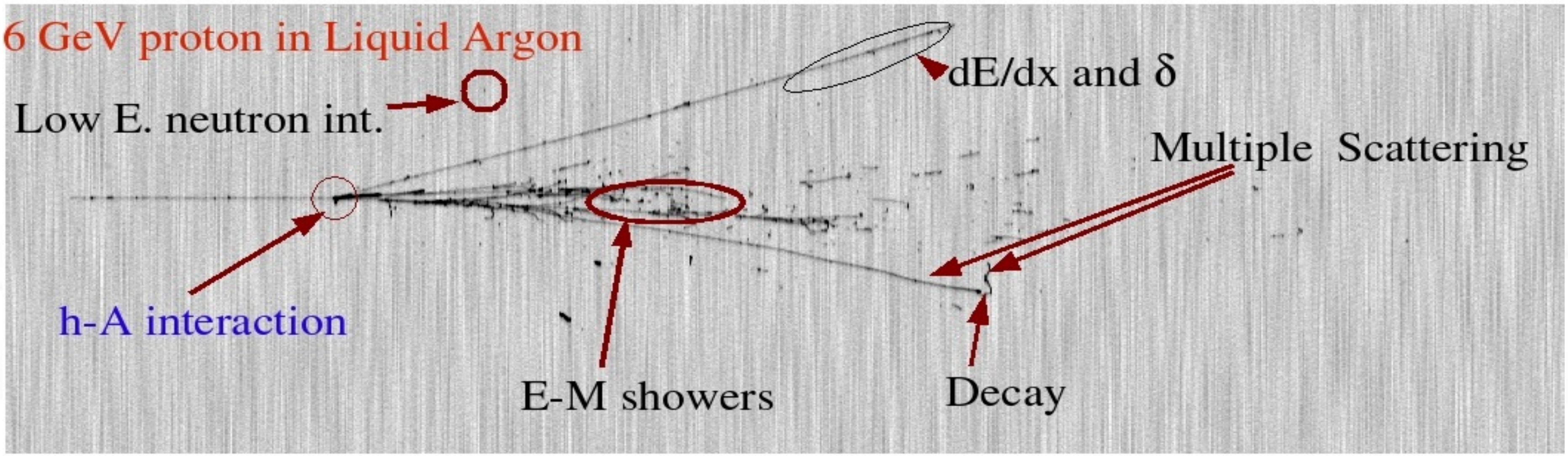

Developed and maintained under an INFN-CERN agreement

>4000 users

http://www.fluka.org

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Generalities

- A lot to be simulated:
- What happens inside the detector -> response, linearity, resolution etc
- What happens outside -> acceptance, pile-up, background
- What may happen -> radiation damage
- Need “reliable” simulations from hadronic interactions at LHC energy to keV electron transport : the FLUKA approach is to
  - Develop microscopic models, as good as we can
  - Keep the consistency and correlations among all radiation components
  - Use the same physics models for all cases (no toolkit)
- Need anyhow some problem-specific settings
  - geometry, materials of course
  - Transport thresholds, specific prcesses
- There are effects that are NOT simulated and **must** be accounted for by the “user” , for instance
  - Electronic noise
  - Electron drift/multiplication in wire chambers (Rob..)

Outline

- The bottom line: energy deposition in a "detector" , with examples
- Photons and electrons: a glimpse of latest developments
- Hadronic physics and calorimeters
- Time is also a variable: neutrinos, prompt photons for medical imaging
- Backgrounds and radiation damage
- How-to

Charged particle dE/dx: Bethe-Bloch

Spin 0
(spin1 is similar):

~ln $\beta^4\gamma^4$ relativistic rise

$$\left(\frac{dE}{dx}\right)_0 = \frac{2\pi\, n_e r_e^2 m_e c^2 z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2 T_{max}}{I^2(1-\beta^2)}\right) - 2\beta^2 + 2zL_1(\beta) + 2z^2L_2(\beta) - 2\frac{C}{Z} - \delta + G\right]$$

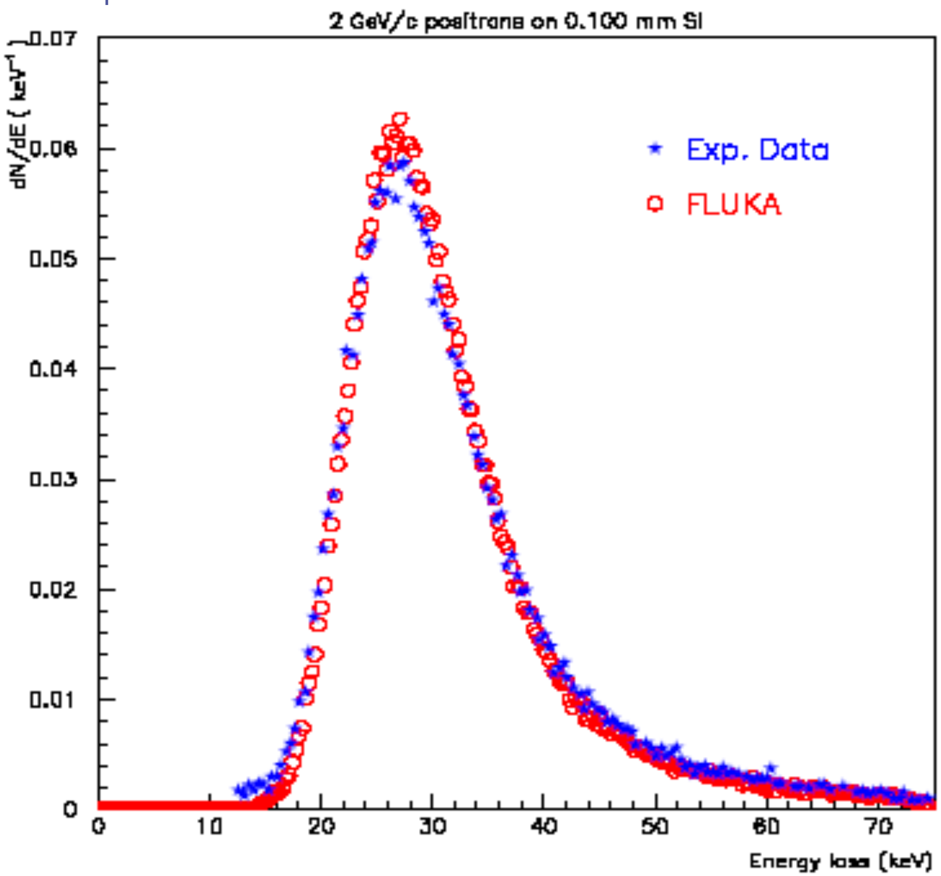
- I : mean excitation energy , material-dependent;
- δ : density correction;
- C : is the shell correction, important at low energies
- T_{max} : maximum energy transfer to an electron (from kinematics);
- Higher order corrections implemented in FLUKA
- L_1 : Barkas correction (z^3) responsible for the difference in stopping power for particles-antiparticles;
- L_2 : Bloch (z^4) correction
- G : Mott corrections

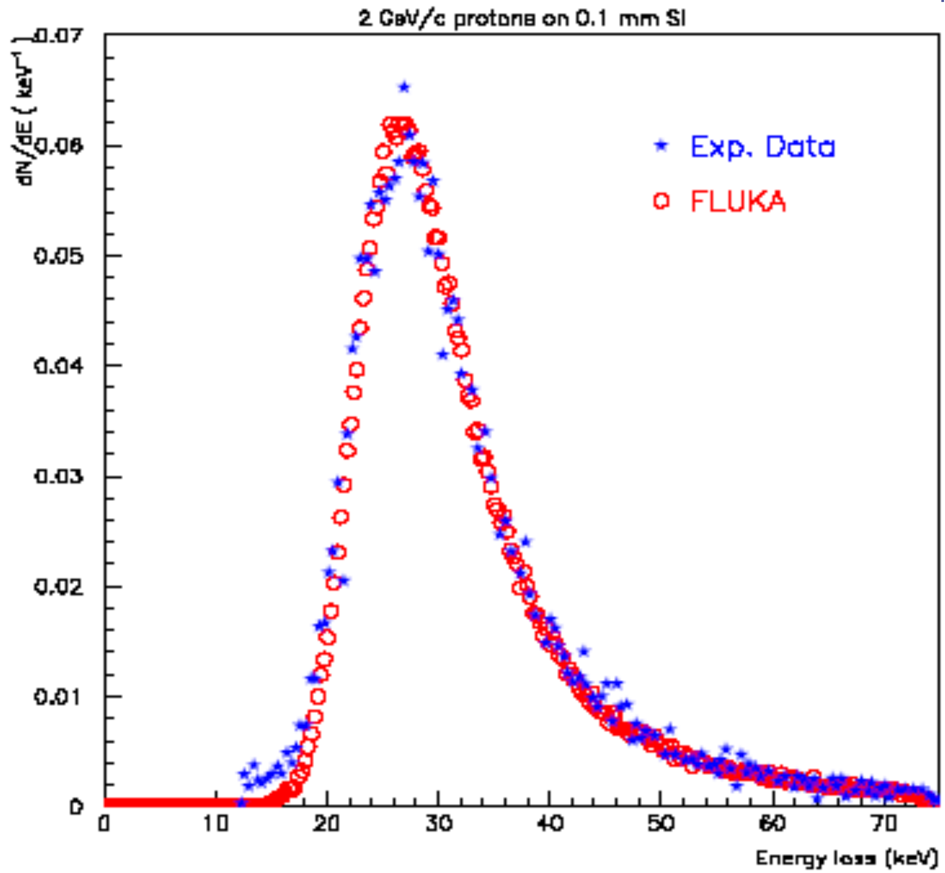
Valid for $m \gg m_e$. However, the formulation for electron/positrons is similar, except for the "energetic" collisions with atomic electrons.

dE/dx atomic interactions

Discrete events: Delta-ray production above a user-defined threshold

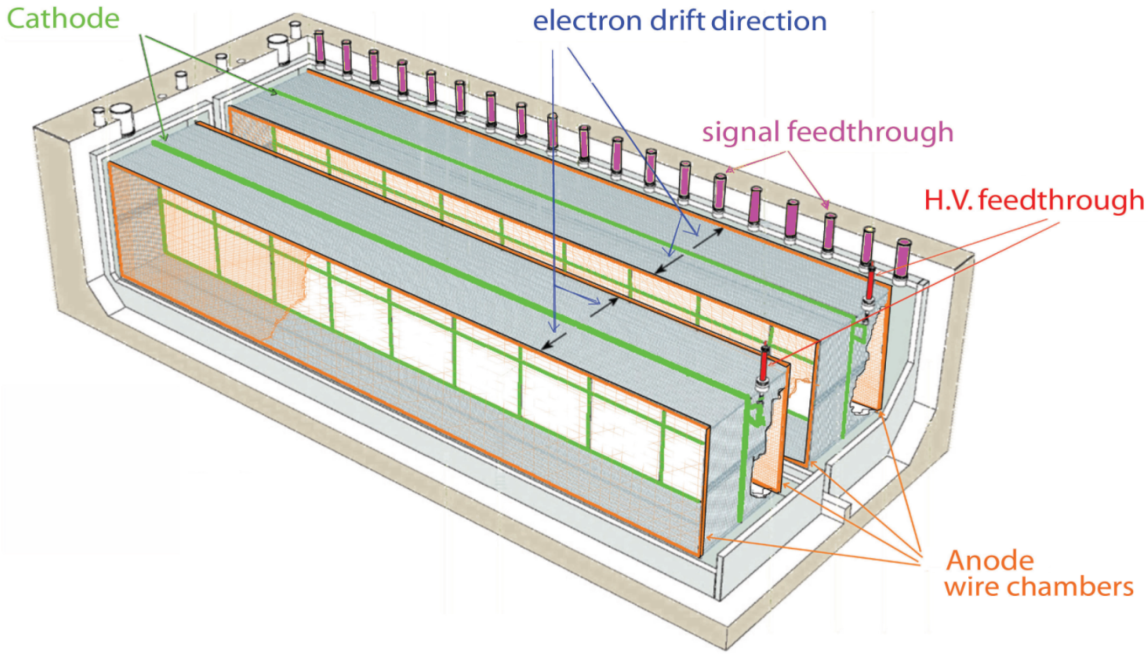
Continuous energy loss: ***Cumulants*** **approach to dE/dx fluctuations**

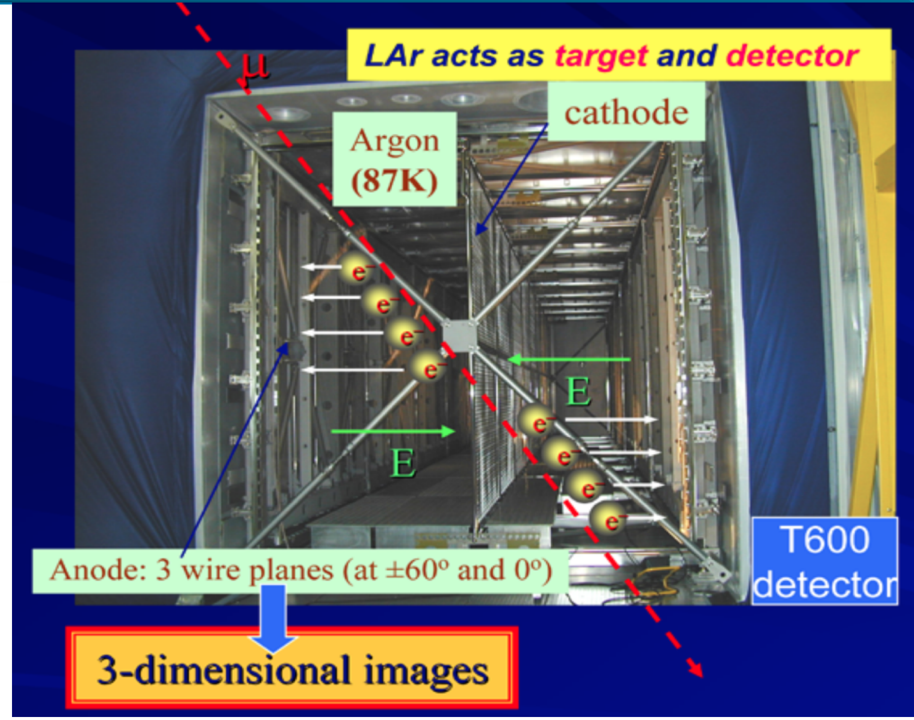




Experimental [1] and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100μm of Si J.Bak et al. NPB288, 681 (1987)

The ICARUS T600 detector



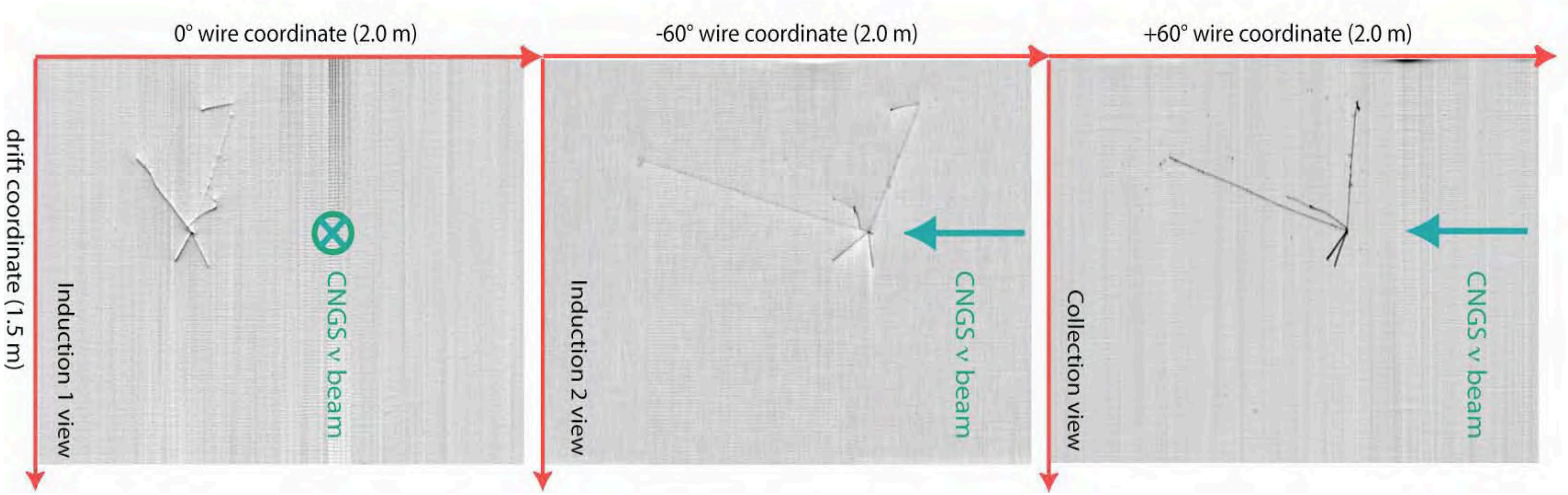


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs

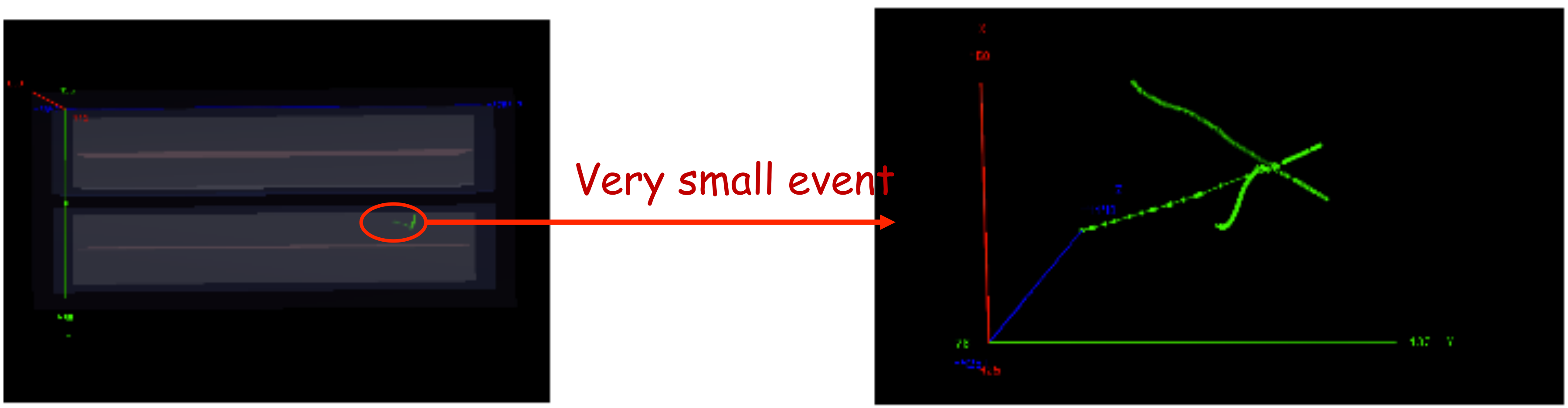
Taking data in LNGS hall B

- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

Atmospheric ν candidate



- Total visible energy: 887 MeV (including quenching and e⁻ lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35°.

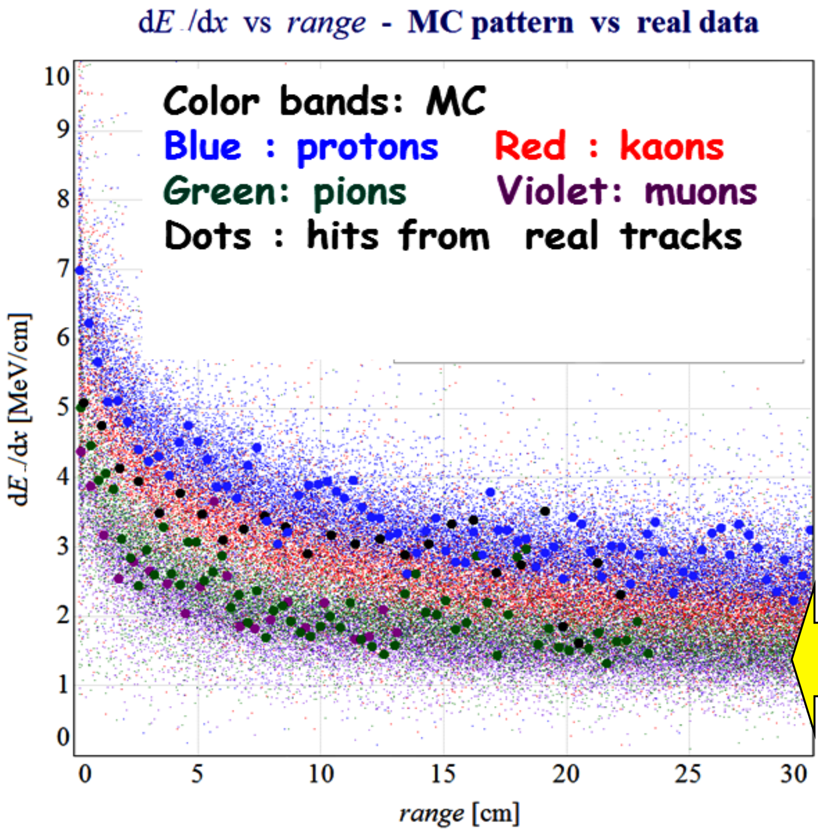


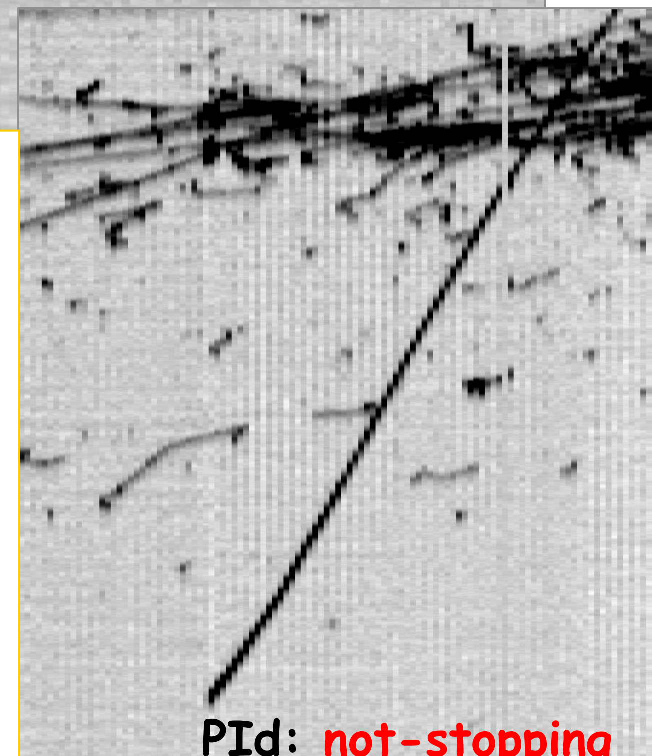
MC simulations for ICARUS

Complete simulation environment based on FLUKA

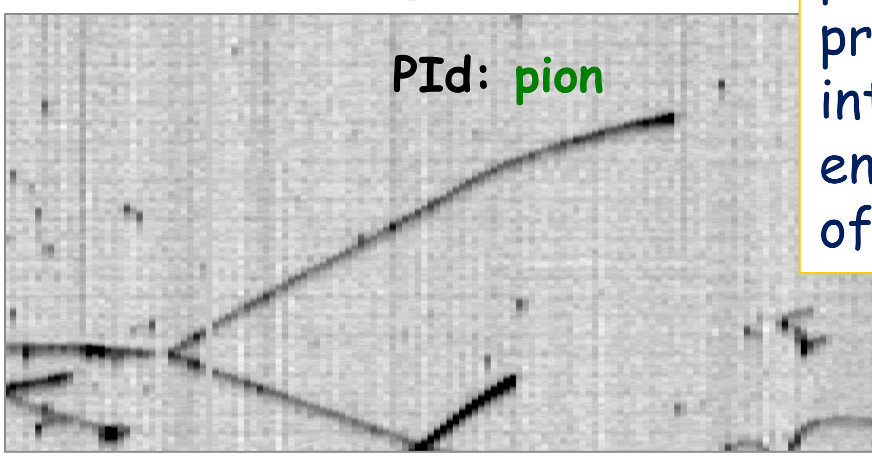
- CNGS beam composition (www.cern.ch/cngs)
- Neutrinos from cosmic rays showers
- Neutrino events with nuclear effects
- Full detector simulation with
  - Electron recombination (quenching), parameters according to data, correction on-line
  - Production an transport of scintillation and Cerenkov light
  - Mapping into views
- Added off-line
  - Calibration (deposited energy -> number of electron-ion pairs)
  - Signal shaping, according to response of electronics chain
  - Noise, added randomly on each wire , derived from data

stopping particle identification : examples





- Deposited dE/dx vs residual range
- No quenching corr.
- Black dots: not consistent with any pattern, most probably protons interacting at very low energy with emission of ns, γ

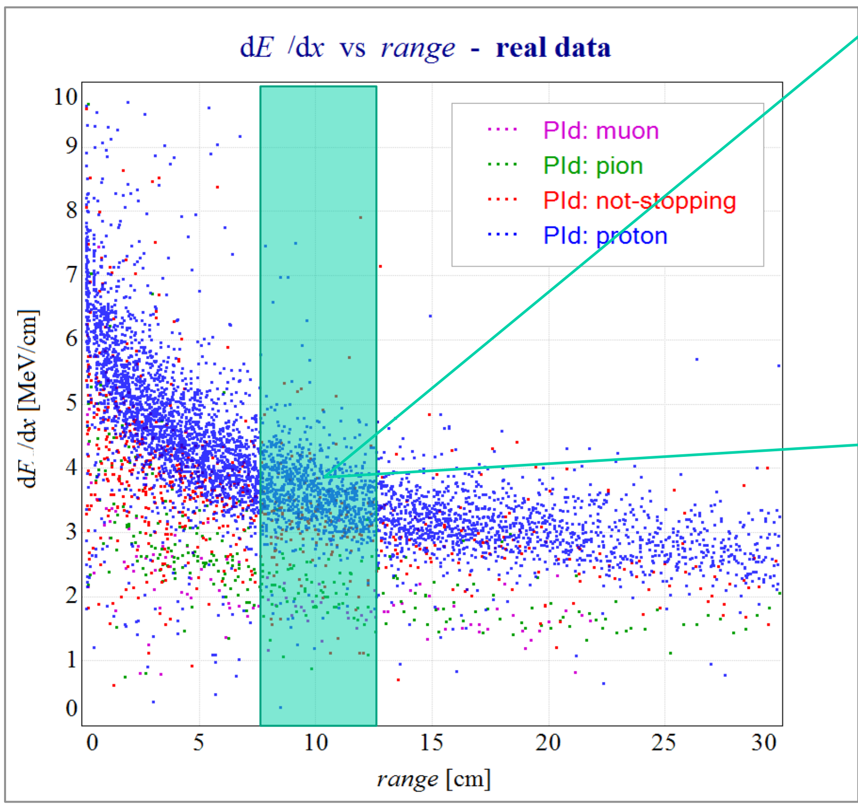


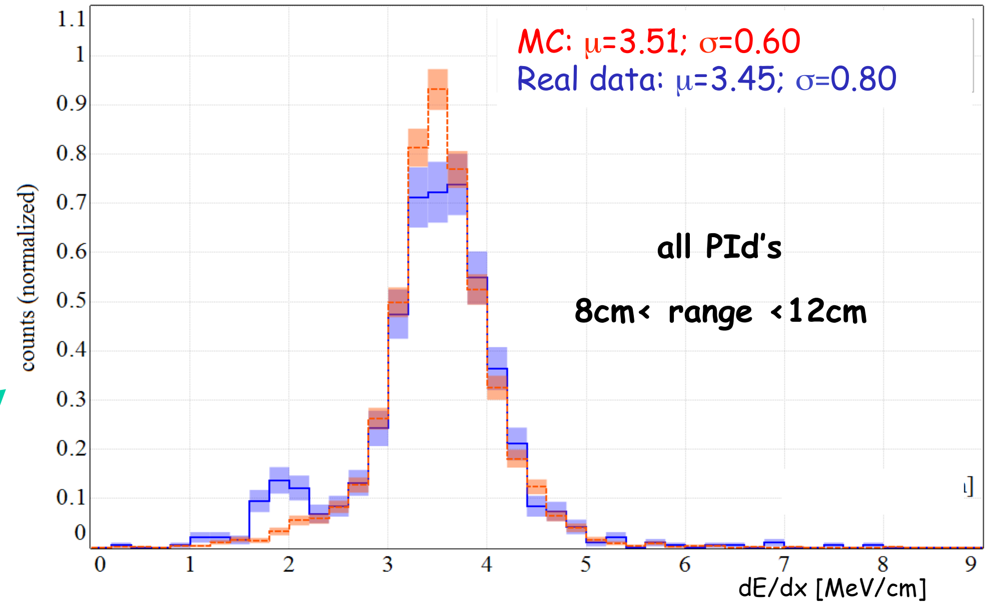
Methods for identification of non-stopping particles are under development

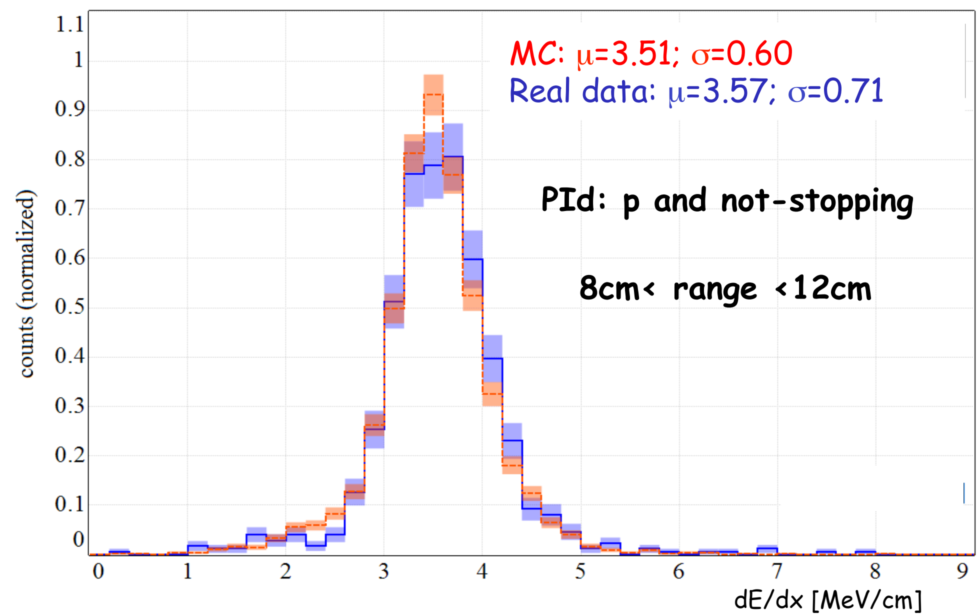
Stopping tracks

Data and MC dE/dx for tracks (residual range between 8 and 12cm)

- Very good agreement
- π clearly separated from protons
- MC: only protons are considered



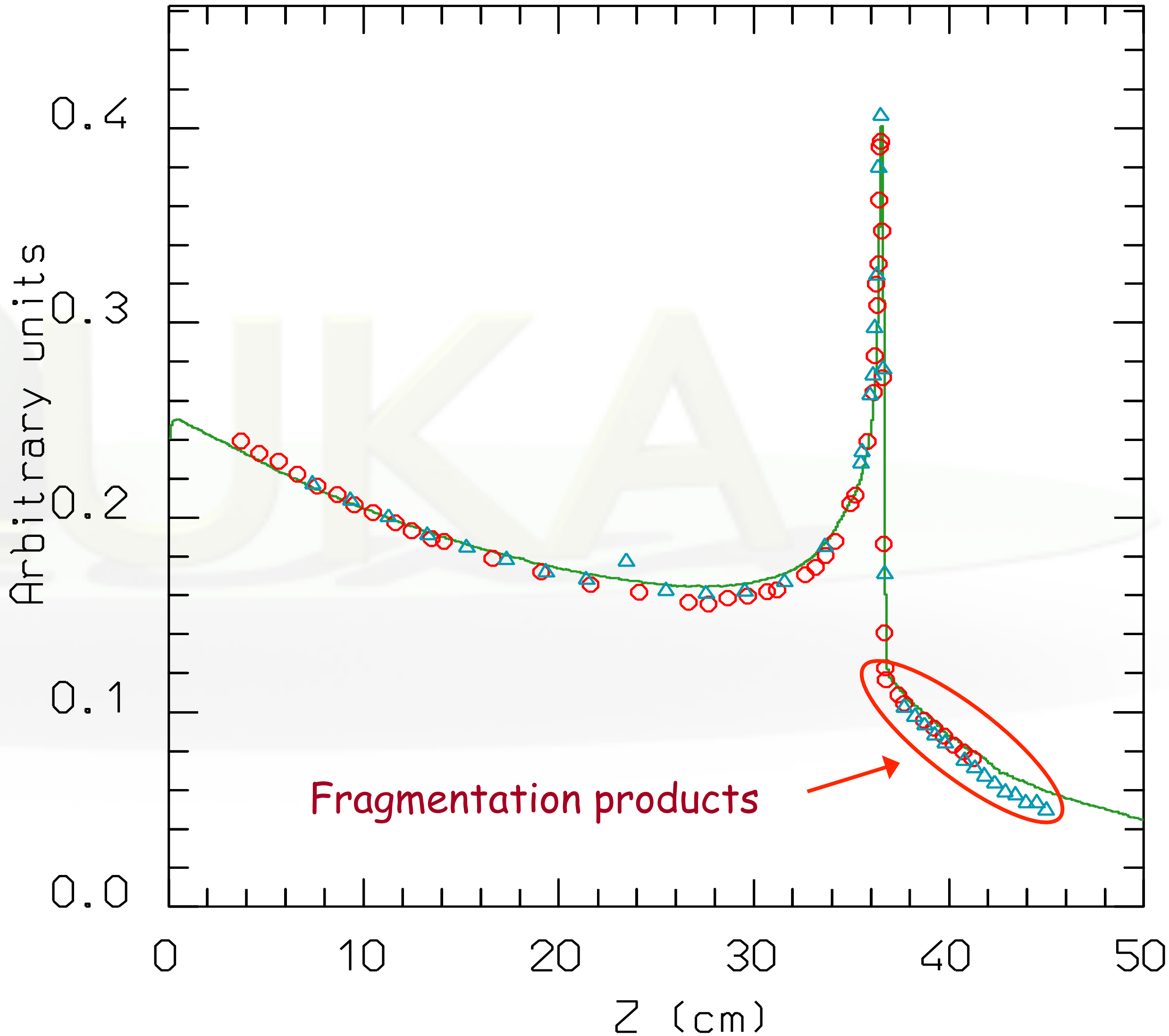




Ions dE/dx

Dose vs depth distribution for 670 MeV/n ^{20}Ne ions on a water phantom.
The green line is the FLUKA prediction
The symbols are exp data from LBL and GSI

Exp. Data Jpn.J.Med.Phys. 18, 1,1998



Here more ingredients like effective charge and its fluctuations
Many recent developments

Applications to hadron therapy

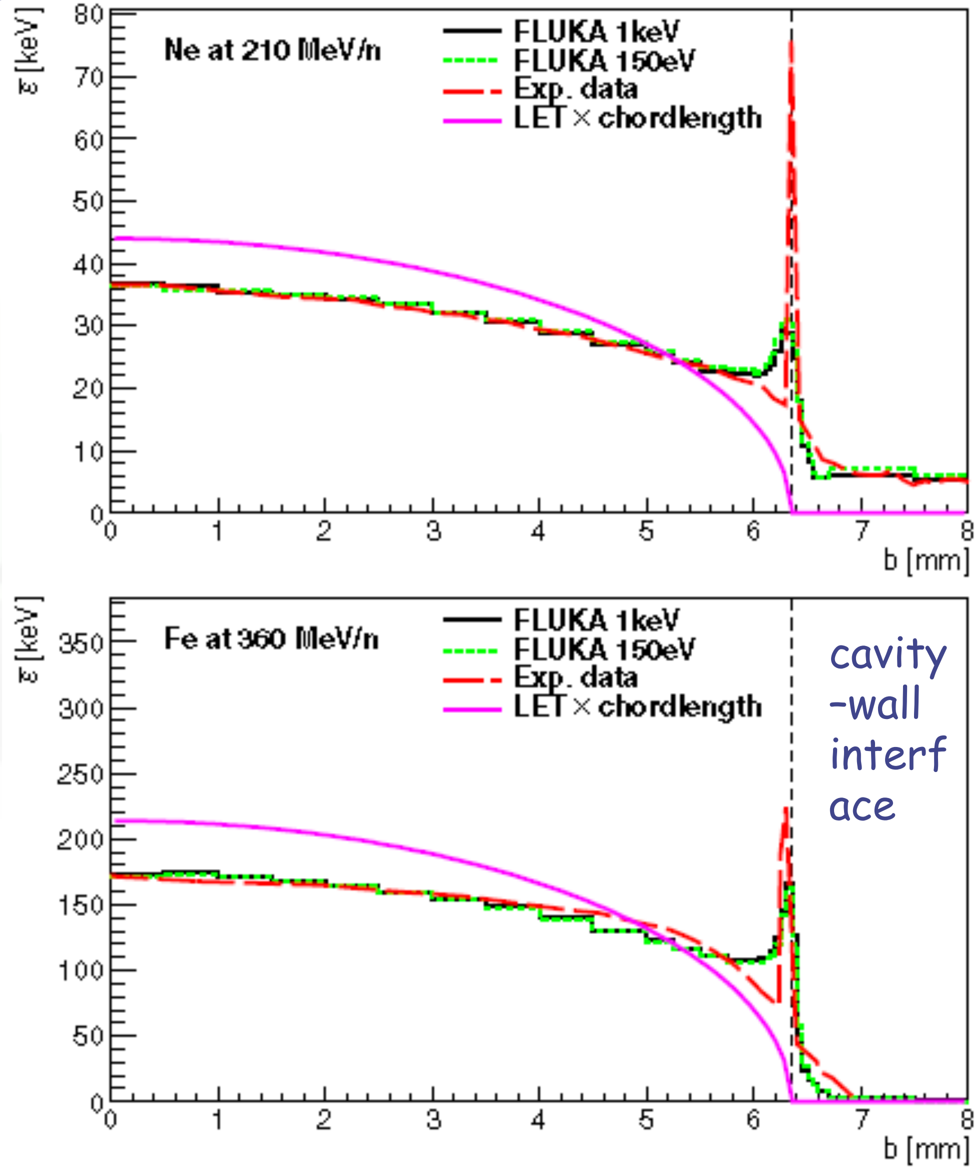
Example : TEPC (T.T. Boehlen et al, Phys. Med. Biol. **56** **(2011)** **6545**)

- Tissue-equivalent proportional counters (TEPC) measure the imparted energy ε and derived quantities such as the lineal energy y in volumes which mimic dimensions and medium characteristics of a mammalian cell nucleus (ICRU 1983) and are one of the principal instruments used in microdosimetry.
- They respond to ions passing the sensitive volume of the TEPC as well as to delta-rays from ions passing close to the sensitive volume which penetrate the cavity.
- Fluka compared with several measurements with a spherical TEPC
  - sensitive volume filled with a tissue-equivalent gas
  - inner diameter of 12.7mm.
  - Gas pressure adapted to simulate tissue of diameters between *1.0 and 3.0 μm.*
  - An anode wire extends through the centre of the cavity, surrounded by a helical grid which forms a uniform field close to the wire
  - The cavity is surrounded by conductive tissue-equivalent plastic with a thickness between 1.27 and 3*.7mm.*

TEPC : Response vs. position

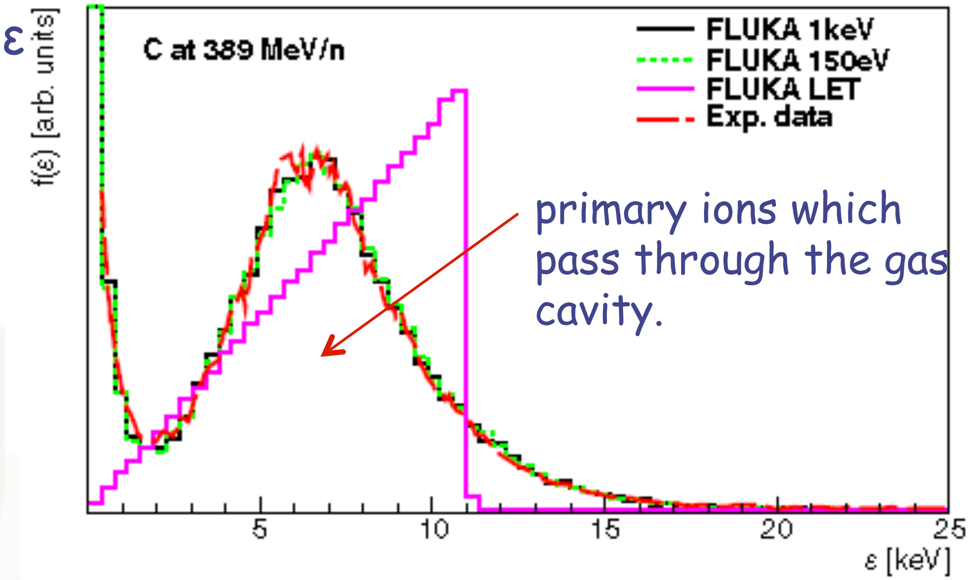
(Phys. Med. Biol. 56 (2011) 6545)

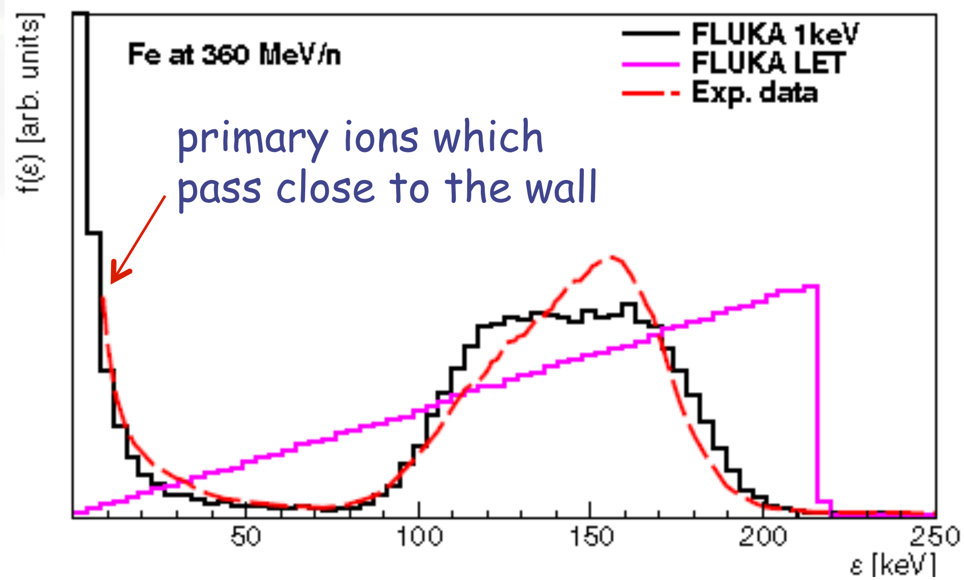
- FLUKA sim. and measurements of the mean imparted energy ε in the TEPC cavity vs. the impact parameter *b* for Ne ions at 210MeV/n and Fe ions at 360MeV/n
- Simulations with a δ-ray threshold of 150 eV and 1 keV are shown.
- The unrestricted LET times the chord-length in the cavity is also shown: this gives the "geometrical" response .
- Ions which pass in the wall close to the cavity surface produce delta-rays with energies large enough to penetrate in the cavity.



TEPC : Response

- Spectra of the imparted energy ε in the TEPC for C ions at 389MeV/n and for Fe ions at 360MeV/n.
- FLUKA simulations marked as 'FLUKA LET' were performed with electromagnetic particle production, energy loss fluctuations, scattering and inelastic interactions switched off to mimic energy depositions according to the LET concept. As expected, they yield triangle-shaped curves.





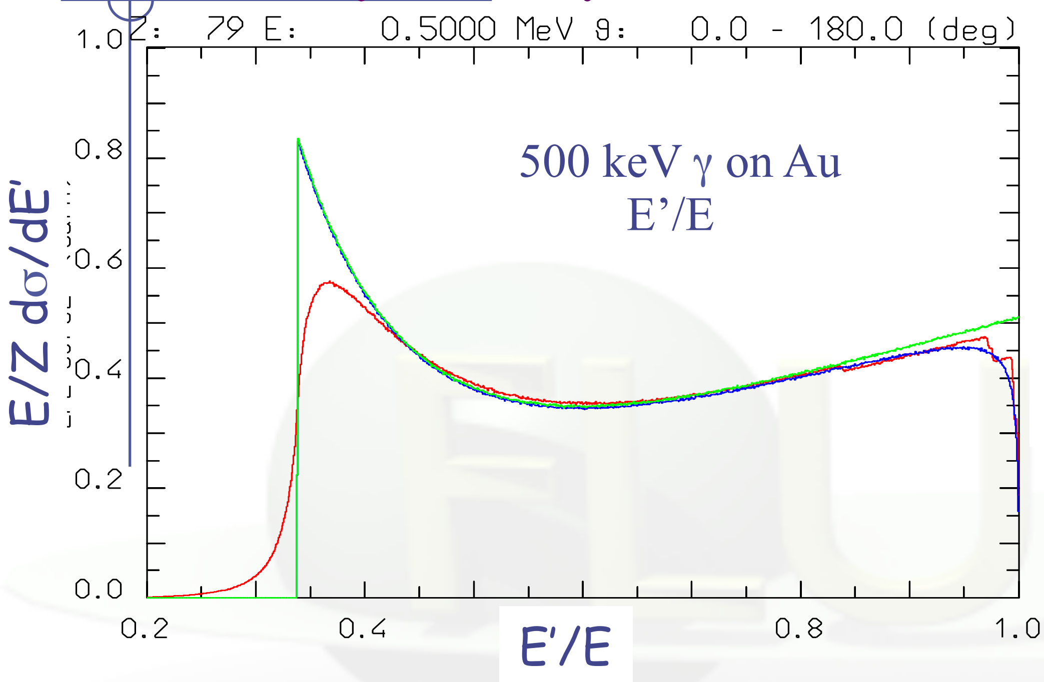
EMF ElectroMagneticFluka

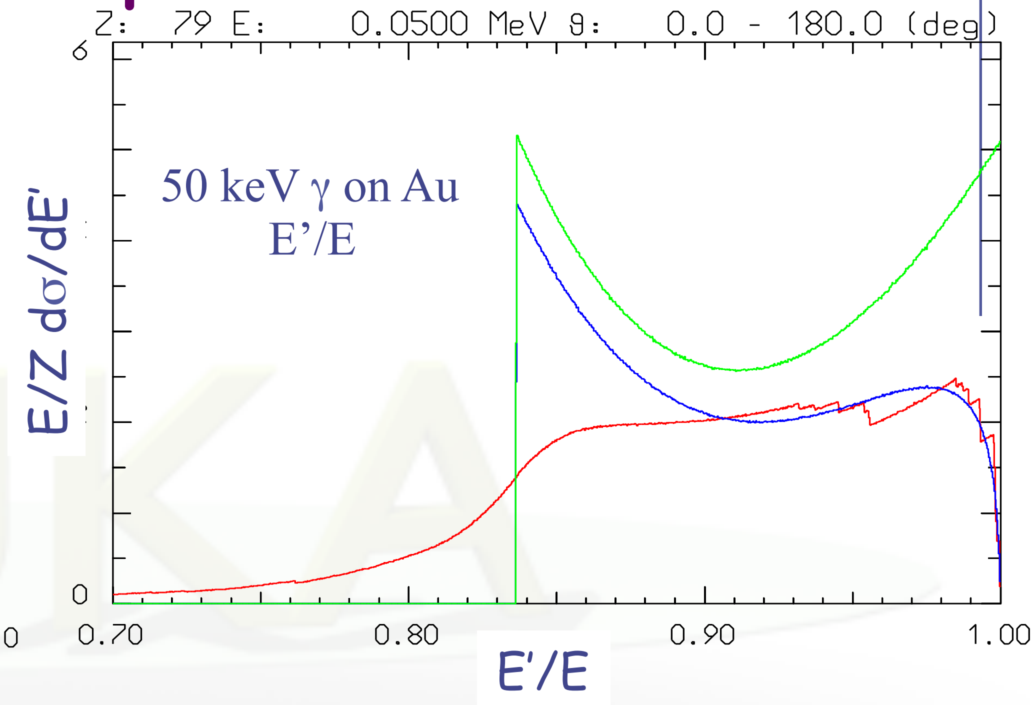
- Photoelectric: fluorescence, angular distribution, Auger, polarization
- Compton and Rayleigh: atomic bonds, polarization
- Pair production correlated angular and energy distribution; also μ-pair production and direct e^+e^- for μ
- Photonuclear interactions; also for μ
- Bremsstrahlung : LPM, angular distribution, ... also for μ
- Bhabha and Møller scattering
- Positron annihilation at rest and in flight
- μ capture at rest
- Optical photon (Cherenkov) production and transport
- Multiple or single scattering on option

Compton and annihilation on bound electrons:

- **Bound electron momentum distributions** parameterized out of available (relativistic) Hartee-Fock calculations for all (sub)shells for all elements
- **Fermi momentum distribution** for conduction electrons in **metals**
- **Explicit bound-electron – photon kinematics for Compton scattering,** with full account for energy, momentum conservation (since 2008)
- Same approach for **(quasi) first-principle based acolinearity** description for **positron annihilation** at rest

Compton profile examples

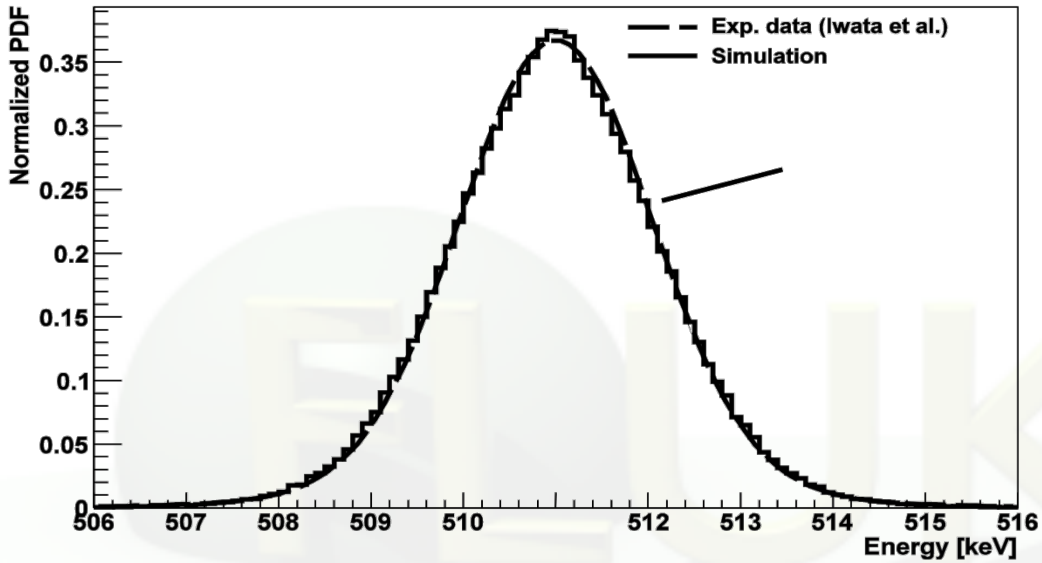




green = free electron
blue = binding with form factors
red = binding with shells and orbital motion

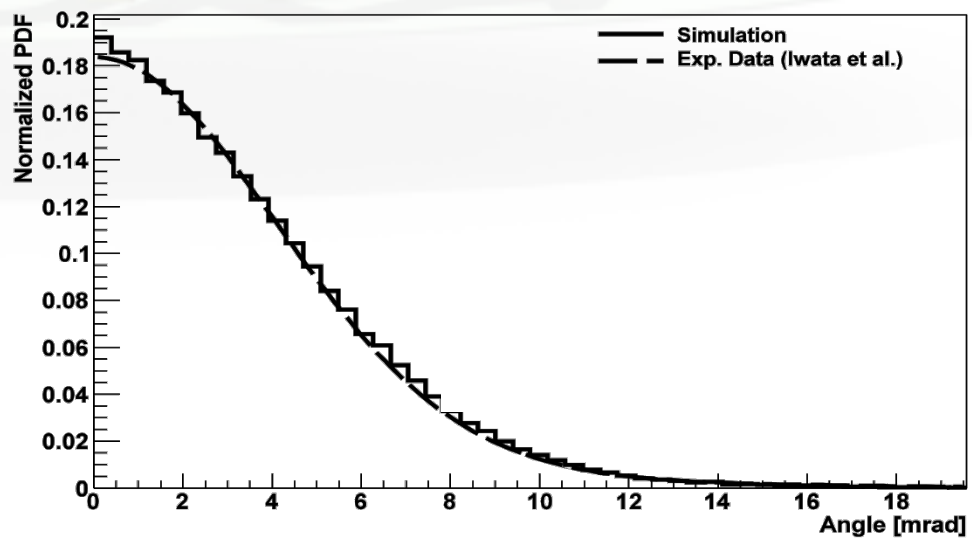
Larger effect at very low energies, where, however, the dominant process is photoelectric.
Visible: shell structure near E'=E, smearing from motion at low E'

Annihilation on bound electrons: H_2O



← Energy

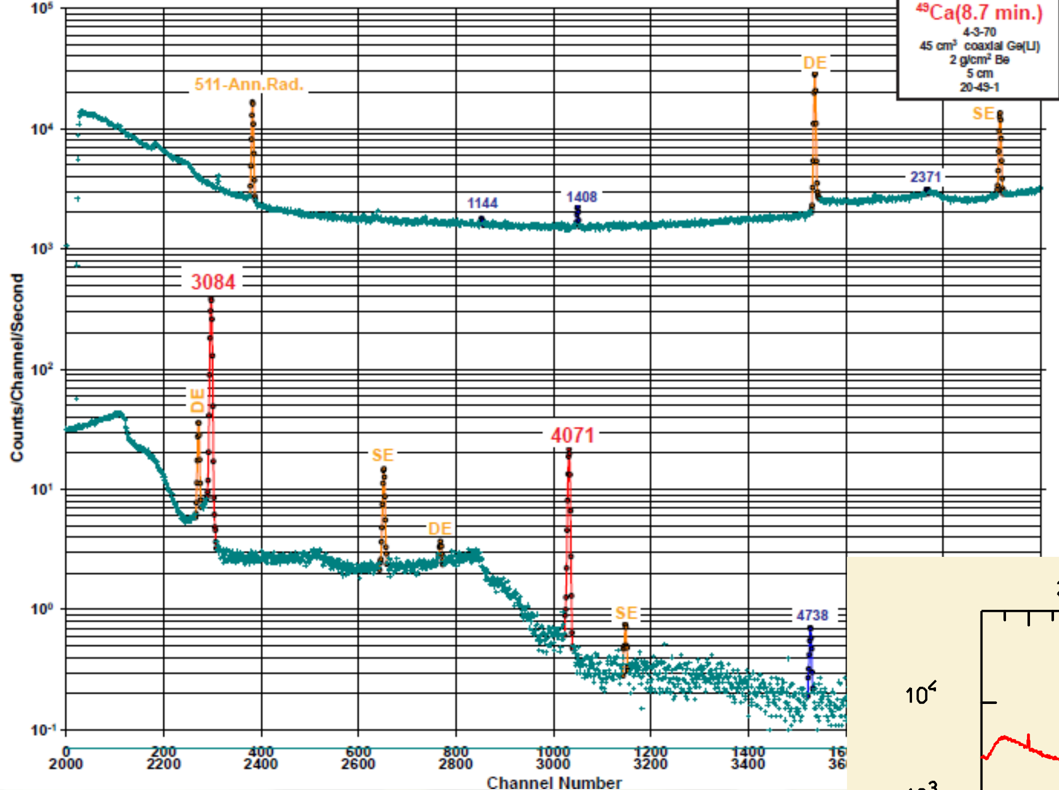
Angle →

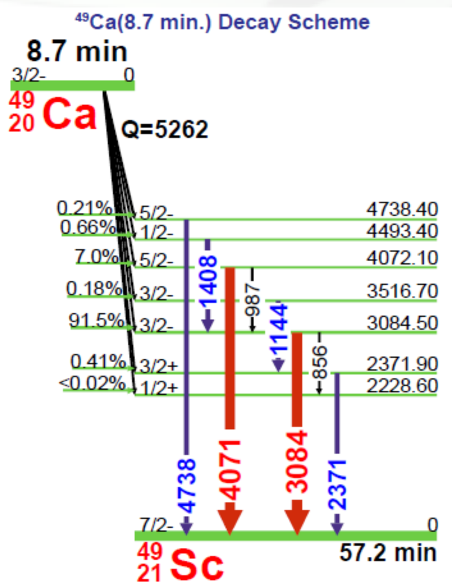


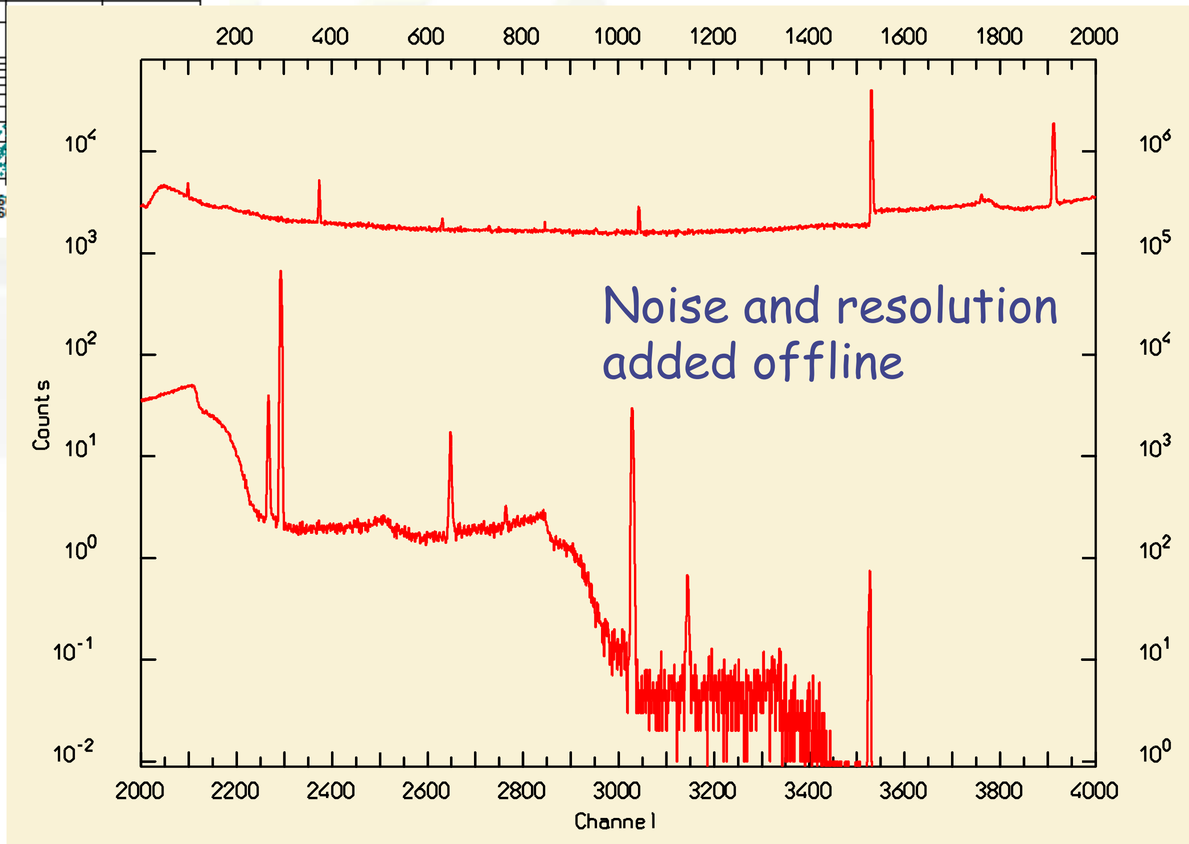
Example of γ spectrum in Ge(Li)

Data from Gamma Ray Spectrum Catalogue http://id.inel.gov/gamma

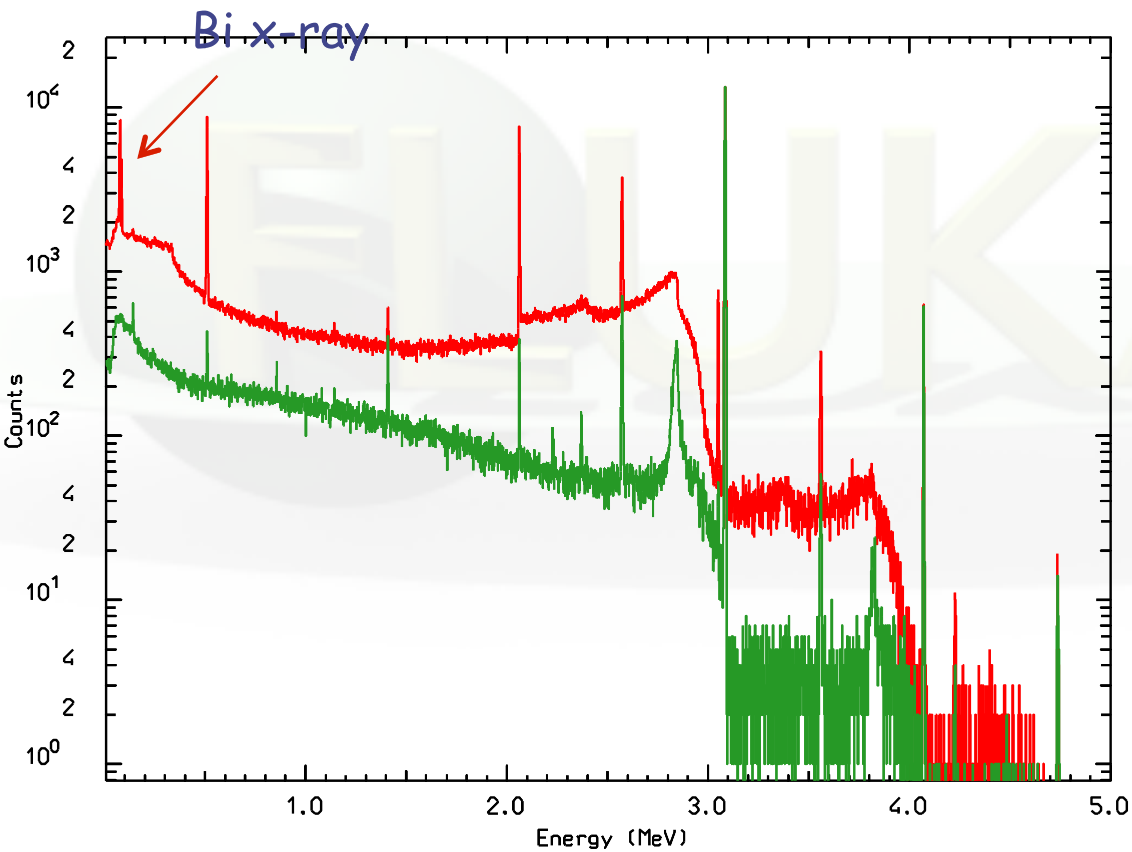
In Fluka : direct simulation of β-decay with correlated γ cascade, from decay and nucl. level database (see later)

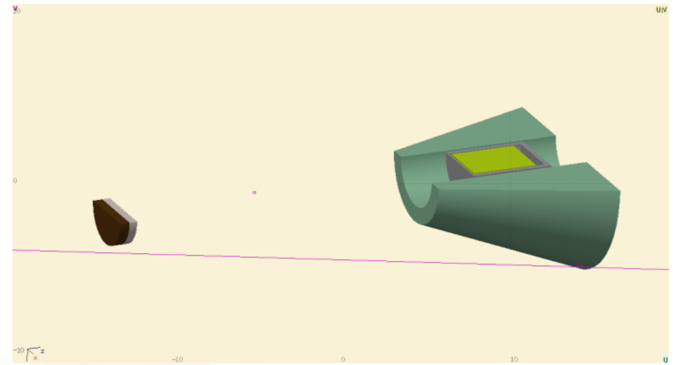






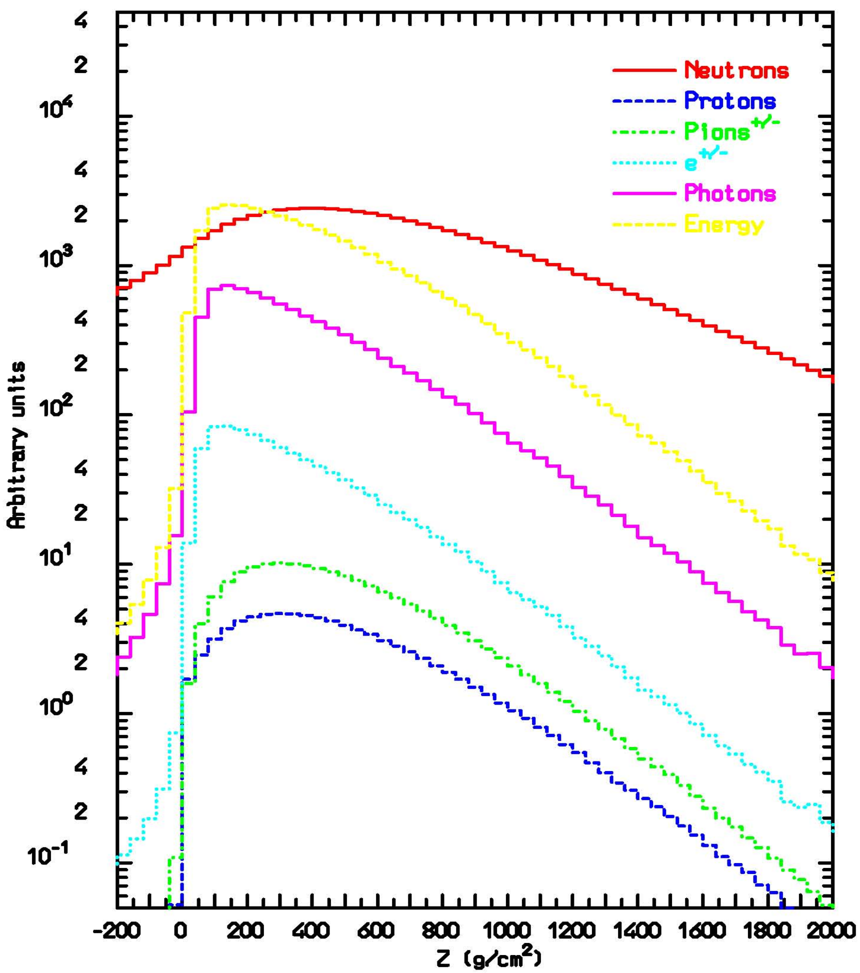
Add a BGO anti-compton shield



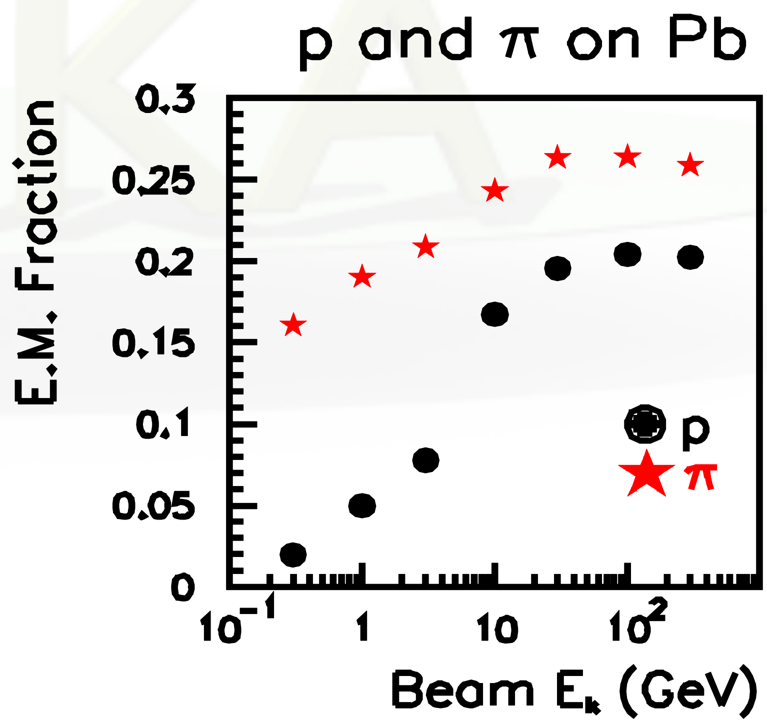


Hadronic Showers → calorimetry, bckg, damage..

100 GeV p on Pb
shower longitudinal development



Fraction of the beam energy converted into π^0 and γ for interactions in Lead as a function of projectile energy



The FLUKA hadronic Models

Hadron-nucleus: PEANUT

Elastic, exchange
Phase shifts data, eikonal

P<3-5GeV/c
Resonance prod and decay

low E
π, K
Special

High Energy
DPM hadronization

Sophisticated G-Intranuclear Cascade

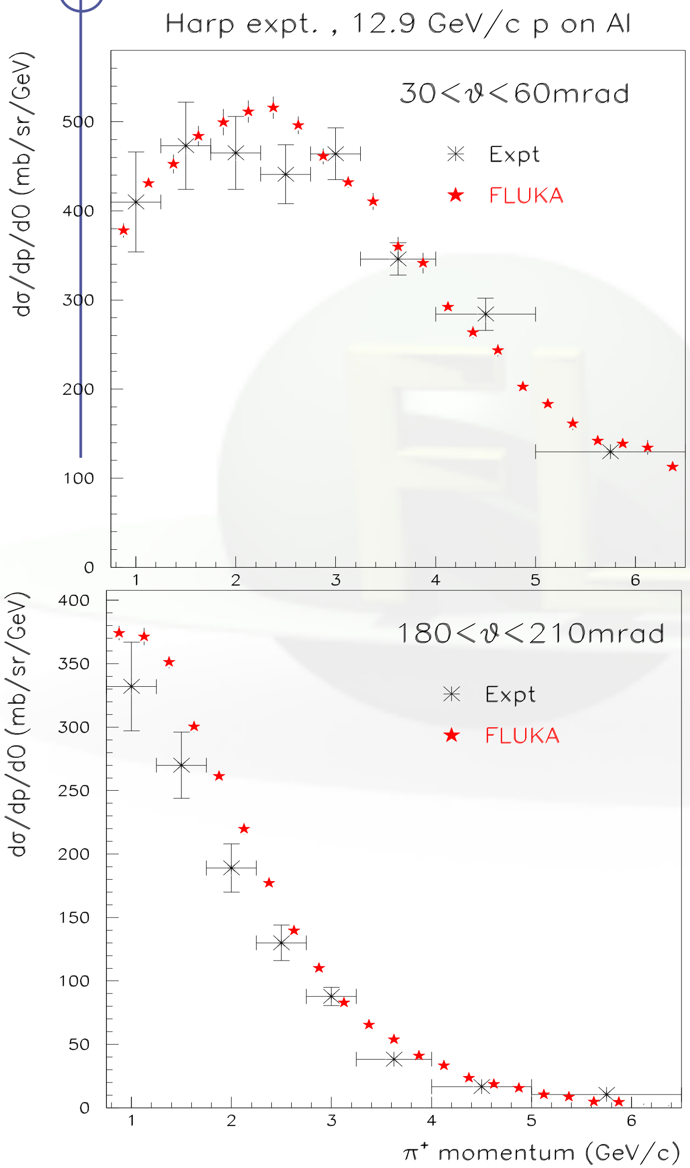
Gradual onset of Glauber-Gribov multiple interactions

Preequilibrium

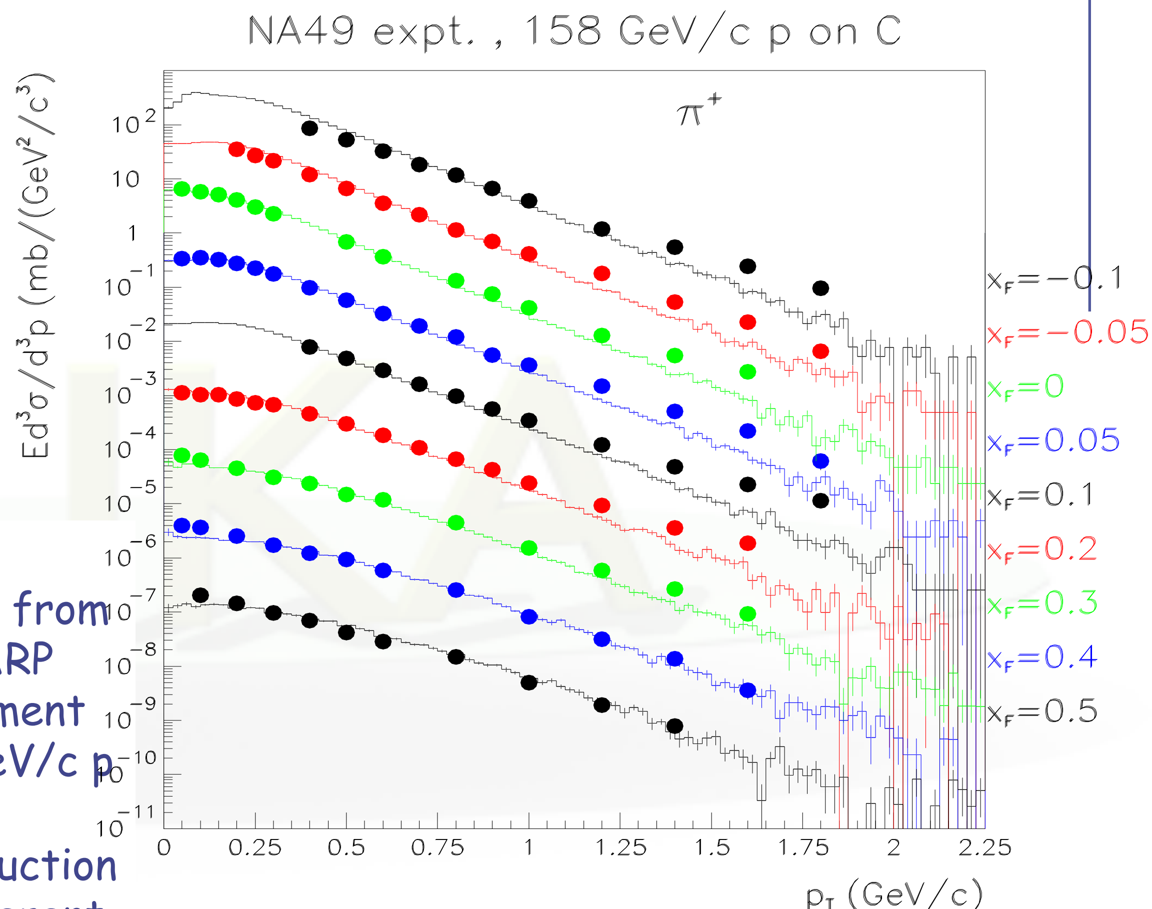
Coalescence

Evaporation/Fission/Fermi break-up
γ deexcitation

Nonelastic hA interactions at high energies: examples



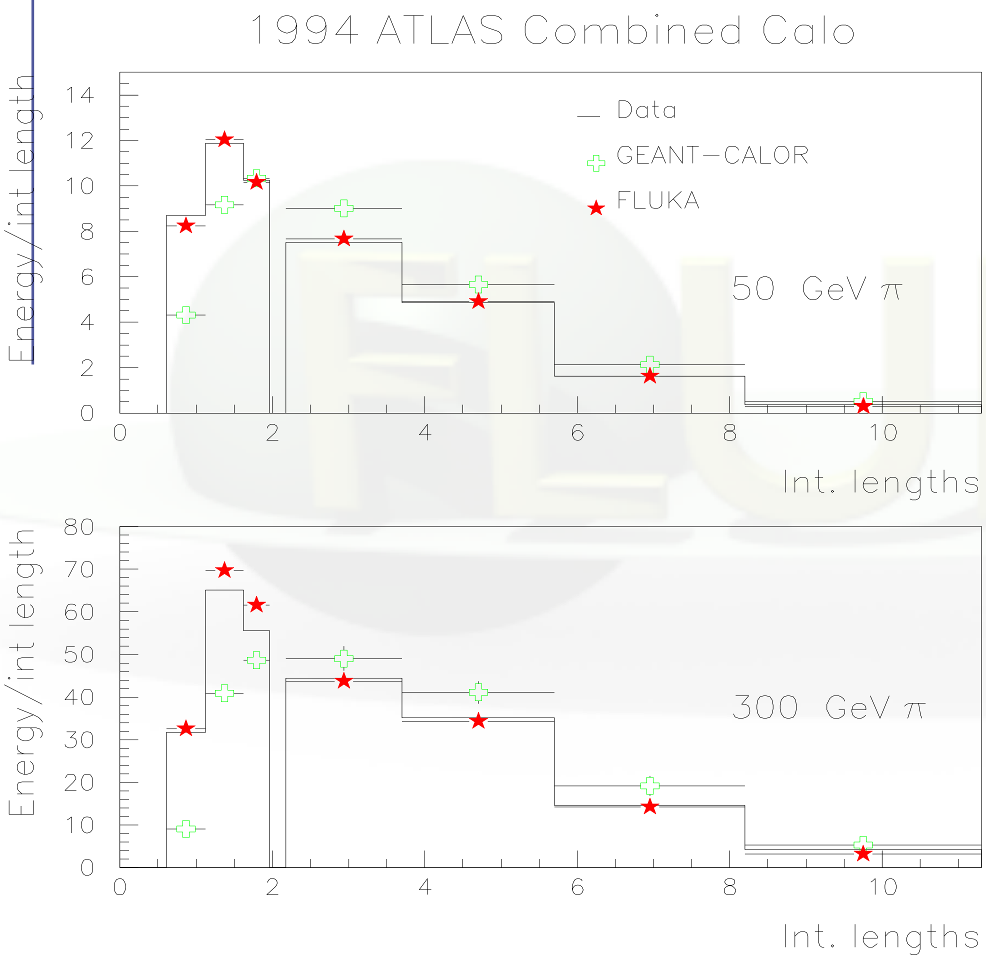
Recent results from the HARP experiment 12.9 GeV/c p on Al π^+ production at different angles

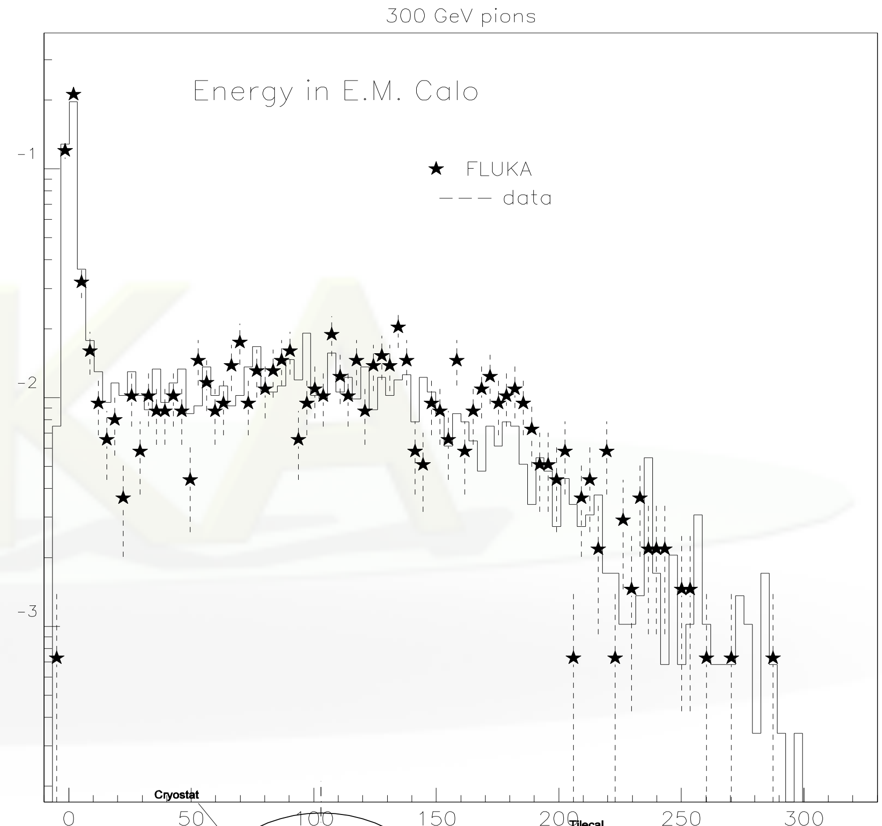


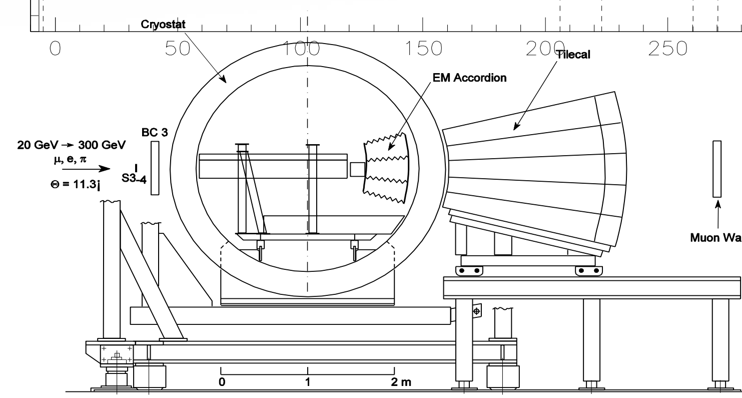
Double differential π+ production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)

Atlas combined calo test beam: 1994 data

pion beams: longitudinal shower development and its fluctuations

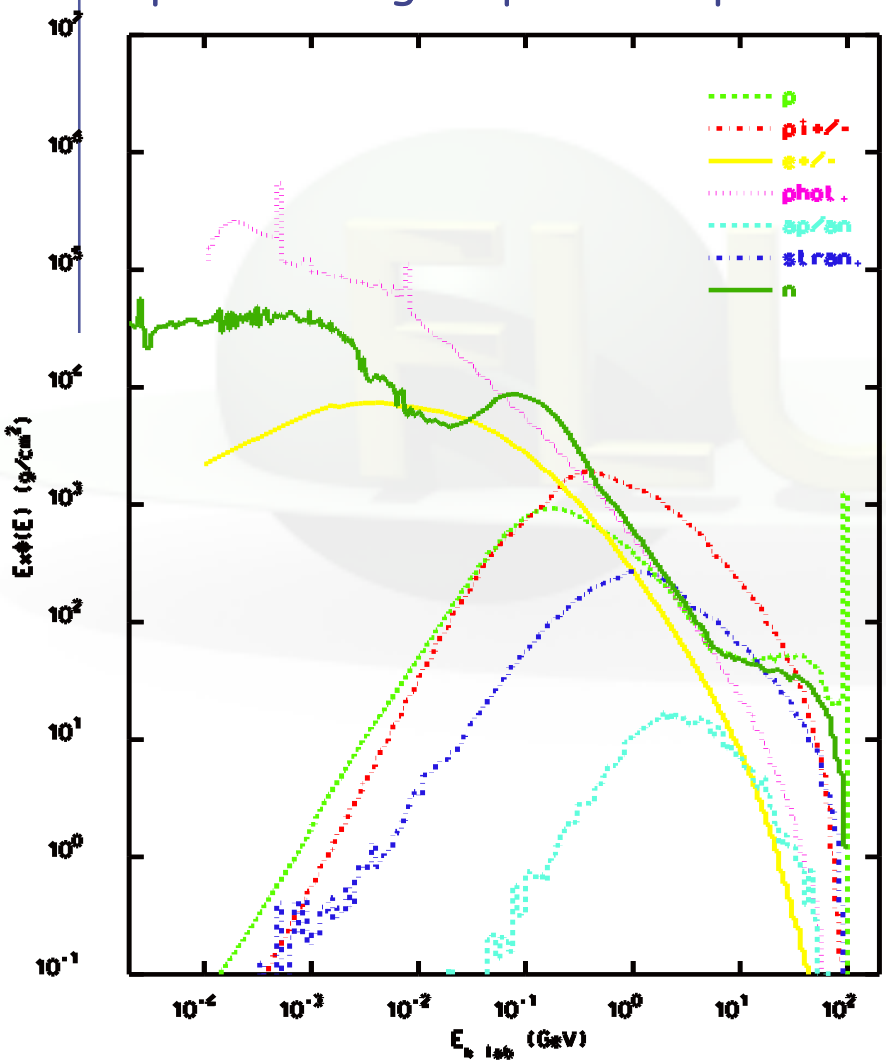


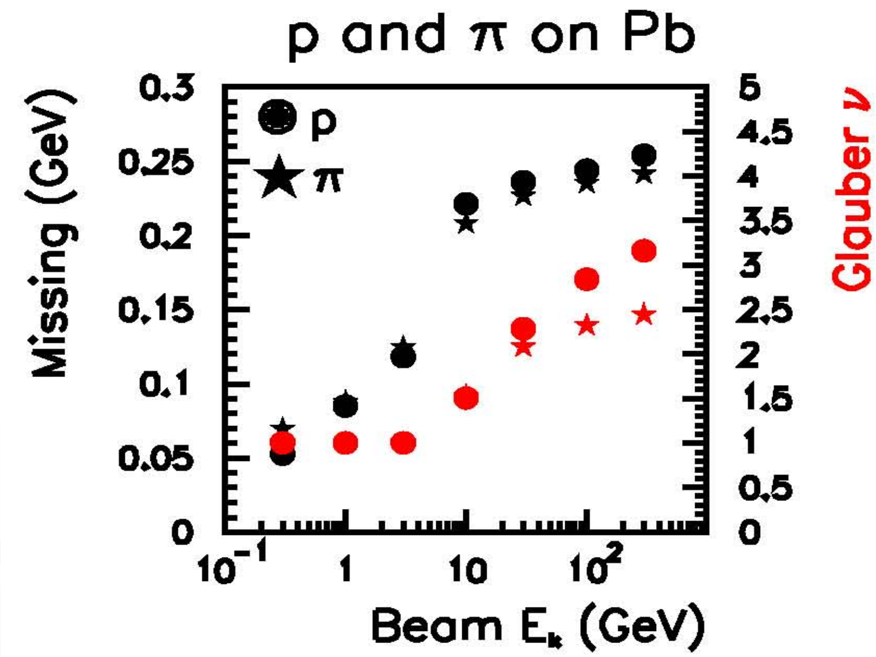




The importance of low E interactions and nuclear physics

100 GeV p in a Fe absorber:
space-averaged particle spectra





Average binding energy losses for interactions in lead. The number of primary collisions are also reported

Nuclear interactions in PEANUT:

Target nucleus description (density, Fermi motion, etc)

⇓

Glauber-Gribov cascade with formation zone

⇓

Generalized IntraNuclear cascade with quantum effects

⇓

Preequilibrium stage with evolving exciton configuration and excitation energy

⇓

Evaporation/Fragmentation/Fission model

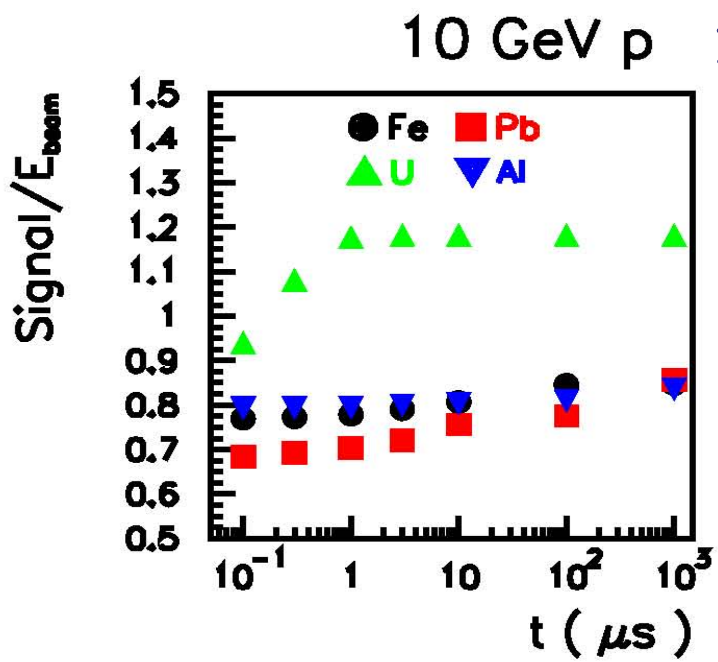
⇓

γ deexcitation

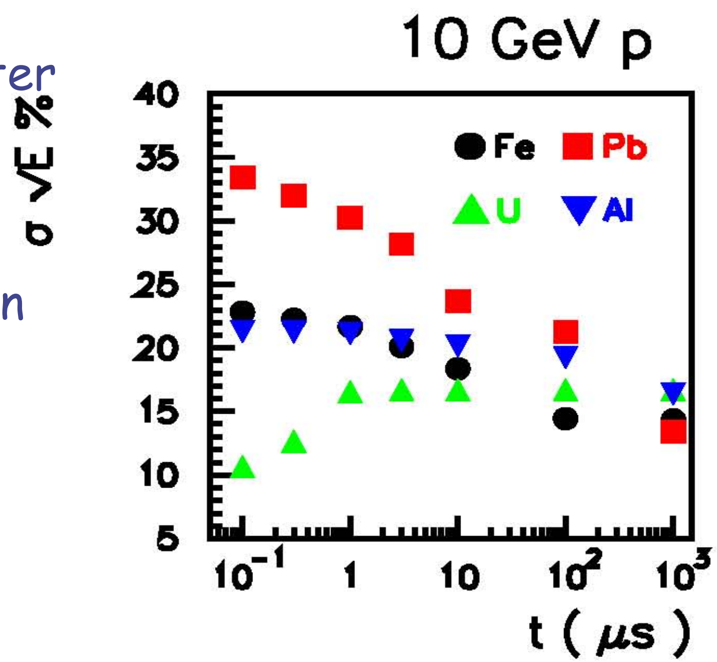
Exact conservation of energy, momenta and all addititive quantum numbers, including nuclear recoil

Low energy (< 20MeV neutrons)

- The fraction of visible energy due to neutrons below 10-20 MeV is significant.
- Most of their kinetic E is spent via elastic interactions →recoils →non-ionizing or quenched. (except for interactions on Hydrogen).
- Most of the low energy neutron contribution comes from capture γ rays.
- The capture probability is maximal in the thermal region: thermalization times can vary from μs to ms depending on the material composition



Infinite calorimeter
← visible E
resolution →
vs
signal integration
time



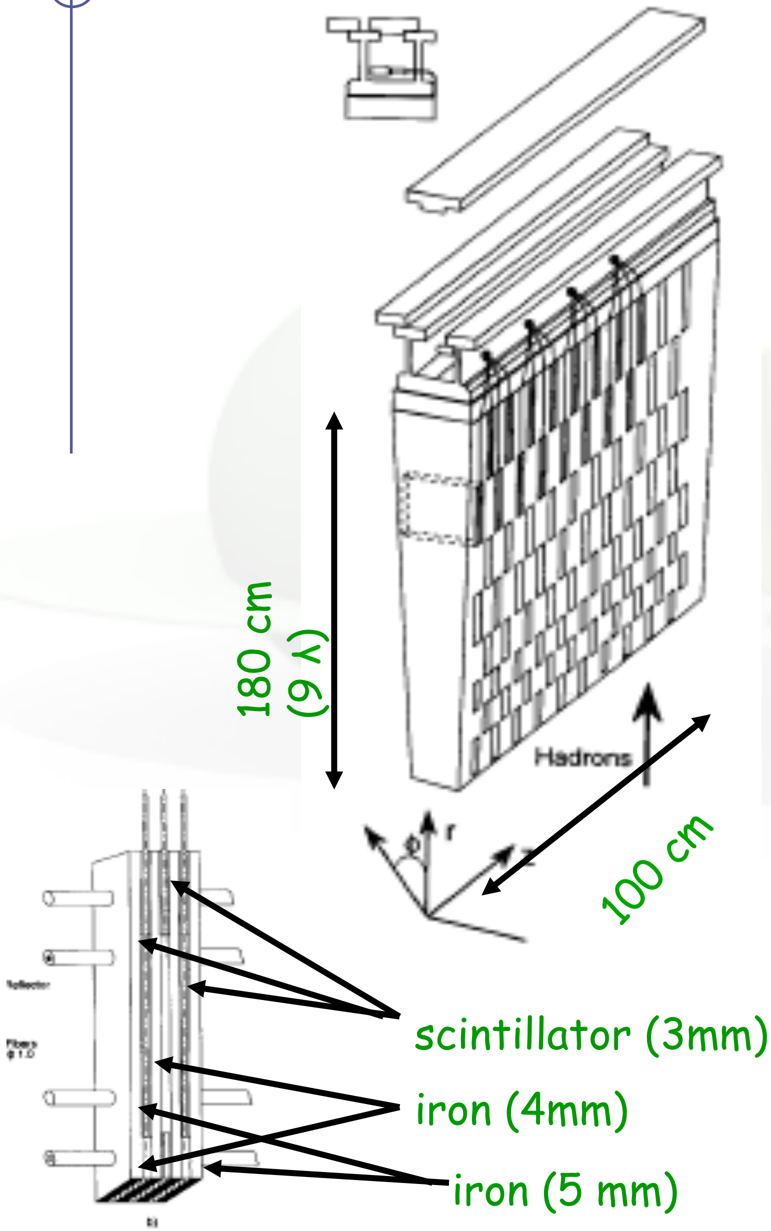
Low-energy neutron transport in FLUKA

performed by a multigroup algorithm

- Energy range up to 20 MeV divided in 260 energy groups (30 thermal) and 40 groups for secondary gamma generation
- The library contains ≈230 different materials/temperatures/Self shielding
- Hydrogen cross sections available for different types of molecular binding (free, H_2O, CH_2)
- Pointwise, fully correlated, with explicit generation of all secondary recoils, cross sections available for reactions in H, ^{6}Li , Ar and partially for ^{14}N and ^{10}B (^{4}He, ^{12}C and ^{16}O in preparation)
- gamma transport by the standard EM FLUKA modules
- For most materials, information on the residual nuclei produced by low-energy neutron interactions are available in the FLUKA library

ATLAS TILE Calorimeter (1994 setup)

1994 Test beam : 5 modules, positrons and positive pions beam, 20-300 GeV/c
NIM A394,384 (1994)



proton contamination in the beam measured (Cerenkov counters) in a later testbeam:

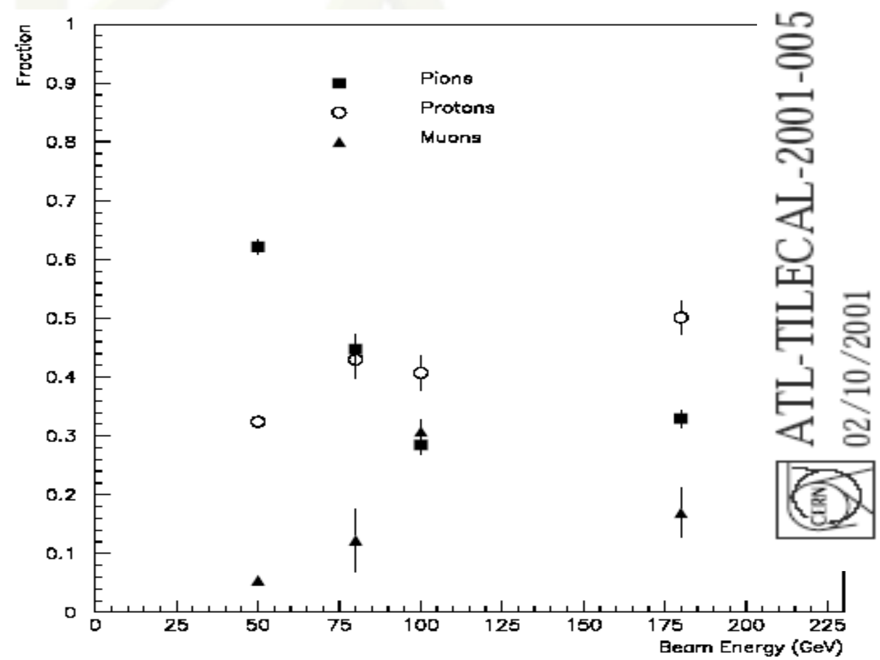
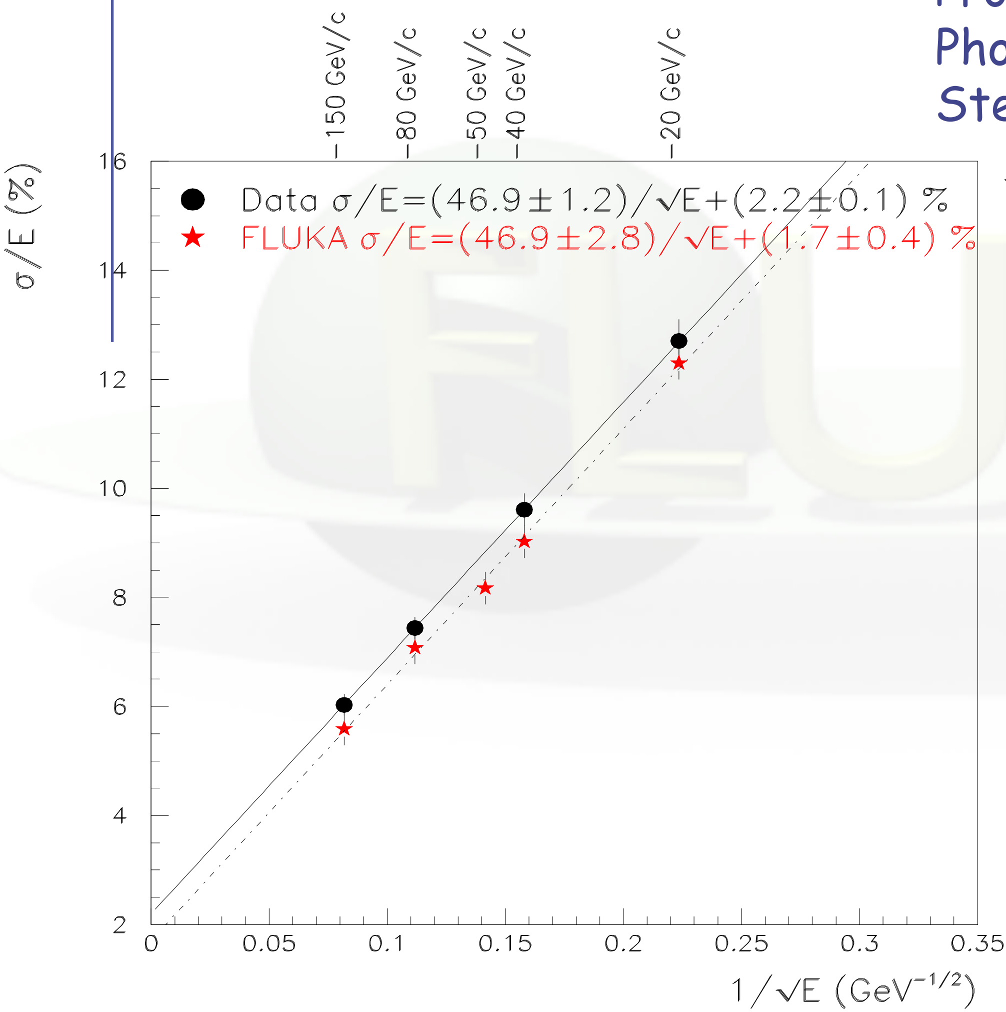


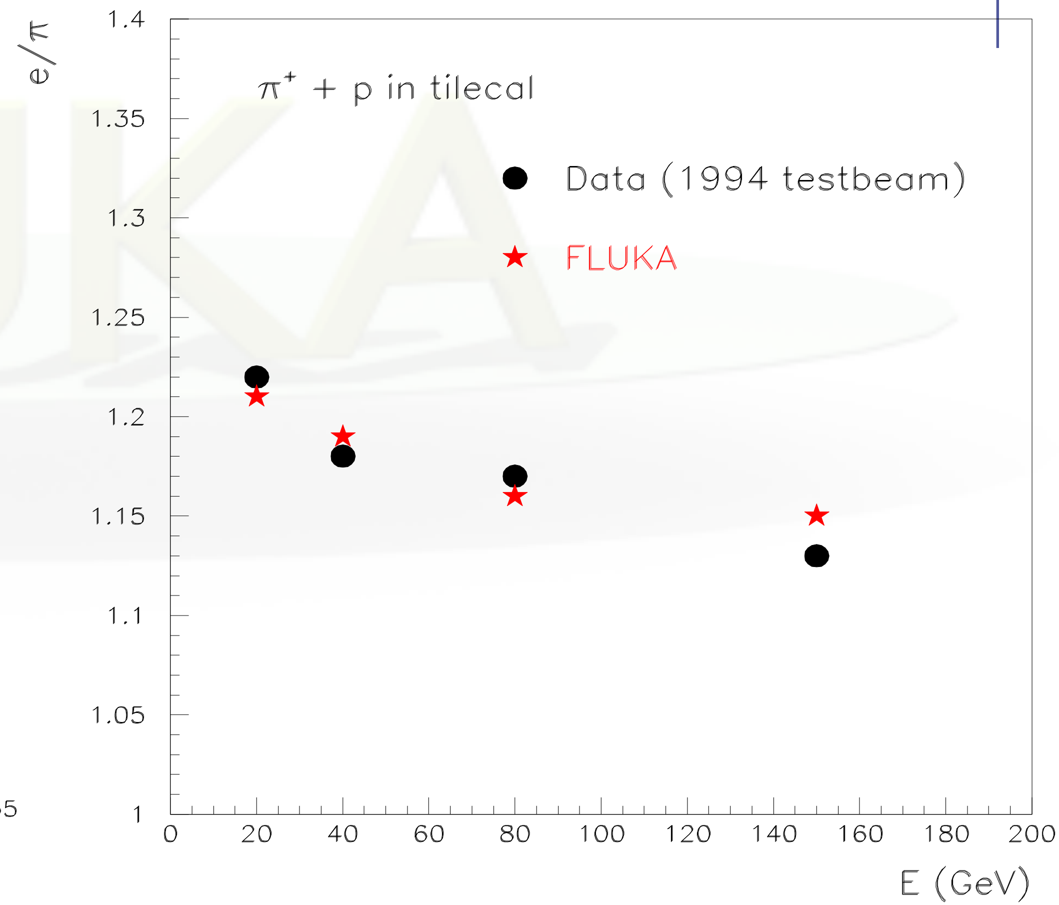
Figure 3: The fractions of pions, protons and muons in the positive pion beam energy.

TILE Calorimeter: resolution and e/π

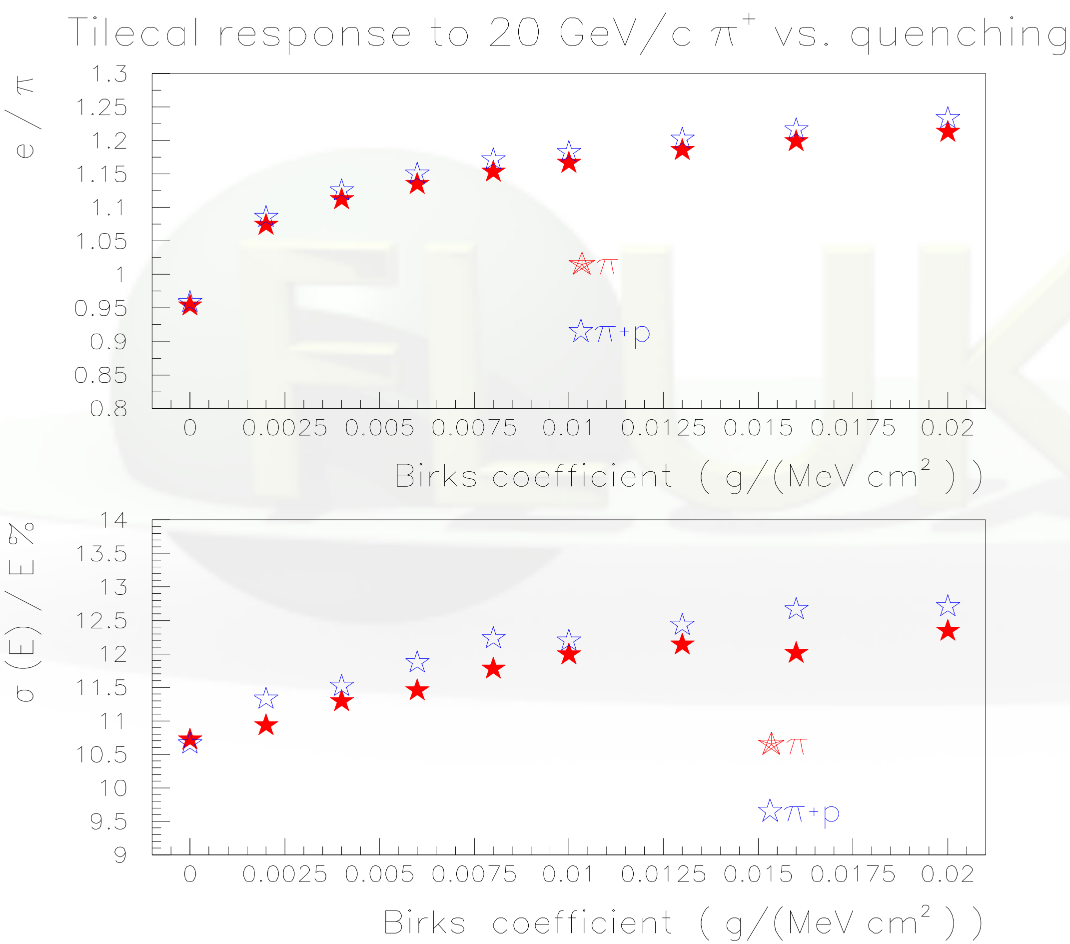
FLUKA simulations with:
Proton contamination
Photostatistics convoluted offline
Step-by-step signal quenching online

Beam at 20⁰ incidence





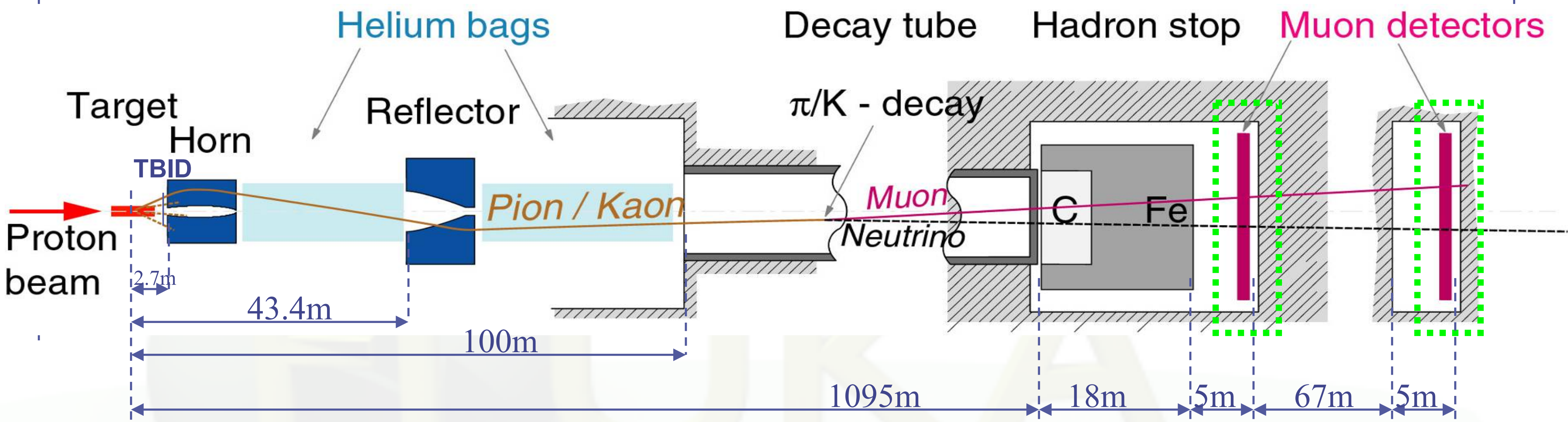
Tile Calorimeter: effect of quenching



$$Q_{vis} = \frac{Q}{1 + k_B \frac{dE}{dx}}$$

FLUKA simulations,
20 GeV/c
20^0 incidence
diferent quenching parameters and effect of beam contamination on e/π
and resolution

Diamond detectors for CNGS (Cern Neutrino to Gran Sasso)



$p + C \rightarrow$ (interactions) $\rightarrow \pi^+, K^+ \rightarrow$ (decay in flight) $\rightarrow \mu^+ + \nu_\mu$

Flight path to Gran Sasso : 732 km.

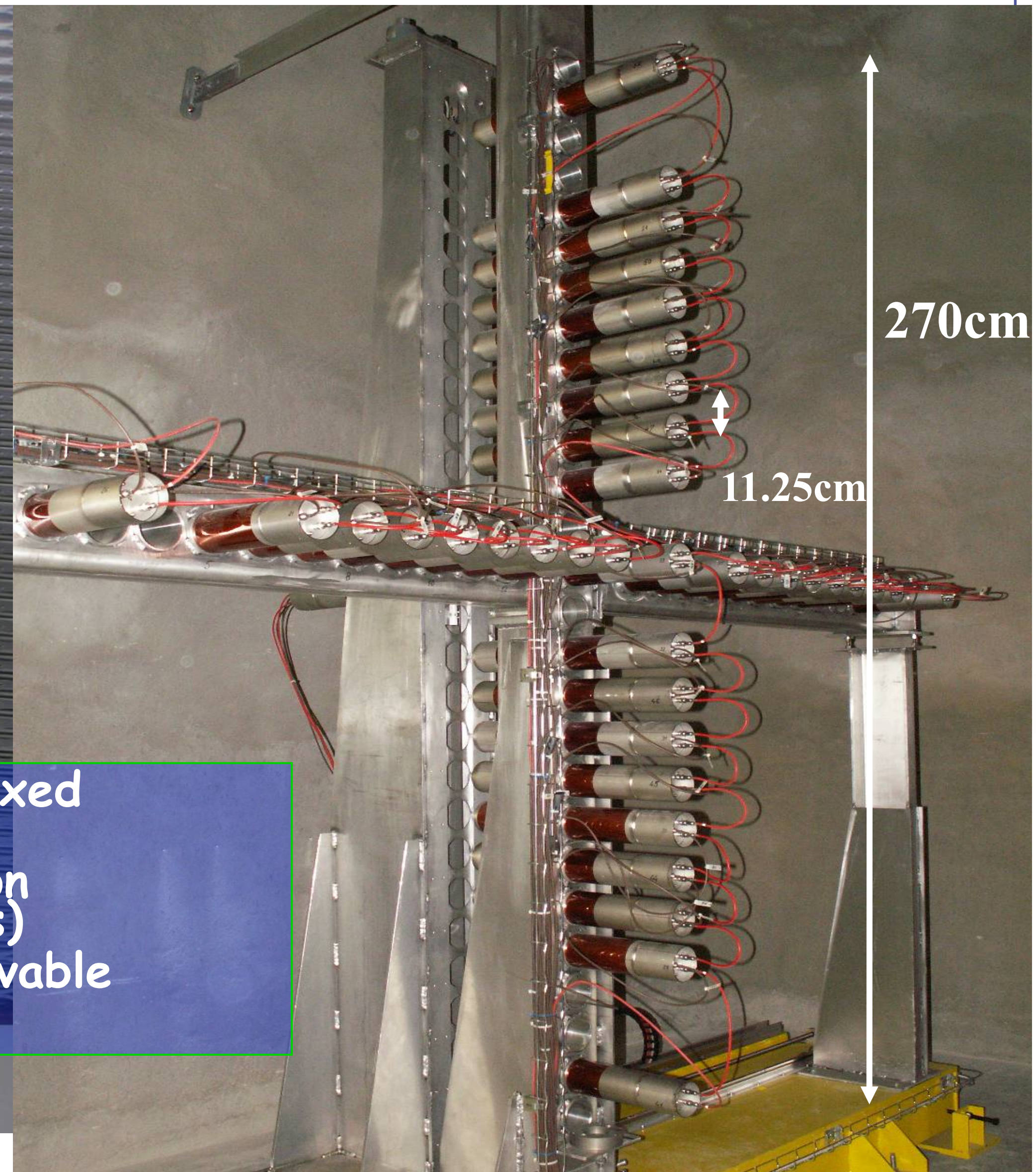
After the "superluminal " claim from OPERA, checks started. One of them: measure the transit time between the primary proton monitor and the muon pits→ check of the "start" in the nu-tof measurement (proton beam monitor)

Paper in preparation

muon pit instrumentation

LHC type Beam Loss Monitors

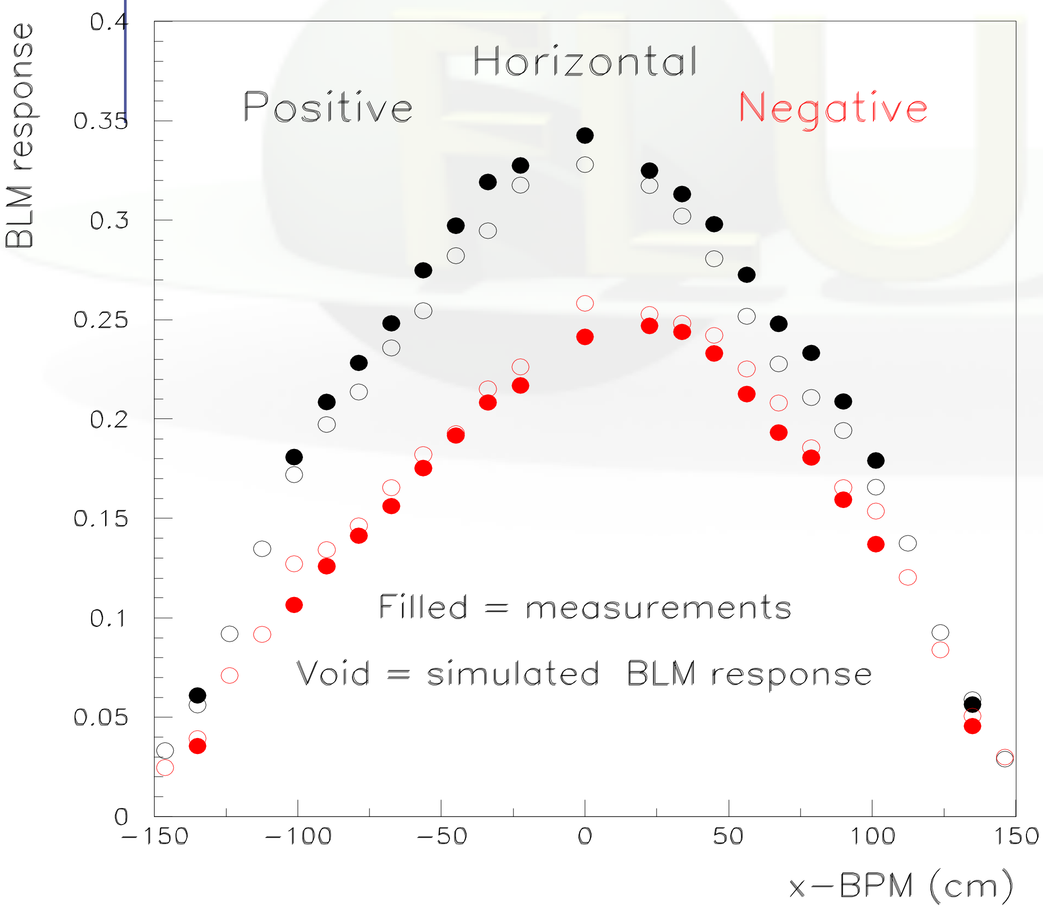
- Stainless steel cylinder
- Al electrodes, 0.5cm separation
- N_2 gas filling



- 2 x 37 fixed monitors (Ionization Chambers)
- 2 x 1 movable monitor

Muon data Comparison with simulation

FLUKA simulation: from the primary proton interaction to neutrinos at GranSasso
In between: particles in the muon pits and response of the muon monitors
External input : average energy needed for a electron-ion pair in N2

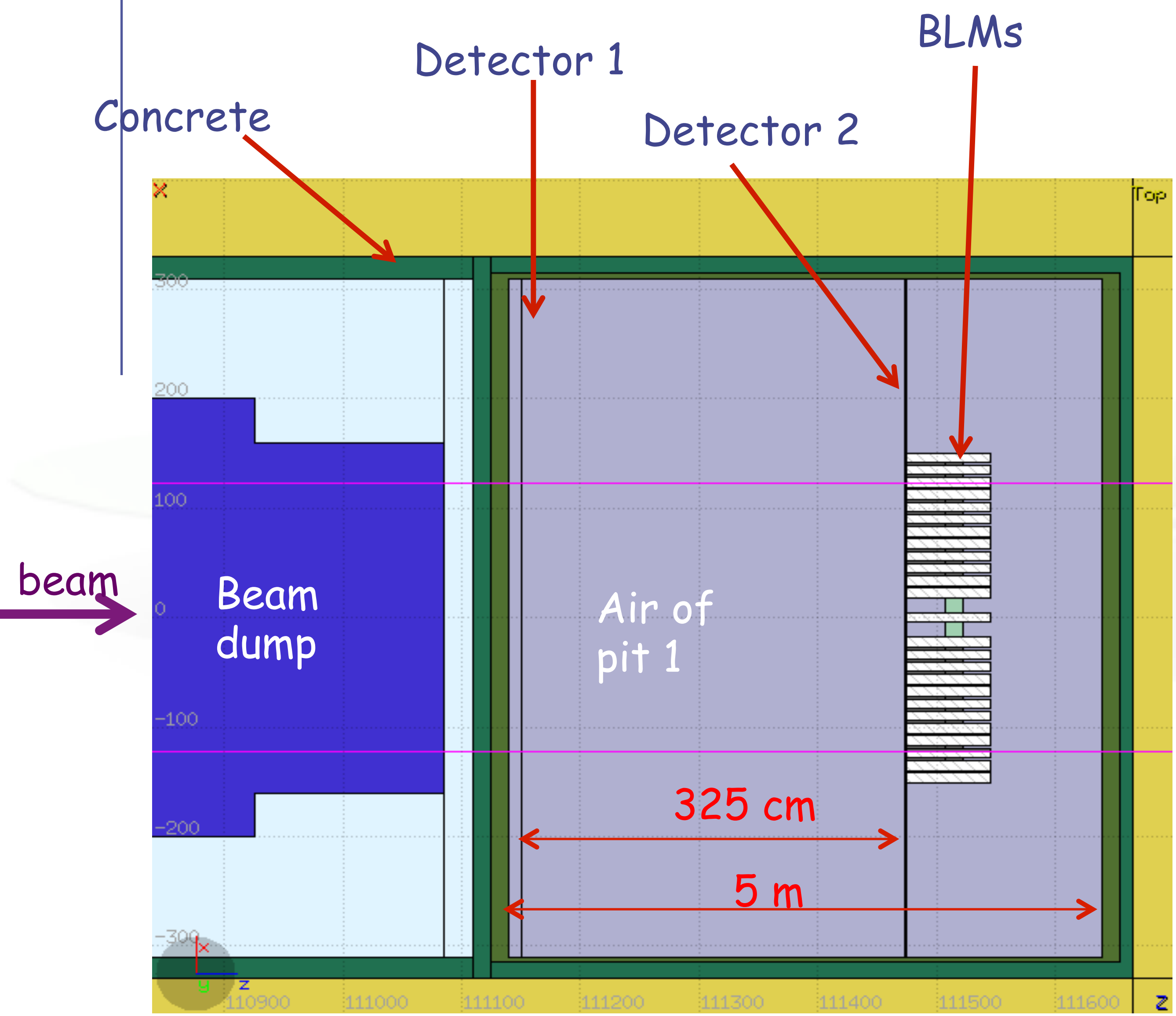


Simulated response of the muon monitors, in electrons/ pot, including the effect of the earth magnetic field and a 1mm horizontal displacement of target vs horn/reflector

The asymmetry is perfectly reproduced

The absolute comparison of simulation and muon pit data is within 5% in 1st pit

Geometry



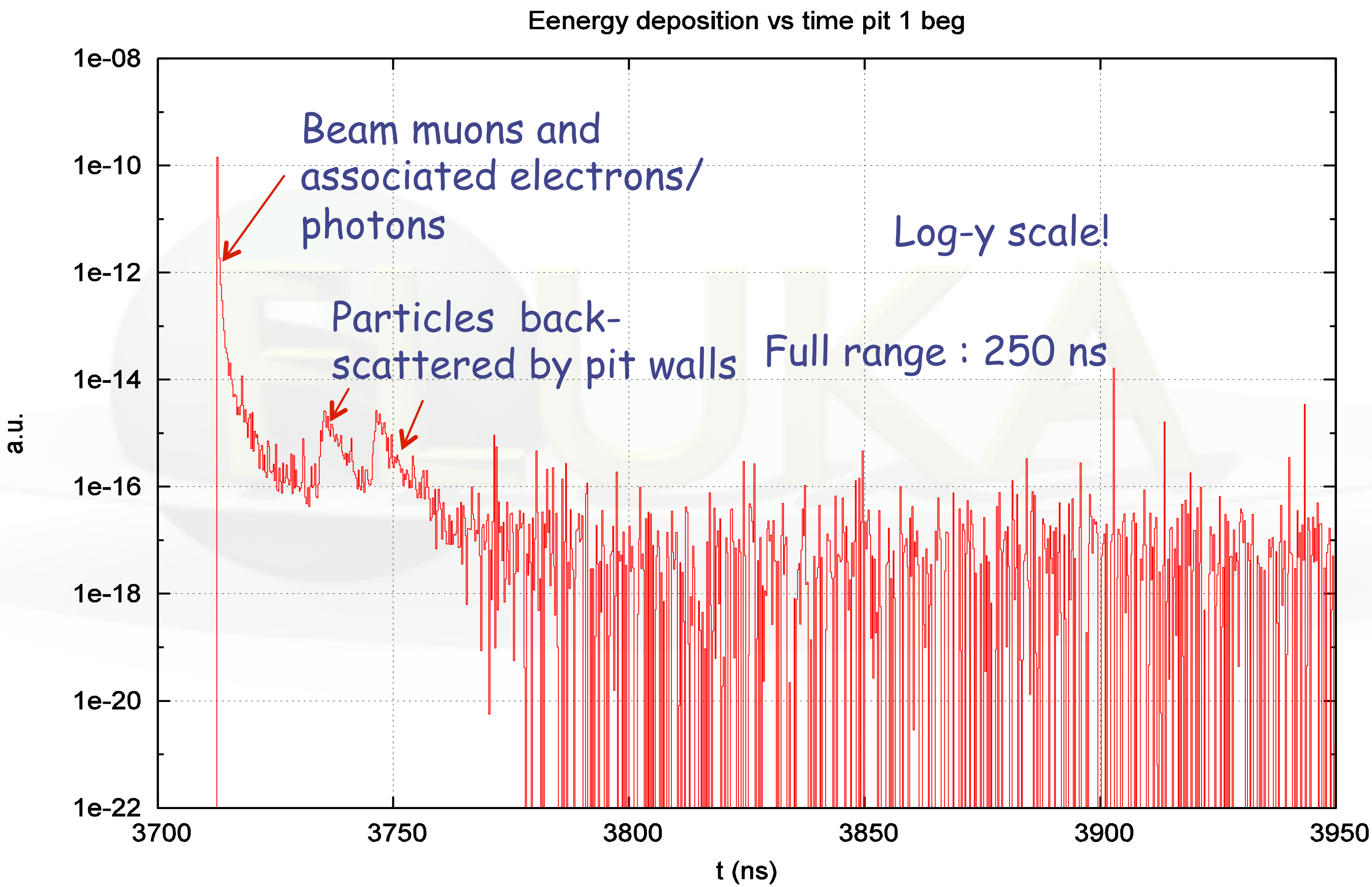
Here: pit1. (pit2 is the same) .
Approximated layout of detectors:
(the timing results are not affected by 2nd order details)

- supports: 3 mm Al plates, in front and behind diamonds
- Detectors: 100μm C density 3.52

Two positions :

- Detector1 at 10 cm from the pit entrance wall,
- Detector2 just before the BLMs

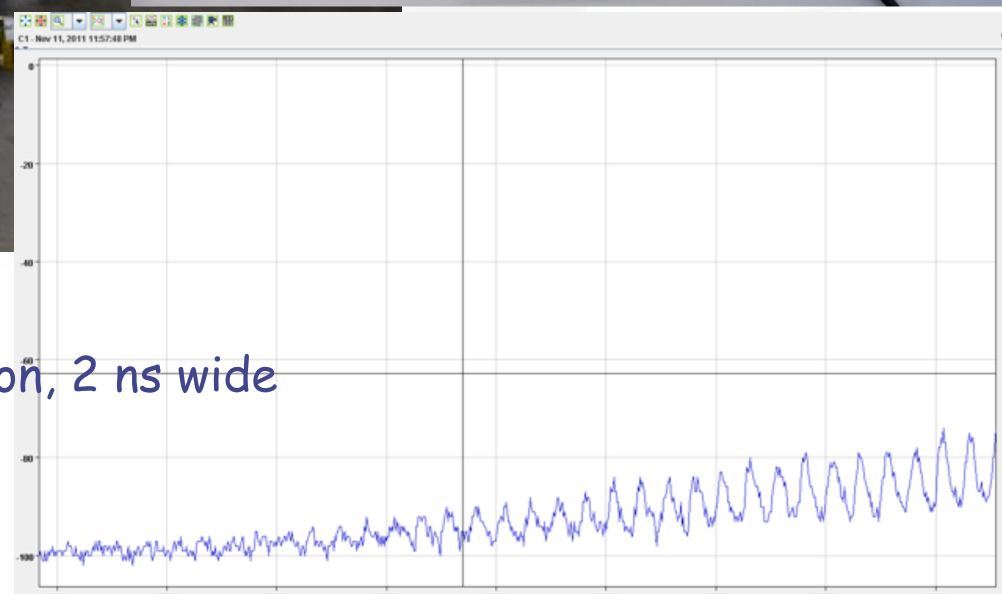
Diamond Pit 1 (det 1): energy dep. vs time



ns

Obtained with minor modification of buiilt-in scoring

Diamond Detectors in the muon pits



One beam spill :2100 pulses, 5 ns separation, 2 ns wide
-> pulses are separated
-> timing w.r.t. start consistent with c

Prompt photons in medical imaging

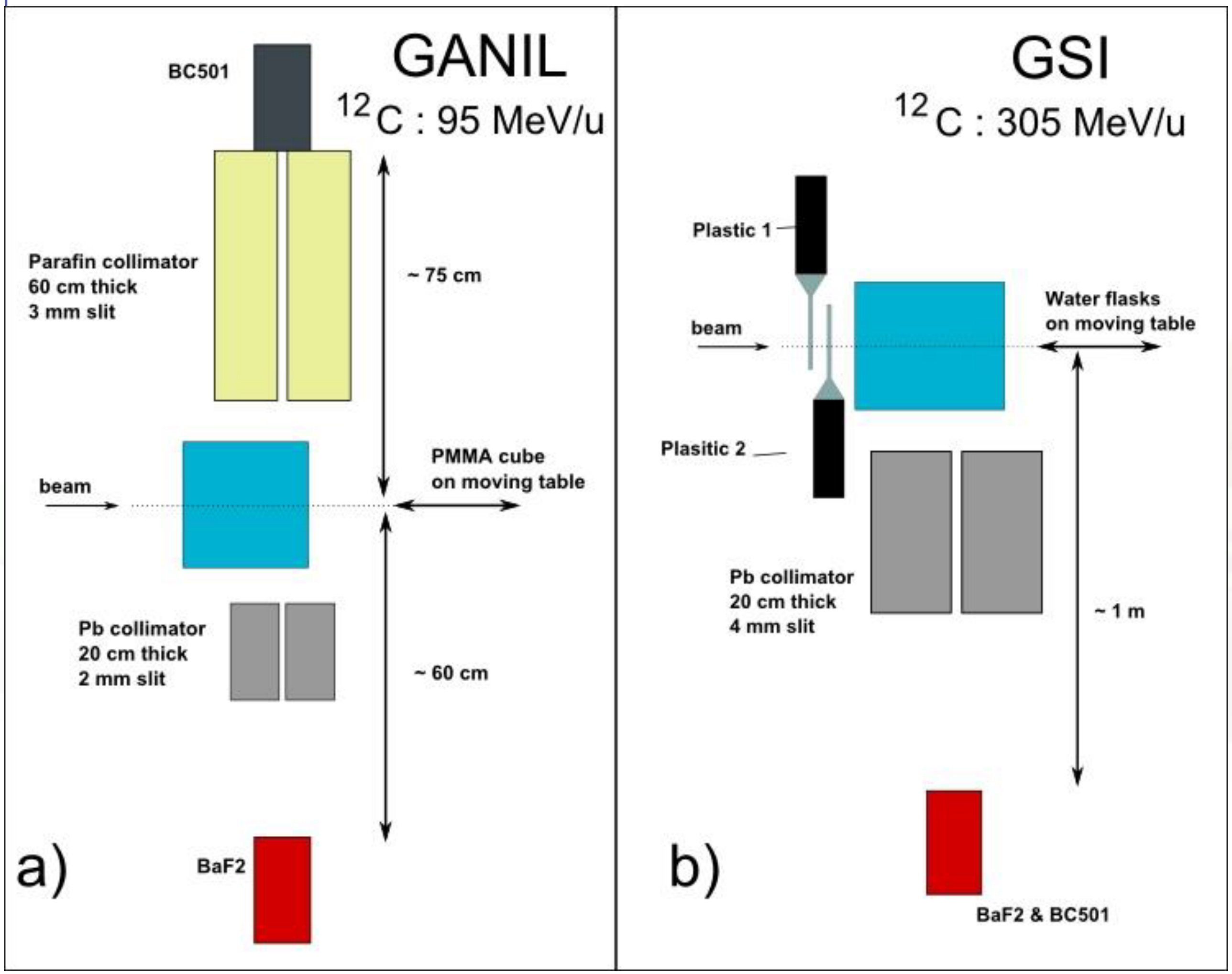
- Prompt-gamma ray imaging in hadron therapy:
- measure high energy γ rays generated in nuclear interactions to provide real-time information about the local dose both for proton and carbon ion therapy.
- Unlike PET, prompt photons are not affected by biological washout
- Still in the R&D phase, MC needed for feasibility and optimisation
- Developments in FLUKA
  - Improvements in the nucleus nucleus interactions
  - Gamma deexcitation trough know nuclear levels
  - Discrete nuclear levels in evaporation
  - Discrete nuclear levels in low energy ion interactions
- Also within the ENVISION european program

Heavy ion interaction models

- DPMJET-III for energies ≥ 5 GeV/n
  - DPMJET (R. Engel, J. Ranft and S. Roesler) Nucleus-Nucleus interaction model
  - Energy range: from 5-10 GeV/n up to the highest Cosmic Ray energies (10^{18}-10^{20} eV)
  - Used in many Cosmic Ray shower codes
  - Based on the Dual Parton Model and the Glauber model, like the high-energy FLUKA hadron-nucleus event generator
- Modified and improved version of rQMD-2.4 for 0.1 < E < 5 GeV/n
  - rQMD-2.4 (H. Sorge et al.) Cascade-Relativistic QMD model
  - Energy range: from 0.1 GeV/n up to several hundred GeV/n
  - Successfully applied to relativistic A-A particle production
- BME (Boltzmann Master Equation) for E < 0.1 GeV/n
  - FLUKA implementation of BME from E.Gadioli et al (Milan)

- Standard FLUKA evaporation/fission/fragmentation used in both Target/Projectile final de-excitation
- Electromagnetic dissociation

Prompt photons: benchmarks



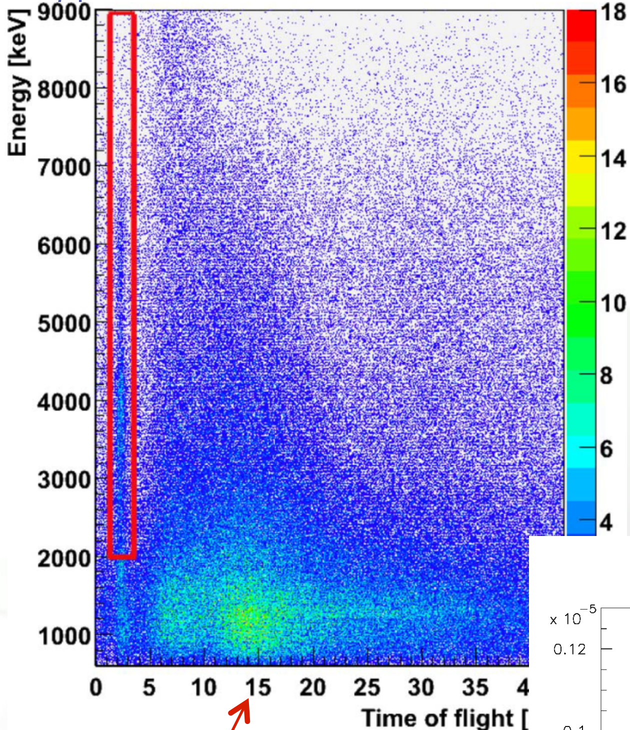
[figures and exp. data taken from F. Le Foulher et al IEEE TNS 57 (2009), E. Testa et al, NIMB 267 (2009) 993]

Prompt photons measured during irradiation of water and PMMA phantoms with C ions.

Photon spectra measured at 90^0 wrt beam

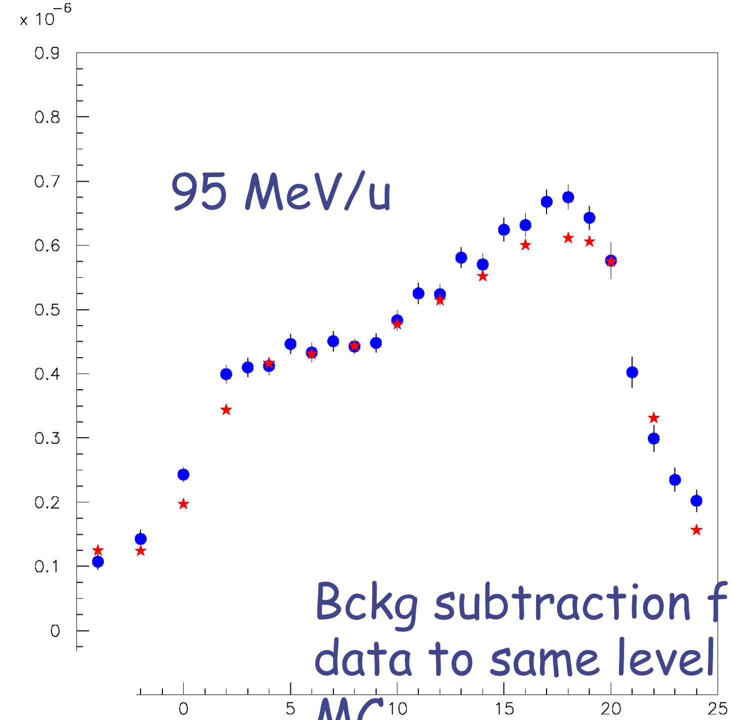
Time-of-flight to discriminate neutron background

Threshold at 2 MeV to discriminate photons from secondary photons, bremsstrahlung etc.

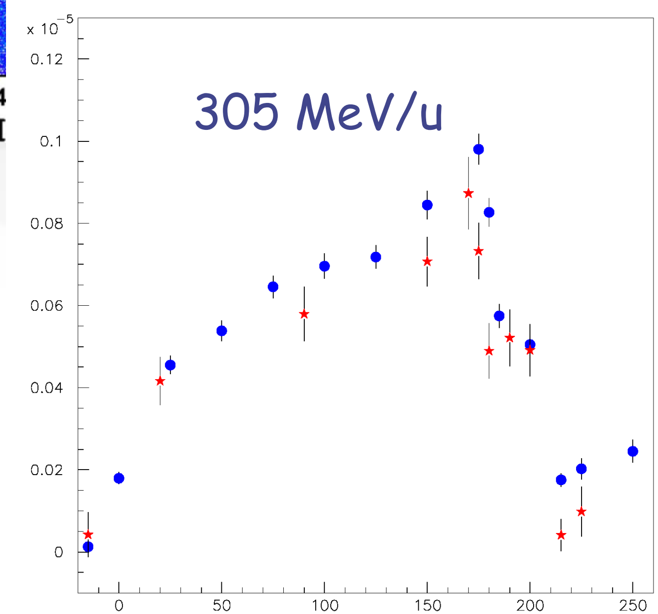


Exp. Energy/tof Distribution and Window

Counts/ion vs position along the phantom



Bckg subtraction from data to same level as MC



Blue: fluka
Red: data

MAIN RADIATION EFFECTS ON ELECTRONICS

			relevant physical quantity the effect is scaling with
Single Event effects (Random in time)	***Single Event Upset (SEU)***	Memory bit flip (soft error) Temporary functional failure	High energy hadron fluence [cm^{-2}] (but also thermal neutrons!)
	Single Event Latchup (SEL)	Abnormal high current state Permanent/destructive if not protected	High energy hadron fluence [cm^{-2}]
Cumulative effects (Long term)	***Total Ionizing Dose (TID)***	Charge build-up in oxide Threshold shift & increased leakage current Ultimately destructive	Ionizing dose [Gy]
	Displacement damage	Atomic displacements Degradation over time Ultimately destructive	Silicon 1 MeV-equivalent neutron fluence [cm^{-2}] {NIEL -> DPA}

Radiation Damage

- In FLUKA:
- Built-in scoring of all the relevant quantities:
- Dose
- E>20MeV hadron fluence
- Silicon 1 MeV-equivalent neutron fluence
- NIEL
- DPA

- On DPA lots of recent developments, for hadrons and EM

dpa: Displacements Per Atom

- Is a measure of the amount of radiation damage in irradiated materials
- Displacement damage can be induced by all particles produced in a hadronic cascade, including high energy photons
- The dpa quantity is directly related to energy transfers to atomic nuclei i.e. to the NIEL (non ionizing energy loss) → NUCLEAR STOPPING POWER

$$dpa \div \kappa \frac{\xi(T)T}{2E_{th}}$$

T=energy of the recoil

Displacement threshold

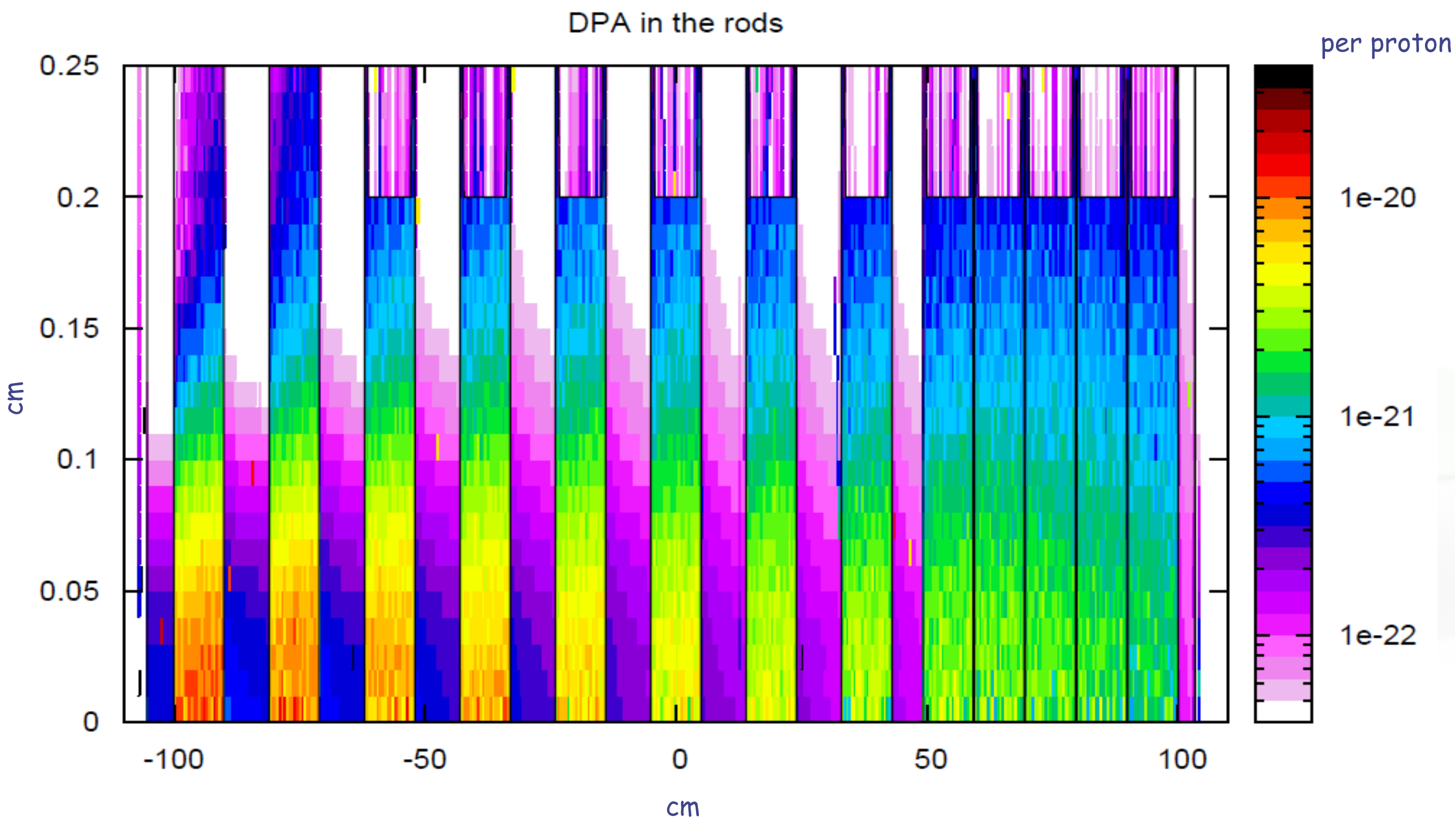
$\xi = S_n/(S_n+S_e)$

- The common Lindhard approximation uses the **unrestricted NIEL**, including all the energy losses, also those below the displacement threshold E_{th}
- A more accurate way is to use the **restricted nuclear losses:** only energy losses above E_{th}

S_n/S is going down with energy (and up with charge)
→ NIEL/DPA are dominated by low energy (heavy) recoils!!

DETERIORATION: TARGETS

CNGS, SPS proton beam on graphite, 400 GeV, 0.53 mm σ, 1.4 10^{20} p.o.t. since 2007



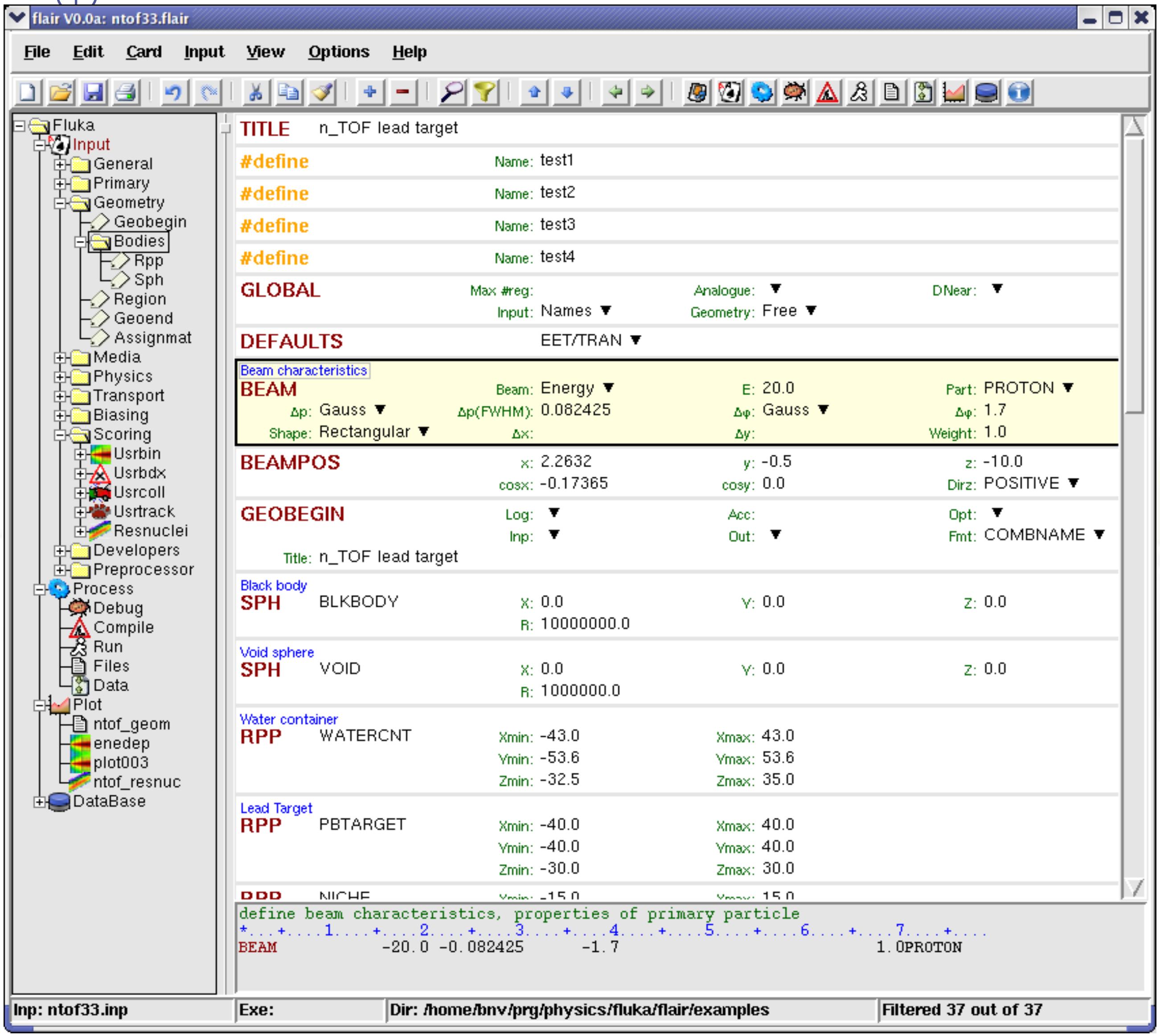
peak of few DPA !

how?

- FLUKA is available from www.fluka.org and from NEA
- Written in Fortran
- Input from data-cards
- Built-in scoring
- → EASY ! No need to write code, or to process hits
- If really needed, customizable user-routines available
- Geometry: Combinatorial + lattice + voxel, with debugging and 3D viewer
- Courses for beginners / advanced twice a year (next advanced in Vancouver , sept. 2012; next beginner Paris spring 2013)
- User support through mailing list

Flair

FLUKA Advanced Interface [http://www.fluka.org/flair]

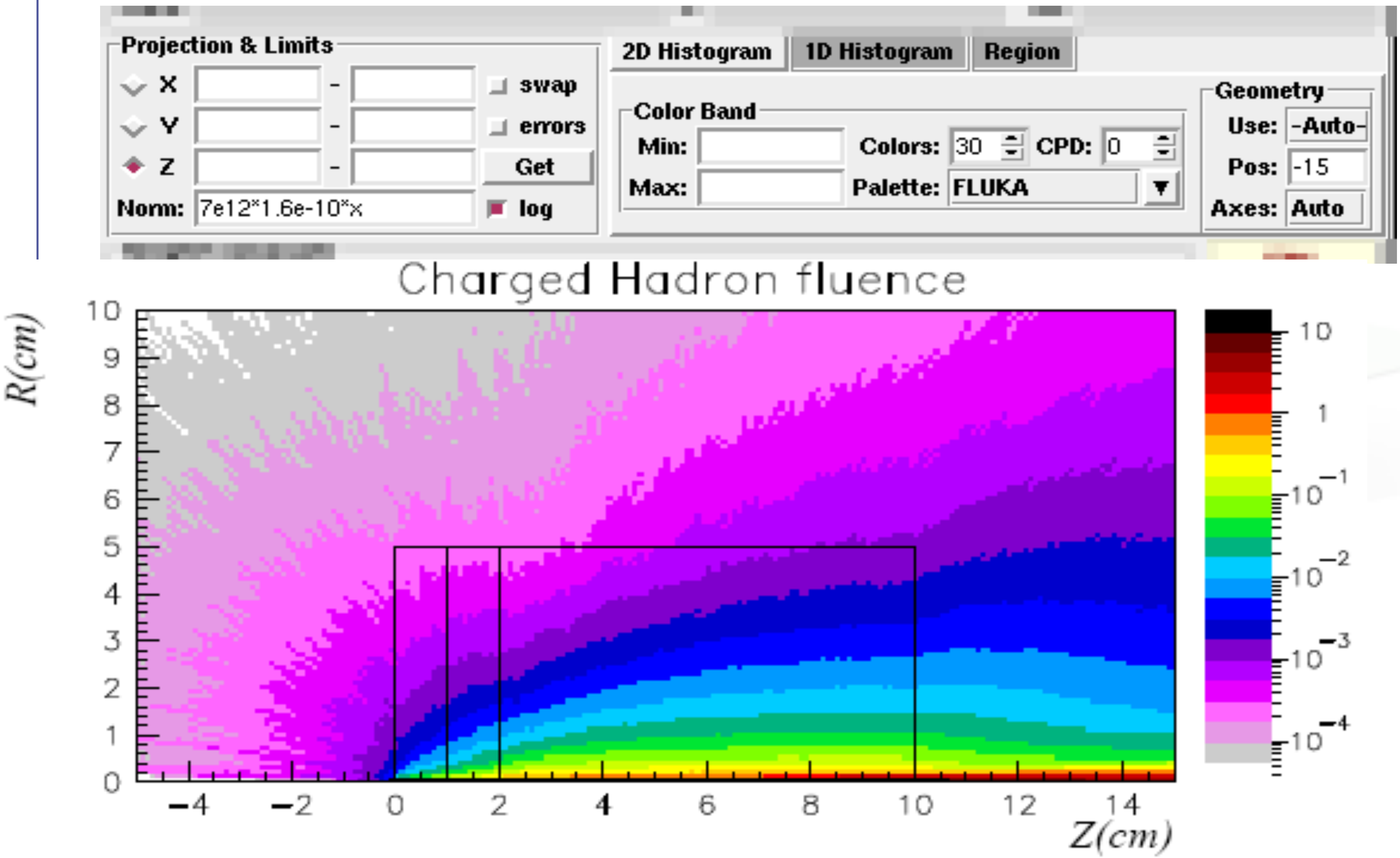


- Input:
  - Filtering Cards
  - Show card links
  - Units: i.e. 20 GeV/c
  - Data validation
  - Import/Export on various formats
- Process:
  - Debugging
  - Compilation
  - Run monitoring
  - Merging

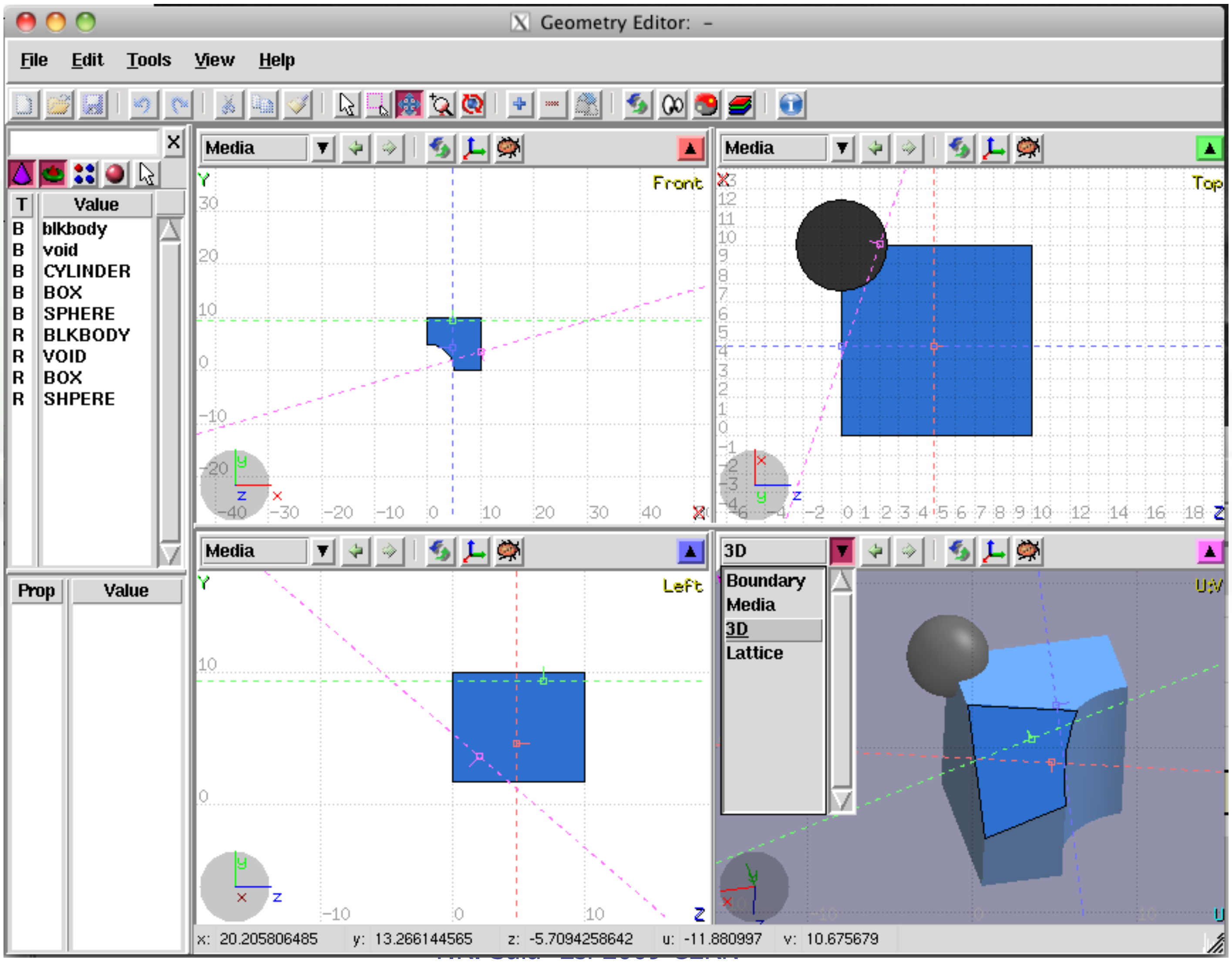
Flair

FLUKA Advanced Interface [http://www.fluka.org/flair]

Plotting , Databases of materials, isotopes etc



Geometry visualization, debugging, editing through Flair



end