FLUKA for CNGS

NBI06

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Outline of the presentation:

- FLUKA
  - Short introduction
  - A few benchmarks relevant for neutrino beams
- FLUKA applied to the (old) WANF beam and NOMAD
- FLUKA for CNGS
  - Geometry description
  - Physics calculations
  - Safety and engineering calculations

FLUKA

Interaction and Transport Monte Carlo code

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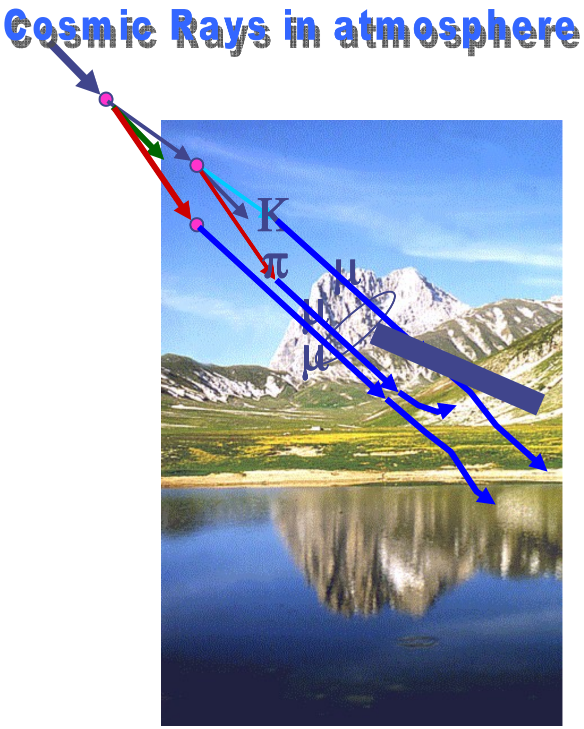

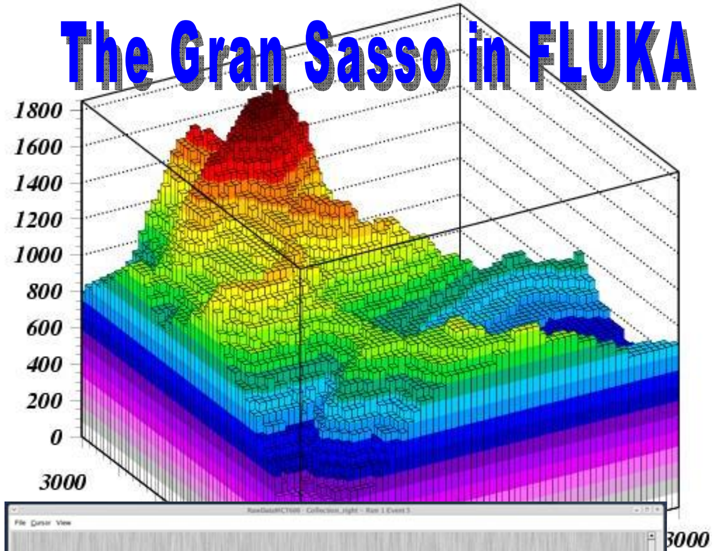

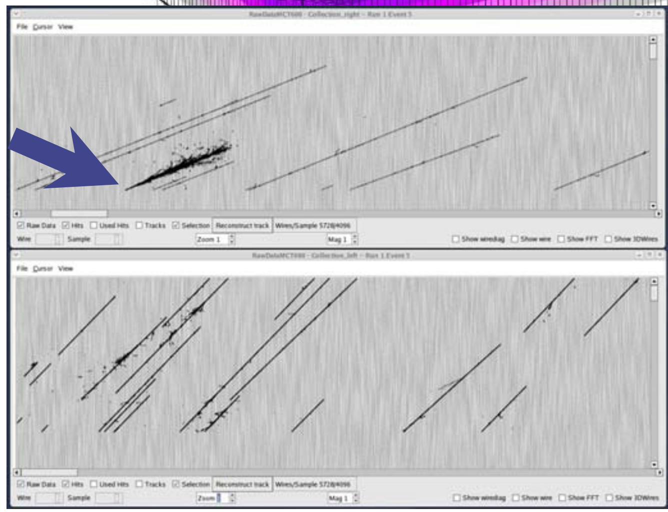

FLUKA collaboration

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- More than 1000 users all over the world

FLUKA Description

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc.
- 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interactions 0-10000 TeV
  - Electromagnetic and μ interactions 1 keV – 10000 TeV
  - Nucleus-nucleus interactions 0-10000 TeV/n
  - Charged particle transport – ionization energy loss
  - Neutron multi-group transport and interactions 0-20 MeV
  - ν interactions
  - Transport in magnetic field
  - Combinatorial (boolean) and Voxel geometry
  - Double capability to run either fully analogue and/or biased calculations

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http://www.fluka.org

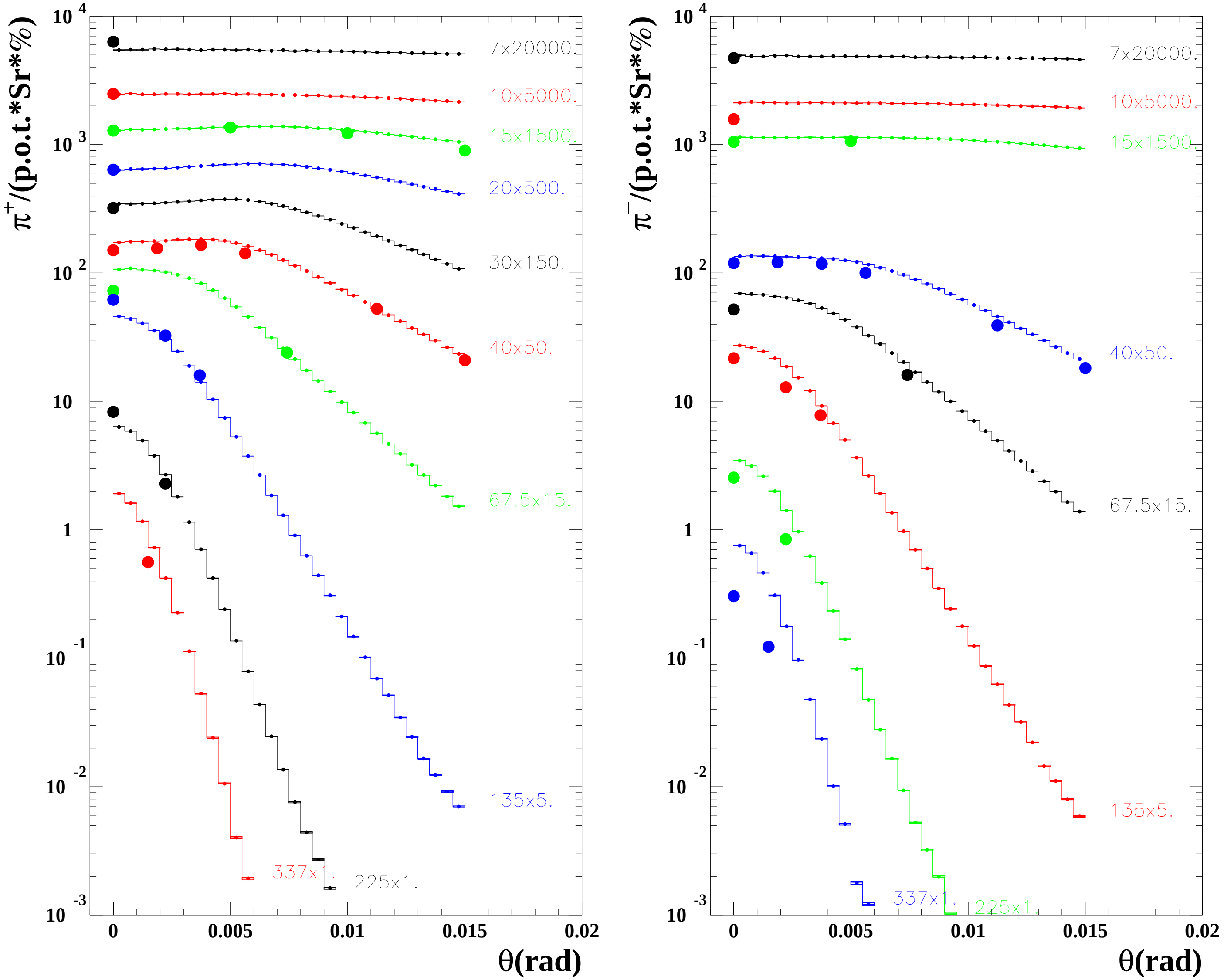
Fluka Applications

- cosmic ray physics
- accelerator design ($\rightarrow$ LHC systems)
- particle physics: calorimetry, tracking and detector simulation etc. ($\rightarrow$ ALICE, ICARUS, ...)
- shielding design
- dosimetry and radioprotection
- space radiation
- hadron therapy
- neutronics
- ADS systems ($\rightarrow$"Energy amplifier")

Why do we reasonably trust Fluka for CNGS like calculations?

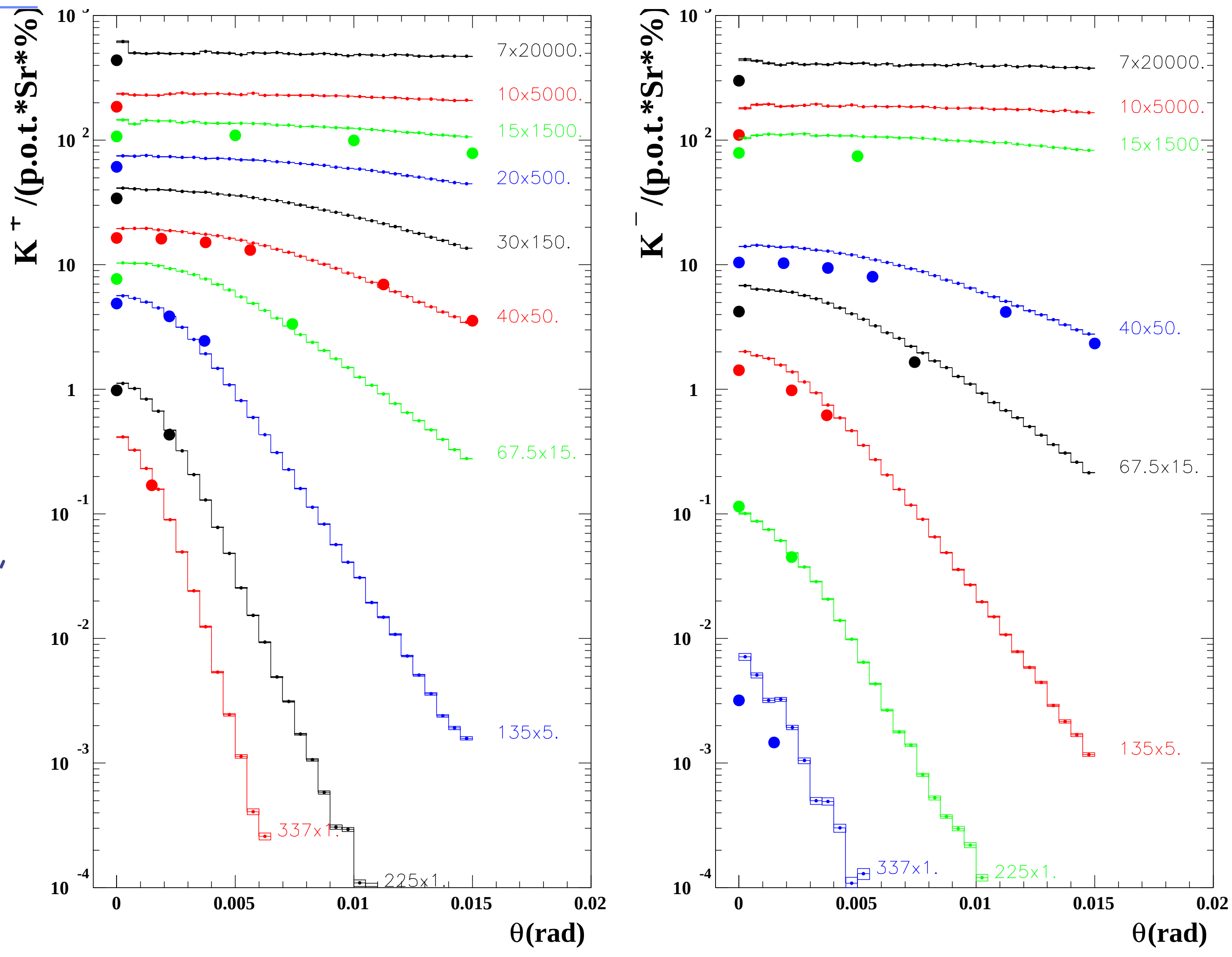
Comparison with SPY data: 450 GeV p on Be

Double diff distribution for π^{+}/π^{-} production from 450 GeV/c p on Be
H.W Atherton CERN 80-06
SPY : PLB 425, 208 (1998)

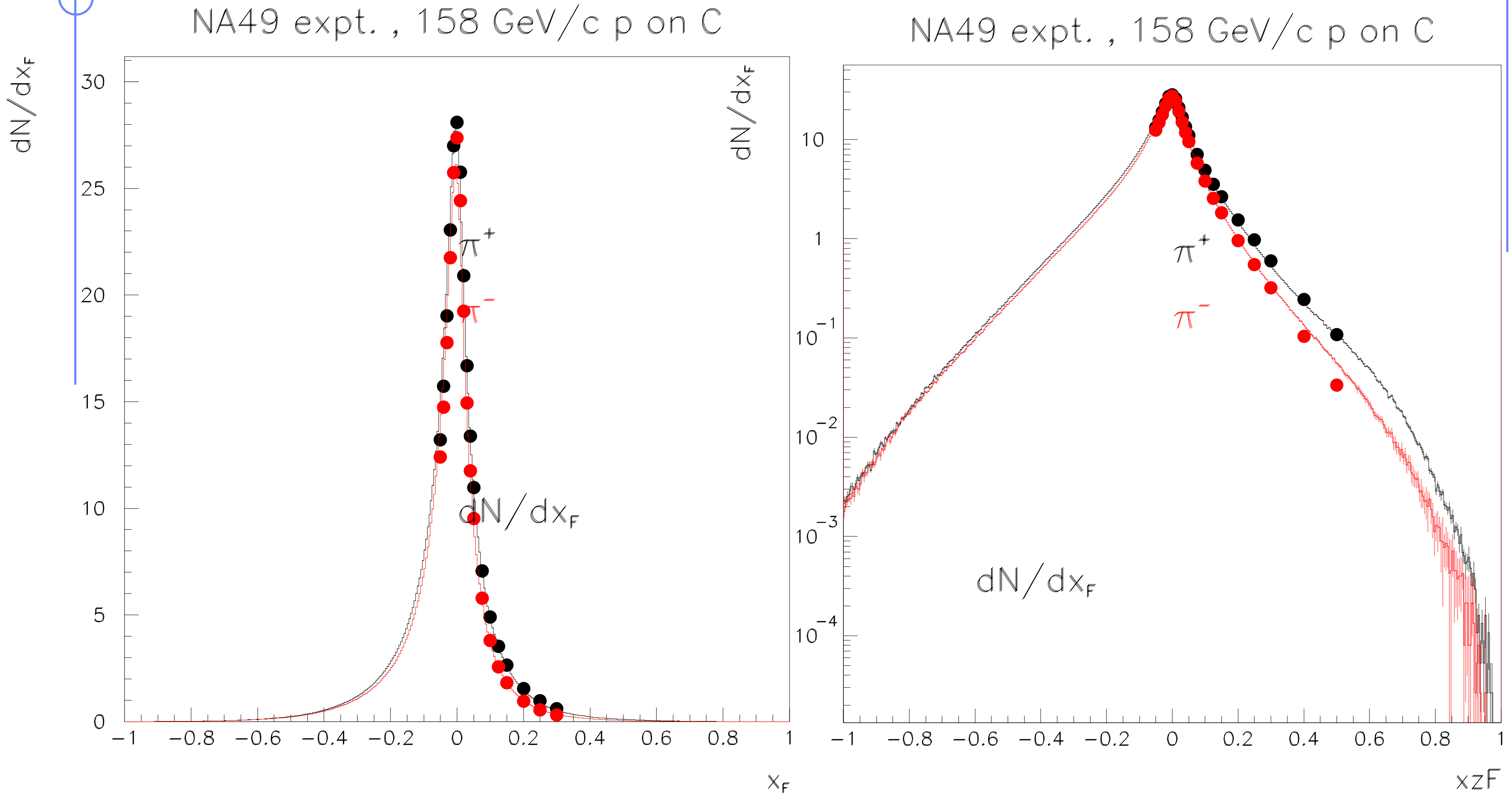


Comparison with SPY data: 450 GeV p on Be

Double diff distribution for K+/K- production from 450 GeV/c p on Be
H.W Atherton CERN 80-06
SPY : PLB 425, 208 (1998)

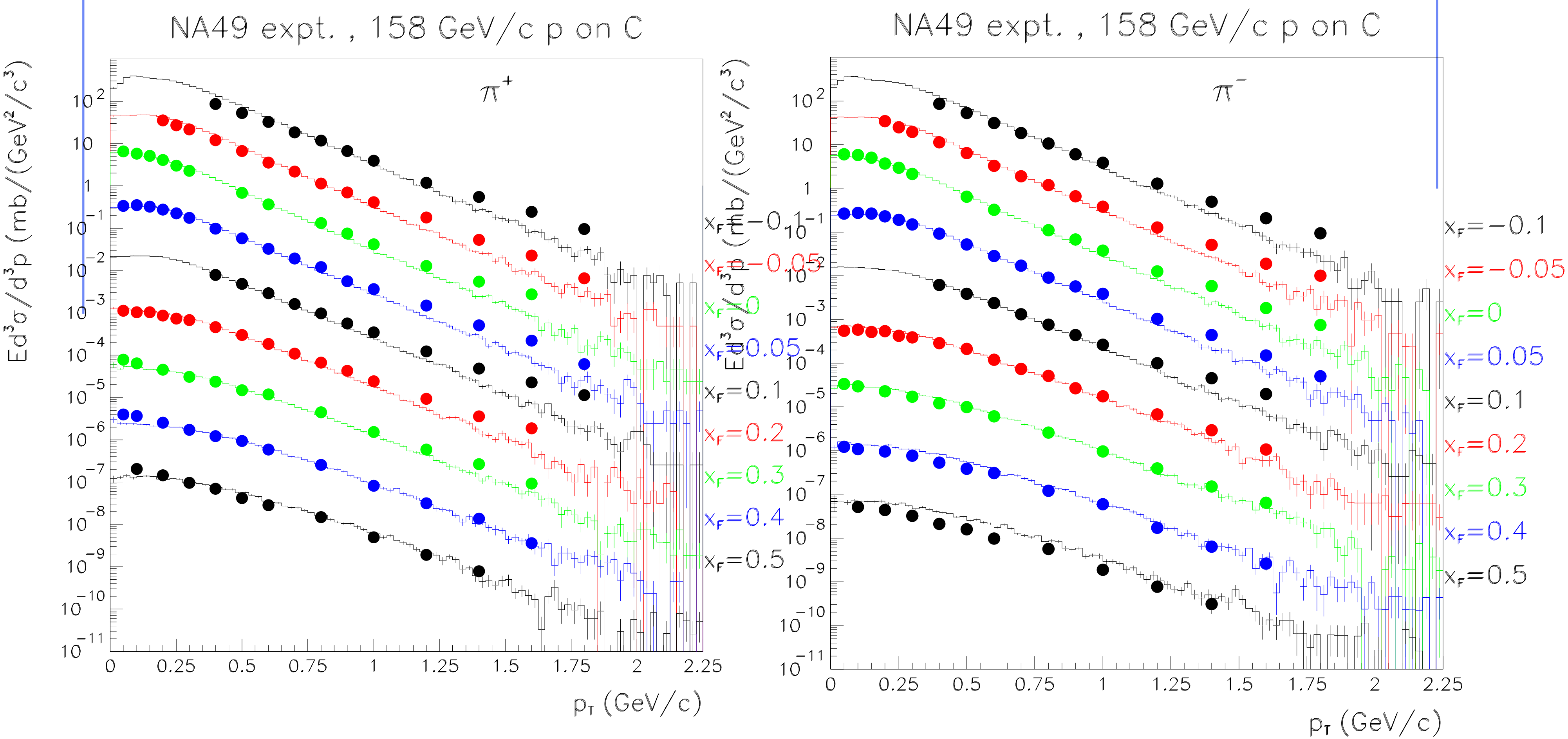


NA49 p on C



Feynmann X distributions for π^+ π^- production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)

NA49 p on C



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

FLUKA and Cosmic Ray physics: Atmospheric Showers

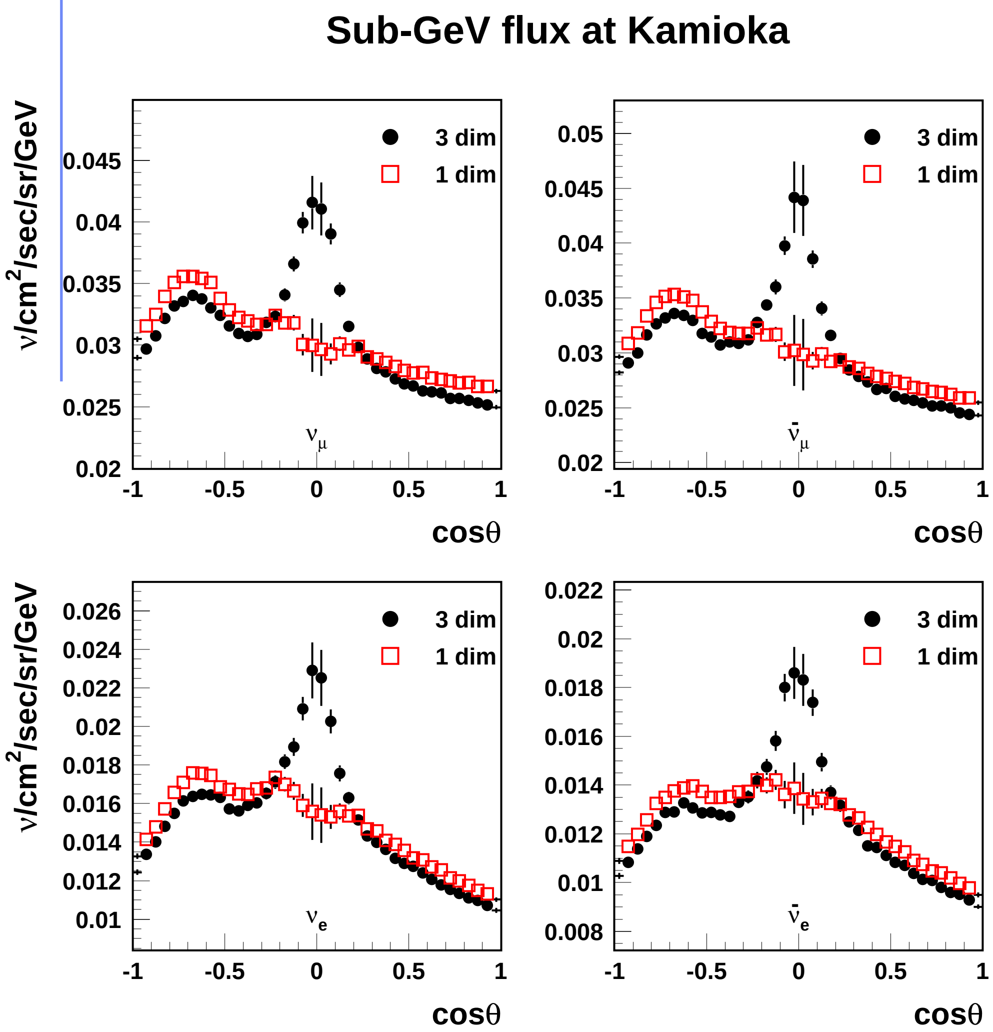
Two different streams:

- Basic research on Cosmic Ray physics (muons, neutrinos, EAS, underground physics,...)
- Application to dosimetry in civil aviation (DOSMAX Collaboration: Dosimetry of Aircrew Exposure to Radiation During Solar Maximum, research project funded by the EU)

Available dedicated FLUKA library + additional packages including:

- Primary spectra from Z = 1 to Z = 28 (derived from NASA and updated to most recent measurements.)
- Solar Modulation model (correlated to neutron monitors)
- Atmospheric model (MSIS Mass-Spectrometer-Incoherent-Scatter)
- 3D geometry of Earth + atmosphere
- Geomagnetic model

(3D) Calculation of Atmospheric ν Flux



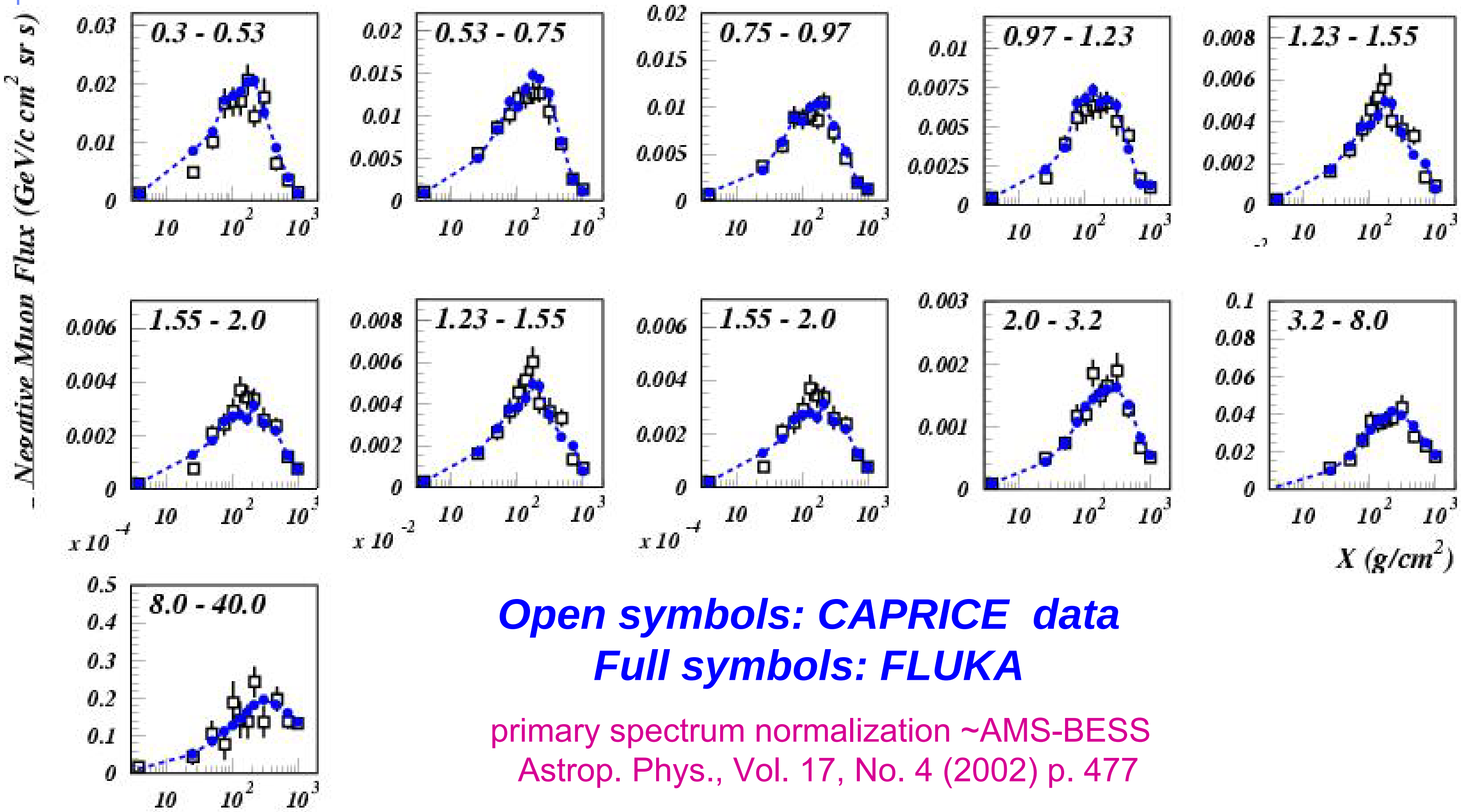
The first 3-D calculation of atmospheric neutrinos was done with FLUKA.

The enhancement in the horizontal direction, which cannot be predicted by a 1-D calculation, was fully unexpected, but is now generally acknowledged.

In the figure: angular distribution of ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$.

In red: 1-D calculation

Negative muons at floating altitudes: CAPRICE94

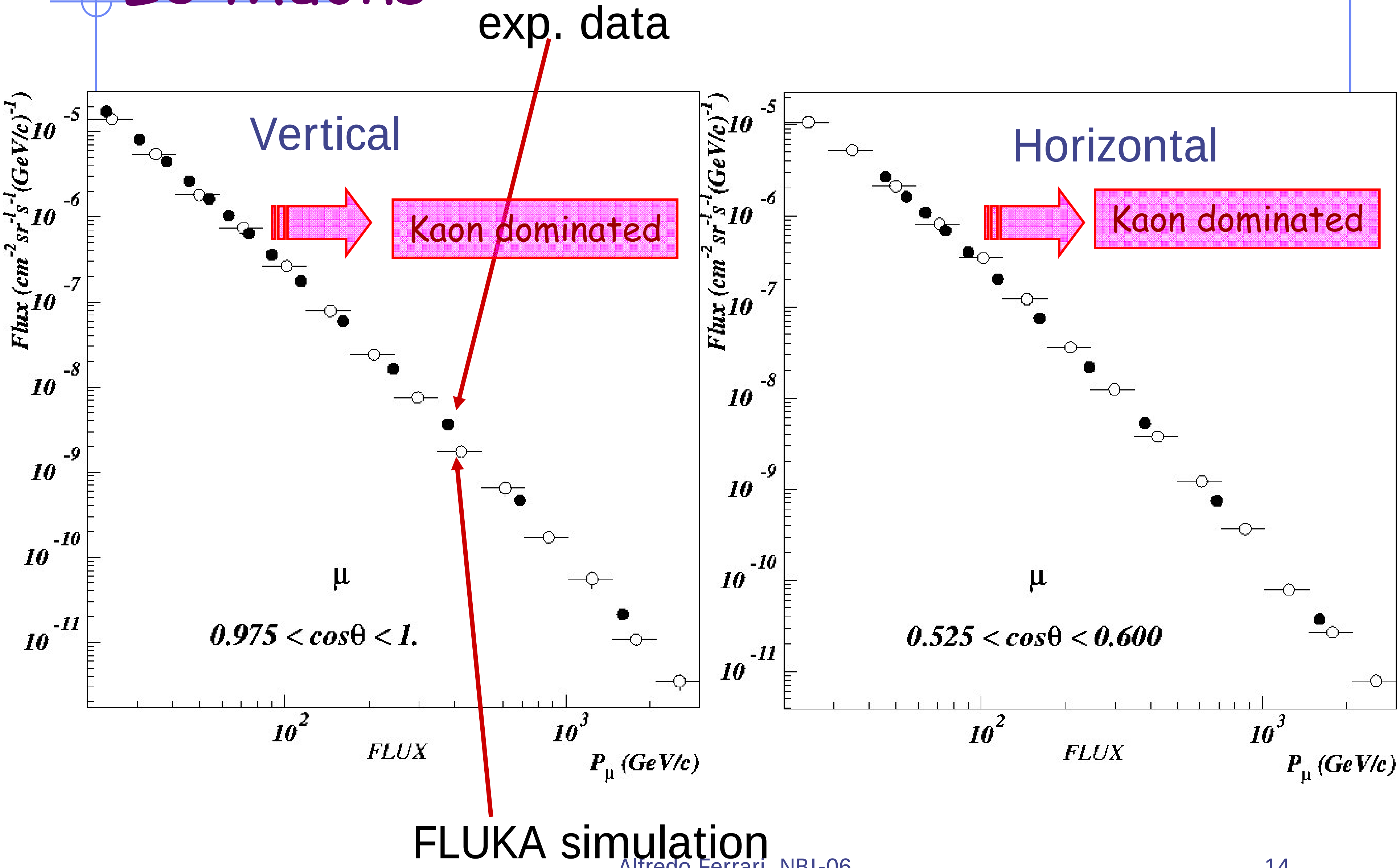


Open symbols: CAPRICE data
Full symbols: FLUKA

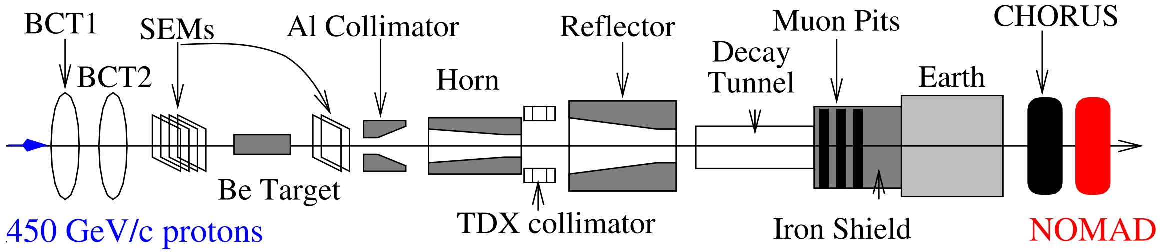
primary spectrum normalization ~AMS-BESS
Astrop. Phys., Vol. 17, No. 4 (2002) p. 477

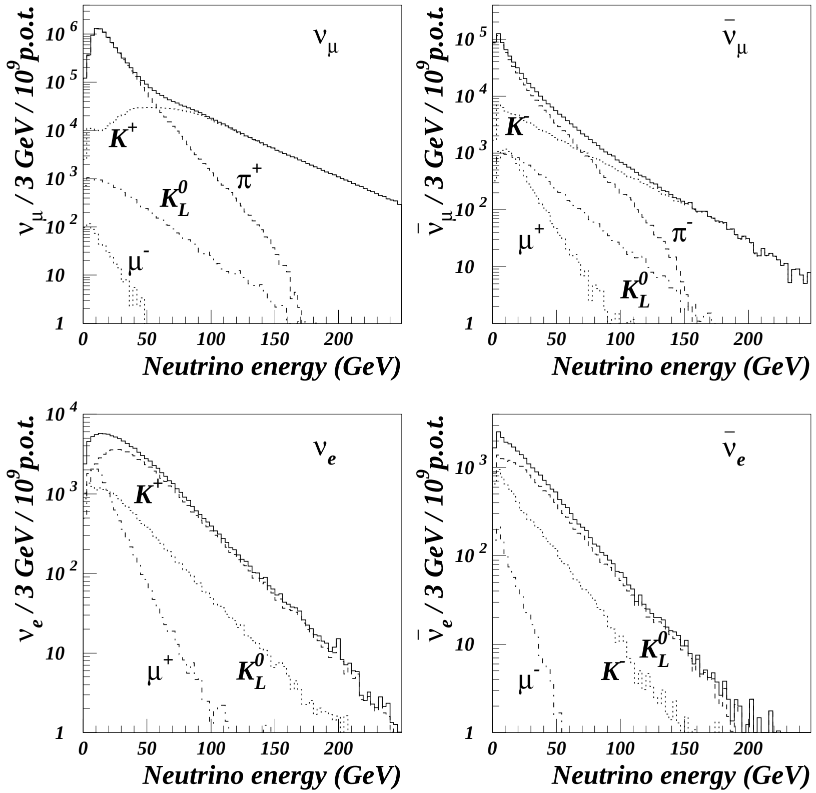
Some recent achievements: L3 Muons

(S.Muraro, PhD thesis Milano)



Comparison with the WANF data (NOMAD)





- ν_μ: $< E_{\nu_\mu} > \sim 24.3$ GeV
- $\bar\nu_\mu$: 7 %, $< E_{\bar\nu_\mu} > \sim 17.2$ GeV
- ν_e: 1 %, $< E_{\nu_e} > \sim 36.4$ GeV
- $\bar\nu_e$: 0.3 %, $< E_{\bar\nu_e} > \sim 27.6$ GeV

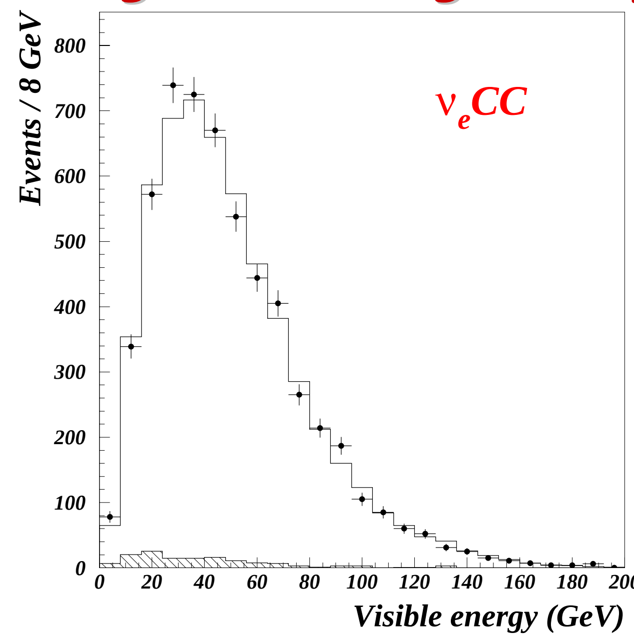
Correct reconstruction of:
- ν_μ from π^+, K^+ + … decays
- $\bar\nu_\mu$ from π^-, K^-. K^0 + … decays
- ν_e from K^0, K^- + … decays

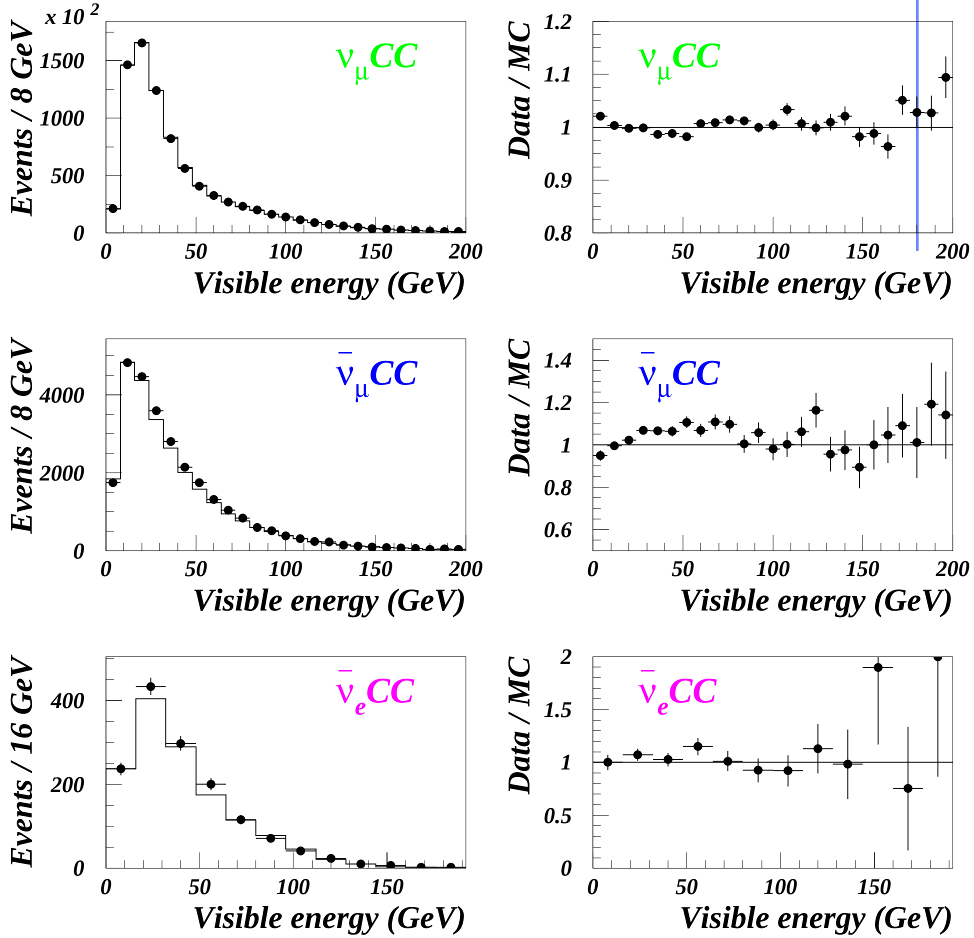
Accurate prediction of ν_e (K^+, K^0 and μ^+) which was the main background for the $\nu_\mu \rightarrow \nu_e$ search in NOMAD

Comparison with NOMAD Data

- prompt isolated μ in the final state
- prompt isolated e in the final state
- charge/momentum measurements
  - B = 0.4 T, $\Delta p/p \approx 4$ % at 1 GeV/c
- visible energy (hadrons + leptons)
  - $\Delta E/E_{e.m} \approx 3.5\%\sqrt{E(GeV)}$
- syst. errors on ν flux:
  - 7 % on ν_μ and ν_e
  - ν_e/ν_μ 4.2 % normaliz., 5 % E-dep.

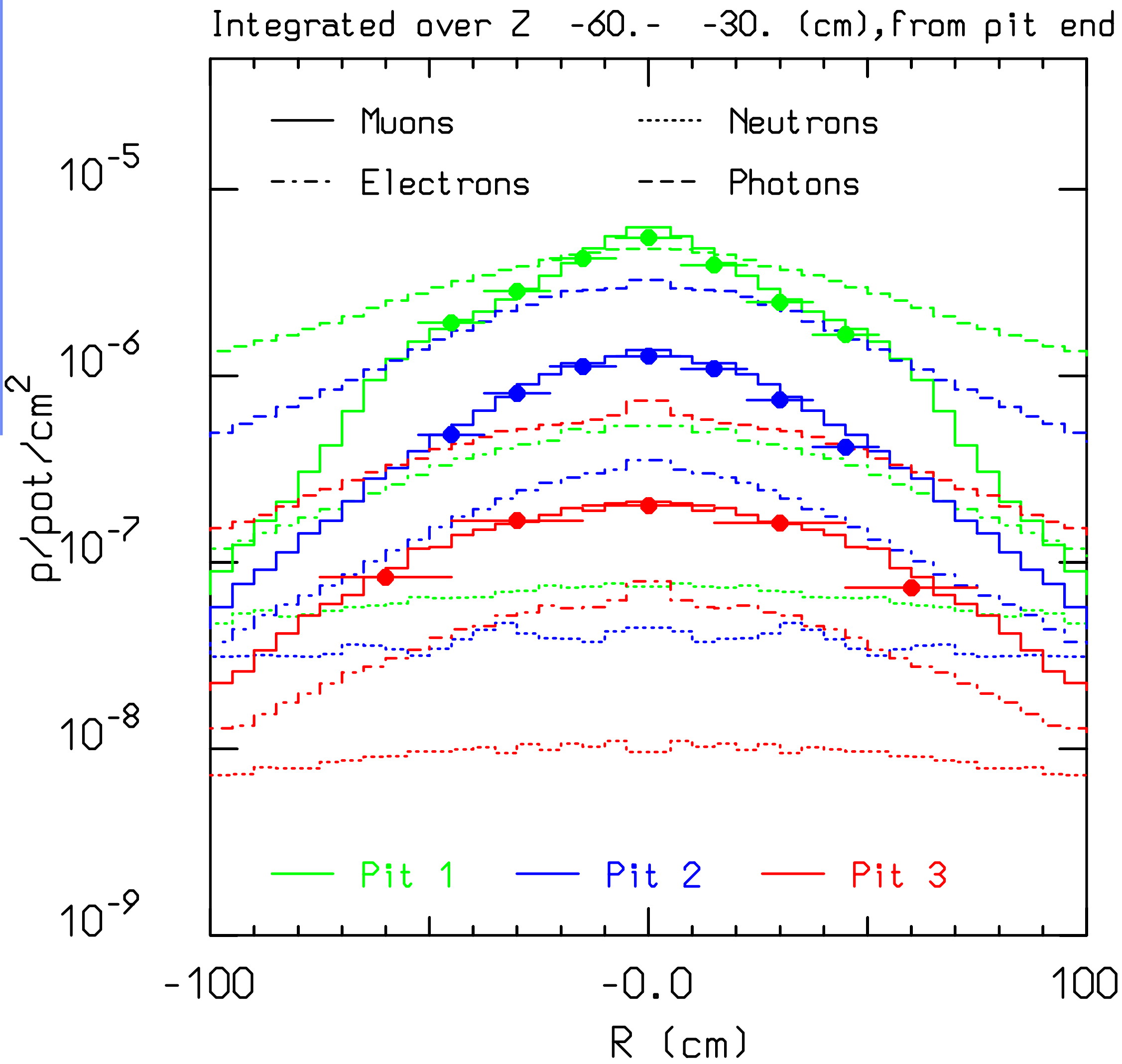
nice agreement→ good K prod.





Control samples: ν_μ anti ν_μ .
CC ν_μ normalized to data

Wanf muon pits



Precise μ calibration available for one pit. Calibration from the other derived from that one accounting for geometrical differences. Almost perfect reproduction of the observed signals in the 3 pits

CNGS simulations with FLUKA

The same detailed description/ auxiliary programs for
- Energy deposition→ mechanical and thermal analysis
- Prompt and residual dose rates → radioprotection
- Beam monitors response → commissioning and diagnostics
- Neutrino beam at Gran Sasso: energy, composition,"history"

Proton beam parameters:
- 400 GeV/c p
- $\sigma_x = \sigma_y = 0.53$ mm
- $\sigma_\theta = 0.53$ mrad

Physics calculations:
= 2.4 10^{13} per spill
= 4.5 10^{19} pot/year

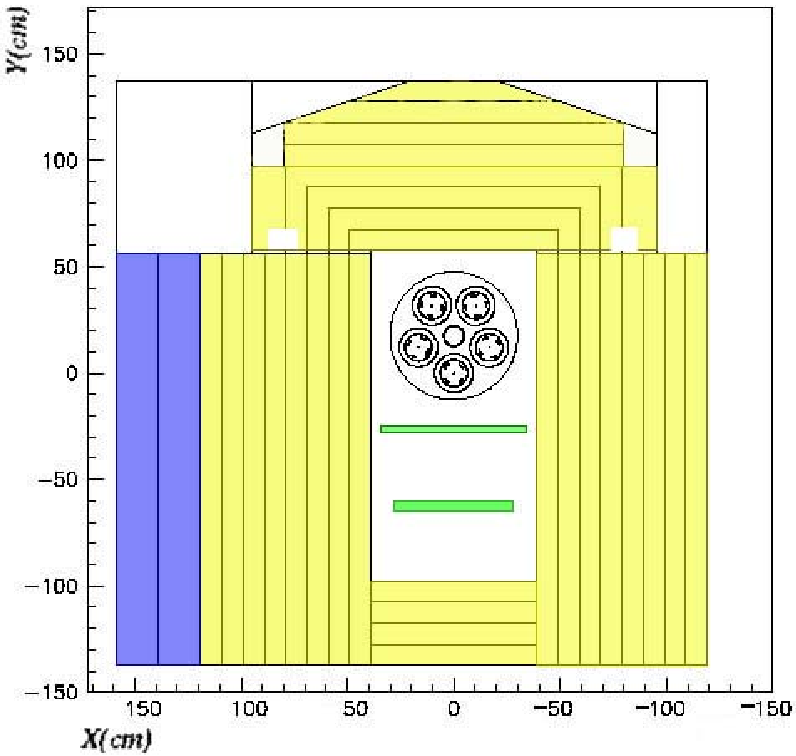
Heat deposition:
ultimate intensity
= 3.5 10^{13} p per spill
Beam dump and dose equivalent:
~ 8 10^{12} protons/s
over 200 days
~ 1,5 10^{20} pot/year

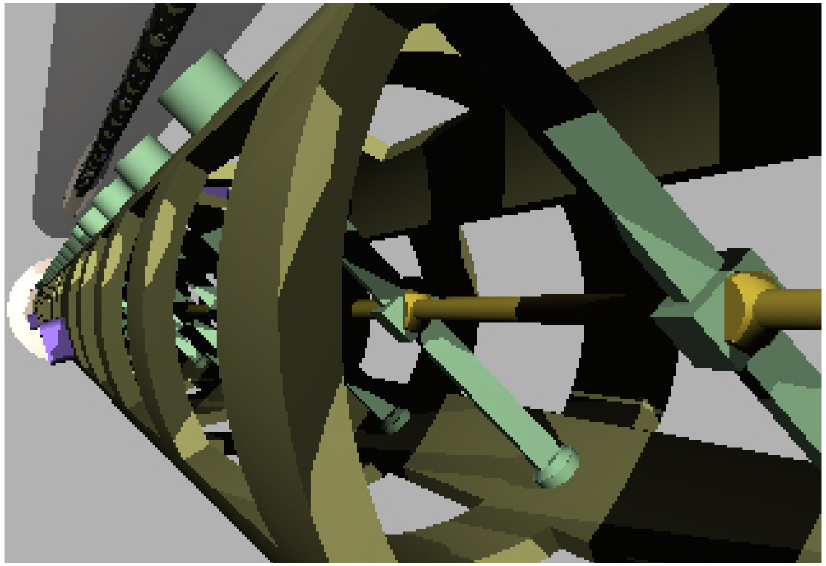
In the geometry: beam line, shielding, service galleries…

Different biasing and transport options depending on studied case

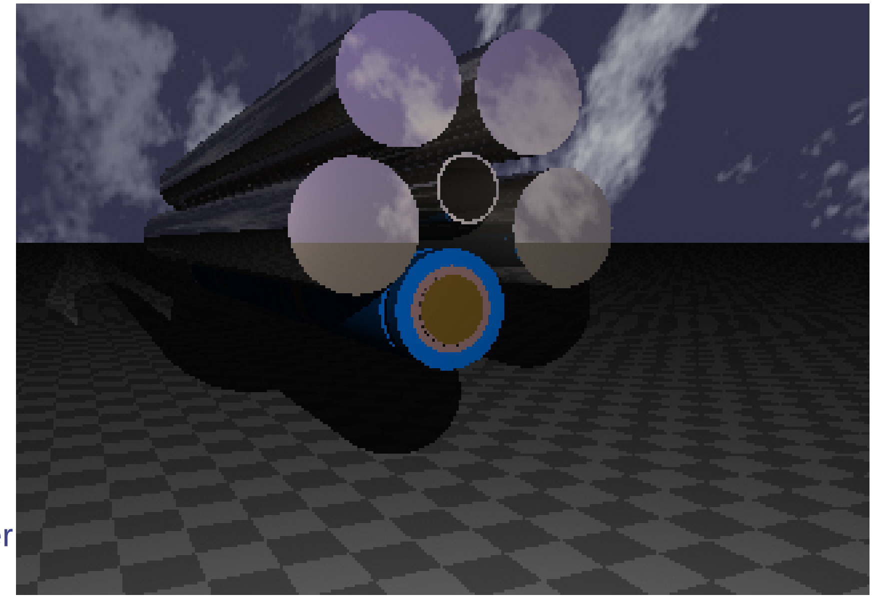
The target

Cross-section of the target / target shielding as described in FLUKA





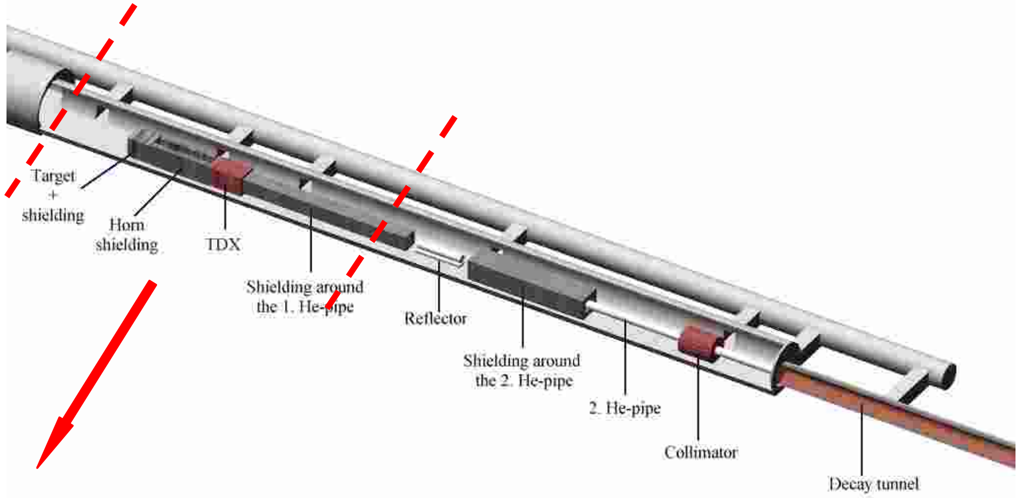
3D views of the target rods/supports and of the target revolver as modeled in FLUKA



Residual dose rate: example

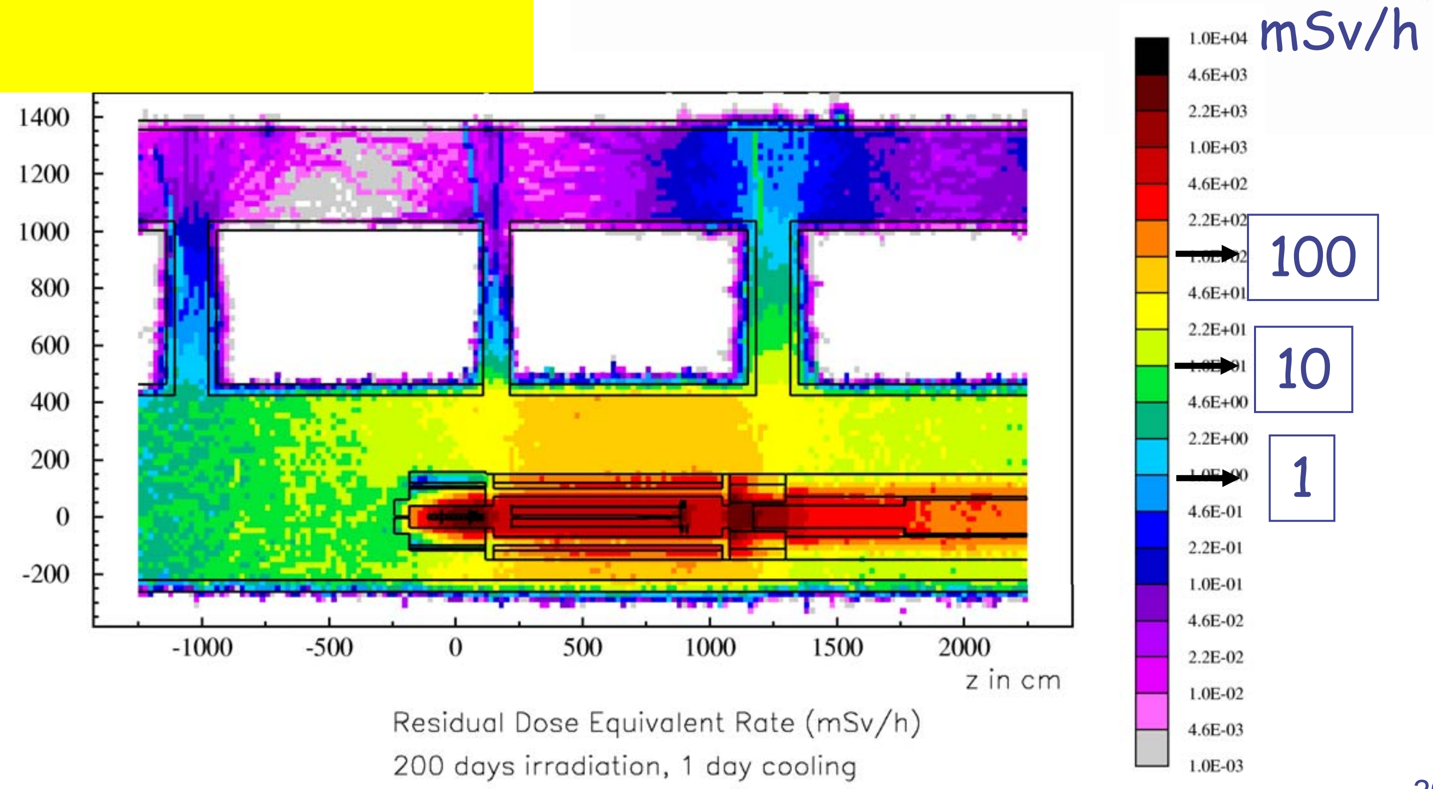
Target and horn region

Fluka calculates dose and time evolution of activation online



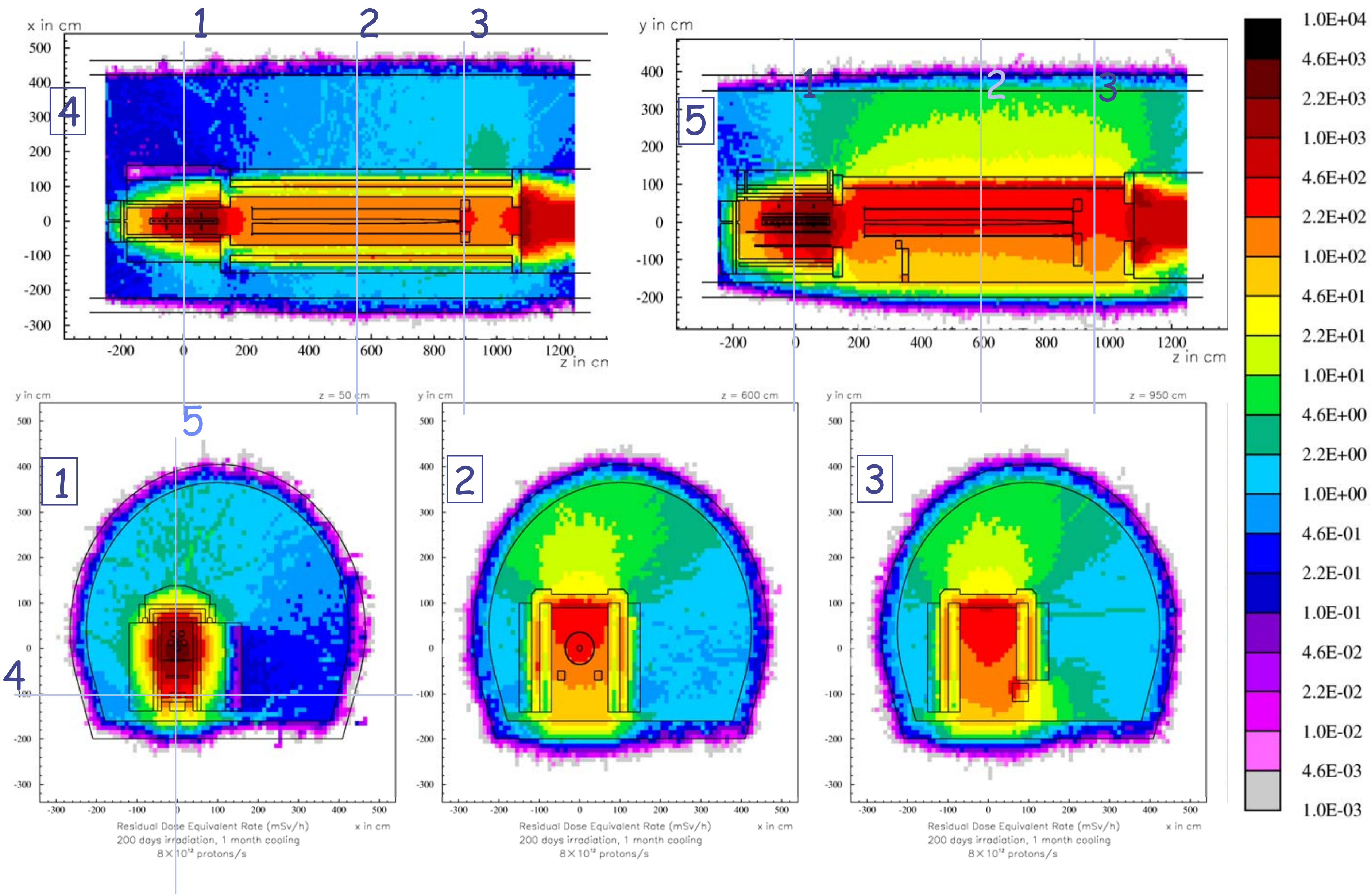
Example:

t_{cool} = 1 day



Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 day cooling
8×10^{12} protons/s

CNGS…



x in cm
z in cm
y in cm
z = 50 cm
z = 600 cm
z = 950 cm
x in cm
Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 month cooling
8×10¹² protons/s
1.0E+04
4.6E+03
2.2E+03
1.0E+03
4.6E+02
2.2E+02
1.0E+02
4.6E+01
2.2E+01
1.0E+01
4.6E+00
2.2E+00
1.0E+00
4.6E-01
2.2E-01
1.0E-01
4.6E-02
2.2E-02
1.0E-02
4.6E-03
1.0E-03

Beam Monitoring

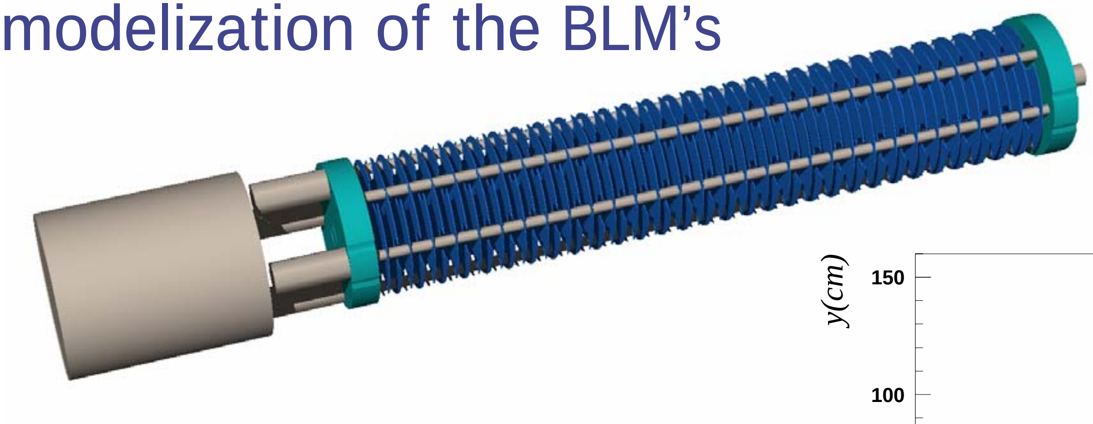
- TBID
- Particle fluence at the locations of the ionization chambers, upstream and downstream target
- "Cross hair" and particle fluences at monitor positions
- Muon pits: full description of ionization chamber, simulation of the charge signal from energy deposition in the active gas and average energy spent in N_2 ionization (waiting for a calibration)

Various scenarios: horn on/off, refl. on/off, target in/out

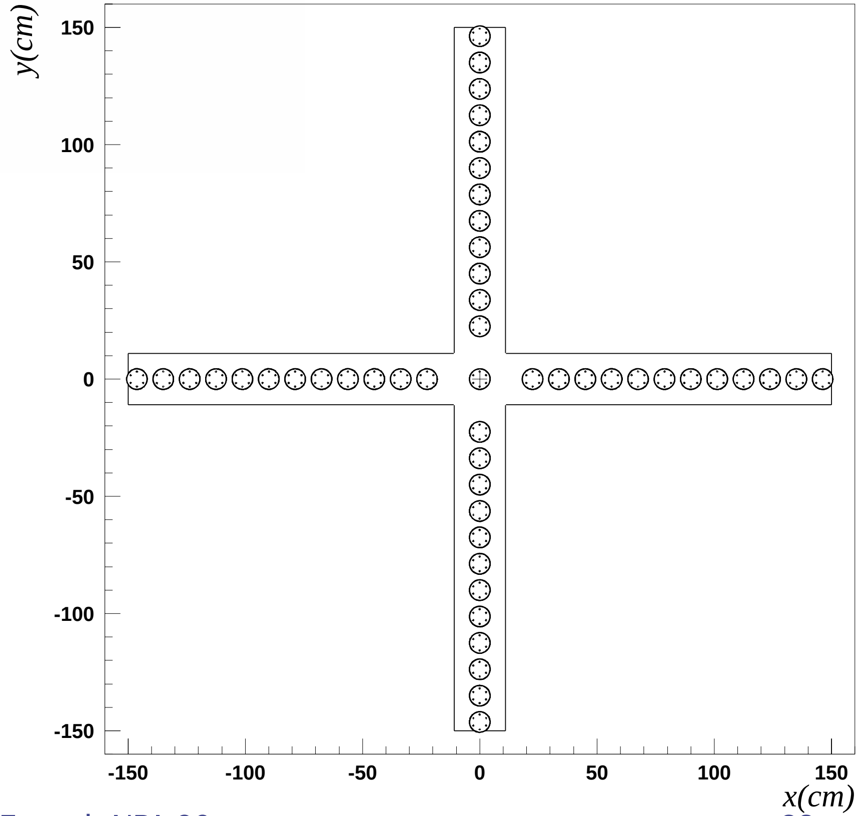
Beam monitoring: ionization chambers

3D view of the FLUKA modelization of the BLM's

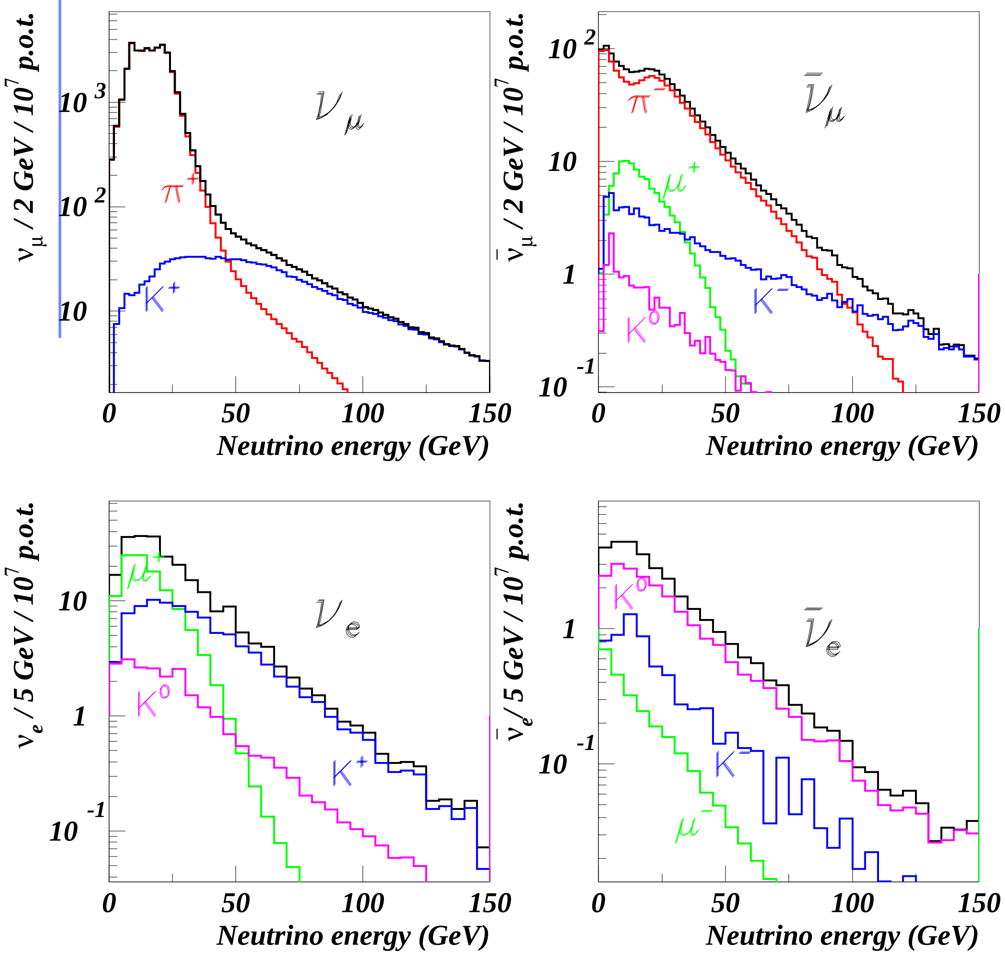
Thanks to M.Brugger et al (see NIMA562, 827 (2006) for the plotting code)



BLM positions in the muon pits (recent upgrade: previous calculations with only 19 BLM/pit)



Neutrinos at Gran Sasso



	Flux (ν/cm^2/10^{19}pot)	$< E_\nu >$ $[GeV]$	ν_i/ν_μ (%)	ν_i/ν_μ-CC (%)
ν_μ	$7.4 \cdot 10^6$	17.9		
$\bar{\nu}_\mu$	$2.9 \cdot 10^5$	21.8	3.9	2.40
ν_e	$4.7 \cdot 10^4$	24.5	0.65	0.89
$\bar{\nu}_e$	$6.0 \cdot 10^3$	24.4	0.08	0.06

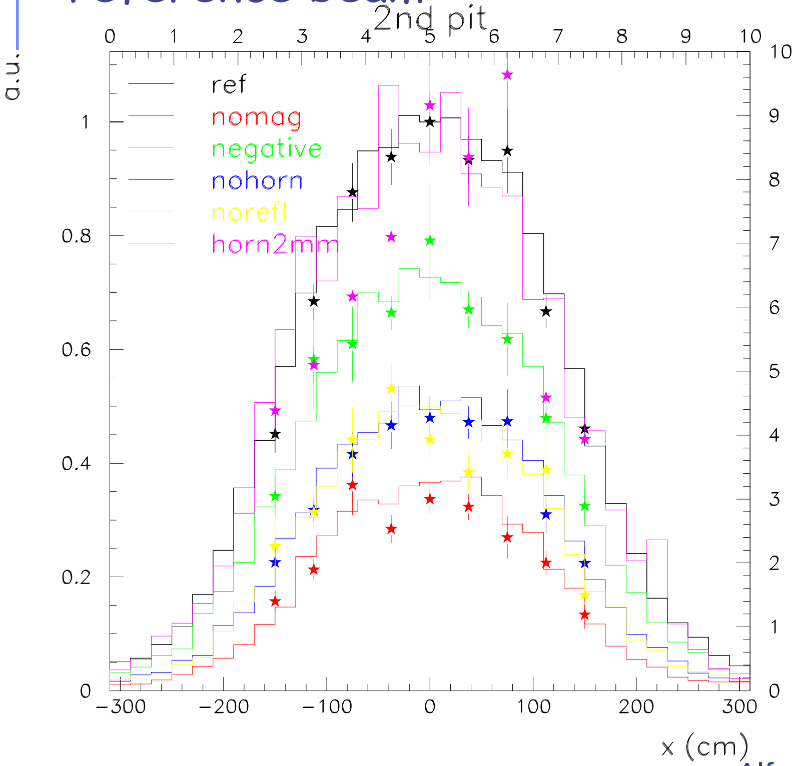
expected event rate:
2800 ν_μCC/kt/y

last ν-parent

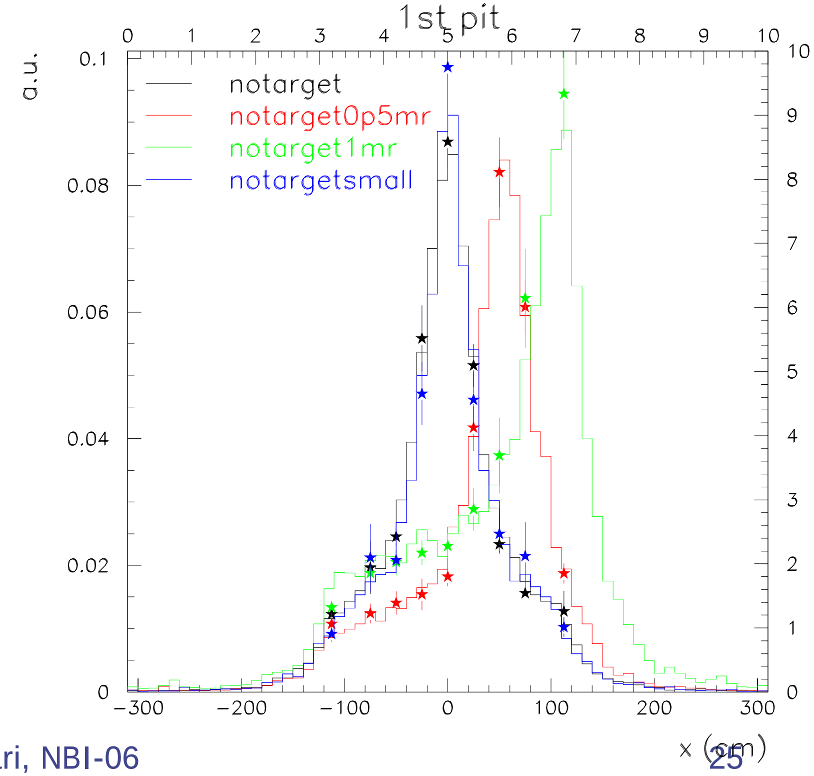
- ν_μ: from π^+(97 %), K^+ (3 %)
- $\bar{\nu}_\mu$: from π^- (85 %), μ^+ (8 %), K^- (6 %)+ ...
- ν_e: from μ^+ (47 %), K^+ (39 %), K^0 (10 %) + ...
- $\bar{\nu}_e$: from K^0 (70 %), K^- (22 %) μ^- (8 %)

Muon monitors examples

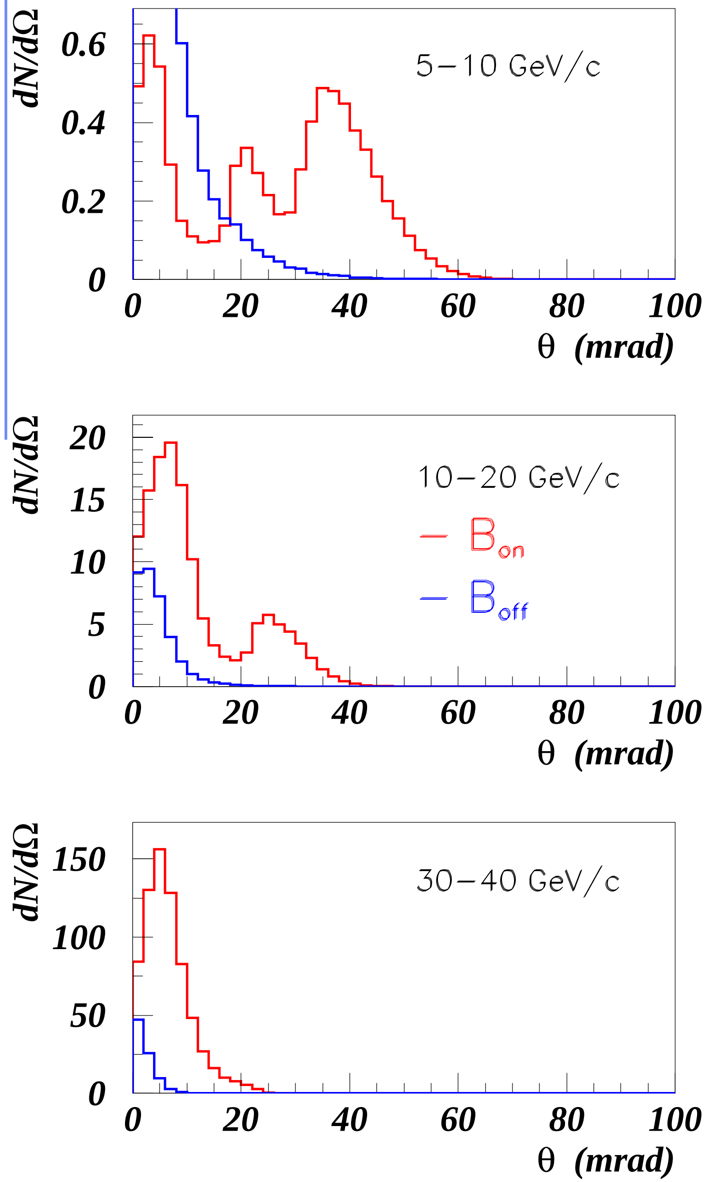
2nd muon pit: horizontal behavior of
muon fluences and
monitor response in different focusing conditions
Normalized to central detector, reference beam



1st muon pit: muon fluences and monitor response in absence of target,
for different angular misalignment of the proton beam
Muons are produced in the beam dump



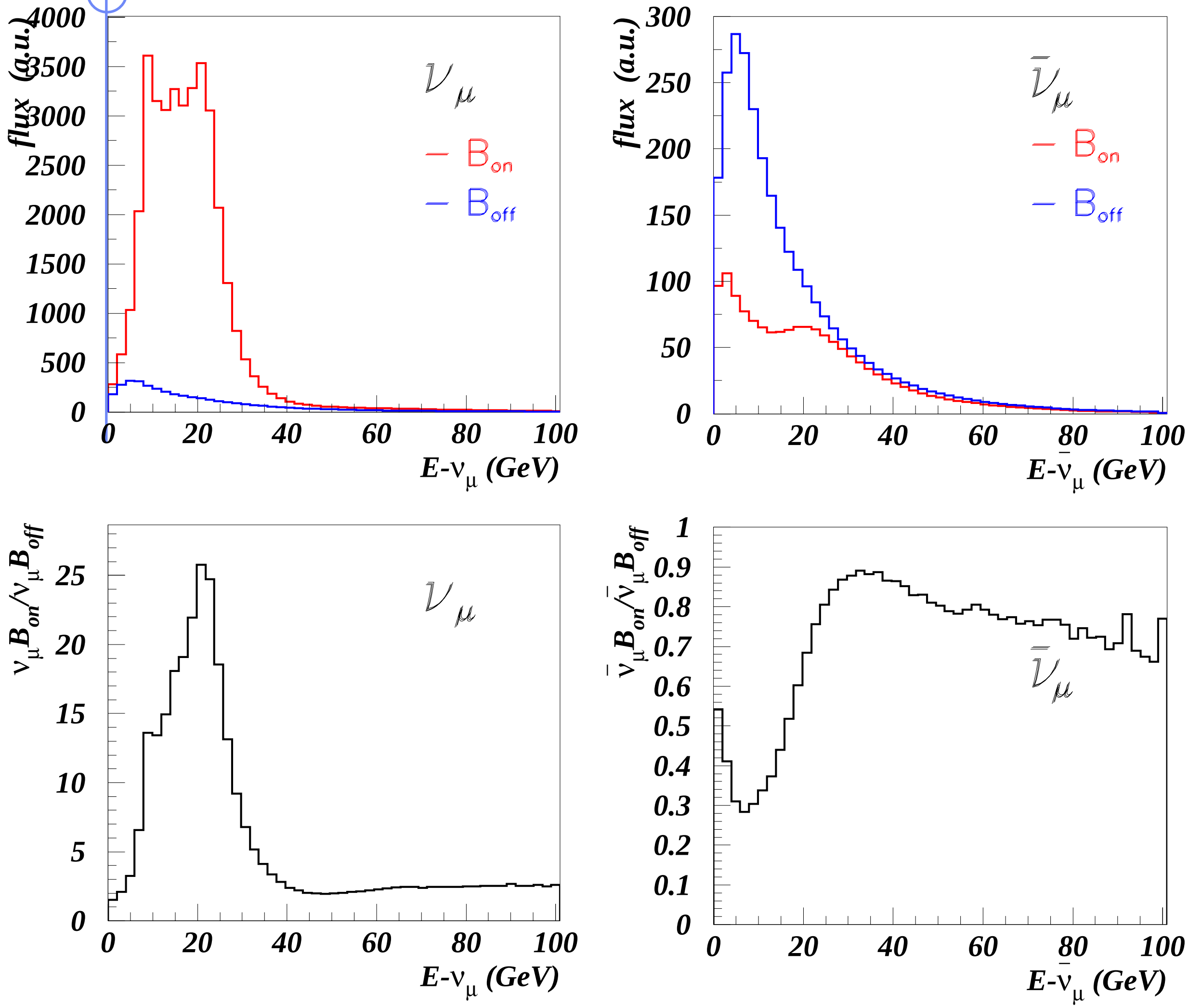
Horn and Reflector focalization



Horn + Reflector focusing angular acceptance:
by comparing B_{ON} and B_{OFF} distributions of production angle θ (at rod) for $\pi^+ \rightarrow \nu_\mu$ at Gran Sasso:

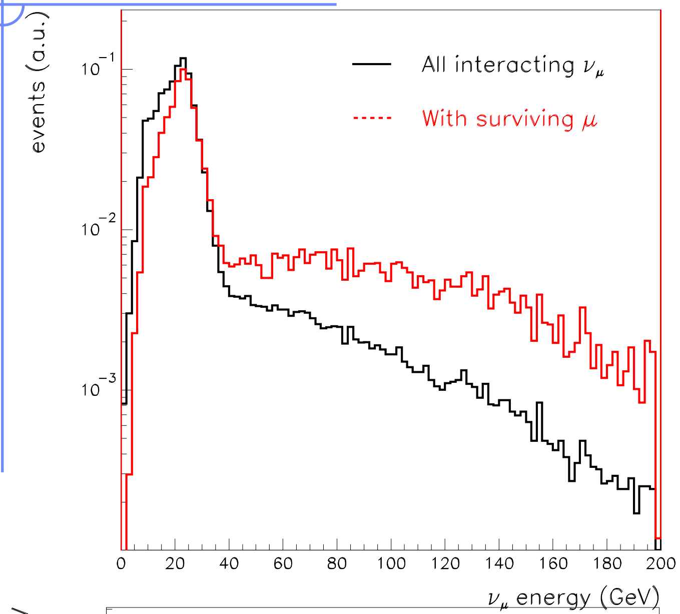
- at low momenta (< 10 GeV/c)
  - horn focus π+ up to 35 mrad
  - overfocusing for $\theta \lesssim$15mrad
  - reflector extends the action up to 60 mrad
- at higher momenta: combined angular acceptance of horn + reflector
  - extends up to 25 mrad for momenta p $\lesssim$50 GeV/c

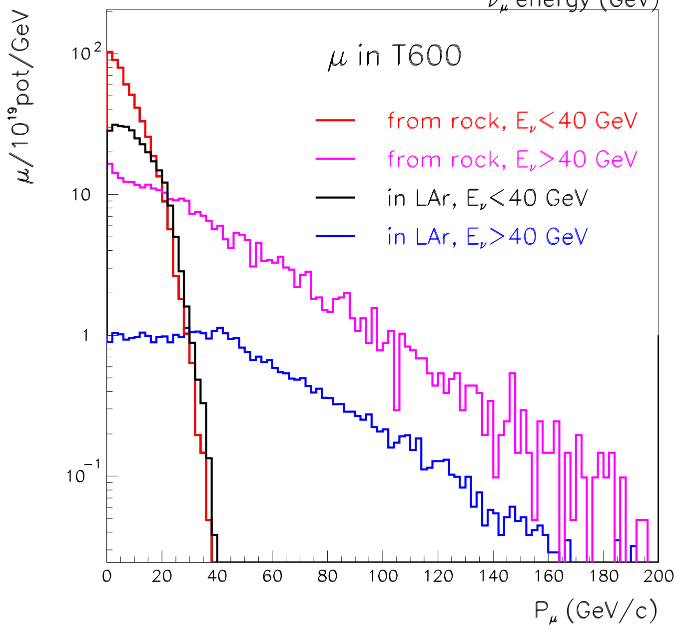
Effect of horn and reflector at LNGS



- $\nu_\mu^{Bon} / \nu_\mu^{Boff} = 10.1$: by focusing forward π^+, K^+
  - flux peak at $E_\nu \approx 20$ GeV
- $\bar{\nu}_\mu^{Bon} / \bar{\nu}_\mu^{Boff} = 0.52$: by defocusing forward π^{--},K^-
  - $\bar{\nu}_\mu/\nu_\mu$ contamination reduced by a factor ≈20

μ from ν interactions in the Gran Sasso rock: a monitor for ν flux





- ν interaction points uniformly sampled in a 300 m rock slab
- expected μ fluence:
  - 41 μ /m²/10¹⁹ pot
  - → 0.9 μ /m²/day

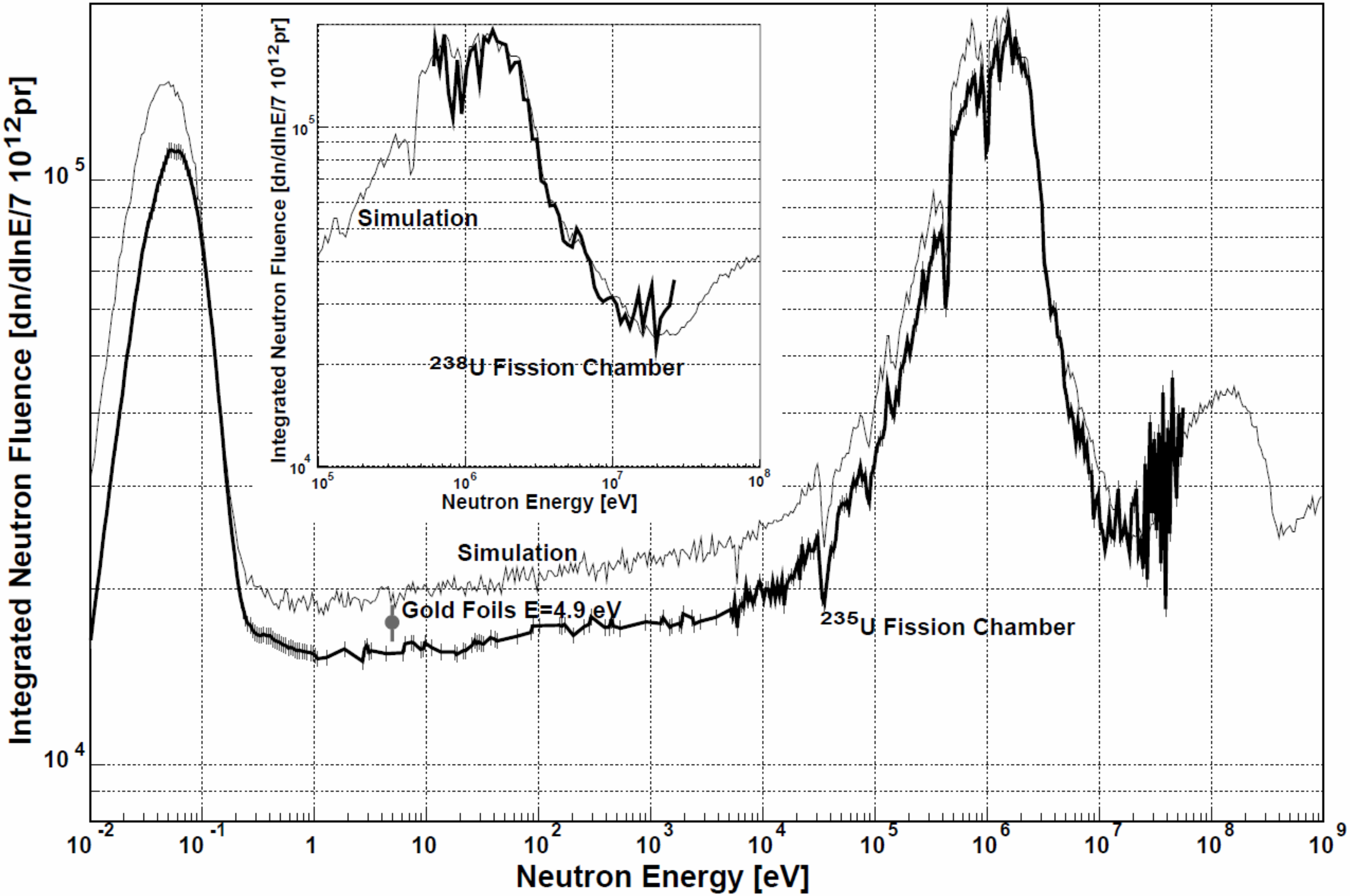
ICARUS T600
≈ 3500 μ/y (nominal beam)
870μ/y with P_μ> 20 GeV/c
coming mainly from high energy ν

- assuming a good knowledge of the bulk of the ν beam

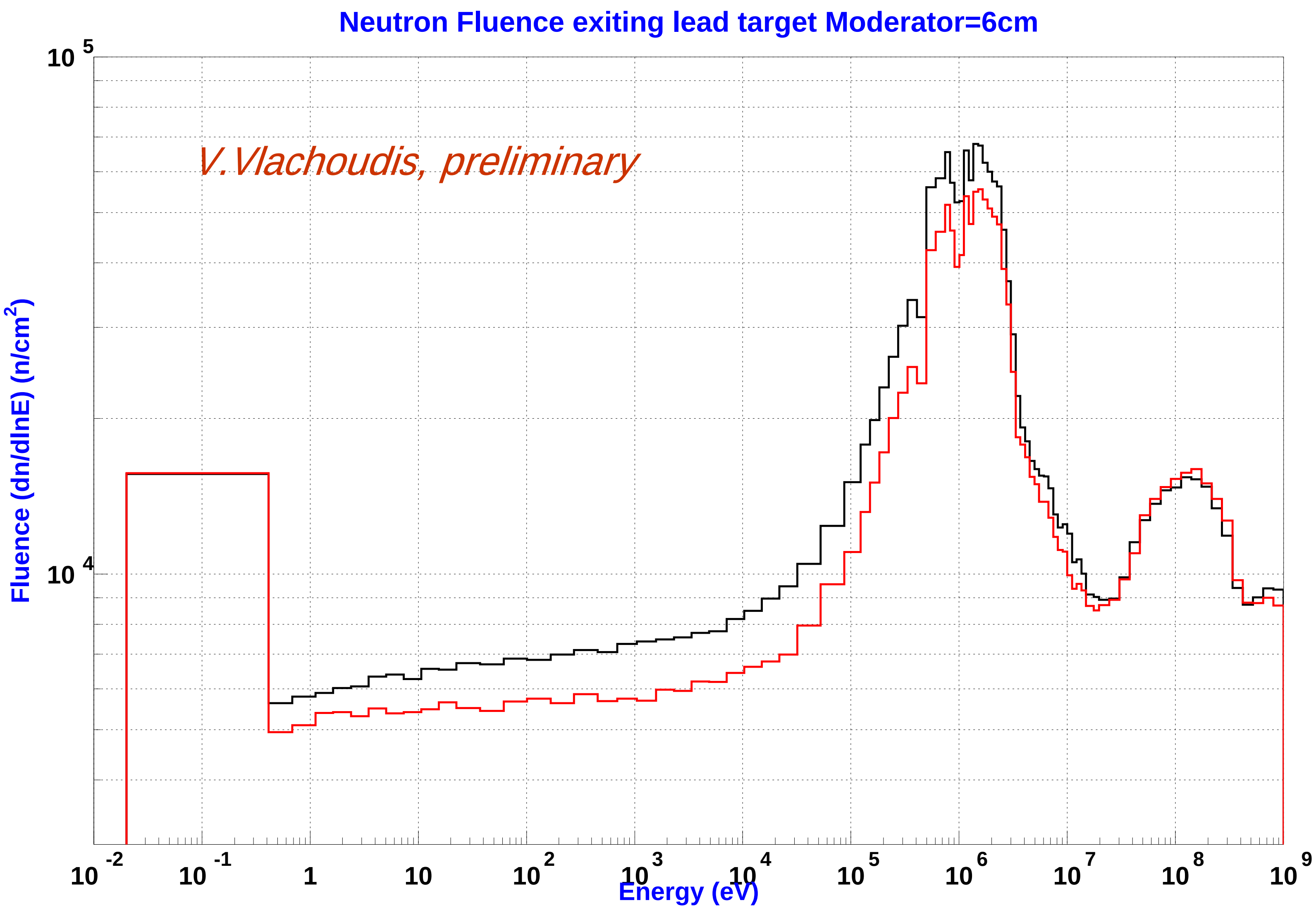
⇒ measurement of ν fluence above 40 GeV with good statistical accuracy

THE END

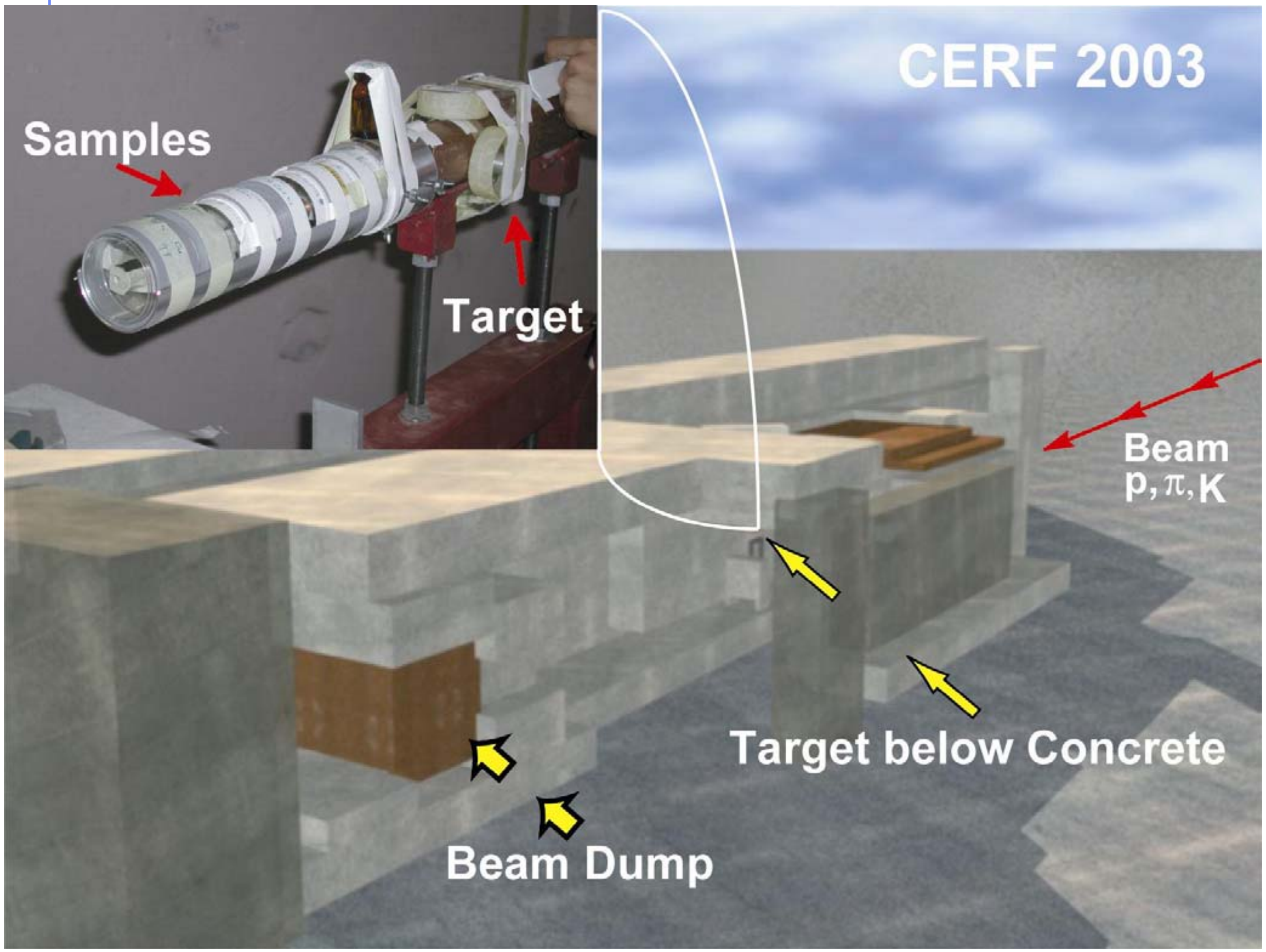
n_ToF measured vs simulated n flux as published



(Simulated) effect of the extra 1 cm of water moderator recently "discovered" wrt the design one (5 cm)



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

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**

Activation: Stainless Steel

Table 1: Stainless Steel, cooling times 1d 6h 28m, 17d 10h 39m

Isotope	$t_{1/2}$	Exp Bq/g	± %	OLD FLUKA/Exp	± %	FLUKA/Exp	± %
Be 7	53.29d	0.205	24	0.096	34	1.070	30
Na 24	14.96h	0.513	4.3	0.278	8.6	0.406	13
K 43	22.30h	1.08	4.6	0.628	8.7	0.814	11
Ca 47	4.54d	0.098	25	0.424	44	(0.295	62)
Sc 44	3.93h	13.8	4.8	0.692	5.8	0.622	6.2
mSc 44	58.60h	6.51	7.1	1.372	8.1	1.233	8.6
Sc 46	83.79d	0.873	8.3	0.841	9.1	0.859	9.5
Sc 47	80.28h	6.57	8.2	0.970	9.7	1.050	13
Sc 48	43.67h	1.57	5.2	1.266	8.4	1.403	11
V 48	15.97d	8.97	3.1	1.464	3.8	1.354	4.8
Cr 48	21.56h	0.584	6.7	1.084	11	1.032	12
Cr 51	27.70d	15.1	12	1.261	13	1.231	13
Mn 54	312.12d	2.85	10	1.061	10	1.060	11
Co 55	17.53h	1.04	4.6	1.112	7.7	0.980	10
Co 56	77.27d	0.485	7.6	1.422	9.0	1.332	10
Co 57	271.79d	0.463	11	1.180	12	1.140	12
Co 58	70.82d	2.21	5.9	0.930	6.3	0.881	6.9
Ni 57	35.60h	3.52	4.5	1.477	6.5	1.412	8.2

M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

Activation: Aluminum

Table 2: Al, cooling times 1d 16h, 16d 08h , 51d 09h

Isotope	$t_{1/2}$	Exp Bq/g	± %	OLD FLUKA/Exp	± %	FLUKA/Exp	± %
Be 7	53.29d	0.789	13	0.364	16	0.688	19
Na 22	2.60y	0.365	9.6	0.841	11	0.752	11
Na 24	14.96h	38.6	3.6	0.854	4.0	0.815	4.6
Sc 44	3.93h	0.229	24	2.219	27	0.820	36
Sc 46	83.79d	0.025	16	1.571	19	0.902	28
Sc 47	80.28h	0.163	12	0.986	27	(1.486	43)
V 48	15.97d	0.199	7.4	0.931	18	(0.938	29)
Cr 51	27.70d	0.257	17	0.873	23	0.942	28
Mn 52	5.59d	0.224	5.6	2.369	9.6	0.936	24
Mn 54	312.12d	0.081	11	0.972	15	0.917	19
Co 57	271.79d	0.00424	32	0.833	50	(0.760	67)
Co 58	70.82d	0.019	22	1.820	27	0.841	39

M. Brugger, *et al.*, Proceedings of the Int. Conf. on Accelerator Applications (AccApp'05), Venice, Italy, 2005

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
- Multifragmentation (**NOW DEVELOPED AND PRESENTED AT INT. CONF. ON NUCLEAR DATA FOR SCIENCE AND TECHN. (Santa Fe 2004)**) has significantly improved the agreement for intermediate and small mass isotopes
- 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 → Part 2

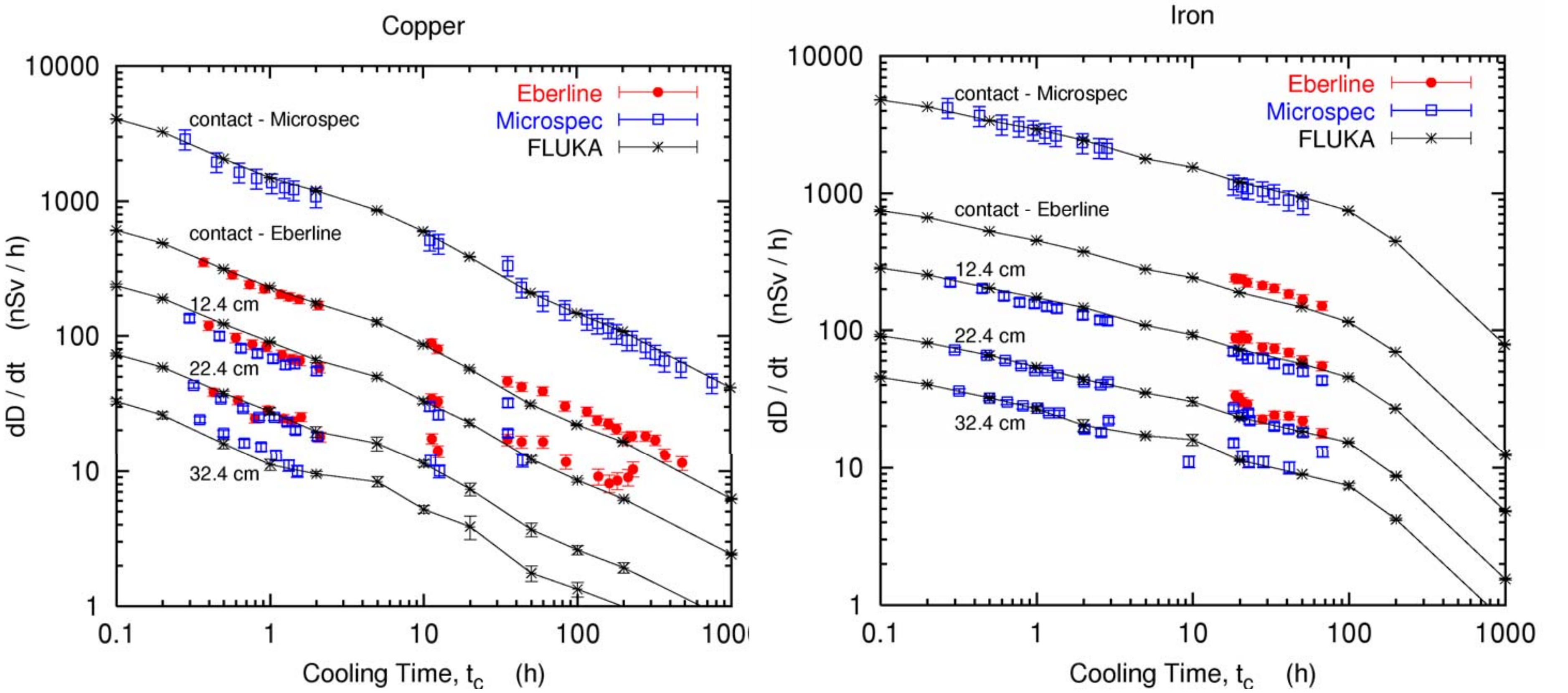
Part 2: Radioactivity Produced in LHC Materials: Residual Dose Rates

- Levels of residual 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

Benchmark experiment – *Results 1*

M. Brugger *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

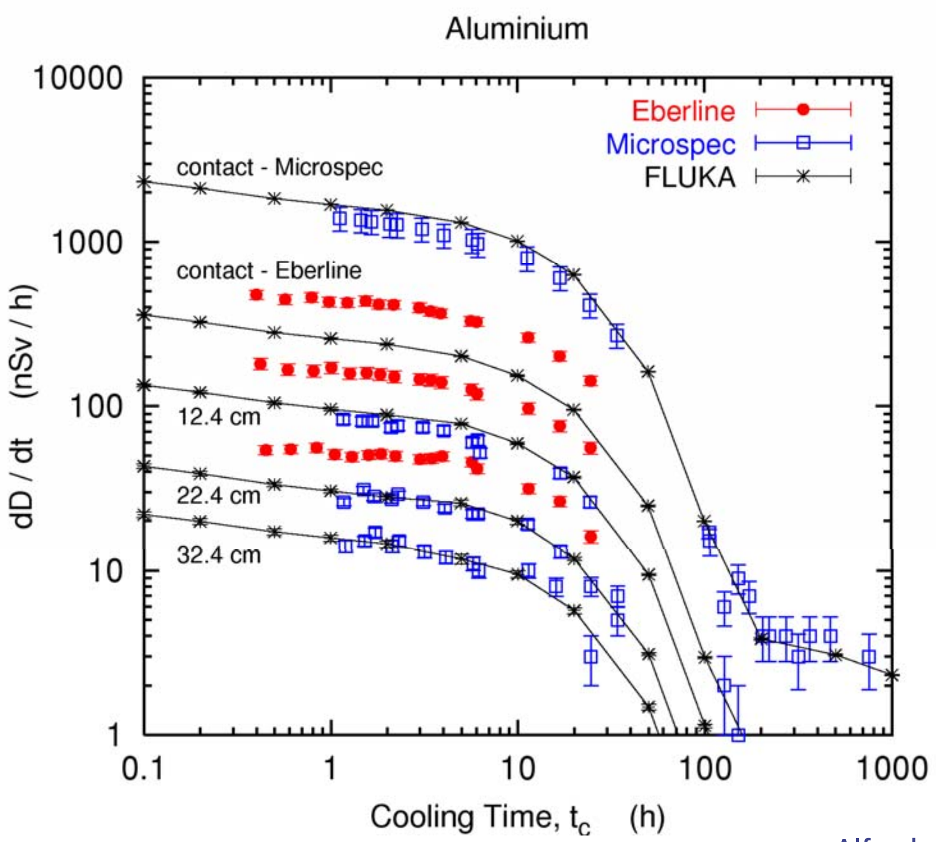
Dose rate as function of cooling time
for different distances between sample and detector

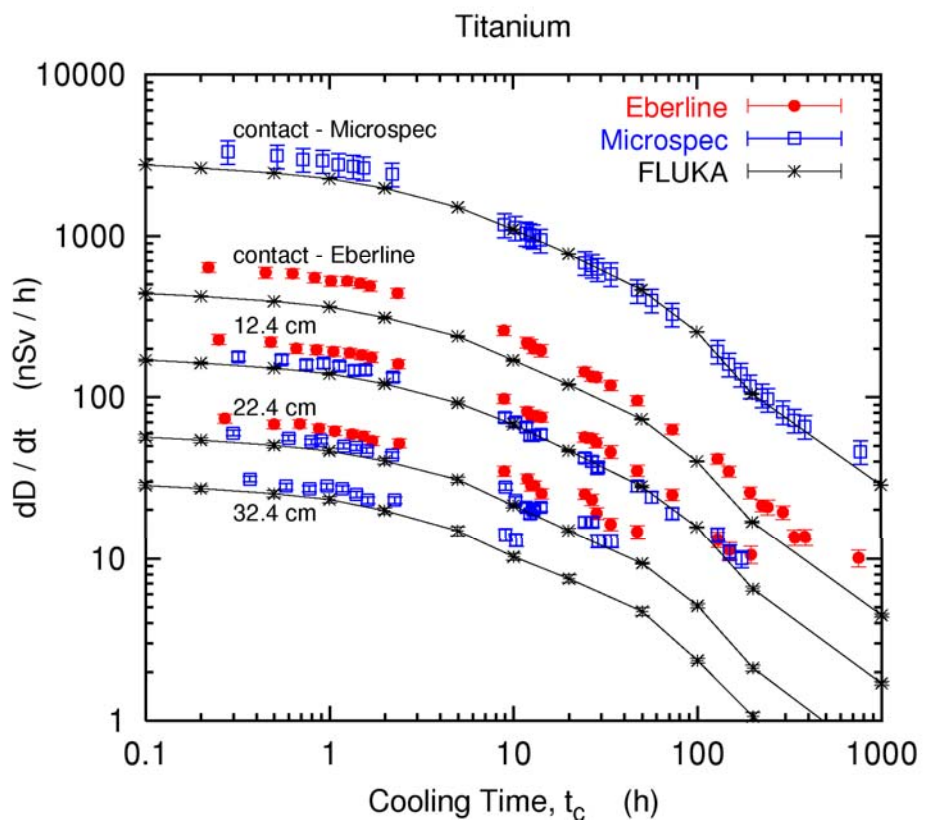


Benchmark experiment – *Results 2*

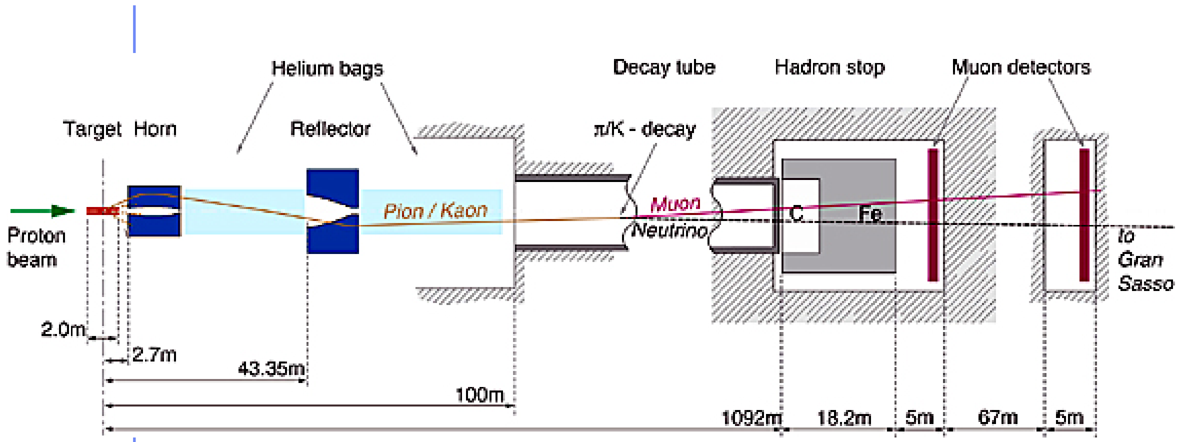
M. Brugger *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

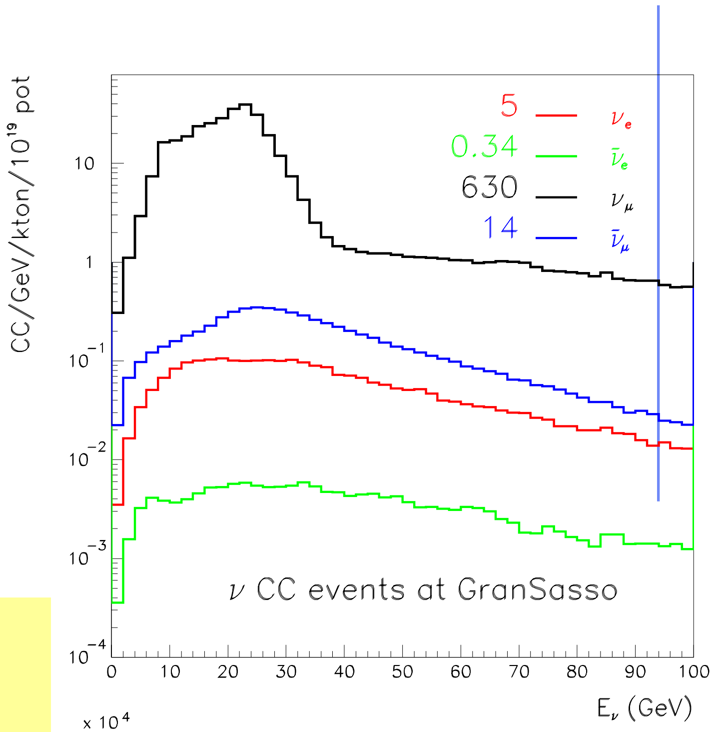
Dose rate as function of cooling time
for different distances between sample and detector



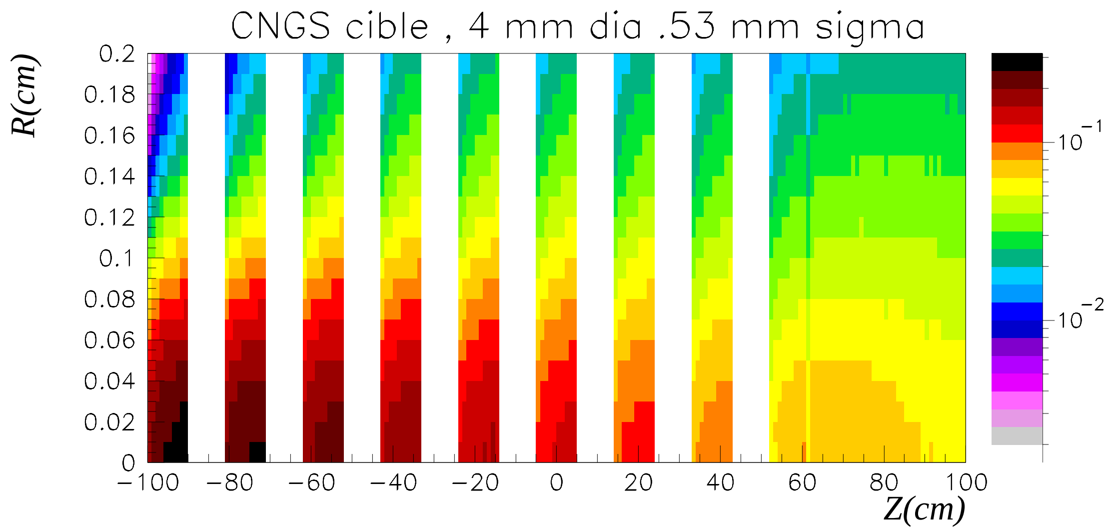


Cern Neutrino to Gran Sasso

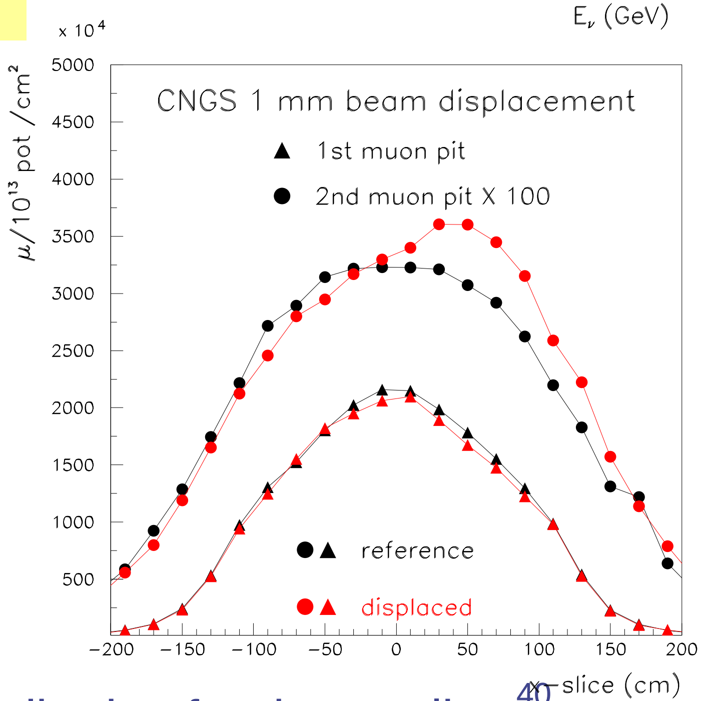




Engineering and physics: target heating, shielding, activation, beam monitors, neutrino spectra



Energy dep. in CNGS target rods, GeV/cm^3/pot



Muons in muon pits: horizontal distribution for beam alignment