Benchmarking of the FLUKA code

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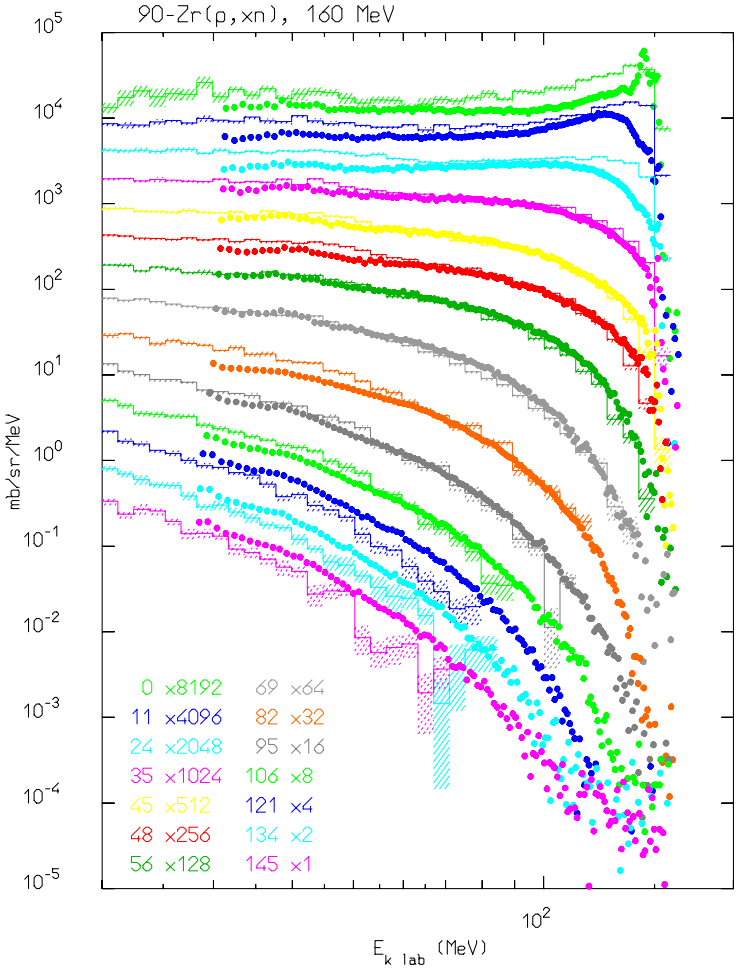
INFN Milan, Italy
Alfredo Ferrari
CERN
HSS06

Thin target

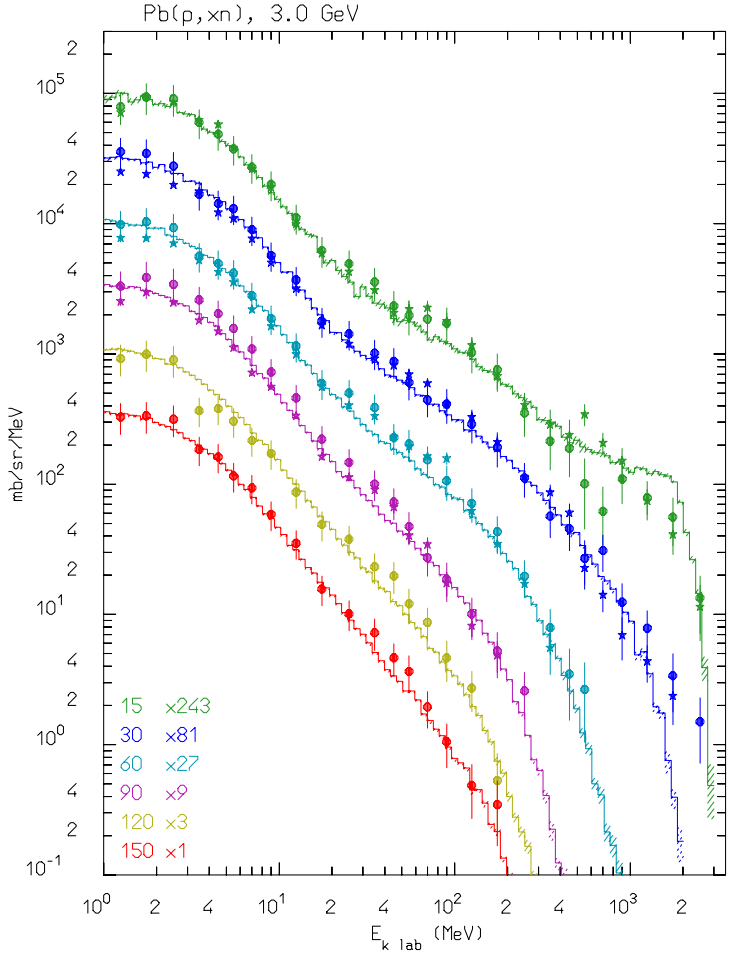
Neutron production at low-intermediate energies

where most of the interactions occur..

160 MeV protons on Zr
Phys. Rev. C41,2010 (1990)

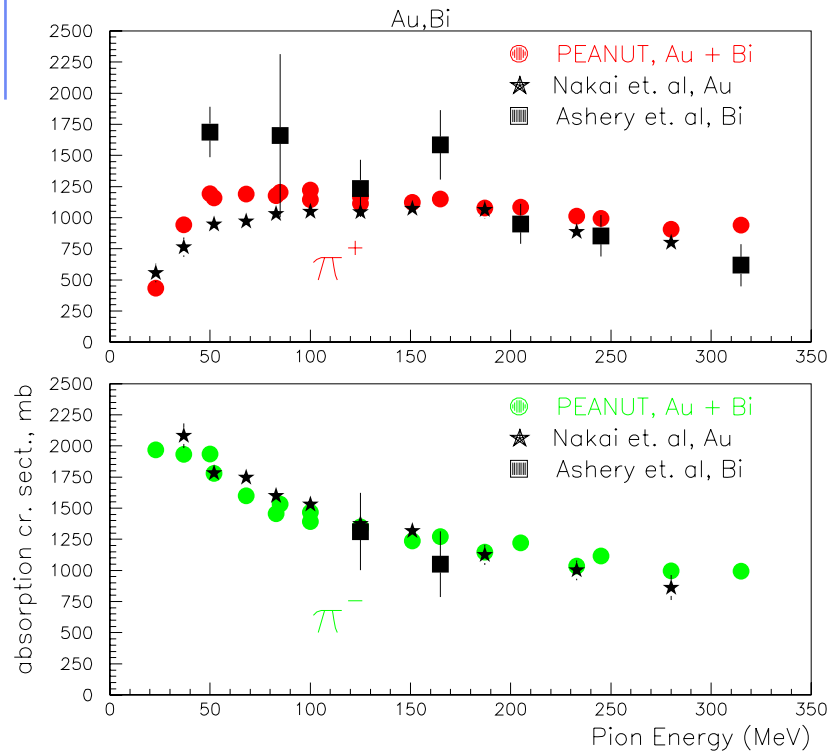


3 Gev p on Pb
Nuc. Sci. Technol. 32, 827 (1995)

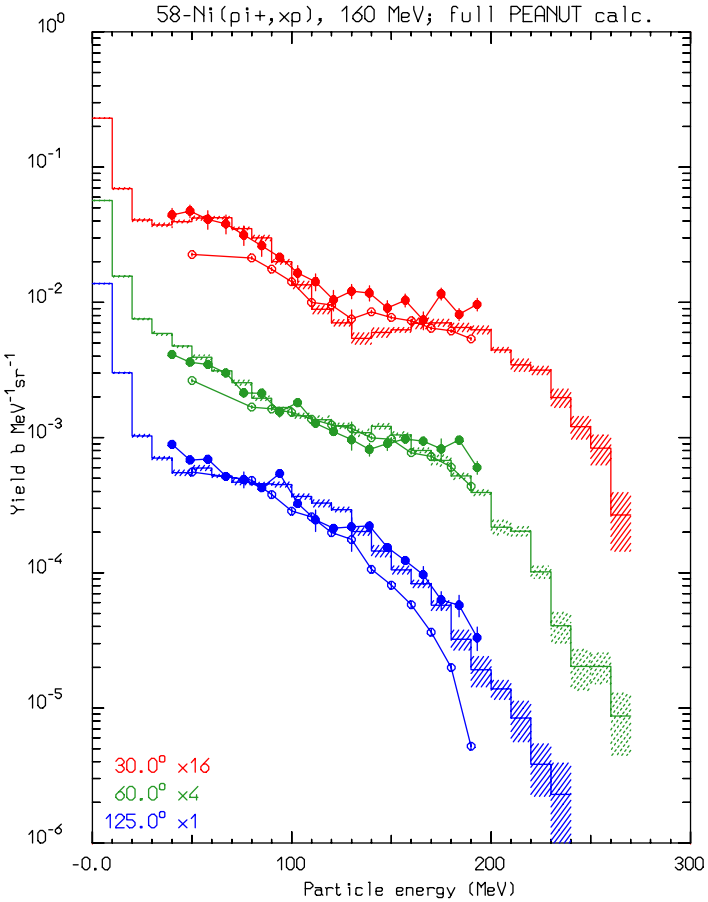


Pion absorption

Pin absorption cross section on Gold and Bismuth in the Δ resonance region (multibody absorption in PEANUT)



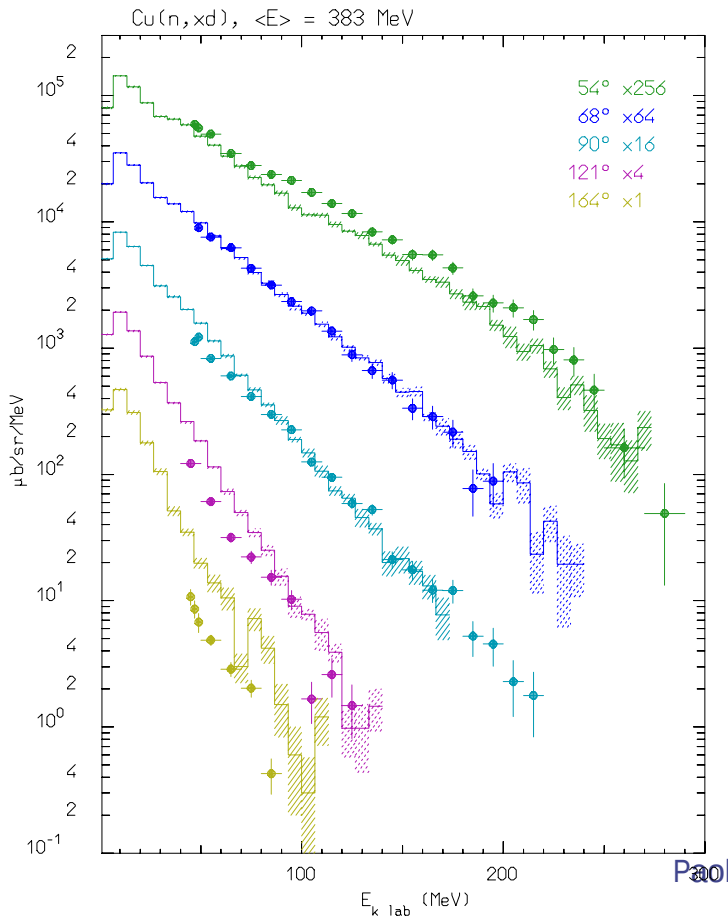
Emitted proton spectra at different angles , 160 MeV π^+ on Ni
Phys. Rev. C41,2215 (1990)
Phys. Rev. C24,211 (1981)
Proton spectra extend up to 300 MeV



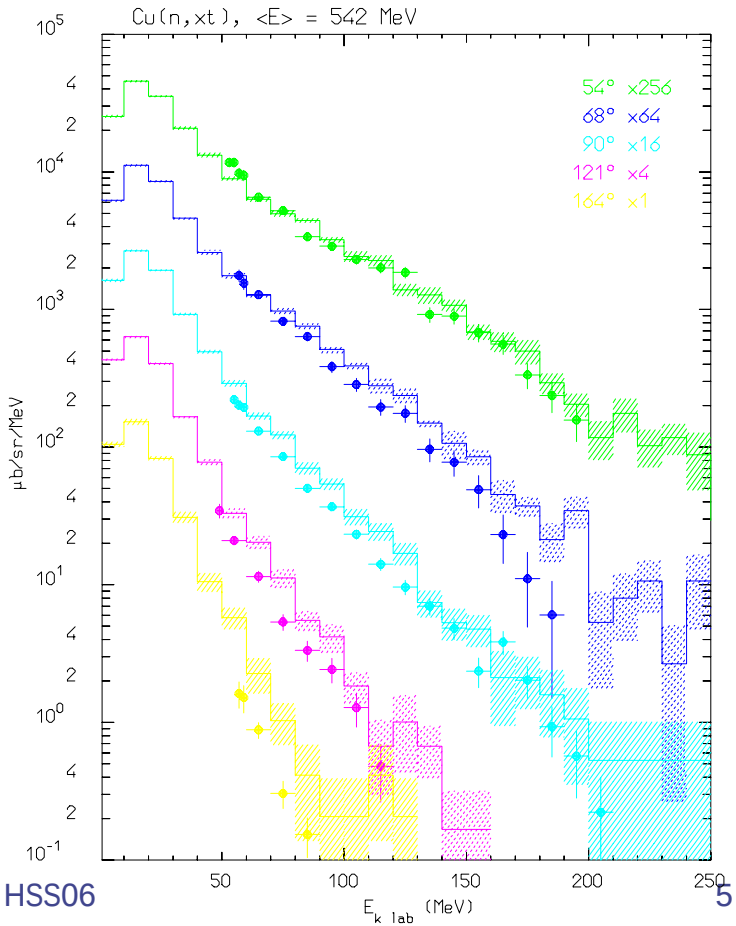
Coalescence

High energy light fragments through the coalescence mechanism

double differential d production
from 383 MeV neutrons on Copper
Nucl. Phys. A510, 774 (1990)



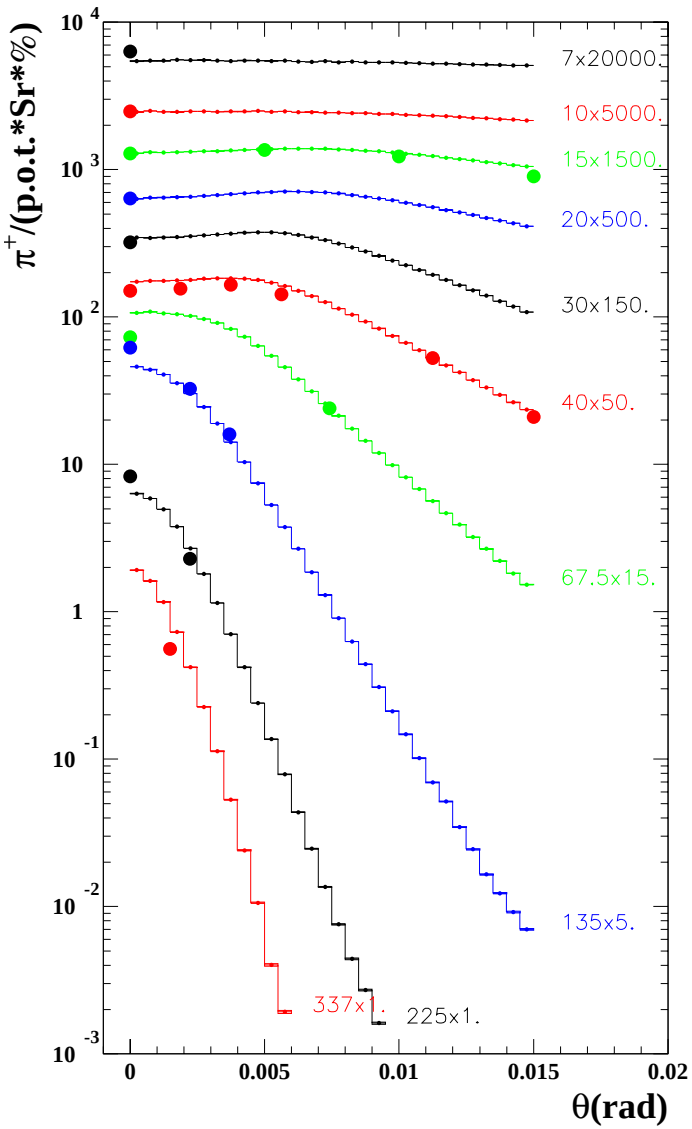
double differential t production
from 542 MeV neutrons on Copper

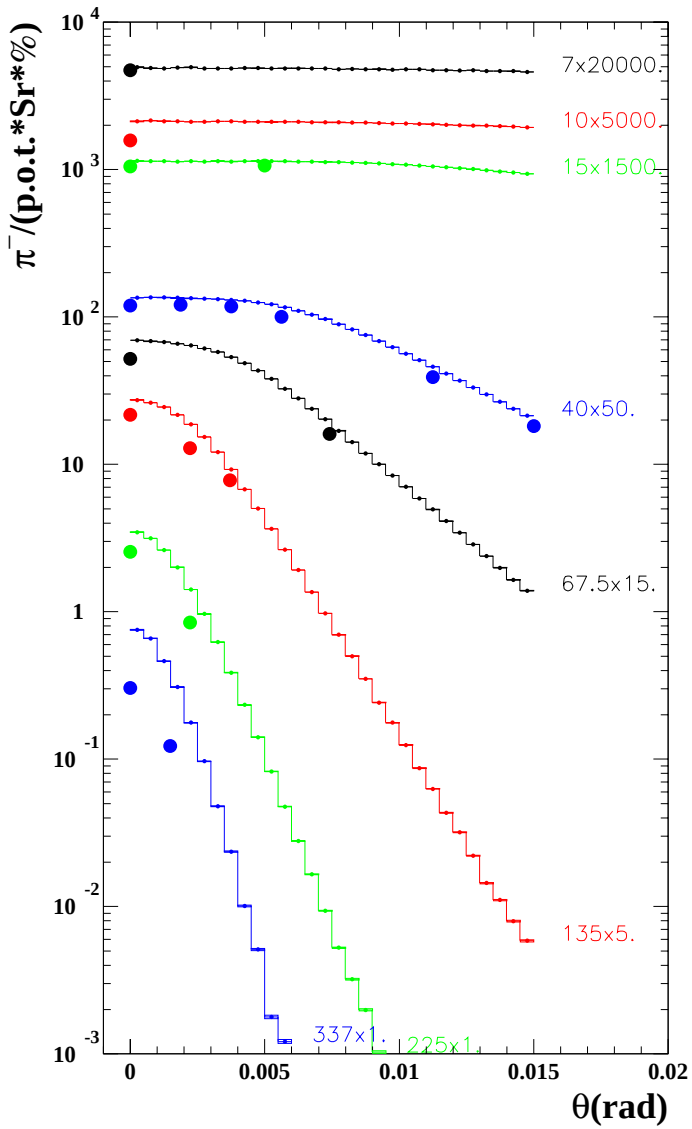


Comparison with SPY data: 450 GeV p on Be

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)

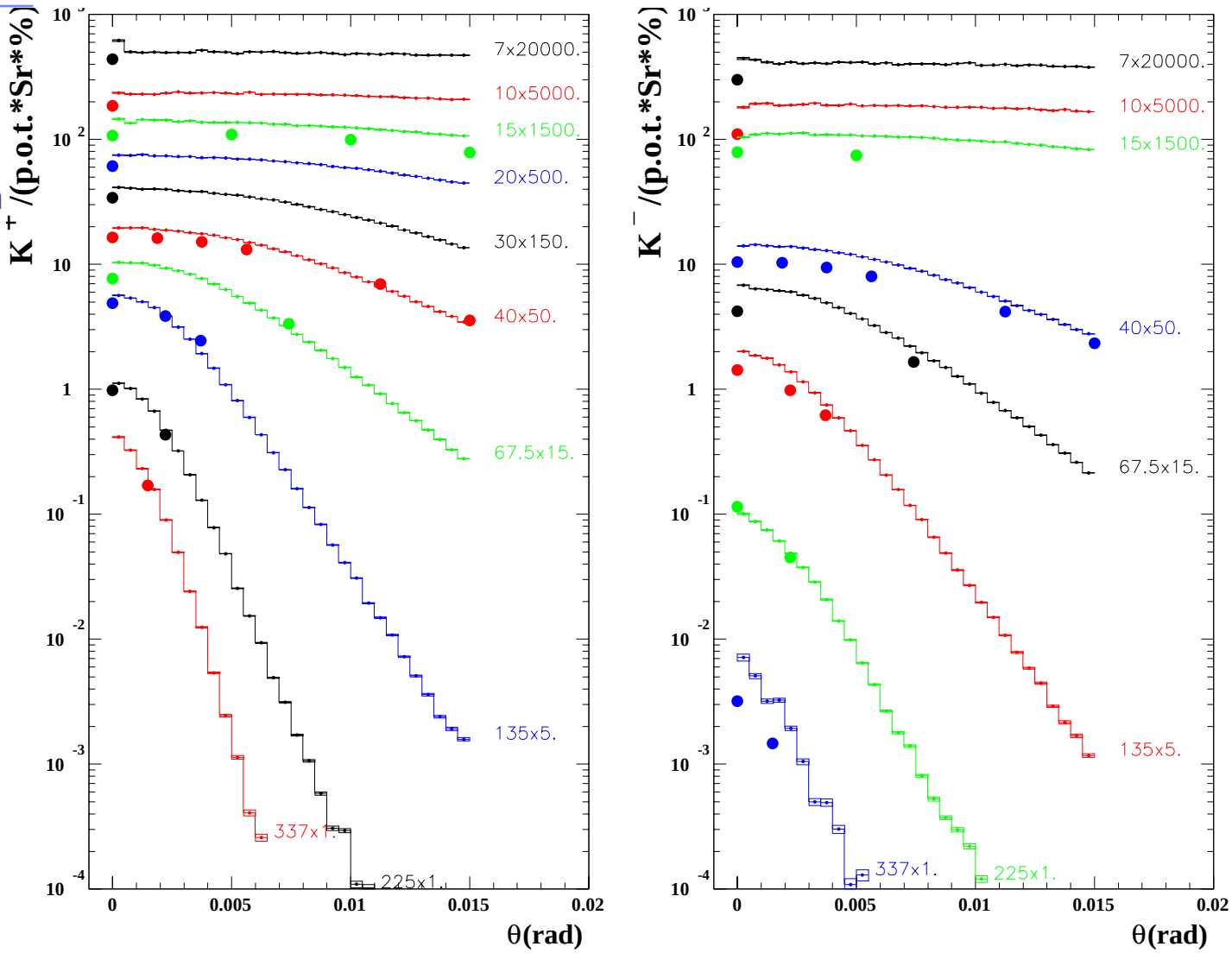




Comparison with SPY data: 450 GeV p on Be

Double diff distribution for K+/K- production from 450 GeV/c p on Be

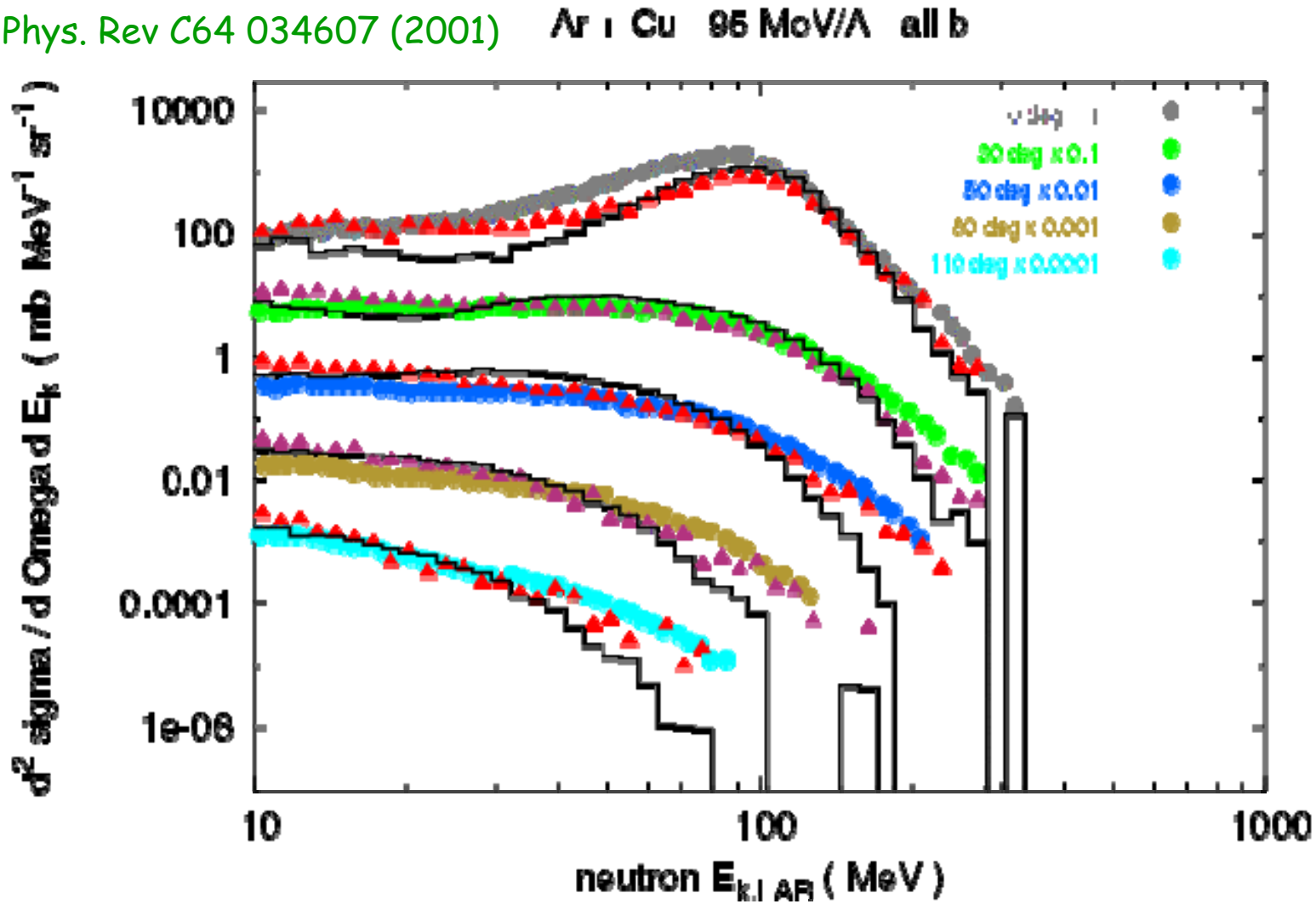
H.W Atherton CERN 80-06 SPY : PLB 425, 208 (1998)



Heavy Ions

QMD's: Neutron production cross section

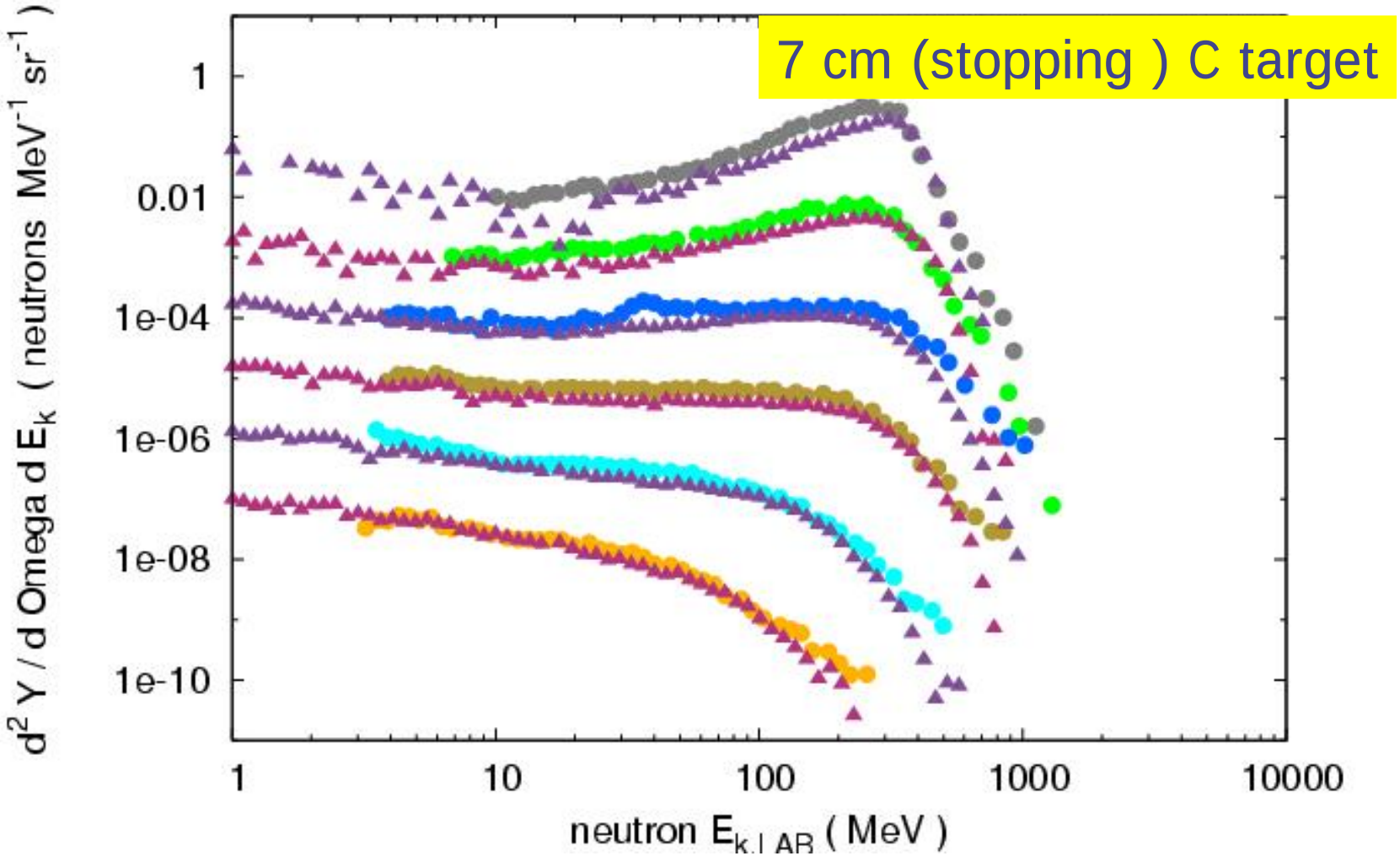
Phys. Rev C64 034607 (2001)



RQMD + FLUKA ▲ QMD + FLUKA ● EXP data

The new QMD model: thick target example (full interface to FLUKA)

Phys. ReV. C62 044615 (2000) Ar + C 400 MeV/A all b



▲ QMD + FLUKA ● EXP data

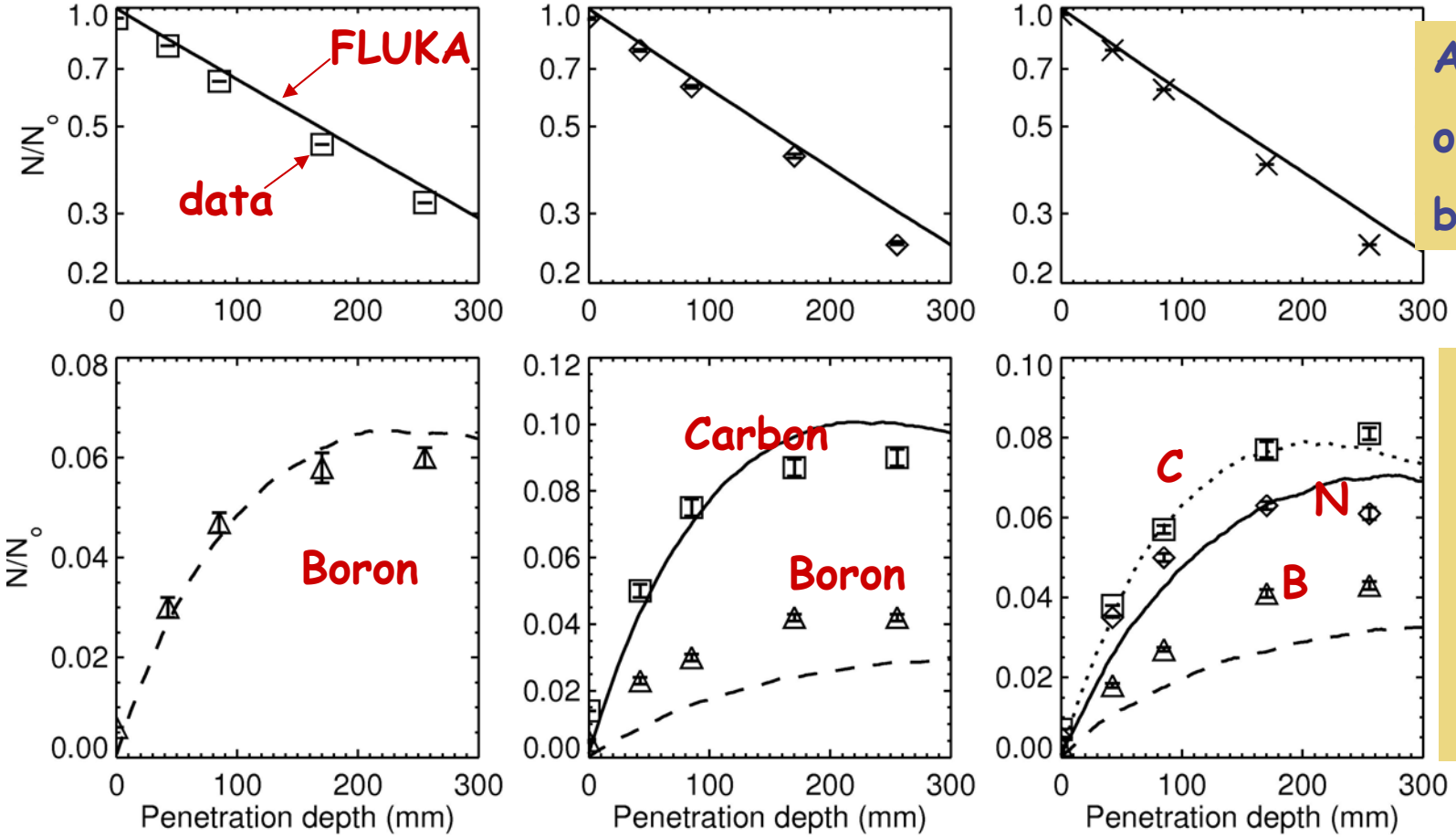
Fragmentation of therapeutic beams in a water target

^{12}C 676 MeV/u

^{14}N 674 MeV/u

^{16}O 672 MeV/u

NIM B 117, 221 (1996)



Attenuation of primary beam

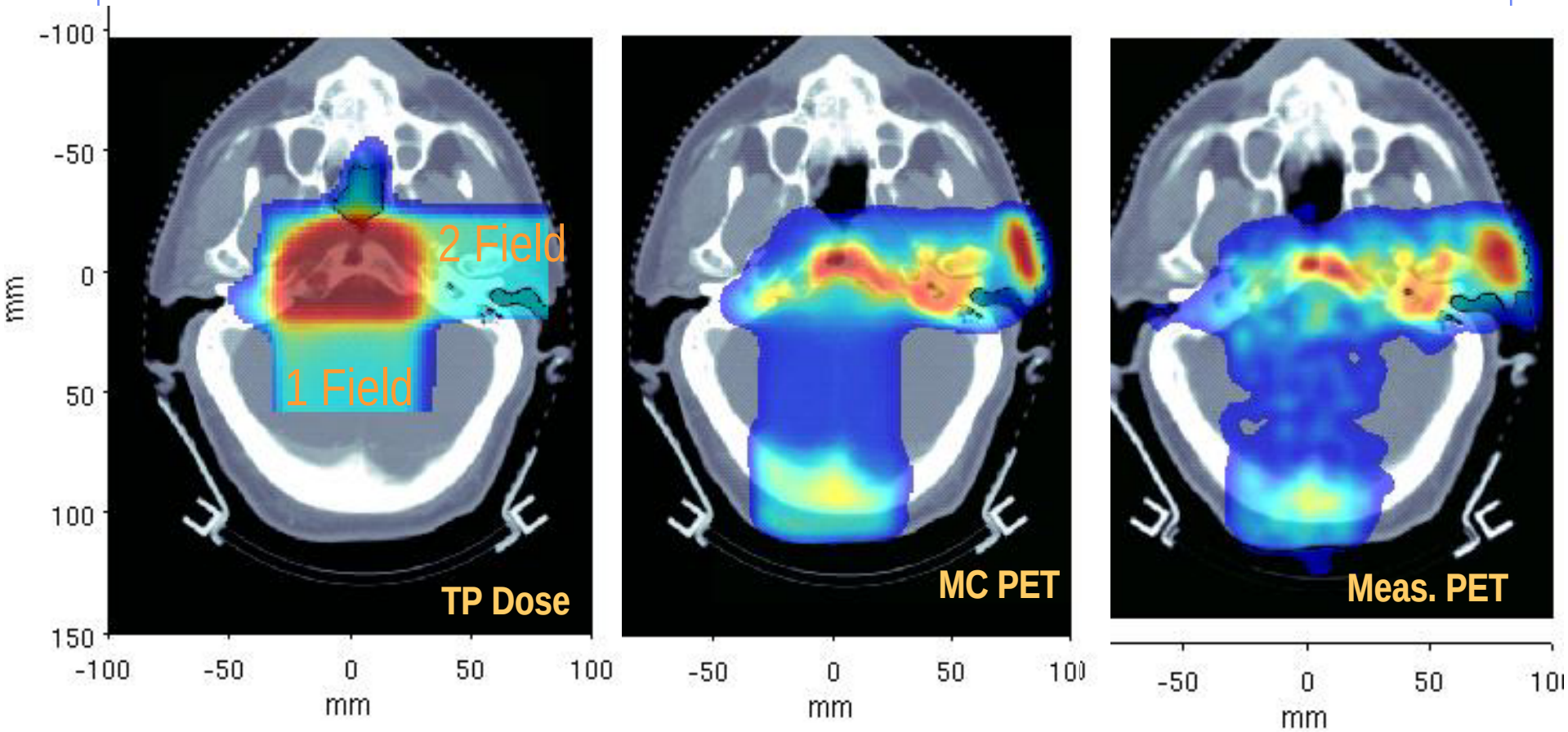
Build-up of secondary fragments

As a function of depth

Simulations by F. Sommerer, K.Parodi, W. Enghardt, A.Aiginger
Forscungszentrum Rossendorf (Dresden) , Vienna Univ. of technology and CERN

Preliminary results: Head *K. Parodi et al., to be published*

Clival Chordoma, 0.96 GyE / field, ΔT_1 ~ 26 min, ΔT_2 ~ 16 min

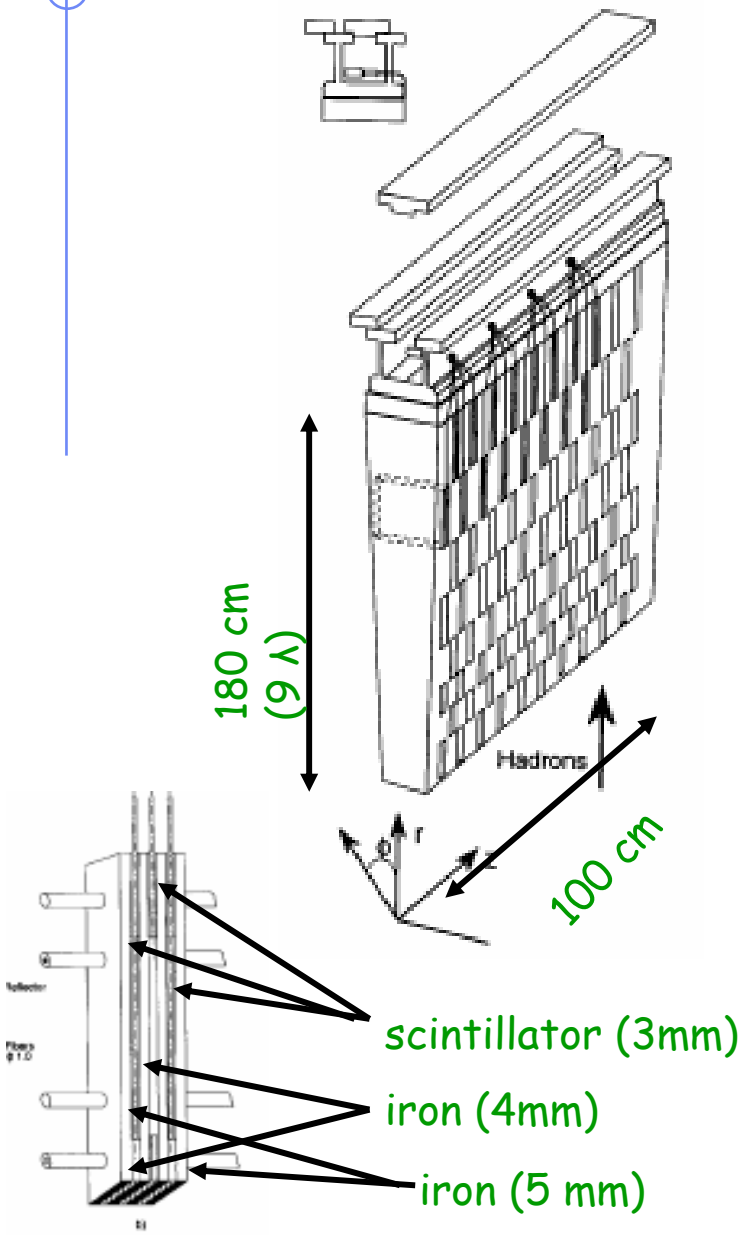


* K. Parodi, H. Paganetti and T. Bortfeld, Massachusetts General Hospital

Calorimeters

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:

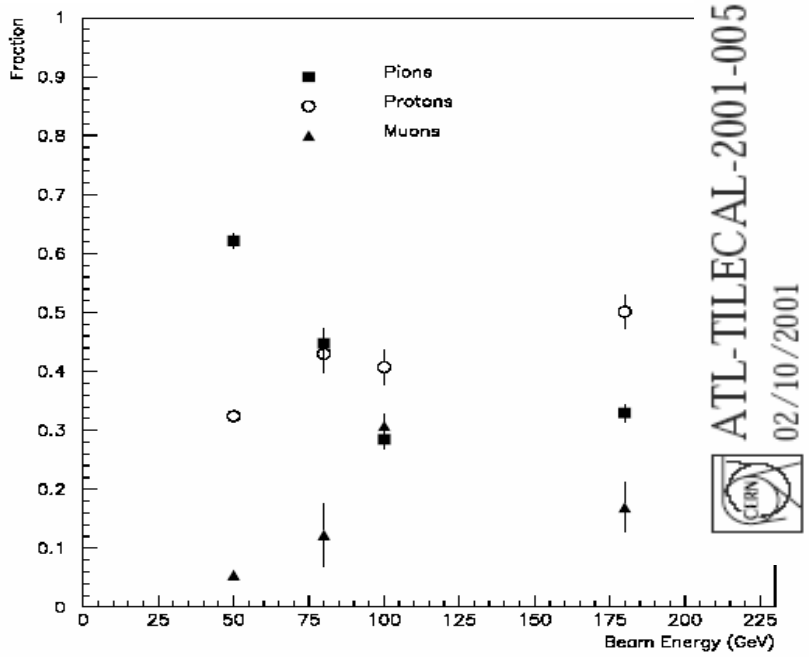
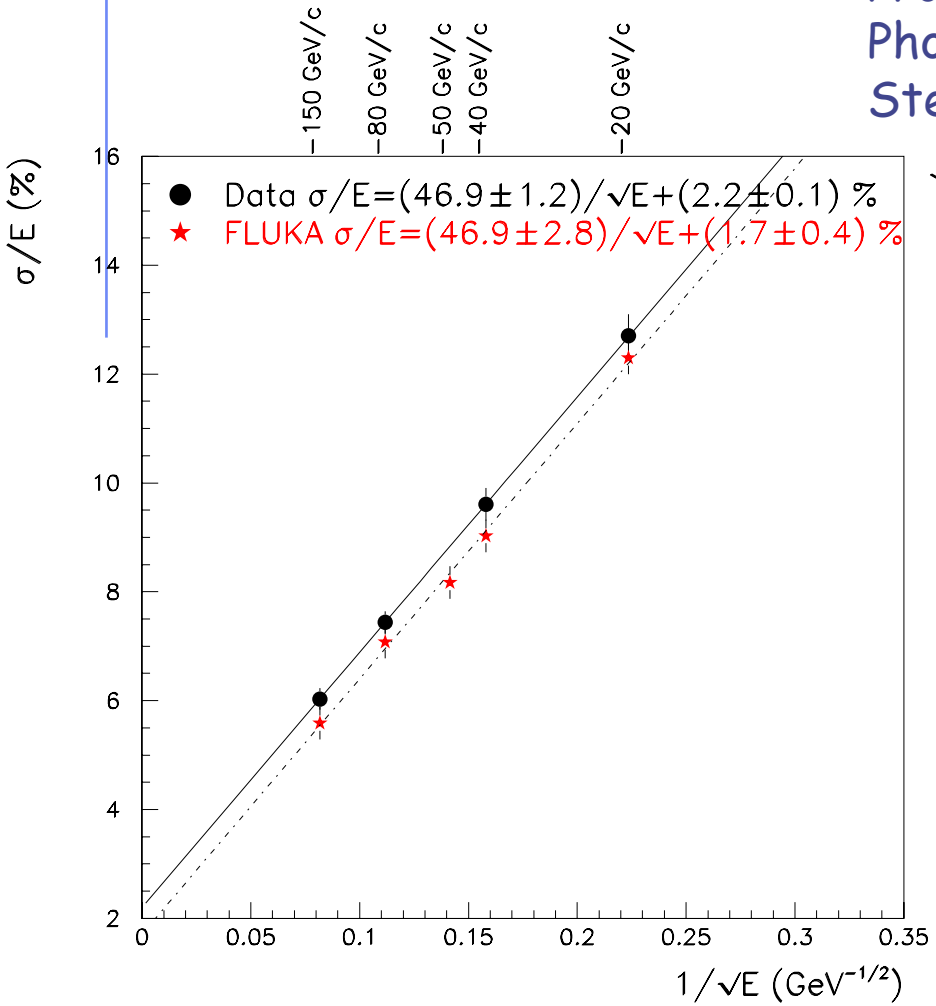


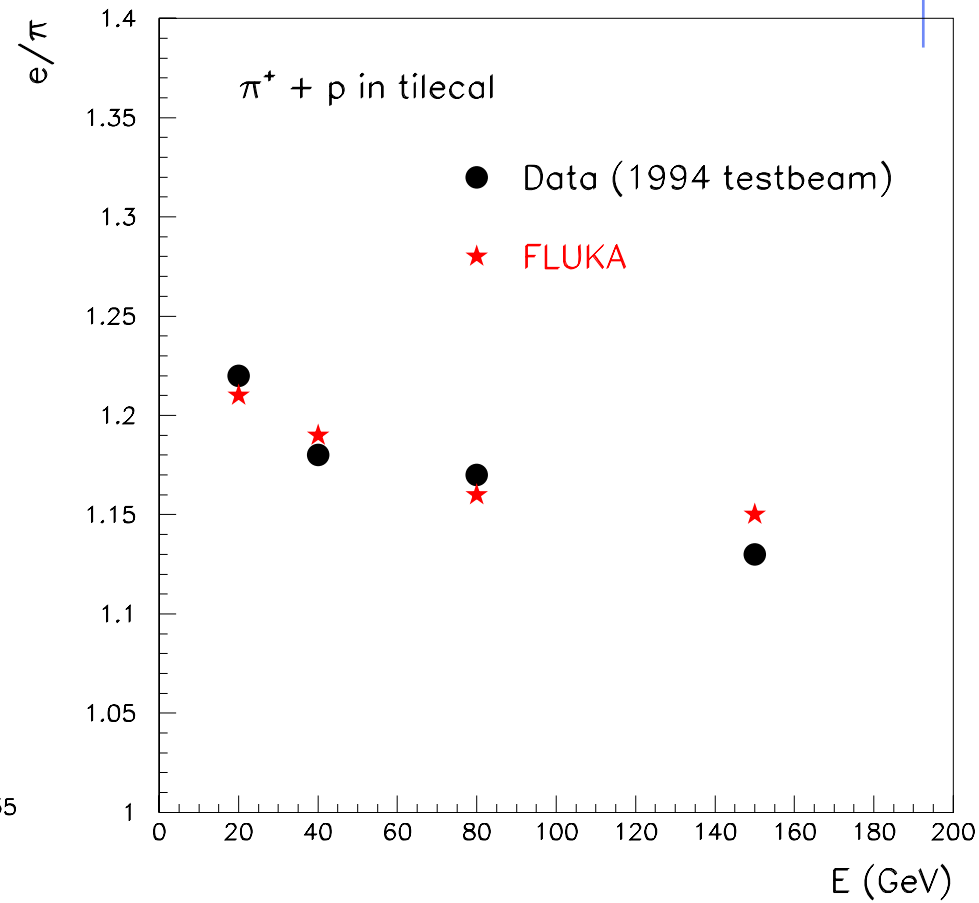
Figure 3: The fractions of pions, protons and muons in the positive pion bea energy.

TILE Calorimeter: resolution and e/π

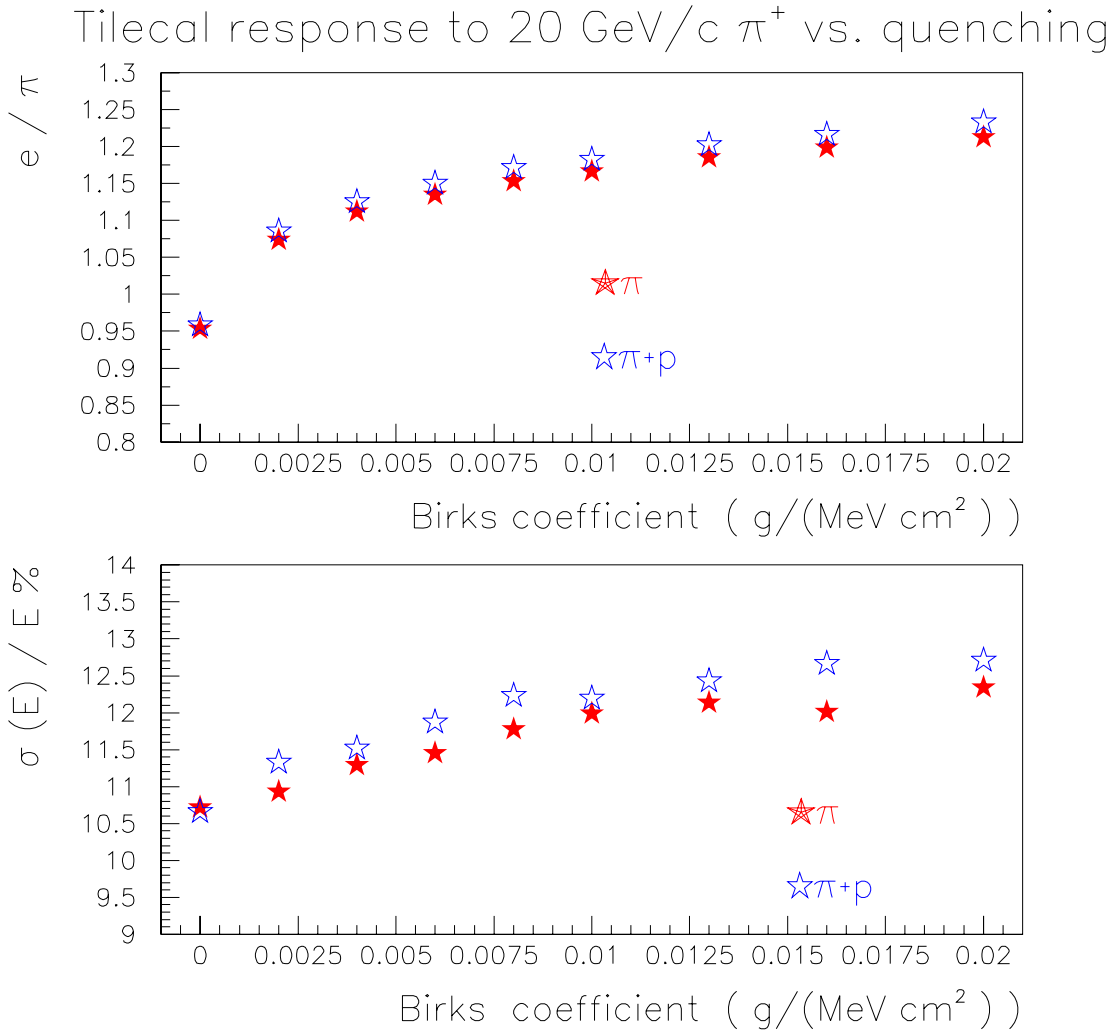
Beam at 20^0 incidence

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





Tile Calorimeter: effect of quenching



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

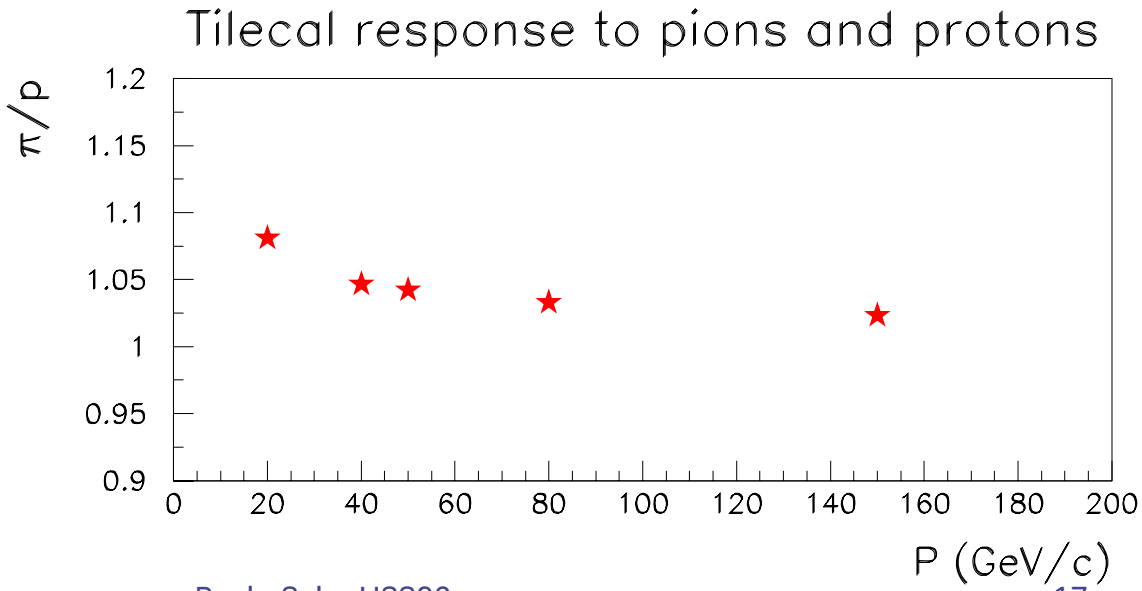
Tilecal: pion/proton difference

P (GeV/c)	π signal/ proton signal		π resolution/ proton resolution	
	Data	Fluka	Data	Fluka
50	1.048	1.042	1.11	1.07 ±0.03
80	1.036	1.034	1.17	1.09 ±0.03

Data : ATL-TILECAL-2001-005

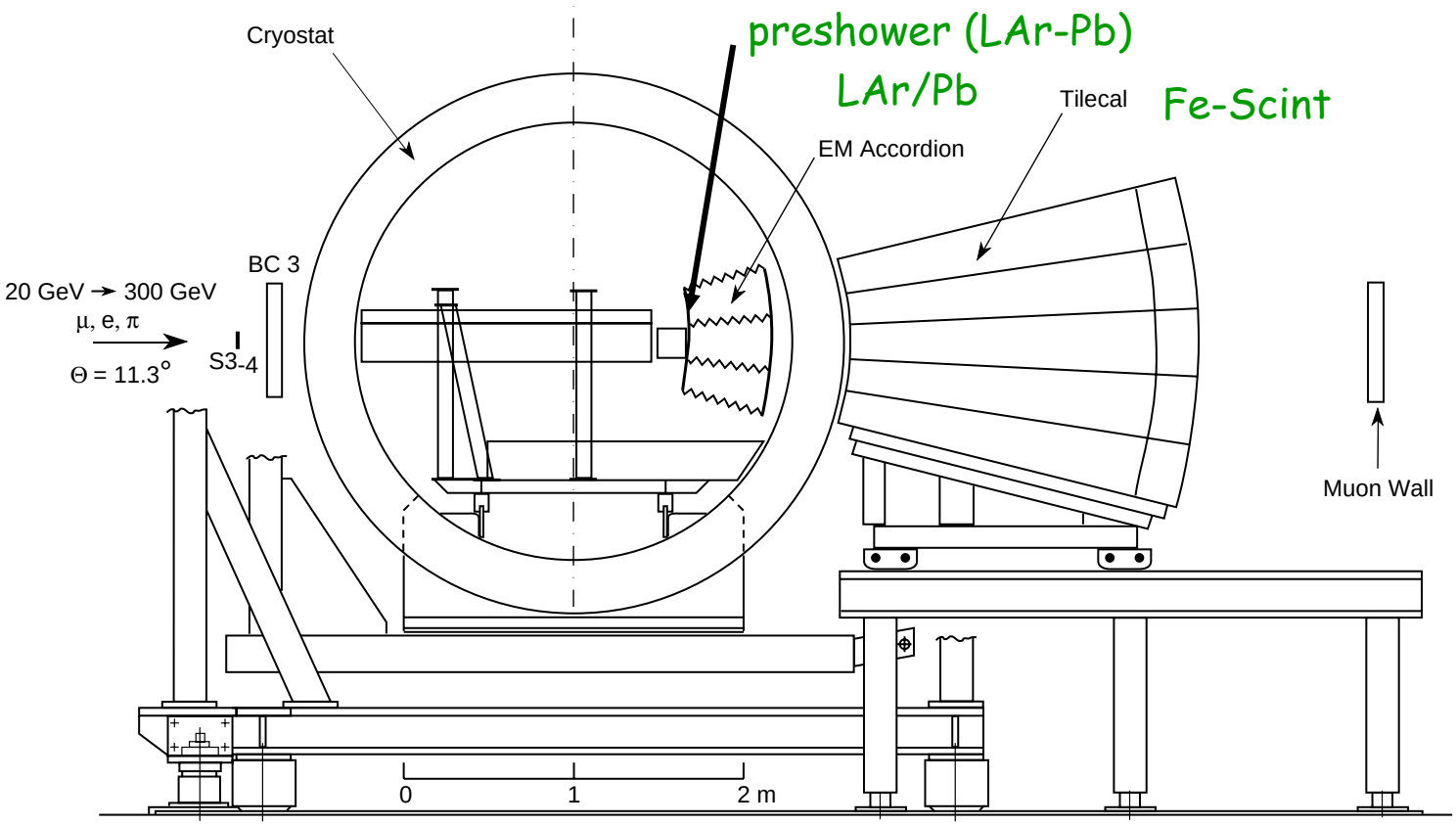
WARNINGS: data/fluka have different tile configurations angle of incidence is also different

FLUKA simulations: energy dependence



ATLAS combined calorimeter test beam

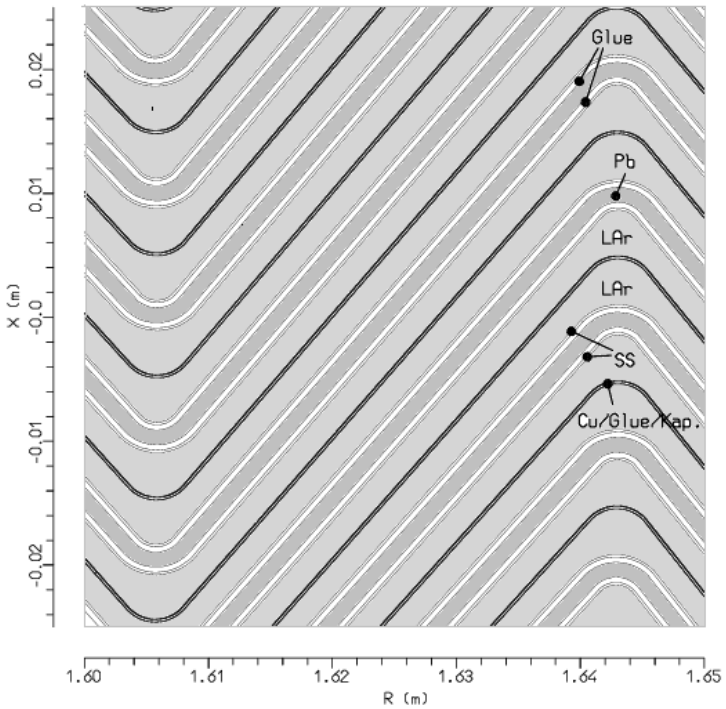
Layout of the experimental set-up (NIM A387,333(1997), NIM A449,461 (2000))
Test beams in 1994 and 1997, electrons and positive pions



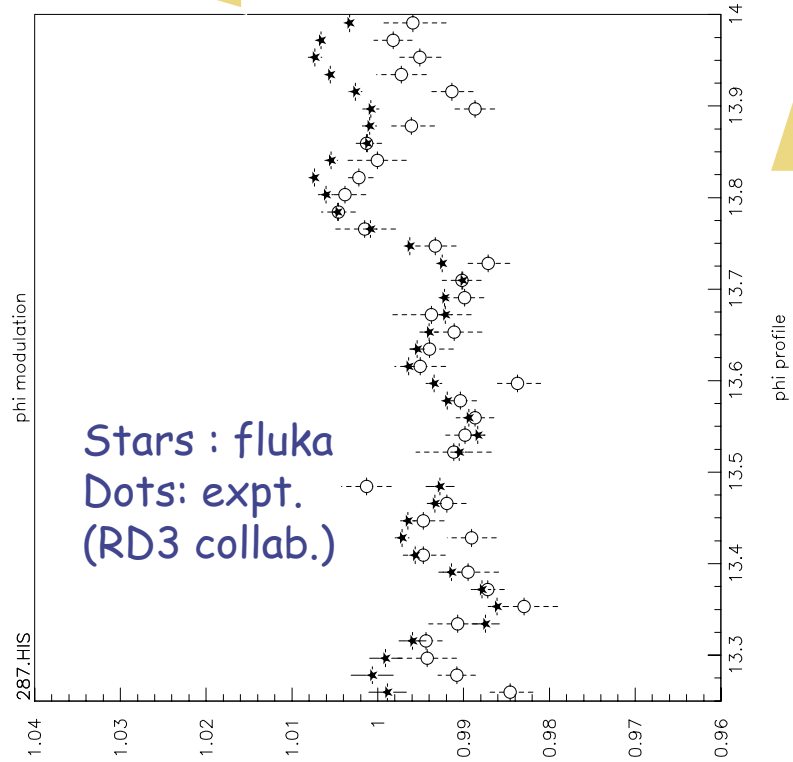
The EM calo (from standalone test beams)

Detail of the FLUKA geometry and response vs. electron impact position

287 GeV electron beam



deposited energy



impact position

Longitudinal Development

E	E1/E		r.m.s.	
GeV	Data	Fluka	Data	Fluka
100	0.68	0.69		
287	0.61	0.58	.091	.094

Energy resolution 10-100 GeV:

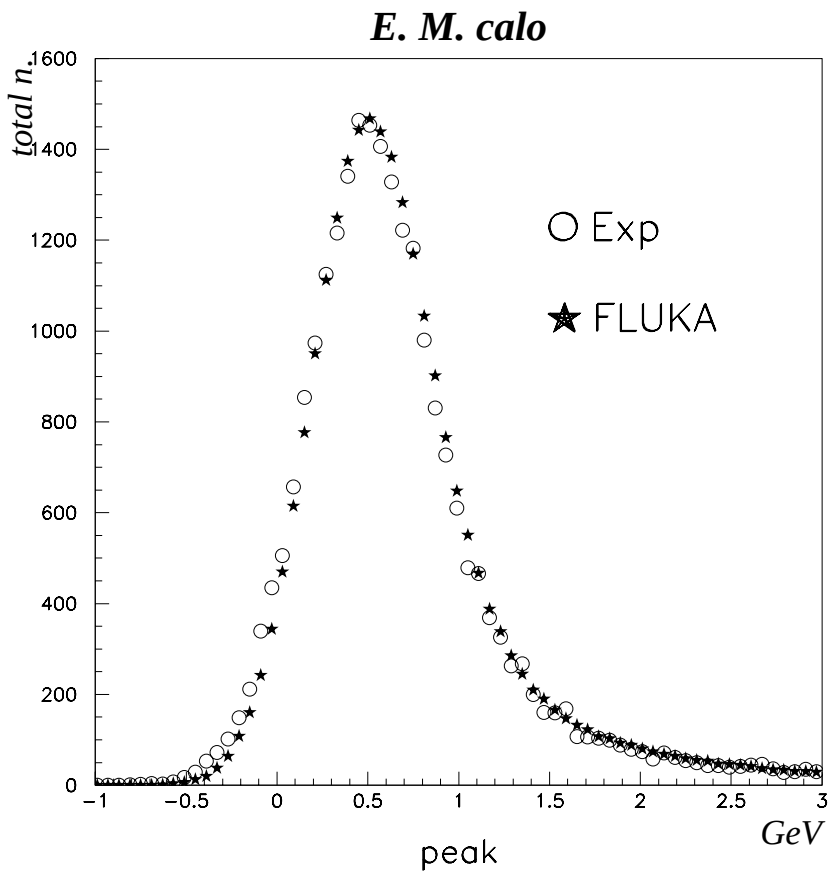
$$Exp: \frac{\sigma}{E} = \frac{9.8 \pm 0.4\%}{\sqrt{E}}$$

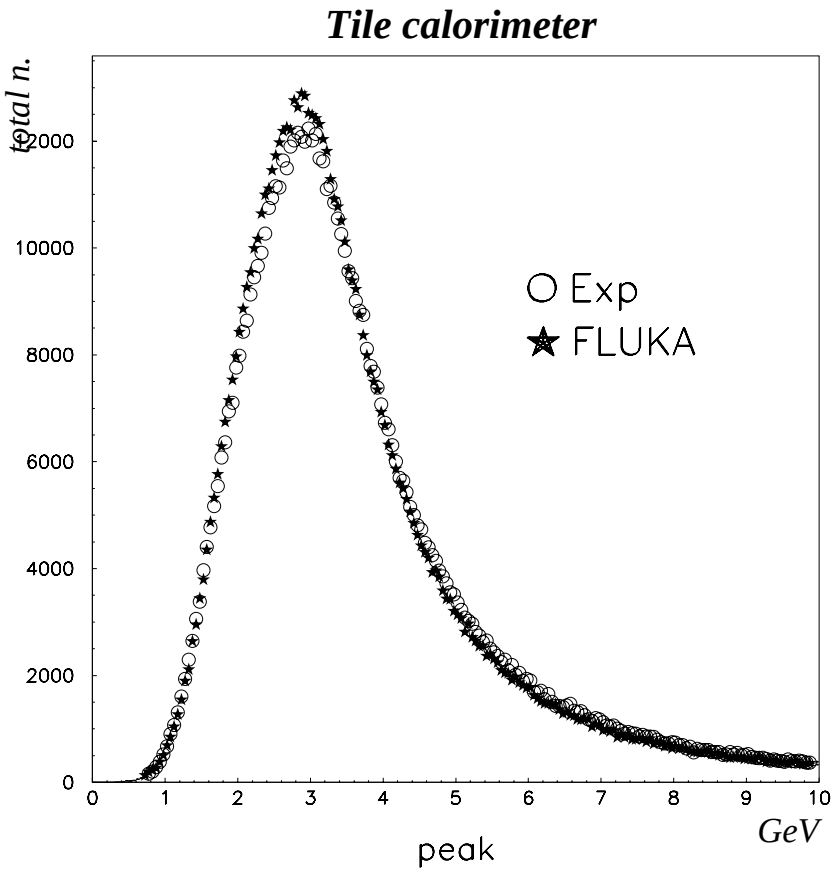
$$Fluka: \frac{\sigma}{E} = \frac{9.2 \pm 0.3\%}{\sqrt{E}}$$

Paola Sala, HSS06

300 GeV μ in ATLAS combined calo

Calibration in electron scale, electronic noise added





Proc. of Calor96

Comparison with PION data

DATA

Cut on mip in presampler

Cut on beam position (beam chambers)

SIMULATIONS

Calibration in electron scale

Scintillator quenching included

Photostatistics convoluted

Noise added

Proton contamination taken into account

Cut on preshower

Energy reconstructed using the ``benchmark'' technique

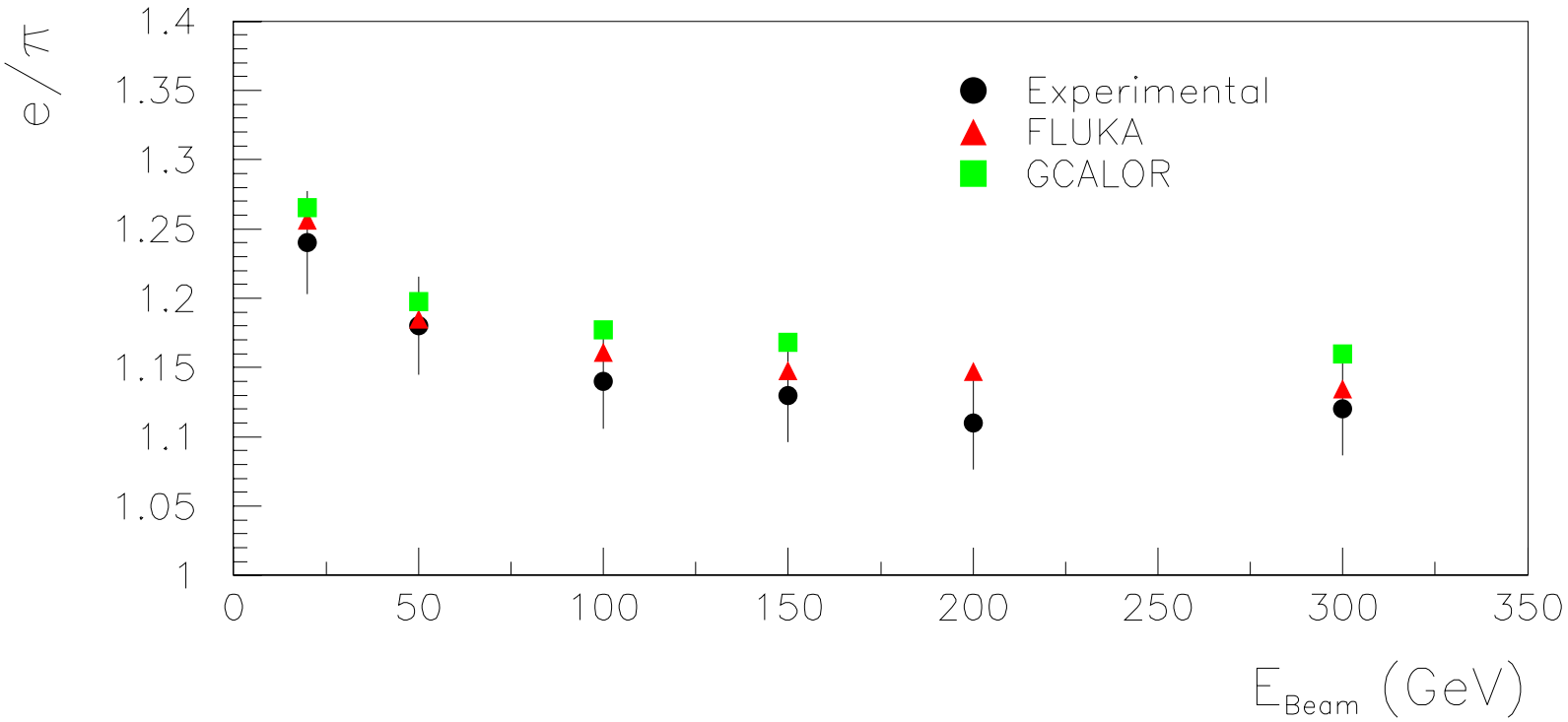
$$E_0 = E_{EM} + a \cdot Q_{had} + b \cdot \sqrt{E_{EM3} \cdot a \cdot Q_{had1}} + c \cdot E_{EM}^2$$

All parameters fixed to minimize σ/E_0 at 300~GeV

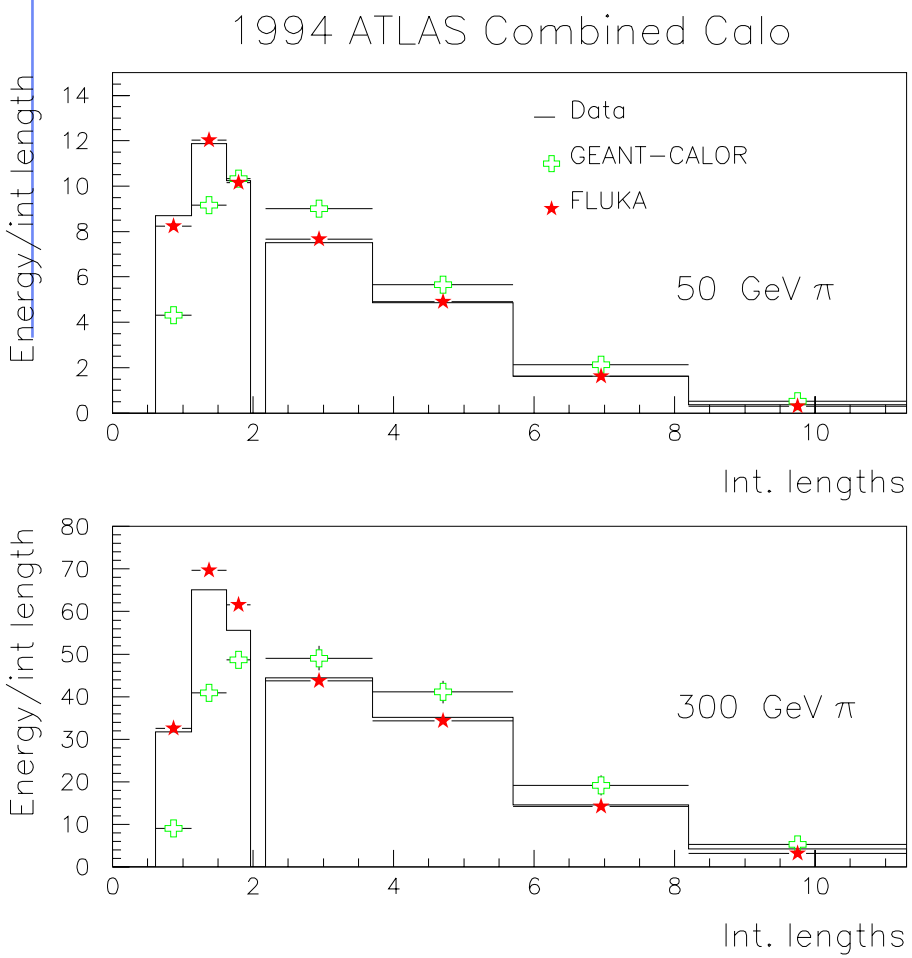
Atlas combined calo test beam: 1994 data

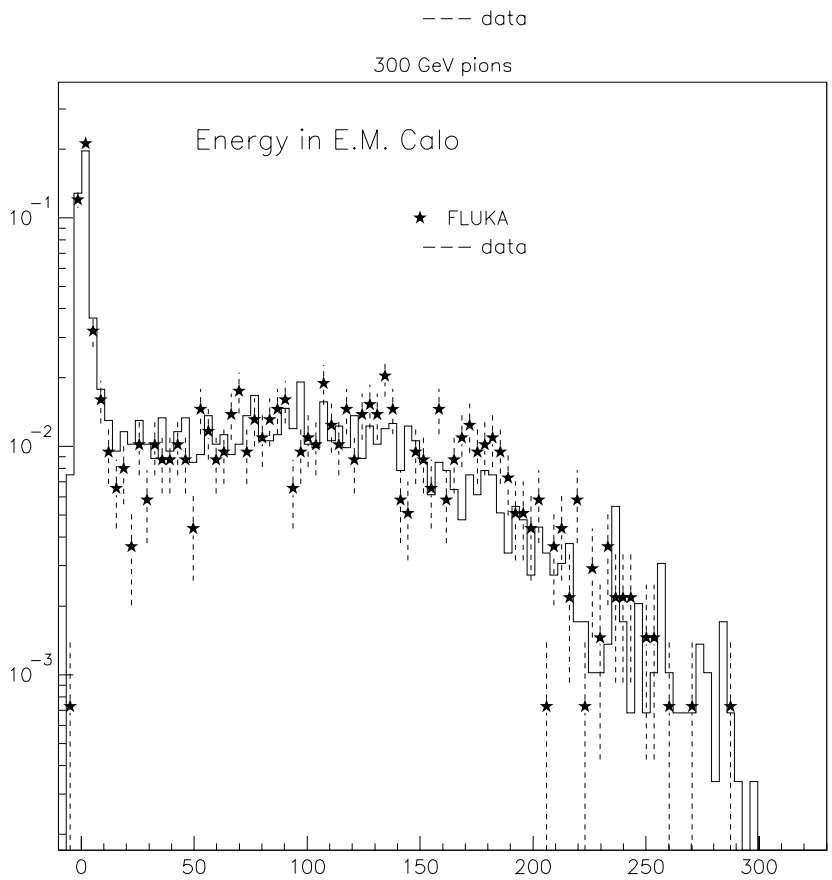
Experimental electron scale calibration available

	a (GeV/pC)	b	c (GeV^{-1})
FLUKA	0.172(2)	0.38(2)	-0.00038(10)
EXP	0.172	0.44	-0.00038



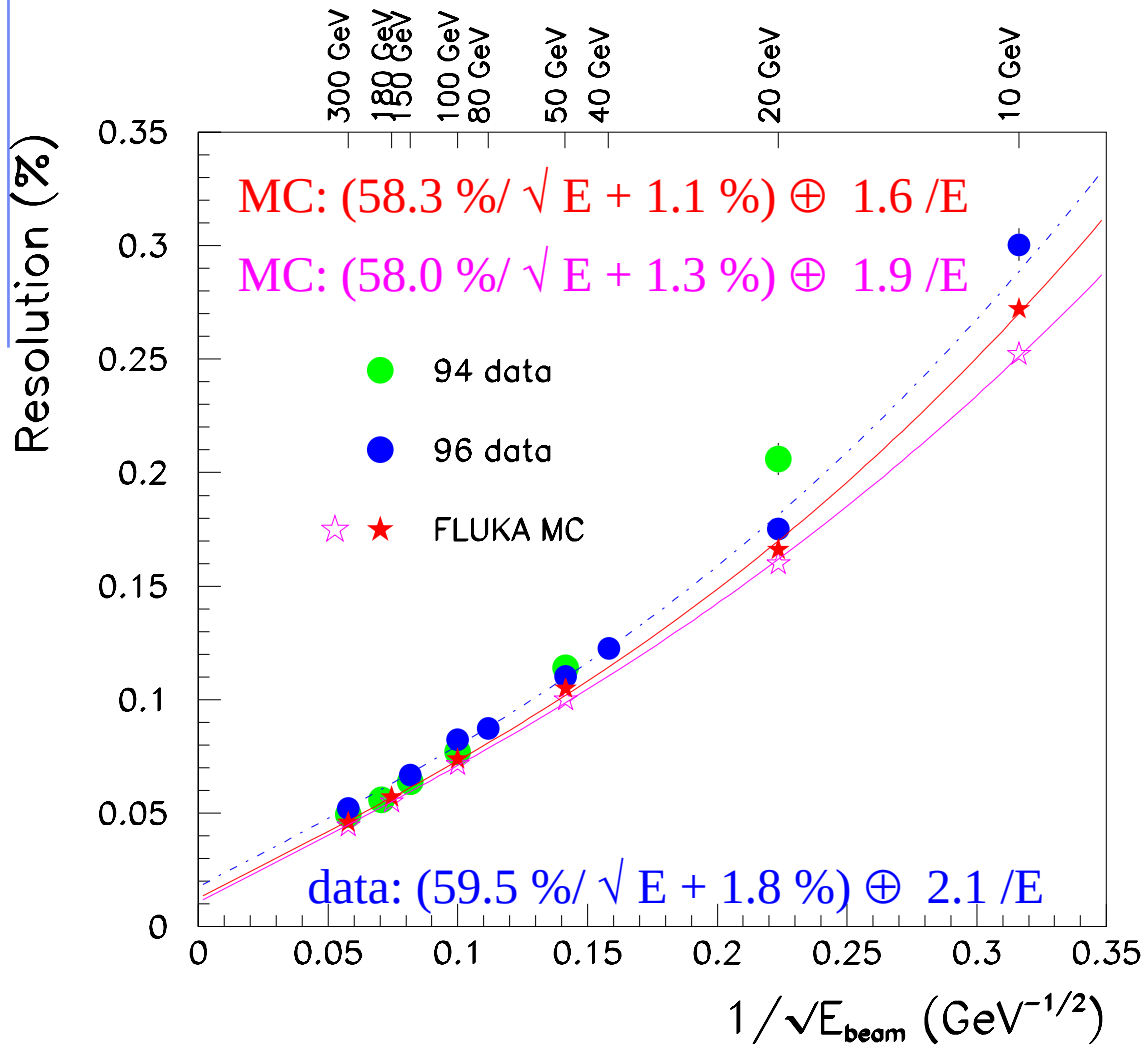
Atlas combined calo test beam: 1994 data





Atlas combined calo test beam: resolution

Energy resolution, 1994+1996 data



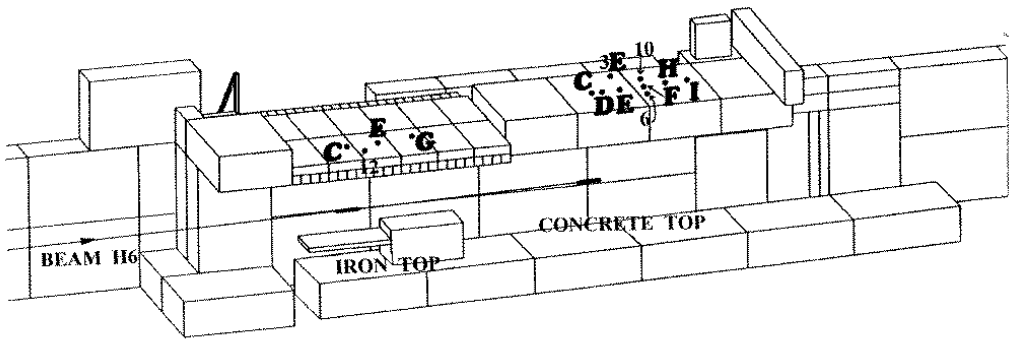
1996 Data
Less electronic noise
Better presampler
No electron calibration

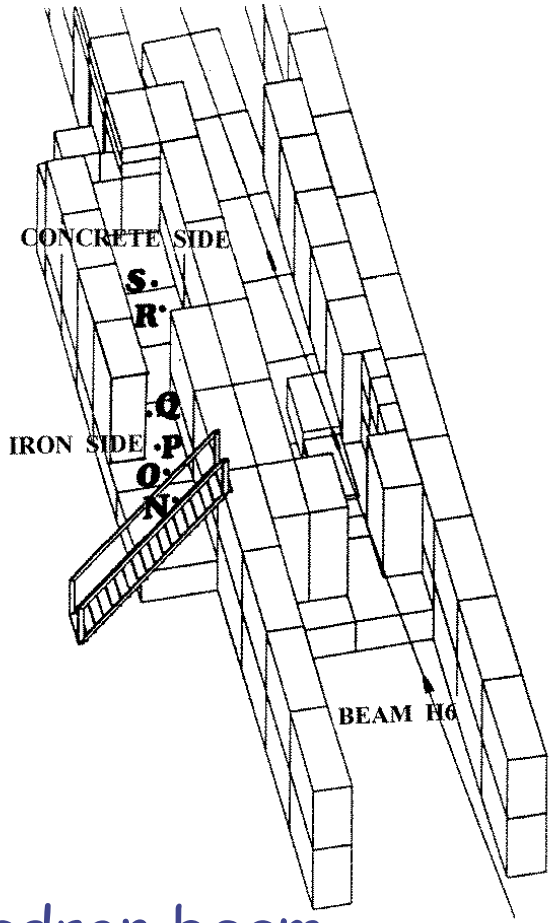
Note the experimental point at 20 GeV

2 simulated curves: different algorithms for preshower reconstruction

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

CERF: neutron measurements





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

120 GeV secondary SPS mixed hadron beam

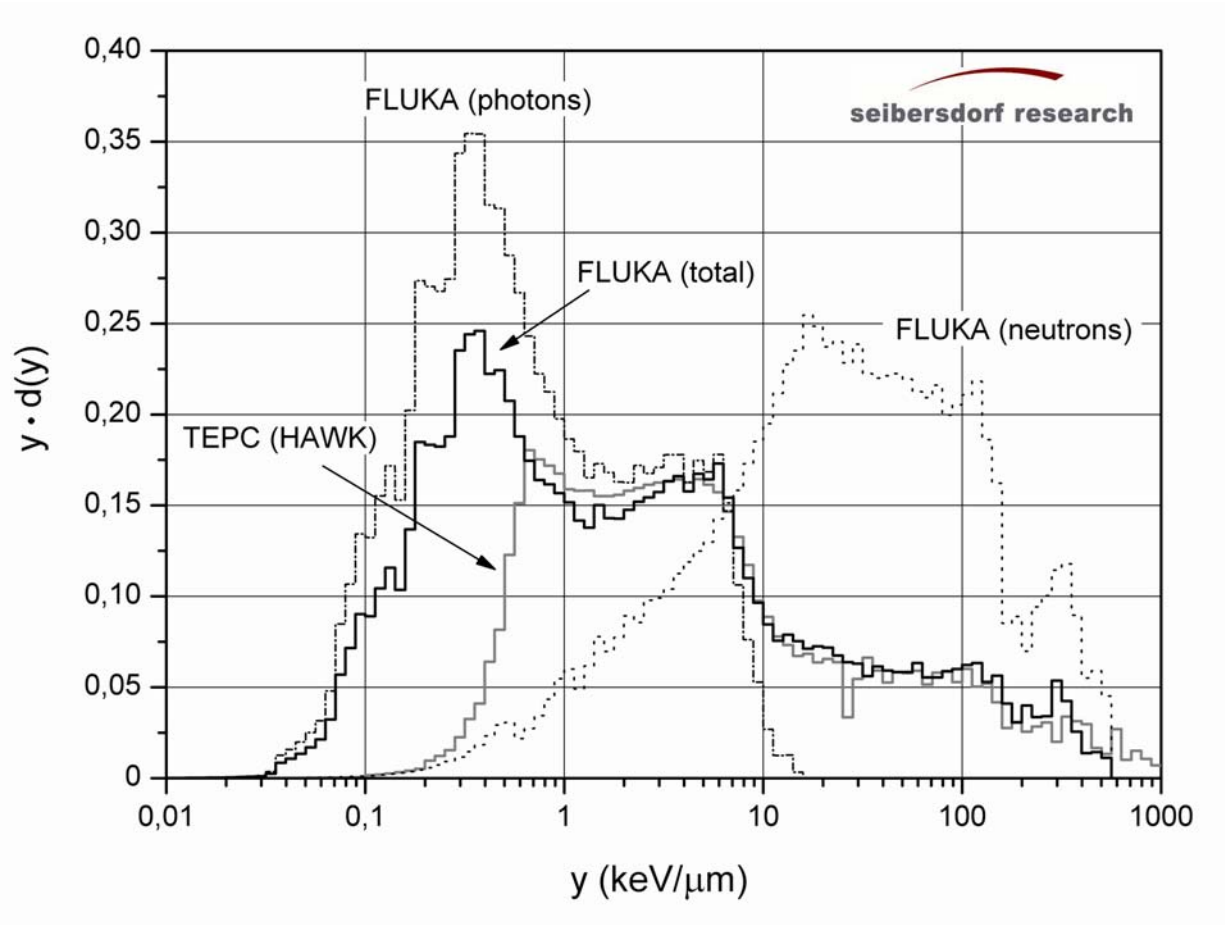
CERF: results

	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

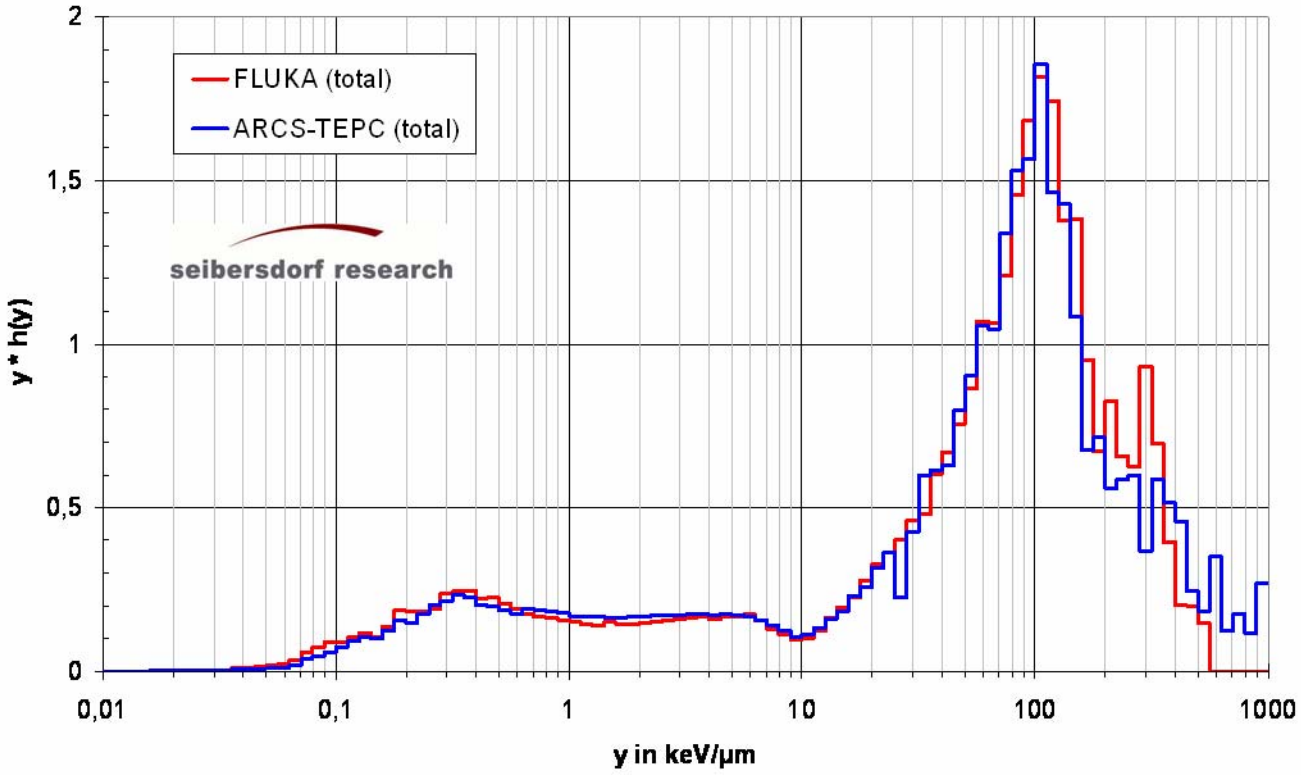
Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN*. The percent statistical (%) uncertainty is indicated

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

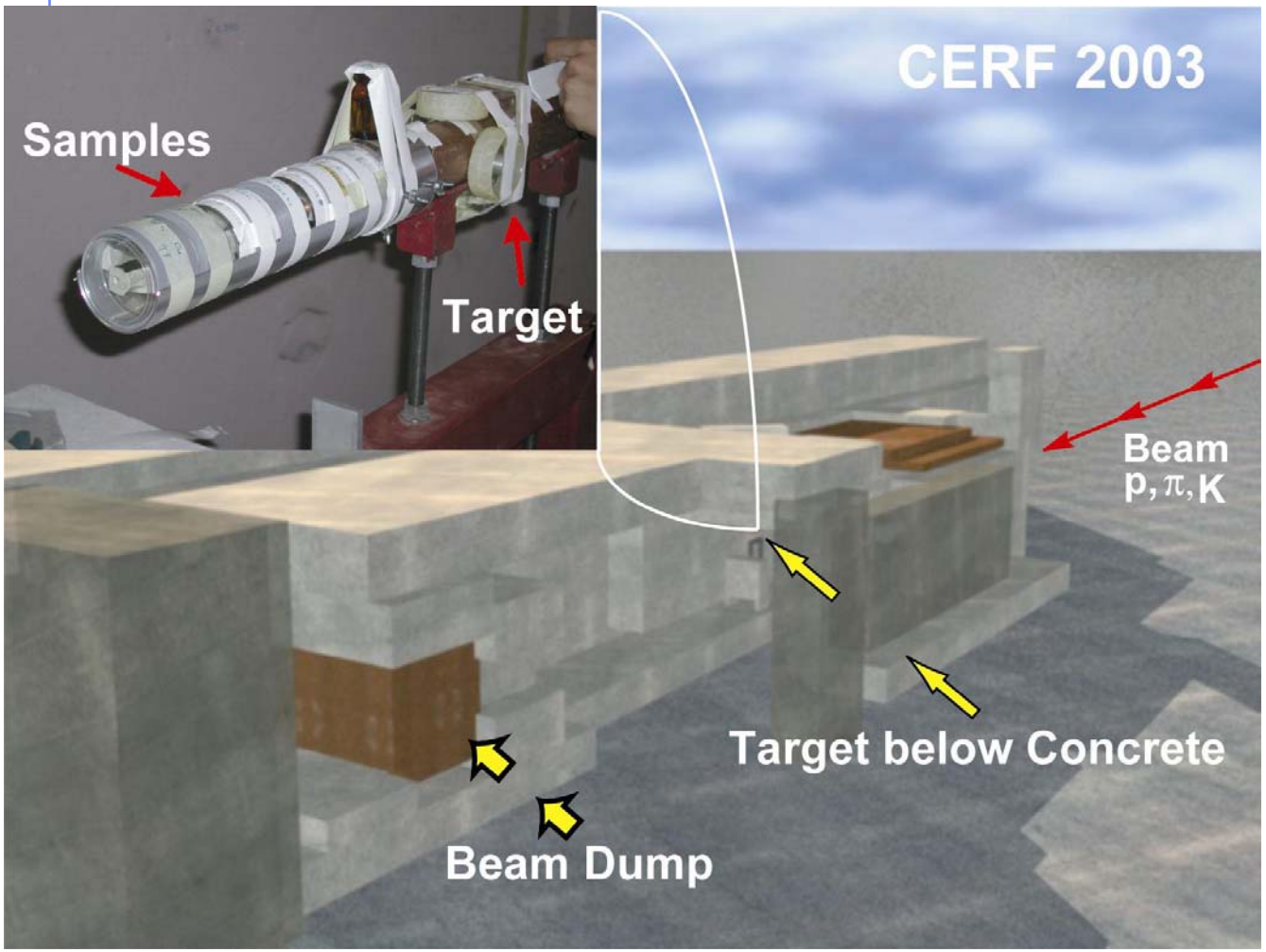
TEPC Absorbed Dose Measurements and FLUKA Simulation CERF facility for mixed Radiation Field



TEPC Dose Equivalent Measurements and FLUKA Simulation CERF facility for mixed Radiation Field



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

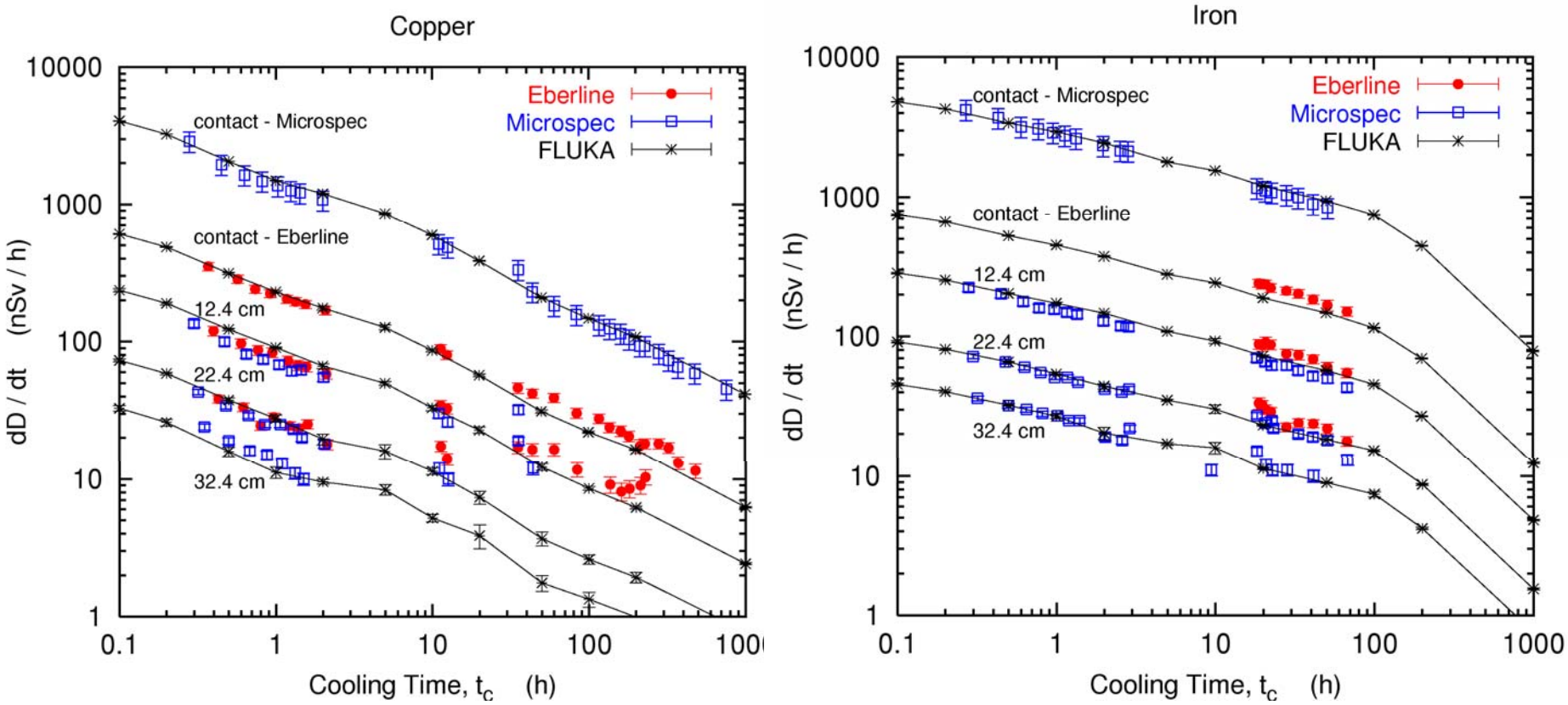
Isotope	$t_{1/2}$	Exp Bq/g	± %	OLD FLUKA/Exp	± %	FLUKA/Exp	± %
Be 7	53.29d	0.205	24	0.096	34	1.070	30
Na 24	14.96h	0.513	4.3	0.278	8.6	0.406	13
K 43	22.30h	1.08	4.6	0.628	8.7	0.814	11
Ca 47	4.54d	0.098	25	0.424	44	(0.295	62)
Sc 44	3.93h	13.8	4.8	0.692	5.8	0.622	6.2
mSc 44	58.60h	6.51	7.1	1.372	8.1	1.233	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

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



Cosmic Rays

FLUKA and Cosmic Ray physics: Atmospheric Showers

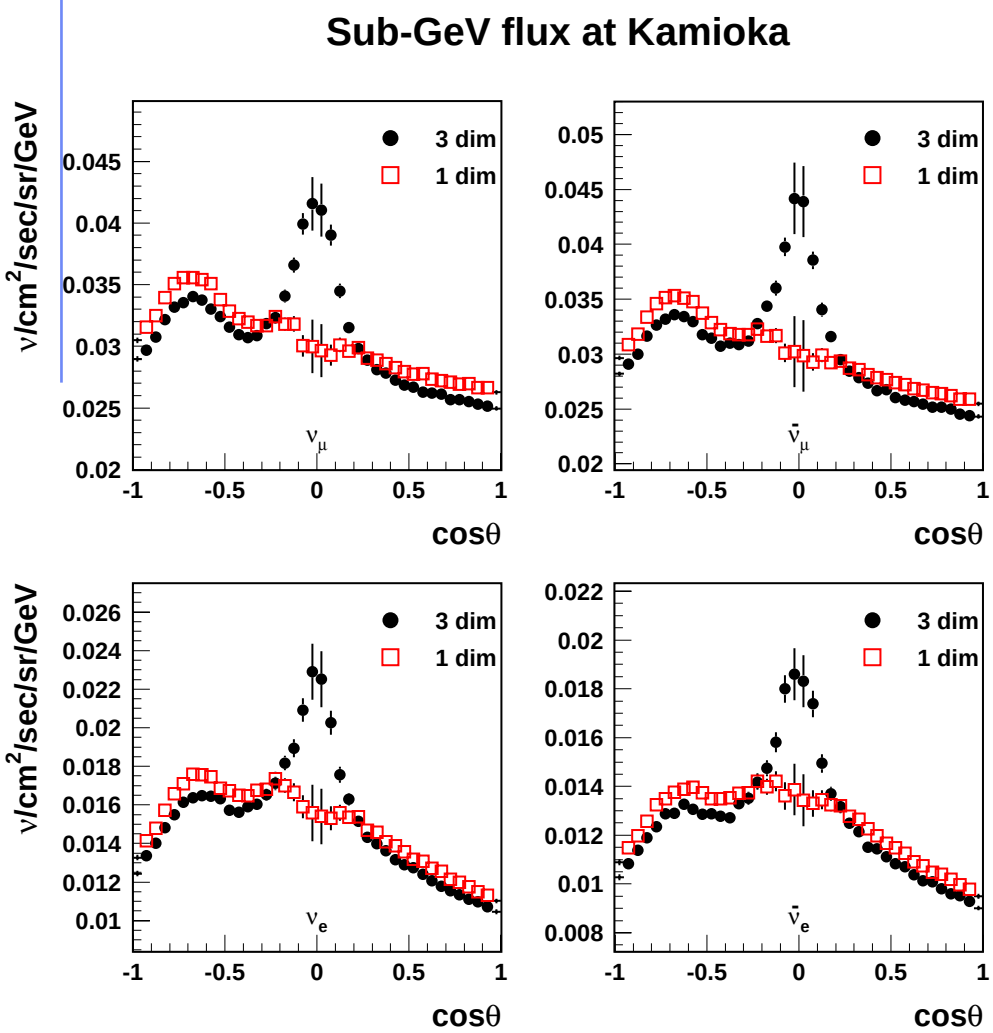
Two different streams:

- 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



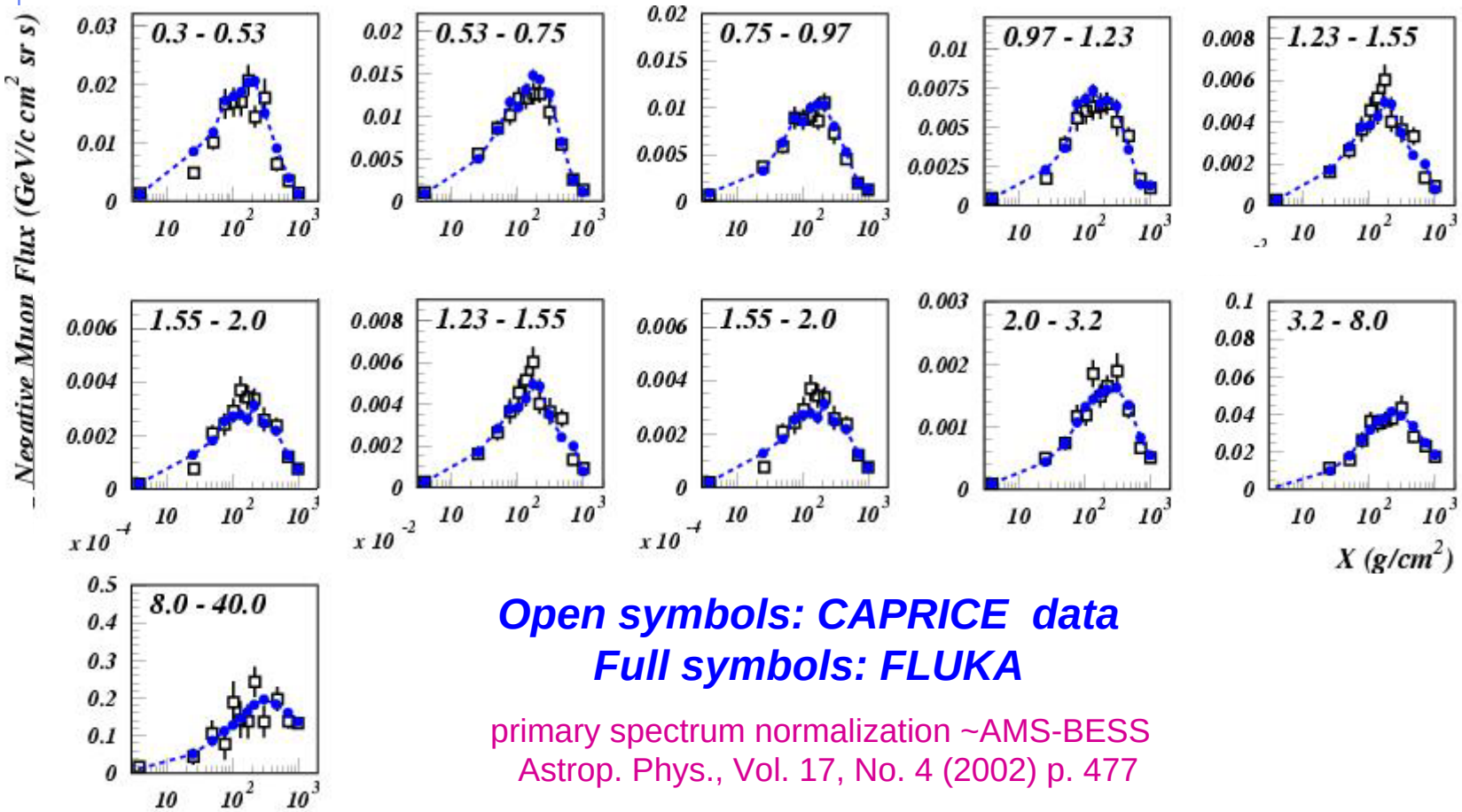
The first 3-D calculation of atmospheric neutrinos was done with FLUKA.

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

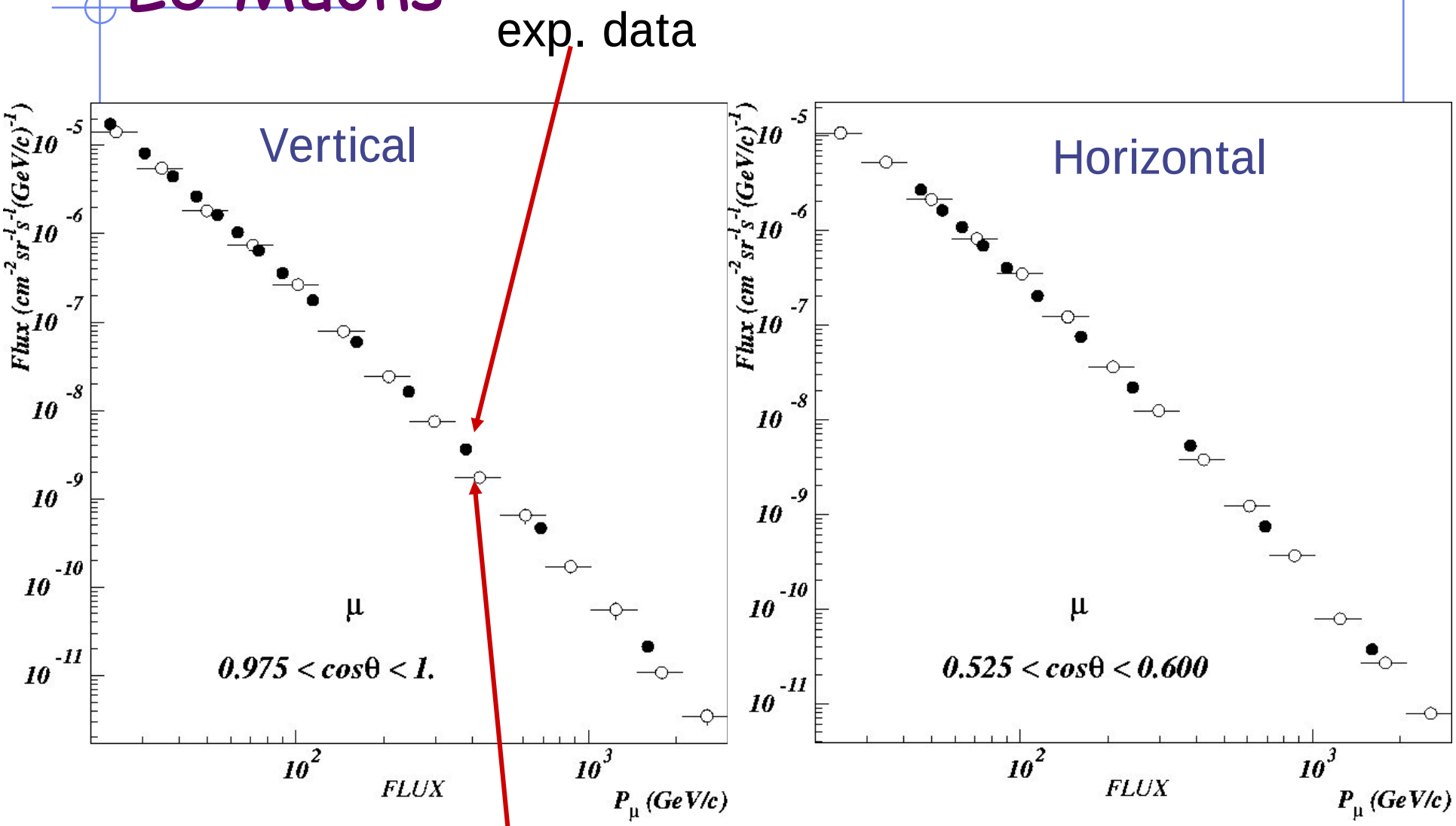


Open symbols: CAPRICE data
Full symbols: FLUKA

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

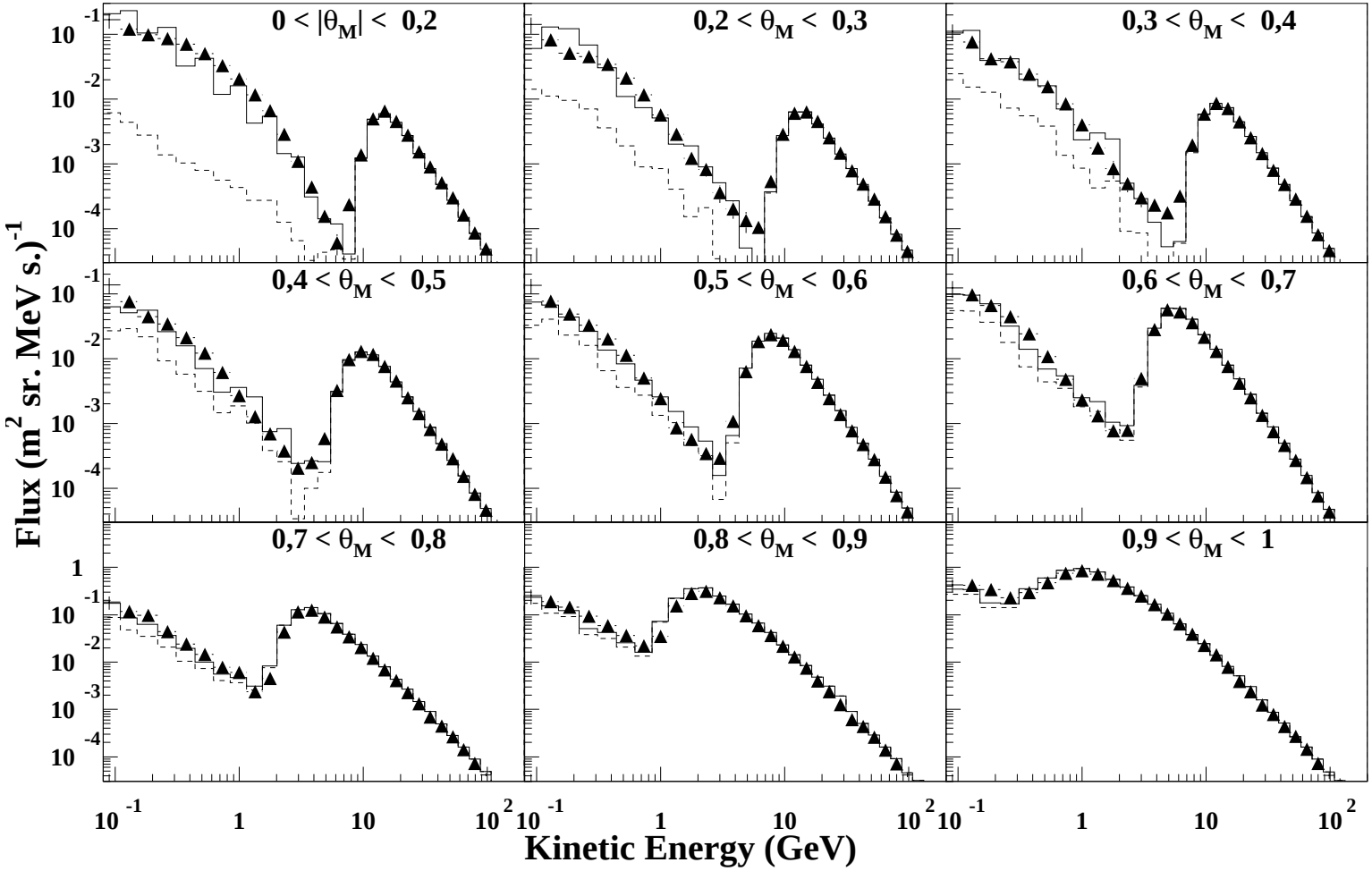
Some recent achievements: L3 Muons

(S.Muraro, PhD thesis Milano)



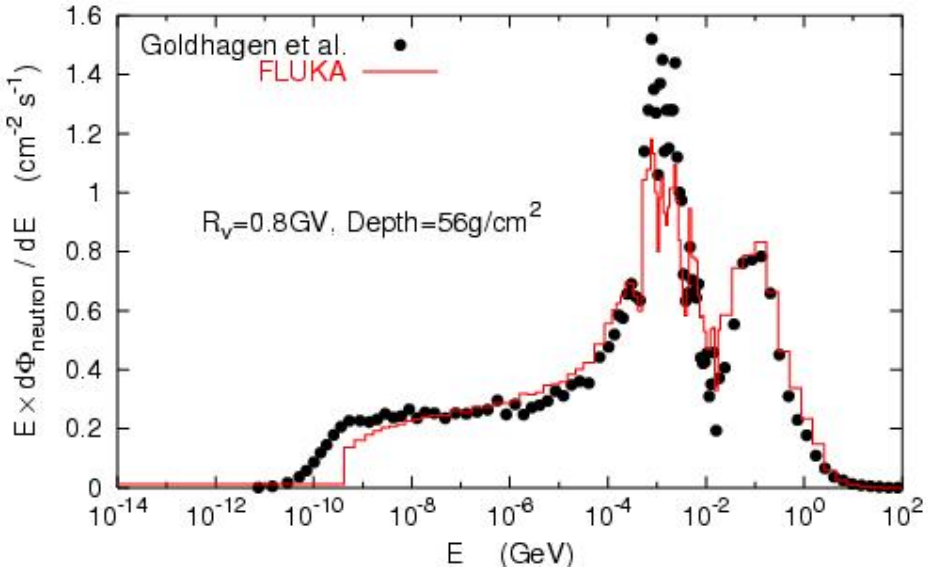
Comparison with AMS data

Protons and leptons below the geomagnetic cutoff have been measured by the AMS experiment at altitudes 370-390 Km, latitude $\pm 51.7^0$ Astrop. Phys. 20,221 (2003)



Downgoing proton flux, simulation(solid line) AMS data(triangles). θ_M is the geomagnetic latitude in radians

Neutrons on the ER-2 plane at 21 km altitude



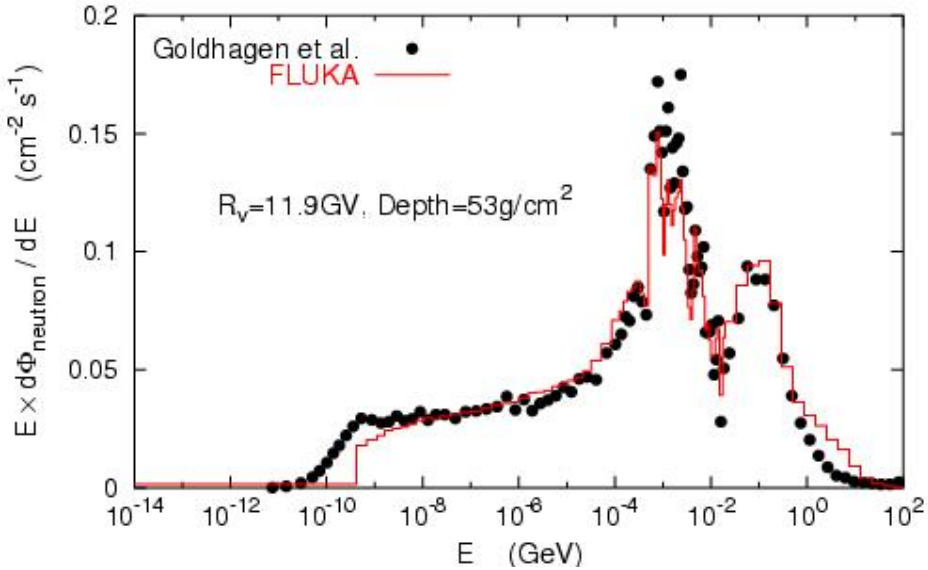
Measurements:

Goldhagen et al., NIM A476, 42 (2002)

Note one order of magnitude difference depending on latitude

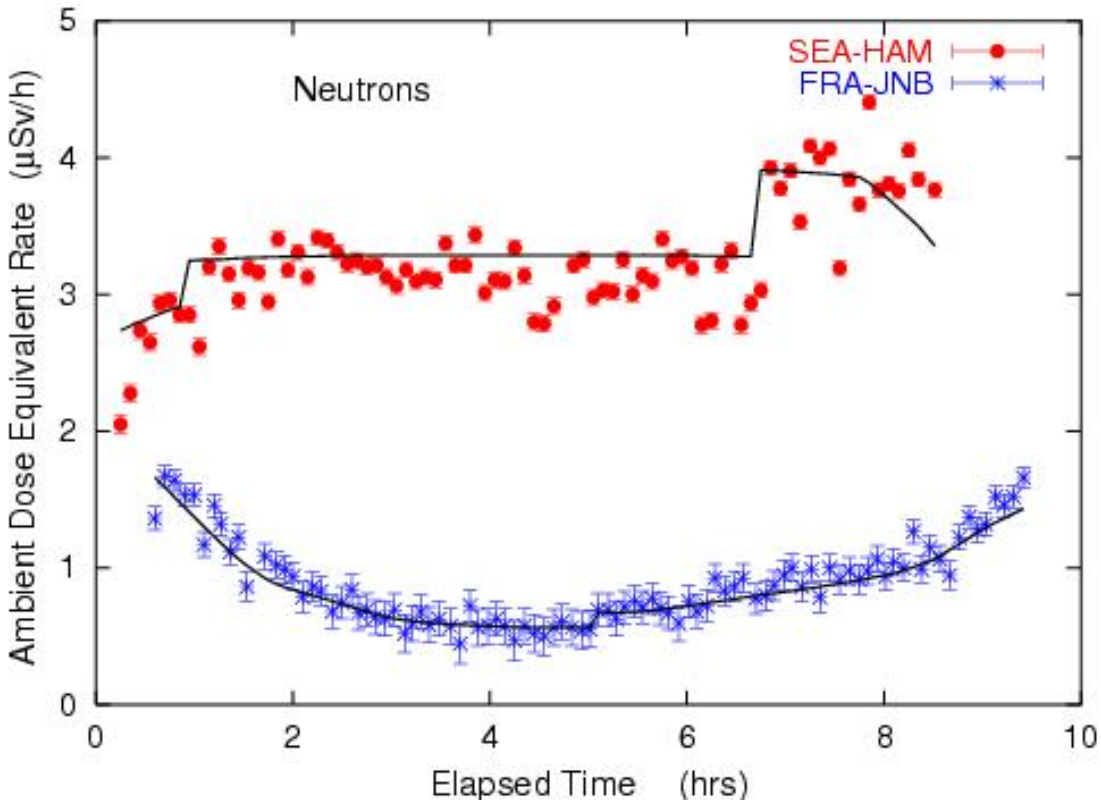
FLUKA calculations:

Roesler et al., Rad. Prot. Dosim. 98, 367 (2002)



Dosimetry Applications

Roesler et al., Rad. Prot. Dosim. 98, 367 (2002)

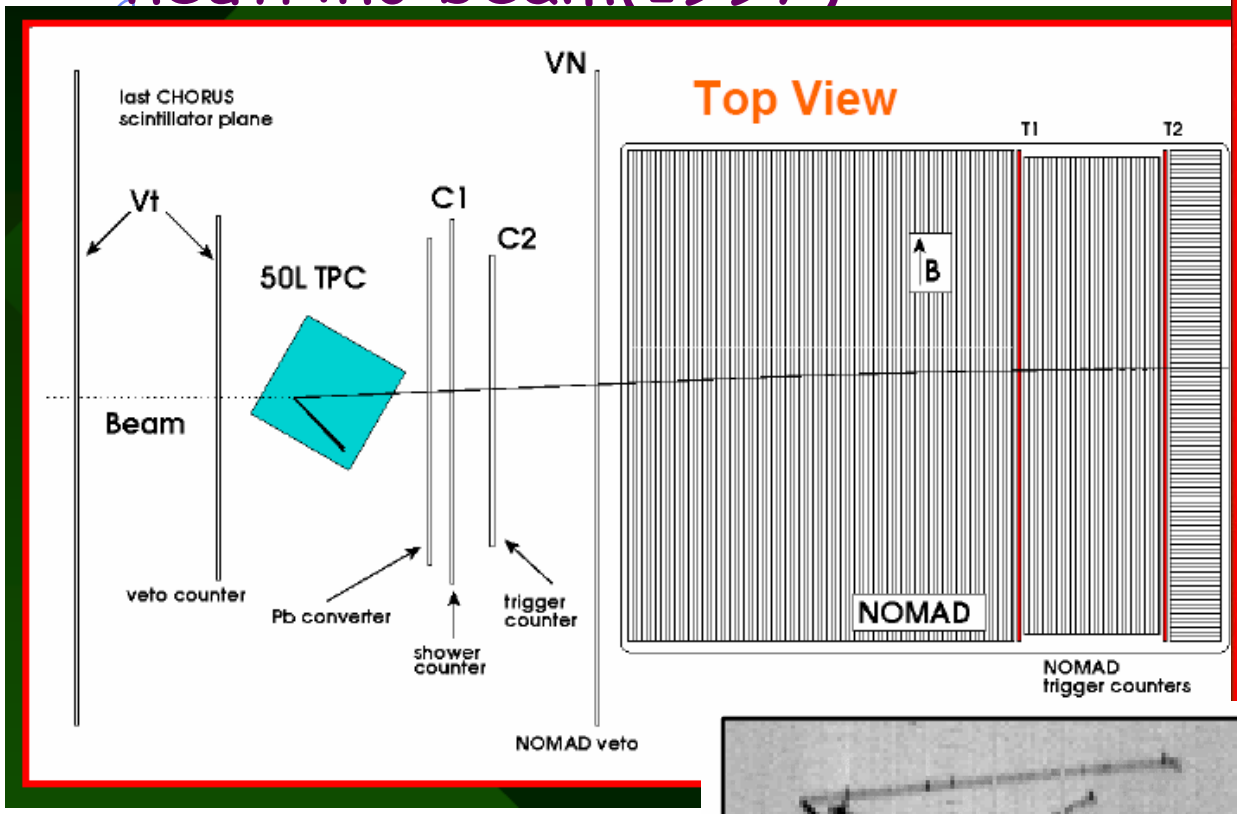


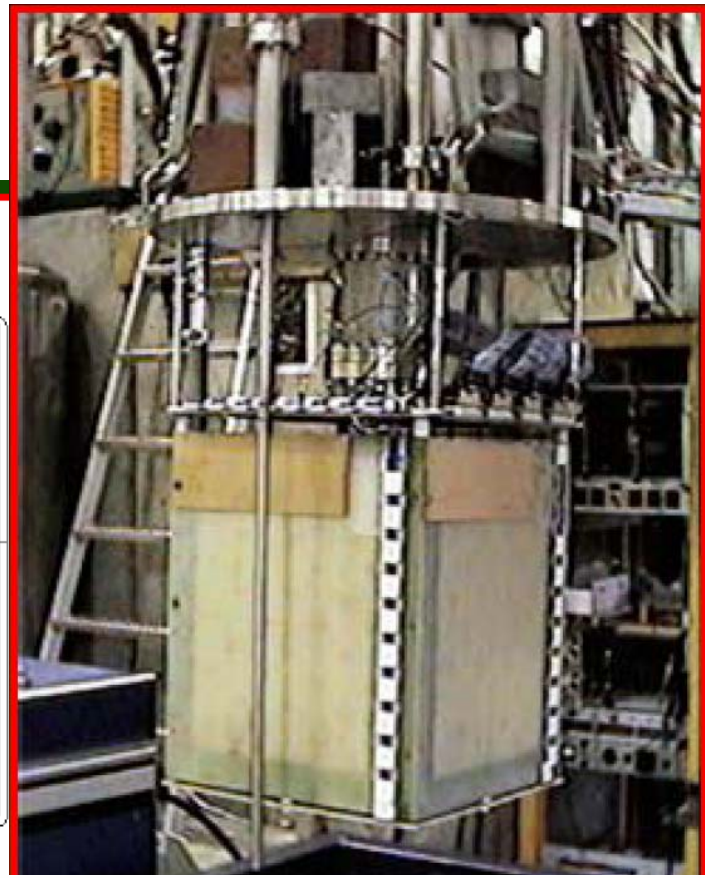
Ambient dose equivalent from neutrons at solar maximum on commercial flights from Seattle to Hamburg and from Frankfurt to Johannesburg.

Solid lines: FLUKA simulation

Neutrino Interactions

The 50l LAr TPC in the WANF neutrino beam(1997)

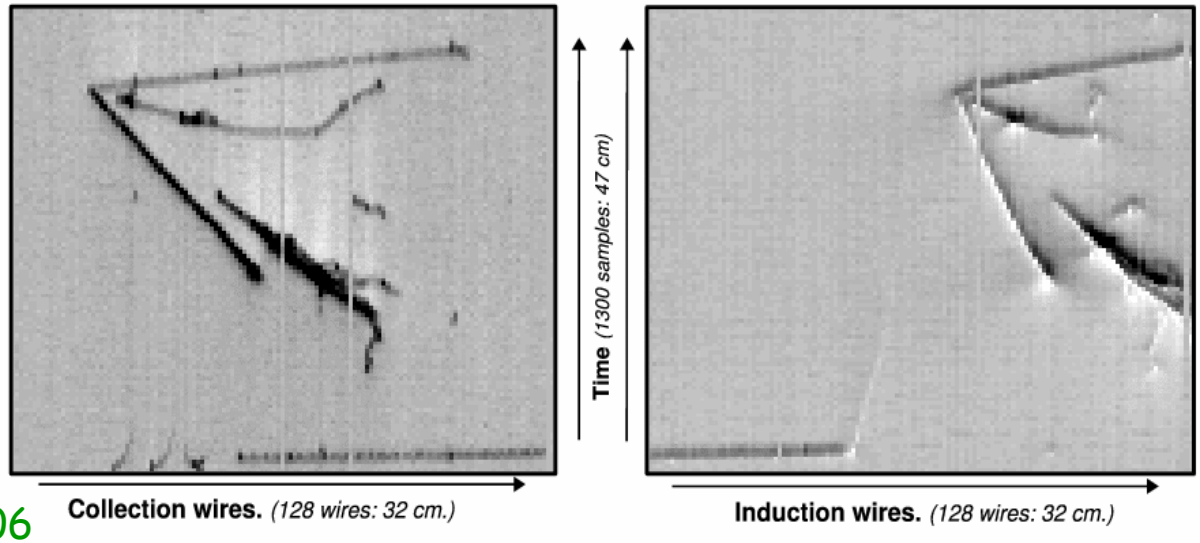


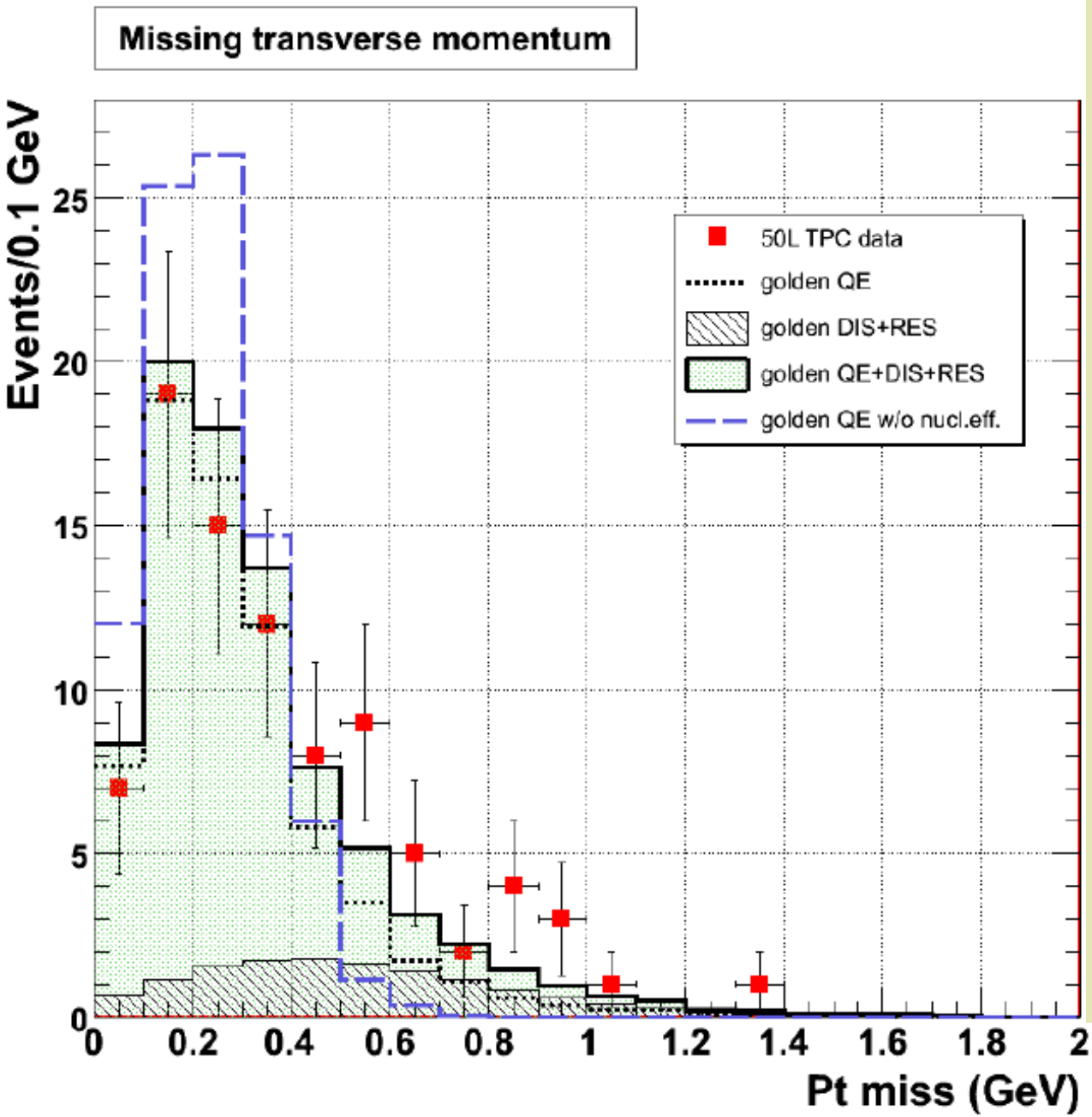


Trigger and μ reconstruction: NOMAD

Event selection:
"GOLDEN sample"
== 1 μ and 1 proton

ICARUS coll. NUFACT06





- from 400 QE – golden fraction 16%
- background – additional 20%

finally expected

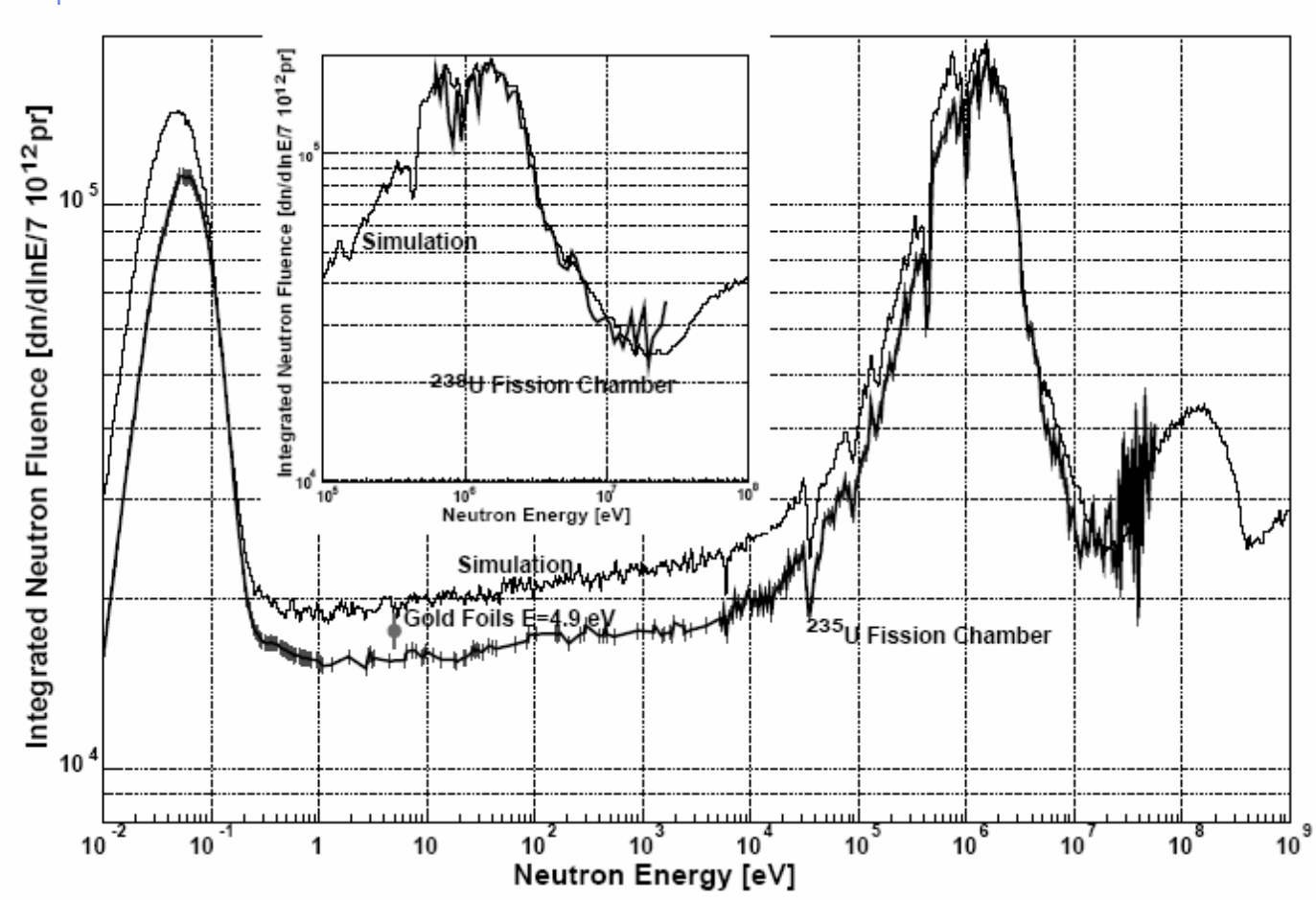
80±9(stat.)±13(syst.
→ mainly QE fraction and beam simul)

to be compared with **86** events observed

Very good consistency with expectations

n-tof

n-TOF

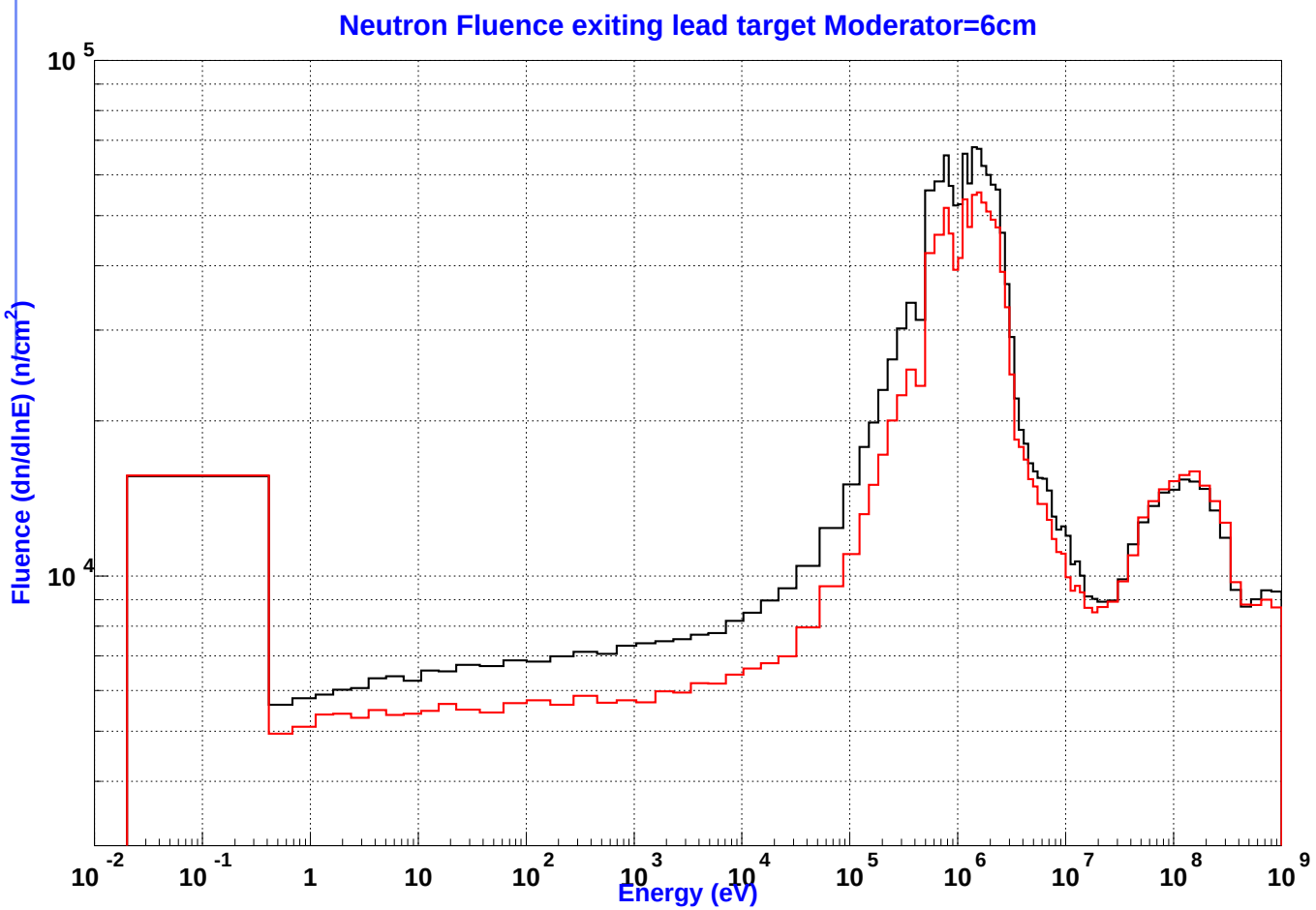


The n-tof facility at CERN: neutron beam with excellent energy resolution for cross section studies

beam from PS : 20 GeV/c protons + Huge Lead target Water moderator neutron beam line

Simulations : FLUKA + C. Rubbia's detailed low energy neutron transport
Assumption : 5 cm water moderator as in the design of the facility
Comparison with measured neutron spectrum shows up to 20% difference in the range 1-10^5 eV (published data)

n-TOF



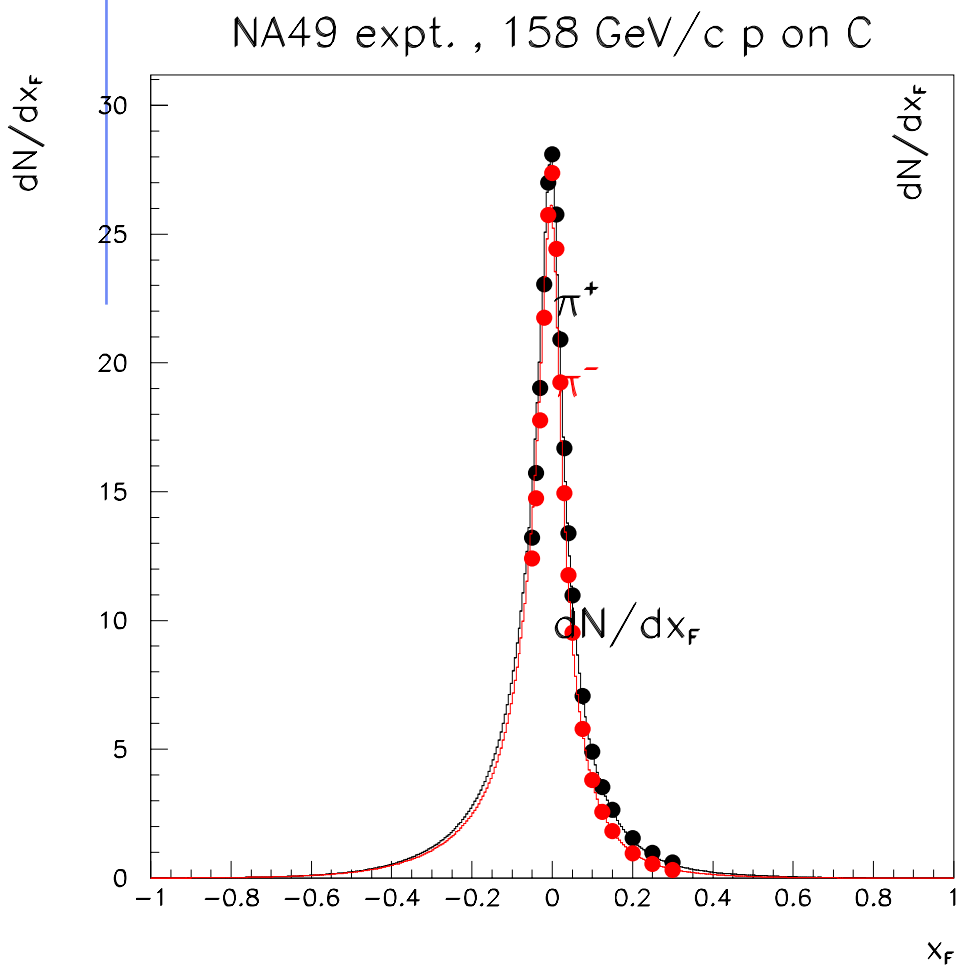
Preparing for Lead target dismount- Discovery that the water layer is 6 cm thick instead of 5

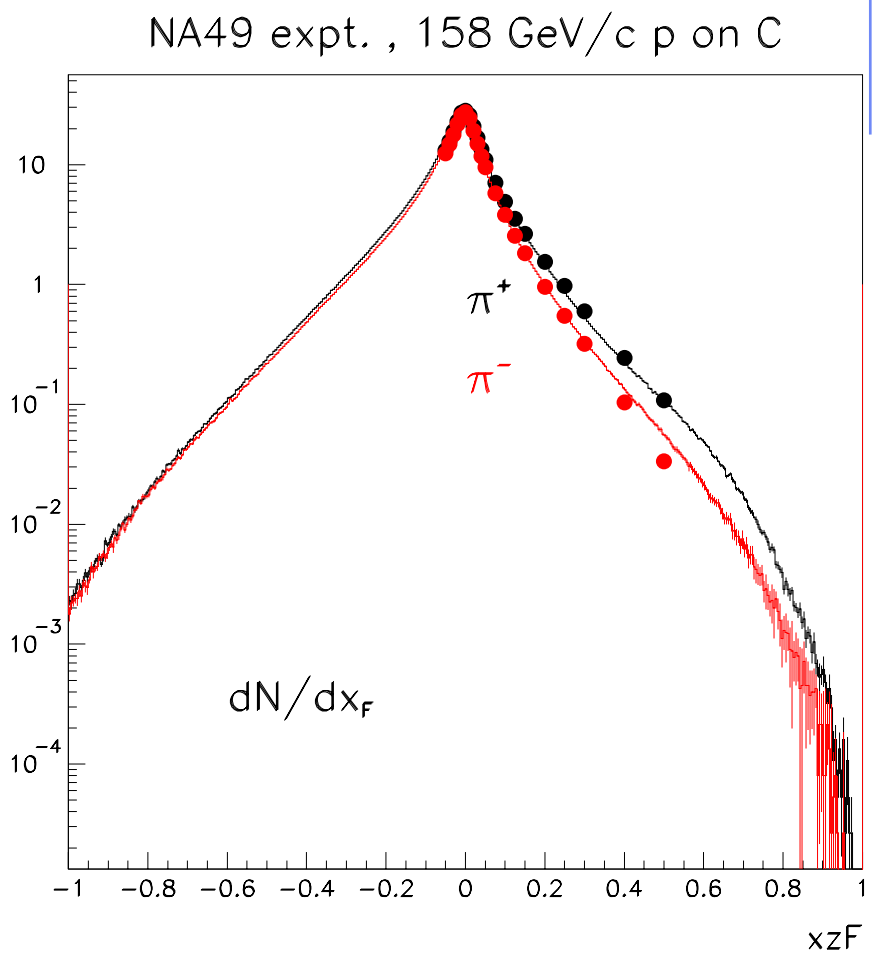
FLUKA simulations with 6 cm water (black) compared with 5 cm (red)

PRELIMINARY, thanks to V. Vlachoudis-CERN

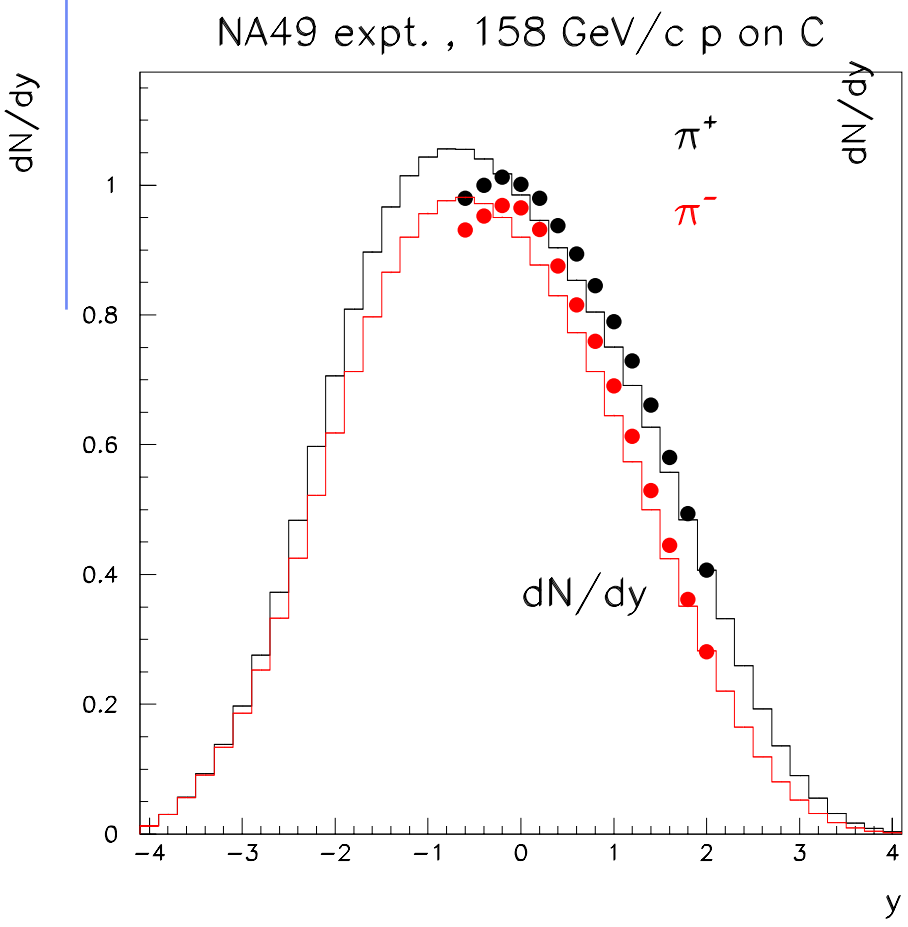
END

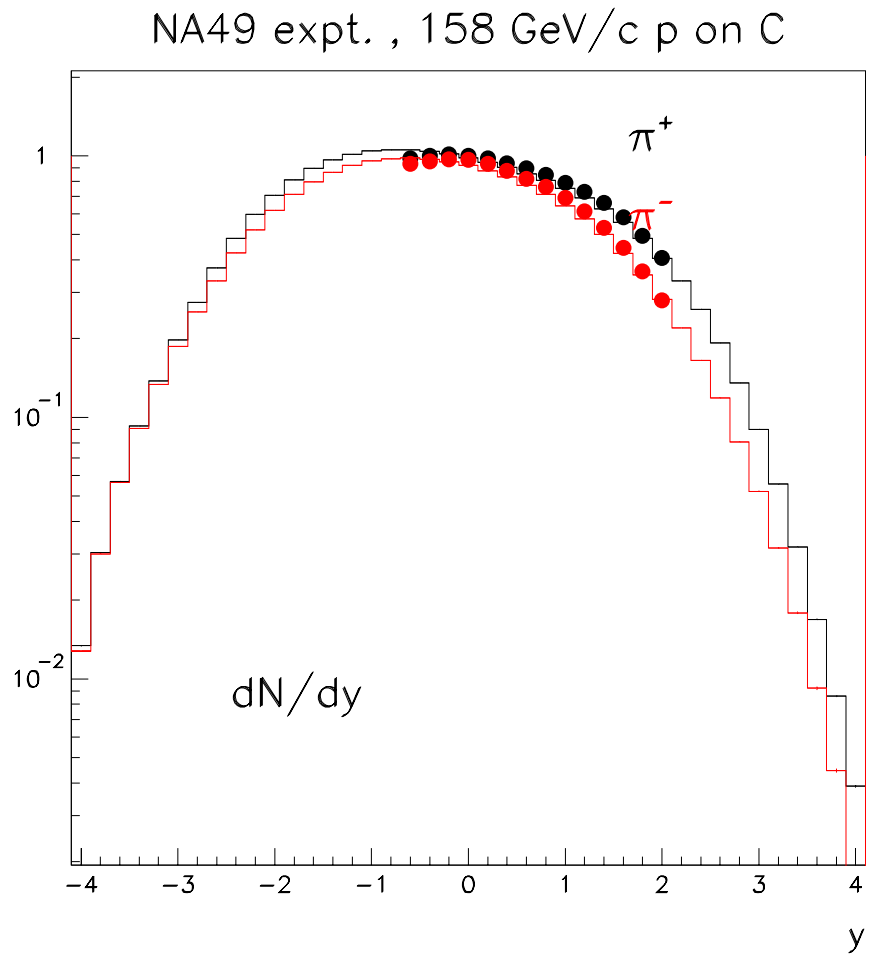
NA49 p on C


NA49 expt. , 158 GeV/c p on C
dN/dx_F
dN/dx_F
π+
π−
dN/dx_F
x_F


NA49 expt. , 158 GeV/c p on C
π+
π−
dN/dx_F
xzF

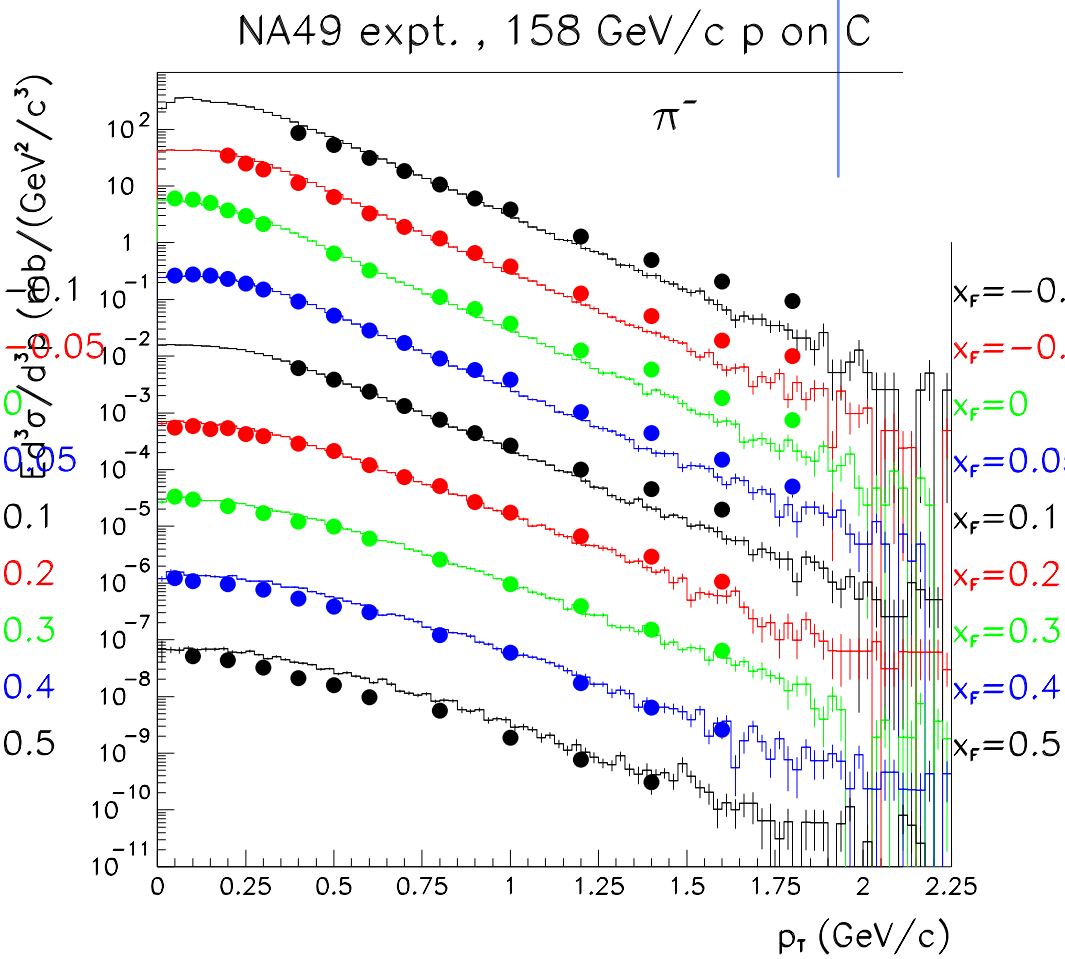
NA49 p on C


NA49 expt. , 158 GeV/c p on C
dN/dy
dN/dy
π+
π-
dN/dy
y

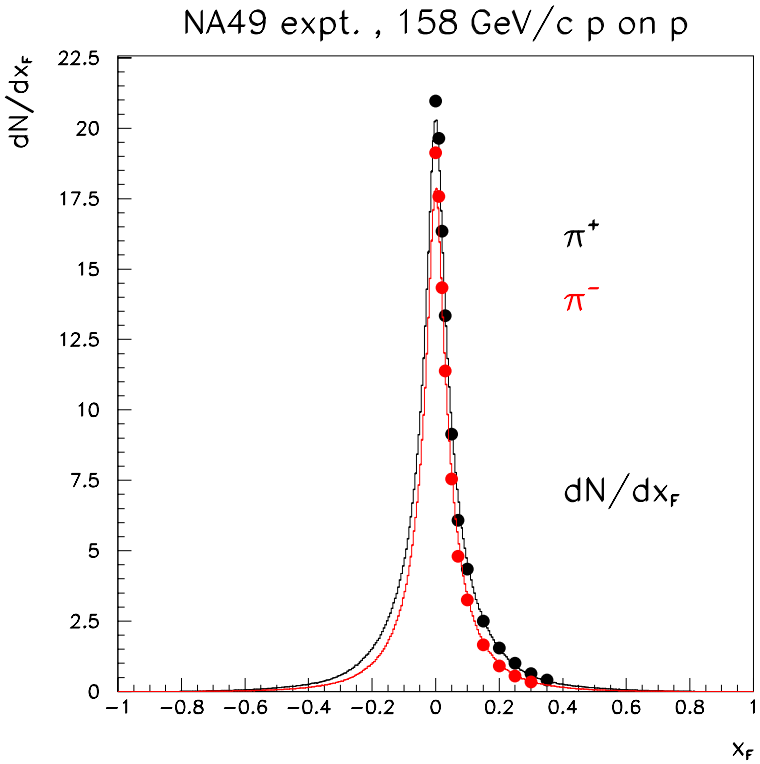

NA49 expt. , 158 GeV/c p on C
π+
π-
dN/dy
y

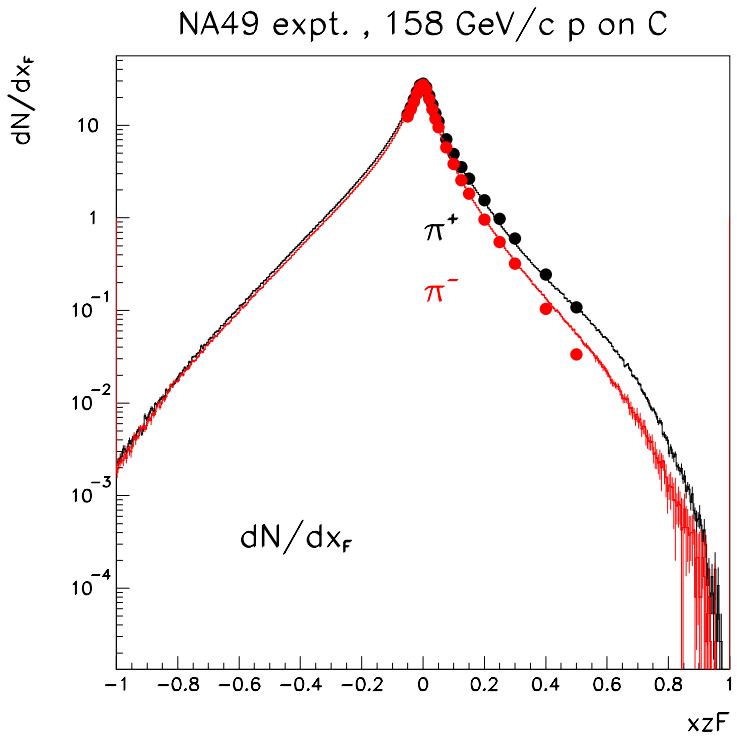
NA49 p on C


NA49 expt. , 158 GeV/c p on C
π^+
$Ed^3\sigma/d^3p$ (mb/(GeV^2/c^3))
p_T (GeV/c)
x_F=−0.1
x_F=−0.05
x_F=0
x_F=0.05
x_F=0.1
x_F=0.2
x_F=0.3
x_F=0.4
x_F=0.5

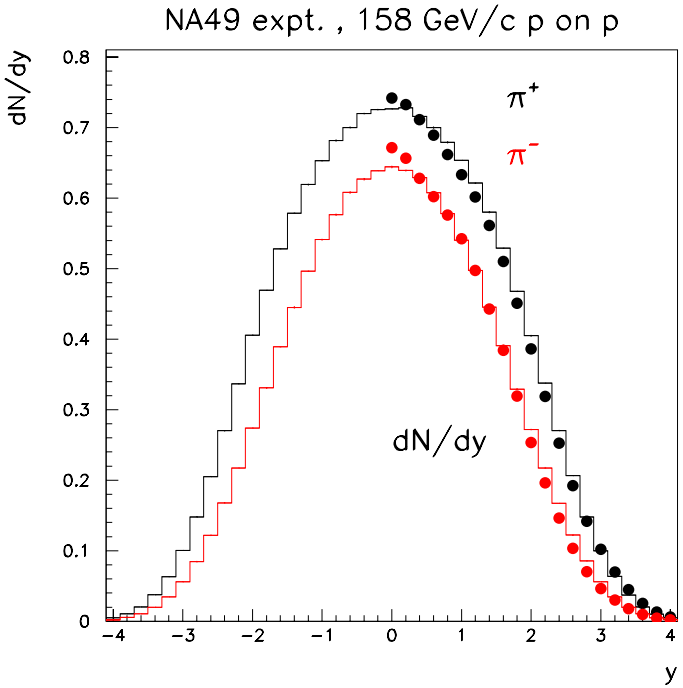

NA49 expt. , 158 GeV/c p on C
π^-
$Ed^3\sigma/d^3p$ (mb/(GeV^2/c^3))
p_T (GeV/c)
x_F=0
x_F=0.1
x_F=0.2
x_F=0.3
x_F=0.4
x_F=0.5

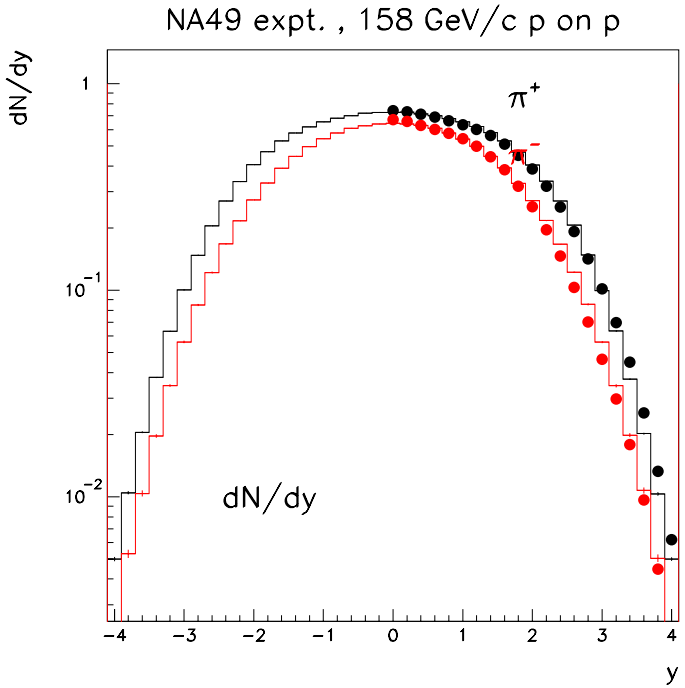
NA49 p on p


NA49 expt. , 158 GeV/c p on p
dN/dx_F
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
x_F
π+
π−
dN/dx_F


NA49 expt. , 158 GeV/c p on C
dN/dx_F
10
1
10^−1
10^−2
10^−3
10^−4
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
xzF
π+
π−
dN/dx_F

NA49 p on p


NA49 expt. , 158 GeV/c p on p
dN/dy
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−4
−3
−2
−1
0
1
2
3
4
y
π+
π−
dN/dy


NA49 expt. , 158 GeV/c p on p
dN/dy
1
10−1
10−2
−4
−3
−2
−1
0
1
2
3
4
y
π+
π−
dN/dy