An Introduction to Fluka:
a Multipurpose Particle Interaction and Transport MC code

23rd FLUKA Beginner's Course
Lanzhou University
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FLUKA

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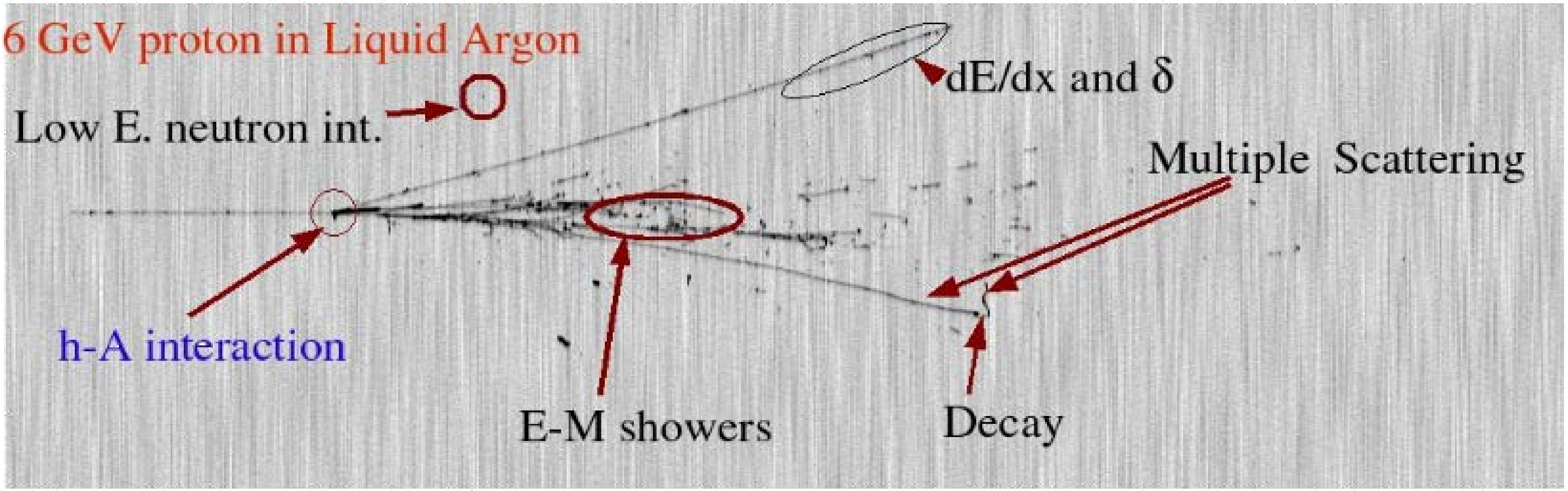

Developed and maintained by the FLUKA Collaboration

>10000 registered users

http://www.fluka.org

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FLUKA short description:

- FLUKA[1,2] is a general purpose tool for calculations of particle transport and interactions with matter
- All Hadrons (p, n, π, K,pbar, nbar, (anti)hyperons…) [0-100 EeV, 10^{20} eV]
- Electromagnetic (γ, $e^{+/-}$) and μ and ν [100 eV/1 keV – 100 EeV]
- Nucleus-nucleus [0-100 EeV/n]
- Low energy neutrons (0-20 MeV, multigroup, pointwise, ENDF…)
- Transport in electric and magnetic field
- Combinatorial (boolean) and Voxel geometries
- Double capability to run either fully analogue and/or biased calculations
- On-line evolution of induced radioactivity and dose
- Radiation damage predictions (NIEL, DPA)
- User-friendly GUI interface thanks to the Flair[3] interface

[1] F. Ballarini et al, "FLUKA: status and perspectives"
NEA (2024), SATIF 15 - Sessions 2 & 3: Code Status, Advances, & Model Converters, OECD Publishing, Paris , page 89

[2] A. Ferrari et al., "FLUKA: a multi-particle transport code",
CERN 2005-10 (2005), INFN/TC_05/11, SLAC-R-773

http://www.fluka.org

[3] V. Vlachoudis, Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, 2009

Particles transported by FLUKA:

FLUKA name	FLUKA number	Symbol	Common name	Standard PDG number (Particle Data Group) [142]
4-HELIUM (1)	-6	α	Alpha	—
3-HELIUM (1)	-5	^{3}He	Helium 3	—
TRITON (1)	-4	^{3}H	Triton	—
DEUTERON (1)	-3	^{2}H	Deuteron	—
HEAVYION (1)	-2	—	Generic Heavy Ion with $Z > 2$ (see command HI–PROPE)	—
OPTIPHOT	-1	—	Optical Photon	—
RAY (2)	0	—	Pseudoparticle	—
PROTON	1	p	Proton	2212
APROTON	2	$\bar{\mathrm{p}}$	Antiproton	-2212
ELECTRON	3	e^-	Electron	11
POSITRON	4	e^+	Positron	-11
NEUTRIE	5	ν_e	Electron Neutrino	12
ANEUTRIE	6	$\bar{\nu}_e$	Electron Antineutrino	-12
PHOTON	7	γ	Photon	22
NEUTRON	8	n	Neutron	2112
ANEUTRON	9	$\bar{\mathrm{n}}$	Antineutron	-2112
MUON+	10	μ^+	Positive Muon	-13
MUON-	11	μ^-	Negative Muon	13
KAONLONG	12	K^0_L	Kaon-zero long	130
PION+	13	π^+	Positive Pion	211
PION-	14	π^-	Negative Pion	-211
KAON+	15	K^+	Positive Kaon	321
KAON-	16	K^-	Negative Kaon	-321
LAMBDA	17	Λ	Lambda	3122
ALAMBDA	18	$\bar{\Lambda}$	Antilambda	-3122
KAONSHRT	19	K^0_S	Kaon-zero short	310
SIGMA-	20	Σ^-	Negative Sigma	3112
SIGMA+	21	Σ^+	Positive Sigma	3222
SIGMAZER	22	Σ^0	Sigma-zero	3212
PIZERO	23	π^0	Pion-zero	111
KAONZERO	24	K^0	Kaon-zero	311
AKAONZER	25	$\bar{\mathrm{K}}^0$	Antikaon-zero	-311
Reserved	26	—	—	—
NEUTRIM	27	ν_μ	Muon Neutrino	14
ANEUTRIM	28	$\bar{\nu}_\mu$	Muon Antineutrino	-14
Blank	29	—	—	—

table continues

FLUKA name	FLUKA number	Symbol	Common name	Standard PDG (Particle Data
Reserved	30	—	—	—
ASIGMA-	31	$\bar{\Sigma}^-$	Antisigma-minus	-3222
ASIGMAZE	32	$\bar{\Sigma}^0$	Antisigma-zero	-3212
ASIGMA+	33	$\bar{\Sigma}^+$	Antisigma-plus	-3112
XSIZERO	34	Ξ^0	Xi-zero	3322
AXSIZERO	35	$\bar{\Xi}^0$	Antixi-zero	-3322
XSI-	36	Ξ^-	Negative Xi	3312
AXSI+	37	$\bar{\Xi}^+$	Positive Xi	-3312
OMEGA-	38	Ω^-	Omega-minus	3334
AOMEGA+	39	$\bar{\Omega}^+$	Antiomega	-3334
Reserved	40	—	—	
TAU+	41	τ^+	Positive Tau	-15
TAU-	42	τ^-	Negative Tau	15
NEUTRIT	43	ν_τ	Tau Neutrino	16
ANEUTRIT	44	$\bar{\nu}_\tau$	Tau Antineutrino	-16
D+	45	D^+	D-plus	411
D-	46	D^-	D-minus	-411
D0	47	D^0	D-zero	421
D0BAR	48	$\bar{\mathrm{D}}^0$	AntiD-zero	-421
DS+	49	D_s^+	D_s-plus	431
DS-	50	D_s^-	D_s-minus	-431
LAMBDAC+	51	Λ_c^+	Lambda$_c$-plus	4122
XSIC+	52	Ξ_c^+	Xi$_c$-plus	4232
XSIC0	53	Ξ_c^0	Xi$_c$-zero	4132
XSIPC+	54	$\Xi_c^{\prime +}$	Xi$'_c$-plus	4322
XSIPC0	55	$\Xi_c^{\prime 0}$	Xi$'_c$-zero	4312
OMEGAC0	56	Ω_c^0	Omega$_c$-zero	4332
ALAMBDC-	57	$\bar{\Lambda}_c^-$	Antilambda$_c$-minus	-4122
AXSIC-	58	$\bar{\Xi}_c^-$	AntiXi$_c$-minus	-4232
AXSIC0	59	$\bar{\Xi}_c^0$	AntiXi$_c$-zero	-4132
AXSIPC-	60	$\bar{\Xi}_c^{\prime -}$	AntiXi$'_c$-minus	-4322
AXSIPC0	61	$\bar{\Xi}_c^{\prime 0}$	AntiXi$'_c$-zero	-4312
AOMEGAC0	62	$\bar{\Omega}_c^0$	AntiOmega$_c$-zero	-4332
Reserved	63	—	—	—
Reserved	64	—	—	—

The FLUKA Code design

- Based, as far as possible, on **original** and well-tested microscopic models
- Full cross-talk between all components:
  - hadronic,
  - electromagnetic,
  - neutrons,
  - muons,
  - heavy ions
- It is a "condensed history" MC code, however with the possibility to use single instead of multiple Coulomb scattering

  FLUKA is NOT a toolkit! Its physical models are fully integrated

  - **The user does not need to choose a "physics list"**
  - **The user has, however, the possibility to optimize CPU vs accuracy**
- Fluka provides powerful built-in scoring, tested and suited for most applications
  - **The user does not need to write external code to get results and statistics**

What can be done with FLUKA?

FLUKA

Cosmic ray physics

Hadron therapy

Space radiation

Accelerator design

Neutrino physics

Detector simulation

Shielding design

ADS systems, waste transmutation

Dosimetry and radioprotection

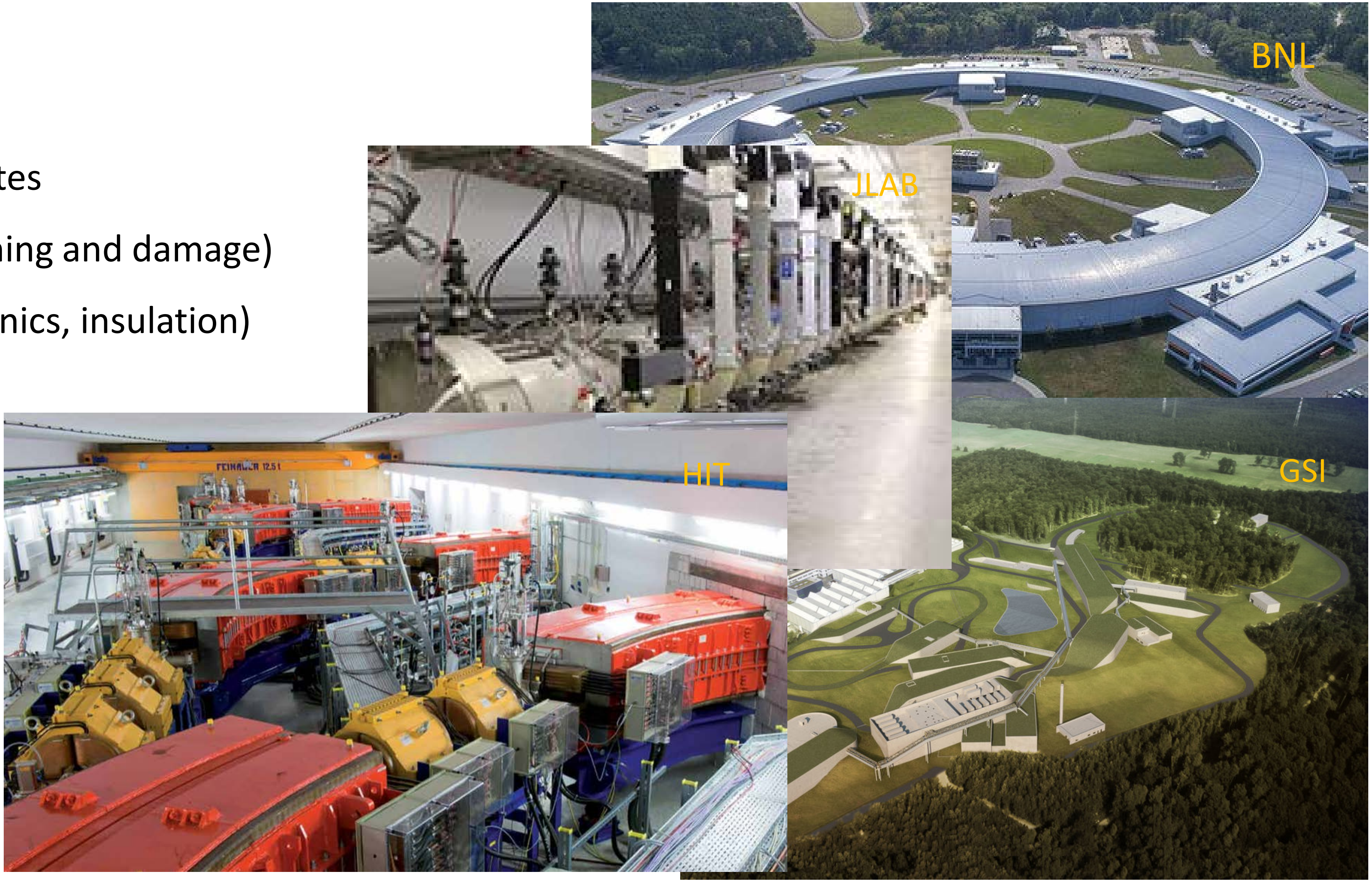
Radiation damage

Neutronics

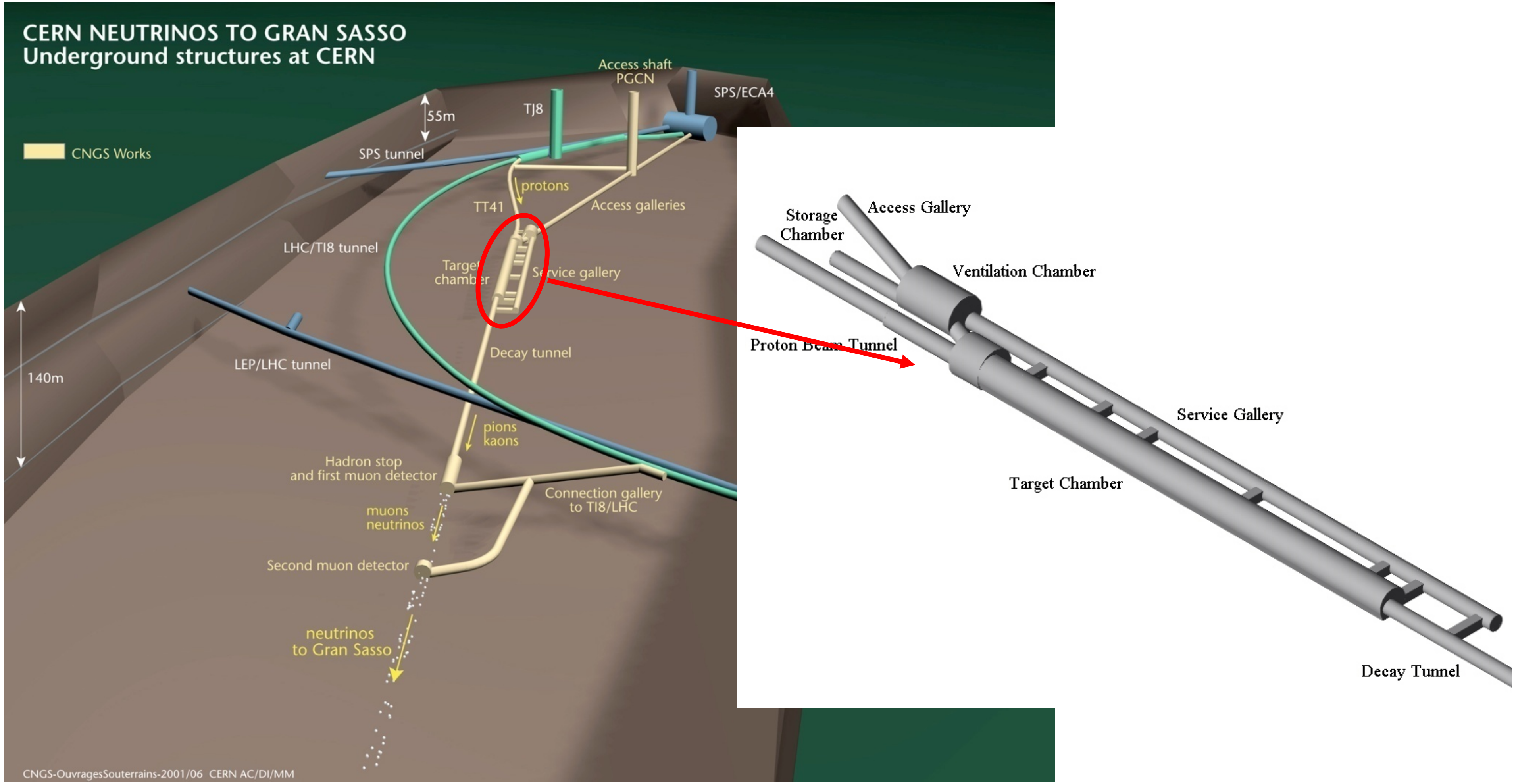
http://www.fluka.org

Accelerators:

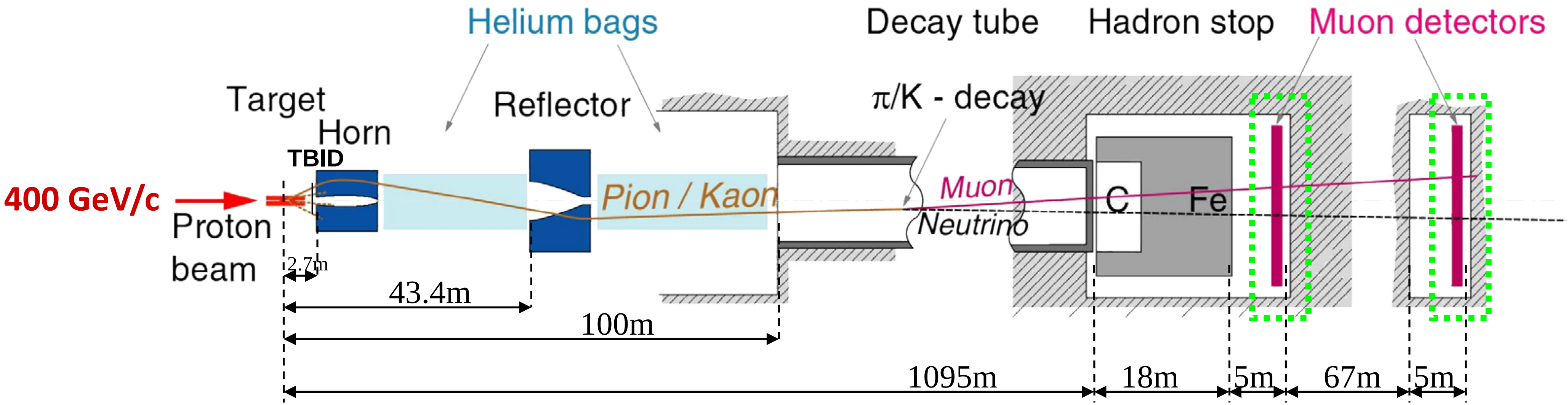
- Neutrino experiments
- Detector simulation
- Shielding, residual dose rates
- Energy deposition (quenching and damage)
- Radiation damage (electronics, insulation)
- Activation, waste disposal
- Shielding design
- Spallation sources
- Secondary beams



Accelerator applications – CNGS neutrino beam



CNGS: ν beam and muon monitors



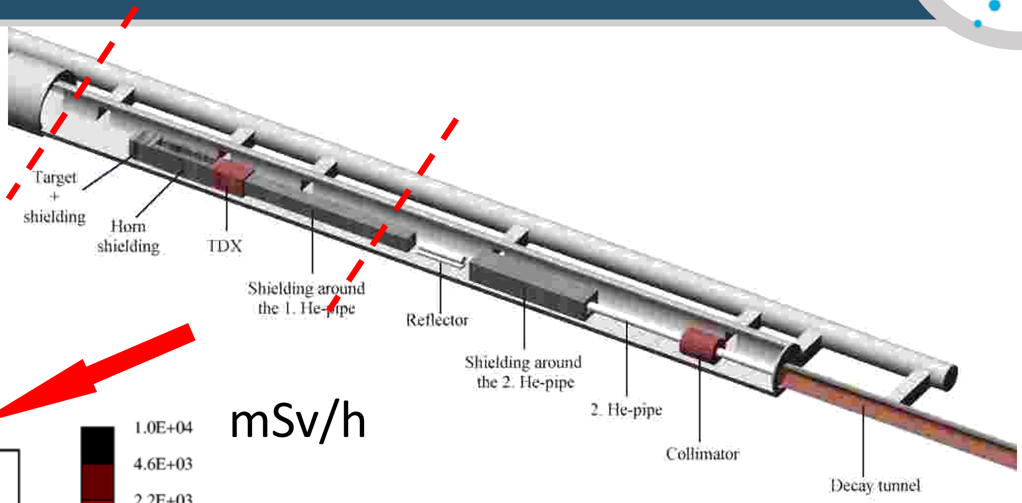
$$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+,\ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$

Flight path to Gran Sasso : 732 km.

CNGS neutrino beam line designed and optimized with **FLUKA**

Muon monitors: a check of neutrino production

Applications – CNGS

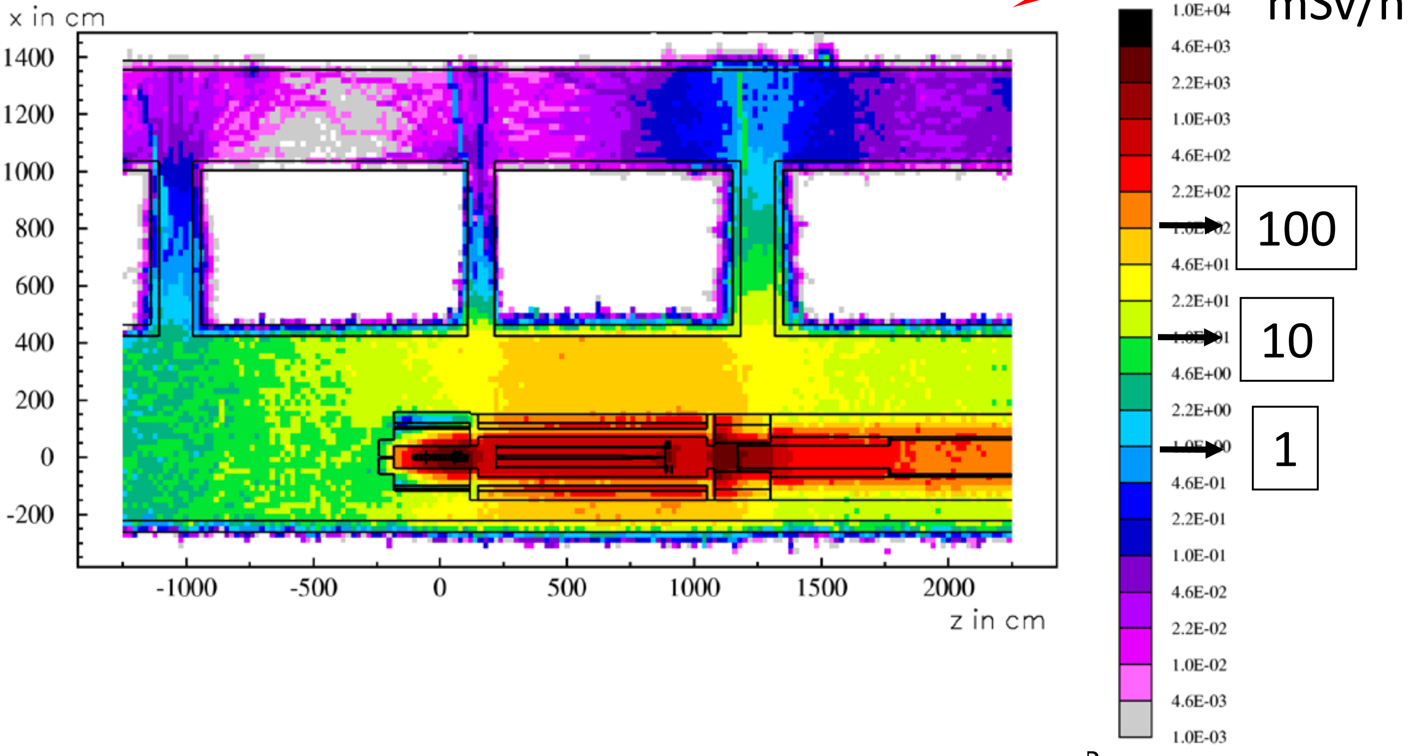


Residual Dose Equivalent Rate (mSv/h):

- 200 day long Irradiation;
- 1 day cooling time
- 8 x 10^{12} 400 GeV/c protons/s

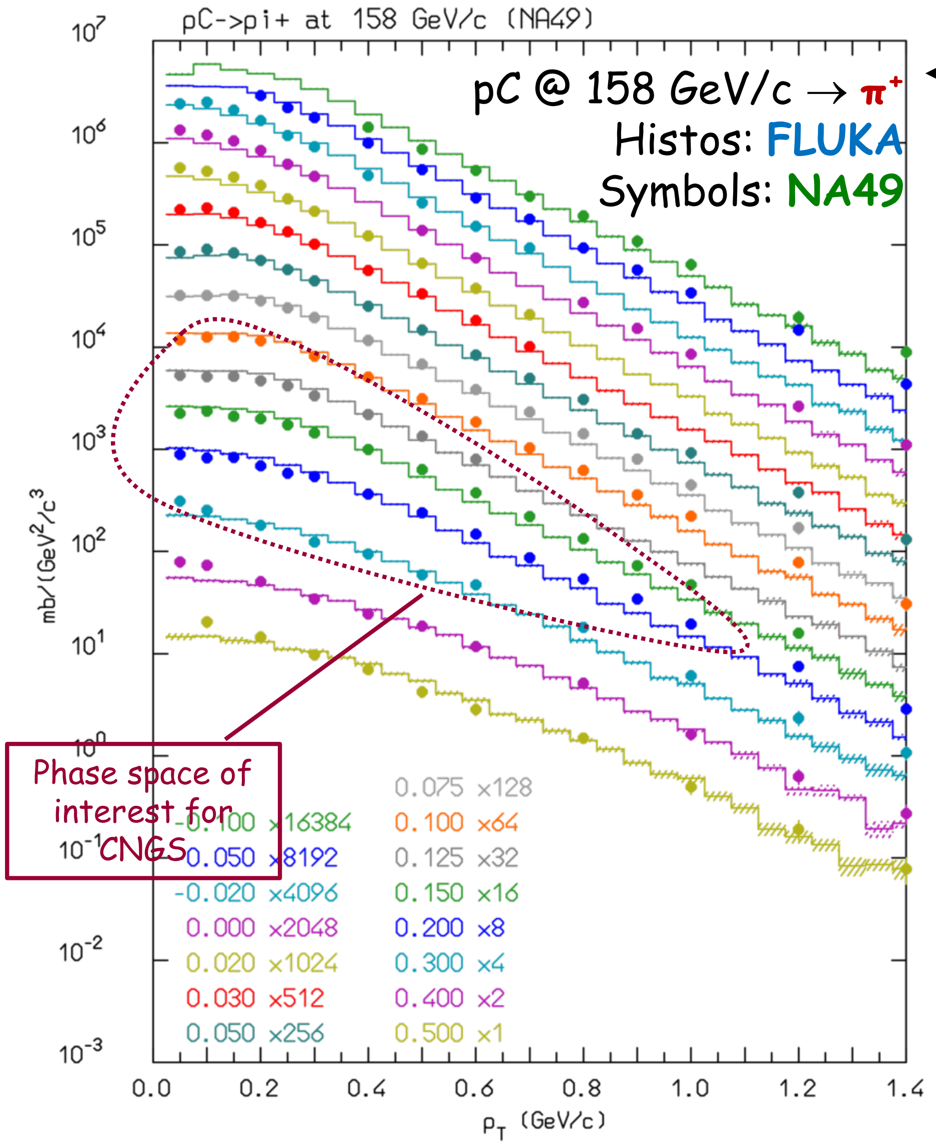
Example:

t_{cool} = 1 day



RN 2008

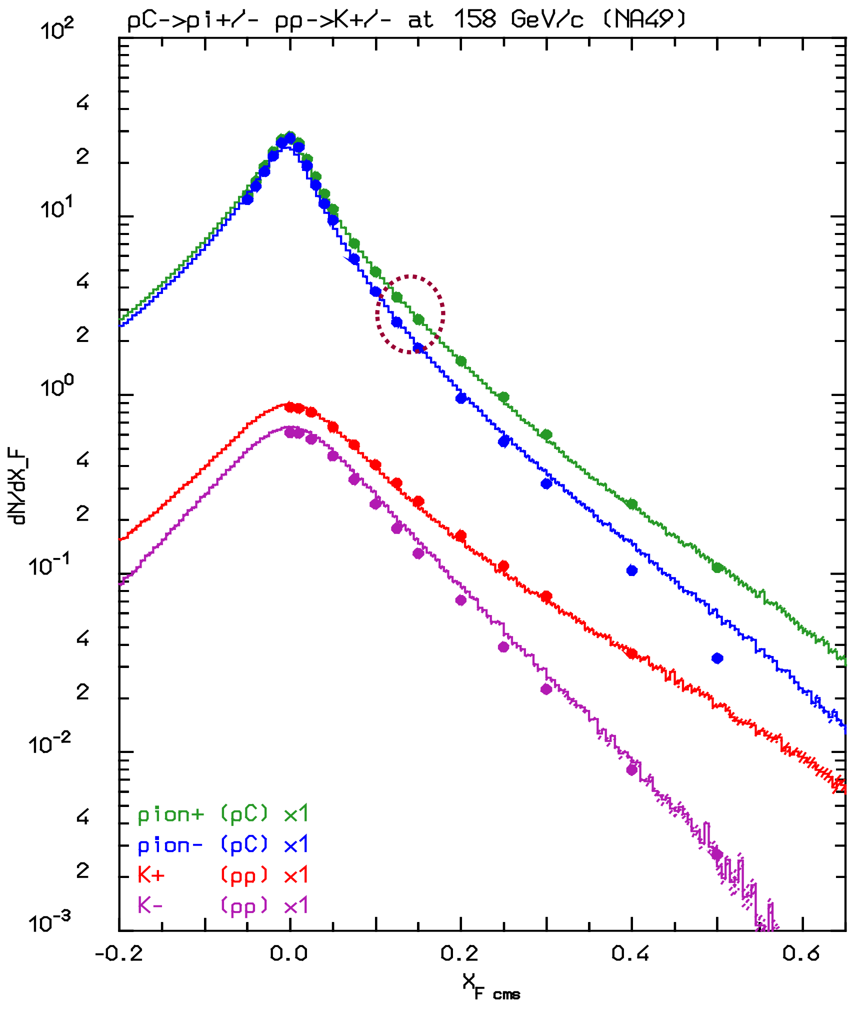
Pion and Kaon production data (ν beams…)



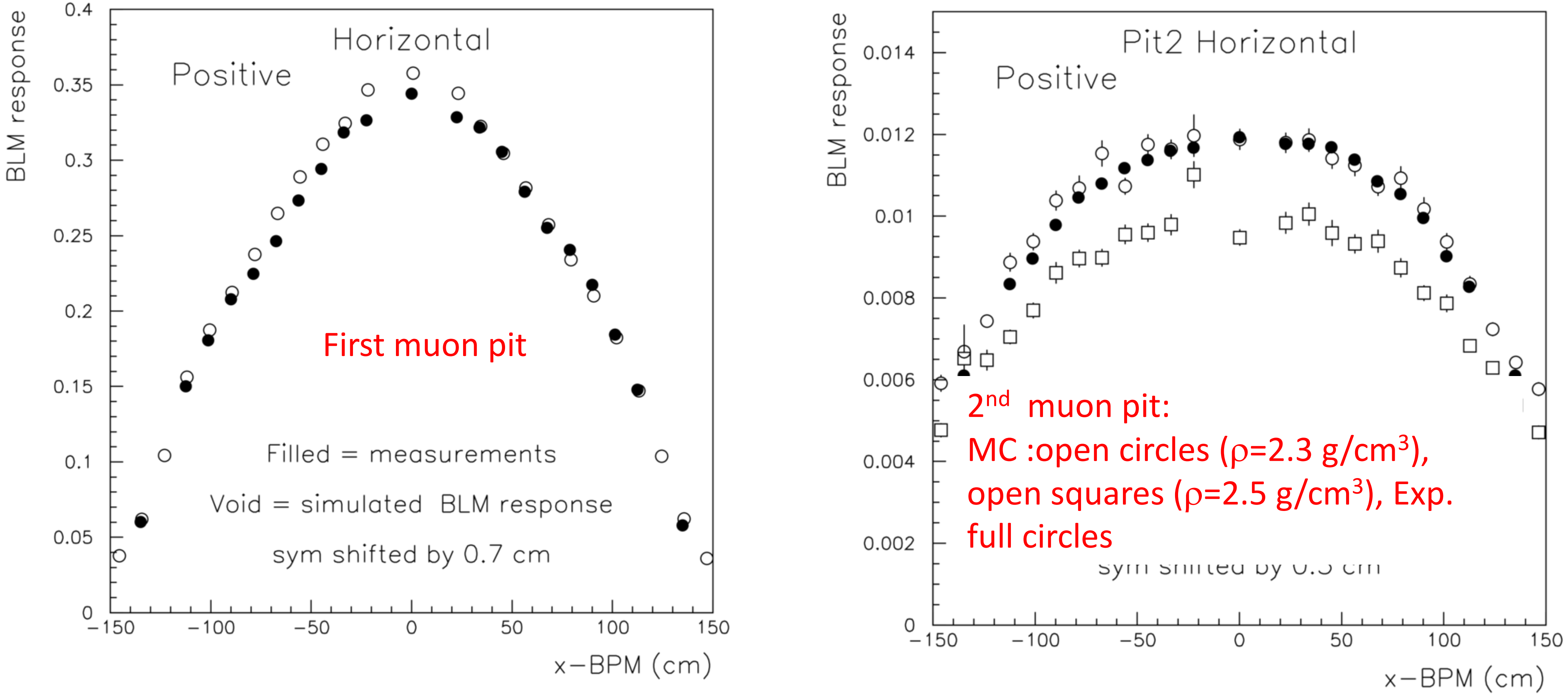
π^+ (left) yield as a function of p_T for different X_F bins for 158 GeV/c p on C

Angle integrated distributions are the most relevant for judging the reliability of ν predictions, at least for the bulk of the spectrum.

The p_T integrated distributions for $pC \rightarrow \pi^+$, π^- and $pp \rightarrow K^+$, K^- are shown in the right Figure as a function of Feynman X_F (dots exp. data, **NA49**, lines **FLUKA** predictions), together with the "focused" zone for **CNGS**

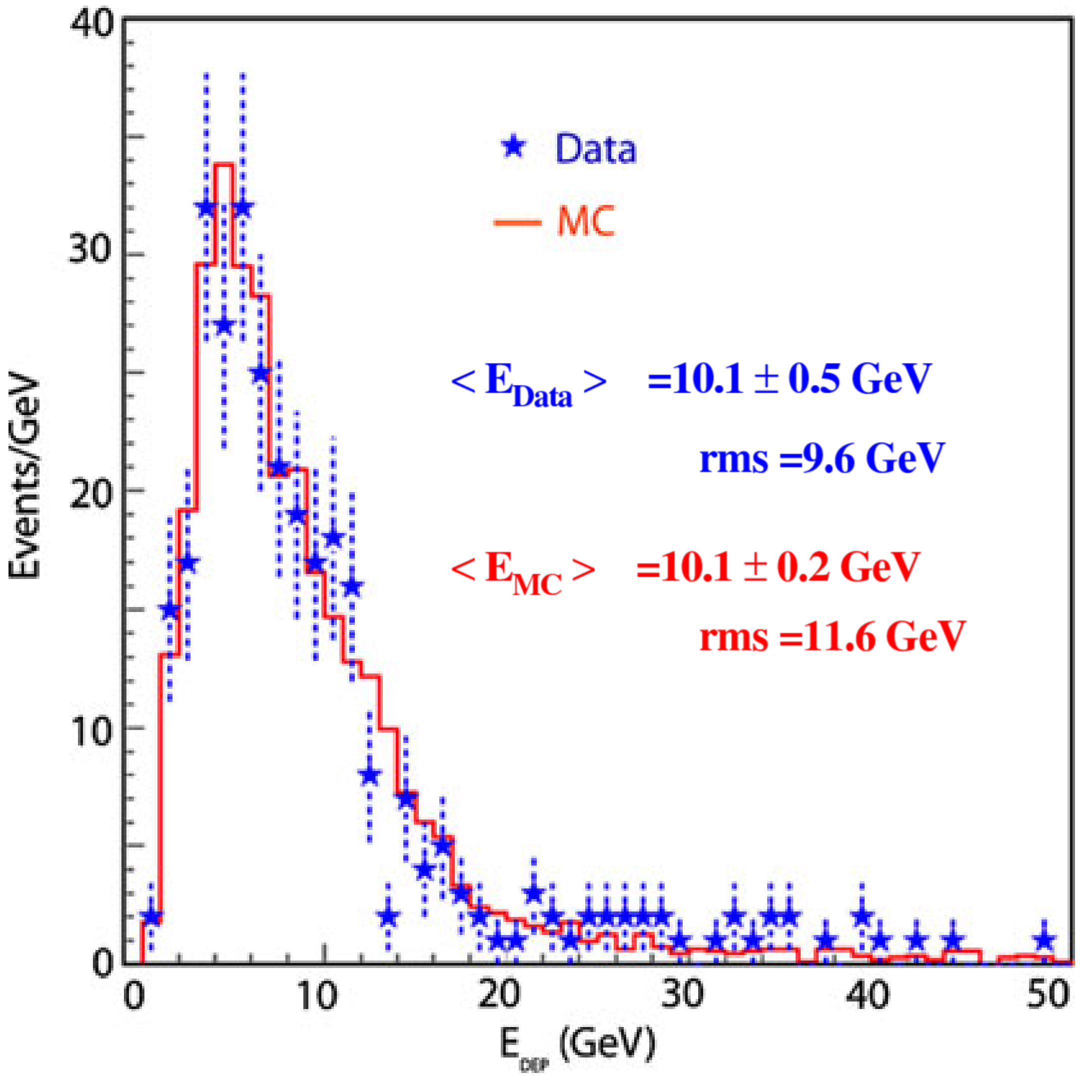


CNGS Muon pits (~110 m underground): data vs MC



Absolute comparison! Included in MC: effect of **earth magnetic field** (in the 1 km long decay tunnel). Experimental uncertainties: detector calibration, density of the rock in between the two pits (67 m)

ICARUS: CNGS data

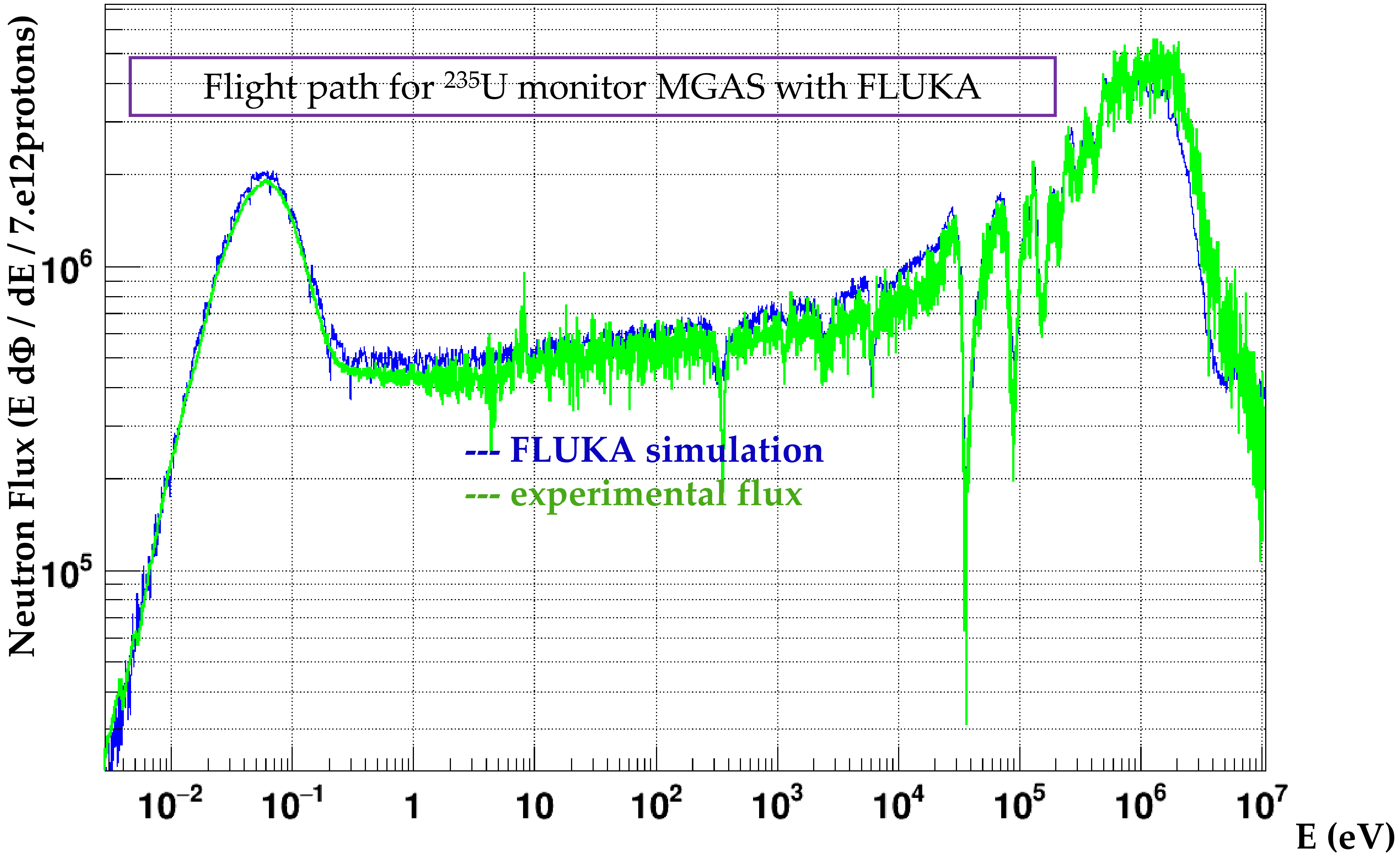


Distribution of total deposited energy in the ICARUS T600 detector

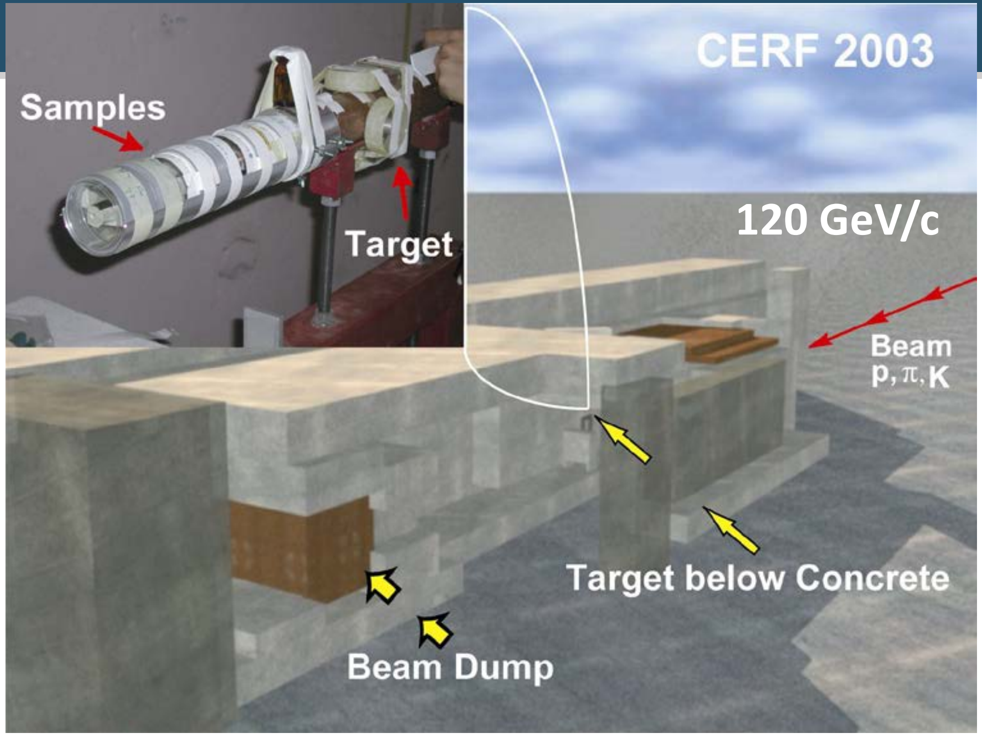
- CNGS numuCC events (~20 GeV E_ν peak)
- Same reconstruction in MC (FLUKA) and Data
- Neutrino fluxes from FLUKA CNGS simulations
- Absolute agreement on neutrino rate within 6%

Eur. Phys. J. C (2013) 73:2345
Phys. Lett. B (2014)

Spallation source n_TOF @ CERN: EAR2



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

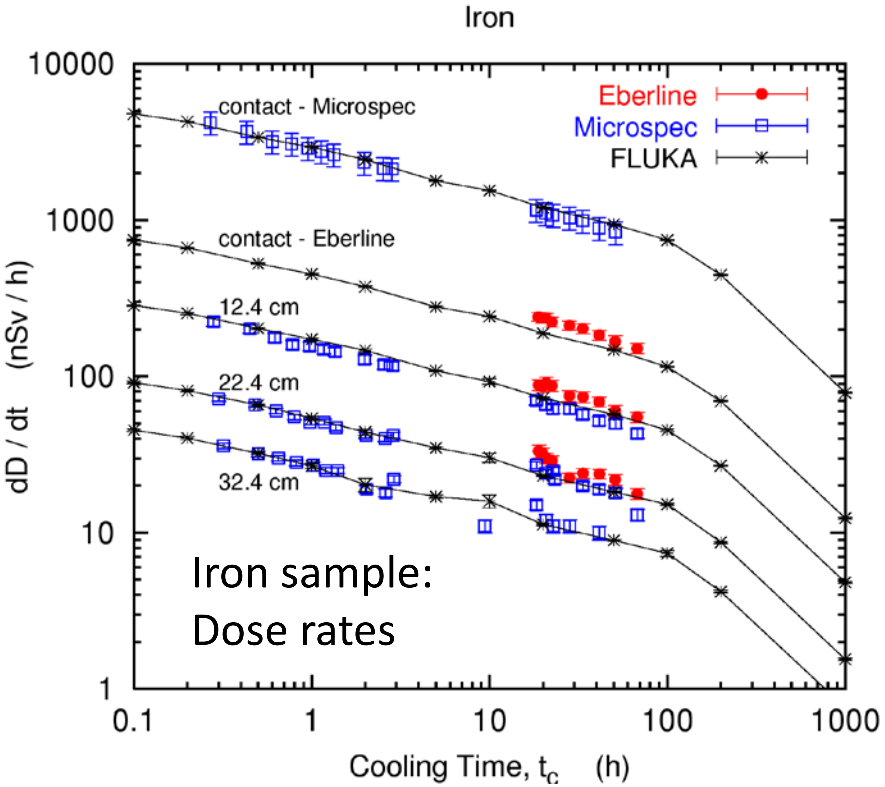


Thermo-Eberline dose-meter FHZ 672

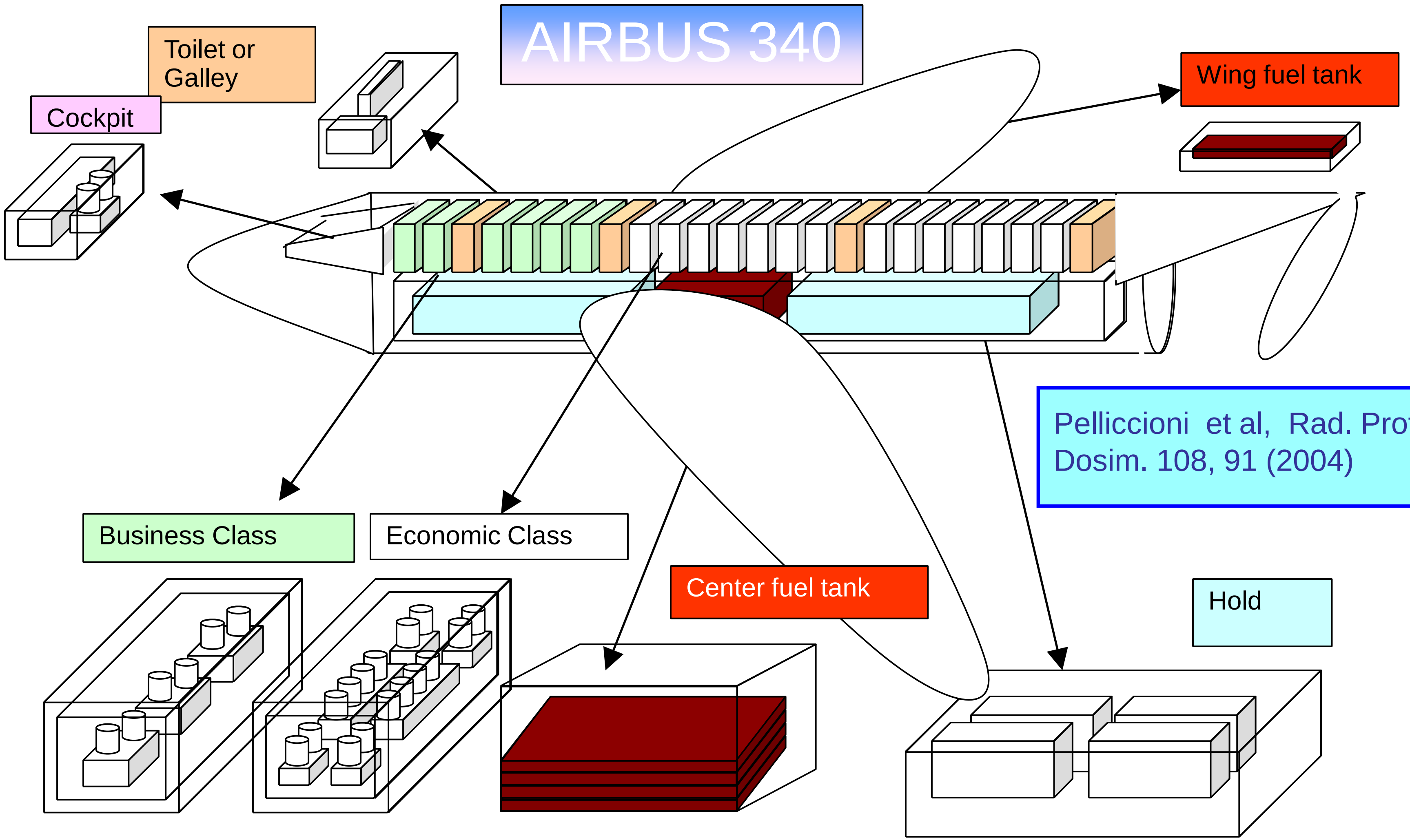
ACTIVATION of various

samples in contact with a 50 cm long, 7 cm diameter copper target, centred on the beam axis, and irradiated with a 120 GeV/c beam

Microspec



Dosimetry applications: doses to aircrew and passengers



Pelliccioni et al, Rad. Prot. Dosim. 108, 91 (2004)

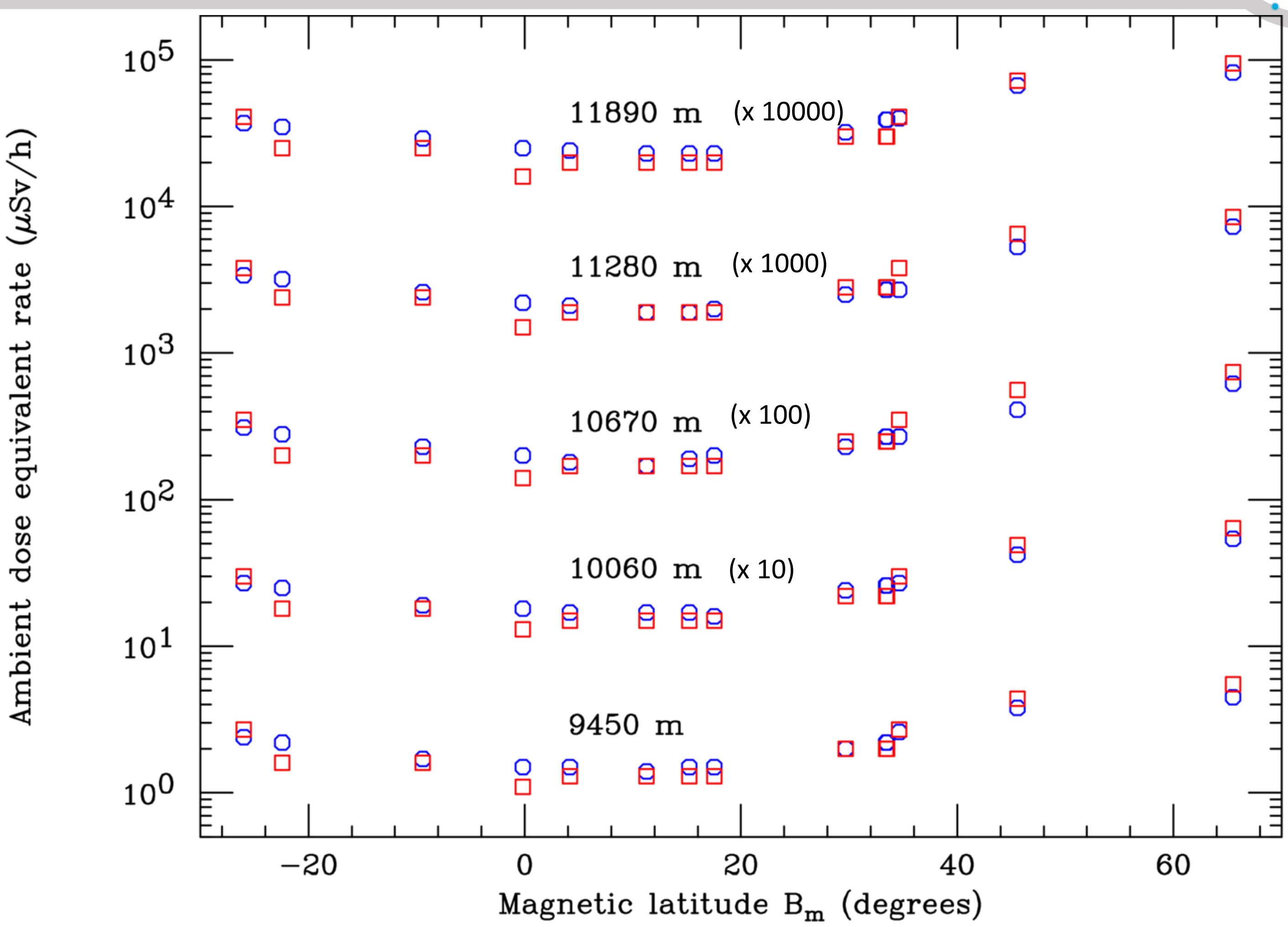
Commercial flight doses: (Pelliccioni et al. RPD93)

Complete FLUKA simulation of cosmic rays interactions in the atmosphere

- Dedicated "cosmic" package available to users
- Ready to use GCR spectra and geomagnetic cut-offs

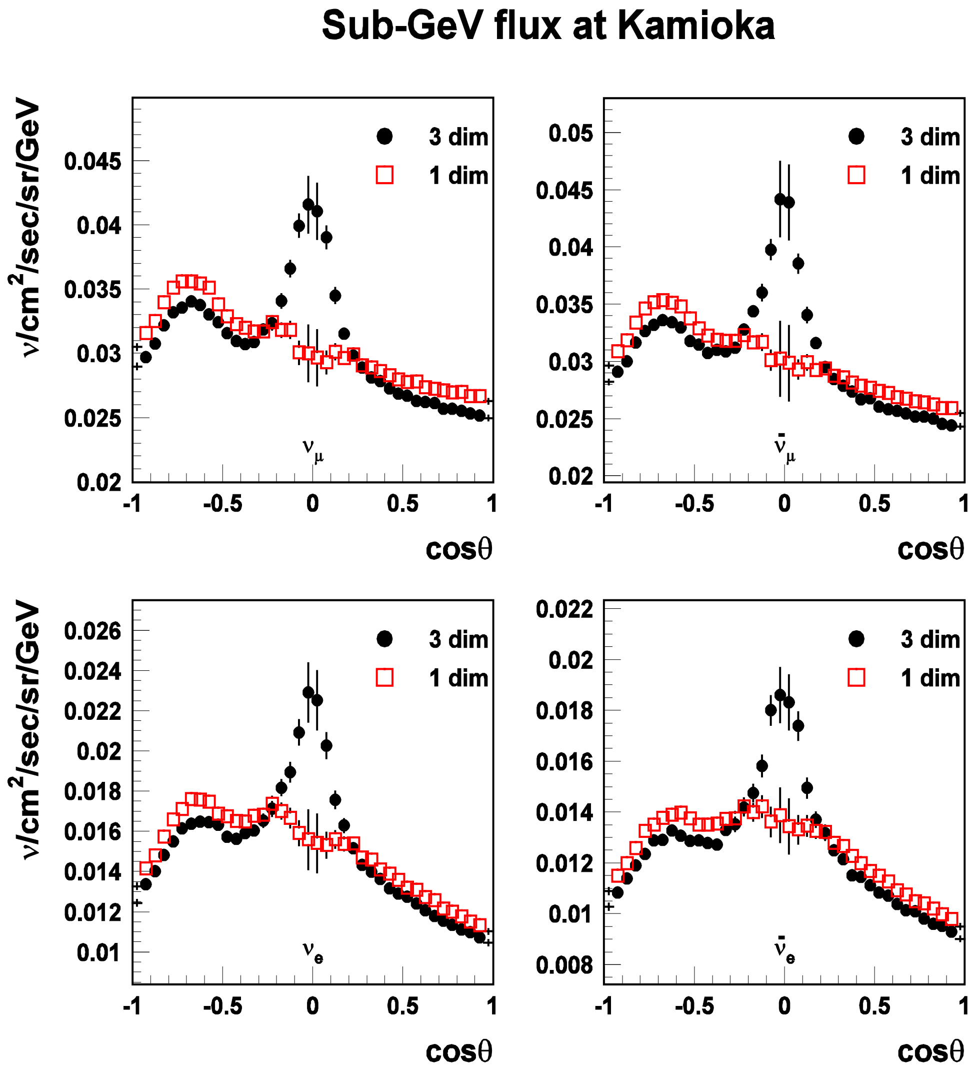
Model of airplane geometry
Response of dosimeters

Dose to aircrew on commercial flights , depending on route



Simulated (**FLUKA, red**) and measured (**blue**, NIMA422, 621, 1999) ambient dose equivalent for various altitudes (scaled by one decade) and geomagnetic cut-off's

(3D) Calculation of Atmospheric n Flux



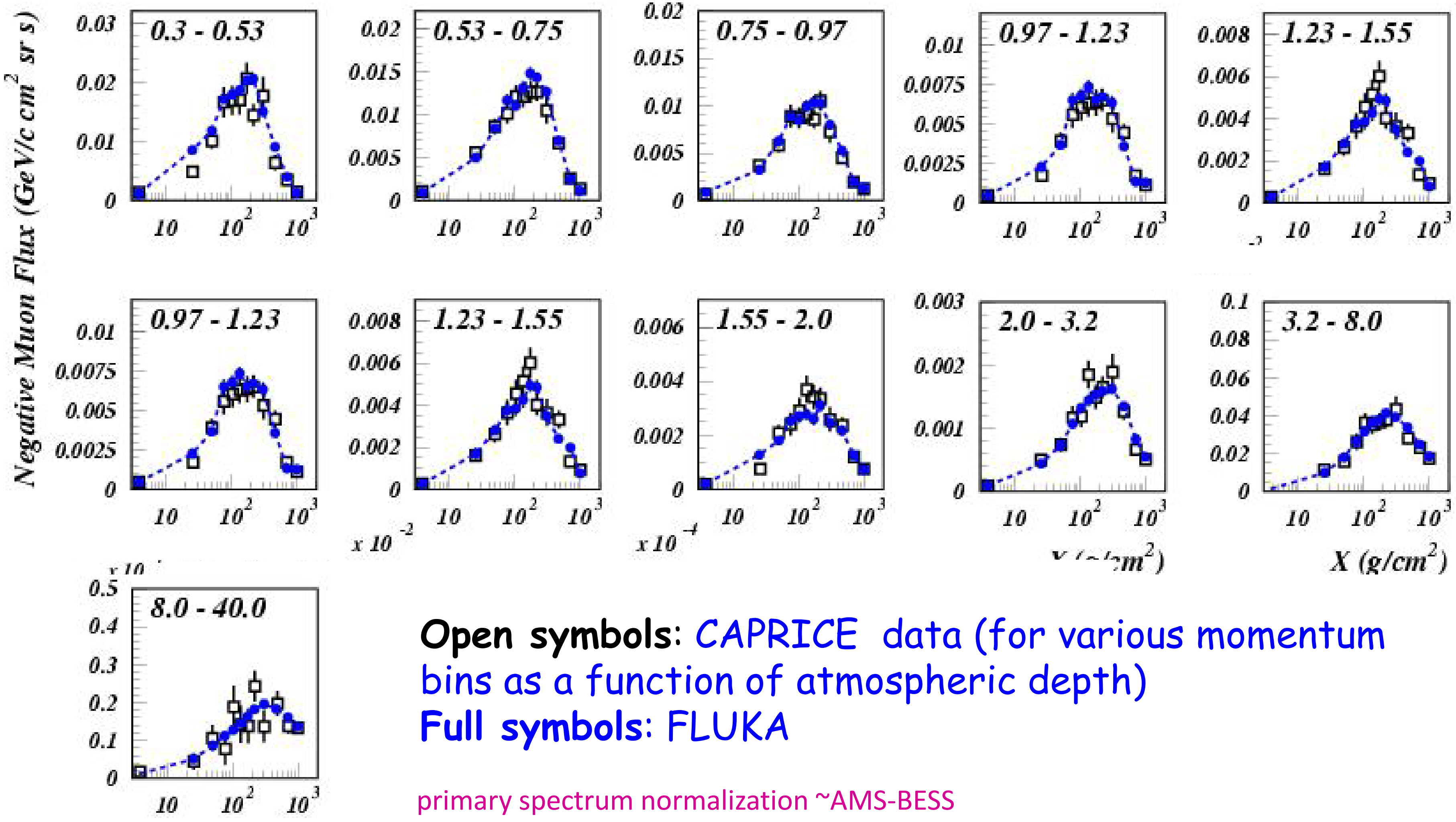
The first 3-D calculation of atmospheric neutrinos was done with FLUKA.

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

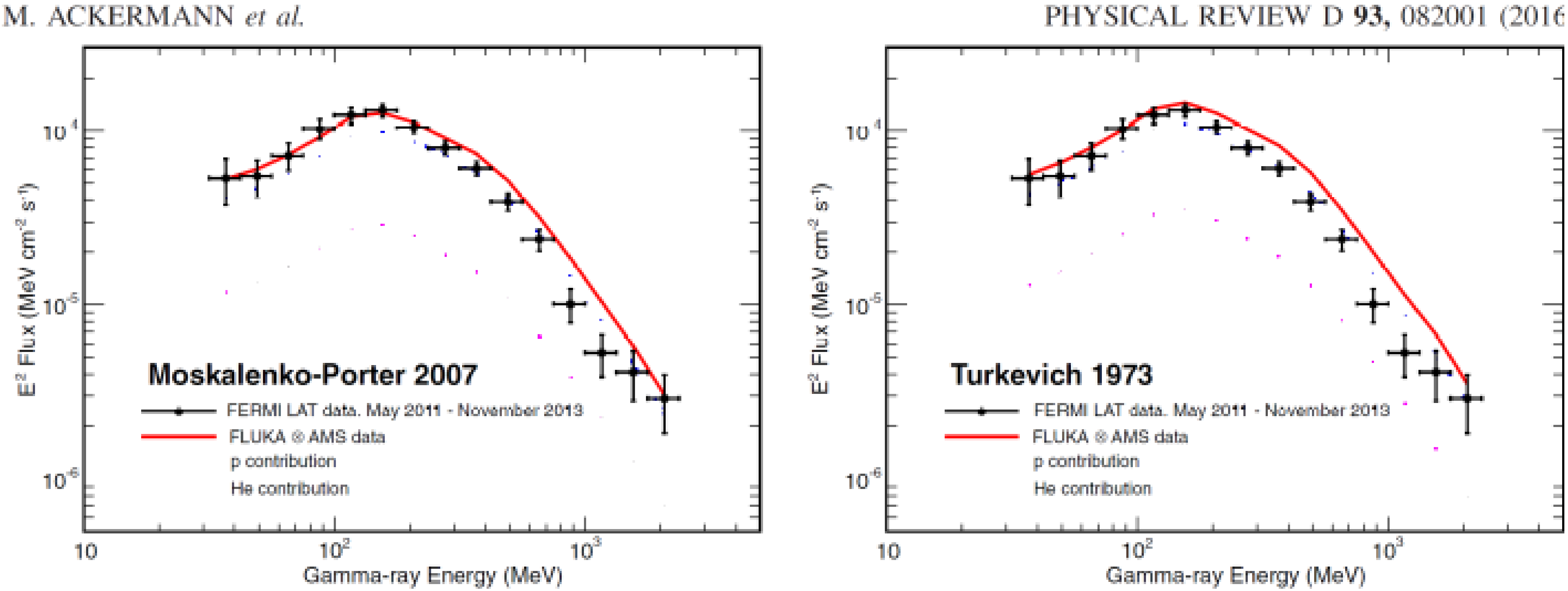
COSMIC RAYS: Negative muons at floating altitudes: CAPRICE94



Open symbols: CAPRICE data (for various momentum bins as a function of atmospheric depth)
Full symbols: FLUKA

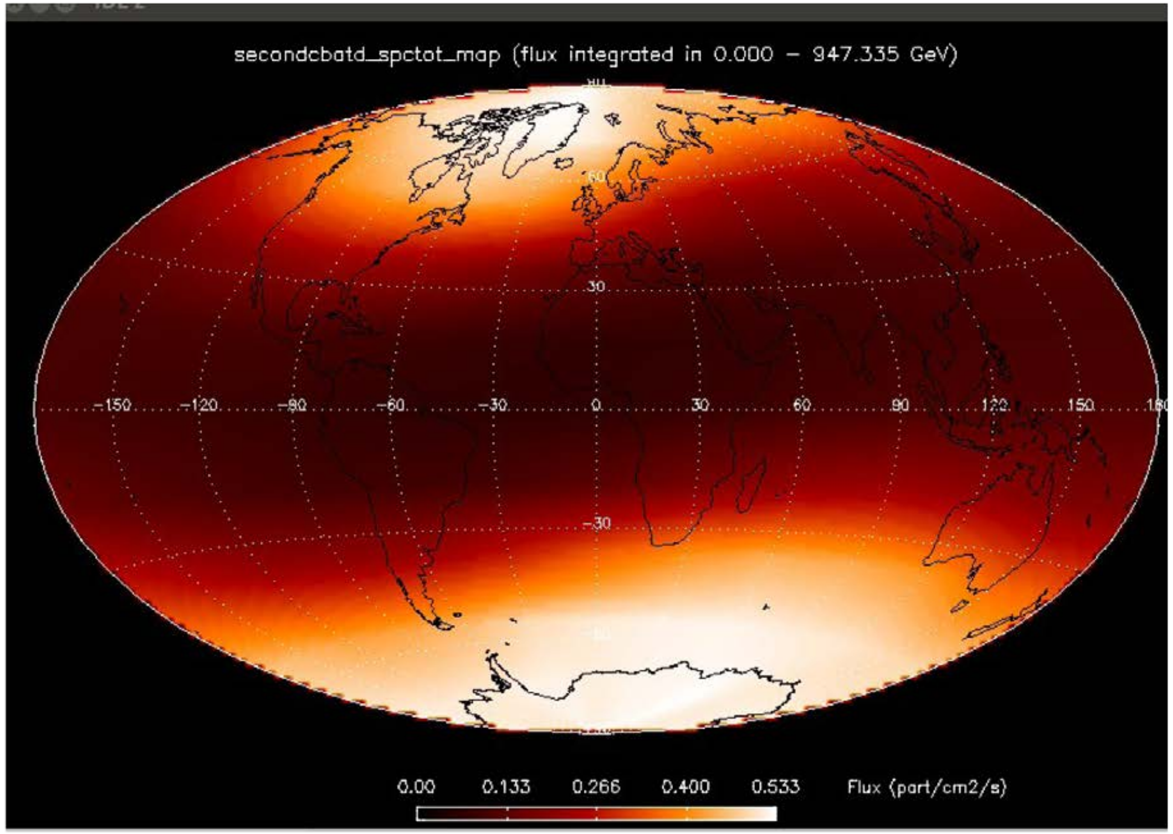
primary spectrum normalization ~AMS-BESS
Astropart. Phys., Vol. 17, No. 4 (2002) p. 477

Gamma rays from GCR interactions with the moon:



Gamma-ray flux from the Moon in the period May 2011 –November 2013, measured (**FERMI-LAT**) and computed (**FLUKA**) for two different Lunar surface composition models (courtesy of M.Mazziotta, INFN Bari). Primary CR spectra from AMS-02

The neutron albedo from GCR's at 400 km altitude*

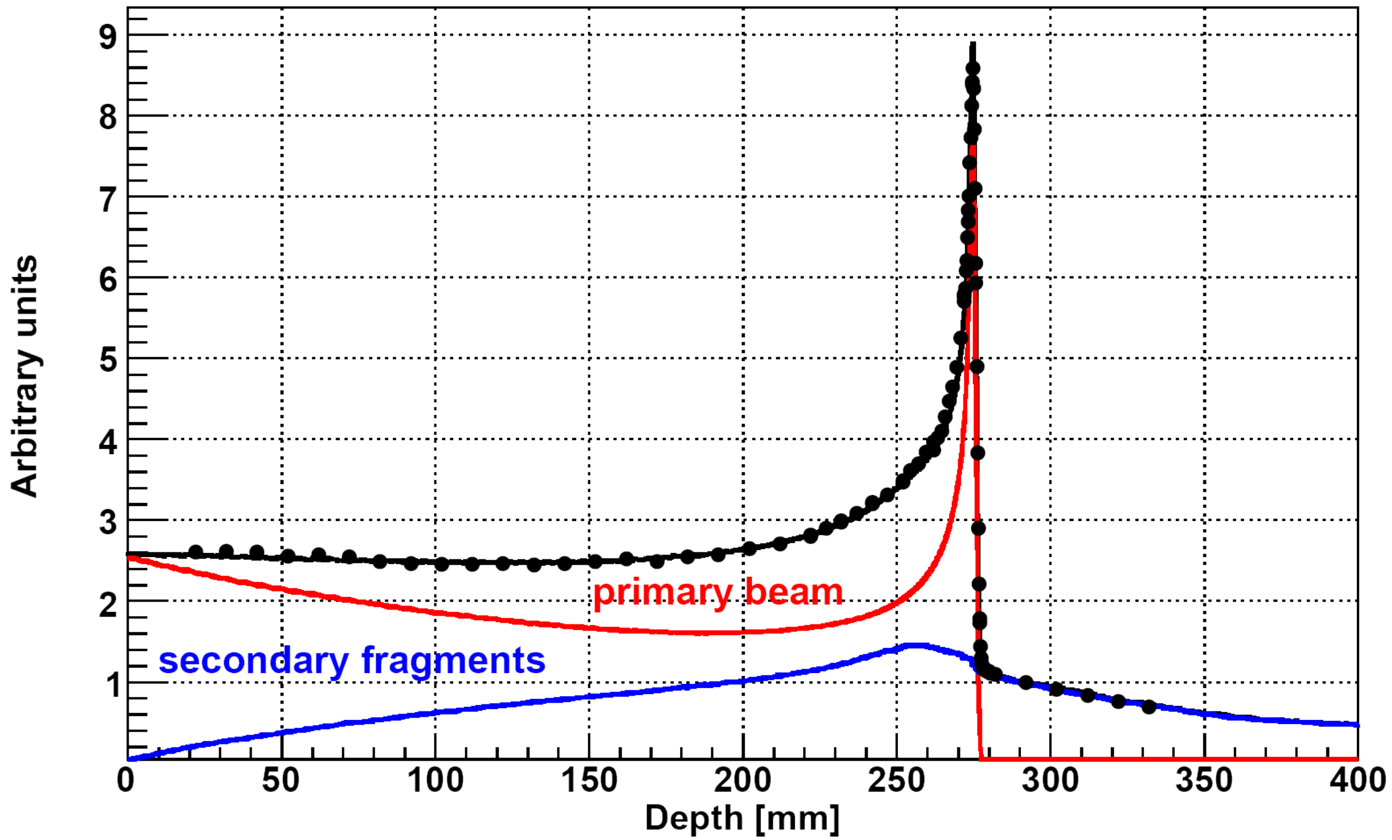


**In collaboration with CEA-Saclay*

Medical physics : Radiotherapy

Bragg peak in a water phantom: 400 MeV/A C beam:

The importance of fragmentation

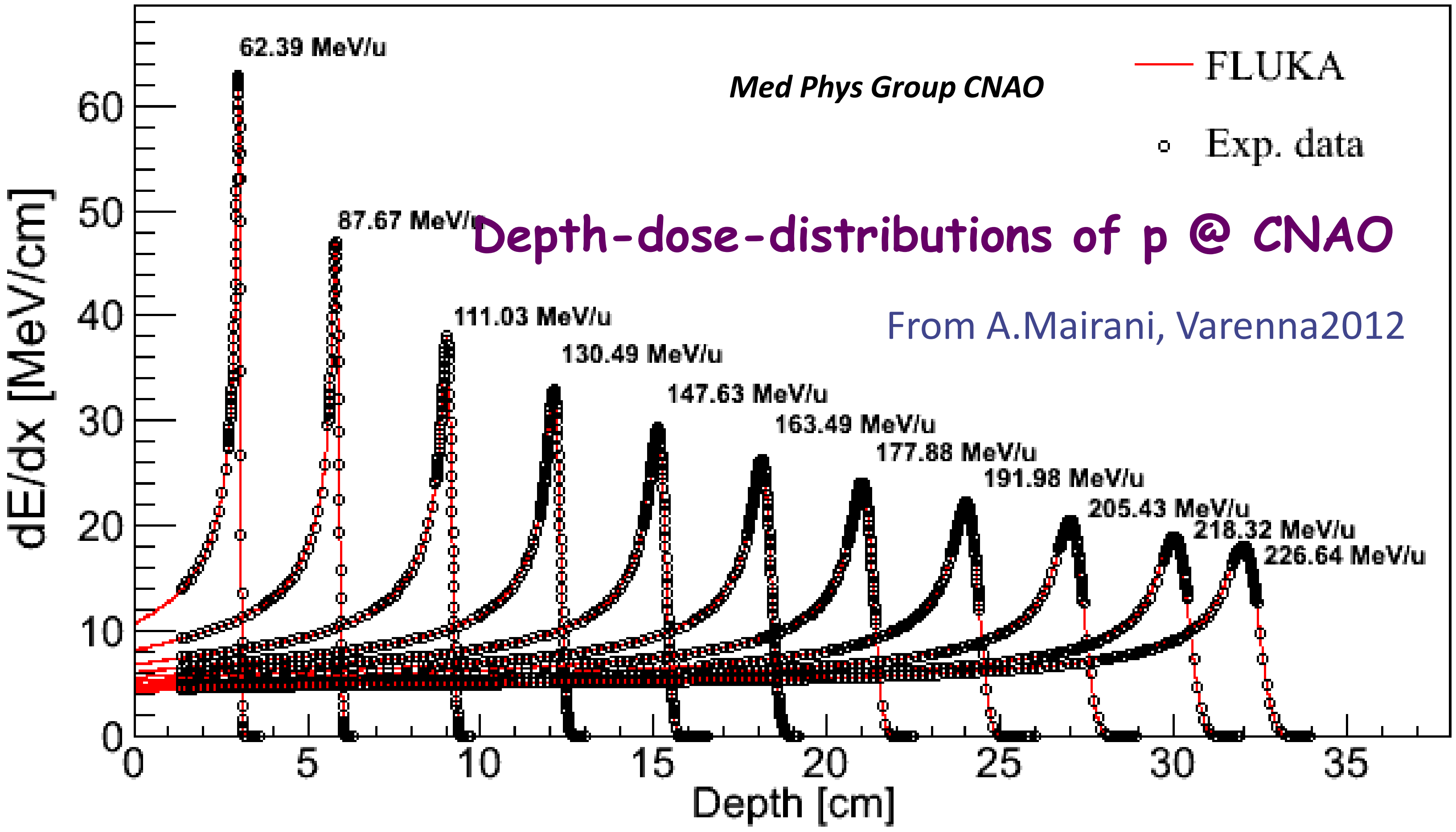


Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006

Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

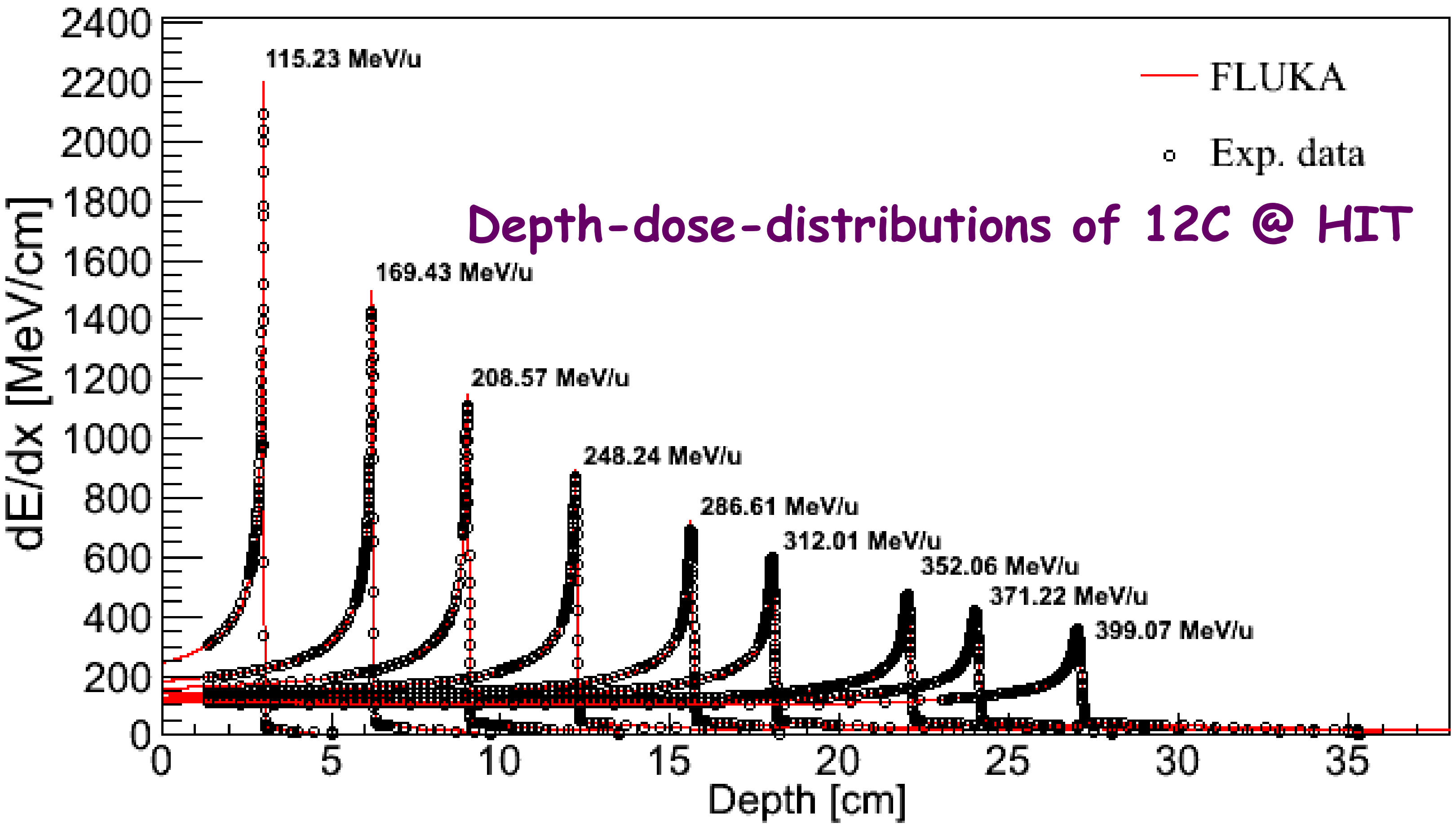
Fluka vs hadrontherapy, present: HIT, CNAO, …

Used for generating p, ^{12}C dose vs depth databases then used for TP

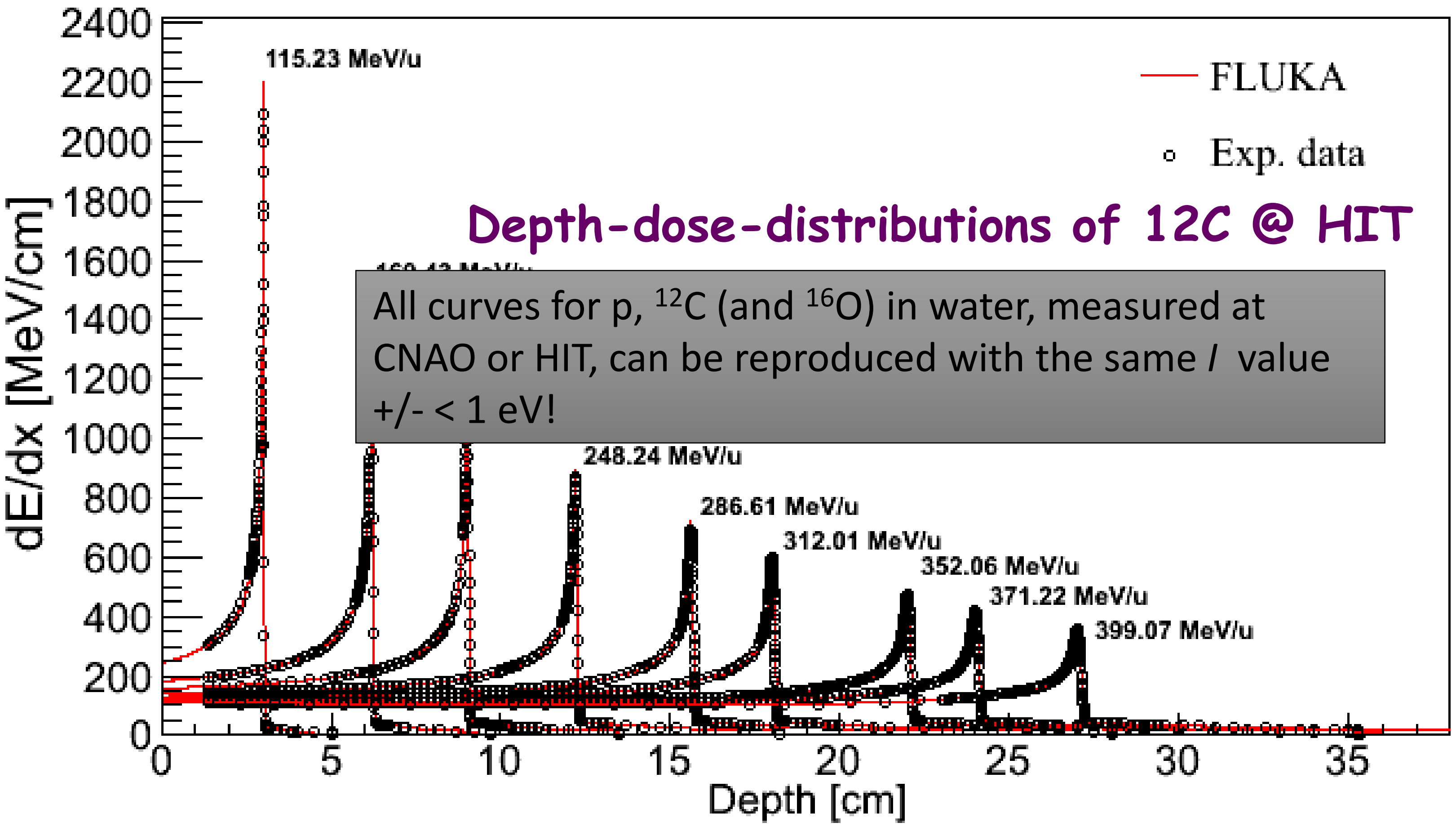


in water wo/with RiFi for the **147** energies in the initial phase of the operation

Fluka vs hadrontherapy, present: HIT, CNAO, …



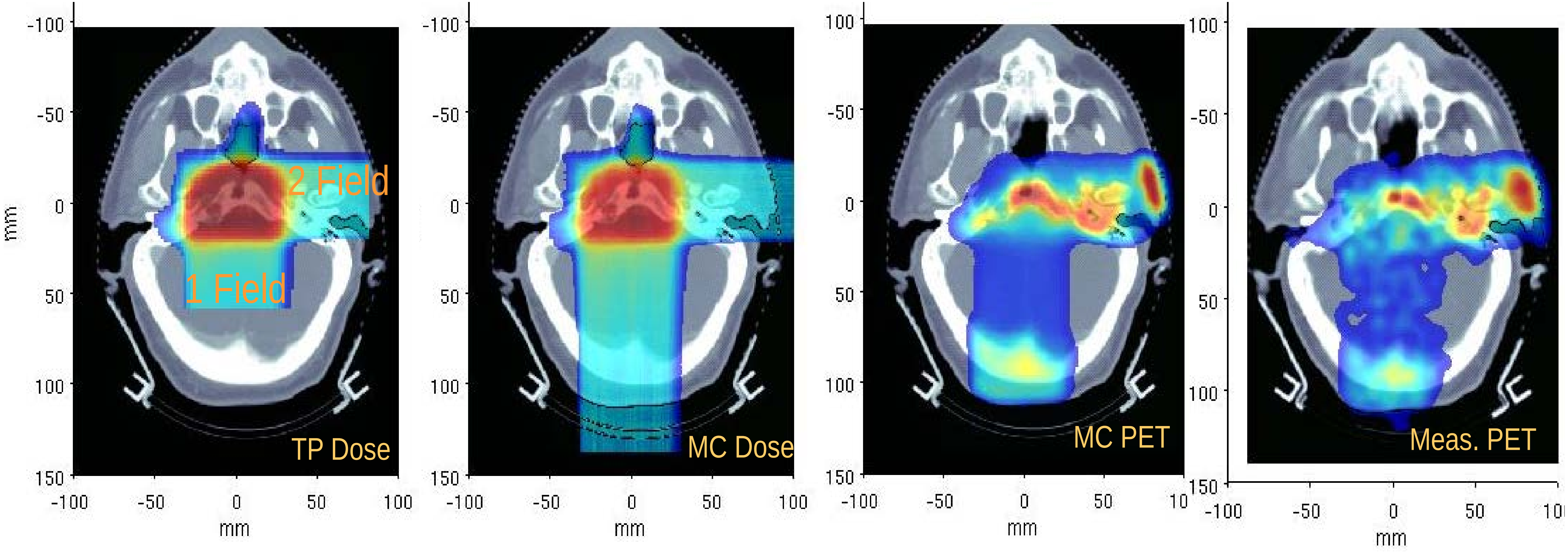
Fluka vs hadrontherapy, present: HIT, CNAO, …



All curves for p, ^{12}C (and ^{16}O) in water, measured at CNAO or HIT, can be reproduced with the same *I* value +/- < 1 eV!

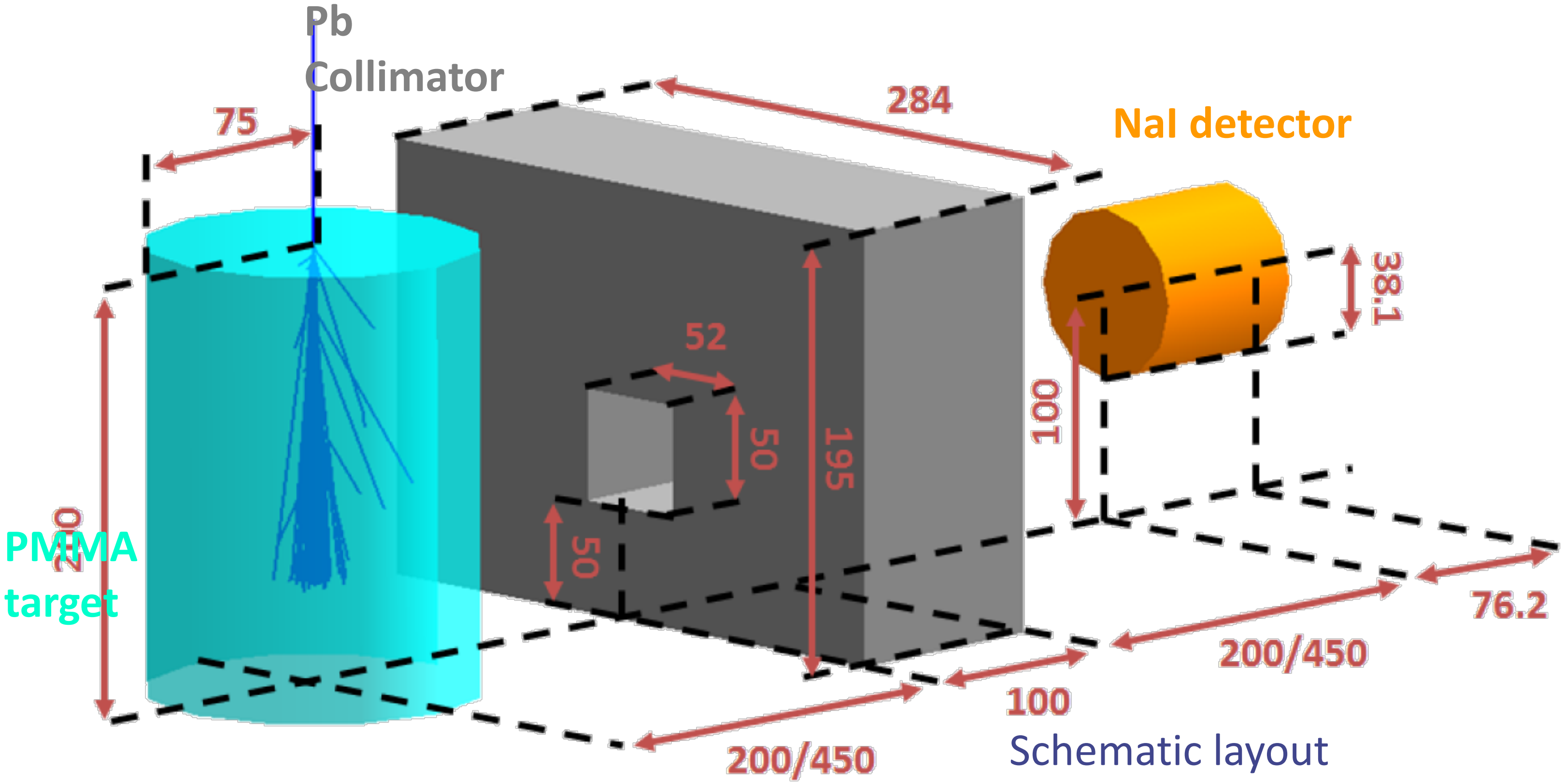
Proton therapy: dose and PET distributions from FLUKA, Head

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



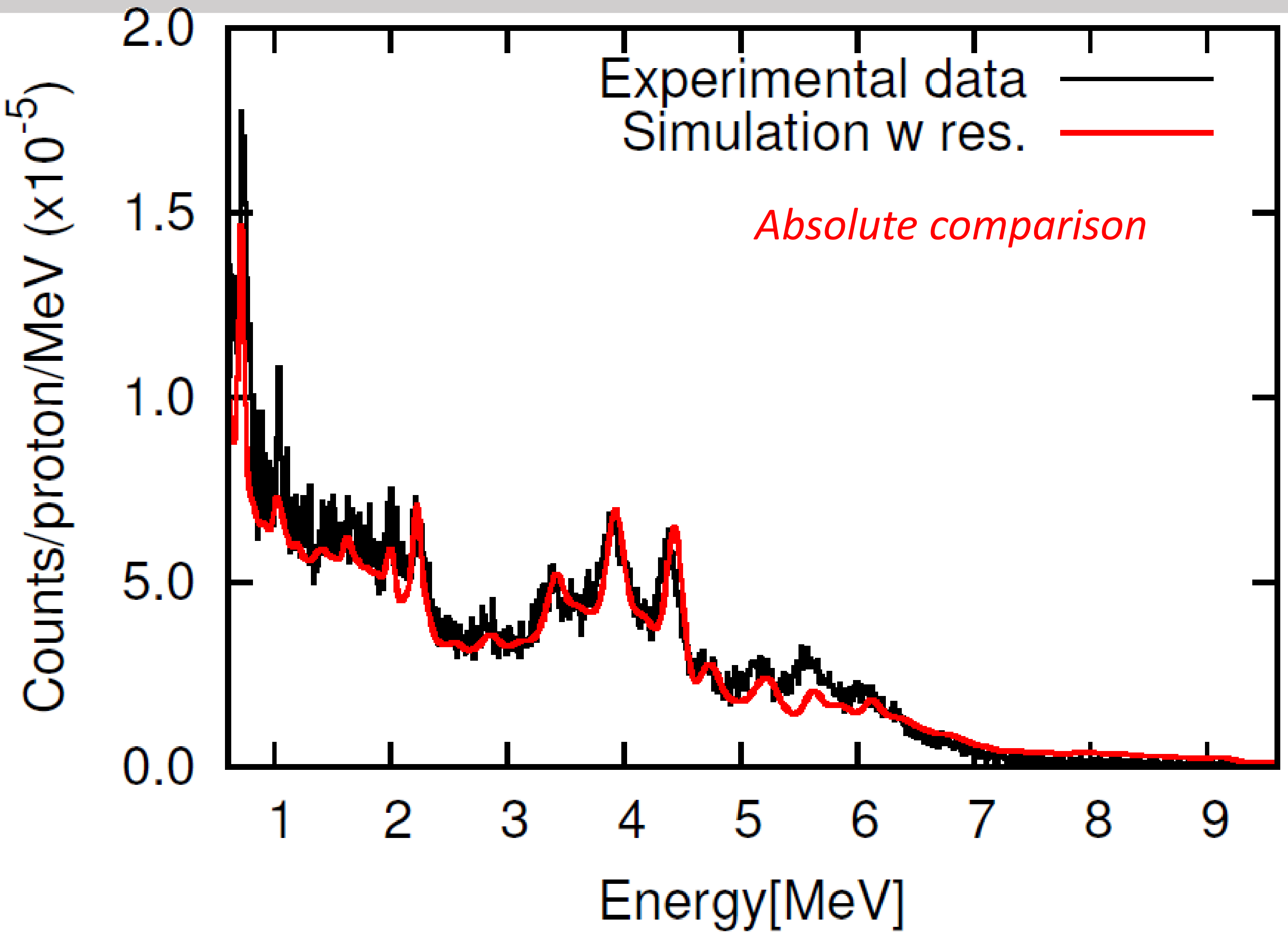
K. Parodi et al., PMB52, 3369 (2007)

Photon yields by 160 MeV p in PMMA



Schematic layout
(dimensions mm)
from J.Smeets et al., IBA

Photon yields by 160 MeV p in PMMA



Energy spectrum of “photons” after background subtraction (collimator open – collimator closed) for 160 MeV p on PMMA. FLUKA **red line**, data **black line** (J.Smeets et al., IBA, ENVISION WP3)

The FLUKA Course: purpose

This course is intended to provide users with the basic

(and possibly more than basic!) knowledge of:

a) The most relevant FLUKA instructions and options
b) The physics models adopted in FLUKA
c) The different scoring options embedded in FLUKA
d) The different running options
e) The tools to plot results
f) The right approach to the existing documentation
g) The procedures to overcome difficulties and problems and related debugging tools
h) etc. etc.

Possible problems:

- People here are not all at the same level of FLUKA knowledge. There are those who already have some experience.
- However we need to start from scratch.
- We apologize to the experienced people and beg them to be patient: it's not excluded a priori that they can learn something new also concerning the very basic elements!
- FLUKA is written in fortran. No knowledge of fortran or other languages is needed in this course, however some of the terminology used might be derived from fortran. If this happens and it causes problems, please ask!
- FLUKA runs in a Linux/Mac OSX environment. A basic knowledge of most common Linux/Unix commands is required, as well as the capability to use a text editor (emacs, vi, gedit..). If some of you has troubles with this, please tell us

The FLUKA version

FLUKA20xx.n(y).m

Major version

Minor version

Patch level

Respin

In this course we are using: FLUKA2024.1.0

The FLUKA license (it is not GPL):

- Standard download: **binary library + user routines**.
  - FLUKA can be used freely for scientific and academic purposes,
    (ad-hoc agreement for commercial purposes)
  - It cannot be used for weapon related applications

- It is possible, by explicit signing of license, to download the **source** for researchers of scientific/academic Institutions.
  - FLUKA can neither be copied into other codes (not even partially), nor translated into another language without permission

- For **commercial use**, trial version (limited in time and random seeds) available.

Please register on www.fluka.org …..and read the license!

The FLUKA mailing lists

- fluka-users@fluka.org

  Users are automatically subscribed here when registering on the web site.
  It is used to communicate the availability of new versions, patches, etc.

- fluka-discuss@fluka.org

  Users are encouraged to subscribe at registration time, but can uncheck the relevant box. It is used to have user-user and user-expert communication about problems, bugs, general inquiries about the code and its physics content

  Users are strongly encouraged to keep this subscription

In the next months the FLUKA mailing lists will migrate to a web-based forum… keep in touch to be ready for the transition

Using FLUKA

Platform: Linux with gfortran (on 64 bit computers) and g77 (on 32 and 64 bit computers)
Mac OSX (both Intel and Apple Silicon) with gfortran

The code should only be compiled/run using operating systems, compilers (and associated) options tested and approved by the development team

Standard Input:

- Command/options driven by “data cards” (ascii file)
  A powerful Graphical interface is available

- Standard Geometry (“Combinatorial geometry”): input by “data cards”

Standard Output and Scoring:

- Highly flexible and powerful, sufficient for most purposes
- Output processing and plotting interface available

Disclaimer

- A good FLUKA user is **not** one that **only** masters technically the program
- BUT a user that:
  - Indeed masters technically the code;
  - Know its limitations and capabilities;
  - Can tune the simulation to the specific requirements and needs of the problem under study;
    - and most of all
  - Has a critical judgment on the results
- Therefore in this course we will equally focus on:
  - The technical aspects of the code
    [building your input, geometry, scoring, biasing, extracting results…]
    - as well as
  - The underlying physics and MC techniques

The course team

Anna Ferrari

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Agenda: Monday

08:00			
	Welcome	*Lanzhou University, Lanzhou, China*	08:30 - 08:40
09:00	**Introduction to FLUKA** This lecture	*Lanzhou University, Lanzhou, China*	08:40 - 09:30
10:00	**Statistics and sampling** MonteCarlo explained, and the importance of random numbers.	*Lanzhou University, Lanzhou, China*	09:30 - 10:30
	Coffee break	*Lanzhou University, Lanzhou, China*	10:30 - 11:00
11:00	**Installing and running** The very first step, do it together. Learn how fluka runs and about output files	*Lanzhou University, Lanzhou, China*	11:00 - 12:00
12:00	**FLUKA manual and basic input** Our first commands, and THE MANUAL!!!!!	*Lanzhou University, Lanzhou, China*	12:00 - 13:00
13:00	**Lunch break**		
14:00		*Lanzhou University, Lanzhou, China*	13:00 - 14:30
15:00	**FLAIR** Introduction to graphical interface, try it with us	*Lanzhou University, Lanzhou, China*	14:30 - 15:30
16:00	**Exercise: Compound materials** First exercise, all by yourself..	*Lanzhou University, Lanzhou, China*	15:30 - 16:30
	Coffee break	*Lanzhou University, Lanzhou, China*	16:30 - 17:00
17:00	**Exercise: Compound materials (continued)** Please ask, we are here to help	*Lanzhou University, Lanzhou, China*	17:00 - 18:00
18:00			

Agenda: Tuesday

09:00	**Geometry**	Learn how to build a geometry in FLUKA	*Lanzhou University, Lanzhou, China*	08:30 - 10:00
10:00	**Exercise: Geometry**	Apply what you learned	*Lanzhou University, Lanzhou, China*	10:00 - 10:30
	Coffee break		*Lanzhou University, Lanzhou, China*	10:30 - 11:00
11:00	**Exercise. Geometry (continued)**	Ask!!	*Lanzhou University, Lanzhou, China*	11:00 - 12:00
12:00	**Physics models I: Hadronic interactions**	Protons, neutrons, and other particles hit friends: see what comes out	*Lanzhou University, Lanzhou, China*	12:00 - 13:00
13:00	**Mount Wuquan visit, and Banquet**			

Agenda: Wednesday

Time	Session	Description	Location	Time slot
08:30	**Scoring, and example**	How to get results out of Fluka, and plot them, with examples	*Lanzhou University, Lanzhou, China*	08:30 - 09:30
09:30	**Low energy neutrons**	Neutrons below 20 MeV: how to deal with them	*Lanzhou University, Lanzhou, China*	09:30 - 10:30
10:30	**Coffee break**		*Lanzhou University, Lanzhou, China*	10:30 - 11:00
11:00	**Exercise: Low energy neutrons**	Apply what you learned about neutrons	*Lanzhou University, Lanzhou, China*	11:00 - 13:00
13:00	**Lunch break**		*Lanzhou University, Lanzhou, China*	13:00 - 14:30
14:30	**Biasing**	How to improve speed, and discover hidden results	*Lanzhou University, Lanzhou, China*	14:30 - 15:30
15:30	**Exercise: Biasing**	Experience by yourself the power of biasing	*Lanzhou University, Lanzhou, China*	15:30 - 16:30
16:30	**Coffee break**		*Lanzhou University, Lanzhou, China*	16:30 - 17:00
17:00	**Exercise: Biasing (continued)**	Neeed help? ASK!!!	*Lanzhou University, Lanzhou, China*	17:00 - 18:00

Agenda: Thursday

Time	Session	Description	Location	Hours
08:30	**Physics models II:EM interactions**	Learn how FLUKA deals with electrons and photons	*Lanzhou University, Lanzhou, China*	08:30 - 09:30
09:30	**Ionization and transport**	Learn about charged particle transport, and how to optimize your simulation	*Lanzhou University, Lanzhou, China*	09:30 - 10:30
10:30	**Coffee break**		*Lanzhou University, Lanzhou, China*	10:30 - 11:00
11:00	**Exercise: Cutoffs**	Work with particle thresholds and more	*Lanzhou University, Lanzhou, China*	11:00 - 13:00
13:00	**Lunch break**		*Lanzhou University, Lanzhou, China*	13:00 - 14:30
14:30	**Heavy Ions**	How ion interact among themselves, and which options you need	*Lanzhou University, Lanzhou, China*	14:30 - 15:30
15:30	**Medical applications I**	Processes and input cards for medical applications	*Lanzhou University, Lanzhou, China*	15:30 - 16:30
16:30	**Coffee break**		*Lanzhou University, Lanzhou, China*	16:30 - 17:00
17:00	**Medical applications II**	Guided application to a therapy-like example	*Lanzhou University, Lanzhou, China*	17:00 - 18:00

Agenda: Friday

Time	Session	Description	Location	Hours
08:30 - 09:30	**Radioactivity**	How to calculate activation of materials, residual doses, inventory, time evolution	*Lanzhou University, Lanzhou, China*	08:30 - 09:30
09:30 - 10:30	**Exercise: Activation**	Apply	*Lanzhou University, Lanzhou, China*	09:30 - 10:30
10:30 - 11:00	**Coffee break**		*Lanzhou University, Lanzhou, China*	10:30 - 11:00
11:00 - 12:00	**Exercise: Activation (continued)**		*Lanzhou University, Lanzhou, China*	11:00 - 12:00
12:00 - 13:00	**Advanced topics**	What you can learn in the advanced course…	*Lanzhou University, Lanzhou, China*	12:00 - 13:00
13:00 - 14:30	**Lunch break**		*Lanzhou University, Lanzhou, China*	13:00 - 14:30
14:30 - 15:30	**Handling of errors and crashes**	Examples of common errors and their solution	*Lanzhou University, Lanzhou, China*	14:30 - 15:30
15:30 - 16:30	**User cases, Q&A**	Free discussion, bring your examples,	*Lanzhou University, Lanzhou, China*	15:30 - 16:30
16:30 - 17:00	**Coffee break**		*Lanzhou University, Lanzhou, China*	16:30 - 17:00
17:00 - 18:00	**User cases, Q&A**	Doubts, And wishes	*Lanzhou University, Lanzhou, China*	17:00 - 18:00
18:00 - 18:10	**Closing**		*Lanzhou University, Lanzhou, China*	18:00 - 18:10

Course material

- All the material for this course is available in the usb stick you received
  - Lectures : the presentations
  - Exercises: subdirectories with
    - Instruction
    - Input files
    - Flair files
- Solutions are also there, try not to look at them until the end of the dedicated time.
- Do NOT work on the usb: always create a new directory for each example/exercise

Exercises

- Exercises will be on your own
- With a description to guide you
- And an input file to start with
- Teachers and support will be around, call us if you need help

- Also during lectures, if you have doubts please do not be shy, ***ask!***

Thanks for your attention!