MonteCarlo benchmarking: validation and progress

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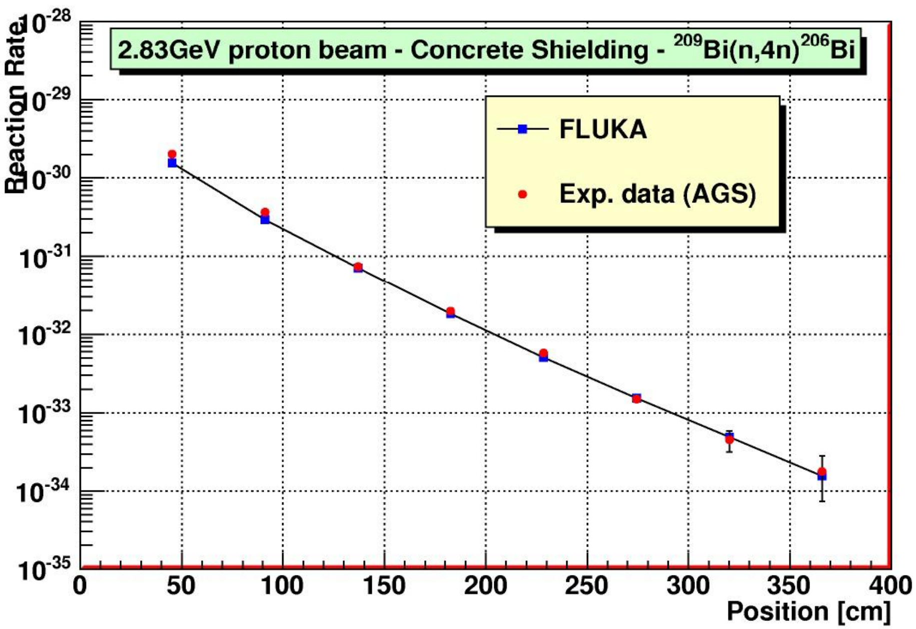
Outline

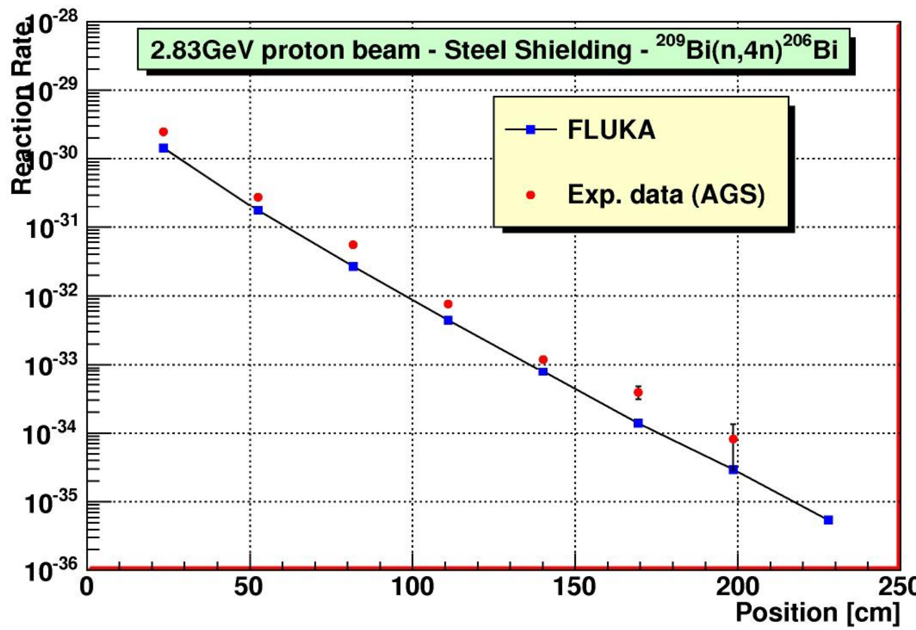
New frontiers for MonteCarlo simulations

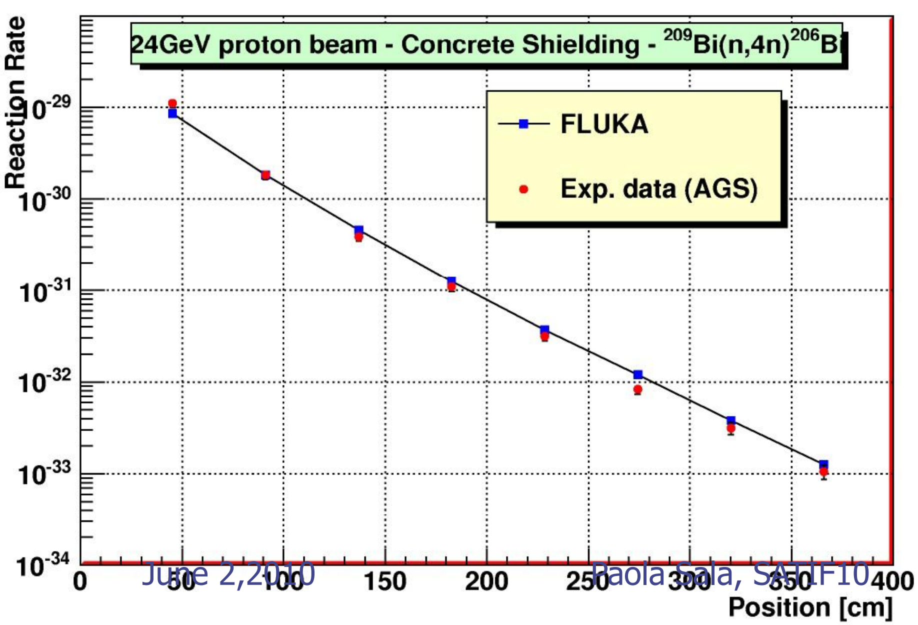
- High intensity accelerators
  - Deep penetration - tails of distributions, biasing
  - Damage to electronics - dose, 1MevEq, see..
  - Damage to materials – DPA
  - Activation – details of hadronic models
- Ion beams
  - ion-ion interactions
- Applications to therapy –
  - the patient is the target, protect the target
- Bright electron accelerators
  - Hadron and muon production becomes important – Photonuclear and photo-muon production
  - All the problems of hadron accelerators.

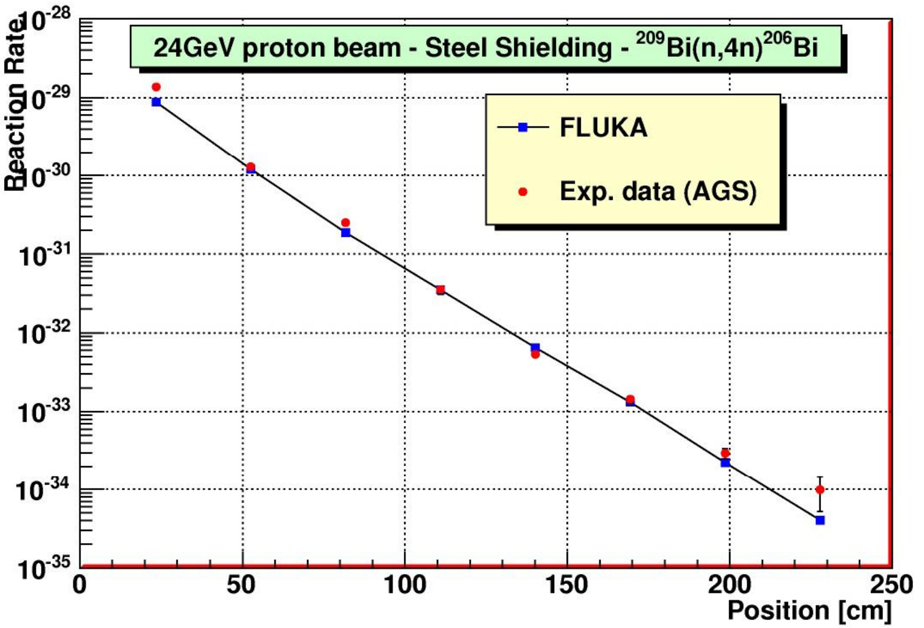
Benchmarking is essential to validate and improve MC models (well, this is trivial..)

Deep penetration : AGS benchmark (see dedicated talk)





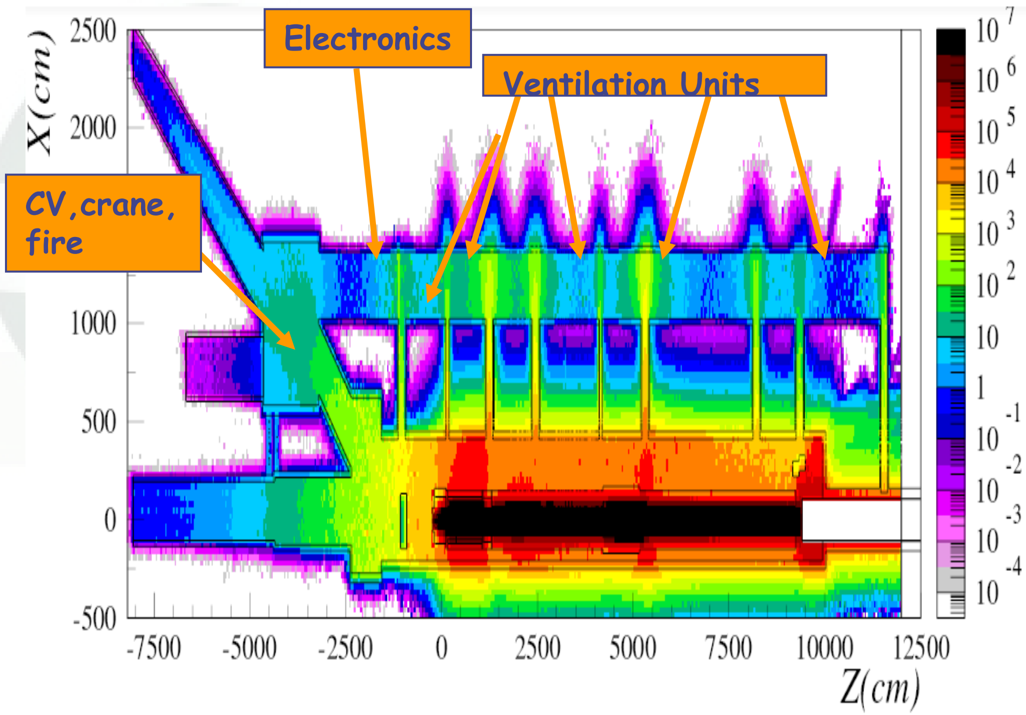




An example of damage to Electronics: Cern Neutrino to Gran Sasso

2007 run: Single event upsets in ventilation electronics: caused ventilation control failure and interruption of communication

2007 Physics run : 8 10^{17}p.o.t. delivered (≈2% of a "CNGS nominal year")

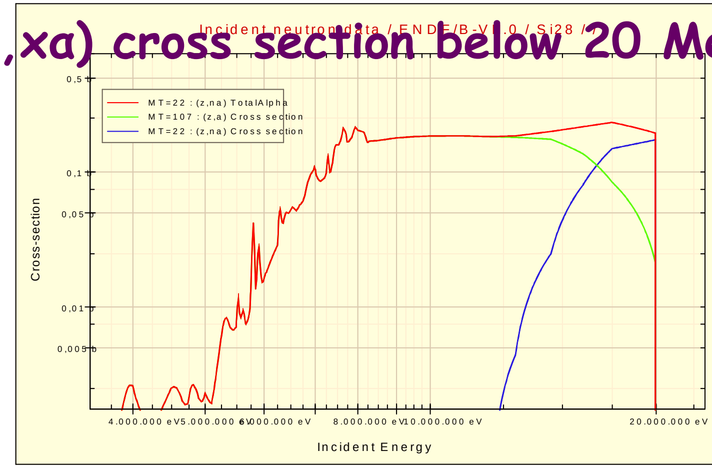


Predicted dose levels
In agreement with measurements

Gy/yr for a nominal CNGS year of 4.5 10^{19} pot @ 400 GeV

Not only dose

$^{28}Si(n,x\alpha)$ cross section below 20 MeV:



- Cumulative damage comes from
  - Energy deposition (dose)
  - Displacement (1-MeV equivalent particle fluxes)
- Stochastic failures can occur (SEE) like in CNGS
- Custom assumption: SEE mostly due to “high” energy hadrons (E>20 MeV)
- ➢ However:
- ➢ No reason for a sharp threshold at 20 MeV
- ➢ Alphas produced by various mechanisms are well known sources of SEEs
- ➢ Alphas from ***(n,xα)*** reactions should make no exception (see ex. on Si)
- ➢ Even thermal neutrons can induce SEU through ***(n,xα)*** reactions
- → Need for analog description of all interactions, even low-E neutrons, in MC
- → Need for calibration of monitors in different particle fields

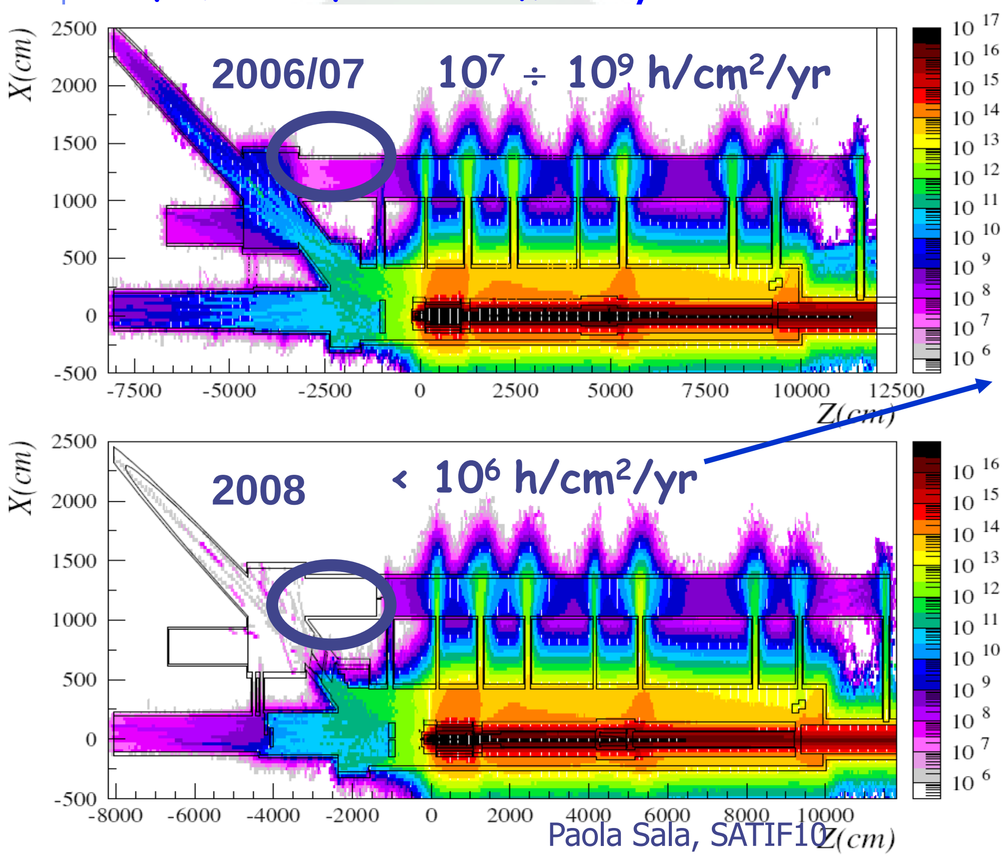
Radiation issues solved

Modifications during shutdown 2007/08:

move as much electronics as possible out of CNGS tunnel area

Create radiation safe area for electronics which needs to stay in CNGS

High-E (>20 MeV) hadron fluence for a nominal year



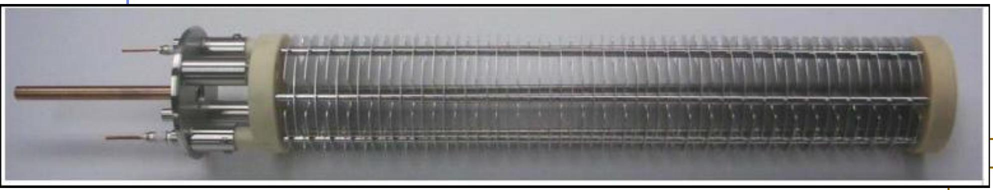
Simulated shielding attenuation factors between 10^3 and 10^6 for

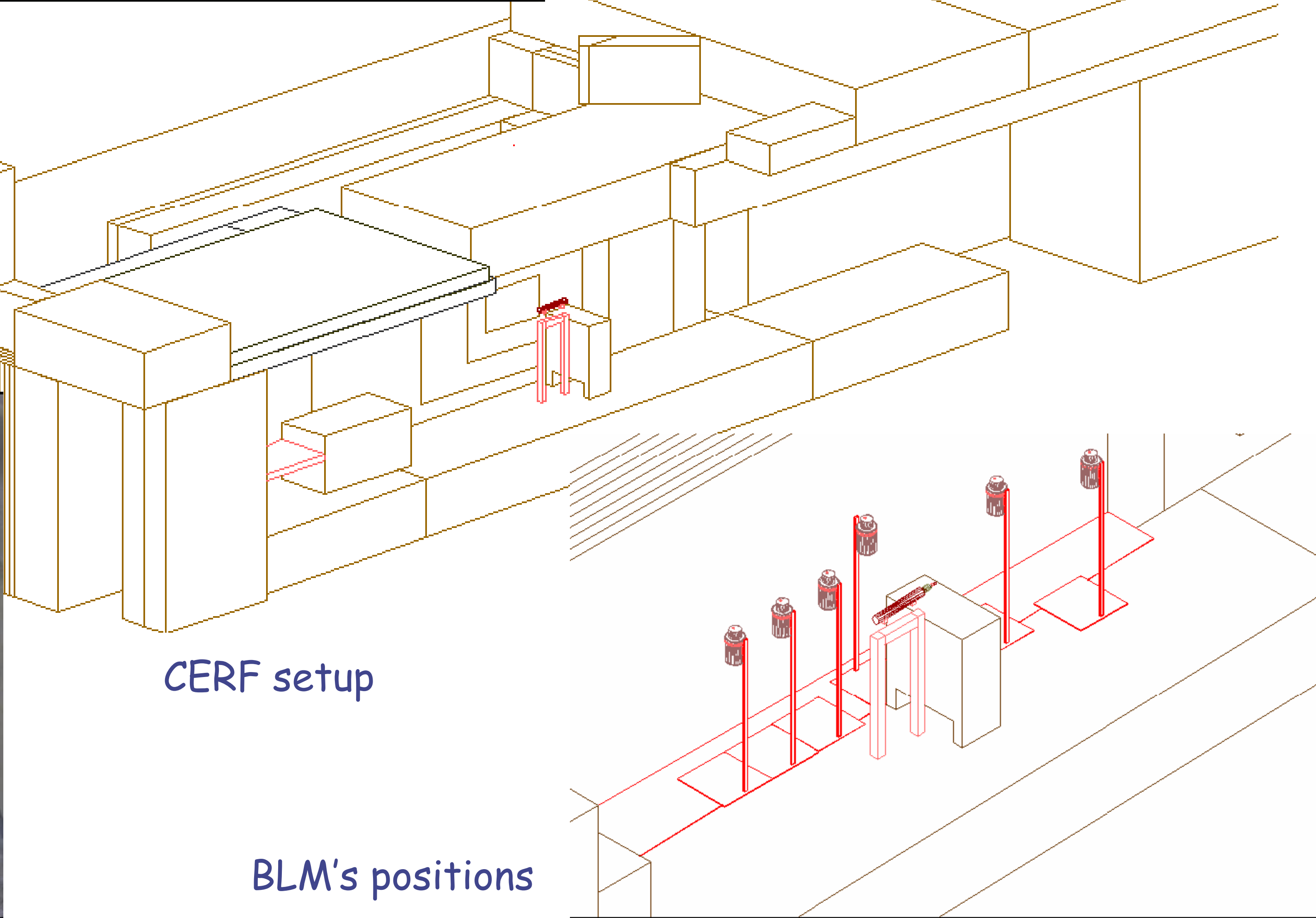
- Absorbed dose
- 1-MeV equivalent neutrons
- High energy hadrons

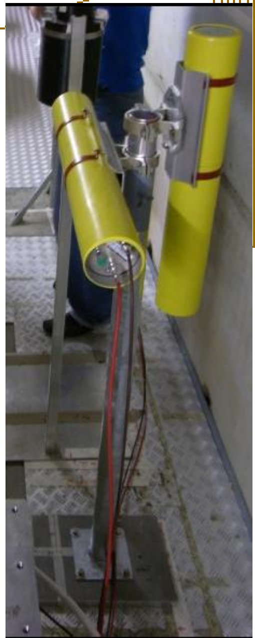
for comparison: h >20MeV from cosmic rays at sea level : $\approx 10^4$-10^5/ cm²/y

Test of instrumentation : Beam Loss Monitors at CERF

CERN-EN-NOTE-2010-002-STI



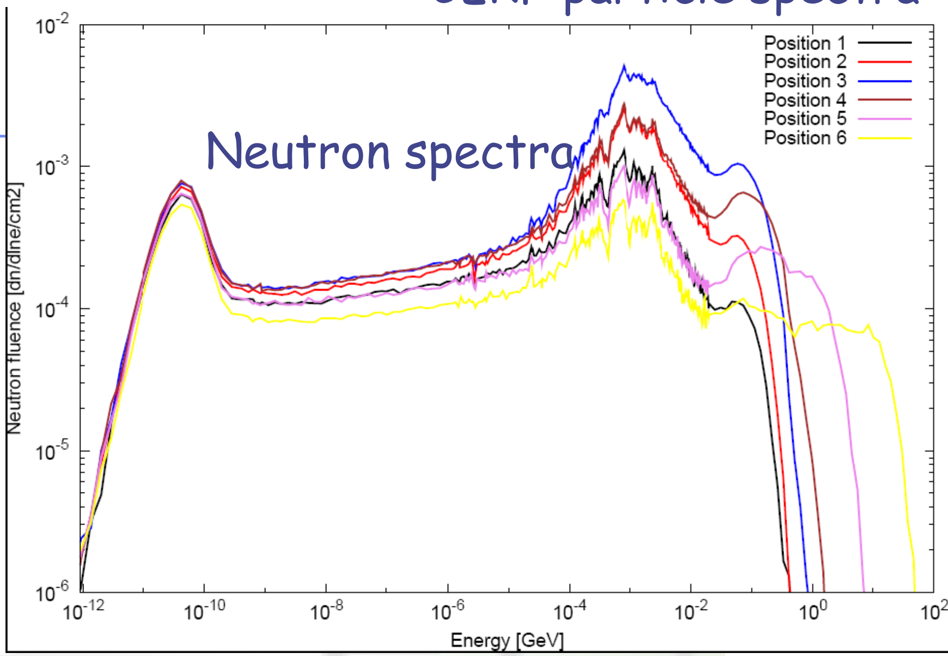


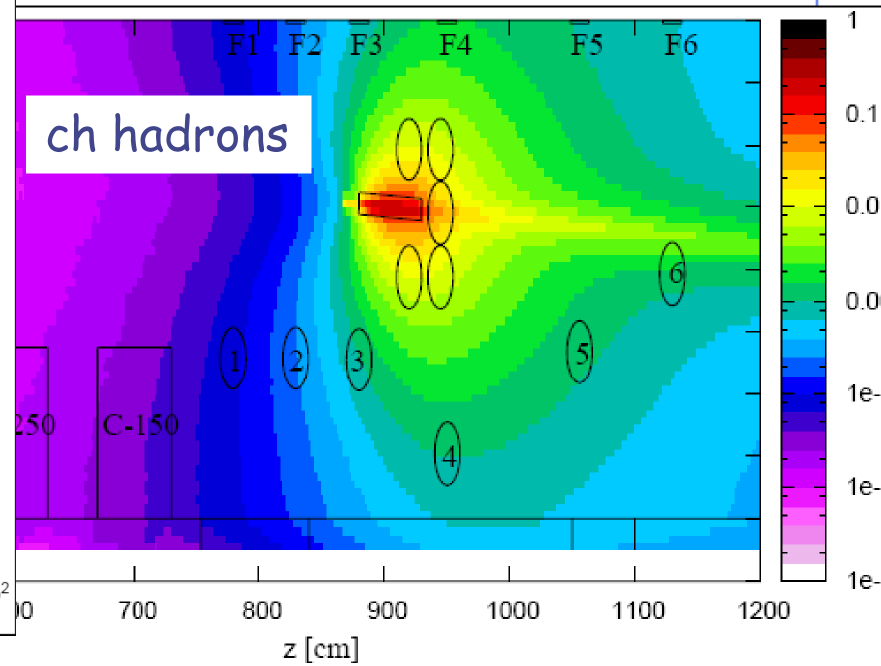


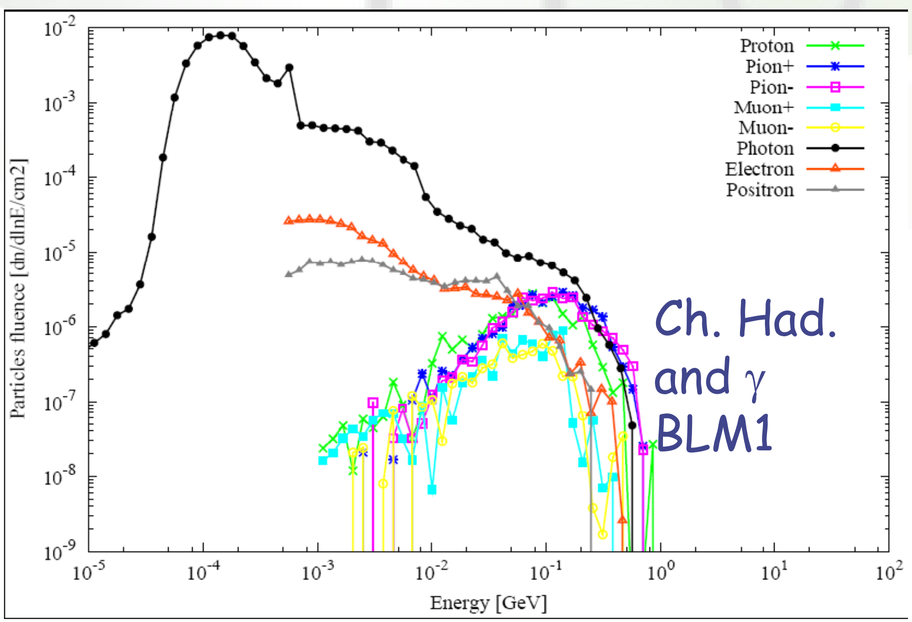
CERF setup

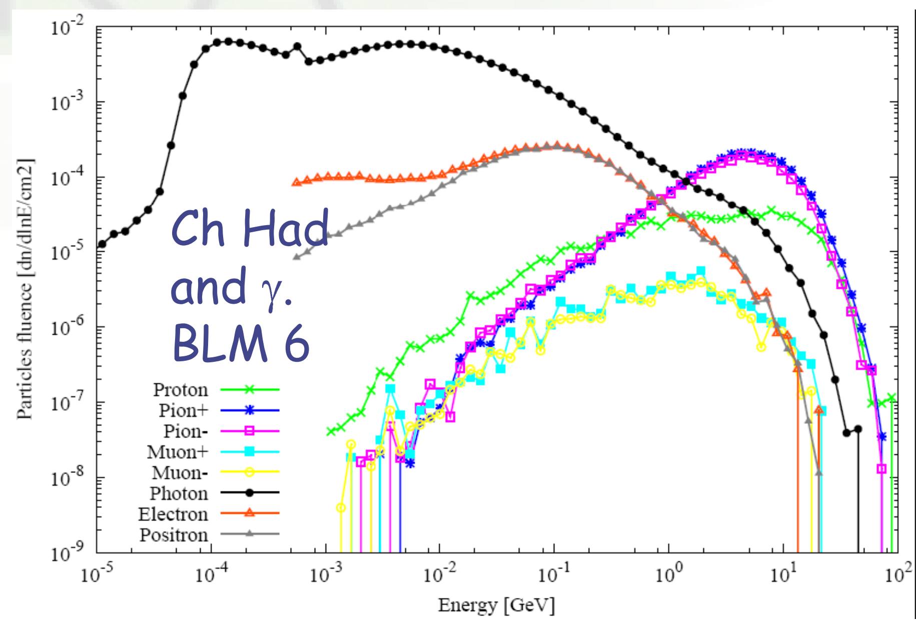
BLM's positions

CERF particle spectra









BLM config	Position	FLUKA/meas	Error [%]
Horizontal cables downstream	1	1.24	5.5
	2	1.07	3.2
	3	1.24	3.4
	4	1.02	1.4
	5	1.22	0.7
Horizontal Cables upstream	1	0.94	4.6
	2	1.04	4.1
	3	1.11	1.5
	4	1.07	1.8
	5	1.21	0.8
	6	1.08	1.3
Vertical cables down	4	1.06	1.7
	5	1.22	1.6
	6	1.08	1.9
Cadmium wrapped Horizontal	4	1.06	5.5
	5	1.22	2.7
	6	1.13	5.0

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 the NIEL (non ionizing energy loss)

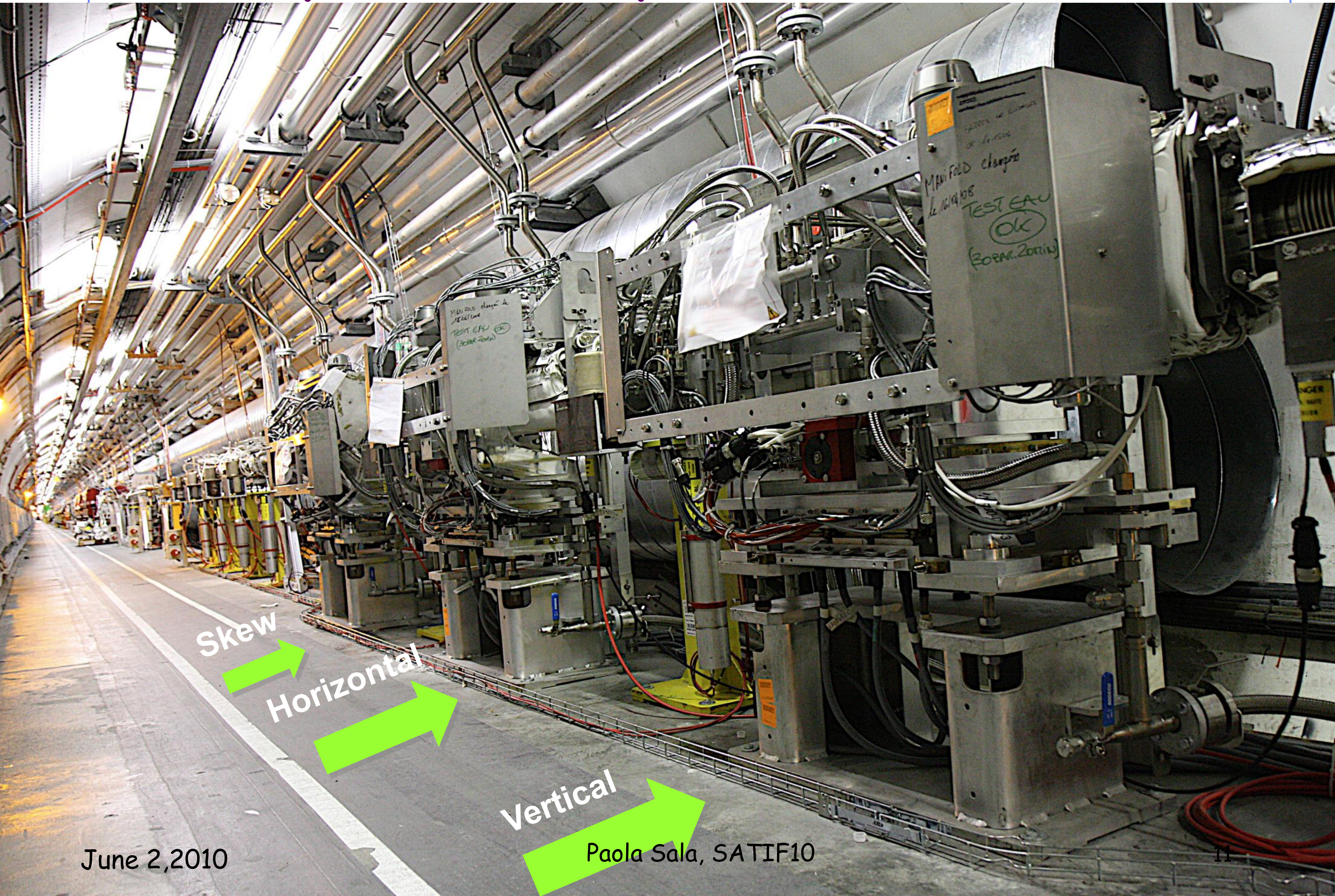
$$dpa \div \kappa \frac{\xi(T)T}{2E_{th}}$$

T=energy of the recoil

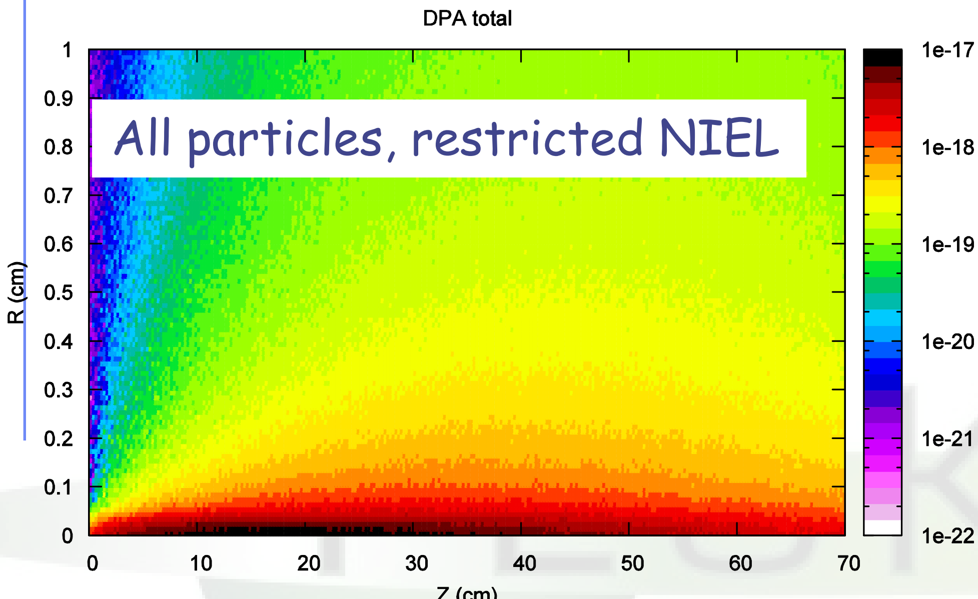
Displacement threshold

- 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}

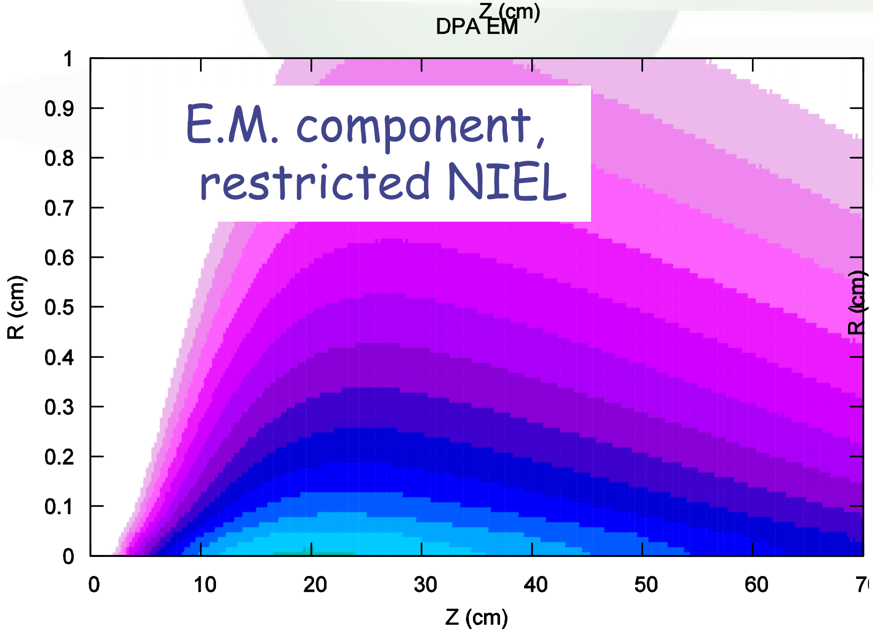
Example: 3 Primary Collimators IR7

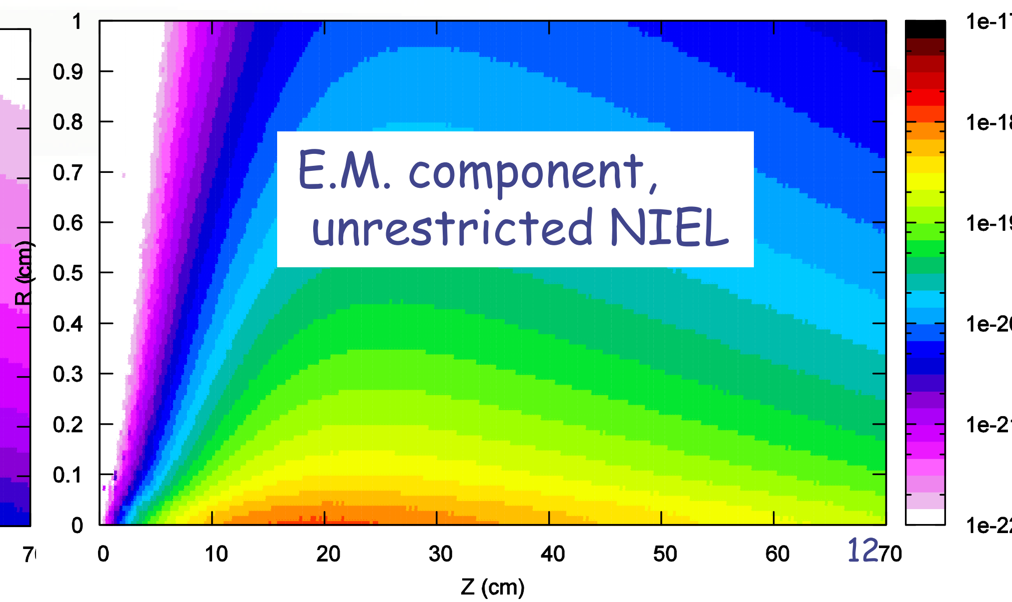


Studies of the radiation damage to the LHC copper collimators



Estimated number of DPA per incident proton (beam size ~ accident case) on a copper jaw





Activation and residual dose

- Nuclear models, in particular evaporation but not only
- On-line evolution of activation, following irradiation and cooling profiles
- On-line calculation of residual dose from activation

Equilibrium particle emission in FLUKA

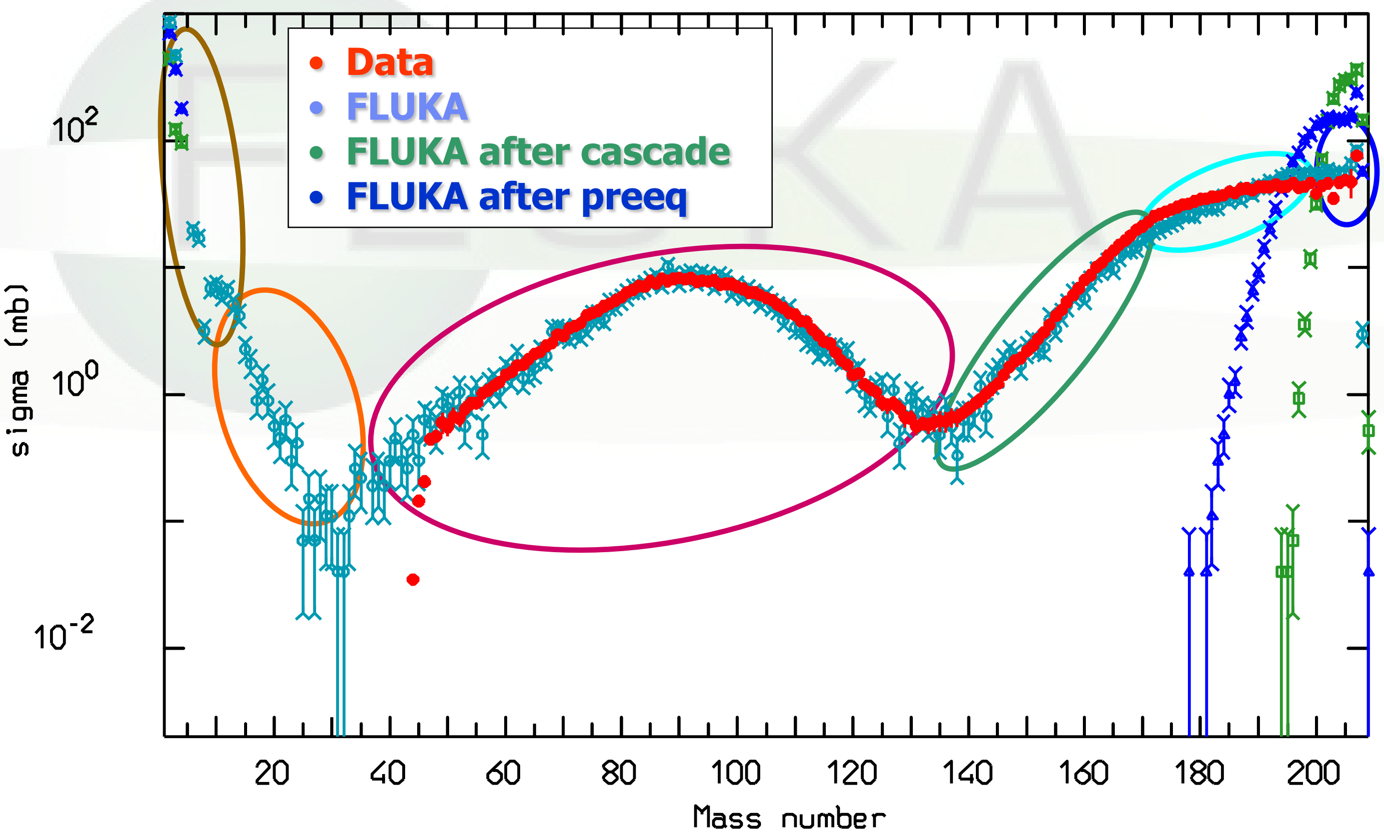
- Evaporation: Weisskopf-Ewing approach
  - ~600 possible emitted particles/states (A<25) with an extended evaporation/fragmentation formalism
  - Full level density formula with level density parameter A,Z and excitation dependent
  - Inverse cross section with proper sub-barrier
  - Analytic solution for the emission widths (neglecting the level density dependence on U, taken into account by rejection)
  - Emission energies from the width expression with no approximation
- Fission: past, improved version of the Atchison algorithm, now
  - Γ_{fis} based of first principles, full competition with evaporation
  - Improved mass and charge widths
  - Myers and Swiatecki fission barriers, with exc. en. dependent level density enhancement at saddle point
- Fermi Break-up for A<18 nuclei
  - ~ 50000 combinations included with up to 6 ejectiles
- γ de-excitation: statistical + rotational + tabulated levels

> In ALL reaction steps, from first interaction to last γ :
> Exact energy conservation
> including binding energy and recoil of residual nucleus

Example of fission/evaporation

- Quasi-elastic products
- Spallation products
- Deep spallation products
- Fission products
- Fragmentation products
- Evaporation products

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



Example of fission/evaporation

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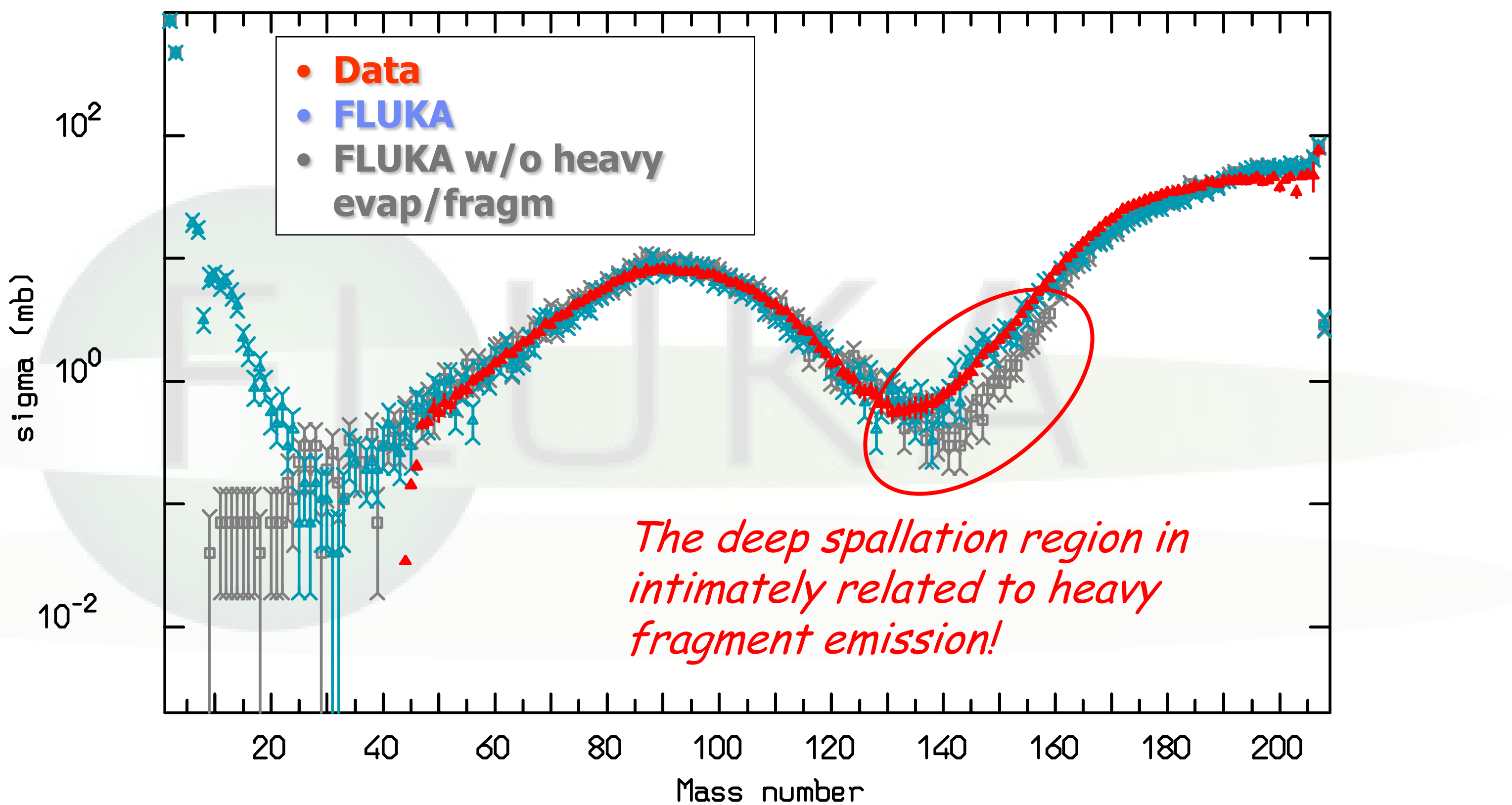


FLUKA *standard,* and *without heavy evaporation/fragmentation*

Preequilibrium:

- The normal ("naïve") conditions for considering a system equilibrated enough to transition to equilibrium is (n = number of excitons, g=single particle level density, E^*=excitation energy):

$$n \geq n_{eq} = \sqrt{gE^*}$$

- Veselski (NPA705, 193, (2002)), analyzing heavy ion reactions has proposed that the probability of pre-equilibrium emission for a given reaction stage is evaluated randomly for $n<n_{eq}$, according to (a=level density parameter, σ in the range 0.2-0.4):

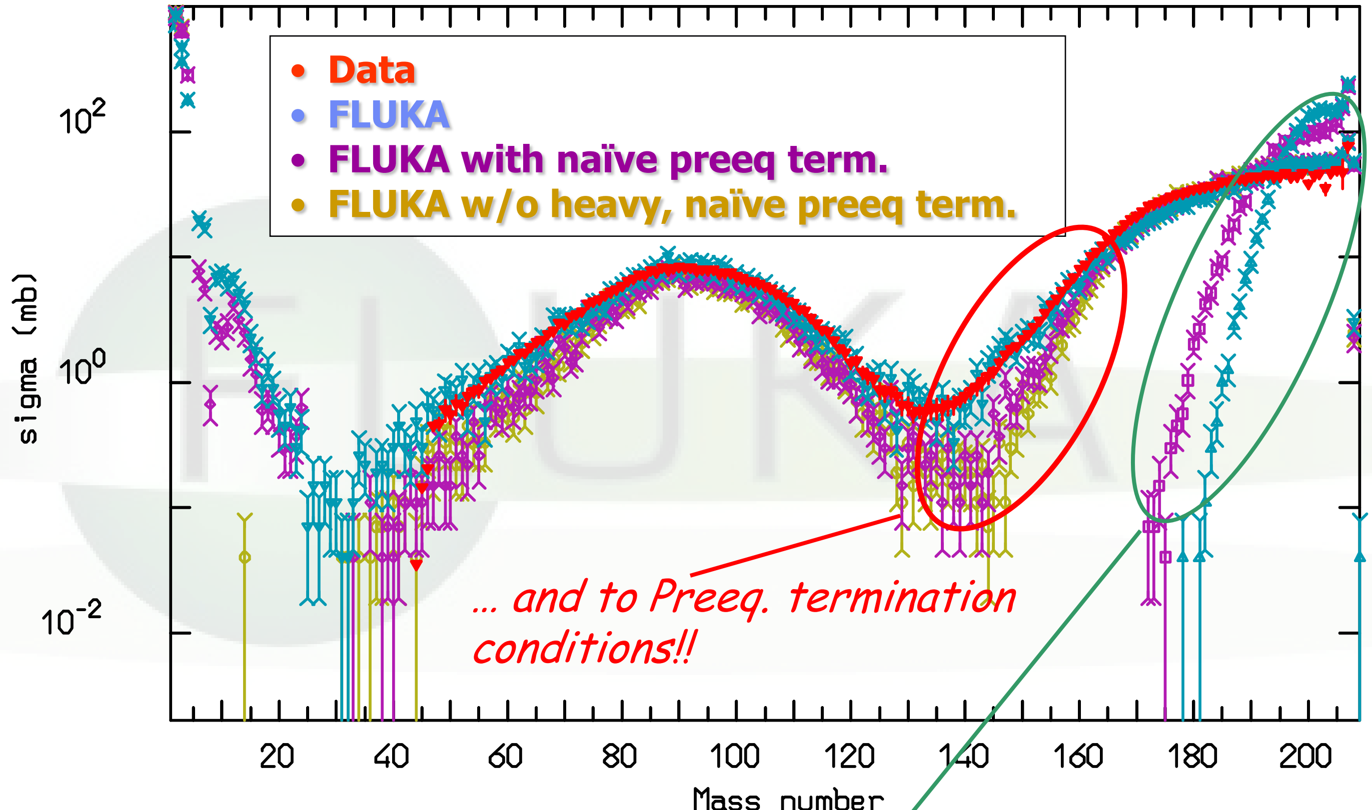
$$P = 1 - e^{-(n/n_{eq}-1)^2/(2\sigma^2)}, \quad n_{eq} = 2gT\ln(2), \; T \approx \sqrt{E^*/a}$$

⇓

This recipe is physically much sounder than the yes/no of the naïve approach, and it is adopted in FLUKA

Example of fission/evaporation

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



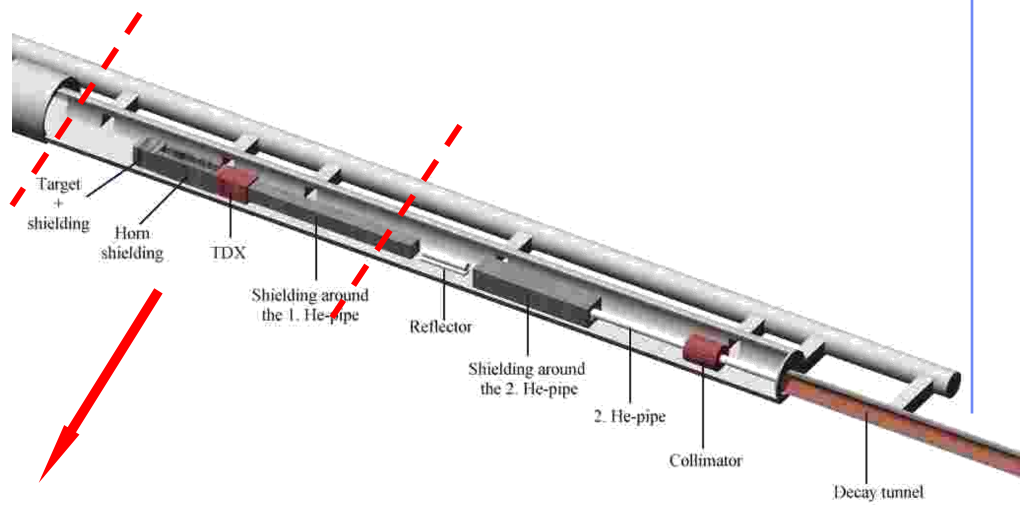
Mass distributions at preequilibrium termination: when preequilibrium is pushed too far too much excitation energy is spent in the emission of particles at energies which are better dealt with by evaporation. Heavy fragment evaporation suffers as well

Online evolution and buildup

- Custom irradiation/cooling down profiles defined by the user of (almost) unlimited complexity
- … residuals produced during the "prompt" part either by "high" energy models, or by "low" energy neutrons processed online
- … time evolution of induced radioactivity calculated analytically with extended Bateman equations
  - Fully coupled build-up and decay
  - Up to 4 different decay channels per isotopes
- Beta and gamma radiation from residual nuclei produced and transported in the same run as the prompt radiation,

Results available for activities and dose : 2D and 3D spatial distributions, and full inventories/activities at each buildup/cooling time

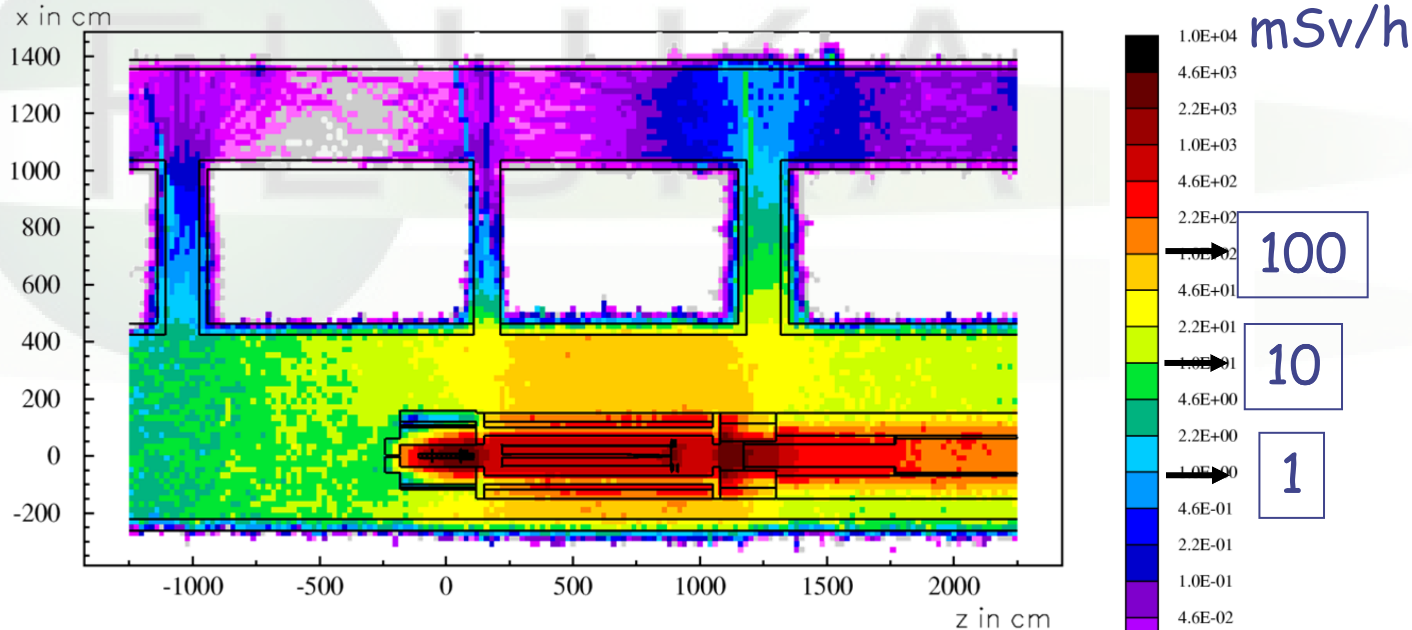
Applications – *CNGS*



Residual dose rate (mSv/h)

Example:

t_{cool} = 1 day



M. Lorenzo-Sentis et al.,
CERN-Open-2006-013/16

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

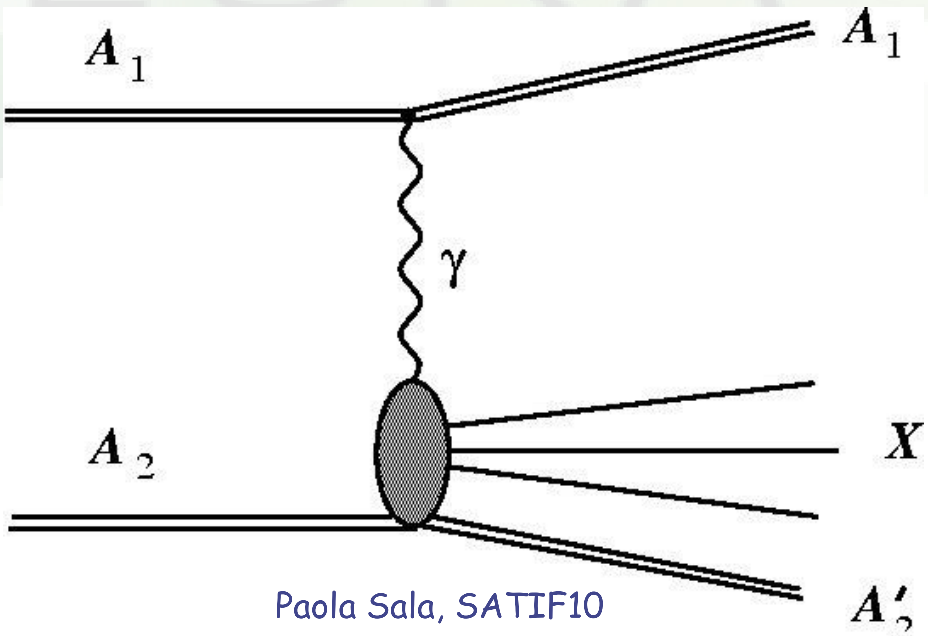
Ion fragmentation at LHC:

- LHC will also run ^{208}Pb beams at 2760 GeV per nucleon
- Pb ion interactions with collimators will be a source of extra hazards relative to proton beams
- Fragments generated in interactions with collimators etc. will travel possibly for long distances in the machine
- Here an example of the effect of electro—magnetic dissociation

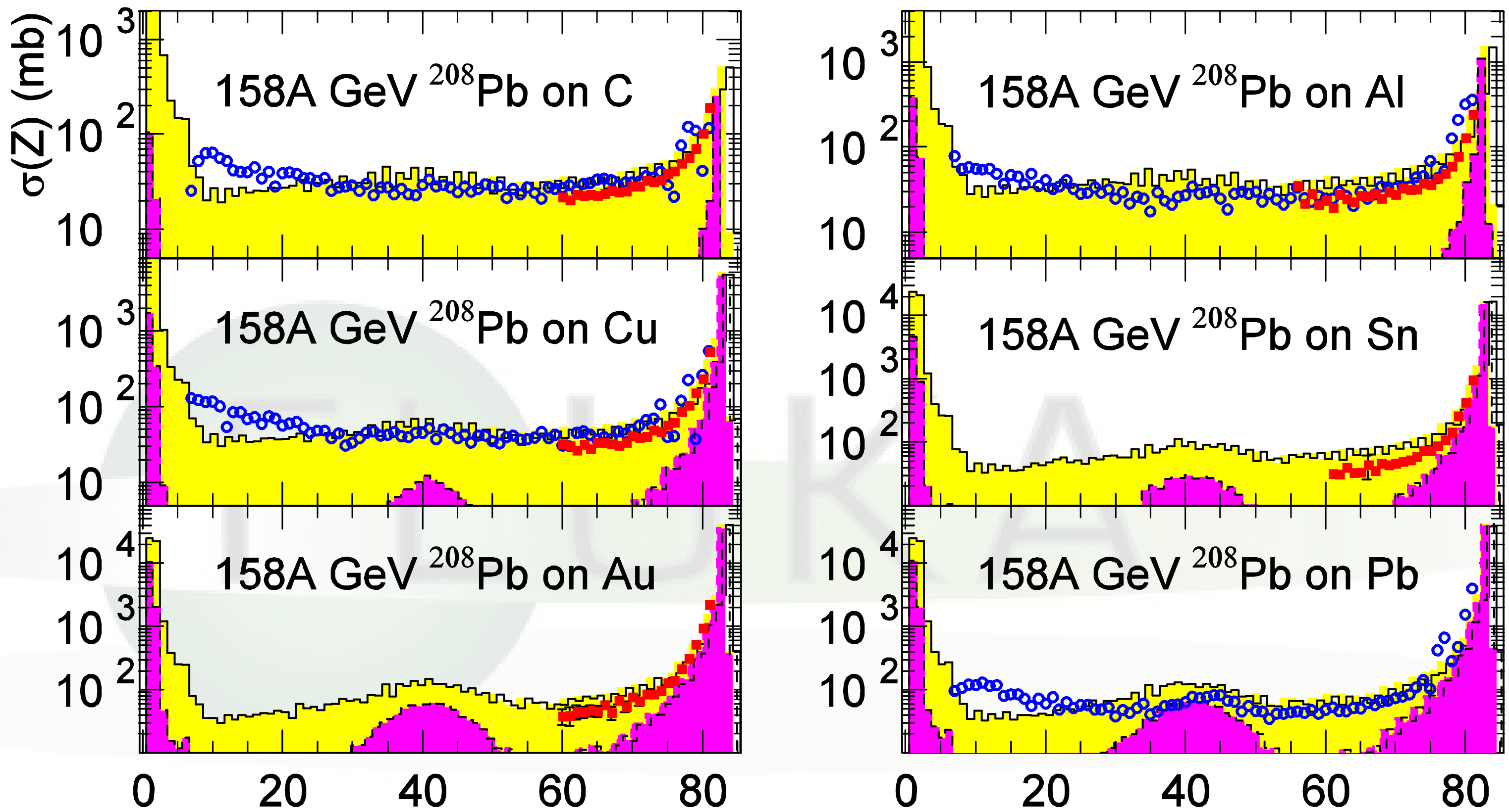
Electromagnetic dissociation

Electromagnetic dissociation: σ_{EM} increasingly large with (target) Z's and energy. Already relevant for few GeV/n ions on heavy targets (σ_{EM} ~ 1 b vs σ_{nucl} ~ 5 b for 1 GeV/n Fe on Pb)

$$\sigma_{1\gamma} = \int \frac{d\omega}{\omega} n_{A_1}(\omega) \sigma_\gamma n_{A_2}(\omega) \propto Z_1^2$$

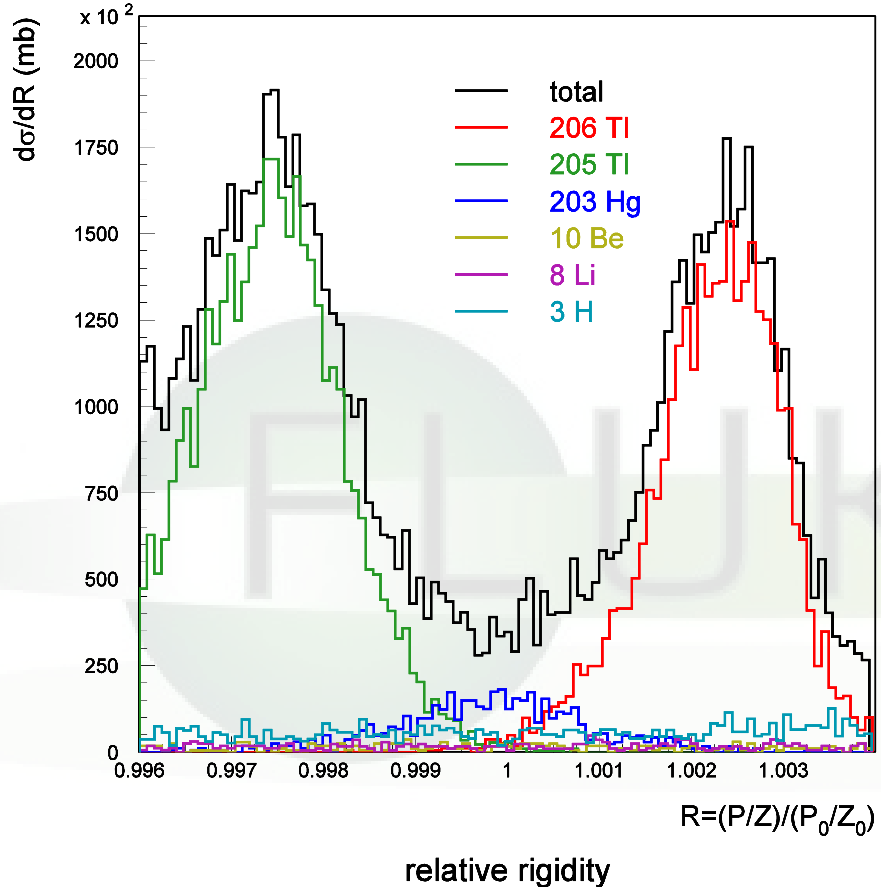


158 GeV/n Pb ion fragmentation



Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), *yellow* histos are FLUKA (with DPMJET-III) predictions: *purple* histos are the electromagnetic dissociation contribution

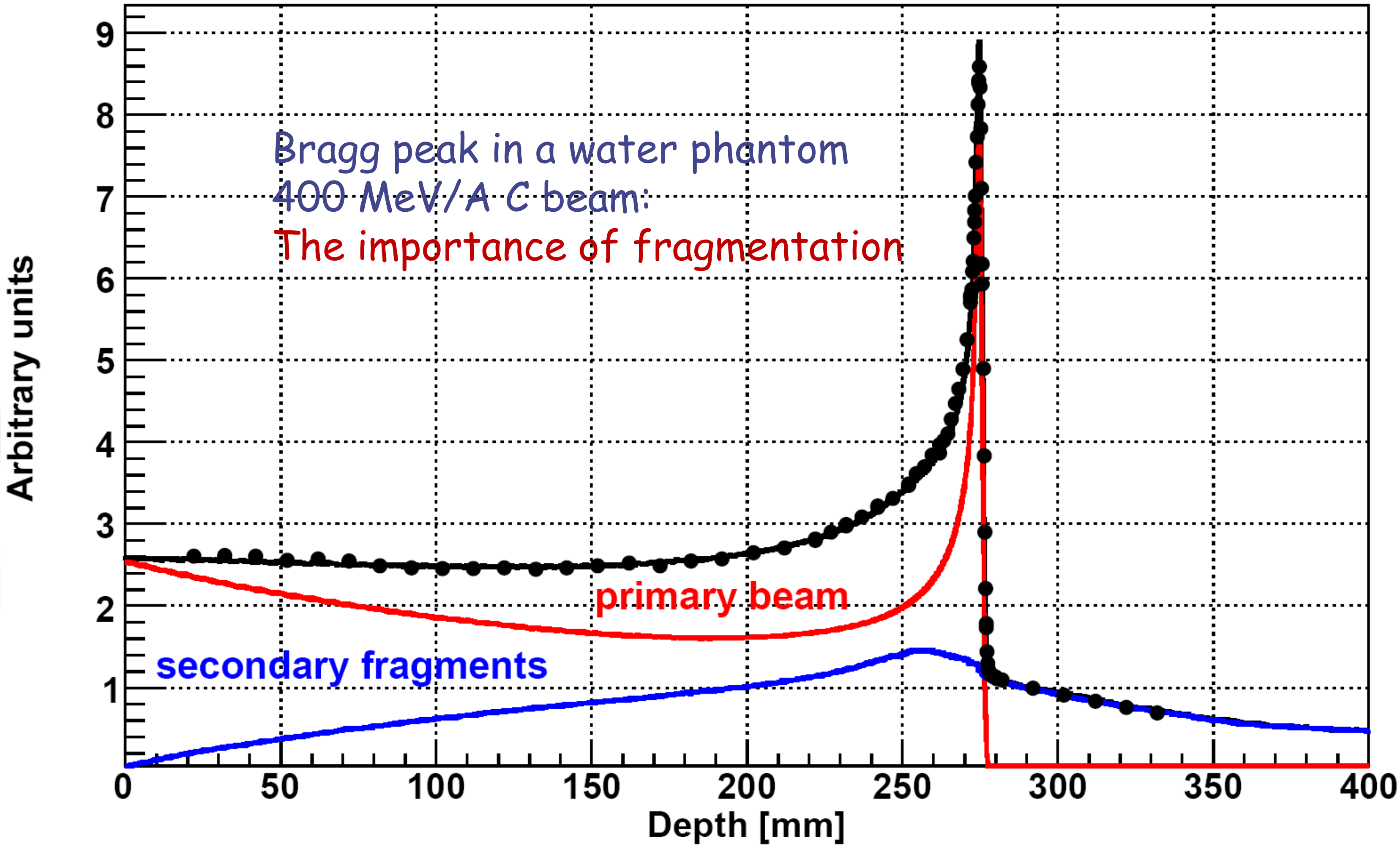
^{208}Pb ions @ 2760 AGeV on Tungsten



Close-up view around the beam rigidity of the normalized rigidity distribution of fragments, with contributions from the most important isotopes. From Pb interactions on W Note the contribution of light fragments and fragments near to projectile

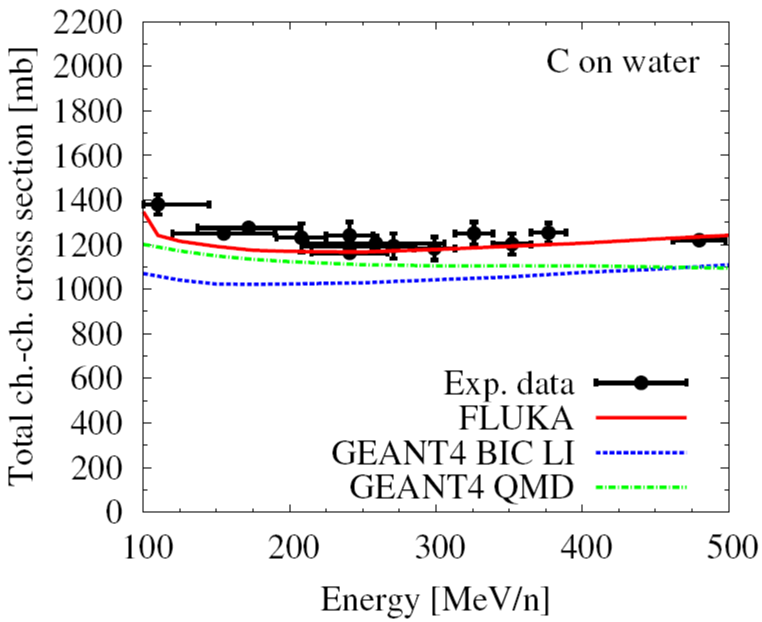
- fragments, i.e. from collimators, can "stay" in the same orbit as the primary beam
- Careful description of fragment production and of their energy distribution needed
- E.M dissociation is the most important process in this case

Carbon Ion Therapy



Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

Data collection and intercomparison in EC projects



Charge changing cross sections in water

T.T. Boehlen et al

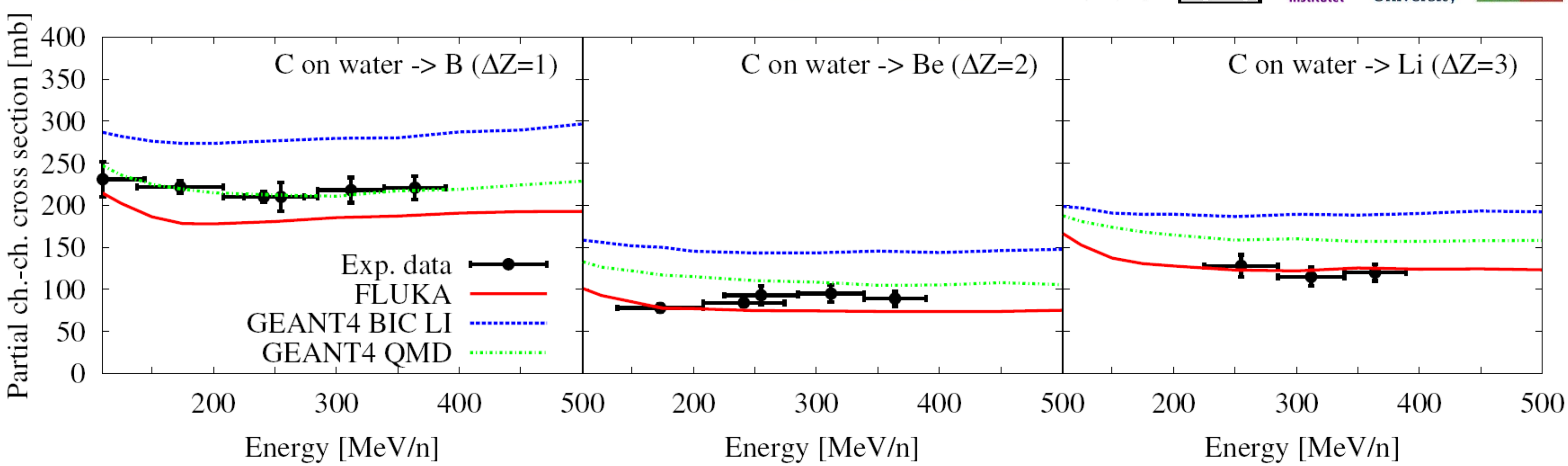
Benchmarking nuclear models of FLUKA and GEANT4 for carbon ion therapy

Submitted to Phys. Med. Bio.

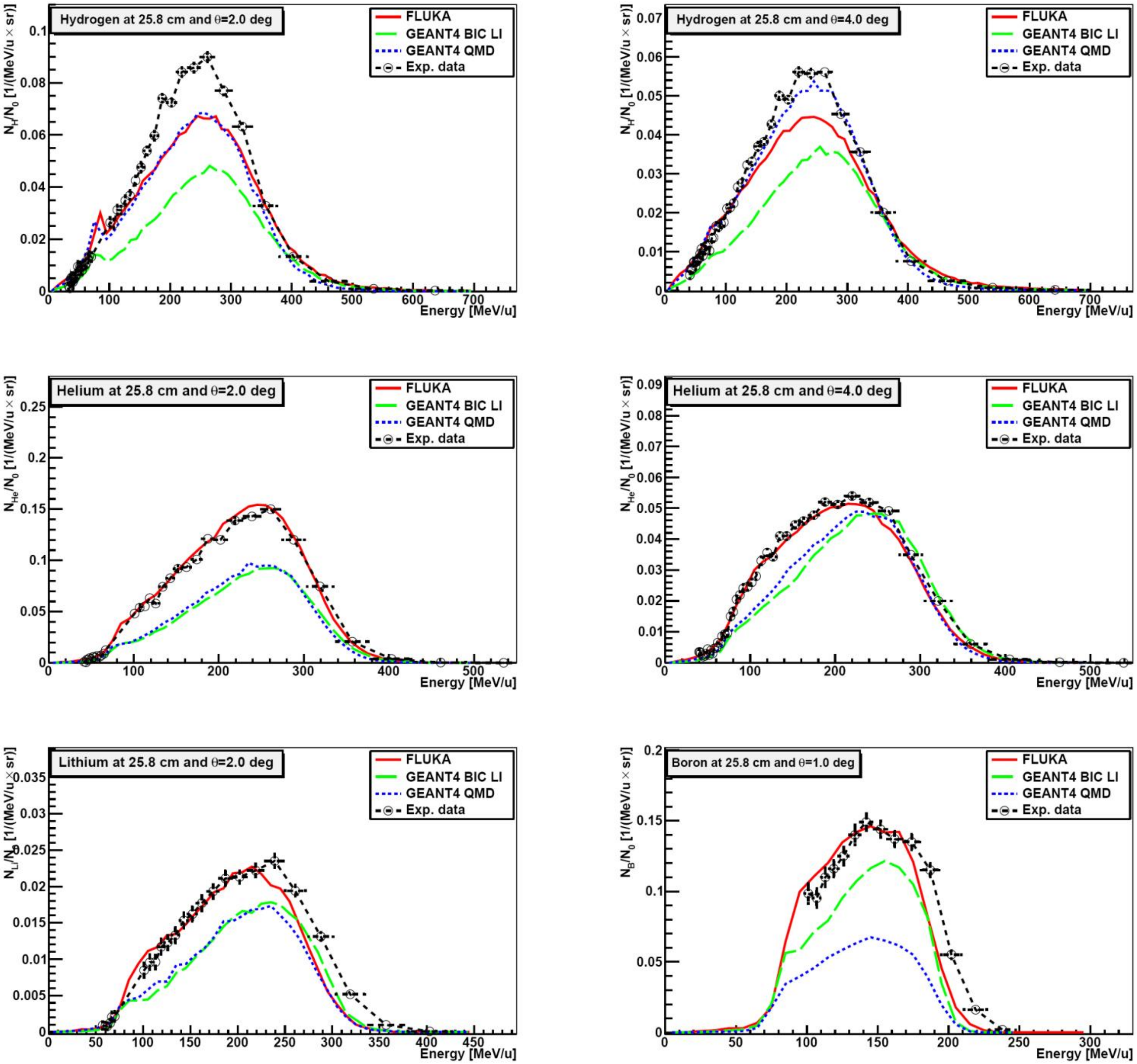
PARTNER

Karolinska Institutet

Stockholm University



Data collection and intercomparison in EC projects

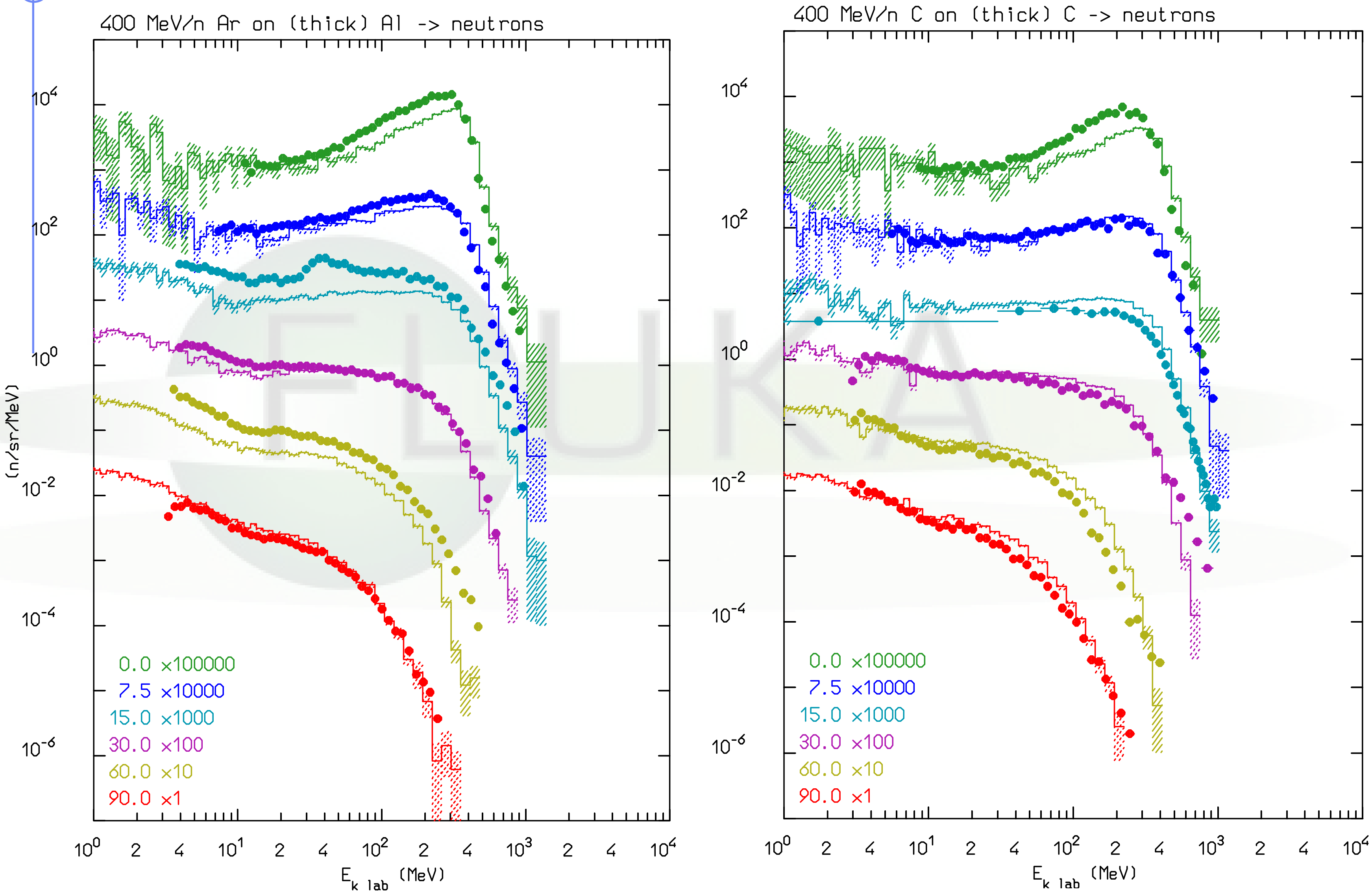


Fragment spectra from a 400MeV/u carbon beam in water.
Graphs are for a water-equivalent thickness of 25.8 cm at selected angles.
Measurements: Haettner 2006

Intermediate energy A-A: more comparisons

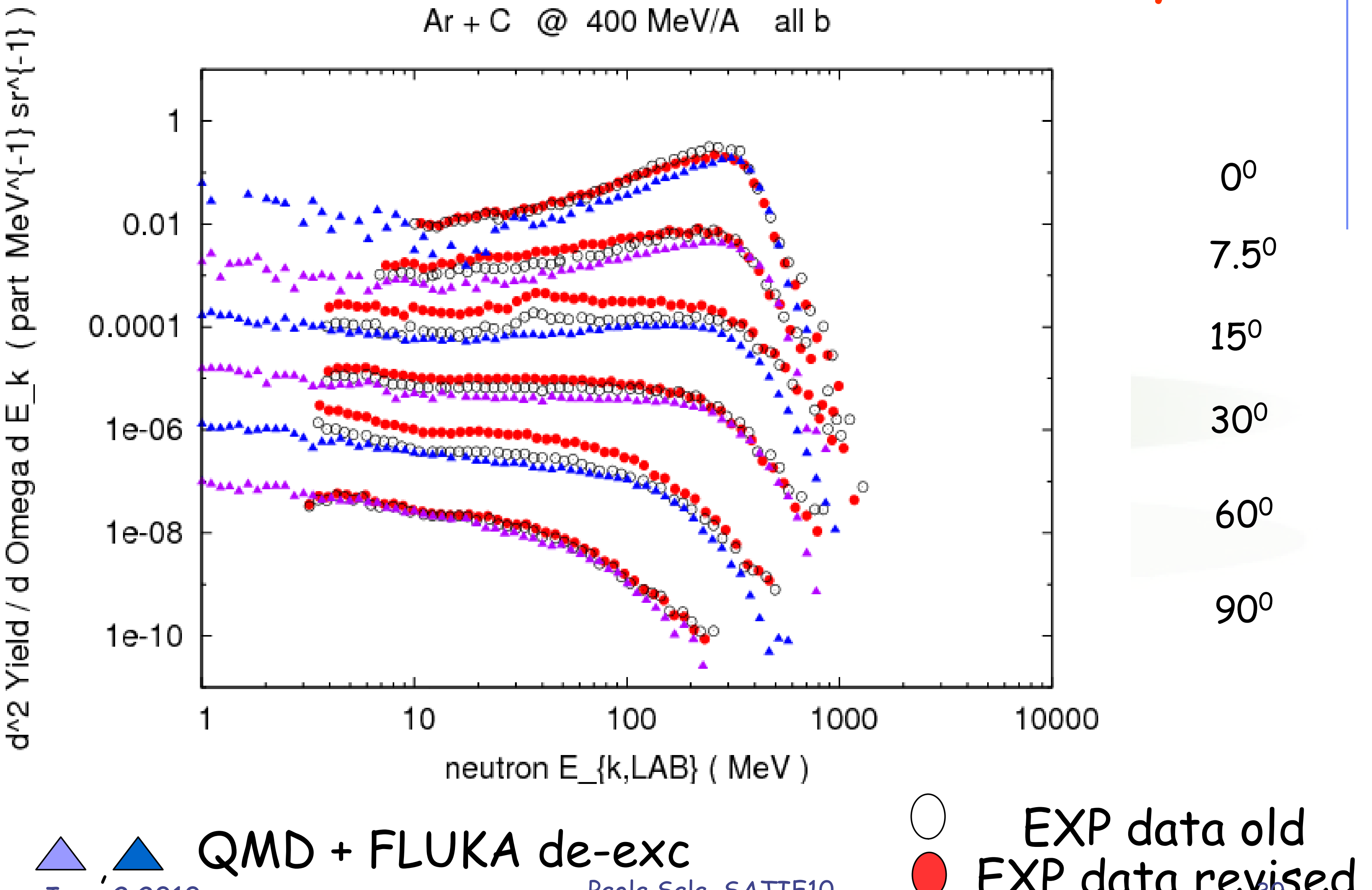
- neutron production data taken at the HIMAC (Heavy Ion Medical Accelarator in Chiba) at the National Institute of Radiological Science, Japan
- Thick targets: **projectile** **energy losses** in the target lead to its **stop** inside the target
- Several projectile/target combinations
- At 400 and 800 MeV/c
- Available in EXFOR and SINBAD databases
- **T. Satoh, T.Kurosawa, T. Sato et al. NIM A 583 (2007), 507 - 515 : Latest data and corrections to previous publications**
- Comparisons with PHITS in the same paper

In FLUKA :modified RQMD (E > 100 MeV/A)
BME (E < 100 MeV/A)

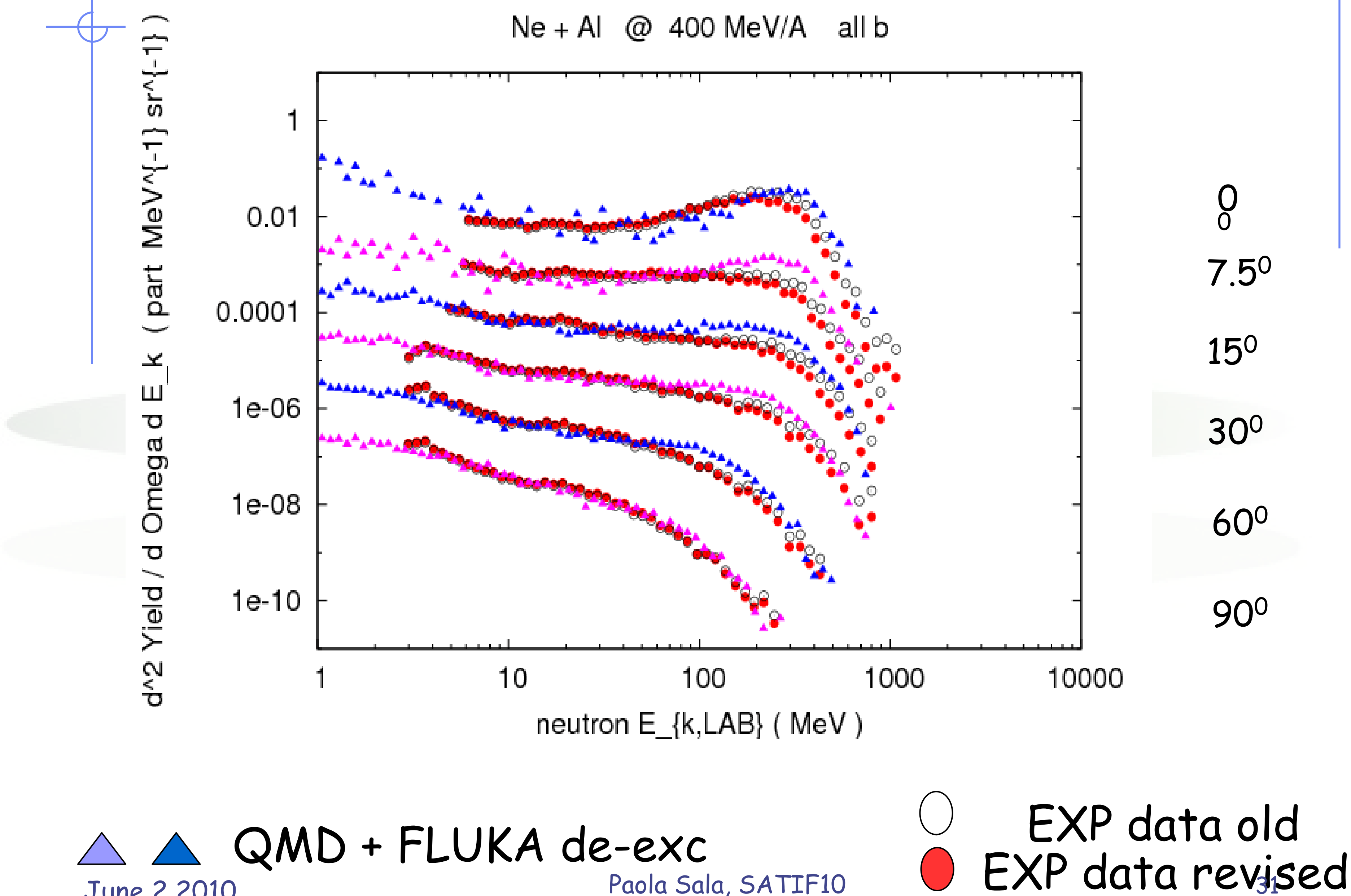


QMD (M.V. Garzelli et al), coupled to Fluka

Ar + C @ 400 MeV/A double differential n yield



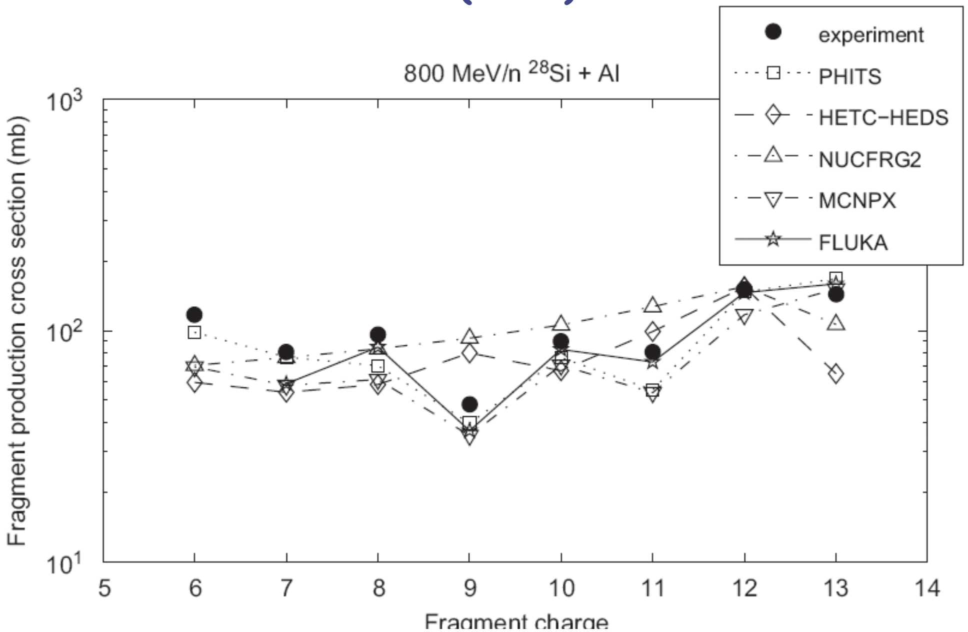
Ne + Al @ 400 MeV/A double differential n yield

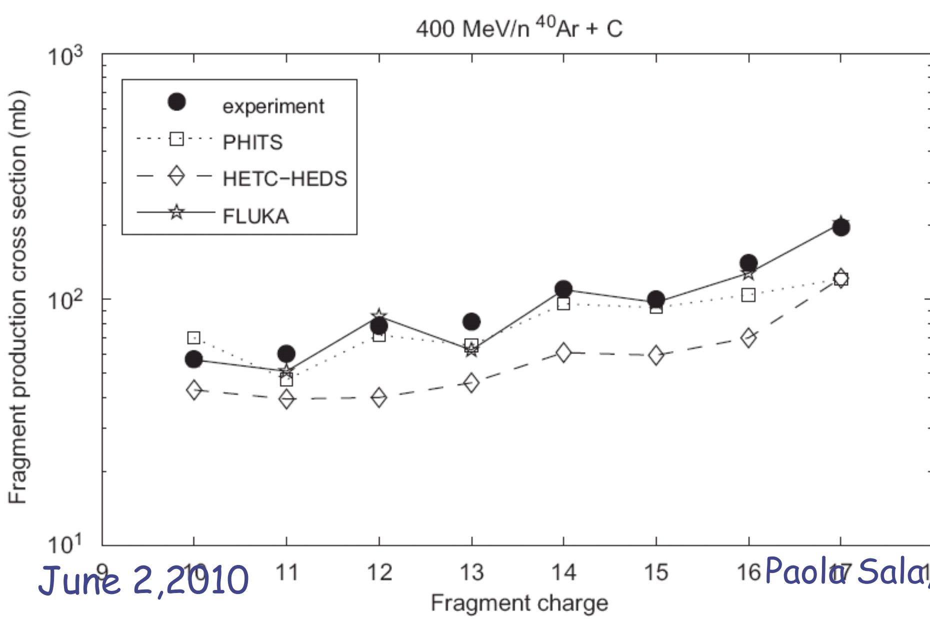


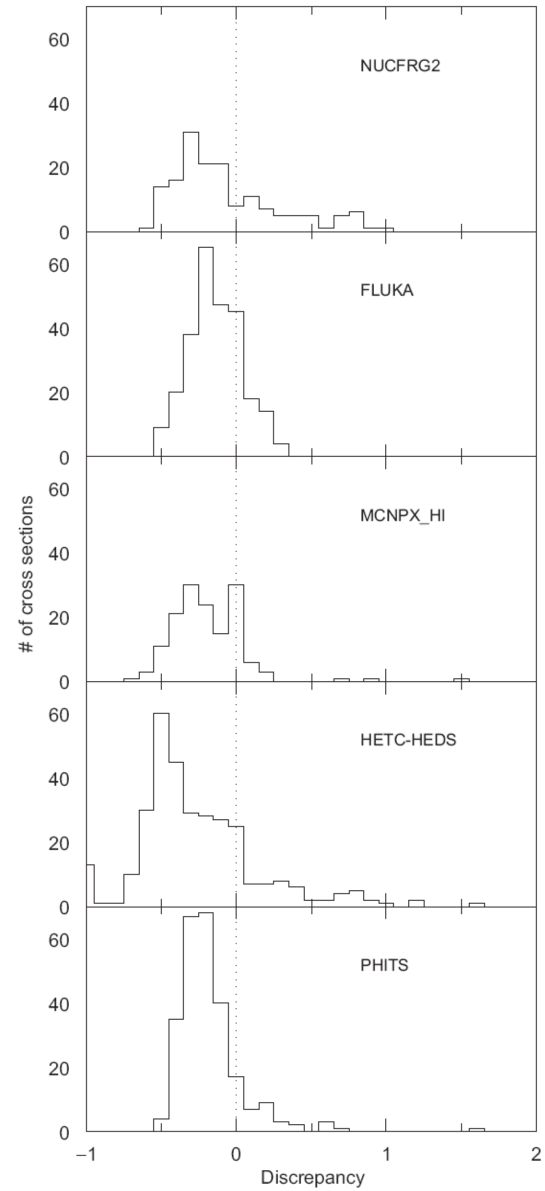
Intermediate energy benchmark

Acta Astronautica 63 (2008) 865 - 877

Measurements of the projectile fragmentation cross-sections by Zeitlin et al. at NASA (NSRL), AGS, BNL, and HIMAC







The low energy frontier

In FLUKA : implementation of the BME (Boltzmann master equation) code

two different reaction paths are considered

1. COMPLETE FUSION

$P_{CF}=\sigma_{CF}/\sigma_R$

pre-equilibrium
according to the BME theory

2. PERIPHERAL COLLISION

$P = 1 - P_{CF}$

work in progress

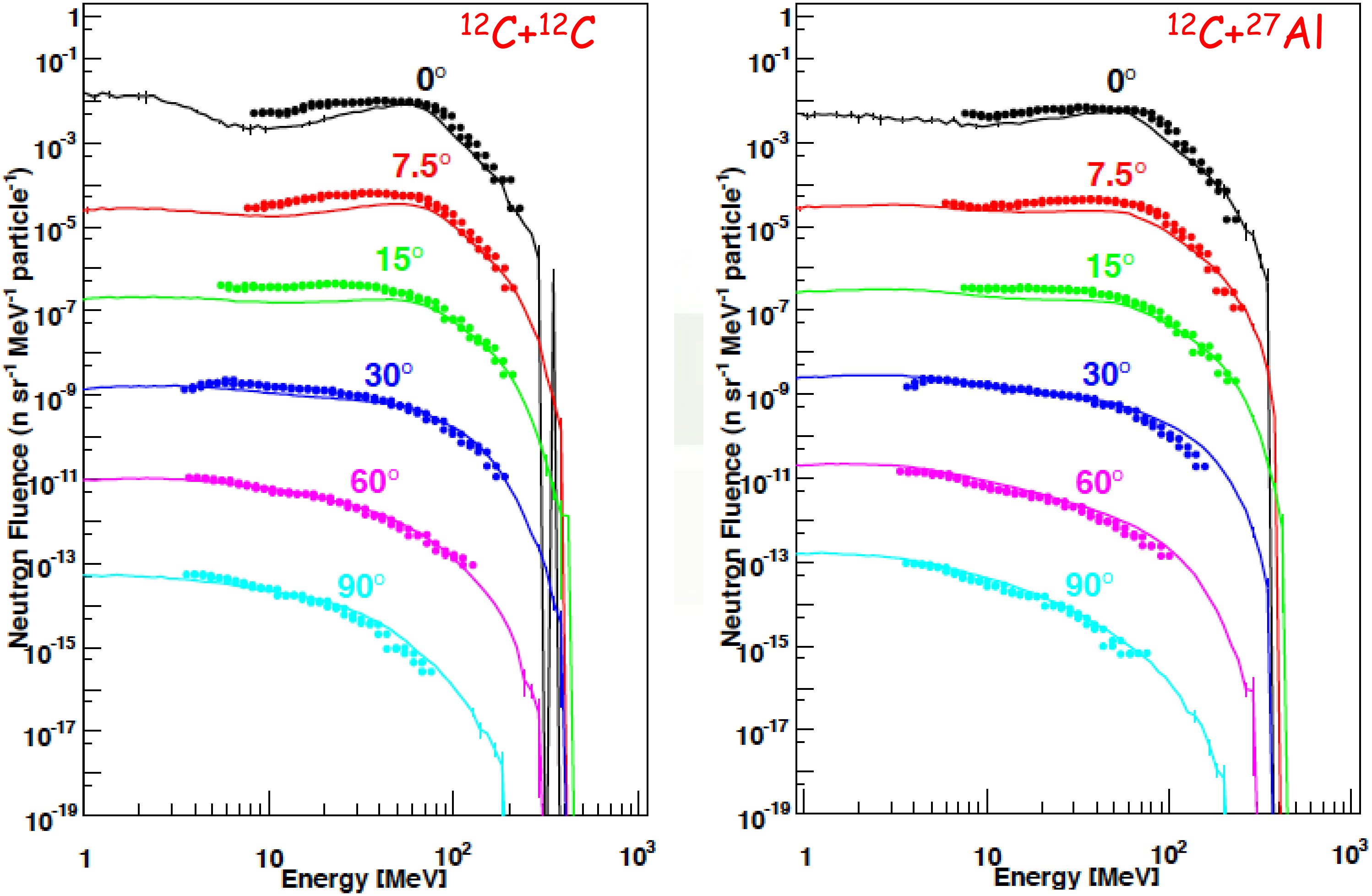
three body mechanism
pickup/stripping
inelastic scattering (at high *b*)

FLUKA evaporation

Low energy AA benchmark [1]

Double differential neutron spectra @ 100 MeV/n

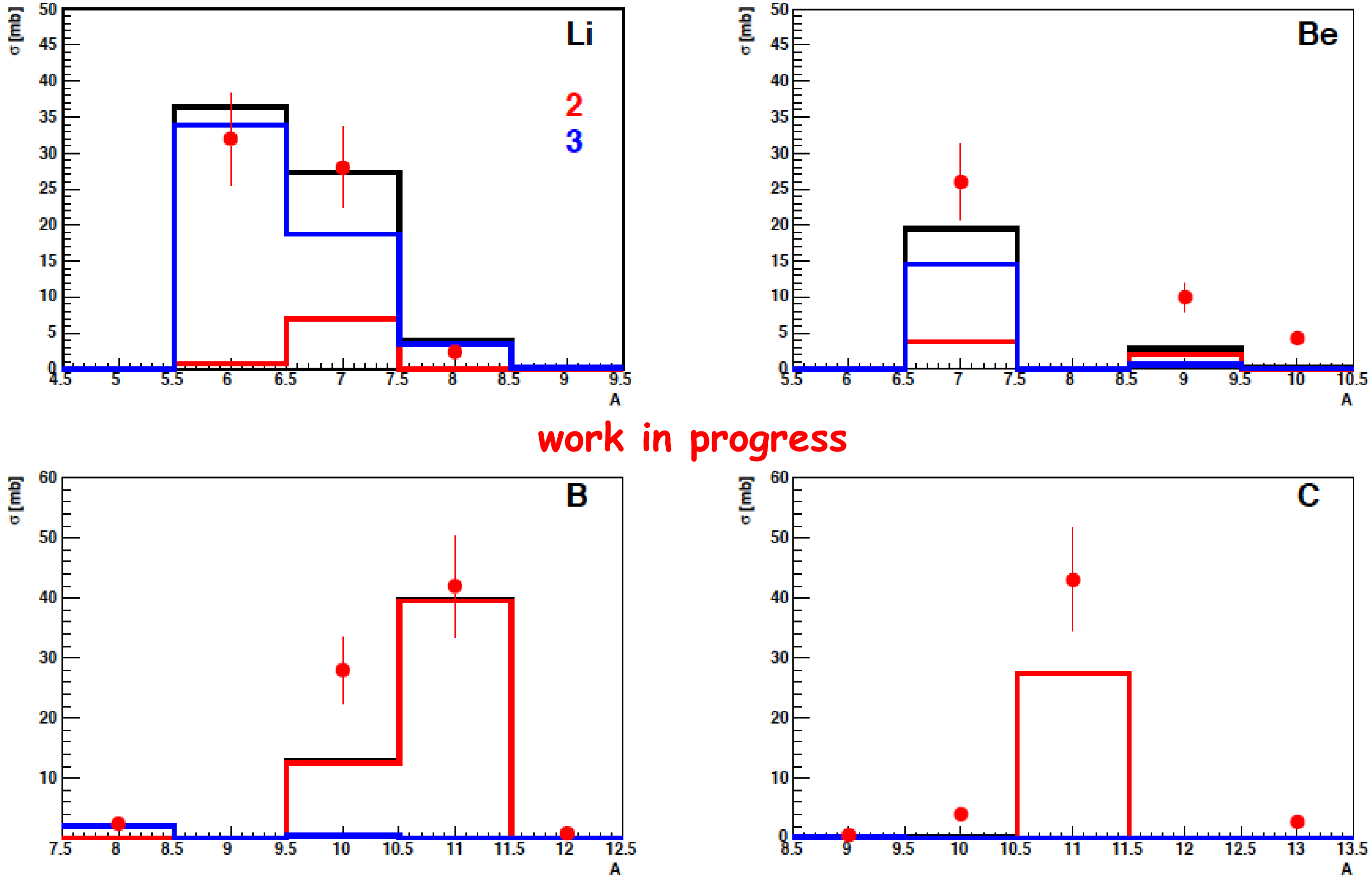
work in progress



Exp. Data (points): T.Kurosawa, N.Nakao, T.Nakamura et al., Nucl. Sci. Eng. 132,30-57(1999)

Low energy AA benchmark [2]

Fragment Production in $^{12}C+^{12}C$ @ 86 MeV/n



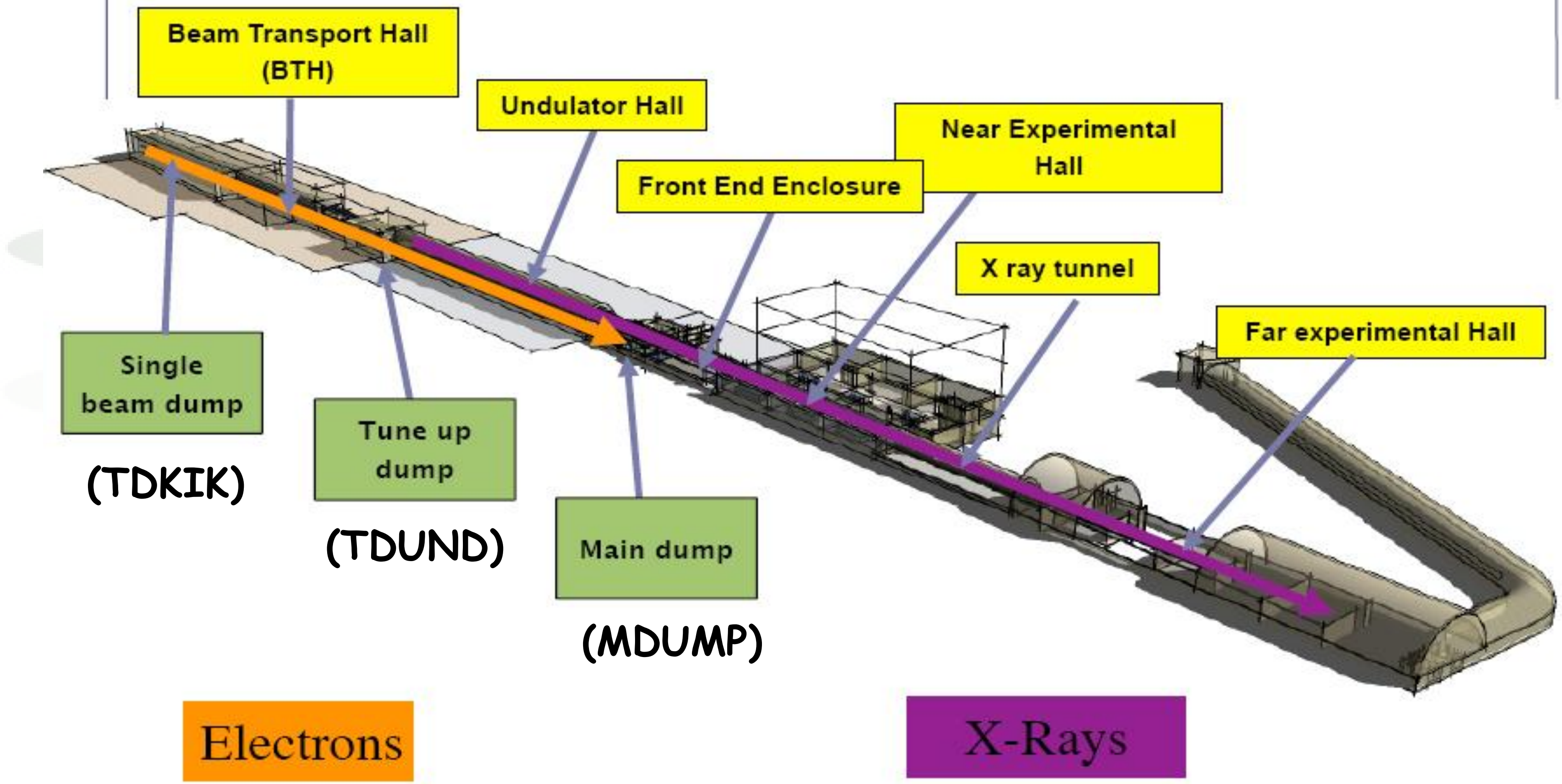
Exp. Data (points): H. Ryde, Physica Scripta T5, 114-117 (1983)

Electron Accelerators

- Activation/contamination/environmental issues with e- beams too! Therefore photonuclear reactions are critical.
- Electronics can also be challenged by photoneutrons
- Photomuon production is critical for forward shielding for energies ~> 10 GeV
- Many e-machines are incorporating FEL facilities → new issues:
  - Some can be studied with Monte Carlo simulations:
    - 1) the permanent magnets of the wigglers (undulators) can be demagnetized with radiation. MC simulations are required to analyze neutron fields in those for mis-steering situations and also for insertion of diagnostics (i.e. beam finder wires).
    - 2) halo scraping and inserted devices generate bremsstrahlung photons that travel along the same path as the FEL, generating radiation close to the (occupied) experimental hutches.
  - Some other issues cannot (yet) be (fully) simulated with FLUKA:
    - 1) (very) low energy photon transport in the hutches
    - 2) synchrotron radiation from the wigglers: Similar problem as bremsstrahlung. Need to write specific source routine.
    - 3) interaction of the Free Electron Laser with matter: reflection in mirrors, plasma creation, damage (ablation) of stoppers.

Linear Coherent Light Source @ SLAC

The first *hard X-ray* machine
LCLS uses the SLAC 2-mile linac to deliver e^- up to 17 GeV
Simulations with FLUKA (here, thanks to SLAC-RP) and MARS



Photonuclear interactions

Photon-nucleus interactions in FLUKA are simulated over the whole energy range, through different mechanisms:

- Giant Resonance interaction
- Quasi-Deuteron effect
- Delta Resonance production
- Vector Meson Dominance ($\gamma \equiv \rho, \Phi$ mesons) at high energies

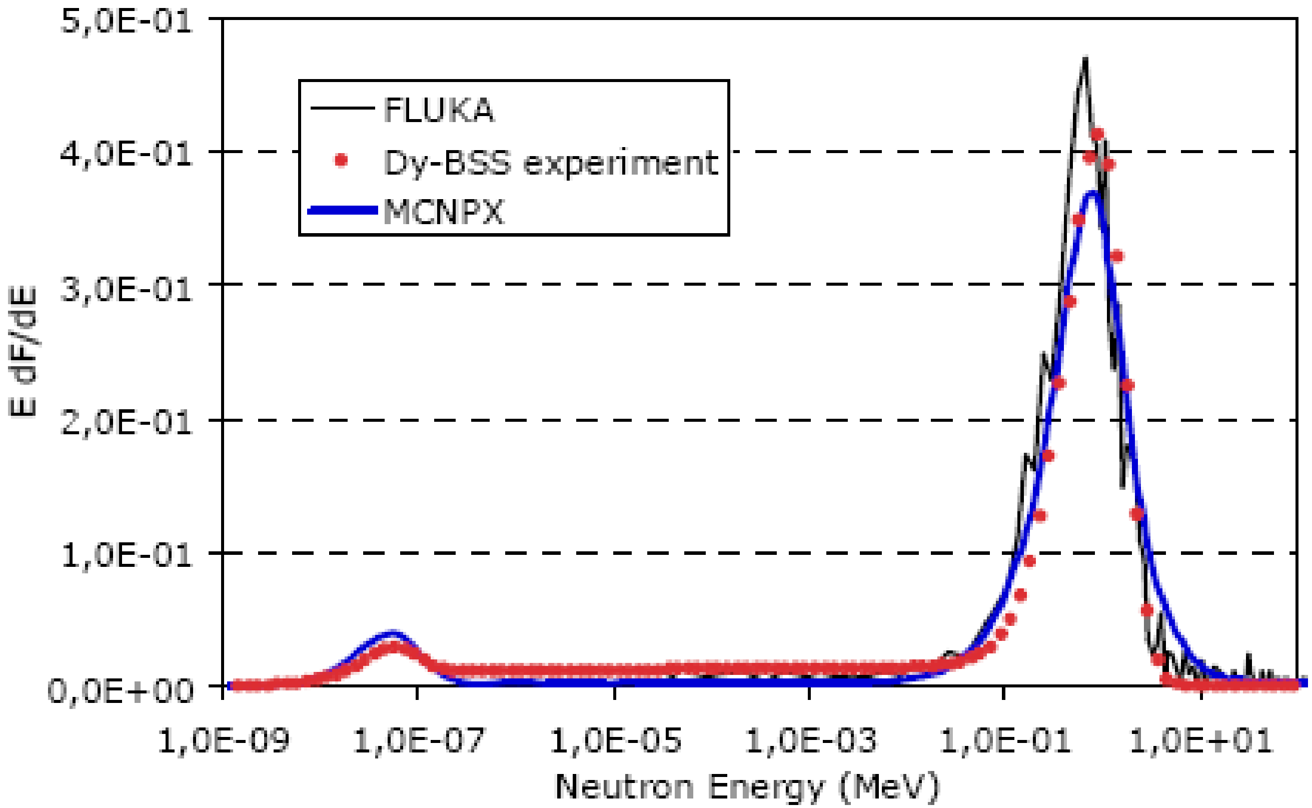
Nuclear effects on the ***initial state*** (i.e. Fermi motion) and on the ***final state*** (reinteraction / emission of reaction products) are treated by the FLUKA hadronic interaction model (PEANUT) ➔ INC + pre-equilibrium + evaporation/fission/breakup
(photofission to be improved !)

The (small) photonuclear interaction probability must be enhanced through biasing

Photo-neutron production n@BTF

G. Mazzitelli et al., presented at IPAC 2010 ; courtesy of Lina Quintieri

Beam from the DAPHNE linac , 750 MeV electrons on a
W target , 6 cm length, 3.5 cm radius



Experimental and computational neutron spectra at 150 cm from the target at 90° wrt beam direction

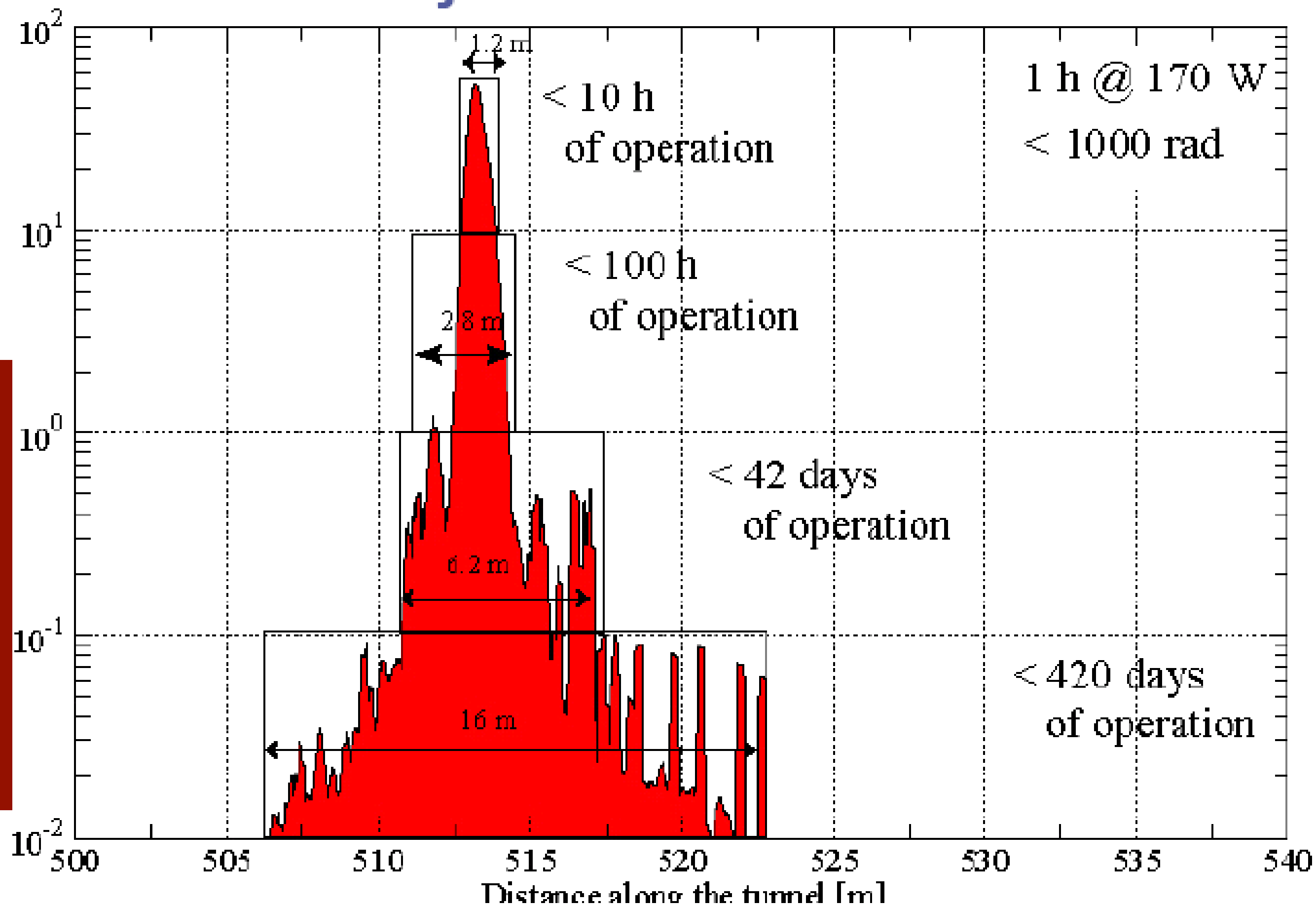
Photoneutrons: damage to electronics

Damage to electronics near the dumps at the Linear Coherent Light Source @ SLAC

The lifetime of electronic components can be estimated as a function of the distance to major sources of radiation

1-MeV neutron equivalent fluence

Calculation of lifetime of electronics equipment as a function of the distance to TDUND



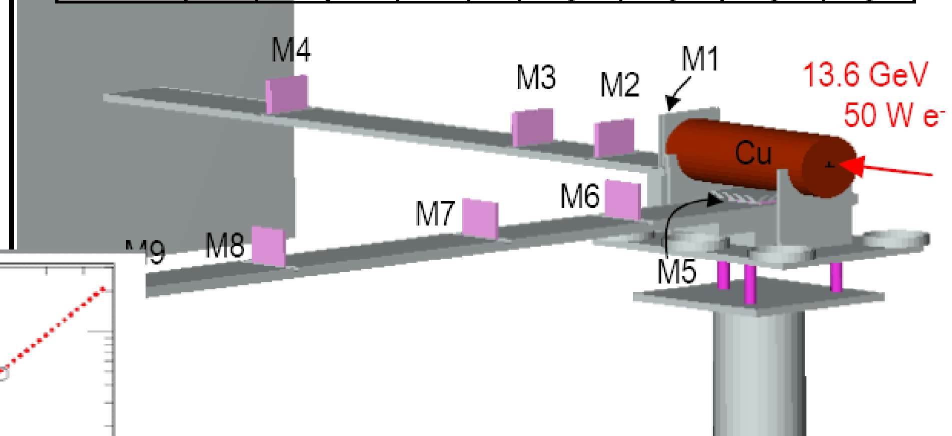
Photoneutrons: demagnetization

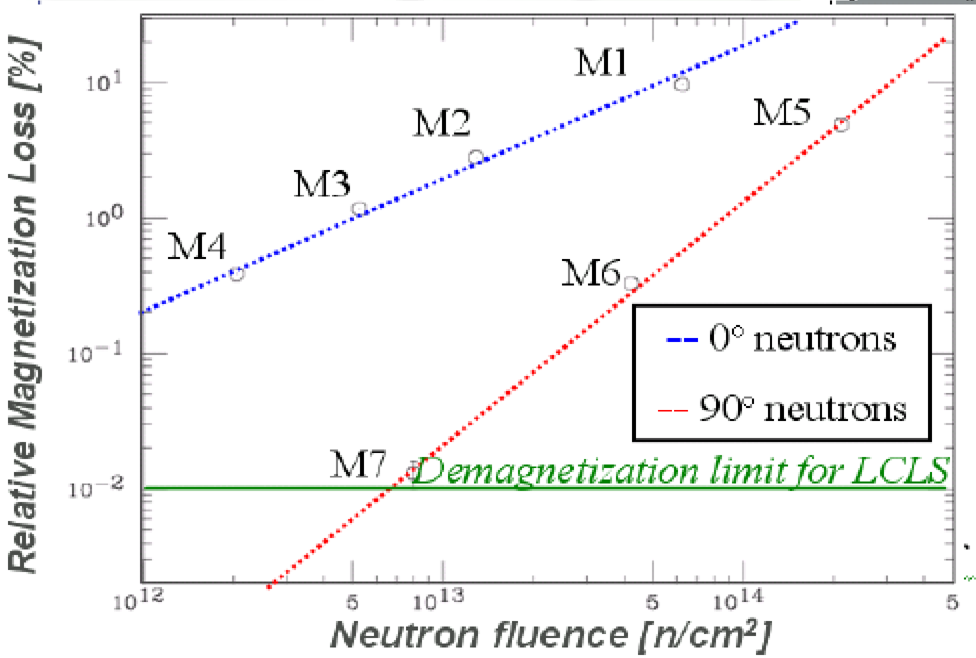
Evaluation of demagnetization response function for the permanent magnets used in the LCLS undulators: irradiation experiment + FLUKA simulations

The response function (demagnetization) to radiation is not fully known

Setup of experiment at ES-A

M	1	2	3	4	5	6	7	8	9
d[cm]	15	28	43	79	7	24.9	50.4	88.4	149
axis	z	z	z	z	x	-y	-y	-y	-y





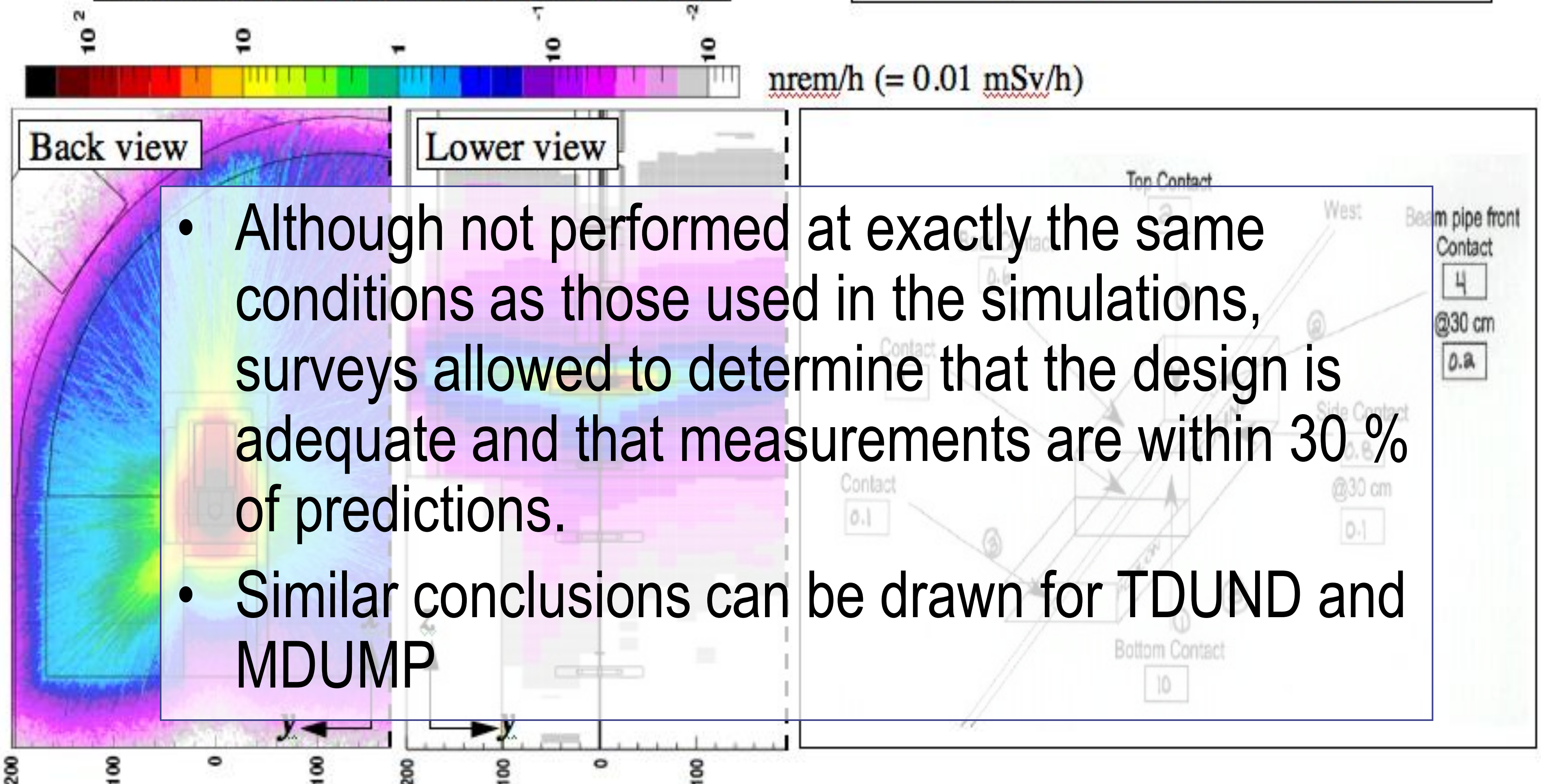
measured demagnetizations and simulated neutron fluences.

Photoneutrons: activation near dumps

TDKIK: residual radiation, FLUKA simulation and survey

Simulation: 2h irradiation @ 170 W

Survey: 1h irradiation @ 100 W



- Although not performed at exactly the same conditions as those used in the simulations, surveys allowed to determine that the design is adequate and that measurements are within 30 % of predictions.
- Similar conclusions can be drawn for TDUND and MDUMP

Photomuon interactions

- A muon pair (+/-) is generated
- Most muons are forward focused
- Previously handled by coupling SLAC mu-carlo with EGS
- It was heavily demanded by SLAC for LCLS design
- Now implemented in FLUKA and MARS
- The photomuon low probability should be enhanced through biasing to reduce the variance
- Muons are hard to shield. Sometimes magnetic spoilers are used. In that case two jets are observed (+/-)

Photomuon benchmark

Simulations: courtesy of T. Sanami,
See also
Code benchmark of muon flux after a several meters of iron from 14 and 18 GeV electron induced reactions in forward direction
SLAC Radiation Physics Note, RP-07-15

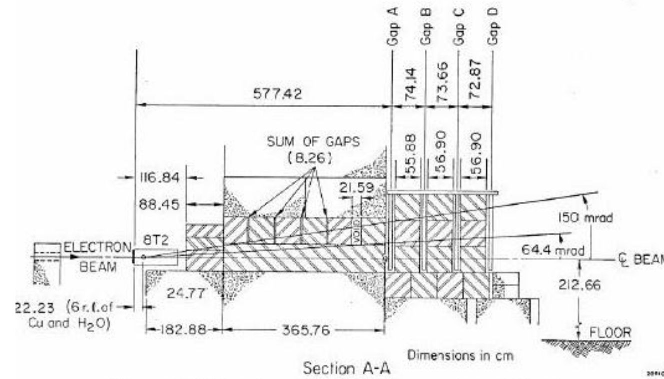
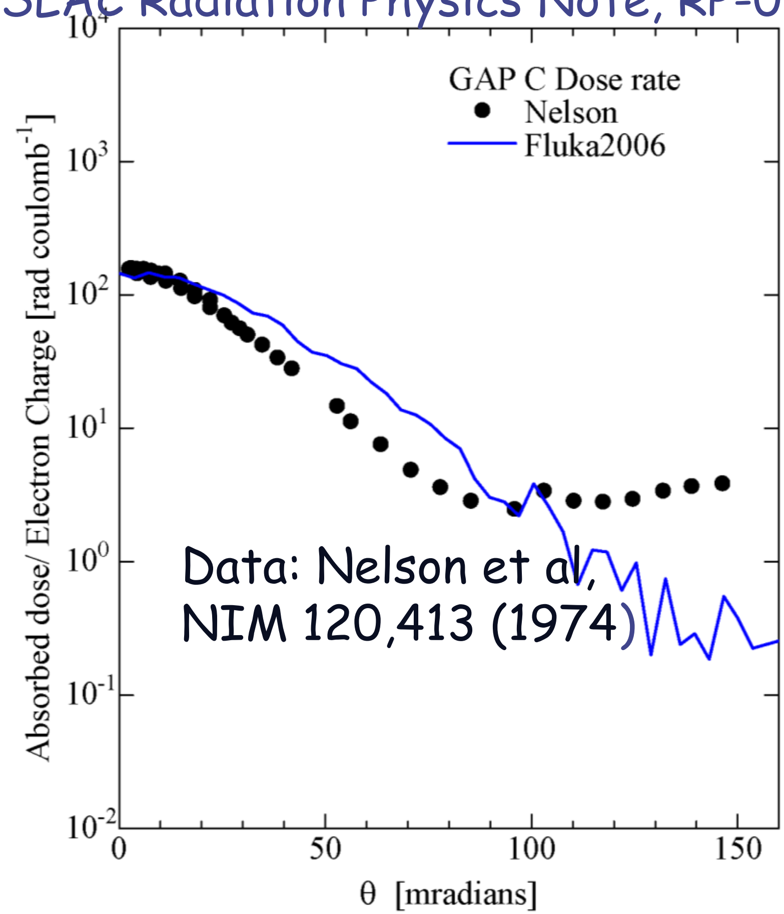
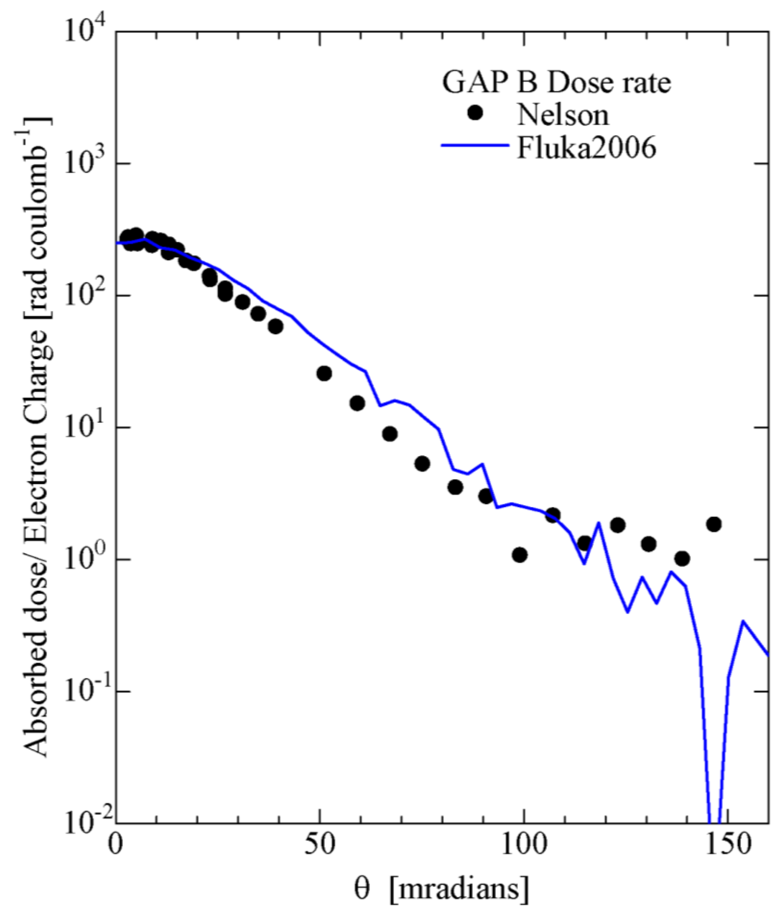


Figure 2. Elevation view of the experimental setup

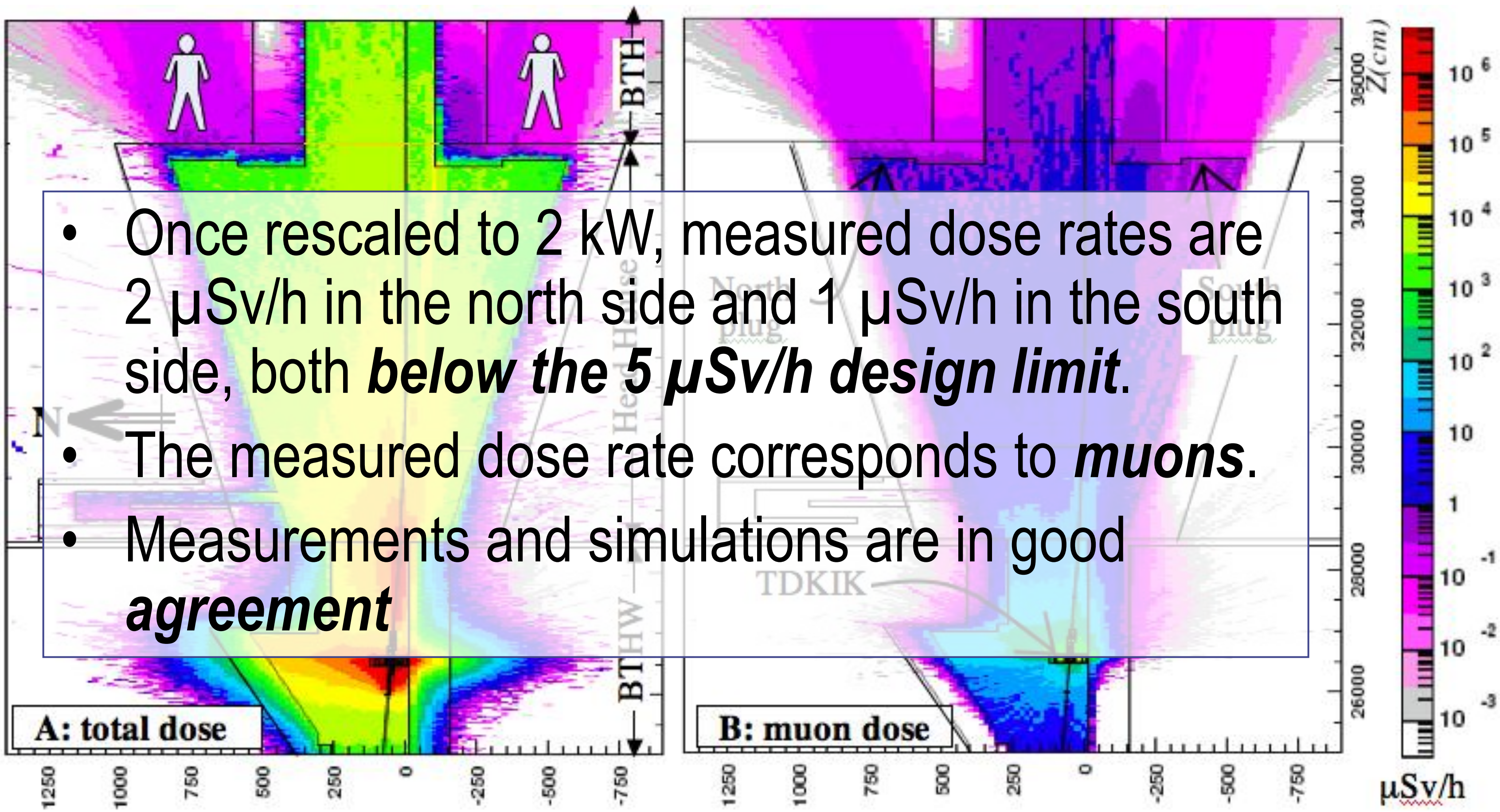


Data: Nelson et al,
NIM 120,413 (1974)



Muon radiation at small angles

- Prompt dose for 2 kW in **TDKIK,** simulations and survey



- Once rescaled to 2 kW, measured dose rates are 2 μSv/h in the north side and 1 μSv/h in the south side, both ***below the 5 μSv/h design limit***.
- The measured dose rate corresponds to ***muons***.
- Measurements and simulations are in good ***agreement***

THANKS FOR YOUR ATTENTION!!!