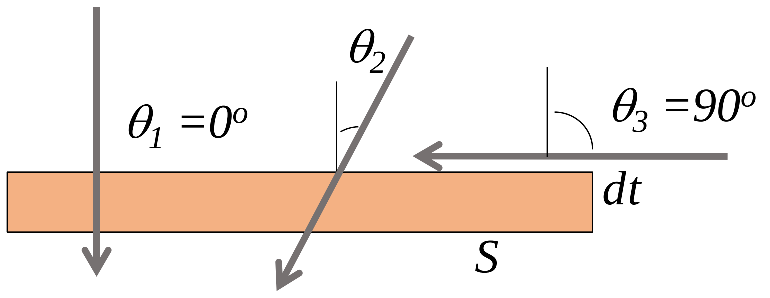
Scoring physics quantities [II]

Differential spectra (**`USRTRACK`**, **`USRYIELD`**, **`USRBDX`**)

Fluence vs Current (1/2)

Surface crossing estimation



- Consider the volume generated by a surface *S* times an infinitesimal thickness *dt.*
  A particle incident with *an angle θ with respect to the normal to the surface S* travels a segment *dt/cosθ* inside the volume.
- The **average fluence** Φ over the surface S is defined as*:*

$$\Phi = \lim_{dt \to 0} \frac{\sum_i \frac{dt}{\cos\theta_i}}{S\,dt}$$

total tracklength inside the volume

volume

- While the **average current** J over the surface S is given by the number of particles crossing the surface divided by the surface area:

J = N/S

Fluence vs Current (2/2)

- Fluence is **independent** of the orientation of the surface S, while current is **not** !
  - On a flat surface in an isotropic particle field $J = \Phi/2$

- Current is meaningful in case one needs to count particles (e.g. for a signal trigger)

- But to estimate dose, activation, radiation damage, instrument response, the relevant quantity to be used is fluence, since it is proportional to the interaction rate

Main FLUKA estimators

- **USRBIN** scores the **spatial distribution** of **energy density** or **fluence** (or star density) in a **regular mesh** (cylindrical, Cartesian, or by region) described by the user
- **USRBDX** scores average **$d^2\Phi/dEd\Omega$ (double-differential fluence or current)** of a given type or family of particles on a **given surface**
- **USRTRACK** (**USRCOLL**) scores average **$d\Phi/dE$ (differential fluence)** of a given type or family of particles in a **given region**
- **USRYIELD** scores a **double differential yield** of particles on a **given surface**
  - The distribution can be with respect to energy and angle, but also other more “exotic” quantities
- All scorings write their results into **logical output units assigned by the user**
  - the unit numbers must be **>20**
  - The only exception is **SCORE** – which scores **energy deposition** (or number of stars) in all regions – whose output is printed in the **standard output**

Result units

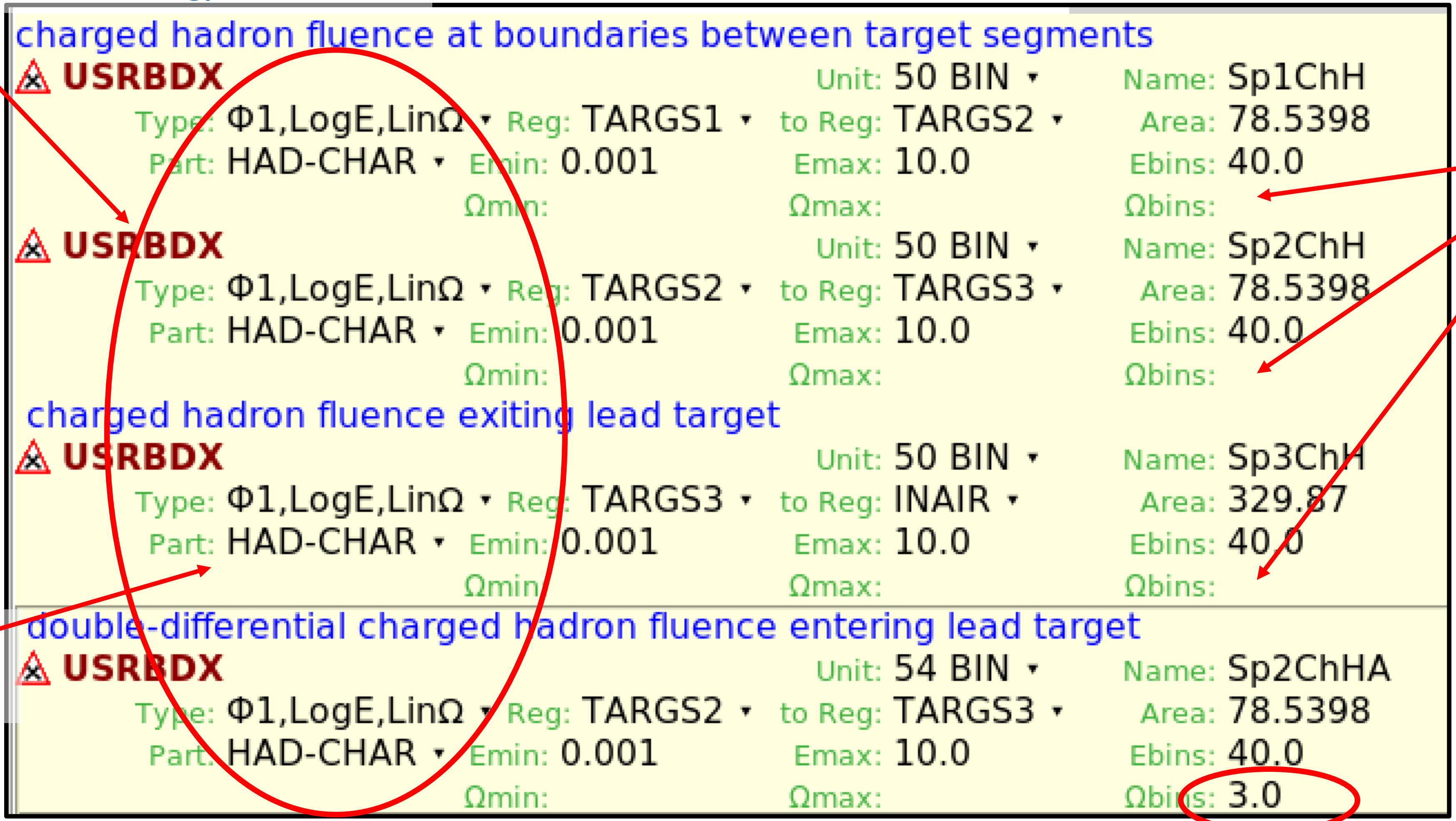
- FLUKA does not calculate **region** volumes and areas.
- As scoring particle *fluence* with **USRTRACK** (**USRBDX**, **USRYIELD**), the resulting value will actually be in cm^{-2} only if the user has provided the region volume (area) in the respective card field. Nevertheless, this is far from being needed, since the desired normalization can be naturally applied at post-processing level.

- Results from **USRTRACK** (**USRCOLL**) are given as differential distributions in energy, in units of GeV^{-1}.
  - To obtain integral results, one has to multiply the value *dN/dE* of each energy bin by the bin width *dE* : $N = \int \frac{dN}{dE} dE$, which is already done in the respective *_sum.lis file !
  - When scoring neutrons, the energy bins below 20 MeV are automatically set and cannot be altered, since they must match the multi-group structure applying to low energy neutron transport
- Results from **USRBDX** and **USRYIELD** are given as double differential distributions.

USRBDX scoring (boundary crossing) definition

One-way fluence across boundary, differential in energy (log binning) and angle (linear binning)

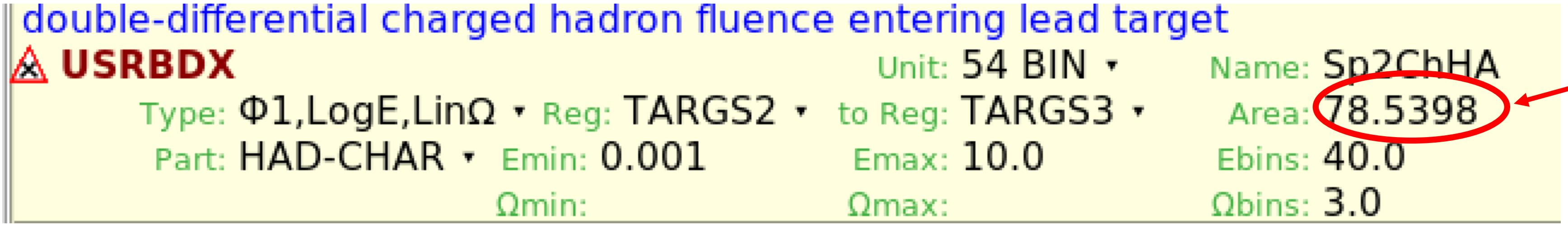
By default ONE angular bin (no angular distribution)



Particle type: charged hadrons

3 angular bins

USRBDX scoring (boundary crossing) output



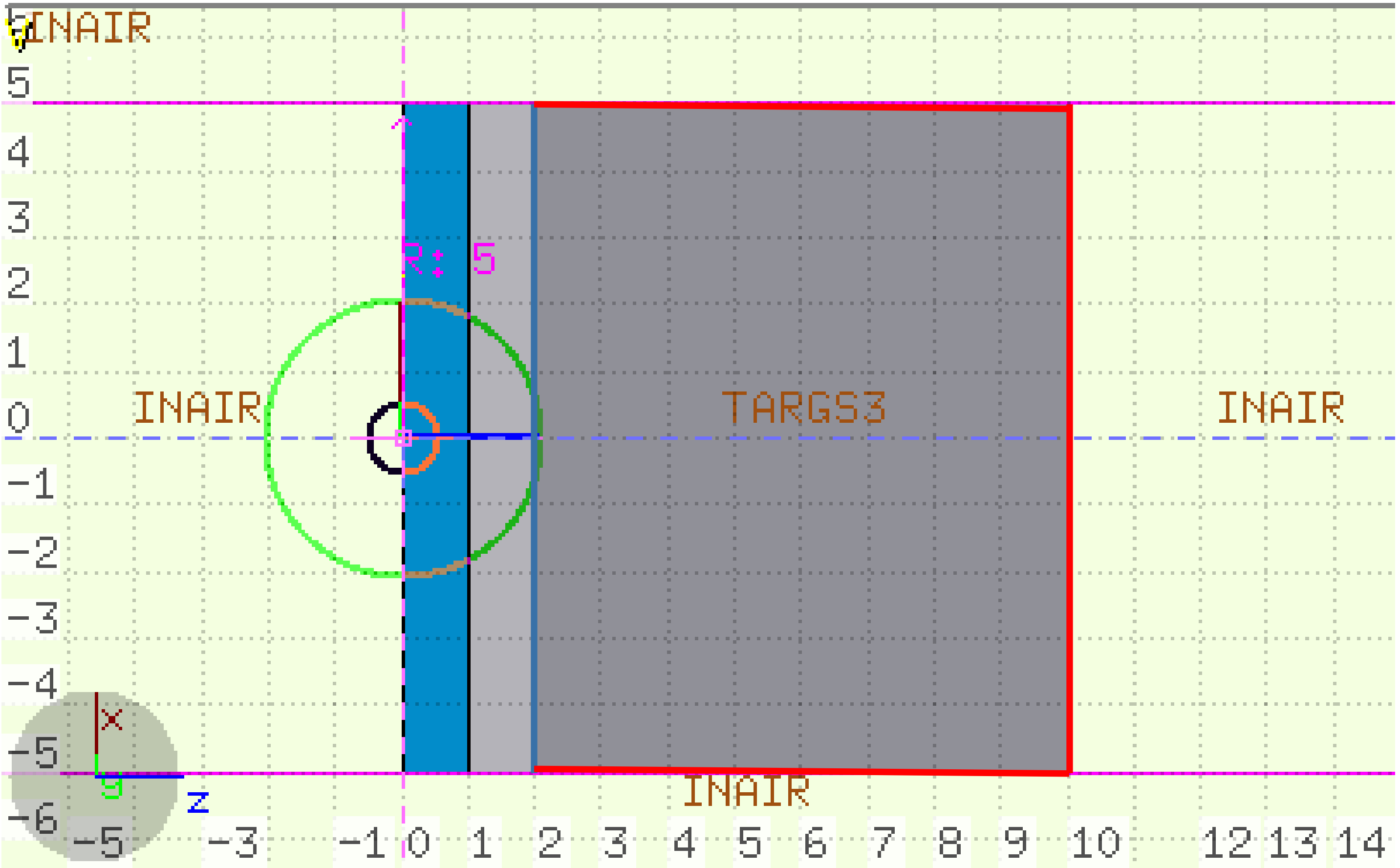
Surface area [cm^2] normalization, which can be independently done at post-processing

The merging/processing action will create 3 files for each **USRBDX** unit:

- **demo_scoring_54.bnx**: binary file containing the merged data from several runs
  [it can replace the N unformatted estimator files for further postprocessing]
- **demo_scoring_54_sum.lis**: ascii file containing all information and in addition energy-integrated cumulative spectra
  demo_scoring_54_tab.lis: ascii file containing the double differential fluence and angle-integrated fluence in tabulated form for immediate plotting → Flair uses this file

Note: even if only one angular bin was requested, differential spectra are always double differential in GeV^{-1} $\mathbf{sr^{-1}}$

USRBDX area normalization

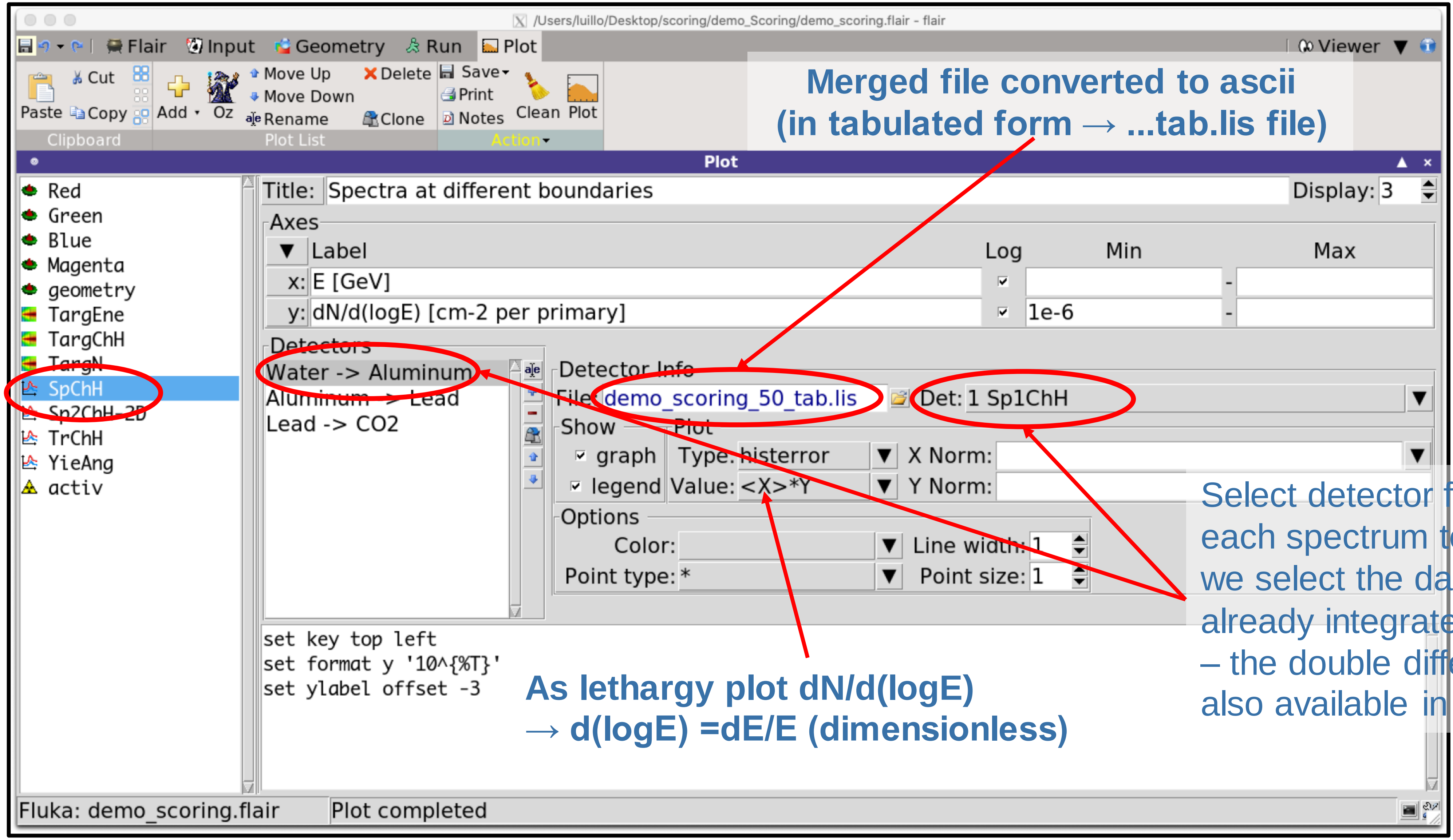


R_{TARG} = 5 cm
ΔZ_{TARGS1} = 1 cm
ΔZ_{TARGS2} = 1 cm
ΔZ_{TARGS3} = 8 cm

Area between TARGS2 and TARGS3: πR_{TARG}^2 = 78.5398 cm^2

Area between TARGS3 and INAIR: $2\pi R_{TARG}\,\Delta Z_{TARGS3} + \pi R_{TARG}^2$ = 329.87 cm^2

Plotting – charged hadron spectra (USRBDX)



Merged file converted to ascii (in tabulated form → ...tab.lis file)

As lethargy plot dN/d(logE) → d(logE) =dE/E (dimensionless)

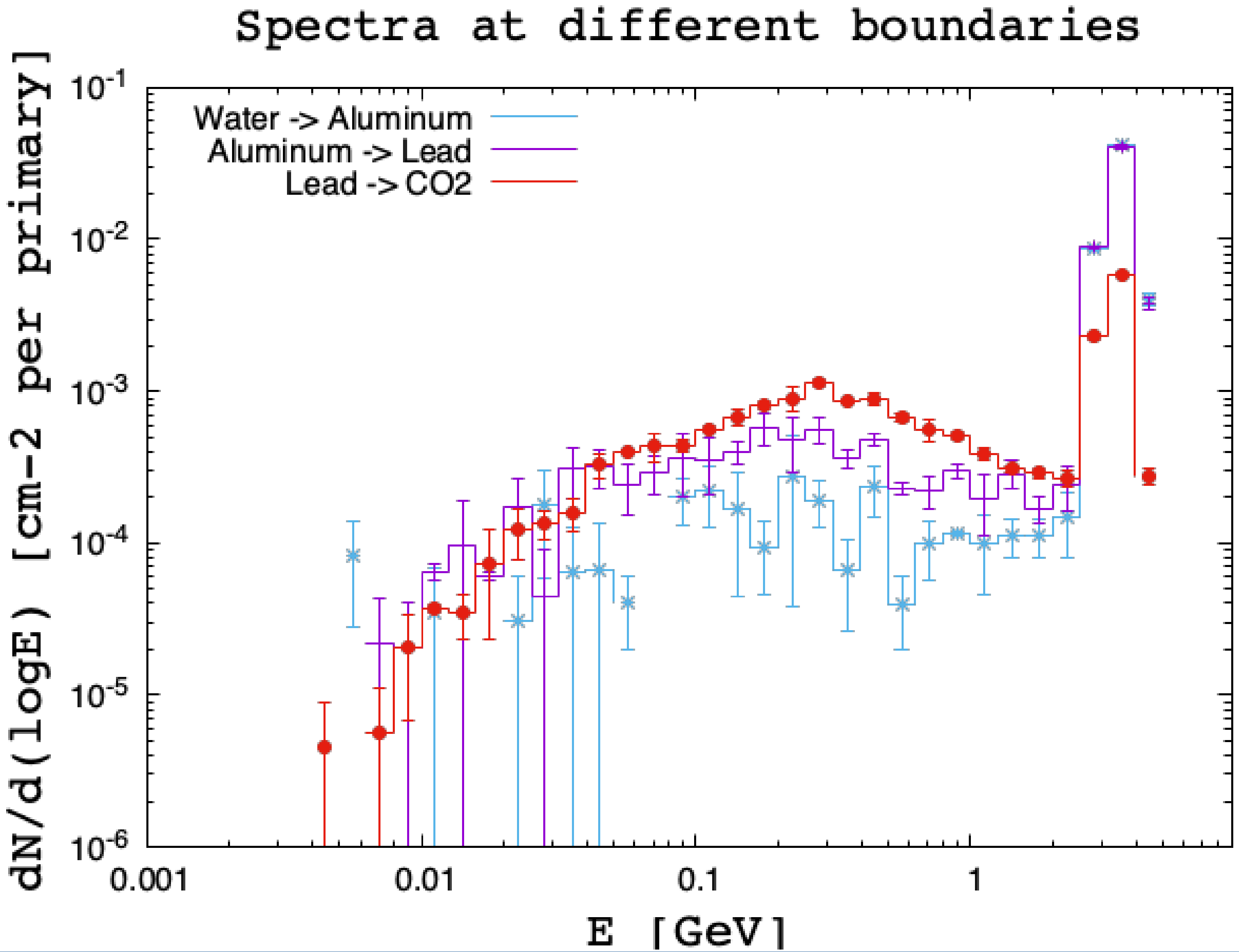
Select detector from file for each spectrum to be plotted (note: we select the data set that is already integrated over solid angle – the double differential spectrum is also available in the same file)

Plot result – charged hadron spectra (USRBDX)

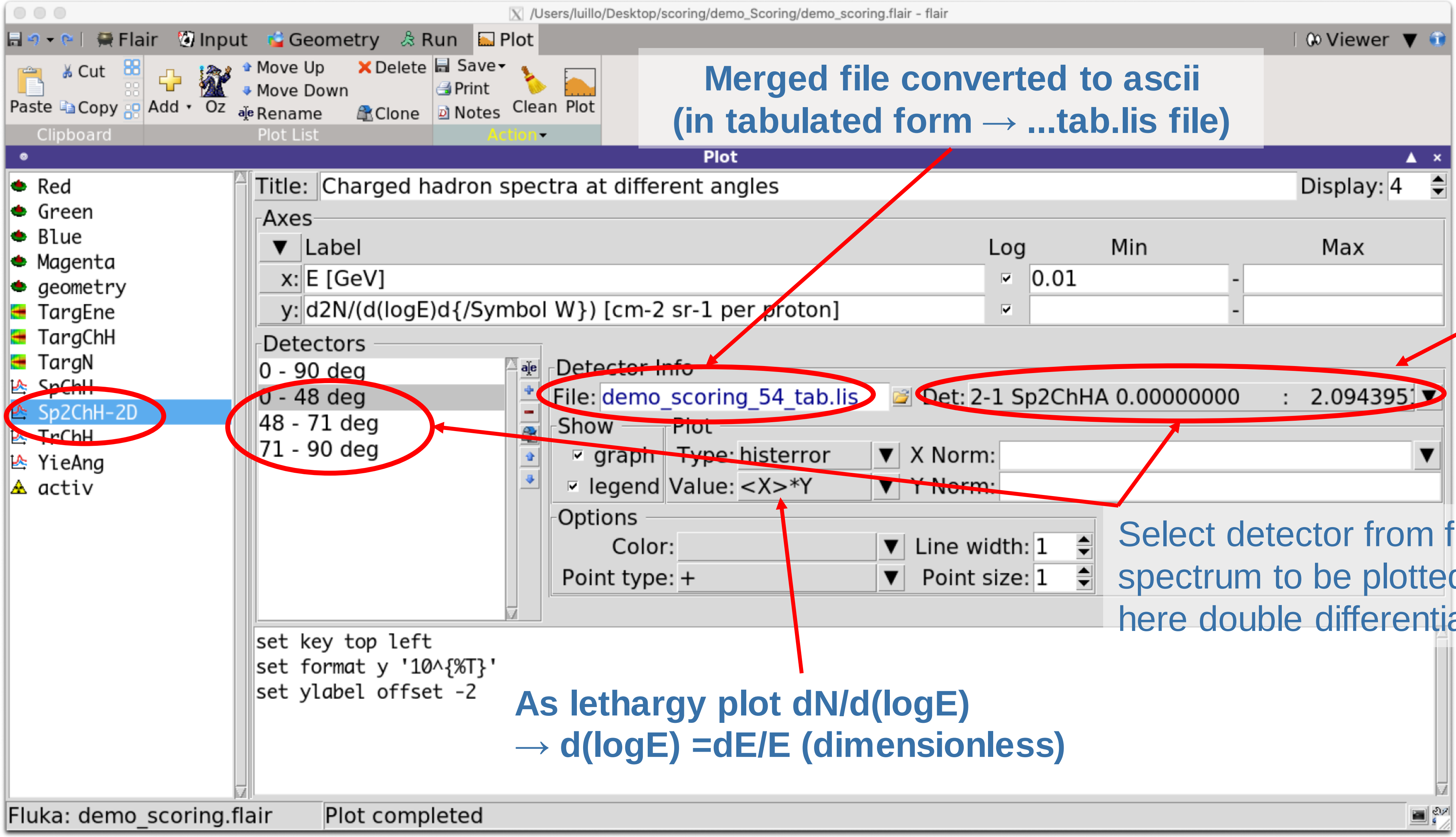
$$y = \frac{dN}{d(logE)} = E\frac{dN}{dE}$$

Value: <X>*Y

Lethargy plot



Plotting – double differential fluence (USRBDX)



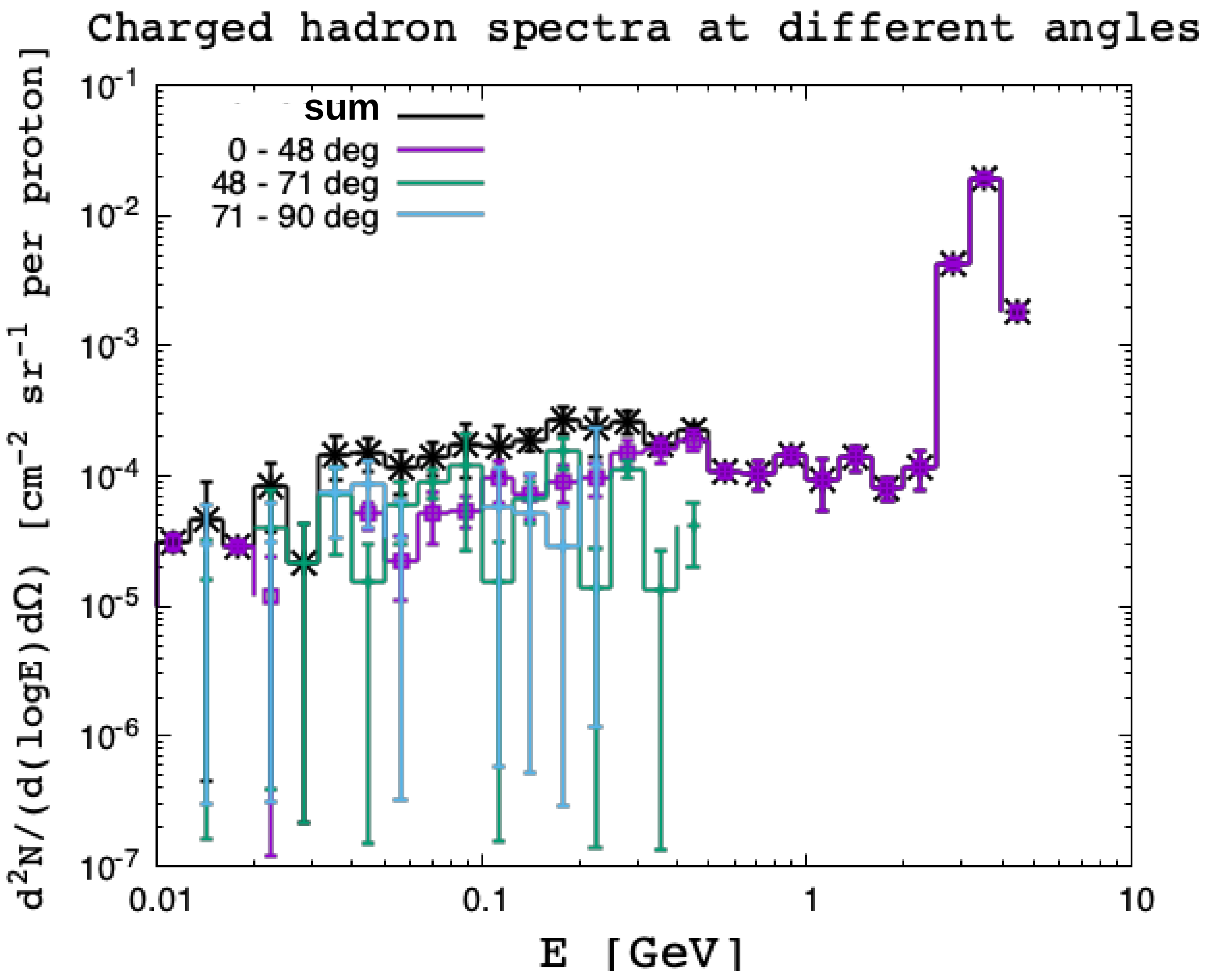
Merged file converted to ascii
(in tabulated form → ...tab.lis file)

2π/3

Select detector from file for each spectrum to be plotted (we use here double differential spectra)

As lethargy plot dN/d(logE)
→ d(logE) =dE/E (dimensionless)

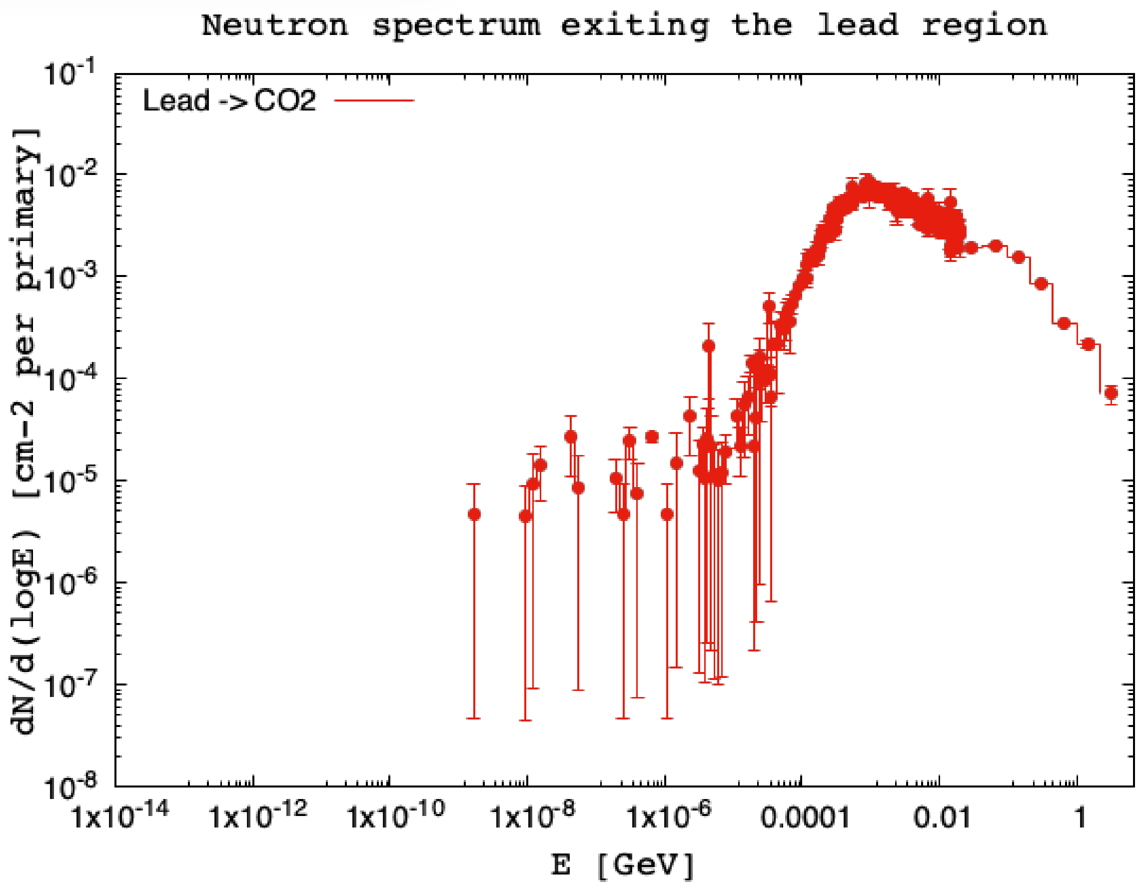
Plot result – double differential fluence (USRBDX)



Neutrons

40 energy bins over 15 decades: the resulting spacing of *≤3 bins per decade* is applied **above 20 MeV**

- Neutrons can interact at any energy, down to thermal
  - Transport and interactions of neutrons below 20 MeV, due to their cross section complexity, are implemented by means of a multi-group treatment based on evaluated data files.
  - When scoring neutron spectra, the energy bins below 20 MeV correspond automatically to the structure of the low energy neutron groups.

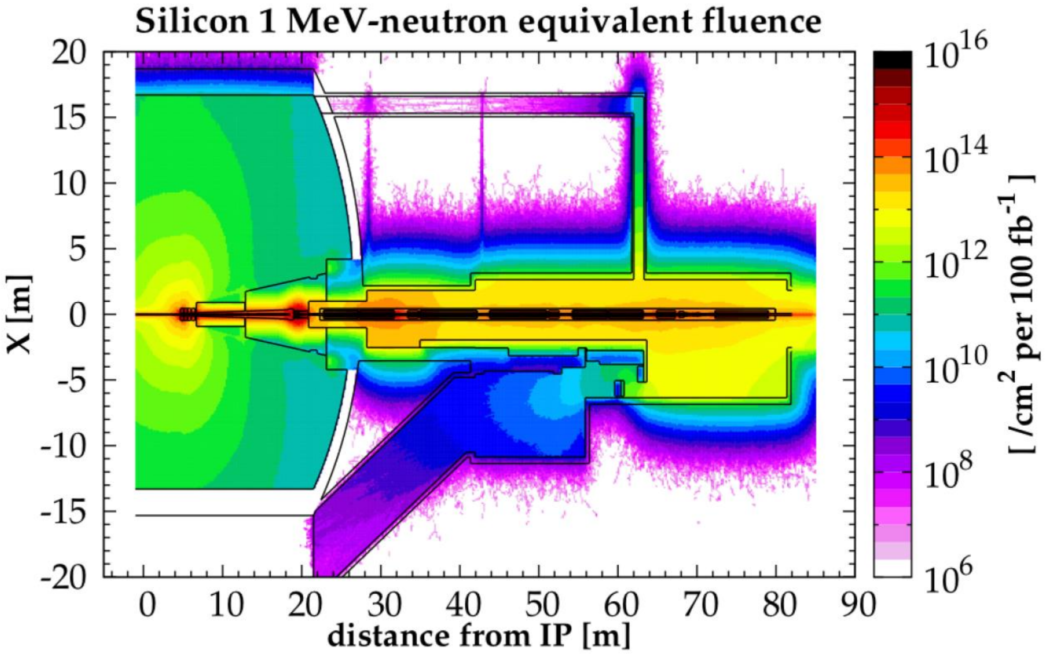


Scoring physics quantities [II]

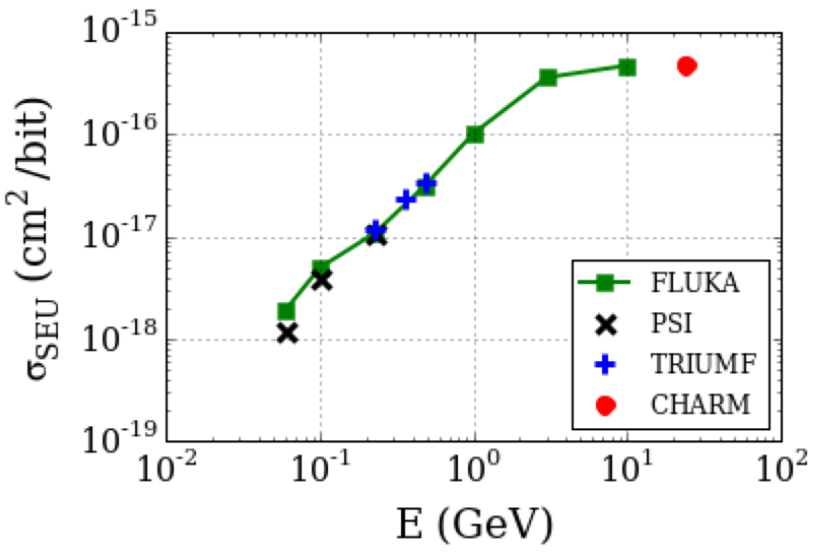
Radiation to Electronics scoring

FLUKA simulations for radiation damage on electronics

- Particle-matter interaction Monte Carlo codes are very useful in the context of radiation damage to electronics, mainly linked to (i) the calculation of the radiation environment and (ii) the analysis of the effects on electronics.



Example of simulation of radiation environment: 1-MeV silicon neutron equivalent fluence in LHC interaction point



Example of simulation of radiation effect: Single Event Upset probability as a function of proton energy

[Note: often not only based on Monte Carlo simulations, but relying on coupling with other simulation tools (e.g. semiconductor or circuit level) and/or additional modeling aspects of the response of electronics to a given physical quantity simulated in FLUKA. More on that later…]

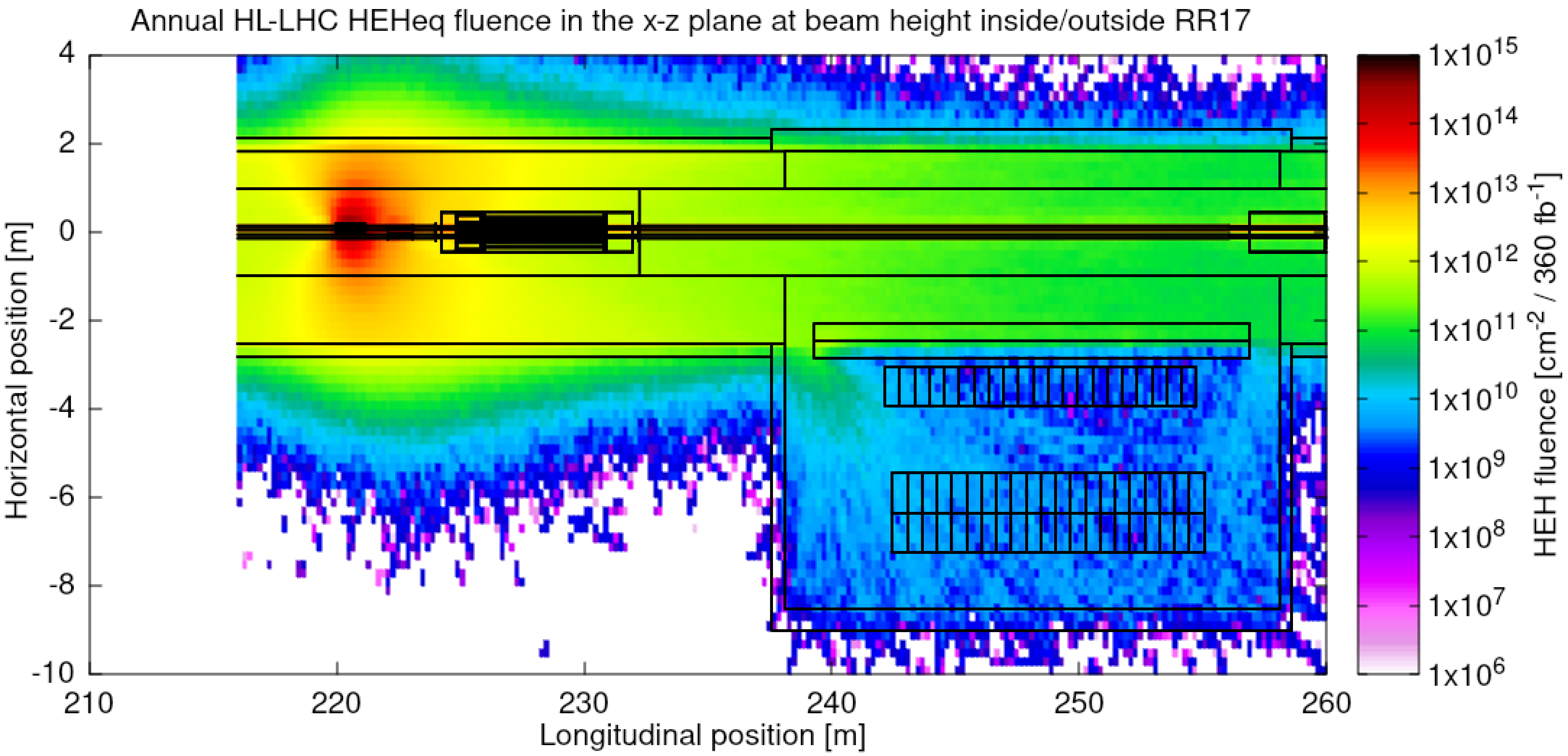
Main radiation effects in electronics

Category	Sub-category	Example of Effect
Stochastic	Non-destructive Single Event Effects (SEEs)	Single Event Upset (SEU): Bit flip in SRAM memory
	Destructive SEEs	Single Event Latchup (SEL): Overcurrent, which can lead to thermal breakdown
Cumulative	Total Ionizing Dose (TID)	Charge build up in oxide, leading to increased leakage current and/or threshold voltage shift
	Displacement Damage (DD)	Atomic displacement leading to dark current increase in CMOS imagers

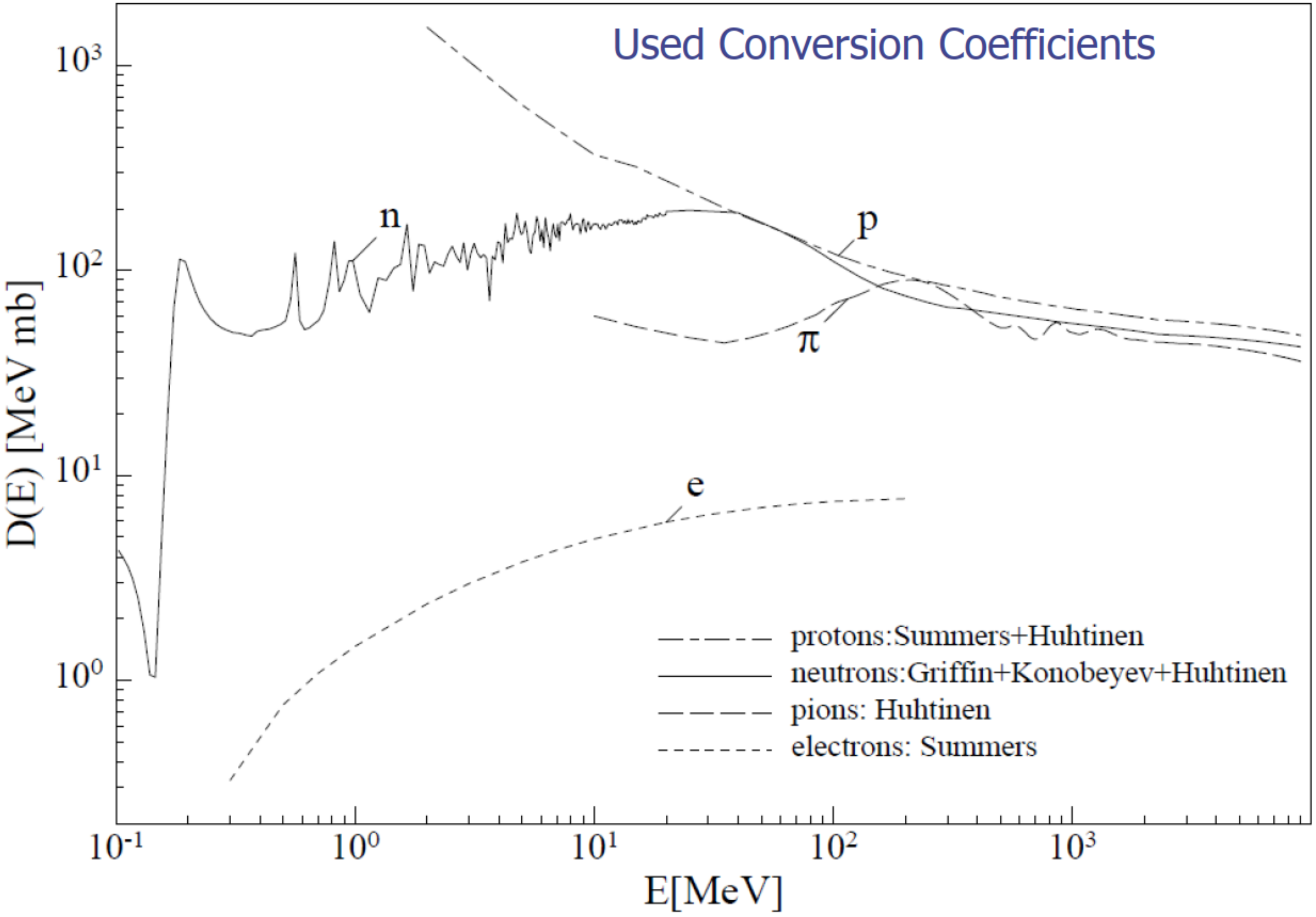
Radiation damage scoring in FLUKA

- All important quantities used to estimate radiation damage on electronics can be retrieved in FLUKA
  - Cumulative damage:
    - Energy deposition (total ionizing dose) by scoring **DOSE** in `USRBIN` (you will need to convert from GeV/g to Gy or rad!)
    - Silicon lattice displacement: 1-MeV neutron equivalent fluences (**SI1MEVNE**), with any related estimator (e.g. `USRTRACK, USRBDX`) or, more commonly, directly in integral form (e.g. `USRBIN`)
  - Stochastic failures (SEEs):
    - Depending on the environment, the particle energy (e.g. `USRTRACK, USRBDX`) or LET spectra (e.g. `USRYIELD`) can be scored and convoluted with the device's response function (i.e. SEE cross section as a function of energy or LET)
    - In FLUKA, three relative response functions are already implemented by default:
      - Hadrons above 20 MeV (**HADGT20M**)
      - Hadrons above 20 MeV, plus weighted neutron contribution in 0.2-20 MeV range (**HEHAD-EQ**)
      - Equivalent thermal neutron flux, weighted as 1/v (**THNEU-EQ**)

Example of high-energy hadron equivalent scoring in the LHC

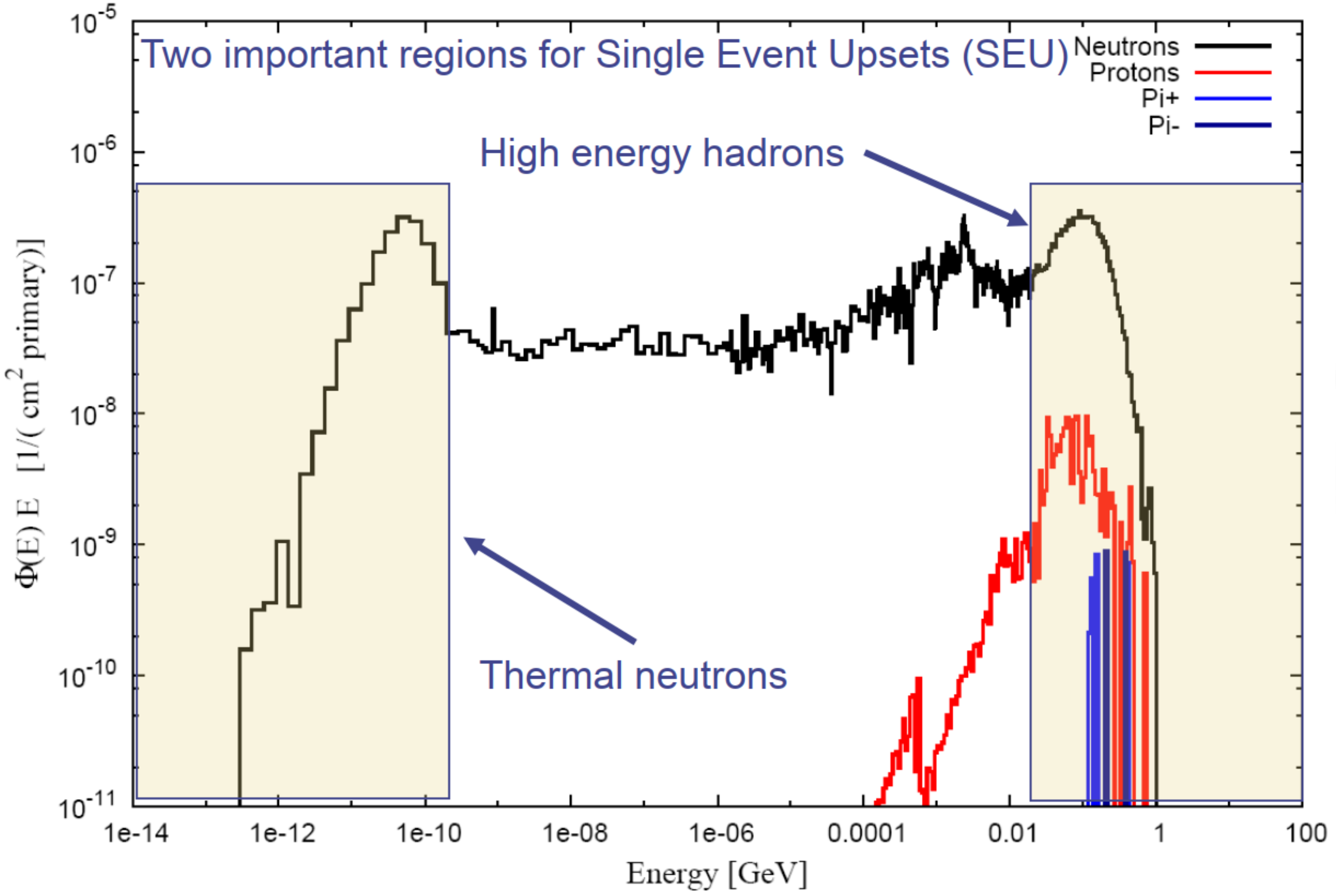


1-MeV neutron equivalent in silicon



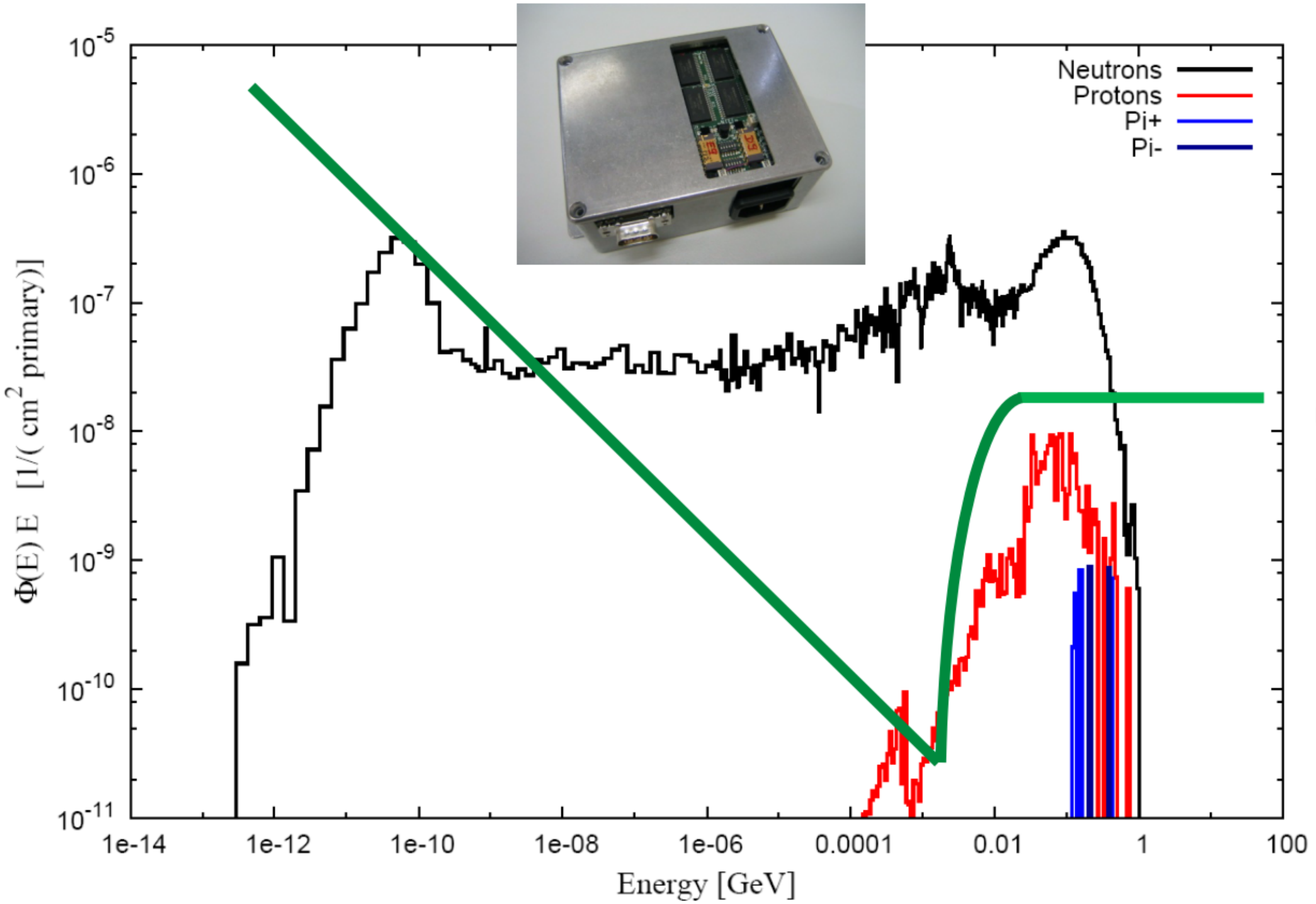
SEUs in mixed radiation field

$$\#SEU = \sigma_{Th.\,n.} \cdot \Phi_{Th.\,n.} + \sigma_{HEH} \cdot \Phi_{HEH}$$



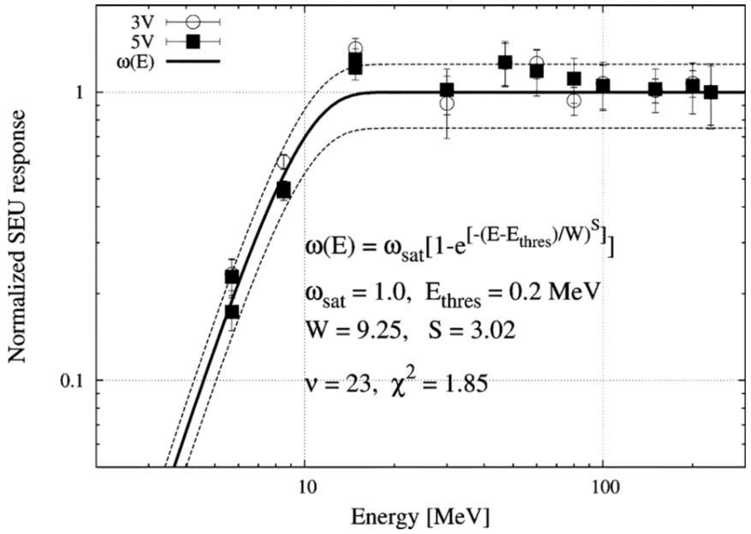
SEUs in mixed radiation fields

e.g. LHC RadMon

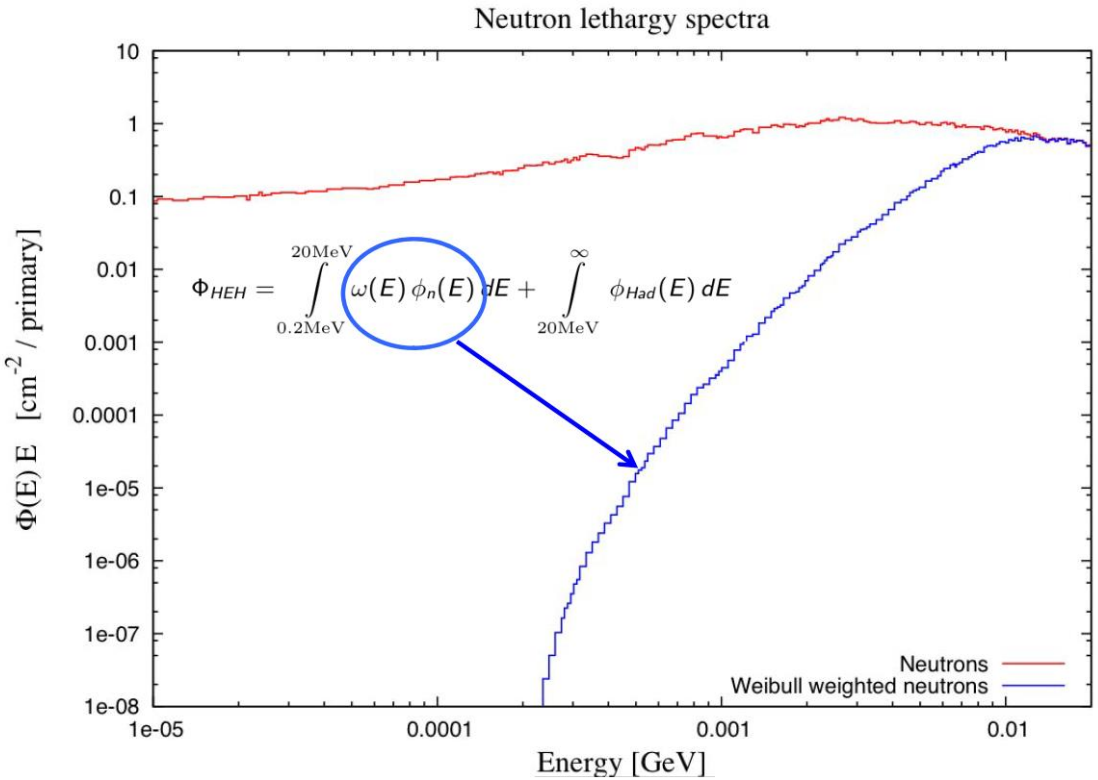


HEHAD-EQ

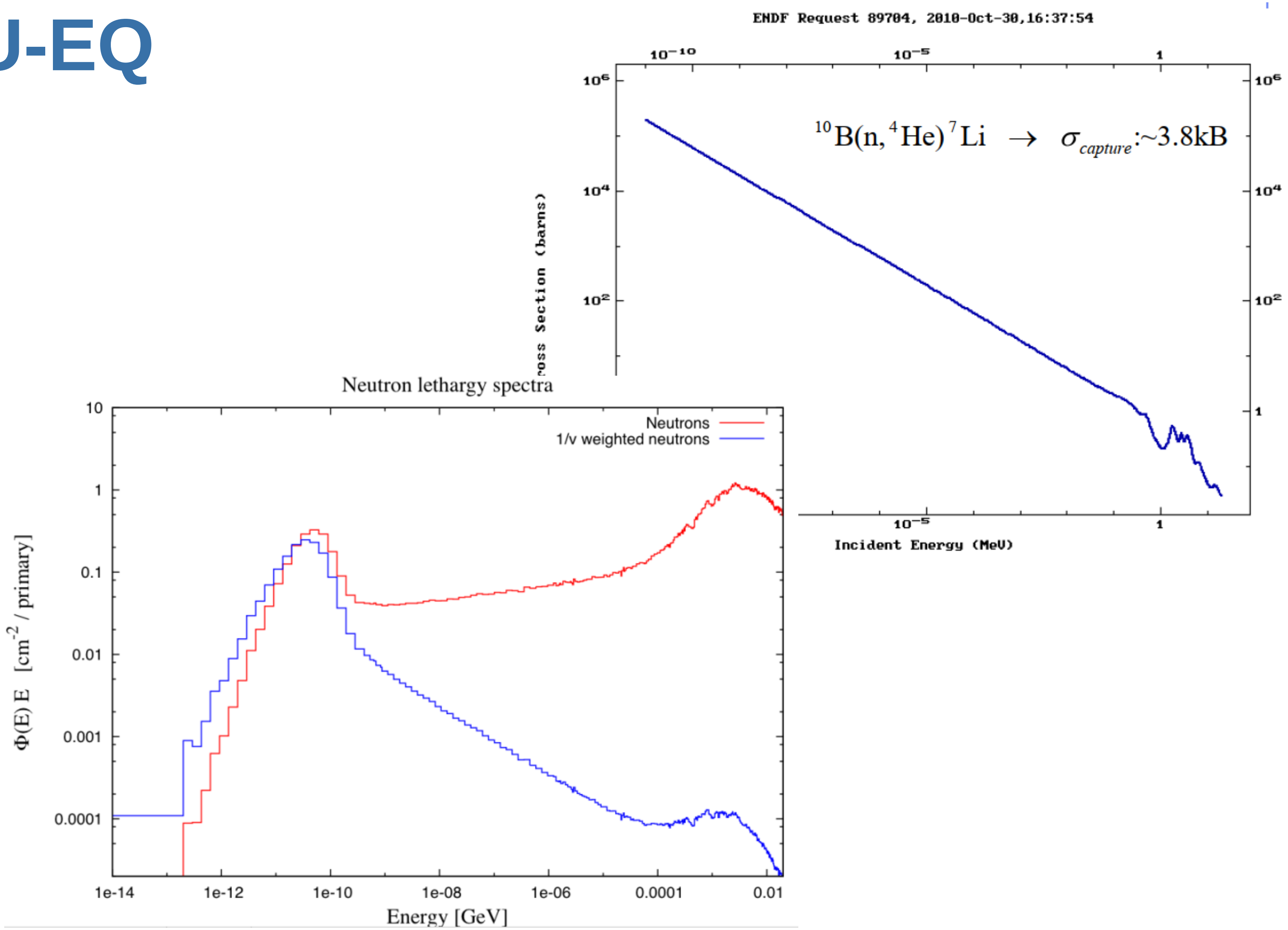
- Based on experimental response function from 0.4 µm technology SRAM



$$\Phi_{HEH} = \int_{0.2\mathrm{MeV}}^{20\mathrm{MeV}} \omega(E)\,\phi_n(E)\,dE + \int_{20\mathrm{MeV}}^{\infty} \phi_{Had}(E)\,dE$$



THNEU-EQ



ENDF Request 89704, 2010-Oct-30,16:37:54
$^{10}B(n,{}^4He){}^7Li \rightarrow \sigma_{capture}$:~3.8kB
Cross Section (barns)
Incident Energy (MeV)
Neutron lethargy spectra
Neutrons
1/v weighted neutrons
Φ(E) E [cm^{-2} / primary]
Energy [GeV]

Overview of SEE estimation in FLUKA

- For radiation environments dominated by hadrons (protons, neutrons, pions…) such as accelerators, ground level applications, and trapped proton belts:
  - If no information about the device response is available, the high-energy hadron equivalent and thermal neutron equivalent fluences are considered the most relevant figures-of-merit for SEE risk (i.e. quantities to be minimized for equipment location, shielding, etc.)
  - If the device response is known via single experimental SEE cross section point (typically, 200 MeV protons, plus thermal neutrons in some cases), the best estimate of the SEE rate is given by:

$$N_{SEE} = \Phi_{th}\sigma_{th} + \Phi_{HEH_{eq}}\sigma_{HEH}$$

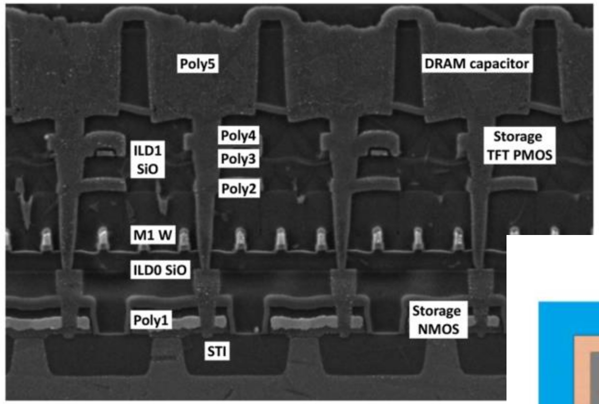
Thermal neutron term

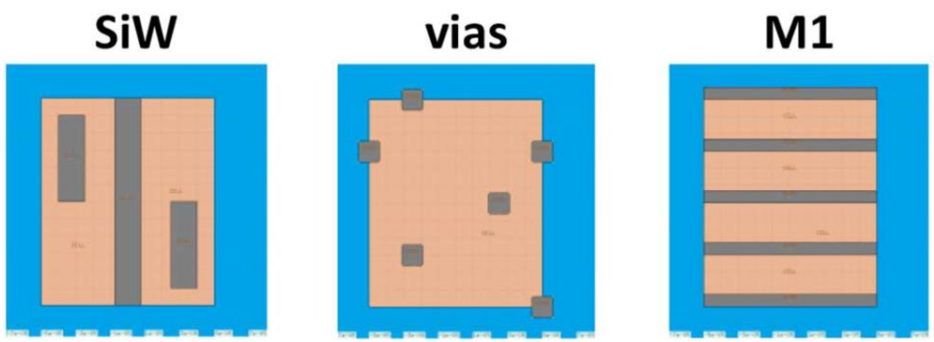
HEH term

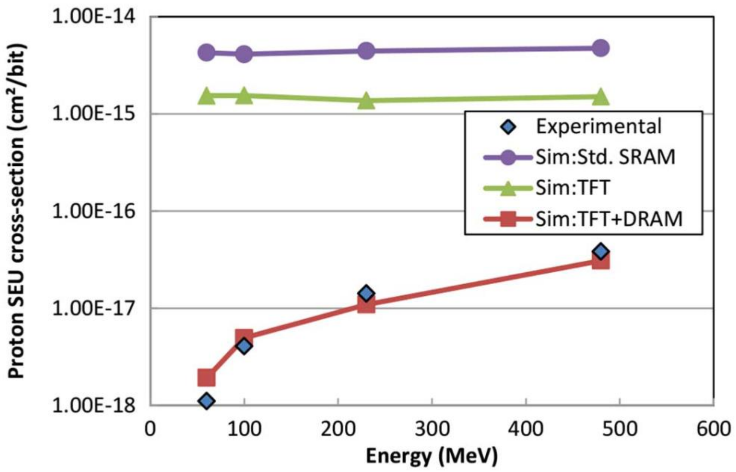
  - If device response is known in full energy range for all relevant particles, one can score the respective energy spectra and fold them with the response function (same applies to LET for environments dominated by heavy ions)

RPP modelling

- If the sensitive volume dimensions and critical charge are known for a given SEE process, in addition to the materials surrounding the sensitive volume, FLUKA can be used (via dedicated user routines) to score the energy deposition distribution and determine the related SEU cross section
- Example: impact of tungsten on SEU response for radiation hardened SRAM







FLUKA