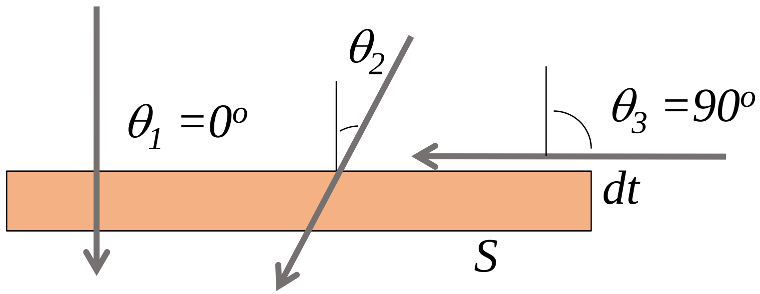
Scoring physics quantities II

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

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 **selection of regions** or in a **regular mesh** (cylindrical, cartesian) described by the user.
- **USRTRACK** (**USRCOLL**) scores average **$d\Phi/dE$ (differential fluence)** of a given type or family of particles in a **given region**.
- **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**.
- **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

in this lecture

- All scorings write their results into **logical output units assigned by the user**
  - Unit numbers must be >20.
  - The only exception is SCORE: its output is printed in the **standard output**.

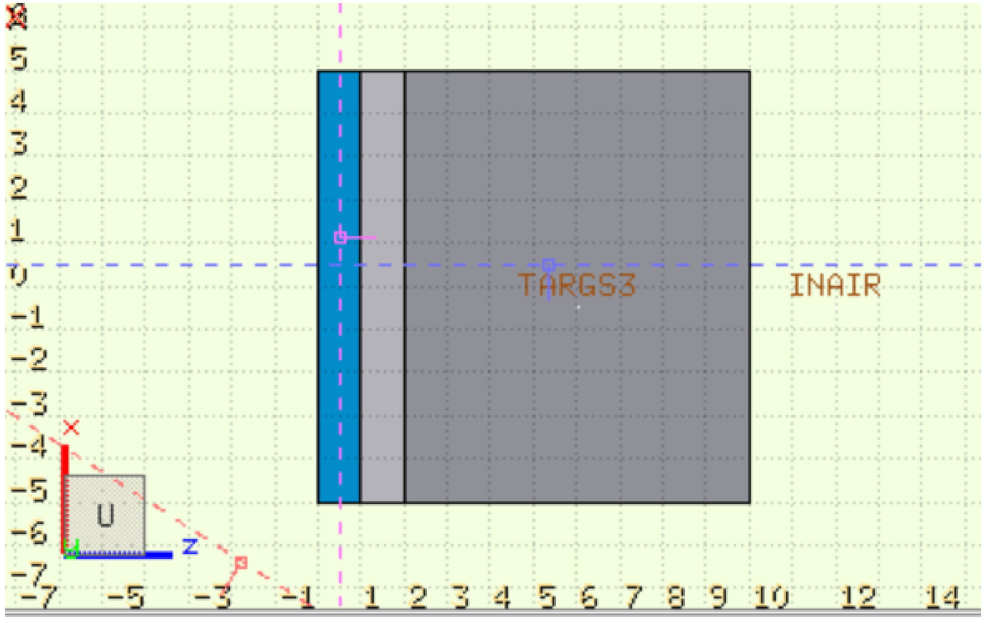
*** *A star is a hadronic inelastic interaction***

Scoring example

beam definitions

BEAM Beam: Energy ▾ E: 3.5 Part: PROTON ▾
Δp: Gauss ▾ Δp(FWHM): 0.8 Δϕ: Gauss ▾ Δϕ (FWHM): 1.7
Shape(X): Rectangular ▾ Δx: Shape(Y): Rectangular ▾ Δy:

BEAMPOS x: y: z: -0.1
cosx: cosy: Type: POSITIVE ▾



3.5 GeV protons on water → aluminum → lead

Results and units

- **FLUKA results in *_tab.lis:**
  - **USRTRACK, USRCOLL**: **single differential distribution in energy [GeV^{-1}]**.
  - **USRBDX**: **single differential distribution in energy [GeV^{-1}] (integrated over solid angle)**.
    In addition, **double differential distribution in energy and solid angle [GeV^{-1} sr^{-1}]**.
  - **USRYIELD**: **double differential distribution in var$_1$ and var$_2$ [var$_1$unit^{-1} var$_2$unit^{-1}]**.
  - All results are **formatted** → Flair can plot from this file.

- **FLUKA results in *_sum.lis:**
  These files include a cumulative distribution, in addition to the above differential distributions.
  The integration is made w.r.t. the 1st variable (energy for USRTRACK, USRCOLL, USRBDX, and var$_1$ for USRYIELD).

  $N = \int \frac{dN}{dE} dE$

  dN/dE: value of each energy bin

  dE: bin width

  → Useful to get **integral over an energy range**.

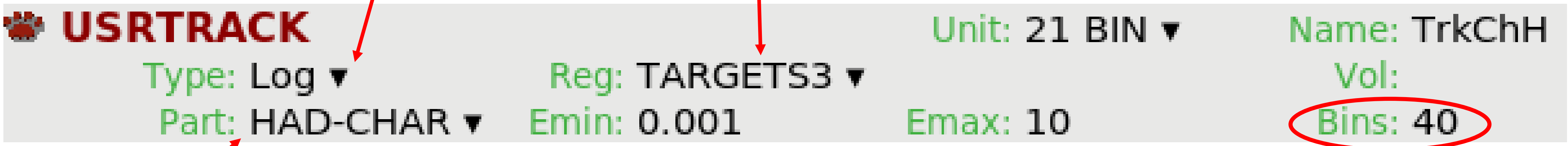
- **FLUKA results are NOT normalized by region volume [boundary area].**
  For example, as scoring particle *fluence* with **USRTRACK [USRBDX, USRYIELD]**, results will only be in *cm^{-2}*:
  - If the user had provided the region volume [boundary area] in the respective card field (before run).
  - Otherwise, if the user applies the desired normalization at post-processing level (e.g. Flair Y Norm).

USRTRACK scoring definition

Tracklength spectrum
(differential in **energy**)

Region choice

Log binning in energy



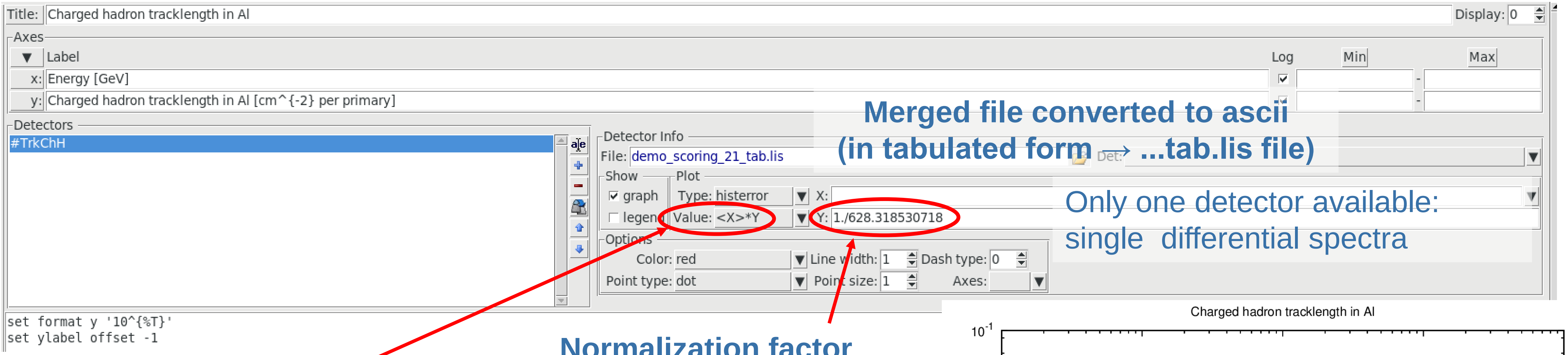
Particle type:
charged
hadrons

40 bins in energy

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

- **demo_scoring_21.trk**: binary file containing the merged data from several runs
- **demo_scoring_21_sum.lis**: ascii file containing energy spectra,
  and in addition energy-integrated cumulative spectra
- **demo_scoring_21_tab.lis**: ascii file containing energy spectra → Flair uses this file

Plotting – single diff. fluence in volume (USRTRACK)



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

Only one detector available: single differential spectra

Normalization factor

Divide by target volume

Note: Flair can compute volumes stochastically (convenient for complex shapes)

Lethargy plot

(1) **Data in *tab.lis** is Y = dI/dE

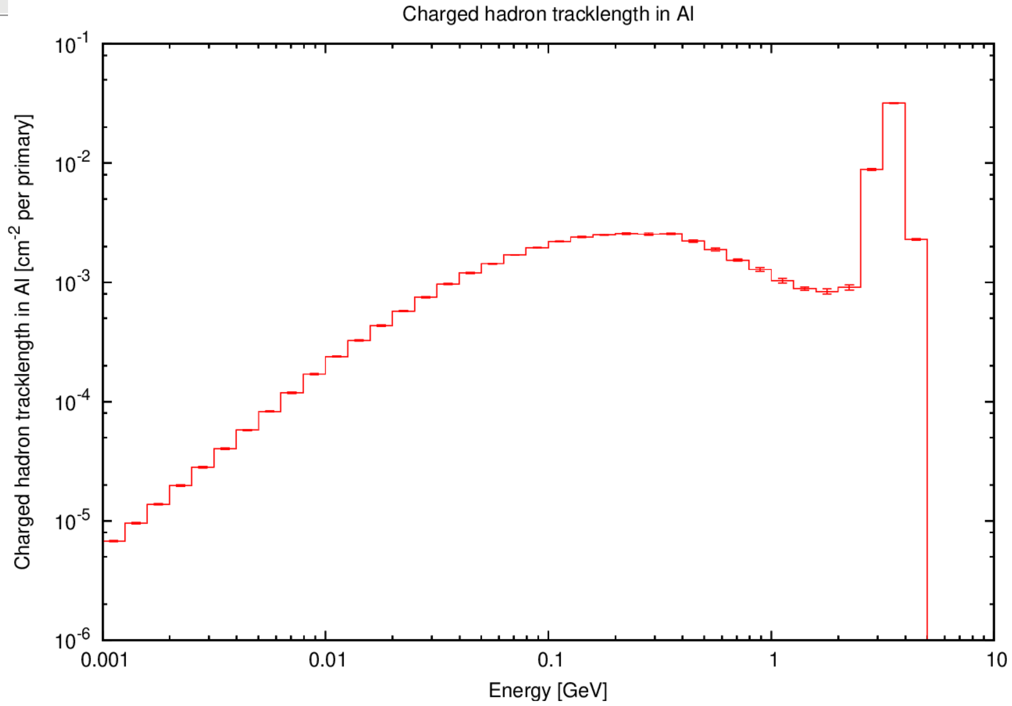
(2) **Flair** multiplies by <X> = E

Note: E is the geometric mean of the energy bin extrema.

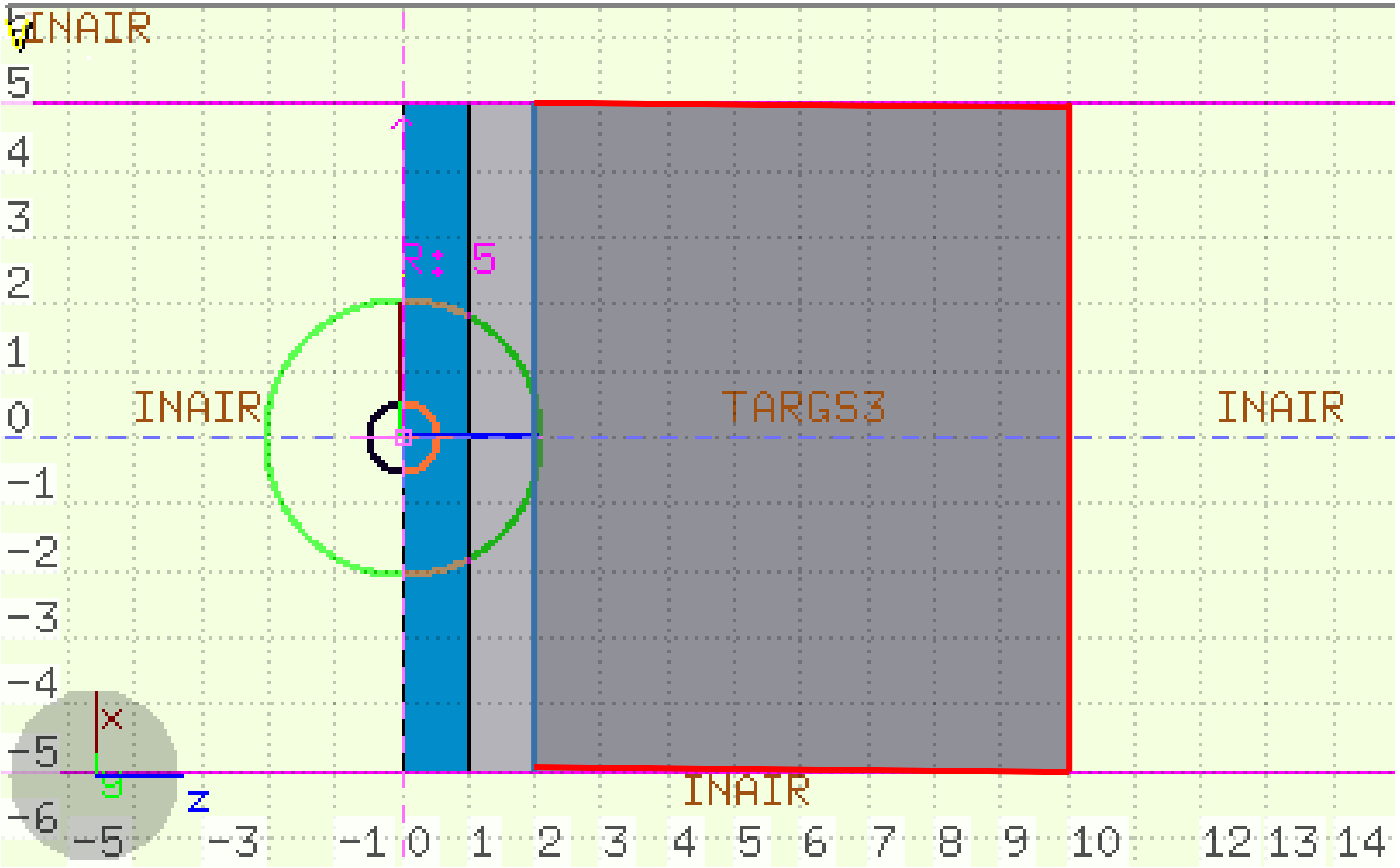
The multiplication is handled via e.g. gnuplot.

(3) One gets **EdI/dE = dI/d(logE)**

Note: Dimensionless



USRBDX area normalization



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

Area between TARGS2 and TARGS3: $\pi R_{TARG}^2 = 78.5398\ cm^2$

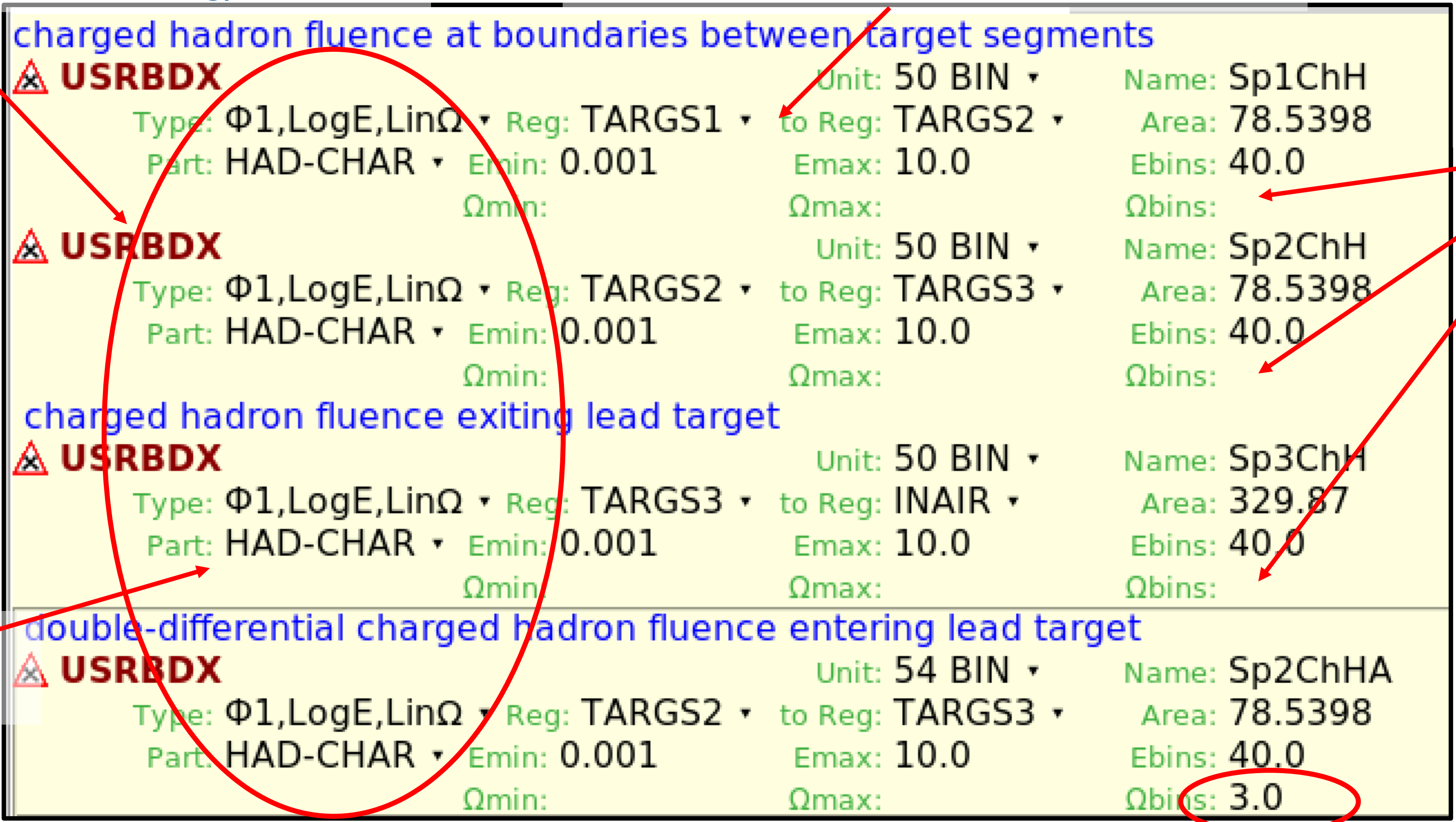
Area between TARGS3 and INAIR: $2\pi R_{TARG}\ \Delta Z_{TARGS3} + \pi R_{TARG}^2 = 329.87\ cm^2$

USRBDX scoring (boundary crossing) definition

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

Only count particles **from TARGS1 to TARGS2 (one-way)**, **not** from TARGS2 to TARGS1

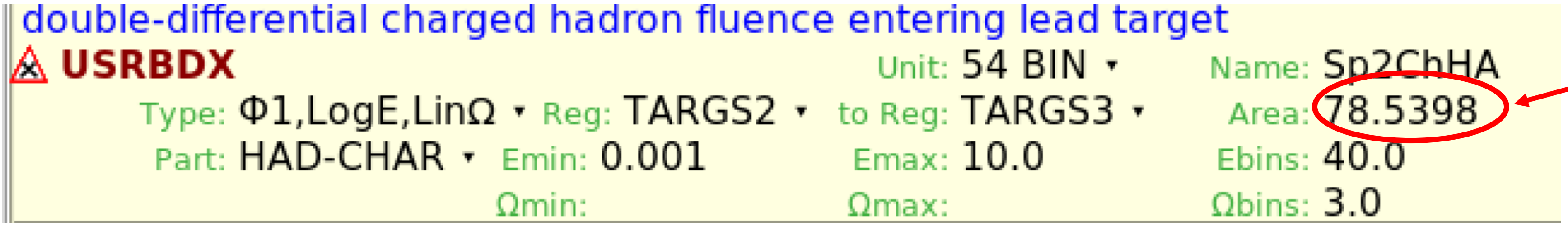
By default **ONE angular bin** (no angular distribution)



Particle type: **charged hadrons**

3 angular bins

USRBDX scoring (boundary crossing) output



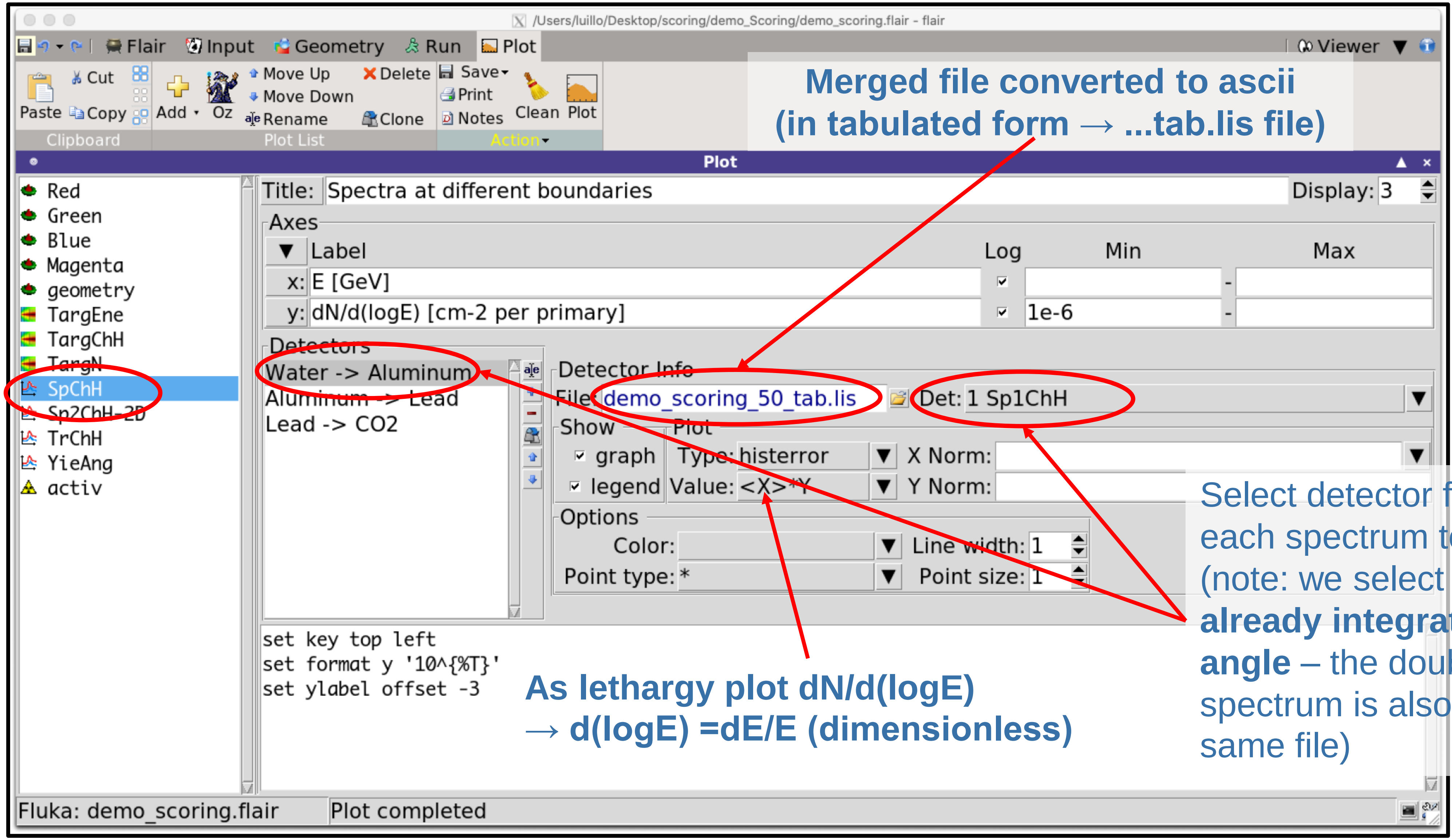
Surface area [cm^2] normalization, which can be independently done at post-processing

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} $\mathbf{sr^{-1}}$

Plotting – single diff. fluence on boundary (USRBDX)



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

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)

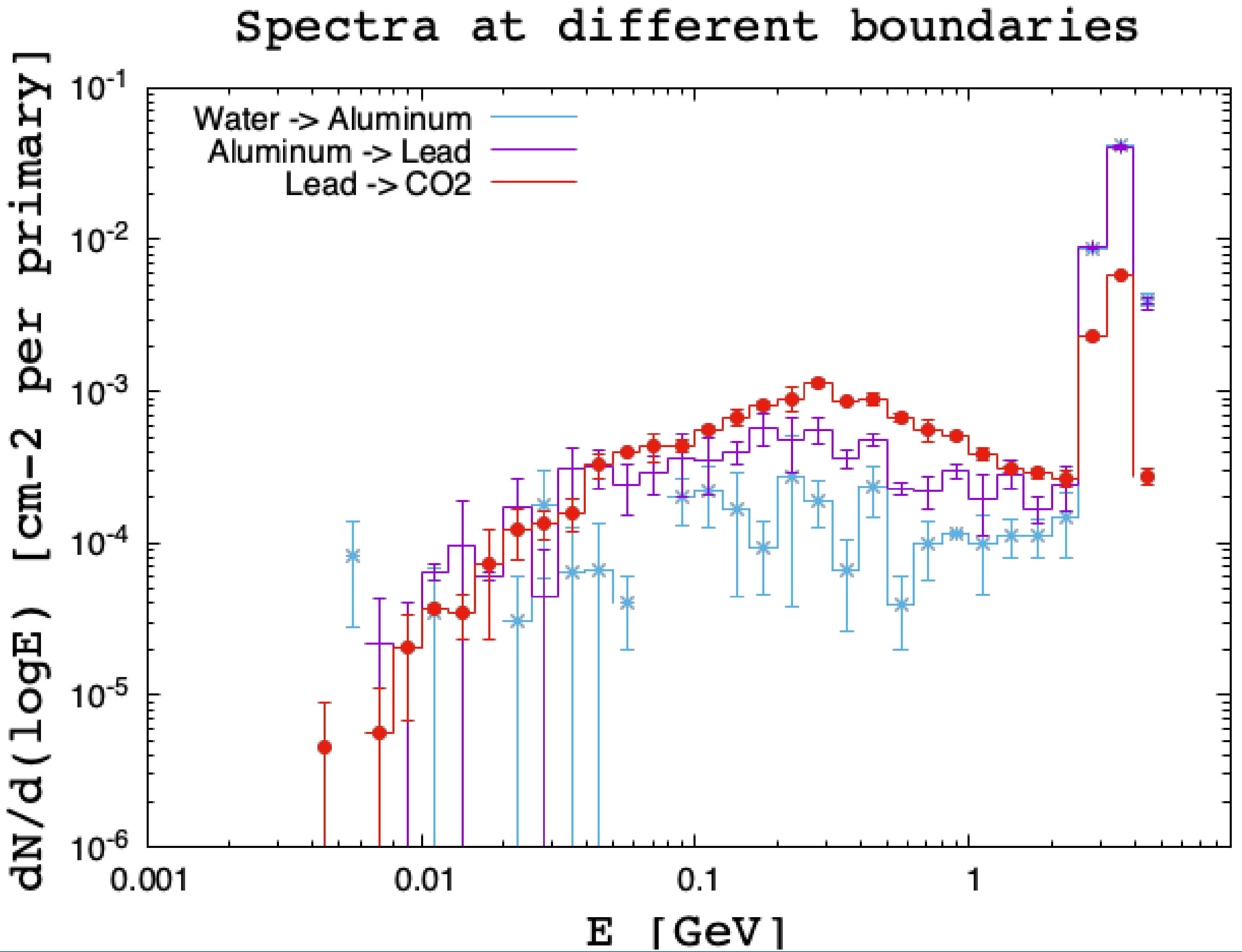
As lethargy plot dN/d(logE) → d(logE) =dE/E (dimensionless)

Plotting – single diff. fluence on boundary (USRBDX)

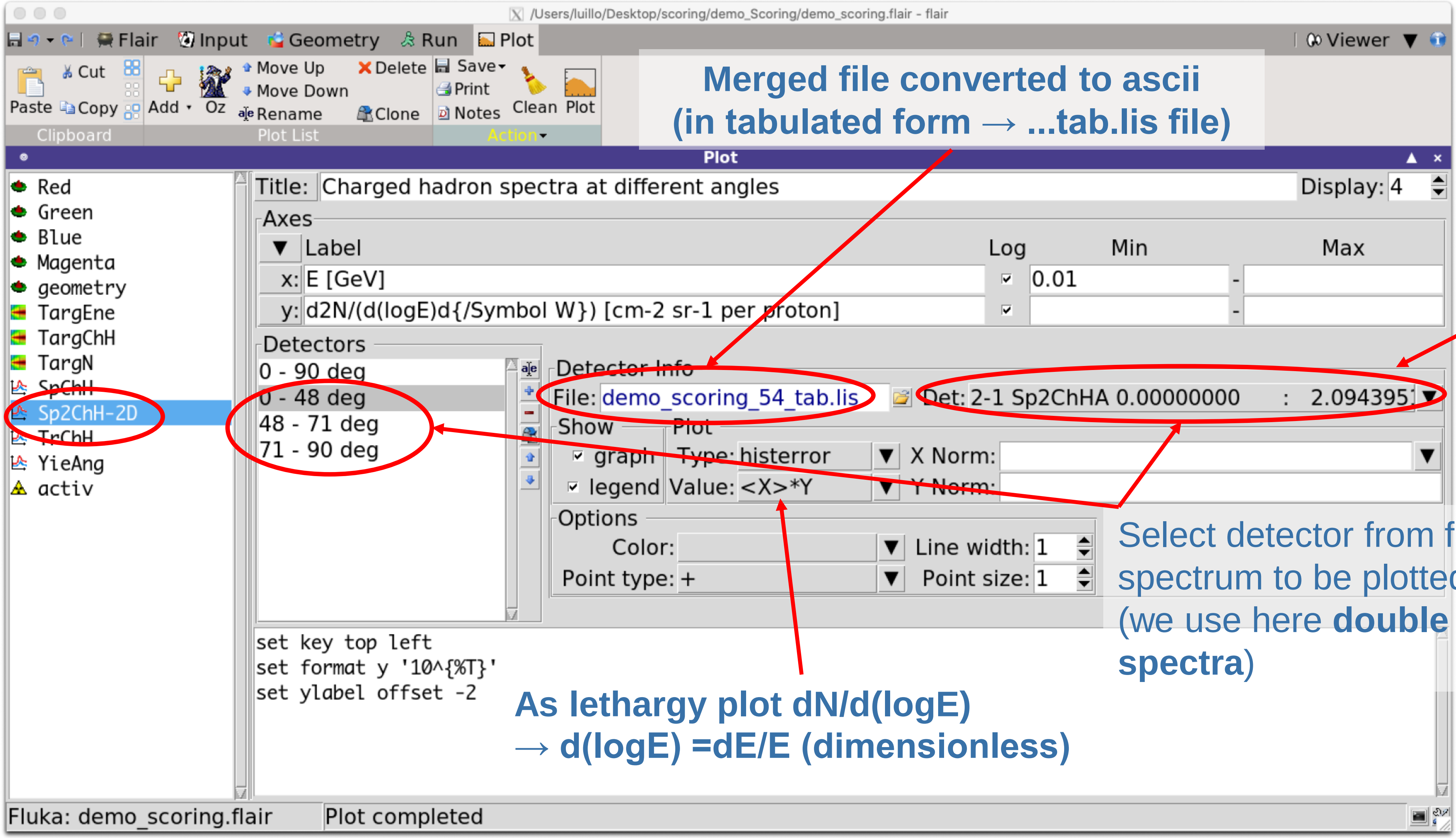
$$y = \frac{dN}{d(logE)} = E\frac{dN}{dE}$$

Value: <X>*Y

Lethargy plot



Plotting – double diff. fluence on boundary (USRBDX)



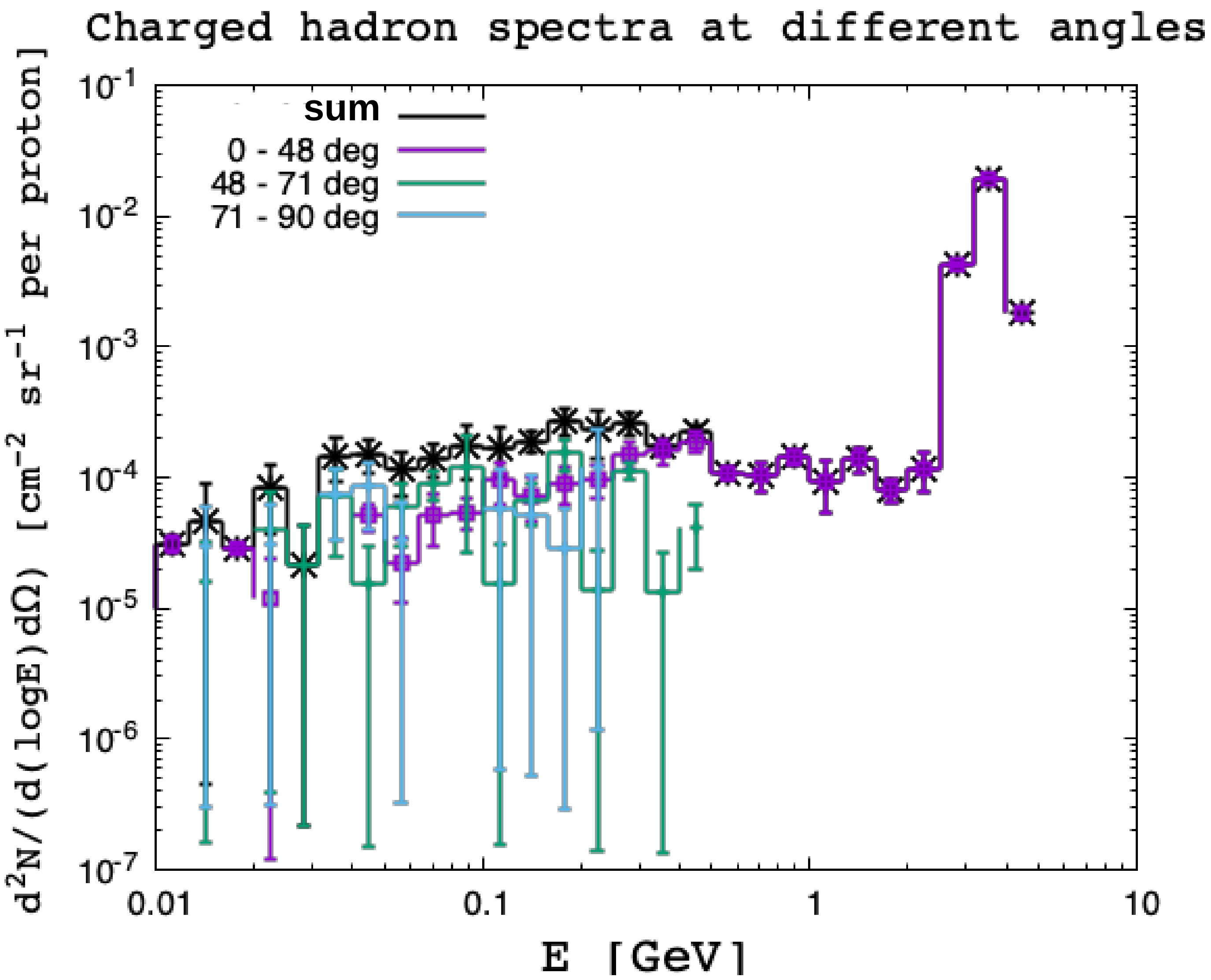
Merged file converted to ascii (in tabulated form → ...tab.lis file)

2π/3 (one-way scoring: max is a half-sphere)

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

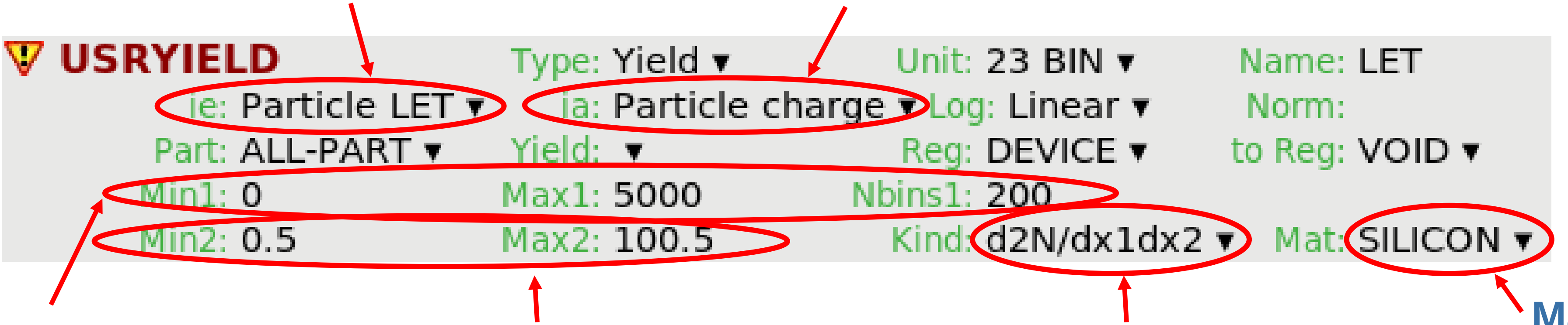
As lethargy plot dN/d(logE) → d(logE) =dE/E (dimensionless)

Plotting – double diff. fluence on boundary (USRBDX)



USRYIELD scoring definition

1st differential variable **2nd differential variable**



1st differential variable
min / max / binning

2nd differential variable
min / max
num bins = 1

Kind:
$d2N/dx_1dx_2$
⇔ current

Material
(Optional)
Needed here because of LET

USRBDX and USRYIELD both provide **differential spectra across a boundary**.
USRYIELD provides a richer choice of weights (see "Kind") and differential variables (see "ie" and "ia").

NB: USRYIELD can additionally be used to score yields of particles emerging from inelastic hadronic interactions with single nuclei (not shown here).

Summary

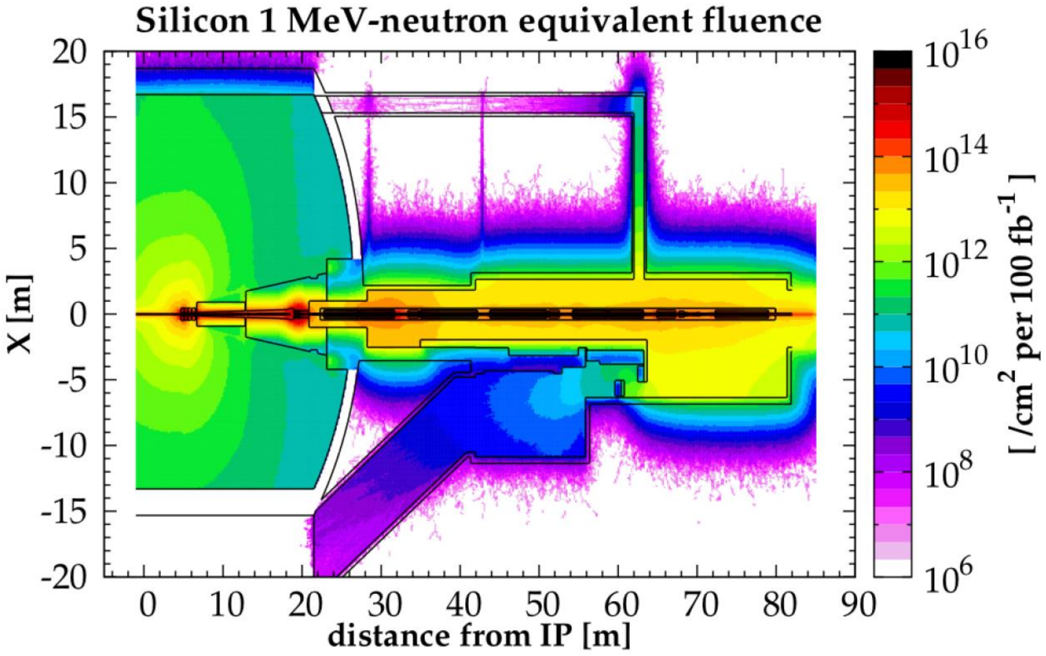
- **USRTRACK**, **USRBDX** and **USRYIELD** are scoring cards which allow to get **differential spectra**.
- Score **tracklength** density in a **volume**
  single differential in energy
  → **USRTRACK**
- Score **fluence or current** across a **boundary**
  single differential in energy, or **double differential in energy and angle with boundary normal**
  → **USRBDX**
- Score **particles count** across a **boundary** in a more customized way:
  more complex weights, or differential variables other than energy / angle with boundary normal (e.g. angle with beam direction, LET, …), etc
  → **USRYIELD**
- It is the user responsibility to ensure normalization by region volume / boundary area.

Scoring physics quantities [II]

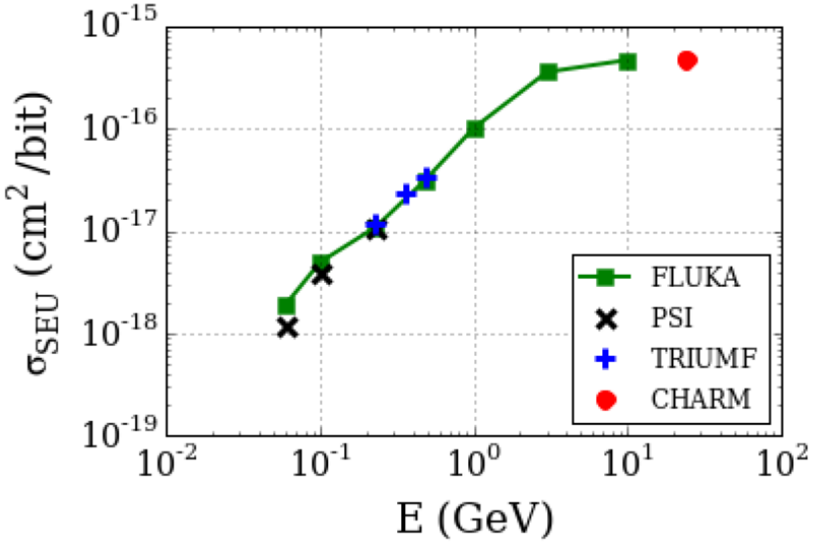
Radiation to Electronics scoring

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…]

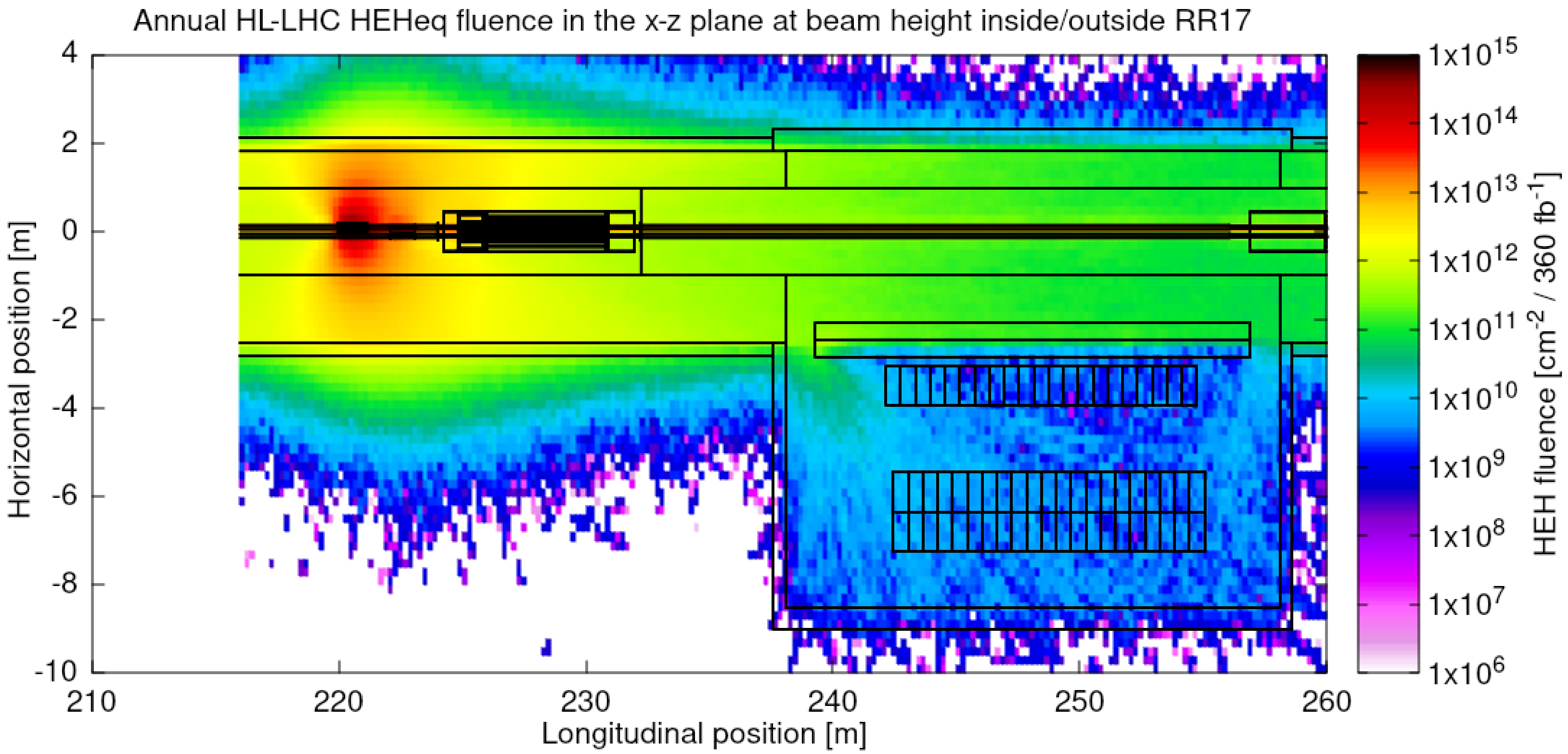
Main radiation effects in electronics

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

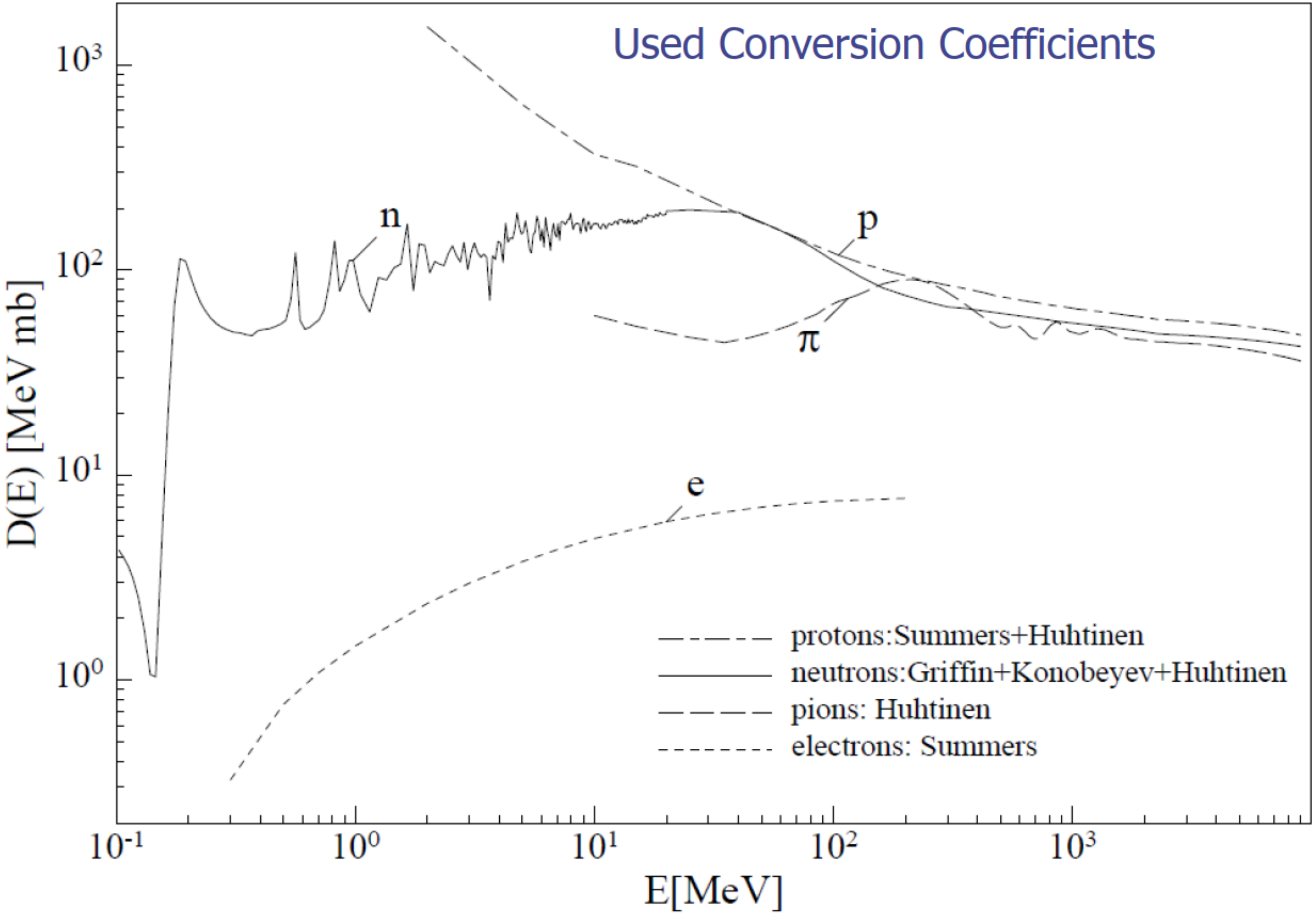
Radiation damage scoring in FLUKA

- 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`)
      - Non-Ionizing Energy Loss (**NIEL**), Displacement Per Atom (**DPA**)
  - 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

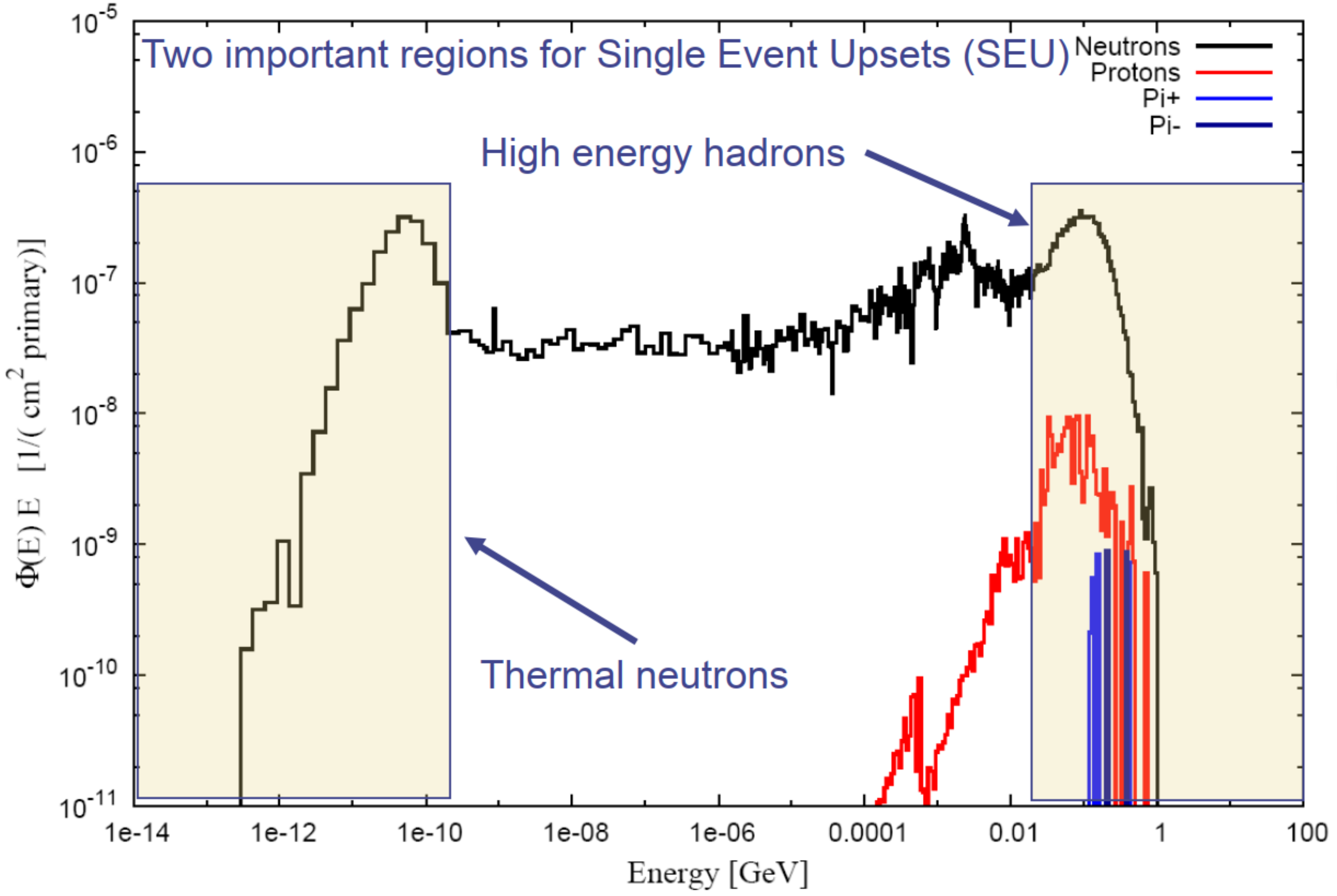


1-MeV neutron equivalent in silicon



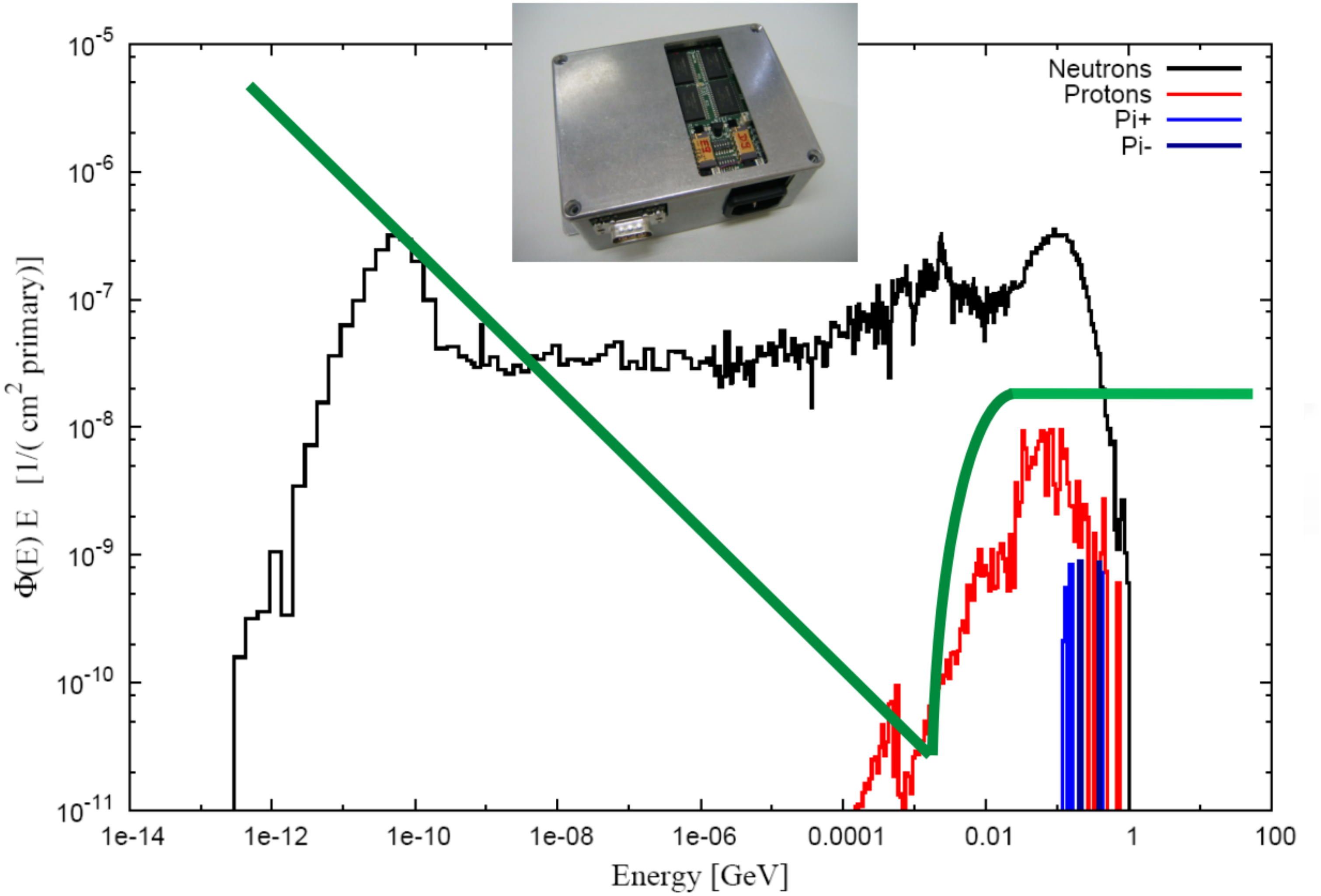
SEUs in mixed radiation field

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



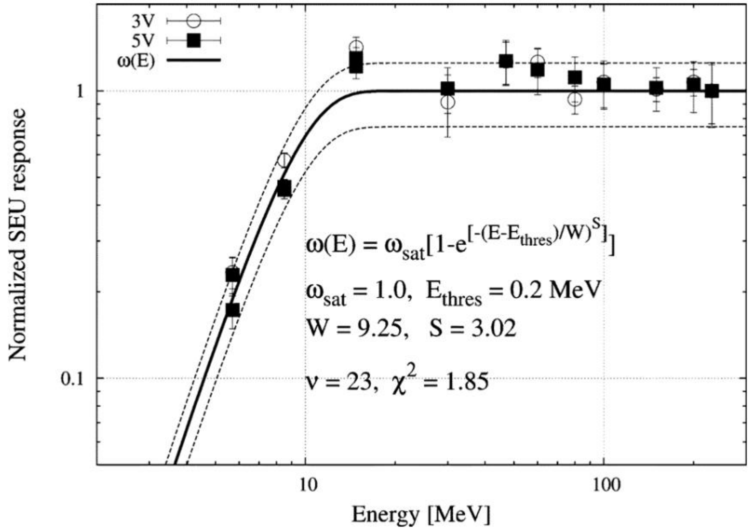
SEUs in mixed radiation fields

e.g. LHC RadMon

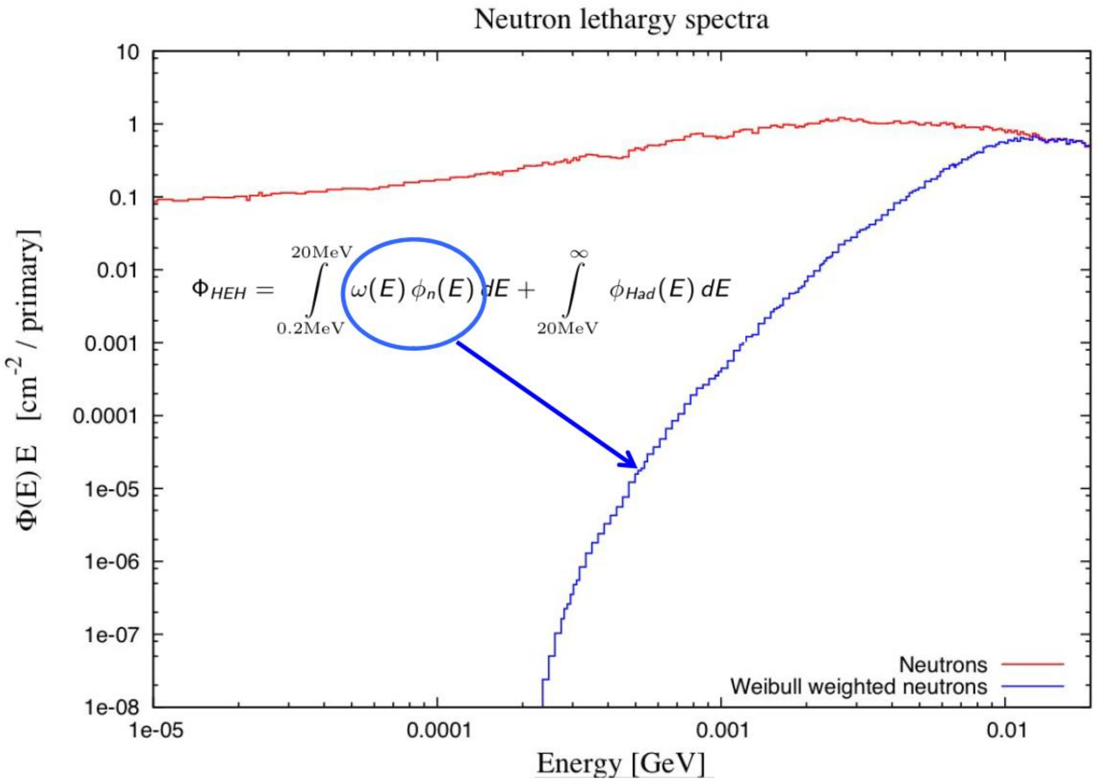


HEHAD-EQ

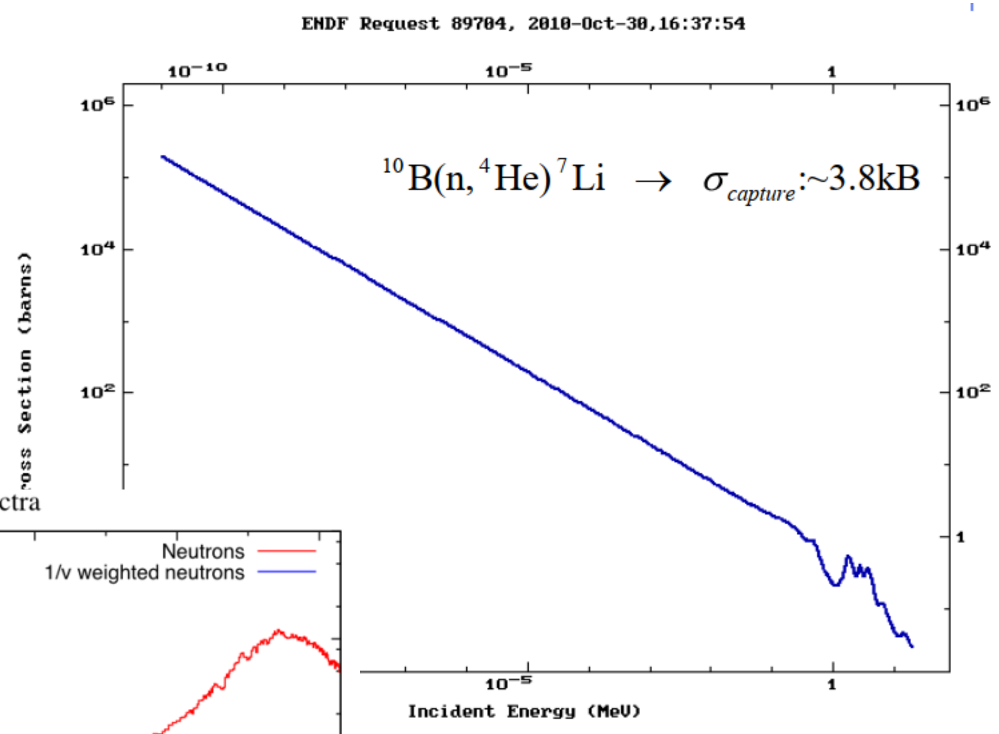
- Based on experimental response function from 0.4 µm technology SRAM

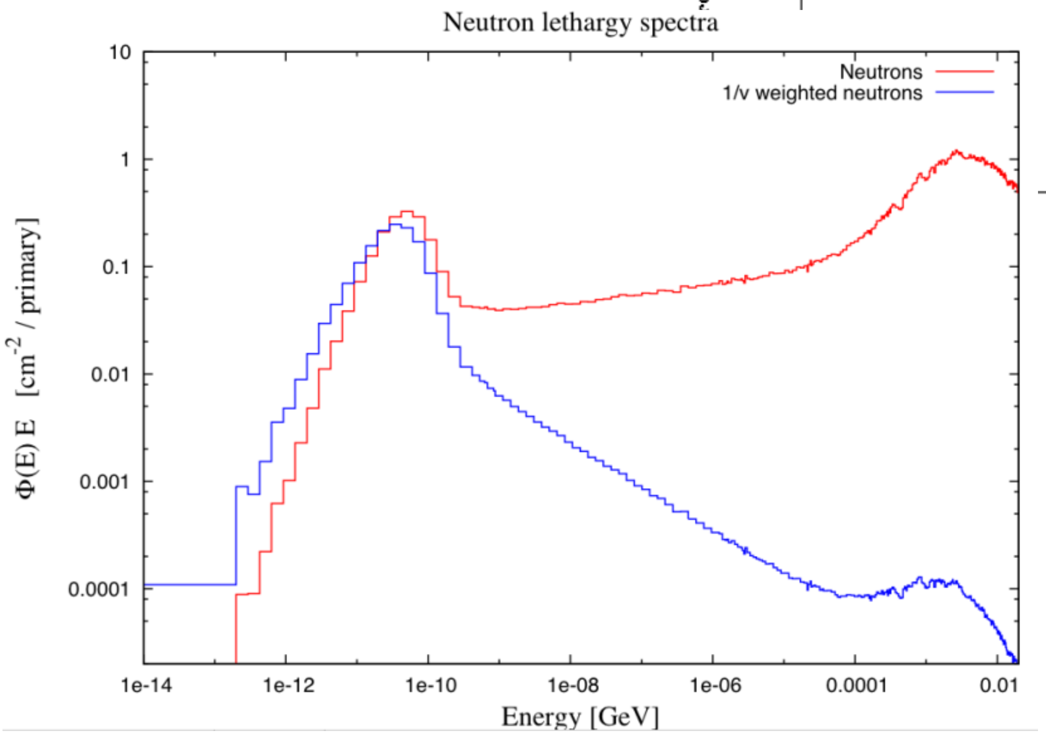


$$\Phi_{HEH} = \int_{0.2\mathrm{MeV}}^{20\mathrm{MeV}} \omega(E)\,\phi_n(E)\,dE + \int_{20\mathrm{MeV}}^{\infty} \phi_{Had}(E)\,dE$$



THNEU-EQ


ENDF Request 89704, 2010-Oct-30,16:37:54
$^{10}B(n,{}^{4}He)^{7}Li \rightarrow \sigma_{capture}$:~3.8kB
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:

$$N_{SEE} = \underbrace{\Phi_{th}\sigma_{th}}_{\text{Thermal neutron term}} + \underbrace{\Phi_{HEH_{eq}}\sigma_{HEH}}_{\text{HEH term}}$$

  - 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)

FLUKA