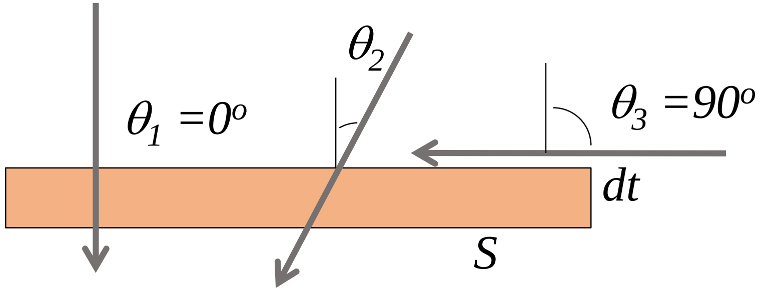
Scoring physics quantities [II]

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

Beginner Course – ULB, May 2022

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** F 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 = F/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

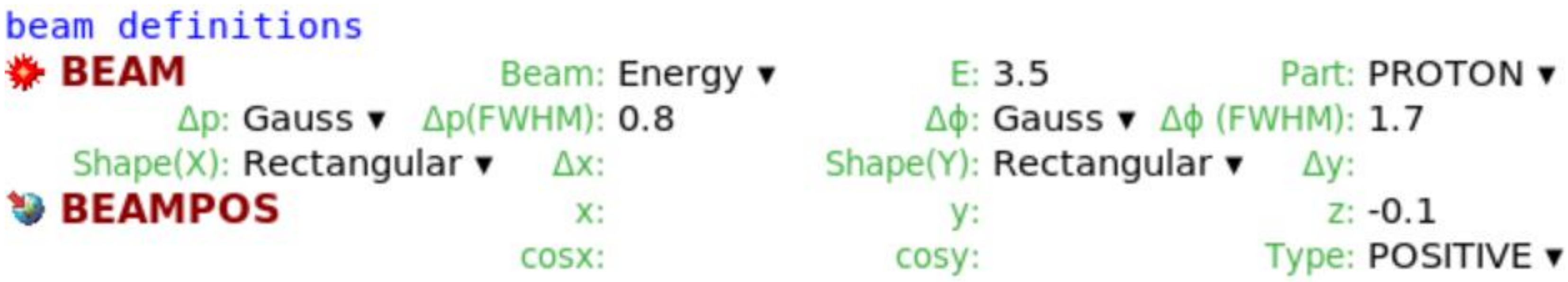
- **`USRBIN`** scores the **spatial distribution** of **energy density** or **fluence** (or star density) in a **regular mesh** (cylindrical, Cartesian, or by region) described by the user
- **`USRBDX`** scores average **$d^2\Phi/dEd\Omega$ (double-differential fluence or current)** of a given type or 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



beam definitions

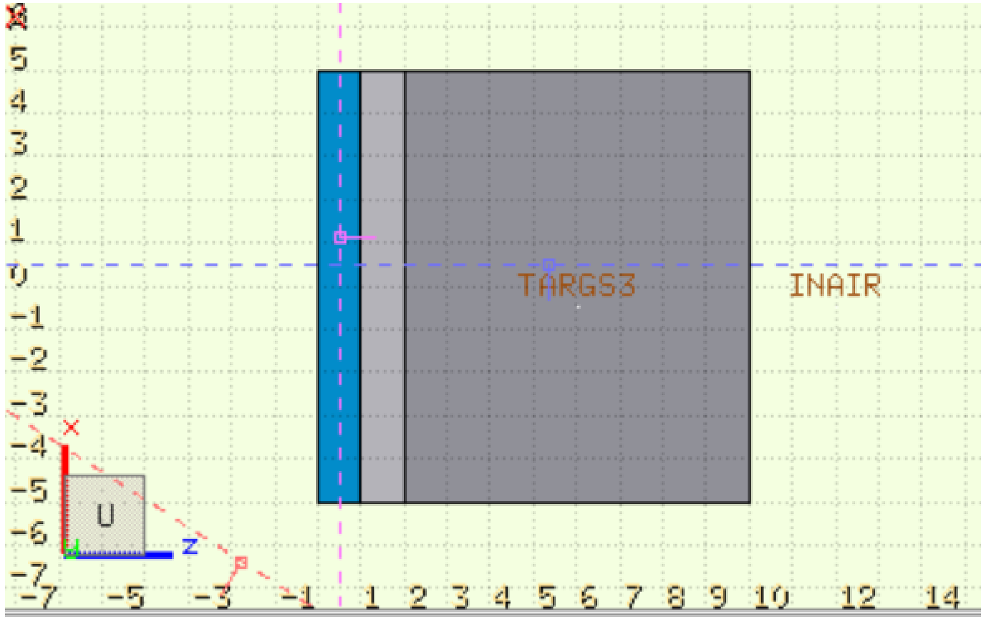
BEAM Beam: Energy ▾ E: 3.5 Part: PROTON ▾

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 ▾

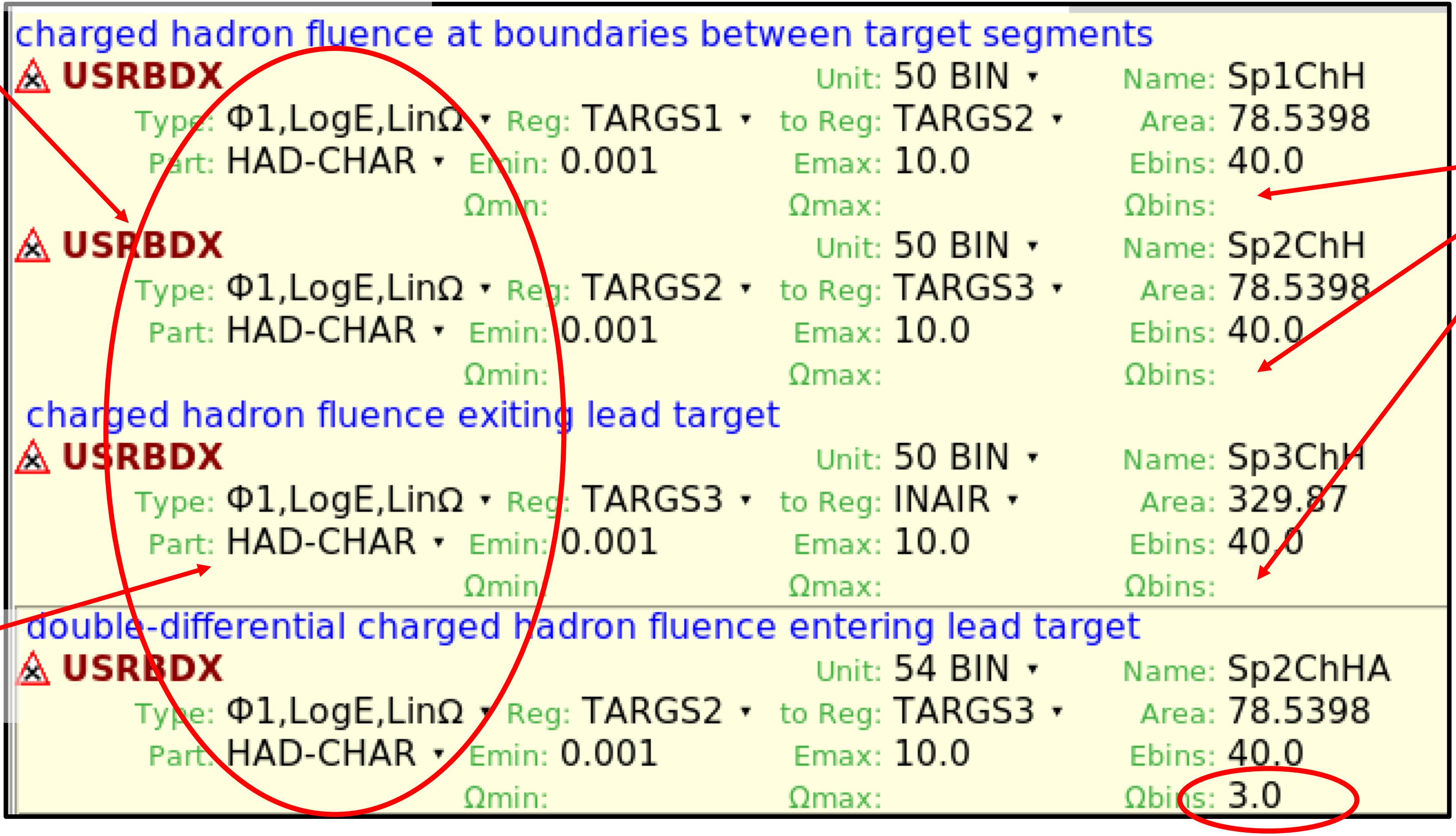


3.5 GeV protons on water → aluminum → lead

`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)



charged hadron fluence at boundaries between target segments

USRBDX Unit: 50 BIN Name: Sp1ChH
Type: Φ1,LogE,LinΩ Reg: TARGS1 to Reg: TARGS2 Area: 78.5398
Part: HAD-CHAR Emin: 0.001 Emax: 10.0 Ebins: 40.0
Ωmin: Ωmax: Ωbins:

USRBDX Unit: 50 BIN Name: Sp2ChH
Type: Φ1,LogE,LinΩ Reg: TARGS2 to Reg: TARGS3 Area: 78.5398
Part: HAD-CHAR Emin: 0.001 Emax: 10.0 Ebins: 40.0
Ωmin: Ωmax: Ωbins:

charged hadron fluence exiting lead target

USRBDX Unit: 50 BIN Name: Sp3ChH
Type: Φ1,LogE,LinΩ Reg: TARGS3 to Reg: INAIR Area: 329.87
Part: HAD-CHAR Emin: 0.001 Emax: 10.0 Ebins: 40.0
Ωmin: Ωmax: Ωbins:

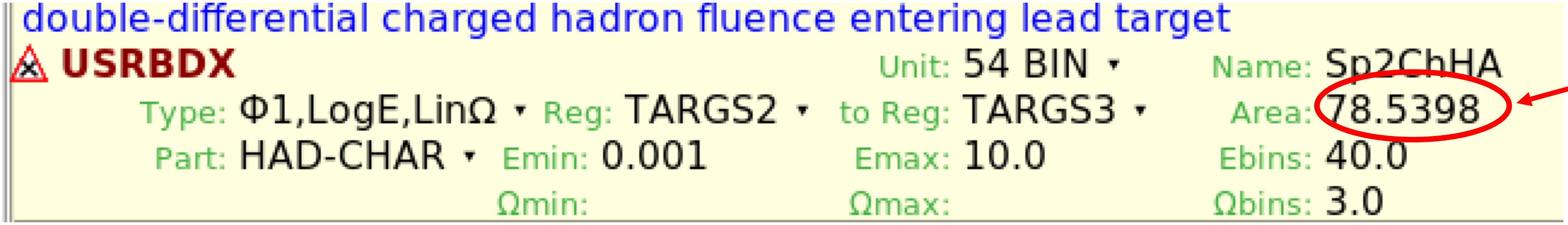
double-differential charged hadron fluence entering lead target

USRBDX Unit: 54 BIN Name: Sp2ChHA
Type: Φ1,LogE,LinΩ Reg: TARGS2 to Reg: TARGS3 Area: 78.5398
Part: HAD-CHAR Emin: 0.001 Emax: 10.0 Ebins: 40.0
Ωmin: Ωmax: Ωbins: 3.0

Particle type:
charged hadrons

3 angular bins

USRBDX scoring (boundary crossing) output


double-differential charged hadron fluence entering lead target

USRBDX Unit: 54 BIN ▾ Name: Sp2ChHA

Type: Φ1,LogE,LinΩ ▾ Reg: TARGS2 ▾ to Reg: TARGS3 ▾ Area: 78.5398

Part: HAD-CHAR ▾ Emin: 0.001 Emax: 10.0 Ebins: 40.0

Ωmin: Ωmax: Ωbins: 3.0

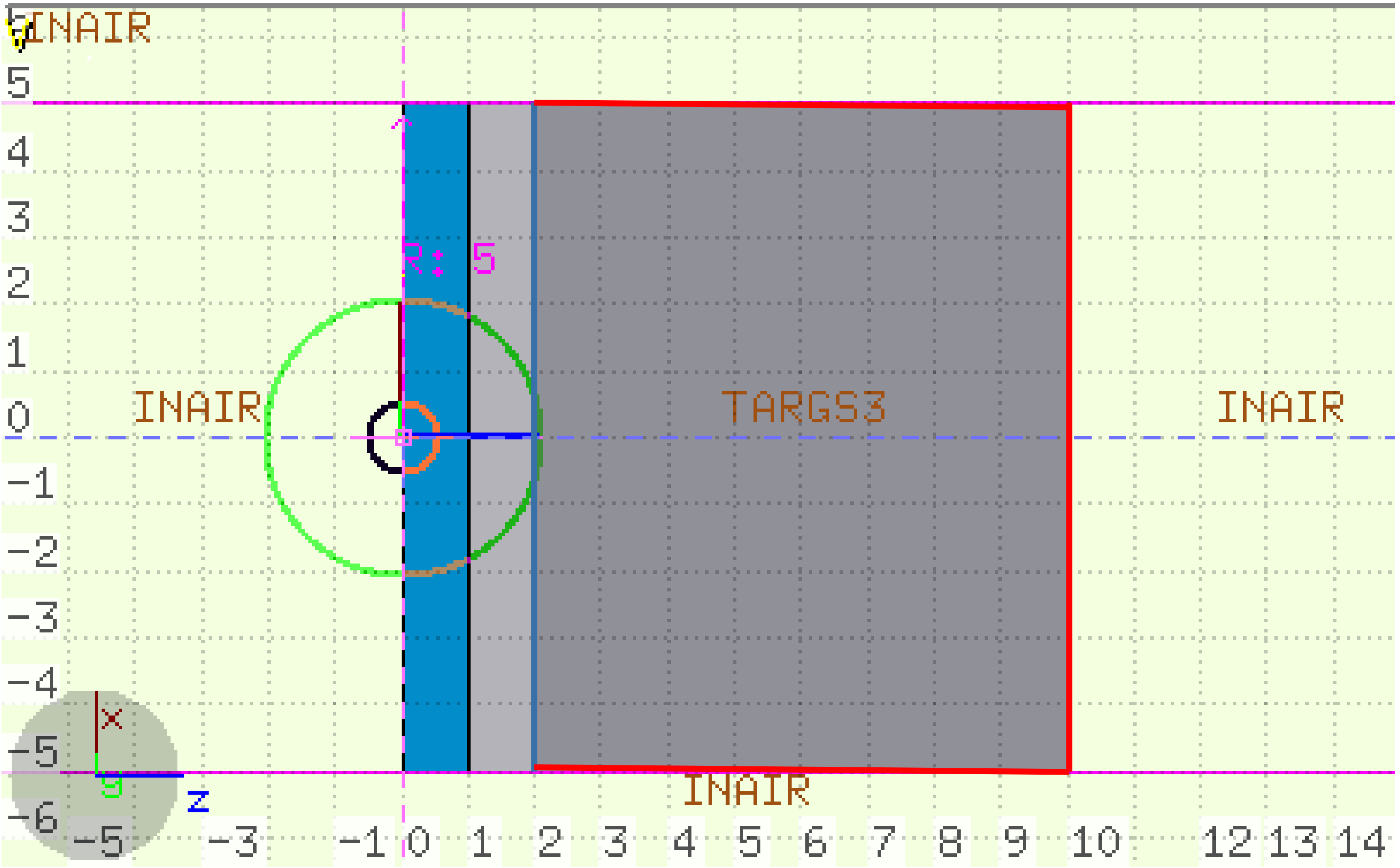
Surface area [cm^2] normalization, which can be independently done at post-processing

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 → <u>Flair uses this file</u>

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

USRBDX area normalization

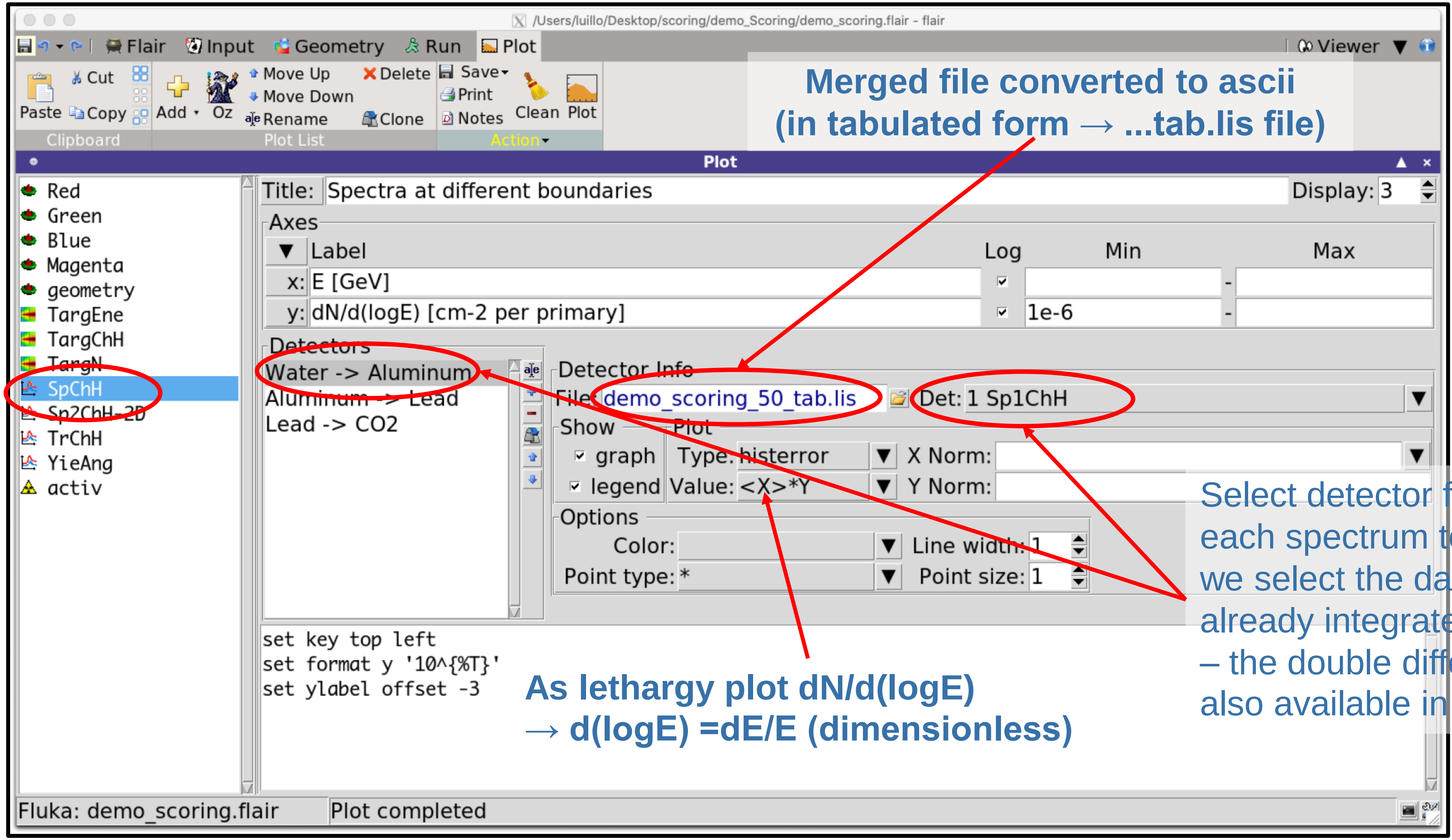


$R_{TARG} = 5$ cm
$\Delta Z_{TARGS1} = 1$ cm
$\Delta Z_{TARGS2} = 1$ cm
$\Delta Z_{TARGS3} = 8$ cm

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

Plotting – charged hadron spectra (USRBDX)



/Users/luillo/Desktop/scoring/demo_Scoring/demo_scoring.flair - flair

Title: Spectra at different boundaries

Display: 3

	Label	Log	Min	Max
x:	E [GeV]	☑		
y:	dN/d(logE) [cm-2 per primary]	☑	1e-6	

Water -> Aluminum
Aluminum -> Lead
Lead -> CO2

File: demo_scoring_50_tab.lis

Det: 1 Sp1ChH

☑ graph
☑ legend

Type: histerror

Value: <X>*Y

X Norm:

Y Norm:

Color:

Line width: 1

Point type: *

Point size: 1

```
set key top left
set format y '10^{%T}'
set ylabel offset -3
```

Fluka: demo_scoring.flair

Plot completed

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)

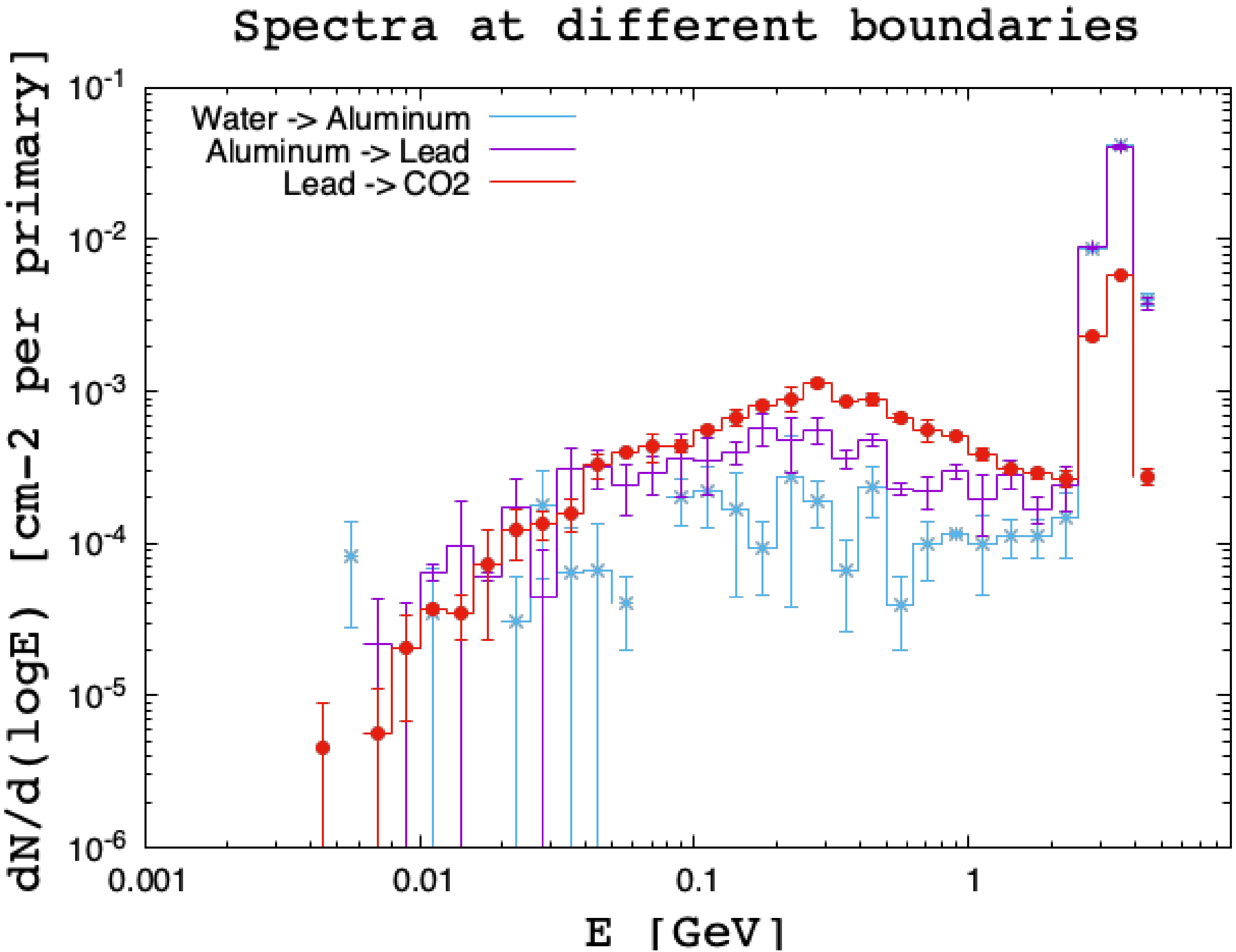
As lethargy plot dN/d(logE) → d(logE) =dE/E (dimensionless)

Plot result – charged hadron spectra (`USRBDX`)

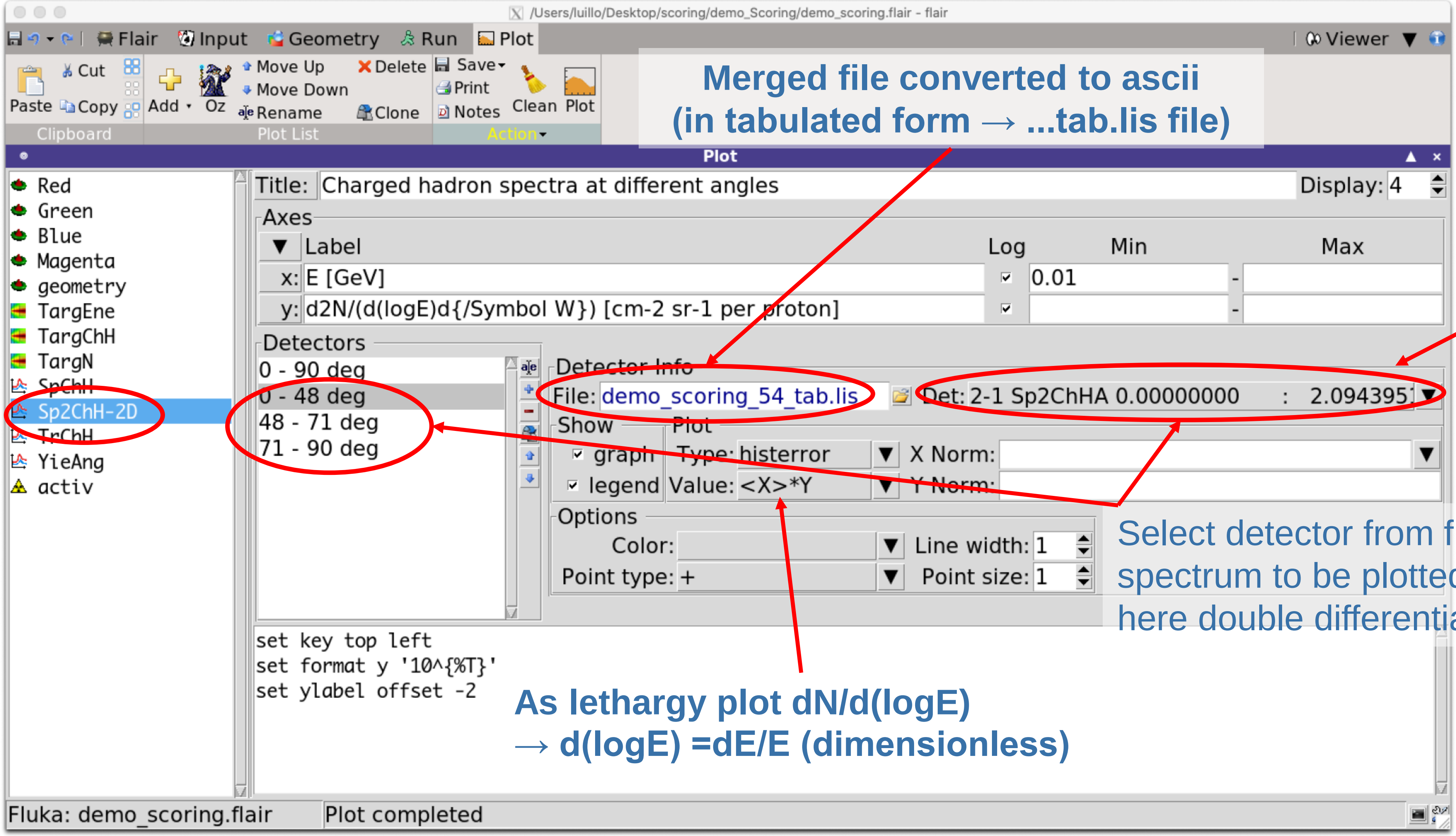
$$y = \frac{dN}{d(logE)} = E\frac{dN}{dE}$$

Value: <X>*Y

Lethargy plot



Plotting – double differential fluence (`USRBDX`)



Title: Charged hadron spectra at different angles

Display: 4

Axes

	Label	Log	Min	Max
x:	E [GeV]	☑	0.01	
y:	d2N/(d(logE)d{/Symbol W}) [cm-2 sr-1 per proton]	☑		

Detectors

0 - 90 deg
0 - 48 deg
48 - 71 deg
71 - 90 deg

Detector Info

File: demo_scoring_54_tab.lis

Det: 2-1 Sp2ChHA 0.00000000 : 2.094395

Show
☑ graph
☑ legend

Plot
Type: histerror
Value: <X>*Y
X Norm:
Y Norm:

Options
Color:
Line width: 1
Point type: +
Point size: 1

```
set key top left
set format y '10^{%T}'
set ylabel offset -2
```

Fluka: demo_scoring.flair

Plot completed

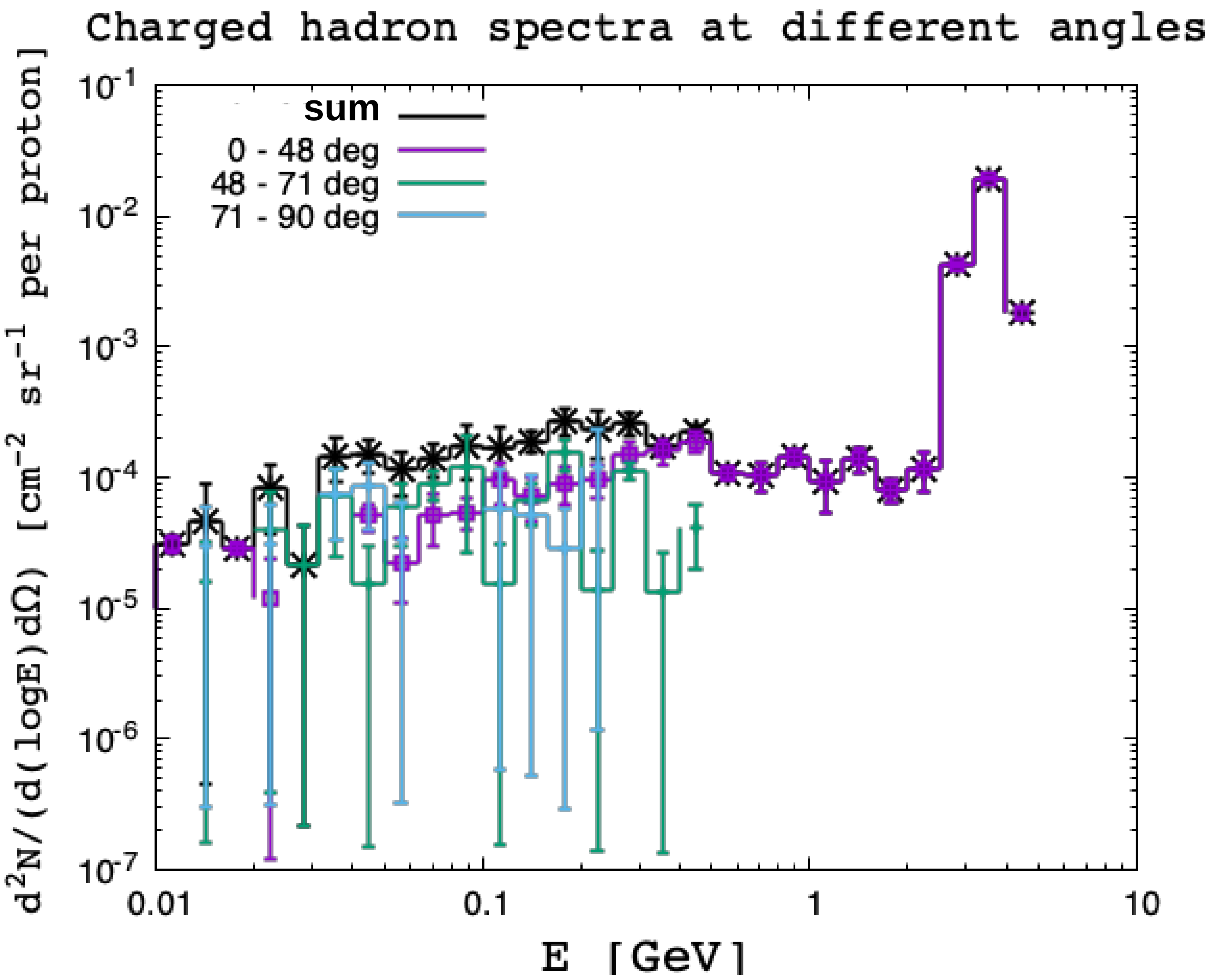
Merged file converted to ascii (in tabulated form → ...tab.lis file)

2p/3

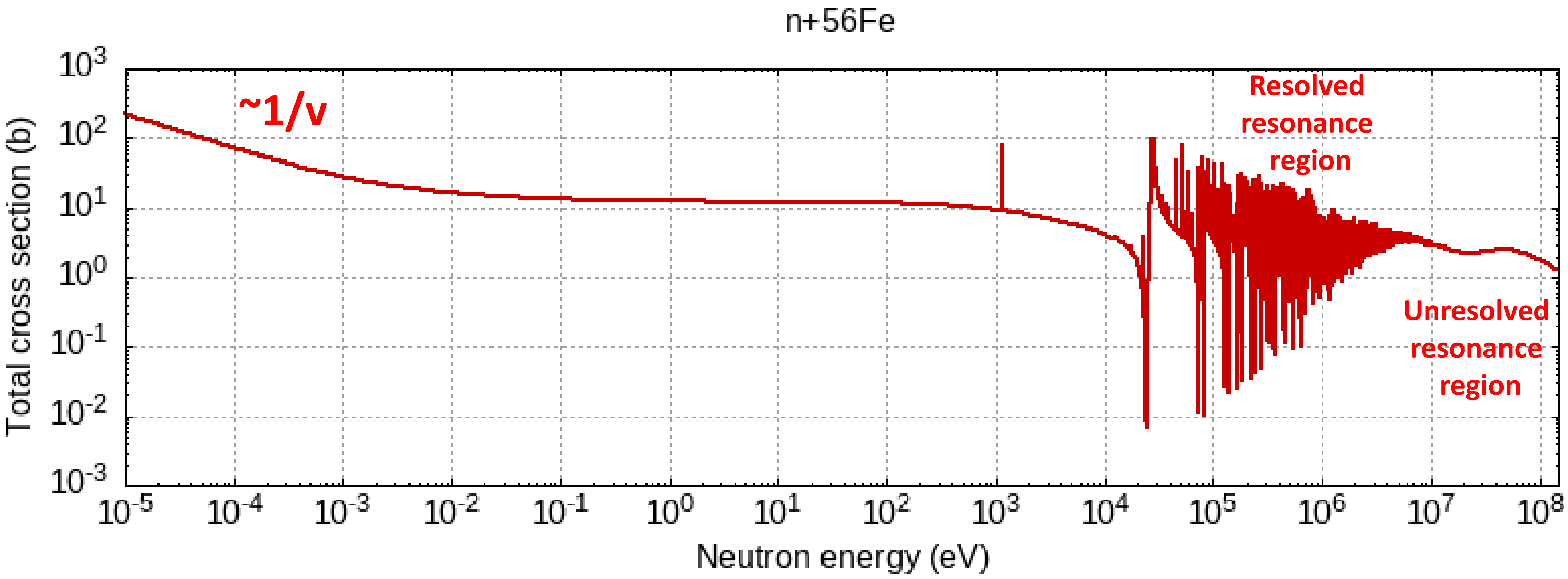
Select detector from file for each spectrum to be plotted (we use here double differential spectra)

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

Plot result – double differential fluence (`USRBDX`)



Low-energy-neutron interaction cross section



- No effective model is able to reproduce the rich resonance structure
- Transport codes rely on libraries of evaluated nuclear data to describe neutron interactions below ~20 MeV for a reasonably comprehensive list of isotopes

Low-energy neutron interactions in FLUKA

- Leaving a handful of exceptional channels aside, **group-wise** treatment up to **v4-2.2**:
  - Coarse fixed energy scale (group binning)
  - Cross sections averaged within each group (260 in FLUKA), washing out sharp resonances
  - Self-shielding effects only for a few isotopes
  - Libraries available for ~70 elements, at a **few temperatures**
  - **Charged secondaries not explicitly tracked** (energy deposition on the spot via kerma factors)
  - Elastic and non-elastic interactions not simulated as exclusive processes, but in terms of group-to-group transfer probabilities
  - Gamma generation within 42 groups when available
  - **No correlation** among shower particles

  - Very fast simulation, adequate for thick targets (self-shielding aside)
  - Problematic for detector simulation

- **Point-wise** treatment coming up for **v4-3.0**:
  - Well resolved resonances
  - No self-shielding issues in resolved resonance region
  - ~550 isotopes (from ENDF, JENDL, JEFF)
  - Doppler broadening at **arbitrary temperature***
  - **Charged secondaries explicitly produced and transported**
  - **Nearly correlated** shower development (n-body emission as subsequent 2-body emissions)
  - Molecular/solid-state binding effects accounted for via a coherent and incoherent scattering function S(α,β,T) for ~20 materials.
  - Interaction sampling heavily optimized for CPU-speed, but still a time penalty is expected
  - Mixed group/point-wise calculation possible
  - Applicable for n detector simulation

Neutrons

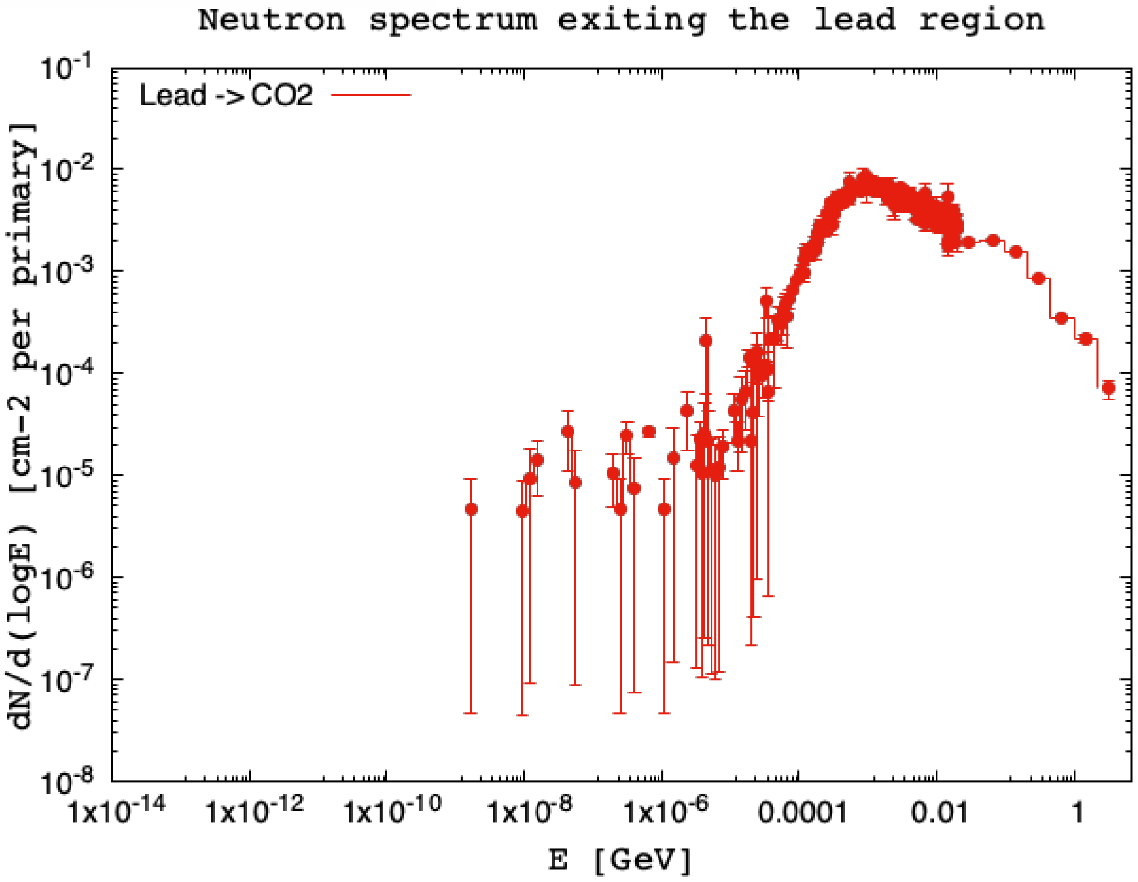
neutron fluence exiting lead target

USRBDX

Type: Φ1,LogE,LinΩ ▾ | Reg: TARGS3 ▾ | Unit: 51 BIN ▾ | Name: Sp3Neutron
Part: NEUTRON ▾ | Emin: 1e-14 | to Reg: INAIR ▾ | Area: 329.87
Emax: 10.0 | Ebins: 40.0
Ωmin: | Ωmax: | Ωbins:

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.

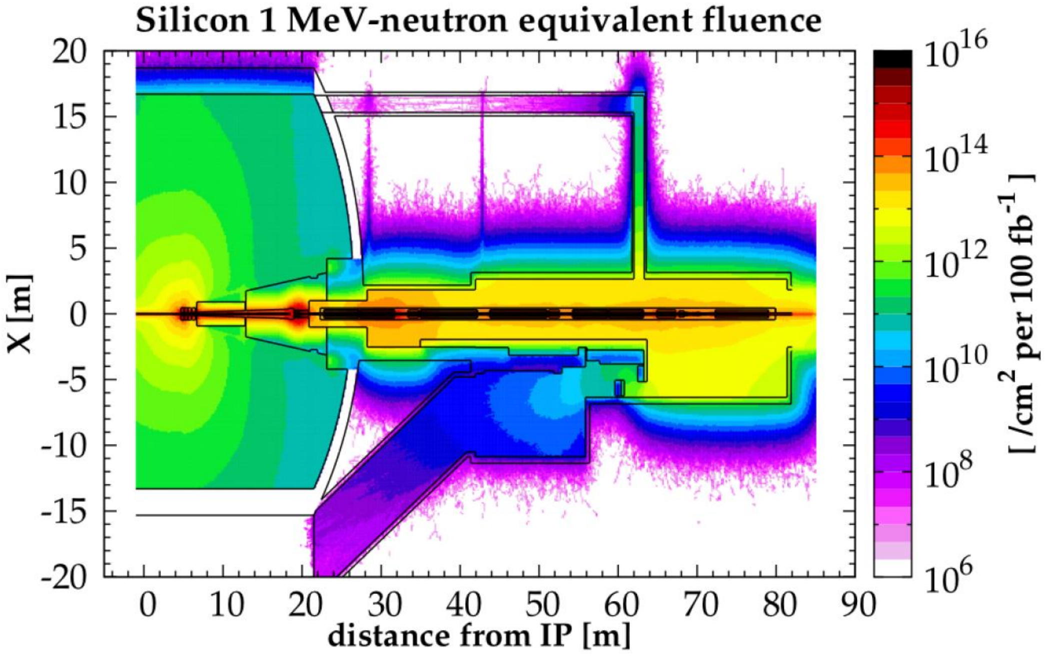


Scoring physics quantities [II]

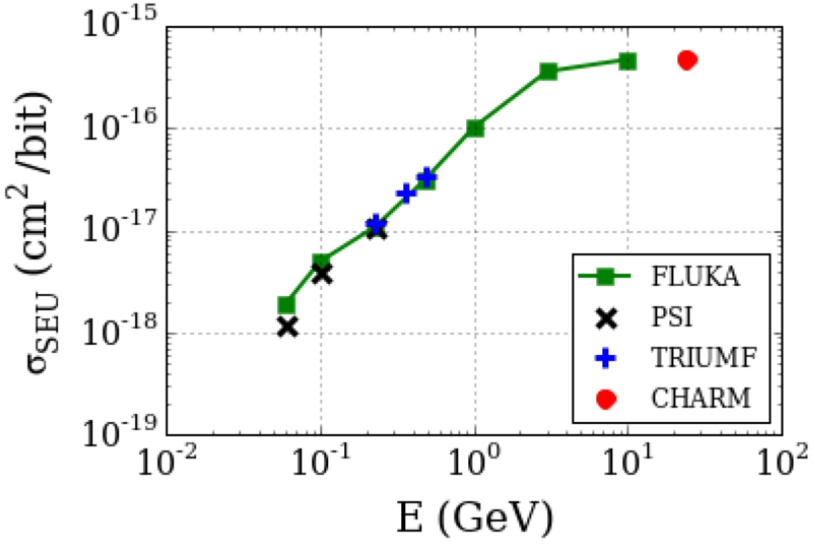
Radiation to Electronics scoring

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 (1/2)

Stochastic failures (SEEs):

- 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**)

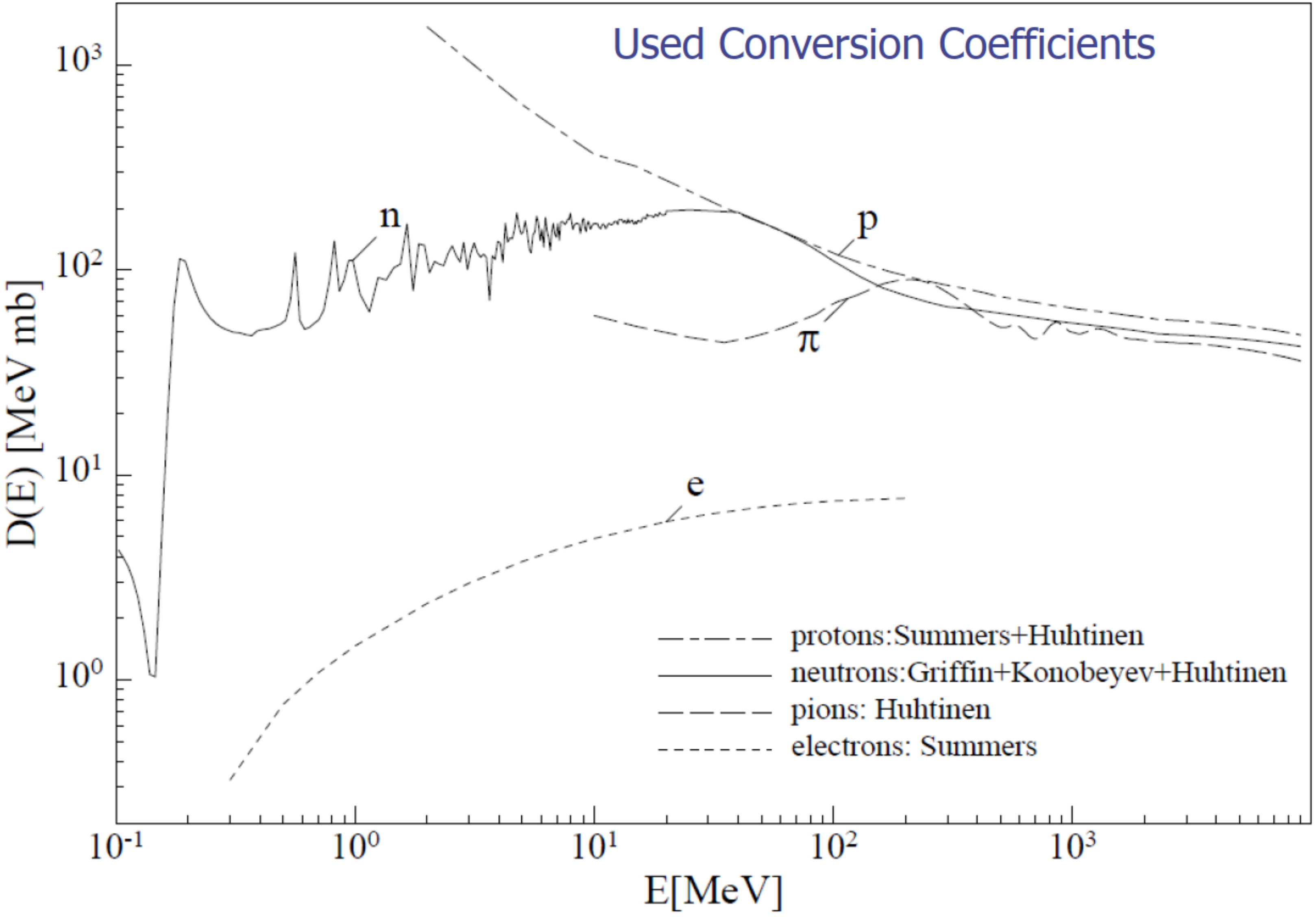
Radiation damage scoring in FLUKA (2/2)

Cumulative damage:

- Energy deposition (total ionizing dose) by scoring **DOSE** in `USRBIN` (you will need to convert from GeV/g to Gy or rad!)

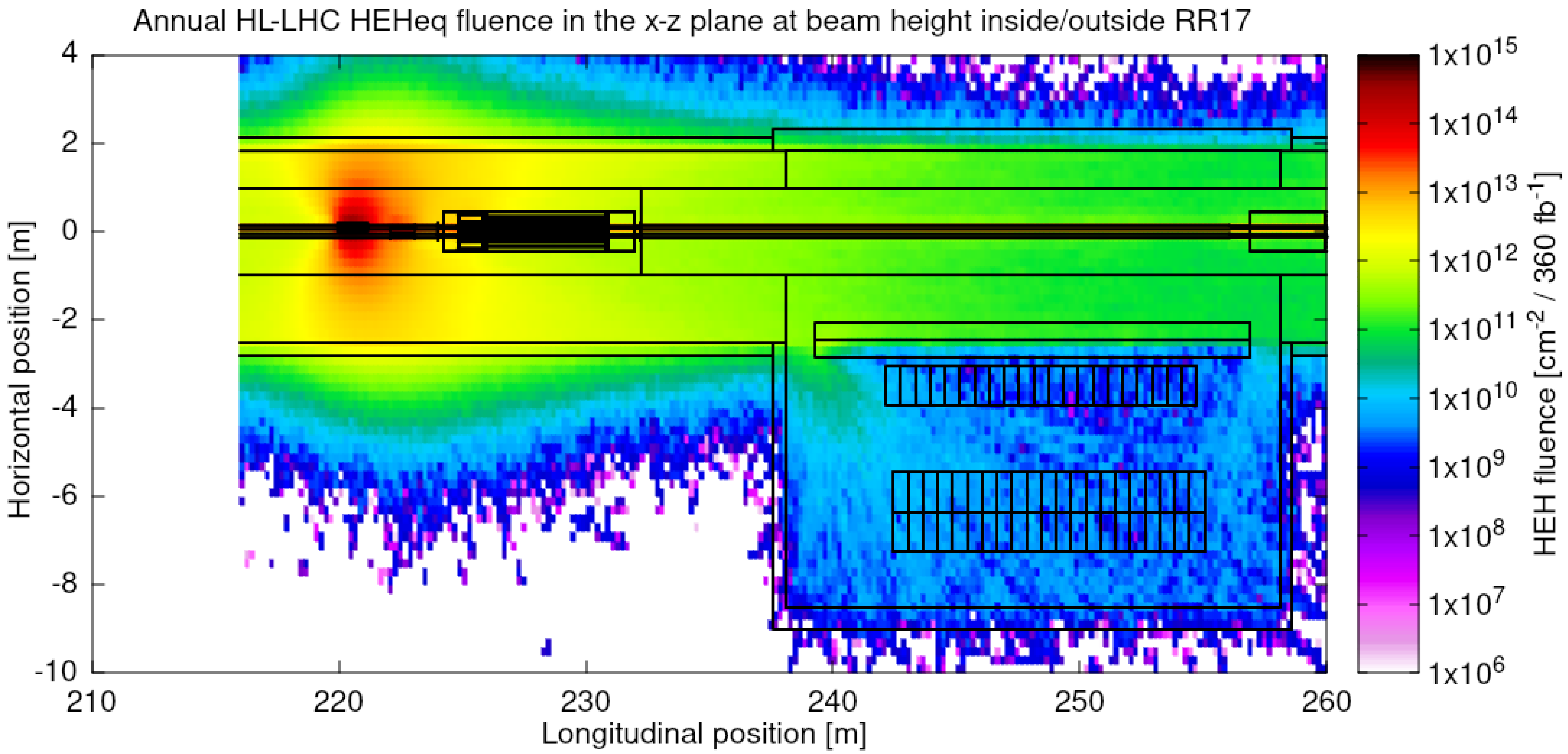
- Silicon lattice displacement:
  - 1-MeV neutron equivalent fluences (**SI1MEVNE**), with any related estimator (e.g. `USRTRACK, USRBDX`) or, more commonly, directly in integral form (e.g. `USRBIN`)
  - Non-Ionizing Energy Loss (**NIEL**), Displacement Per Atom (**DPA**)

1-MeV neutron equivalent in silicon



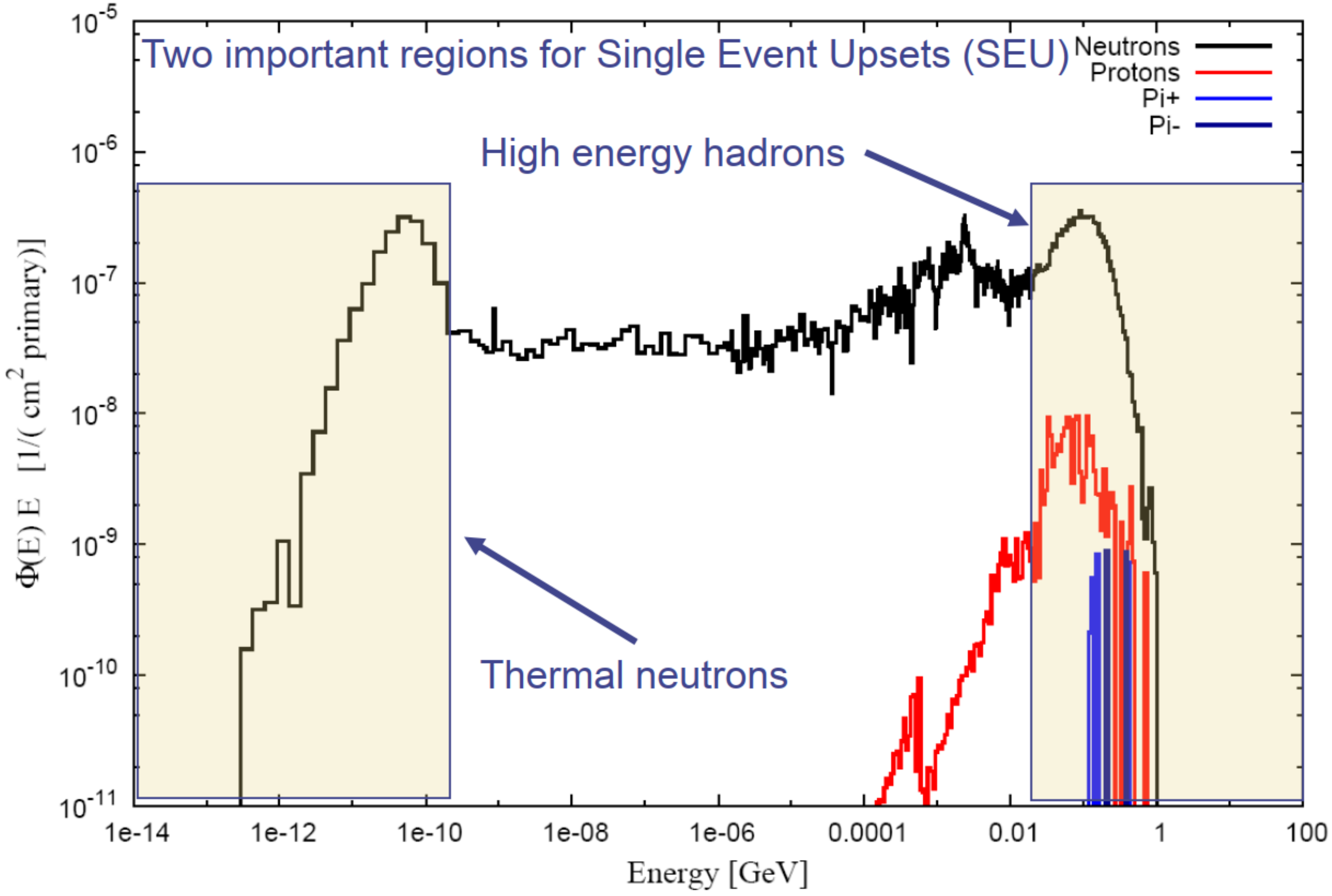

FLUKA

Example of high-energy hadron equivalent scoring in the LHC



SEUs in mixed radiation field

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



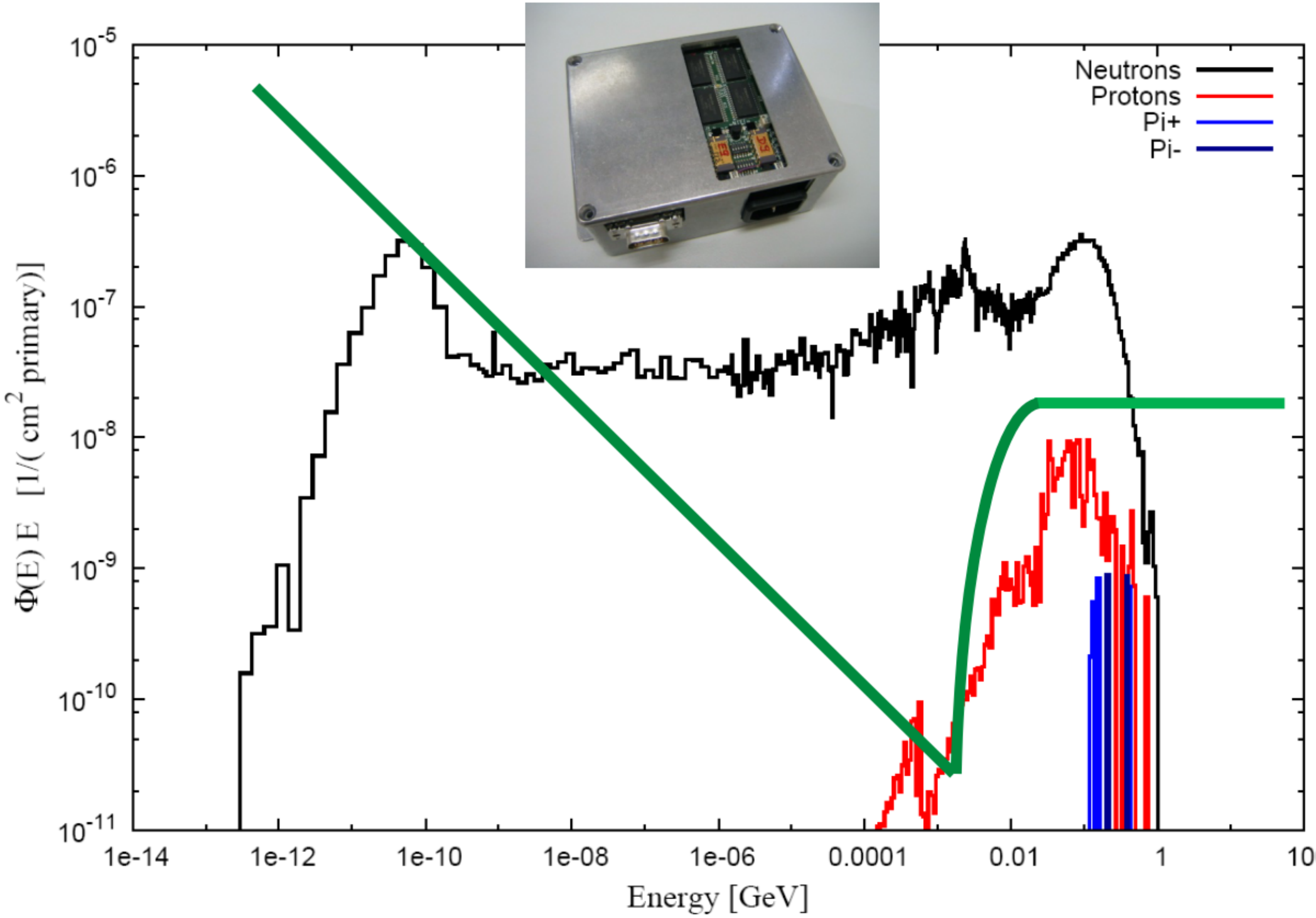
Two important regions for Single Event Upsets (SEU)

High energy hadrons

Thermal neutrons

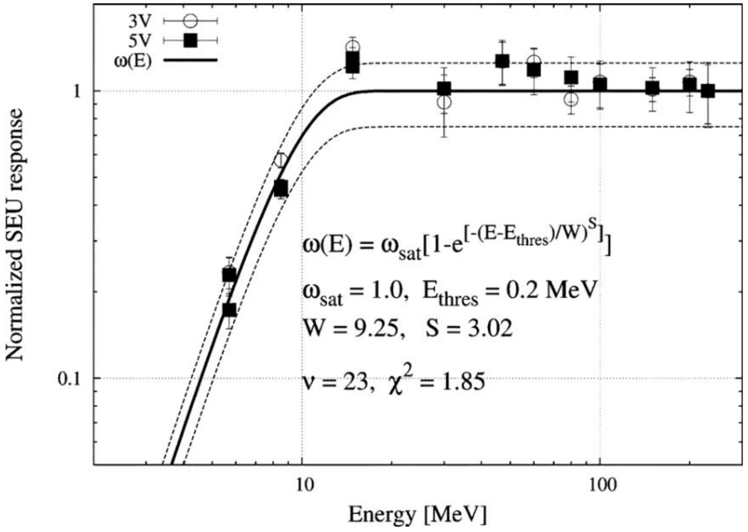
SEUs in mixed radiation fields

e.g. LHC RadMon

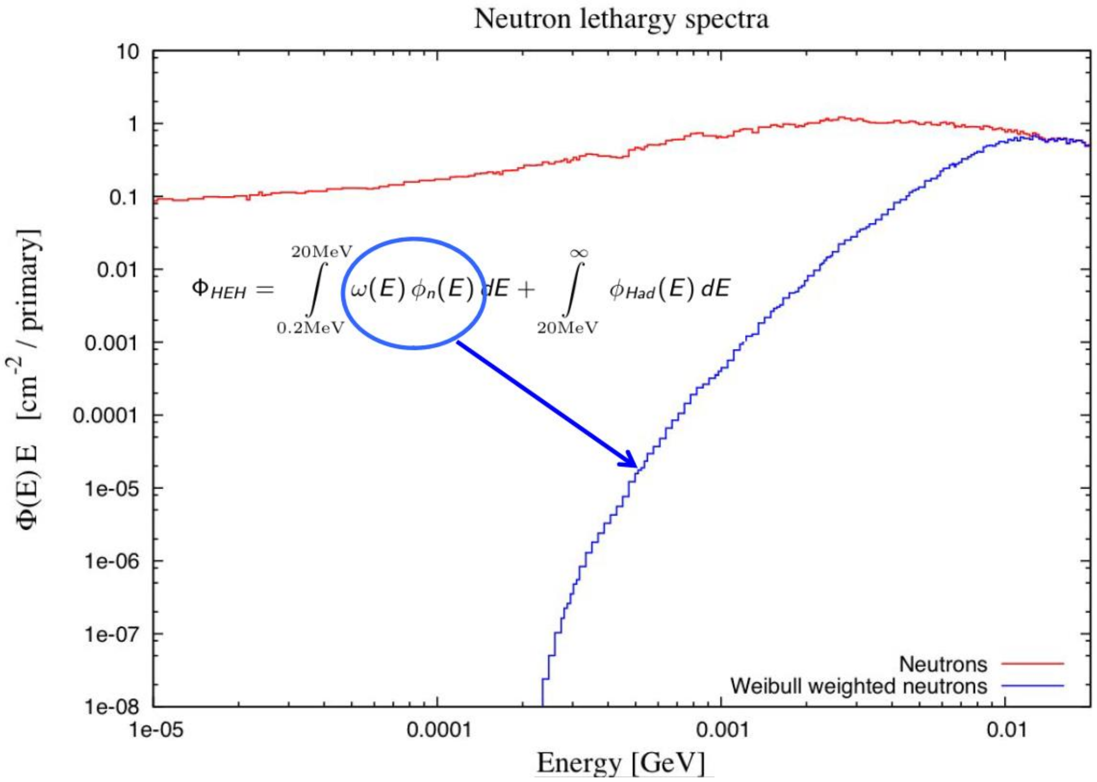


HEHAD-EQ

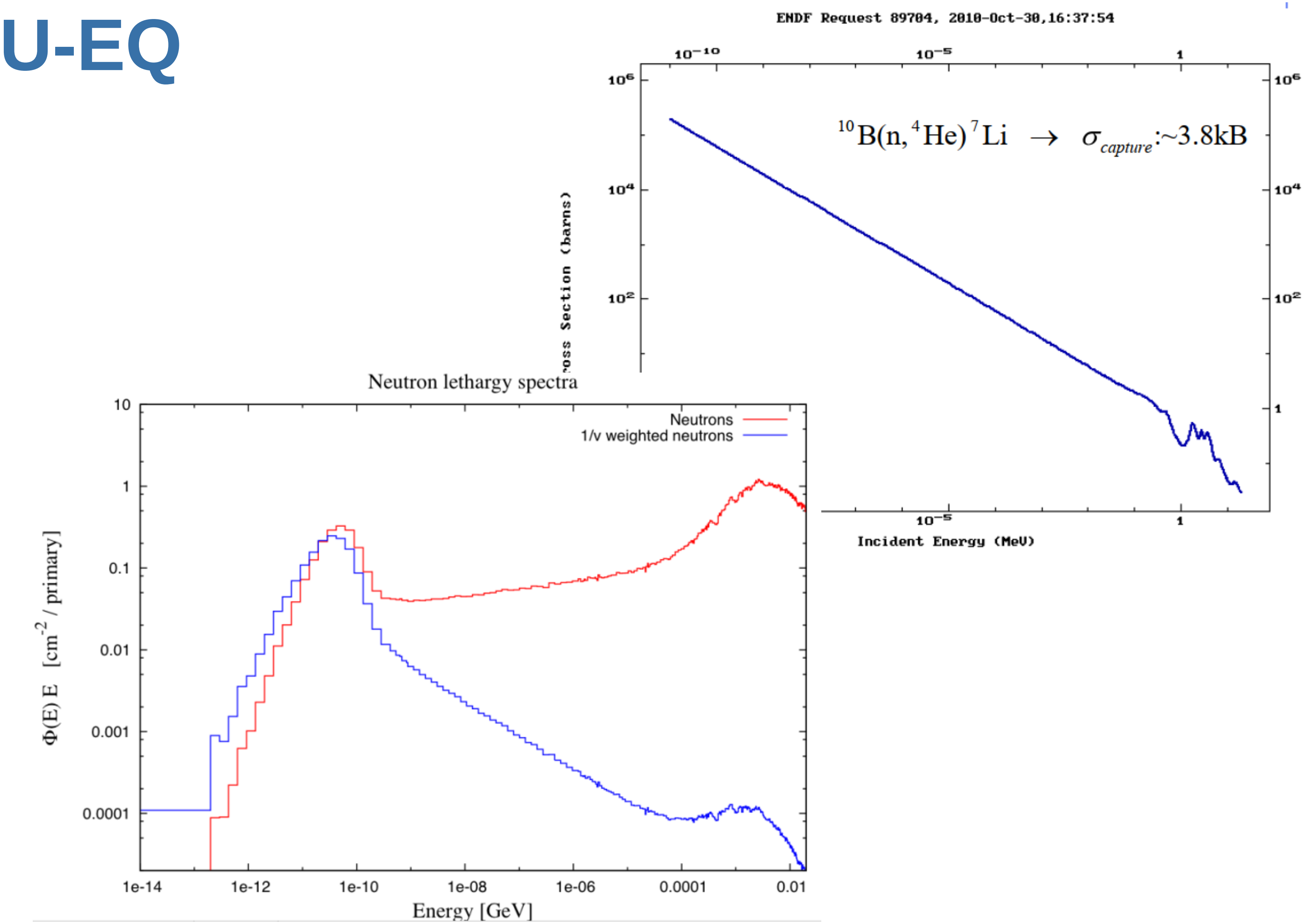
- Based on experimental response function from 0.4 µm technology SRAM



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



THNEU-EQ


ENDF Request 89704, 2010-Oct-30,16:37:54
$^{10}B(n,{}^{4}He){}^{7}Li \rightarrow \sigma_{capture}$:~3.8kB
Cross Section (barns)
Incident Energy (MeV)
10⁻¹⁰
10⁻⁵
1
10⁶
10⁴
10²
Neutron lethargy spectra
Neutrons
1/v weighted neutrons
Φ(E) E [cm⁻² / primary]
Energy [GeV]
10
1
0.1
0.01
0.001
0.0001
1e-14
1e-12
1e-10
1e-08
1e-06
0.0001
0.01

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:

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

  - 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)