



## Scoring physical quantities II

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

Pulse-height spectra (**DETECT**)

Radiation to electronics (R2E) quantities

# Differential spectra

USRTRACK, USRBDX, USRYIELD

# 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 (1-20 reserved by the code)
    - The only exception is SCORE: its output is printed in the **standard output**

\* A star is a hadronic inelastic interaction

# Differential distributions

Various **differential distributions** can be requested:

- **USRTRACK (USRCOLL)** : **single differential distribution in energy [GeV<sup>-1</sup>]**
- **USRBDX**: **single differential distribution in energy [GeV<sup>-1</sup>] (integrated over solid angle) and double differential distribution in energy and solid angle [GeV<sup>-1</sup> sr<sup>-1</sup>]**
- **USRYIELD**: **double differential distribution in var<sub>1</sub> and var<sub>2</sub> [var<sub>1</sub>unit<sup>-1</sup> var<sub>2</sub>unit<sup>-1</sup>]**

After processing, these results are printed in a **formatted \*\_tab.lis** file → Flair can plot from this file.

**Cumulative distributions** are additionally printed in a **\*\_sum.lis** file

- Useful to obtain the **integral over an energy range**.  
The integration is made w.r.t. the 1<sup>st</sup> variable (energy for **USRTRACK**, **USRCOLL**, **USRBDX**, and var<sub>1</sub> for **USRYIELD**).

$$N = \int \frac{dN}{dE} dE, \quad dN/dE: \text{value of each energy bin, } dE: \text{bin width}$$

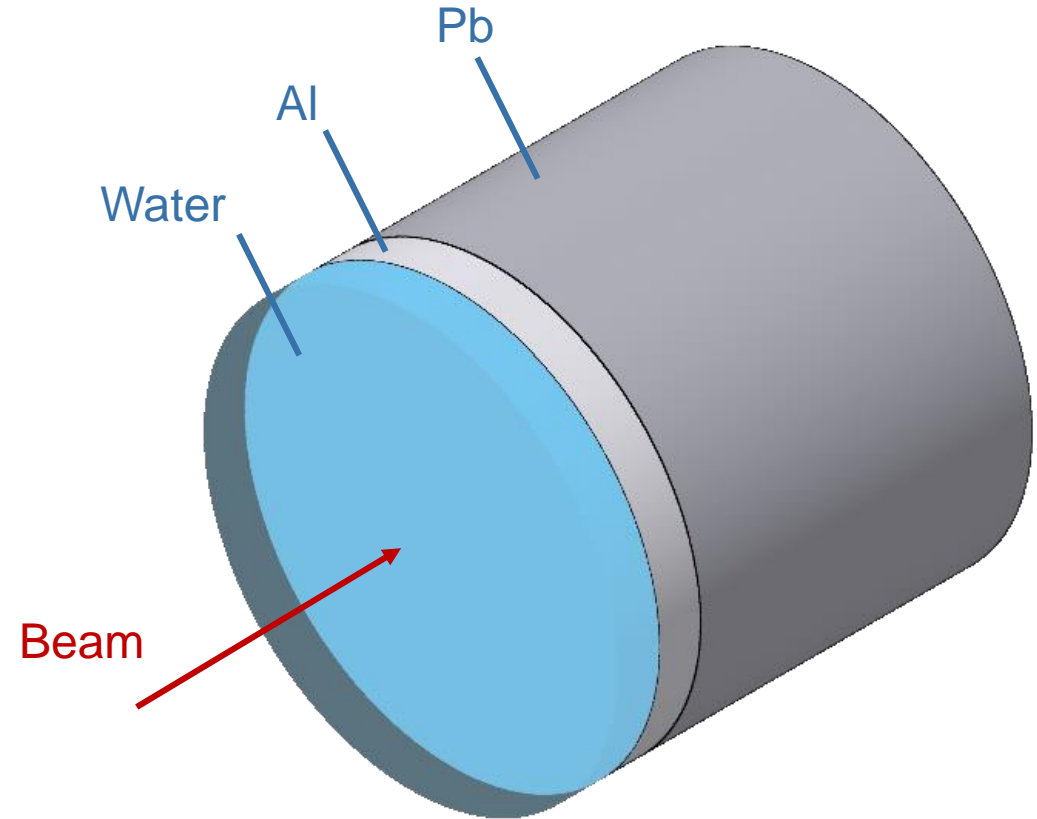
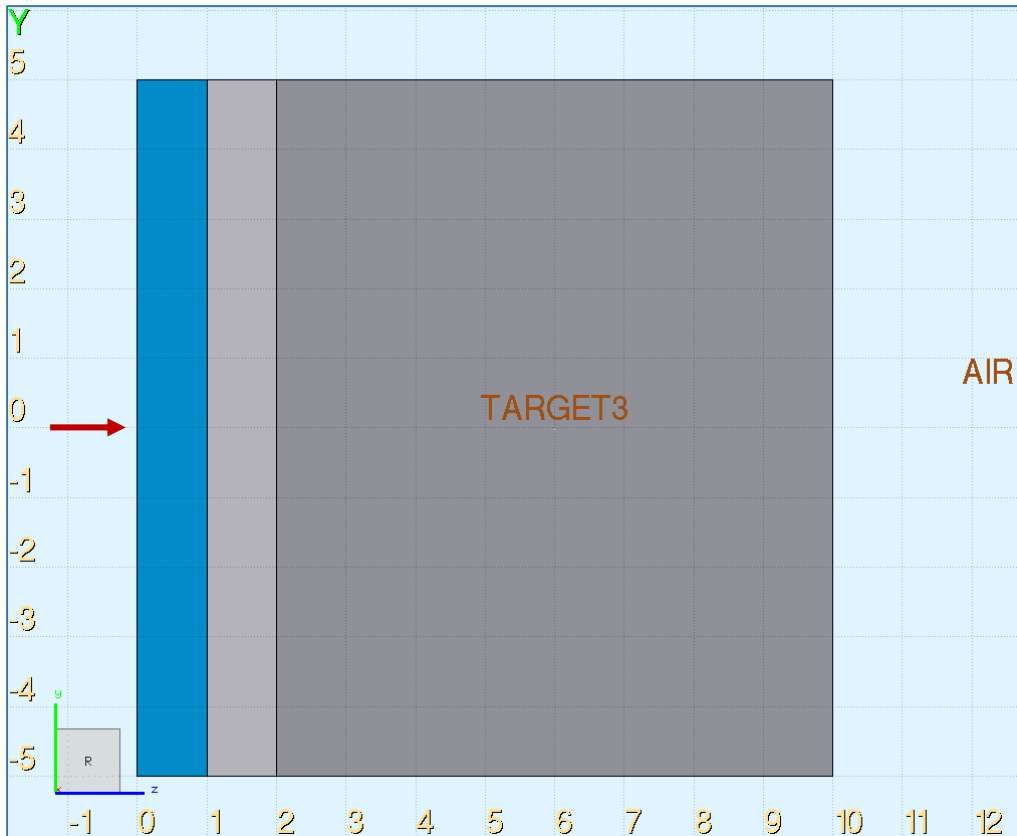
**Results are NOT normalised by region volume [boundary area]!**

For example, when scoring *fluence* with **USRTRACK** [**USRBDX**, **USRYIELD**], results will be in cm<sup>-2</sup> only....:

- If the user has provided the region volume [boundary area] in the respective card (before running).
- Otherwise, if the user applies the desired normalisation at post-processing level (e.g. Flair Y Norm).

# Our example problem

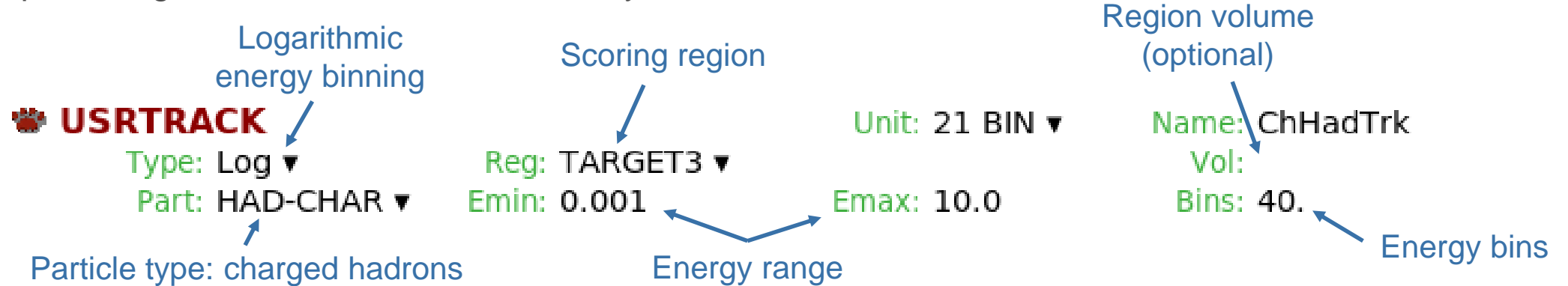
- 3.5 GeV proton beam hitting a cylindrical target with 5 cm radius and 10 cm length composed of three layers (1 cm water, 1 cm aluminium and 8 cm lead)



# USRTRACK

USRTRACK scores track-length density (fluence) differential in energy in a region

- Example: charged hadron fluence in the Pb layer



Volume normalisation:

- If no volume is provided, results are given in track length [cm/primary]
- The volume normalisation should be taken care of in post-processing if not given in the card

Merging and processing the results will create 3 files:

- **\*\_21.trk**: binary file containing the merged data from several runs
- **\*\_21\_tab.lis**: ascii file containing energy spectra → Flair uses this file for plotting
- **\*\_21\_sum.lis**: ascii file containing energy spectra and **energy-integrated cumulative spectra**

# USRTRACK – Plotting

Title: Charged hadron fluence in Pb layer Display: 0

Axes

Label	Log	Min	Max
x: Energy [GeV]	<input checked="" type="checkbox"/>	-	-
y: Charged hadron fluence [cm <sup>-2</sup> /primary]	<input checked="" type="checkbox"/>	-	-

Detectors

Detector 1

Detector Info

File: demo\_scoring/demo\_scoring\_21\_tab.lis Det: 1 ChHadTrk

Show Plot

graph Type: histerror X:

legend Value: <X>\*Y Y: 1.0/(pi\*5.0\*\*2\*8.0)

Options

Color: red Line width: 2 Dash type: 0

Point type: dot Point size: 1 Axes:

set format y '10^{%T}''  
set nokey

## Lethargy plot

Data in the \*tab.lis file is  $Y = \frac{dN}{dE}$

We multiply by  $\langle X \rangle = E$

$E$  is the geometric mean of the bin edges.

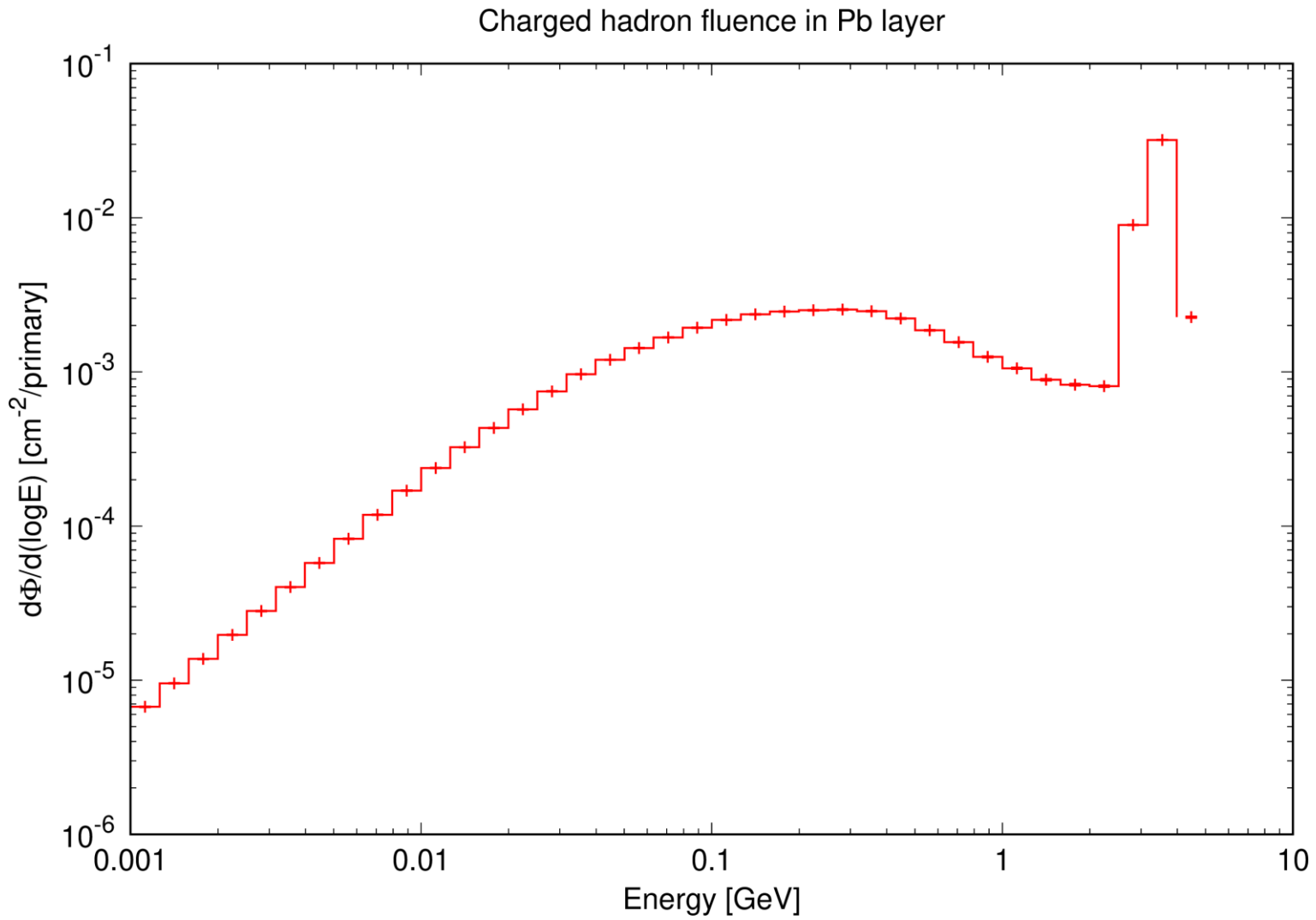
We obtain  $E \frac{dN}{dE} = \frac{dN}{d(\log E)}$  (dimensionless)

It is the proper representation of histograms with logarithmic abscissas

Normalisation  
by region volume

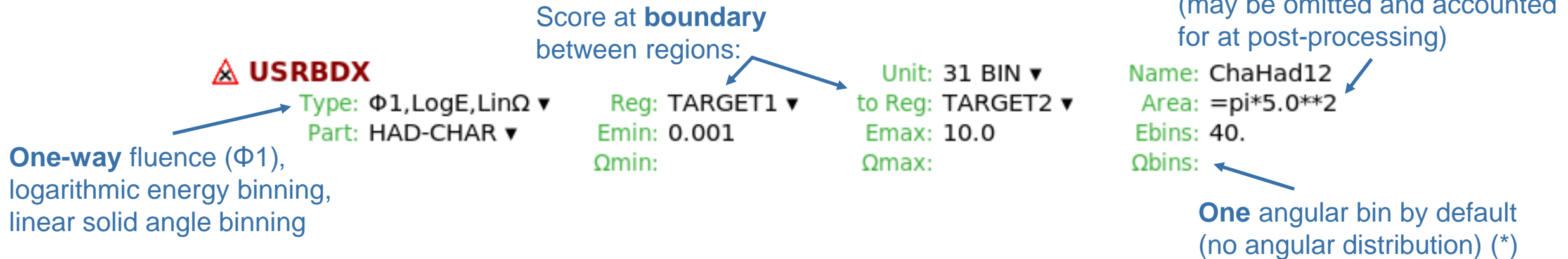
One detector available:  
single differential charged  
hadron fluence spectrum

# USRTRACK – Plotting – single diff. fluence in region



# USRBDX

- **USRBDX** scores one- or two-way double differential **fluence** or **current** in energy and solid angle(\*) at the boundary surface between two regions
  - One-way: fluence/current of particles in one direction (e.g. from Region A to Region B)
  - Two-way: fluence/current of particles crossing between the two regions in any direction



Merging and processing the results will create 3 files:

- \*\_31.bnx: binary file containing the merged data from several runs
- \*\_31\_tab.lis: ascii file containing all spectra → Flair uses this file for plotting
- \*\_31\_sum.lis: ascii file containing all spectra and energy-integrated cumulative spectra

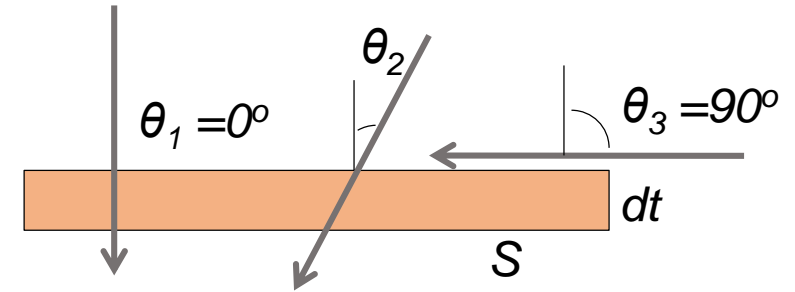
(\*) *Even if only one angular bin is requested, differential spectra are always double differential in energy and solid angle*

# Fluence and 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  $\theta$  with respect to the normal to the surface  $S$  travels a segment  $dt/\cos\theta$  inside the volume.



- The **average fluence**  $\Phi$  over the surface  $S$  is defined as:

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

total track length  
inside the volume

volume

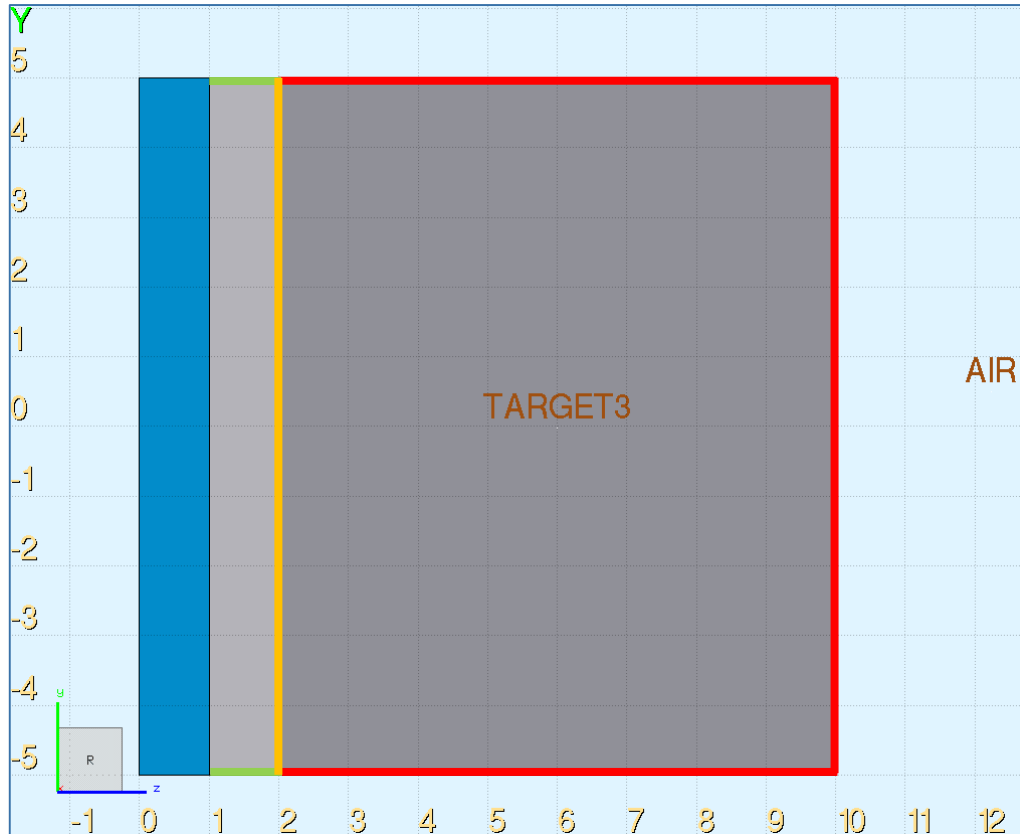
- ...while the **average current**  $J$  over the surface  $S$  is given by the number of particles crossing the surface divided by the surface area:

$$J = N/S$$

# Fluence and 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 if 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

# USRBDX – area normalisation



$$\begin{aligned}\Delta Z_1 &= 1 \text{ cm} & R &= 5 \text{ cm} \\ \Delta Z_2 &= 1 \text{ cm} \\ \Delta Z_3 &= 8 \text{ cm}\end{aligned}$$

Boundary surface normalisation should be taken care of in the card or in post-processing

*Examples – boundary surface between:*

TARGET2-TARGET3:

$$\pi R^2 = 78.54 \text{ cm}^2$$

TARGET2-AIR:

$$2\pi R\Delta Z_2 = 31.42 \text{ cm}^2$$

TARGET3-AIR:

$$2\pi R\Delta Z_3 + \pi R^2 = 329.87 \text{ cm}^2$$

TARGET1-TARGET3:

No shared surface! **USRBDX** results will be empty

# USRBDX – Plotting

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

Title: Charged hadron fluence at different boundaries Display: 0

Axes

Label

x: Energy [GeV] Log Min Max

y: Charged hadron fluence [cm<sup>-2</sup>/primary] Log 1.0E-6 10.0

Detectors

H<sub>2</sub>O -> Al

Al -> Pb

Pb -> Air

Detector Info

File: demo\_scoring/demo\_scoring\_31\_tab.lis Det: 1 ChaHad12 (integrated over solid angle)

Show Plot

graph Type: histerror X:

legend Value: <X>\*Y Y:

Options

Color: red Line width: 2 Dash type: 0

Point type: dot Point size: 1 Axes:

set format y '10^{%T}'

set key left font 'Arial,16'

Lethargy plot

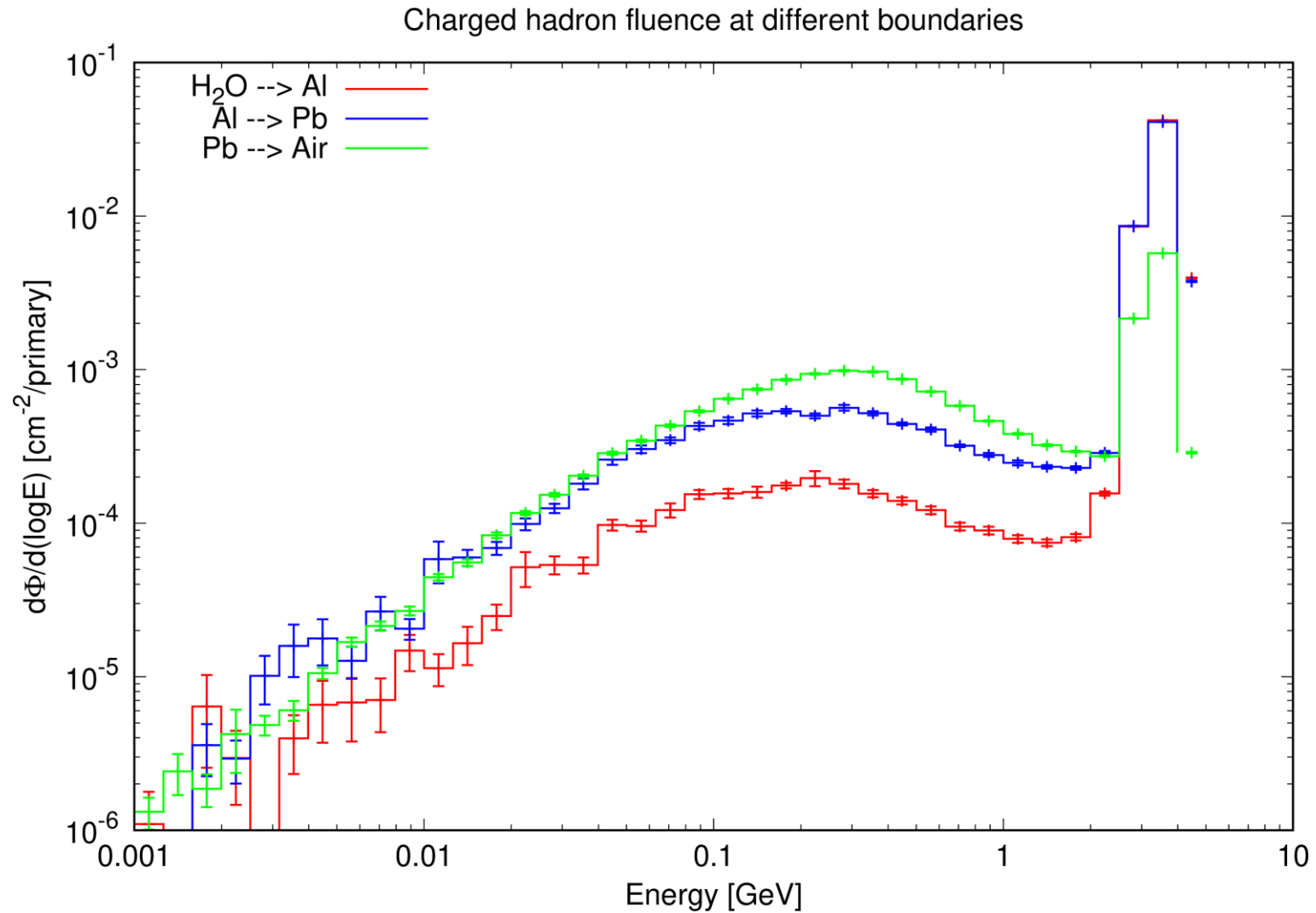
No surface normalisation needed if included in the card

Lethargy plot

No surface normalisation needed if included in the card

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

# USRBDX – Plotting – single diff. fluence on boundary



# Angular distributions

- Angular distributions are intended as distributions in **solid angle**  $\Omega = 2\pi(1 - \cos \theta)$ , where  $\theta$  is the **angle between the particle trajectory and the normal to the boundary at the point of crossing**
  - If no angular information is requested, the spectrum is integrated over solid angle, done automatically by the post-processing utility
  - Example:

## **USRBDX**

Type:  $\Phi$ 1,LogE,Lin $\Omega$  ▼

Part: HAD-CHAR ▼

Reg: TARGET2 ▼

Emin: 0.001

$\Omega$ min:

Unit: 31 BIN ▼

to Reg: TARGET3 ▼

E<sub>max</sub>: 10.0

$\Omega$ max:

Name: ChH23ang

Area: =pi\*5.0\*\*2

Ebins: 40.

$\Omega$ bins: 3.0

← 3 angular bins

- Common pitfall: note that equal intervals in solid angle  $\Omega$  correspond to unequal intervals in angle  $\theta$  (as should be clear from the relation above)
  - Here, 3 equal solid angle bins in a **one-way** scoring will each have a width of  $2\pi/3$  and approximately correspond to the  $\theta$  intervals  $0^\circ$ - $48^\circ$ ,  $48^\circ$ - $71^\circ$  and  $71^\circ$ - $90^\circ$

# USRBDX – Plotting angular distributions

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

Plot

Title: Double differential charged hadron spectra at different angles (Al --> Pb) Display: 0

Axes

Label

x: Energy [GeV] Log Min Max

y:  $d^2N/(d(\log E)dW)$  [ $\text{cm}^{-2} \text{sr}^{-1}$ ]/primary

Detectors

Total 0-90 deg

0-48 deg

48-71 deg

71-90 deg

Detector Info

File: demo\_scoring/demo\_scoring\_31\_tab.lis Det: 8-2 ChH23ang (integrated over solid angle) 2.09439516

Show Plot

graph Type: histerror X:

legend Value: <X>\*Y Y:

Options

Color: blue Line width: 2 Dash type: 0

Point type: dot Point size: 1 Axes:

set format y '10^{%T}'

set key left font 'Arial,16'

1 ChaHad12 (integrated over solid angle)

2-1 ChaHad12 (integrated over solid angle) 0.00000000

3 ChaHad23 (integrated over solid angle)

4-1 ChaHad23 (integrated over solid angle) 0.00000000

5 ChaHad3 (integrated over solid angle)

6-1 ChaHad3 (integrated over solid angle) 0.00000000

7 ChH23ang (integrated over solid angle)

8-1 ChH23ang (integrated over solid angle) 0.00000000

8-2 ChH23ang (integrated over solid angle) 2.09439516

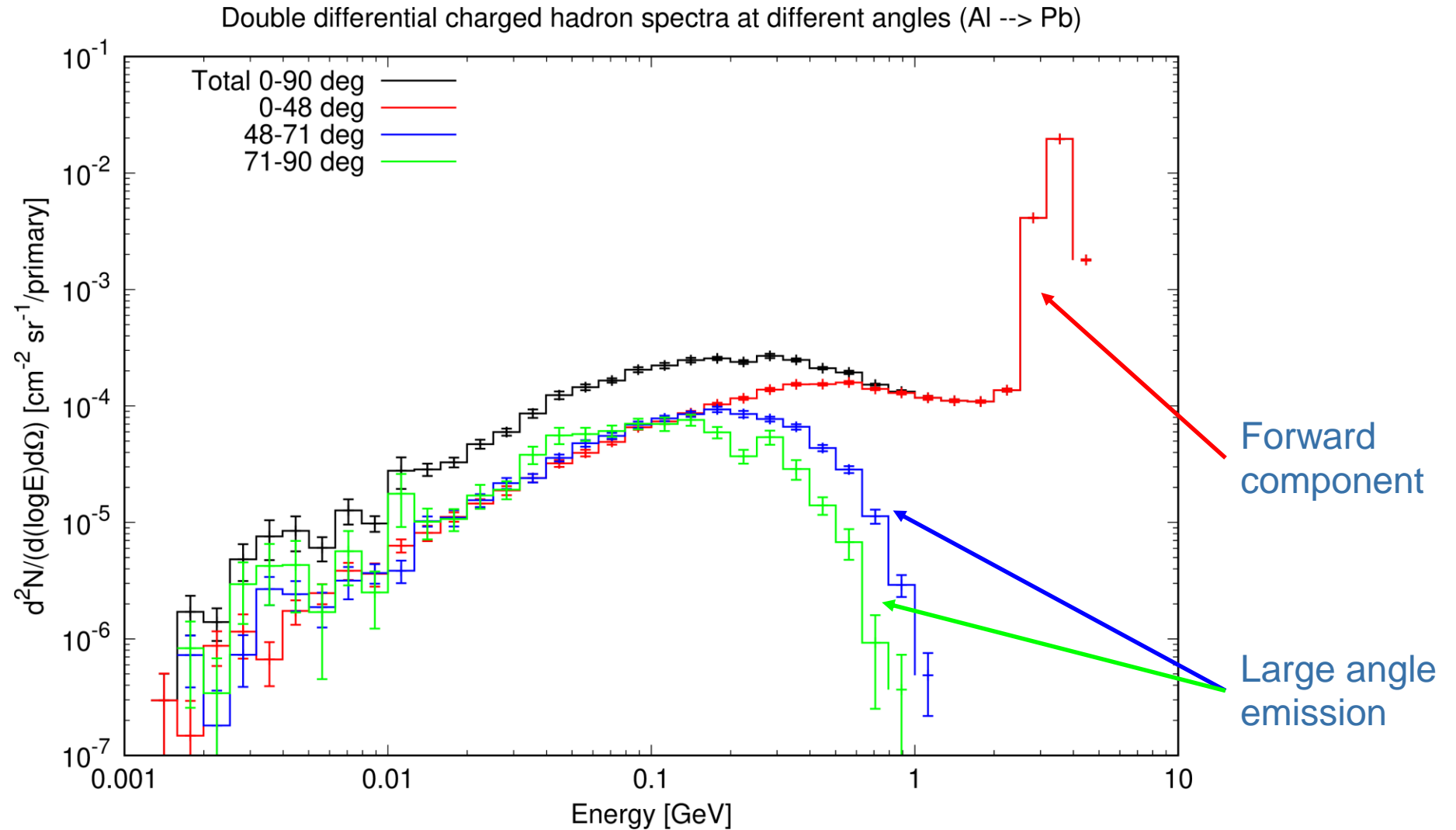
8-3 ChH23ang (integrated over solid angle) 4.18879032

Lethargy plot

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

**0,  $2\pi/3$ ,  $4\pi/3$ ,  $2\pi$**   
Edges of the 3 solid angle bins  
(in one-way scoring the maximum  
is a half-sphere, i.e.  $2\pi$  solid angle)

# Plotting – double diff. fluence on boundary (USRBDX)



# Estimating volumes and surfaces in Flair

- Flair can compute **volumes** and **surfaces** stochastically
  - Convenient for complex shapes for which they cannot be analytically calculated
- In the **Geometry** tab:
  - Select the region of interest
  - Click on the **Volume** button
- The **volume** (and mass) and **total surface** of the region are calculated through an iterative process

The screenshot displays the Flair software interface. The main window shows a 3D model of a complex shape with a red region highlighted. The **Volume Calculation** dialog box is open, showing the following data:

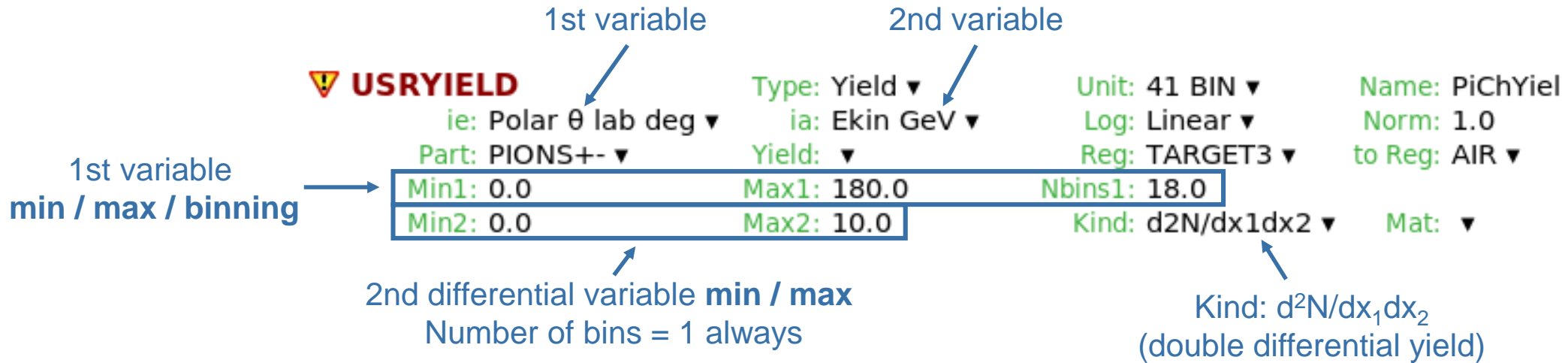
Region	V(cm <sup>3</sup> )	S(cm <sup>2</sup> )	M(g)	err(%)	n
TARGET3	628.33	408.43	7131.6	0.02	25
	real: 628.32	real: 408.41			

The **Volume** button in the **Geometry** tab is circled in red. The **Volume** button is also circled in red in the bottom inset of the screenshot.

# USRYIELD

## USRYIELD scores double-differential particle yields

- Shares some commonalities with **USRBDX**, but with a richer choice of weights ("Kind") and differential variables ("ie" and "ia"), such as kinetic energy, momentum, polar angle (lab/CM), LET, charge, and many more
- Example: *charged pion yield exiting the Pb layer*



**USRYIELD** distributions are calculated with respect to a fixed direction (usually the beam direction, but it can be changed (**USRYIELD** card with **SDUM=BEAMDEF**, see manual)

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

# USRYIELD – Plotting

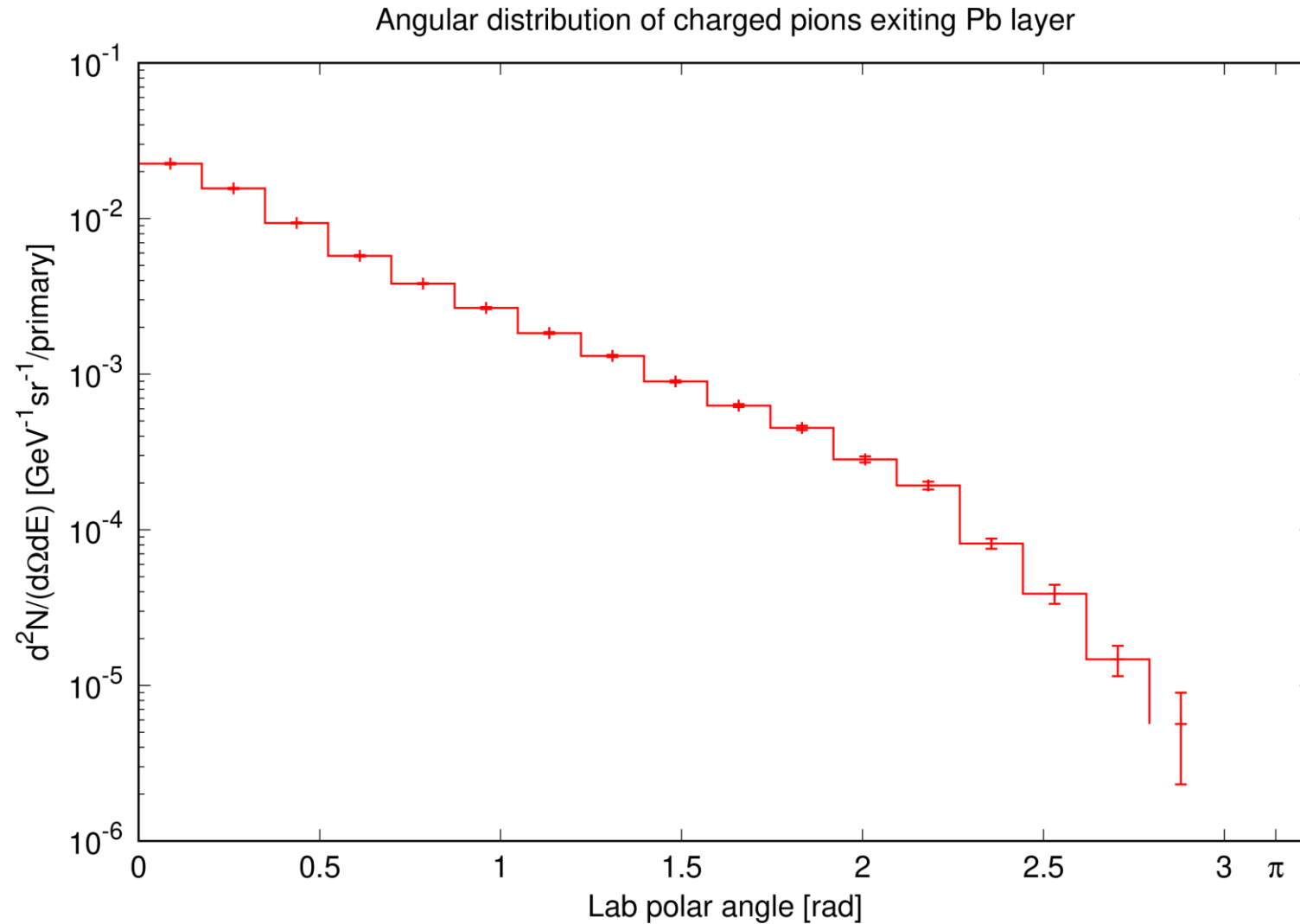
Merged file converted to ascii  
(in tabulated form → ...tab.lis file)

The screenshot shows the USRYIELD plotting interface. The title bar reads "Angular distribution of charged pions exiting Pb layer". The "Axes" section shows the x-axis as "Lab polar angle [rad]" and the y-axis as  $d^2N/(d\Omega dE) [\text{GeV}^{-1}\text{sr}^{-1}/\text{primary}]$ . The "Detectors" list on the left shows "Detector 1" selected. The "Detector Info" section shows the file "demo\_scoring/demo\_scoring\_41\_tab.lis" and detector "1 PiChYiel". The "Plot" section shows "graph" and "legend" checked, with "Type: histerror" and "Value: Y". The "Options" section shows "Color: red", "Line width: 2", "Dash type: 0", "Point type: dot", and "Point size: 1". The command window at the bottom contains the following text:

```
set format y '10^{%T}'  
set nokey  
set xtics add ("{/Symbol p}" 3.14159)
```

Select detector (charged pion yield exiting the Pb layer)

# USRYIELD – Plotting – double diff. yield



# Pulse-height spectra

**DETECT**

# The DETECT card (1/3)

Scores energy deposition in one or more regions on an event-by-event basis

- i.e. energy deposition by the primary particle(s) and all descendant particles produced within a history
- Produces the equivalent of a pulse-height spectrum
- Useful for assessing detector response from single events
- Can also reproduce **coincidence** or **anti-coincidence** triggers

```
2. DETECT
  Emin: 0.0
  Regions: 6 ▼
  Reg4: ▼
  Type: Detector ▼
  Emax: 0.002
  Reg1: DET1 ▼
  Reg5: ▼
  Channels: 8192
  Ecut: 1.0E-8
  Reg2: DET2 ▼
  Reg6: ▼
  Name: MyDet
  Trigger: Coincidence ▼
  Reg3: ▼
```

- Unformatted output written in unit 17, to be processed by **DETSUW** (called automatically by the Flair “Process” command)

**IMPORTANT:** **DETECT** should only be used in fully analogue mode (i.e. without biasing) since biasing destroys correlations. Its use is also incompatible with the activation mode, but isotope sources in semi-analogue mode can be used (see RP calculations lecture)

# The DETECT card (2/3)

**Use case:** quantification of detector response

- 4/6/8 MeV proton beam (1 MeV FWHM) impacting on a thin Si target
- 1024 energy bins (channels)

**2. DETECT**      Type: Detector ▼      Channels: 1024      Name: Edep  
 Emin: 1.0E-4      Emax: 1.0E-2      Trigger: ▼  
 Regions: 1 ▼      Reg1: DET1 ▼

Output: histogram of energy deposition in considered region.

Results normalised by total number of histories in the run.

Users may apply a smearing to reproduce the real detector response.

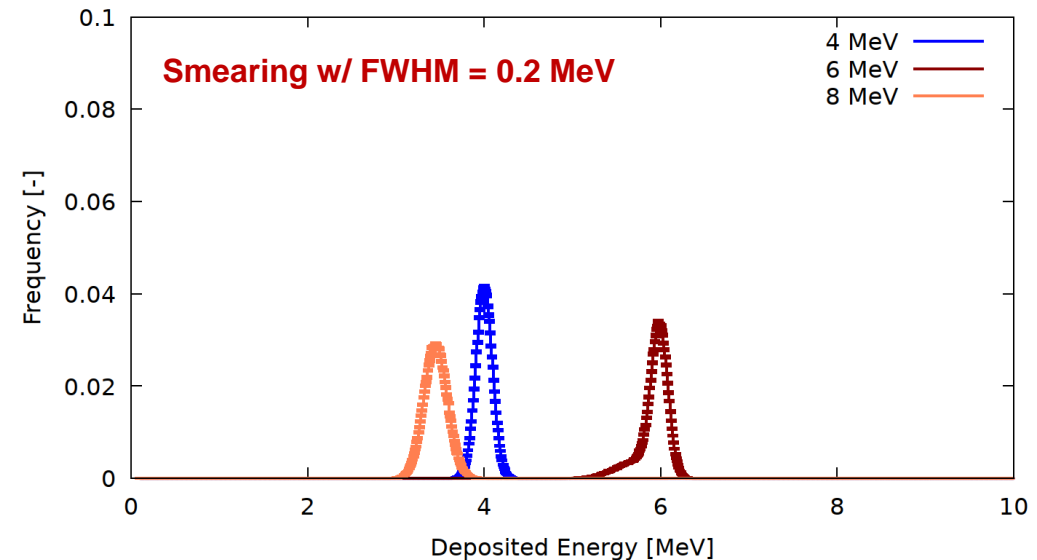
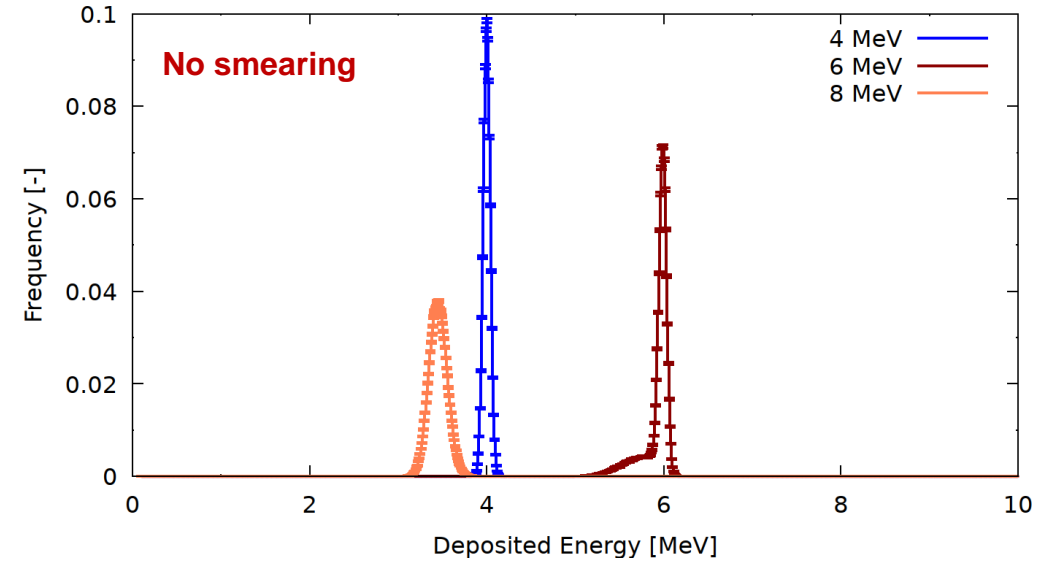
**DETGE** allows to apply the following FWHM to each signal:

$$FWHM = a + b\sqrt{\Delta E} + c(\Delta E)^2$$

where: WHAT(1) = a [GeV]    WHAT(2) = b [GeV<sup>1/2</sup>]    WHAT(3) = c [GeV<sup>-1</sup>]

*Example of energy-independent case (b=0):*

**DETGE**      a: 0.0002      b:      c:  
 Det: ▼      to Det: ▼      Step:



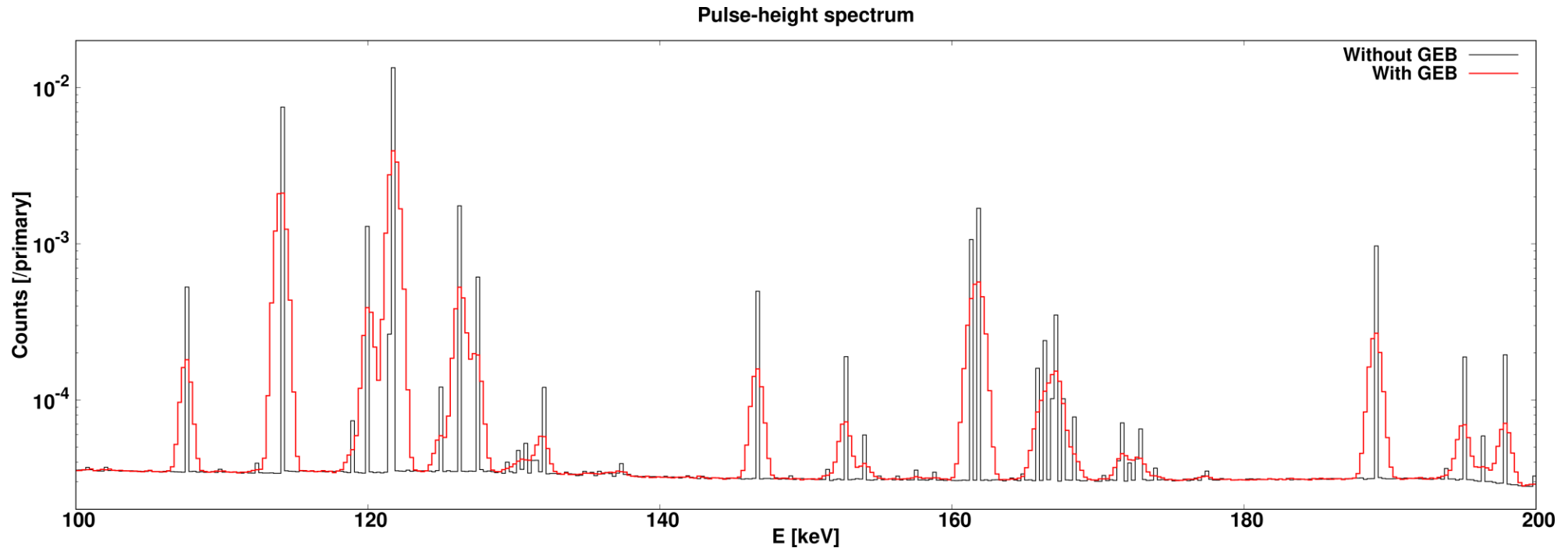
# The DETECT card (3/3)

Example: radioactive source in front of a HPGe detector with/without broadening

```
DETECT Type: Detector Channels: 8192 Name: Spectrum  
Emin: 1.82106E-6 Emax: 2067.67962E-6 Ecut: Trigger:  
Regions: 1 Reg1: CRYSTAL  
#if GEB  
DETGEB a: 3.978209E-7 b: 3.326578E-5 c: 1.368961E3  
where: DETECTOR Det: Spectrum to Det: Step:  
#endif
```

Bins matched to experimental spectrum for direct comparison

Coefficients determined fitting experimental FWHM(E) values



# Radiation to electronics

# Radiation damage to electronics (R2E)

- 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.
- Main radiation effects in electronics:

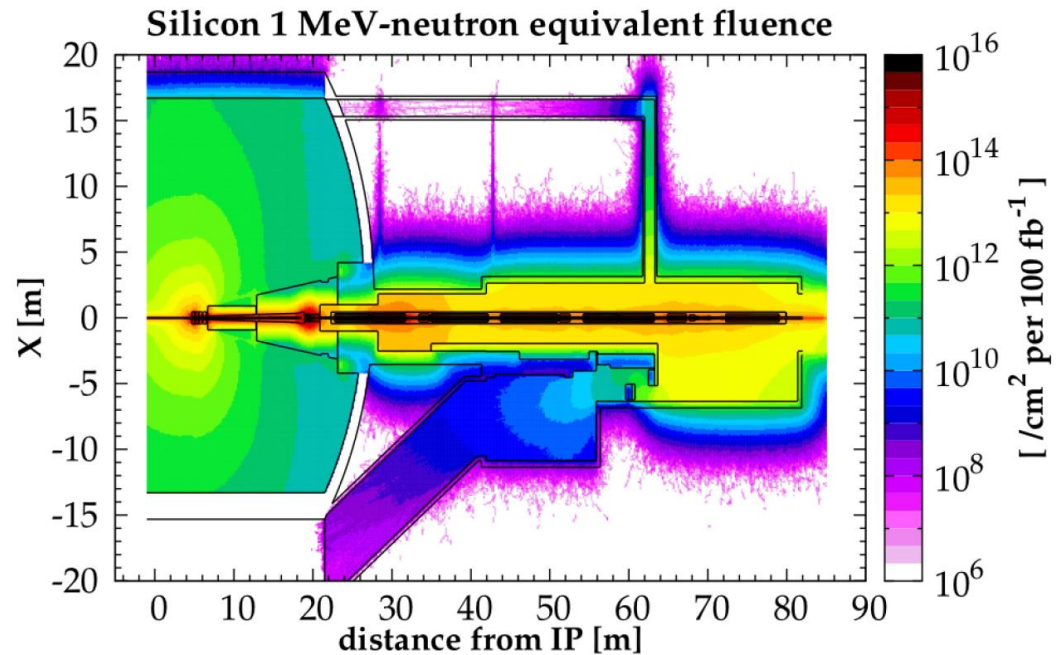
Category	Sub-category	Example of Effect
Stochastic	Non-destructive Single Event Effects (SEEs)	Single Event Upset (SEU): Bit flip in SRAM memory
	Destructive SEEs	Single Event Latchup (SEL): Overcurrent, which can lead to thermal breakdown
Cumulative	Total Ionising Dose (TID)	Charge build-up in oxide, 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

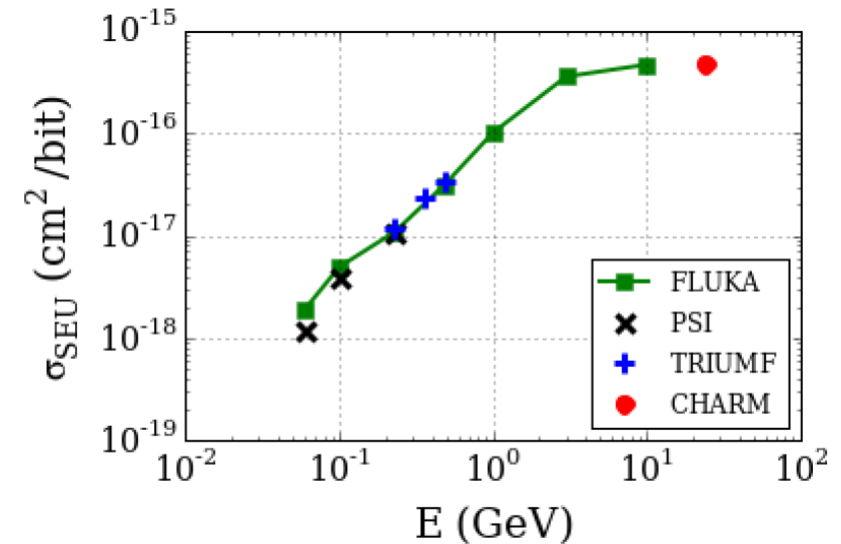
- All important quantities used to estimate radiation damage on electronics can be retrieved in FLUKA
  - Cumulative damage:
    - Energy deposition (total ionising dose) by scoring **DOSE** in **USRBIN** (you will need to convert from GeV/g to Gy or rad!)
    - Silicon lattice displacement:
      - 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-Ionising Energy Loss (**NIEL**), Displacement Per Atom (**DPA**, **ARCDPA**)
  - 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**)

# FLUKA simulations for radiation damage on electronics

- Examples:



**Example of simulation of radiation environment:**  
**1-MeV silicon neutron equivalent fluence in vicinity of 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.]

# Summary

**USRTRACK**, **USRBDX** and **USRYIELD** are scoring cards which allow to obtain **differential spectra**

- Score **track-length** 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 customised 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's responsibility to ensure normalisation by region volume / boundary area.

# Summary

**DETECT** allows to score energy deposition in detector regions on an **event-by-event** basis

- Score a **pulse-height spectrum** in a **detector** in (anti-)coincidence mode  
→ **DETECT**

Various quantities relevant for **R2E studies** can be scored relating to **cumulative damage** (DOSE, SI1MEVNE, NIEL, DPA) or **stochastic failures** (HADGT20M, HEHAD-EQ, THNEU-EQ)

