Estimators and Scorings

21st FLUKA Beginner's Course
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FLUKA Scoring & Results - Estimators

- It is often said that Monte Carlo (MC) is a "mathematical experiment"
  The MC equivalent of the result of a real experiment (*i.e.*, of a measurement) is called an estimator.
- Just as a real measurement, an estimator is obtained by sampling from a statistical distribution and has a statistical error (and in general also a systematic one).
- There are often several different techniques to measure the same physical quantity: in the same way the same quantity can be calculated using different kinds of estimators.
- FLUKA offers numerous different estimators, *i.e.*, directly from the input file the users can request scoring the respective quantities they are interested in.
- As the latter is implemented in a very complete way, users are strongly encouraged to preferably use the built-in estimators with respect to user-defined scoring
- For additional requirements FLUKA user routines are provided

Built-In and User Scoring

- Several pre-defined estimators can be activated in FLUKA.
- One usually refers to these estimators as "scoring" capabilities
- Users have also the possibility to build their own scoring through **user routines**, HOWEVER:
    - Built-in scoring covers most of the **common needs**
    - Built-in scoring has been **extensively tested**
    - Built-in scoring takes BIASING **weights automatically into account**
    - Built-in scoring has **refined algorithms** for track subdivision
    - Built-in scoring comes with **utility programs** that allow to evaluate statistical errors
- Standard scoring can be weighted by means of simple user routines (fluscw, comscw)

FLUKA Scoring & Results

What? Energy deposition, and derivatives (dose), fluence or current versus energy/ angle/ other kinematical variables, time, DPA…..

Where? In regions, on boundaries, on region-independent grids

When?

At the end of each cycle

At each event

Output? Files inp*nnn*_fort.## where ## is logical unit number chosen by user

Results?

Postprocessing utilities (in $FLUPRO/flutil) merge cycles, calculate average and rms, provide data files for plotting

Data merging and plotting available in FLAIR

User code needed

Results normalized **per primary**

The FLUKA Output Files

The FLUKA output consists of:

- A main (standard) output, written on logical output unit LUNOUT (predefined as 11 by default) [*.out]
- A file with the last random number seeds, unit LUNRAN (2 by default) [ran*]
- A file of error messages, unit LUNERR (15 by default) [.err]

- Any number (including zero) of estimator output files. Their logical unit number is defined by the user [*_fort.xx]
- The available range of logical output numbers is: 21-99
- Generally, the user can choose between formatted (ASCII) and unformatted (binary) scoring (negative or positive sign in the logical unit number). Unformatted scoring is mandatory for the use of provided post-processing utilities.
- Several estimators can be output on the same file (same logical unit) provided they are of the same type
- Possible additional output generated by the user in any user routine

Before giving details

- A couple of slides on important definitions / quantities:
- Reaction rate and cross section
- Fluence and the difference wrt current
- Fluence as the correct quantity to evaluate the potential effect of a particle field on a “detector”
- Different methods to evaluate fluence

Definitions

- N: number of identical particles
- N_0 : number of atoms per unit volume
- $\lambda[cm]$: mean free path, i.e. average distance travelled by a particle in a material before an interaction. It depends on the material, particle type and energy.
- l: total distance travelled
- v: average particle velocity

Cross Section

- $\Sigma[cm^{-1}] = 1/\lambda[cm]$: macroscopic cross section, i.e. probability of interaction per unit distance. It depends on the material, particle type and energy.

- $\sigma = \frac{\Sigma}{N_0} = atom\ effective\ area\ , [barn = 10^{-24} cm^2]$: microscopic cross section, i.e.

  i) the area of an atom weighted with the probability of interaction (hence the name "cross section");

  ii) or the probability of interaction per unit length, with the length measured in atoms/cm^2 (the number of atoms contained in a cylinder with a 1 cm^2 base).

Microscopic and macroscopic cross sections have a similar physical meaning of "probability of interaction per unit length", with length measured in different units. Thus, the number of interaction can be obtained by multiplying both by the corresponding particle track-length.

Reaction Rate and Fluence

- $R = \Sigma\Phi V$: number of reactions in a given time interval inside the volume V (where Φ is the fluence and the product $\Sigma\Phi$ is integrated over energy or velocity)

- $\dot{R} = N\frac{dl}{dt}\Sigma = Nv\Sigma$: reaction rate

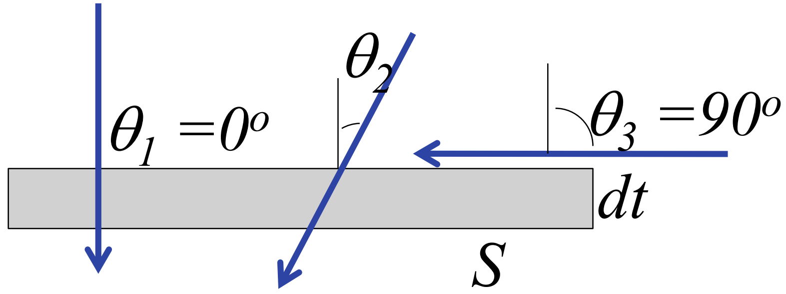
- $\frac{d\dot{R}}{dV} = \frac{dN}{dV}v\,\Sigma = n(\boldsymbol{r},v)v\Sigma$: reaction rate inside the volume element dV

- $\Phi(\boldsymbol{r},v) = n(\boldsymbol{r},v)dl\,,[cm^{-2}]$: fluence, i.e. time integral of the flux density

- $\dot{\Phi}(\boldsymbol{r},v) = n(\boldsymbol{r},v)v\,,[cm^{-3}cms^{-1}] = [cm^{-2}s^{-1}]$: fluence rate or flux density.

- Fluence is measured in particles per cm^2 but in reality it describes the **density of particle tracks**

Fluence vs Current (1/2)



Surface crossing estimation

- Imagine a surface having an infinitesimal thickness dt.
  A particle incident with an angle θ with respect to the normal of the surface S will travel a segment $dt/\cos\theta$.
- Therefore, we can calculate an average surface fluence by adding $dt/\cos\theta$ for each particle crossing the surface, and dividing by the volume $S\,dt$:

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

- While the current J counts the number of particles crossing the surface divided by the surface:

$$J = dN/dS$$

Fluence vs Current (2/2)

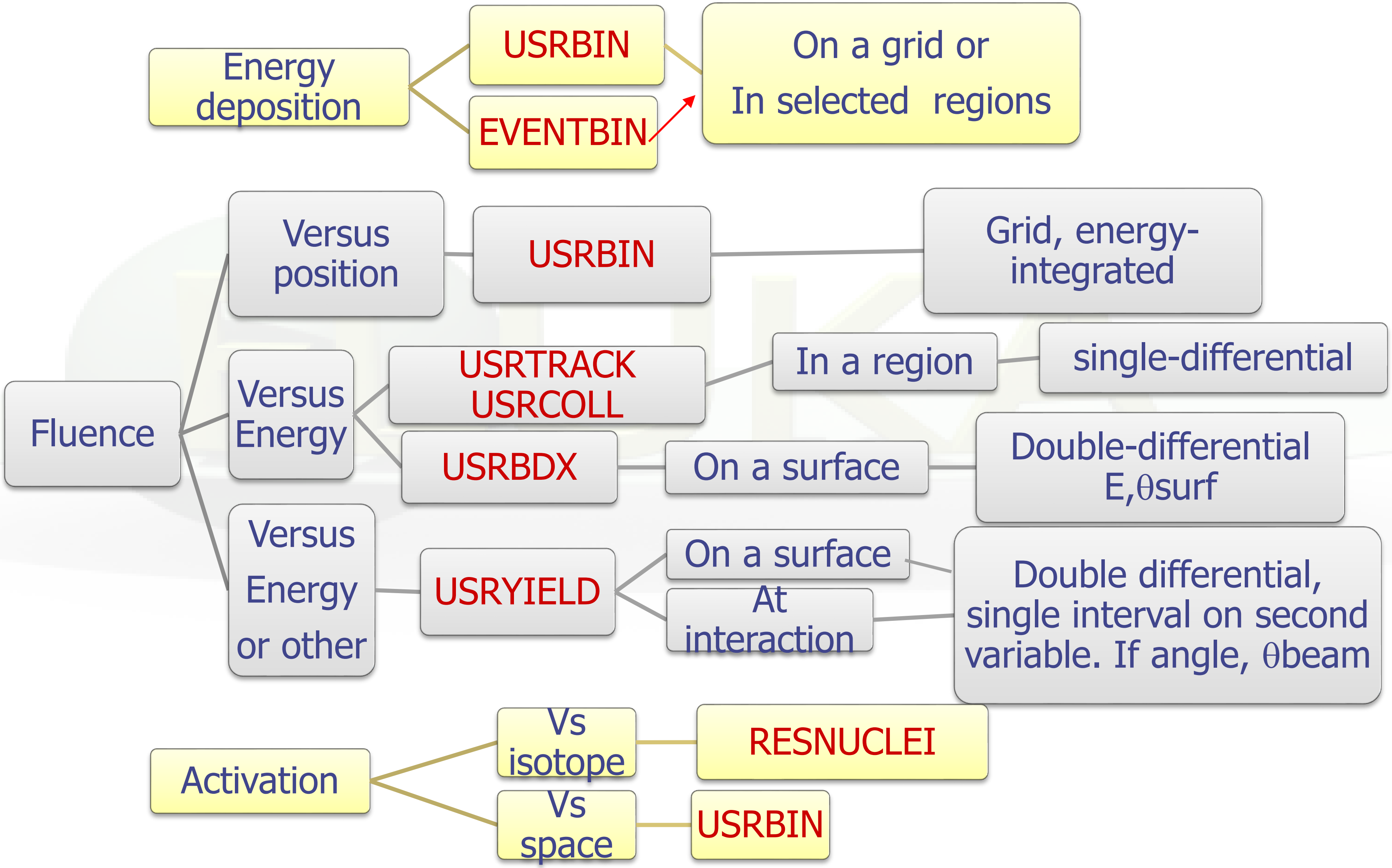
The fluence is independent from the orientation of surface *S*, while the current is NOT!

In an isotropic field can be easily seen that on a flat surface $J = \Phi/2$

Current is *meaningful* if particles are only counted (e.g. signal trigger).

But if someone estimates dose, activation, radiation damage, instrument response the quantity to be used is fluence.

FLUKA estimators (1/2)



FLUKA estimators (2/2)

- USRTRACK, USRCOLL score average $d\Phi/dE$ (differential fluence) of a given type or family of particles in a given region (see next slide);
- 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;
- USRBIN scores the spatial distribution of energy deposited, or total fluence (or star density, or momentum transfer) in a regular mesh (cylindrical, Cartesian o per region) described by the user;
- USRYIELD scores a double differential yield of particles escaping from a surface. The distribution can be with respect to energy and angle, but also other more “exotic” quantities;
- SCORE scores energy deposited (or star density) in all regions;
- The output of SCORE will be printed in the main (standard) output, written on logical output unit LUNOUT (pre-defined as **11** by default)
- All other detectors write their results into logical output units assigned by the user (the unit numbers must be **>20**)

Fluence estimation

- Track length estimation:

USRTRACK

$$\dot{\Phi}(v)\,dt = n(v)\,v\,dt = \frac{dN(v)}{dV}\frac{dl(v)}{dt}dt = \lim_{\Delta V \to 0}\frac{\sum_i l_i(v)}{\Delta V}$$

- Collision density estimation:

USRCOLL

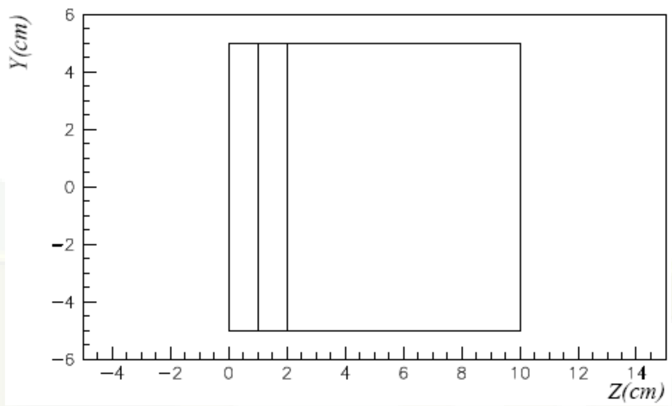
$$\dot{\Phi}(v) = \frac{\dot{R}(v)}{\sigma(v)\,N_o \Delta V} = \frac{\dot{R}(v)}{\Sigma(v)\Delta V} = \frac{\dot{R}(v)\lambda(v)}{\Delta V}$$

More "Special" Scoring

- RESNUCLEi scores residual nuclei in a given region (more details are given in the respective lecture on activation);
- DETECT scores energy deposition in coincidence or anti-coincidence with a trigger, separately for each "event" (primary history);
- EVENTBIN is like USRBIN, but prints the binning output after each event instead of an average over histories;
- ROTPRBIN sets the storage precision (single or double) and assigns rotations/translations for a given user-defined binning (USRBIN or EVENTBIN). Useful in case of LATTICEs;
- TCQUENCH sets scoring time cut-offs and/or Birks quenching parameters for binnings (USRBIN or EVENTBIN) indicated by the user;
- USERDUMP defines the events to be written onto a "collision tape" file;
- AUXSCORE defines filters and conversion coefficients.
- DCYSCORE assigns cooling times (see lecture on activation)

Extending the example with Scoring

- Cylinder along Z, filled by water-aluminum-lead and surrounded by Air



- The USRBIN command allows to define a 3-D grid, either cartesian, cylindrical (R-Z-Φ) or by region.
- On this grid, one can score energy deposition, particle fluence (total or by particle type), as well as the density of interactions;
- An equivalent EVENTBIN command outputs the same quantities event-by-event;
- Using USERWEIG the results can be weighted by the comscw.f or fluscw.f external routines (Advanced).

Example: USRBIN

- Start from the solution of ex_Geometry1 (Either copy your .inp and .flair files and rename them to example_score, or download from the site & rename):

  mkdir example_score ;
  cp ex_Geometry1/ex_Geometry1_final.inp example_score/example_score.inp ;
  cd example_score

  If you had some problem or you could not complete the ex_Geometry1, copy the solution ex_Geometry1_final.inp

  Check that there are **no spurious STOP** in the input file (inserted for the debugging test during the exercise Geometry1).

Example: USRBIN

- Start from the solution of ex_Geometry1 (Either copy your .inp and .flair files and rename them to example_score, or download from the site & rename):

```
mkdir example_score   ;
  cp ex_Geometry1/ex_Geometry1_final.inp example_score/example_score.inp ;
    cd example_score
```

- Open in flair or with your preferred editor
- Add USRBIN to:
  1) score ENERGY on a CYLINDRICAL GRID (r, z, ϕ) covering the target and surroundings: 0<**r**<10 cm, -5 cm<**z**<15 cm, with cells having Δ**r**=Δ**z**=1mm, $\Delta\phi=2\pi$. Output unit = 40 BIN
  2) score Neutron Fluence on the same grid as above. Output unit = 41 BIN
  3) score Charged Hadron Fluence on the same grid. Output unit = 42 BIN
- Run 5 cycles, 1000 primaries each

USRBIN - WHATs

WHAT(1) : code indicating the type of binning selected.
  Example : Usrbin WHAT(1) = 11.0 → Mesh: R-Z or R-Phi-Z, no symmetry
WHAT(2) : particle (or particle family) type to be scored
WHAT(3) = logical output unit

The first three fields have similar meanings for all estimators.
The other WHATs will contain the limits or regions or boundaries, and the number of intervals for cells/histograms

SDUM (optional) : name of the estimator

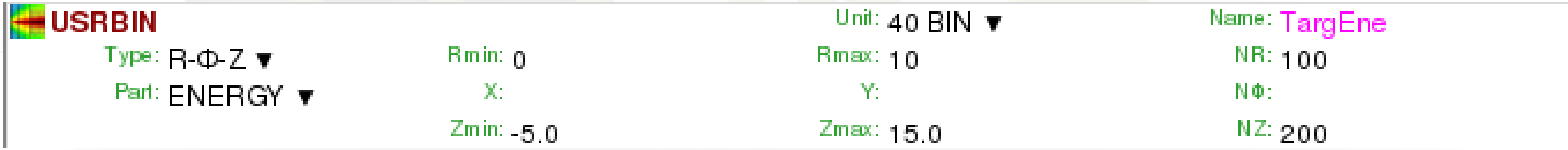
For Ursbin, r-phi-z:
WHAT(4)= For R-Z and R-Phi-Z binning: Rmax
WHAT(5)= For Cartesian binning: Ymax For R-Z and R-Phi-Z binning: Y coordinate of the binning axis

…….. And so on

USRBIN (1)

1) Add USRBIN to score ENERGY on a CYLINDRICAL GRID (r, z, ϕ) covering the target and surroundings: 0<**r**<10 cm, -5 cm<**z**<15 cm, with cells having Δ**r**=Δ**z**=1mm , $\Delta\phi=2\pi$

```
* Energy deposition [GeV/cm³]
*   +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
USRBIN          11.0    ENERGY     -40.0      10.0                15.0TargEne
USRBIN           0.0                -5.0     100.0               200.0&
```

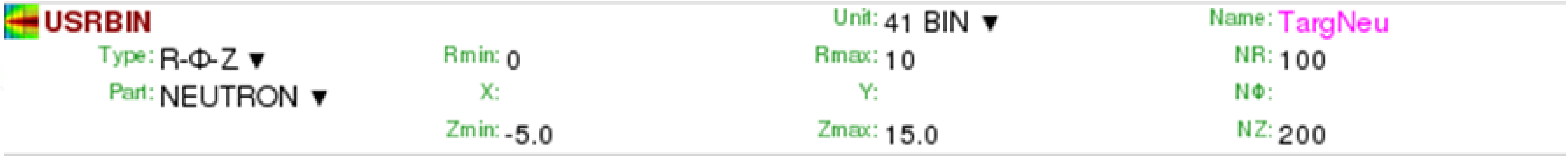


- This is an R-Z-Φ binning (what(1)=11), scoring energy density (generalized particle ENERGY, or 208), writing the unformatted output on unit 40, spanning 0<R<10 cm in 100 bins, $0<\Phi<2\pi$ in 1 bin (default), -5 cm<z<15 cm in 200 bins.

USRBIN (2-3)

2) Add USRBIN to score Neutron Fluence on the same grid as before

```
* Neutron fluence [cm^-2]
*    +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
USRBIN          11.0   NEUTRON     -41.0      10.0                15.0TargNeu
USRBIN           0.0                -5.0     100.0               200.0&
```

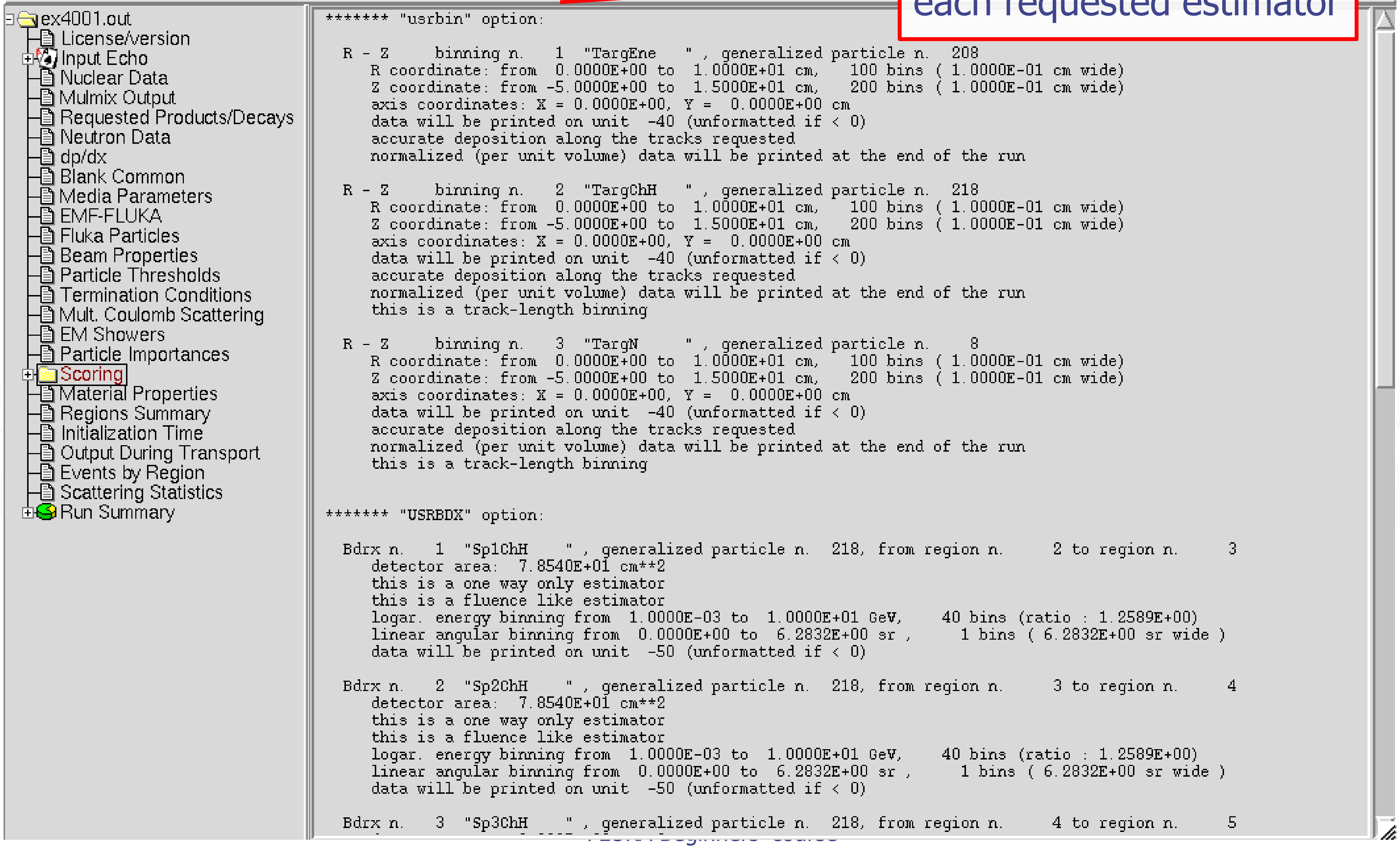


- This is a R-Z-Φ binning (what(1)=11), scoring neutron fluence, writing the unformatted output on unit 40, spanning 0<R<10 cm in 100 bins, $0<\Phi<2\pi$ in 1 bin (default), -5 cm<z<15 cm in 200 bins.

3) Add USRBIN to score Charged Hadron Fluence (HAD-CHAR) on the same grid as before. Output unit = 42 BIN

Check in the .out file

Complete description of each requested estimator



ex4001.out
- License/version
- Input Echo
- Nuclear Data
- Mulmix Output
- Requested Products/Decays
- Neutron Data
- dp/dx
- Blank Common
- Media Parameters
- EMF-FLUKA
- Fluka Particles
- Beam Properties
- Particle Thresholds
- Termination Conditions
- Mult. Coulomb Scattering
- EM Showers
- Particle Importances
- Scoring
- Material Properties
- Regions Summary
- Initialization Time
- Output During Transport
- Events by Region
- Scattering Statistics
- Run Summary

```
******* "usrbin" option:

  R - Z      binning n.   1  "TargEne   " , generalized particle n.  208
     R coordinate: from  0.0000E+00 to  1.0000E+01 cm,   100 bins ( 1.0000E-01 cm wide)
     Z coordinate: from -5.0000E+00 to  1.5000E+01 cm,   200 bins ( 1.0000E-01 cm wide)
     axis coordinates: X = 0.0000E+00, Y =  0.0000E+00 cm
     data will be printed on unit  -40 (unformatted if < 0)
     accurate deposition along the tracks requested
     normalized (per unit volume) data will be printed at the end of the run

  R - Z      binning n.   2  "TargChH   " , generalized particle n.  218
     R coordinate: from  0.0000E+00 to  1.0000E+01 cm,   100 bins ( 1.0000E-01 cm wide)
     Z coordinate: from -5.0000E+00 to  1.5000E+01 cm,   200 bins ( 1.0000E-01 cm wide)
     axis coordinates: X = 0.0000E+00, Y =  0.0000E+00 cm
     data will be printed on unit  -40 (unformatted if < 0)
     accurate deposition along the tracks requested
     normalized (per unit volume) data will be printed at the end of the run
     this is a track-length binning

  R - Z      binning n.   3  "TargN     " , generalized particle n.    8
     R coordinate: from  0.0000E+00 to  1.0000E+01 cm,   100 bins ( 1.0000E-01 cm wide)
     Z coordinate: from -5.0000E+00 to  1.5000E+01 cm,   200 bins ( 1.0000E-01 cm wide)
     axis coordinates: X = 0.0000E+00, Y =  0.0000E+00 cm
     data will be printed on unit  -40 (unformatted if < 0)
     accurate deposition along the tracks requested
     normalized (per unit volume) data will be printed at the end of the run
     this is a track-length binning


******* "USRBDX" option:

  Bdrx n.   1  "Sp1ChH    " , generalized particle n.  218, from region n.     2 to region n.     3
     detector area:  7.8540E+01 cm**2
     this is a one way only estimator
     this is a fluence like estimator
     logar. energy binning from  1.0000E-03 to  1.0000E+01 GeV,    40 bins (ratio : 1.2589E+00)
     linear angular binning from  0.0000E+00 to  6.2832E+00 sr ,     1 bins ( 6.2832E+00 sr wide )
     data will be printed on unit  -50 (unformatted if < 0)

  Bdrx n.   2  "Sp2ChH    " , generalized particle n.  218, from region n.     3 to region n.     4
     detector area:  7.8540E+01 cm**2
     this is a one way only estimator
     this is a fluence like estimator
     logar. energy binning from  1.0000E-03 to  1.0000E+01 GeV,    40 bins (ratio : 1.2589E+00)
     linear angular binning from  0.0000E+00 to  6.2832E+00 sr ,     1 bins ( 6.2832E+00 sr wide )
     data will be printed on unit  -50 (unformatted if < 0)

  Bdrx n.   3  "Sp3ChH    " , generalized particle n.  218, from region n.     4 to region n.     5
```

Standard Postprocessing Programs (1/2)

- To analyse the results of the different scoring options, several programs are made available
- The most natural ones are kept in $FLUPRO/flutil.
- They assume that the **estimator files are unformatted**, and can calculate standard deviations and average values over many cycles:
  - ustsuw.f to analyze USRTRACK and USRCOLL outputs
  - usxsuw.f to analyze USRBDX outputs
  - usysuw.f to analyze USRYIELD outputs
  - usbsuw.f to analyze USRBIN outputs
  - usrsuw.f to analyze RESNUCLEi outputs

Example in the terminal:

$FLUPRO/flutil/*name*.f

Type the input file: inputname###_fort.nn
Type the input file: inputname###_fort.nn
…
Type the input file:
Type the output file: outputname

Standard Postprocessing Programs (2/2)

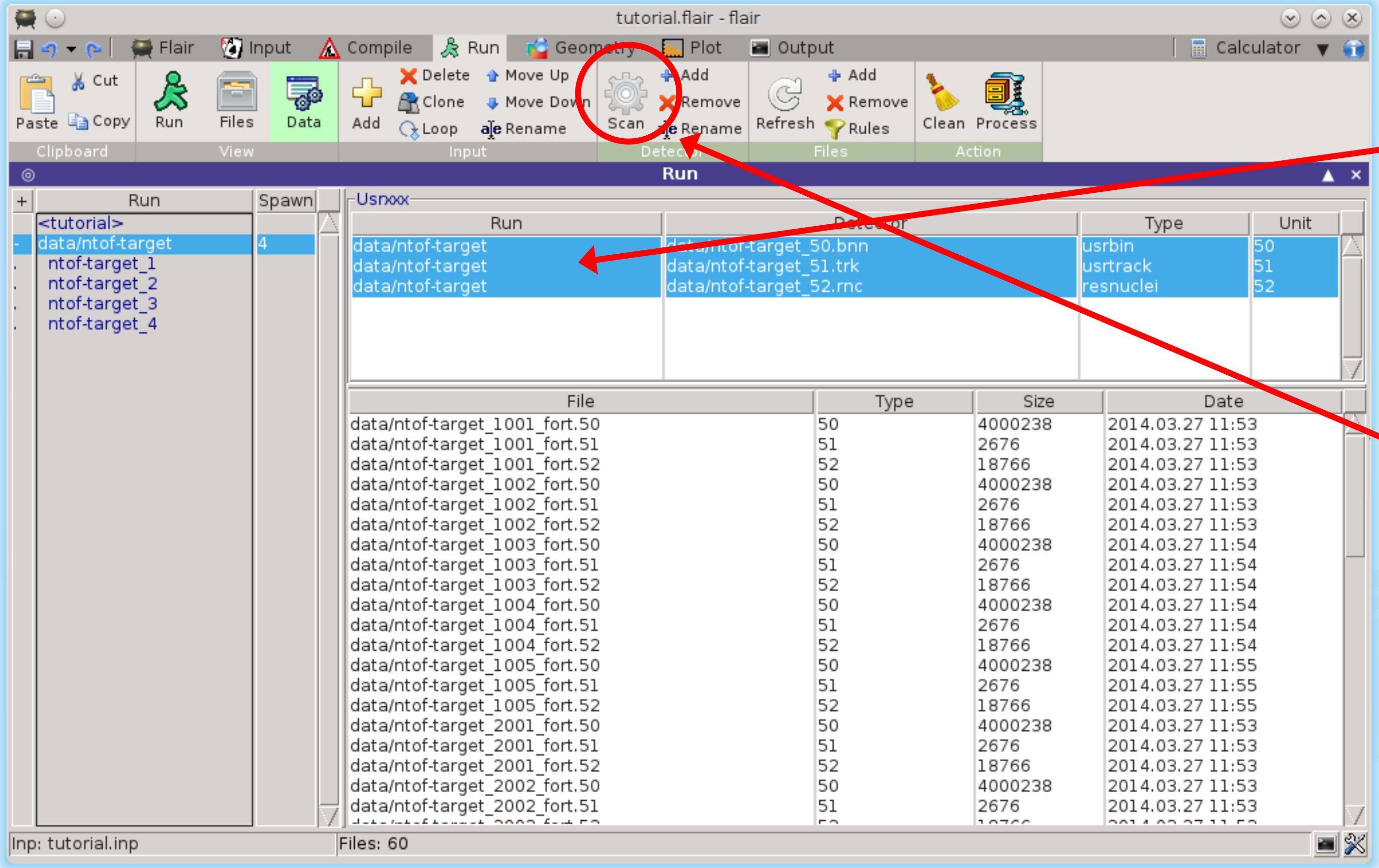
- usbsuw produces a _.bnn file (binary), which can then be read by Flair for plotting

- All other programs (except usbsuw) produces three files:
  - a text file with extension *_sum.lis* which contains averaged distributions, standard deviations, **cumulative (integral)** quantities
  - an unformatted file which can replace the *N* unformatted estimator files in further postprocessing
  - a text file with extension *_tab.lis* to be easily readout by graphics codes

[Simpler programs are also provided in the manual, as guide for users who would like to write their own analysis program].

Flair: Data Processing

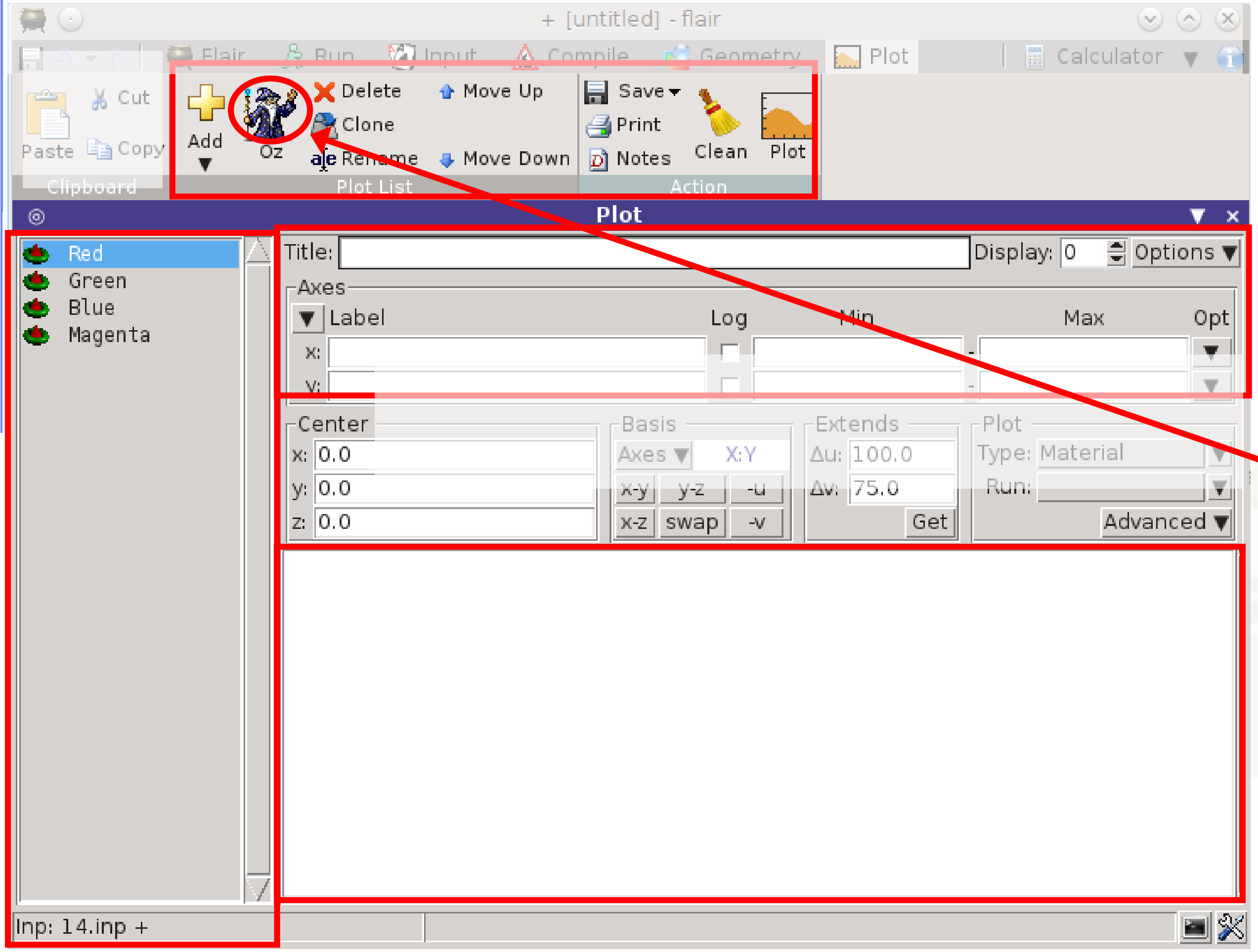
In the run tab



- Flair initially scans the input for possible unformatted output data for each scoring card. It creates automatic rules for processing (merging).
- If in the mean time you have modified the input click the "automatic" scan
- The default names are generated by the rules specified in the preference dialog, can be changed if desired (advanced)

FLAIR uses the auxiliary programs available in $FLUPRO/flutil to merge output data. For USRBIN: the usbsuw code

Plot List

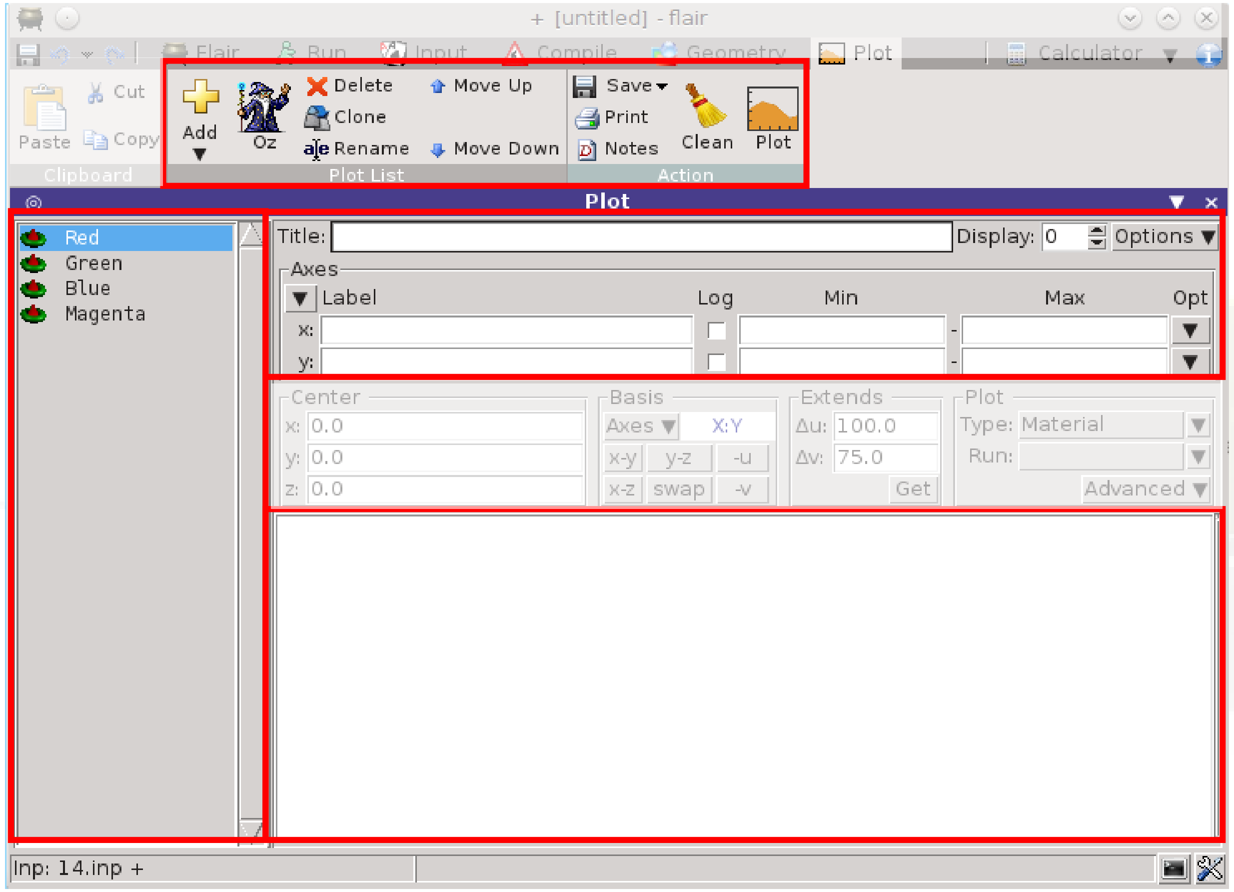


- Plots can be created in the "Plot" list frame. Either Add new plots or Clone from existing ones.
- It is important to set a unique filename for each plot.
  This filename will be used for every auxiliary file that the plot needs (with different extensions)
- The Wizard button creates automatically one plot for each processed unit
- Double click on a plot, or hit Enter or click the Edit icon to display the plotting dialog

Plot Types

- Geometry — For geometry plots
- USRBIN — For plotting the output of USRBIN
- USR-1D cards — To plot single differential quantities from USRBDX, USRTRACK, USRCOLL, USRYIELD
- USR-2D — To plot double differential from USRBDX
- RESNUCLE RESNUCLEi — To plot 1d or 2d distributions of
- USERDUMP — To plot the output of USERDUMP. Useful for visualizing the source distribution.

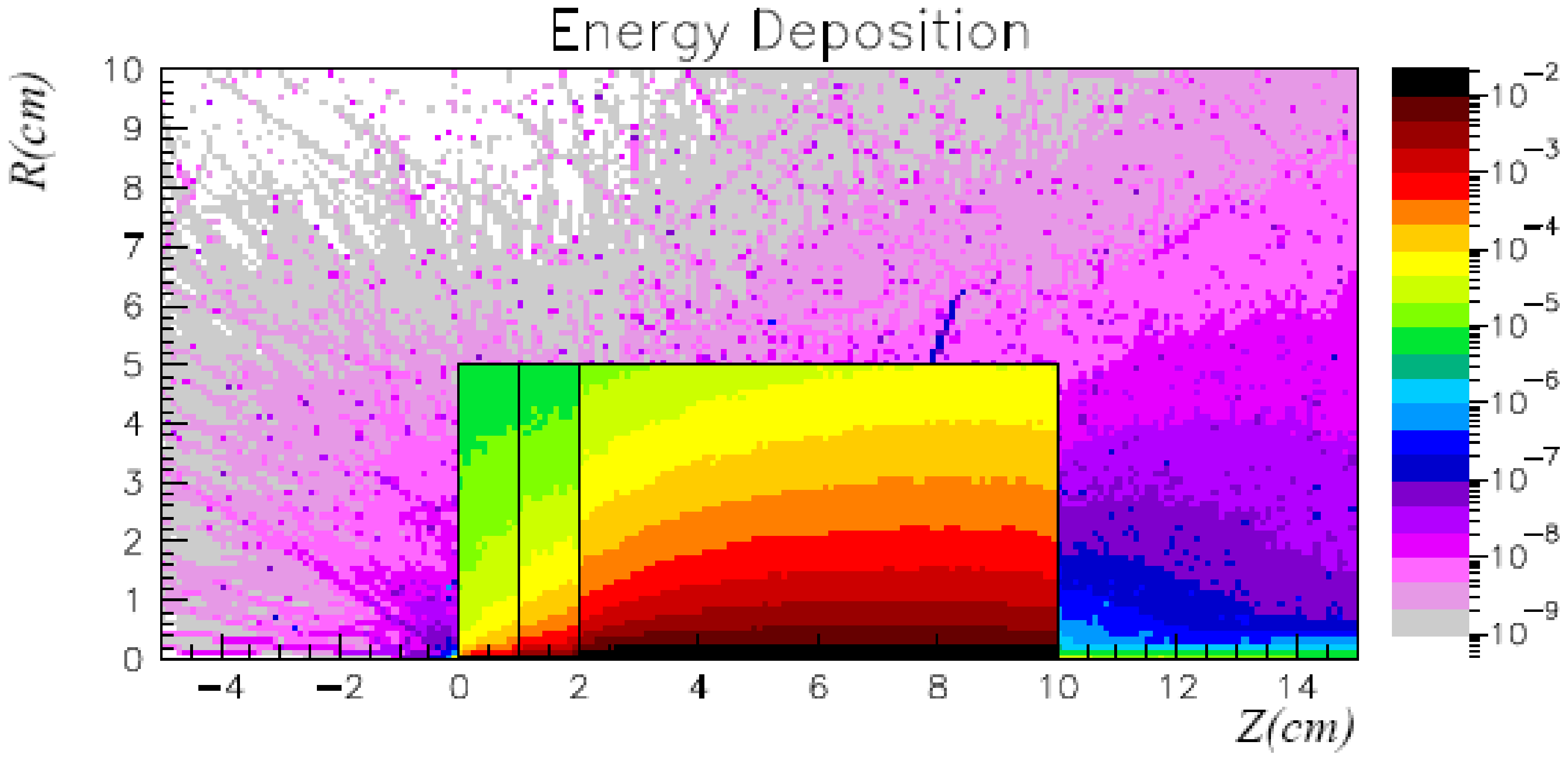
Plotting Frames



- **FLAIR uses gnuplot to produce plots**
- All plot types share some common fields: Title + options, Filename, Axis Labels, Legends (Keys) and Gnuplot Commands.
- Plot button (Ctrl-Enter) will generate all the necessary files to display the plot, ONLY if they do not exist.
- All plots are listed in the Plot List
- Clean button will remove all files generated by Flair during plotting process.
- Check the Gnuplot manual to provide additional customization commands: e.g. To change the title font to Times size=20, add in the Opt: field the command: font 'Times,20'

USRBIN → The Result

WHAT(2) = ENERGY : Energy deposition from a 3.5 GeV proton beam hitting at [0.,0.,0.] directed along z. Results are normalized to **GeV/cm³ per primary**

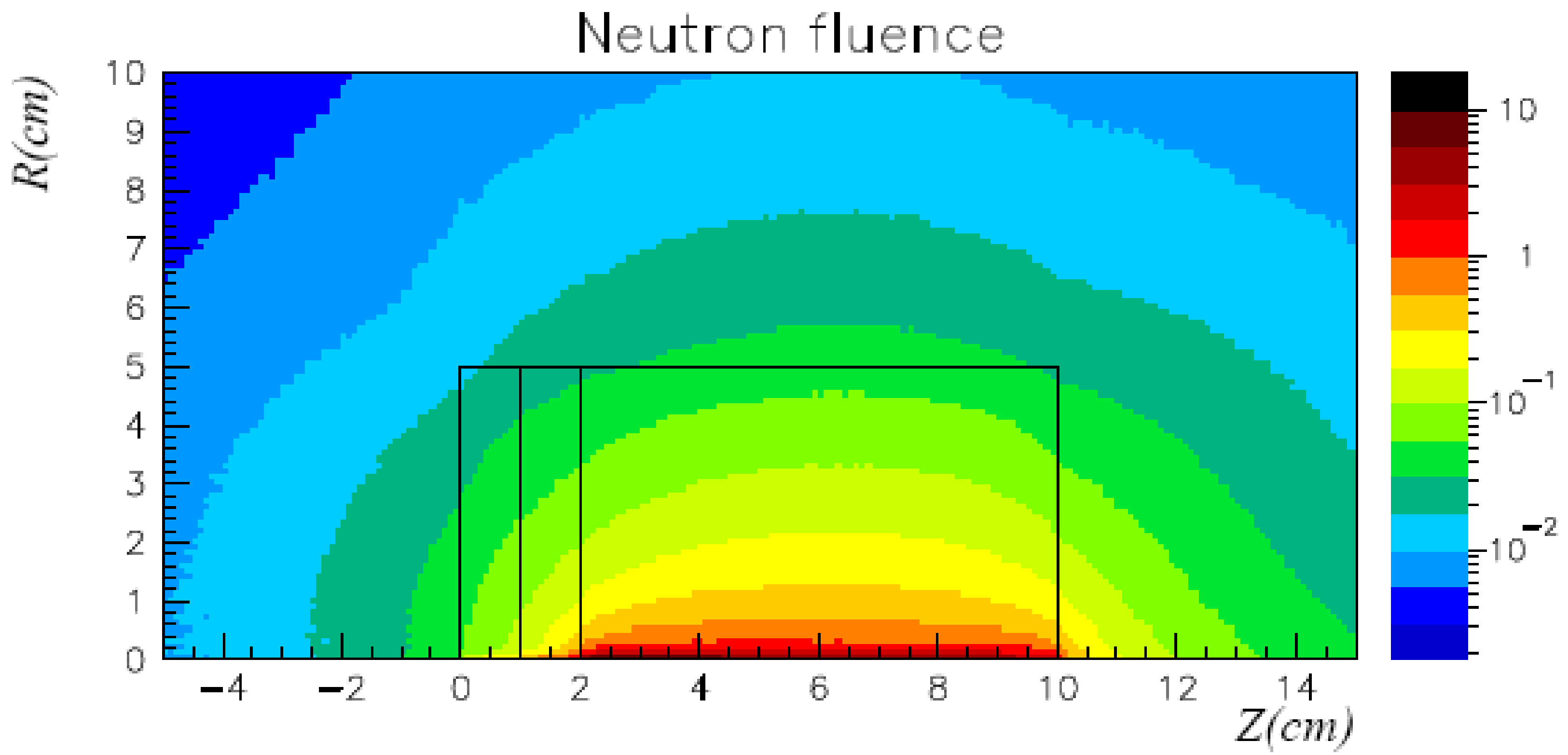


This plot is a 2D projection of a 3D structure→ the result is the AVERAGE over the 3rd coordinate. Projection limits can be set in FLAIR

USRBIN → The Result

Same, WHAT(2)= NEUTRON to get neutron fluence.

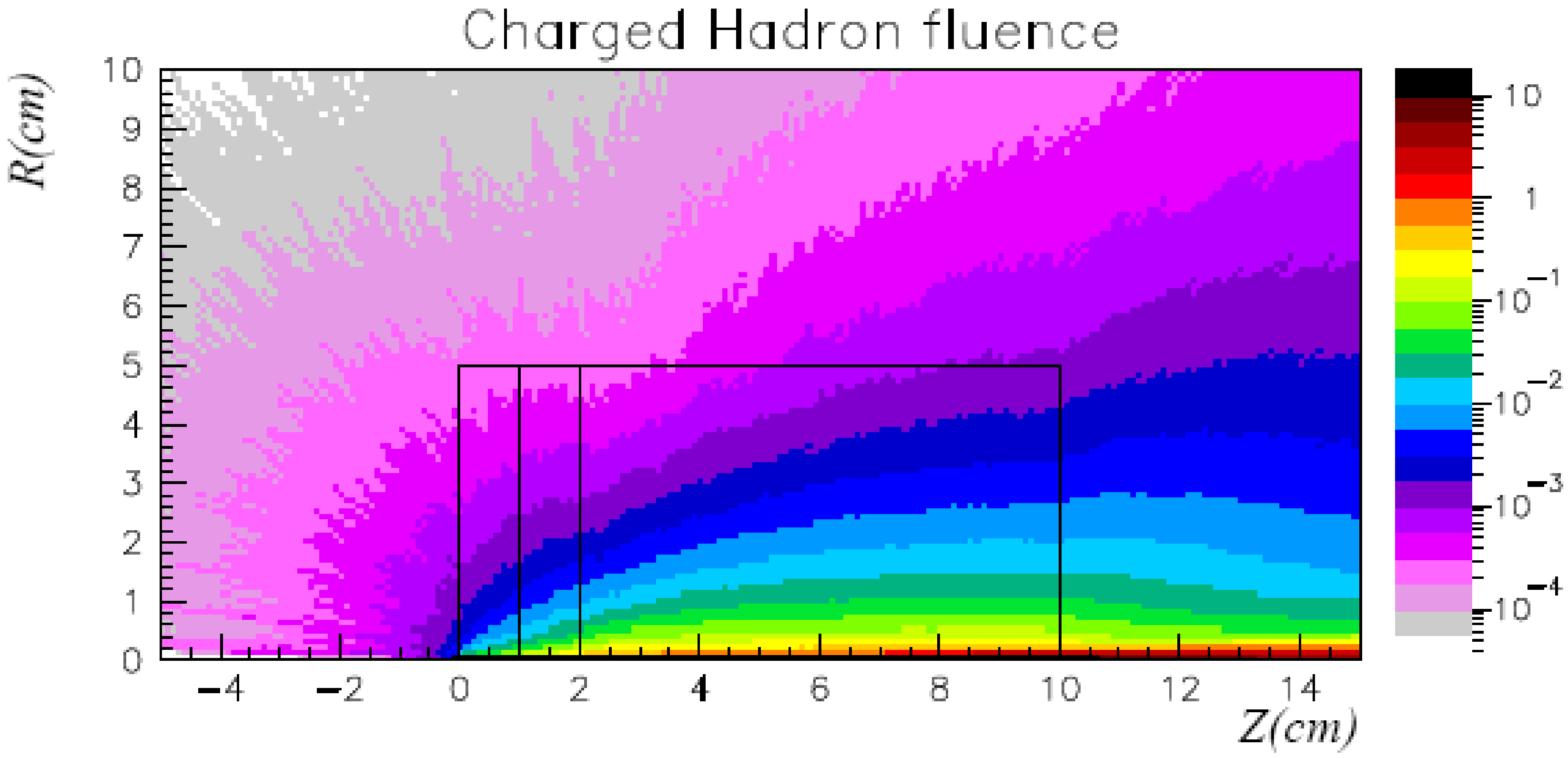
Results are normalized to **particles/cm² per primary**



USRBIN → The Result

Same, WHAT(2)= HAD-CHAR to get charged hadron fluence.

Results are normalized to **particles/cm² per primary**



USRBIN – more quantities

USRBIN can score Particle fluence as well as “Generalized particles”, either fluence-like or energy-like, for instance with what(2) =

- DOSE: Energy/unit mass (GeV/g)
- DPA-SCO: Displacements per atom (see the lecture on Ionization and transport)
- X-MOMENT: x-component of momentum transfer (GeV/c)
- ACTIVITY: activity per unit volume (Bq/cm^3) (see lecture on radioactivity)

- … and more (see in the manual)

USRBDX

USRBDX scores double differential (energy and angle) particle distributions across a boundary surface. The angle is with respect to the normal of the surface.

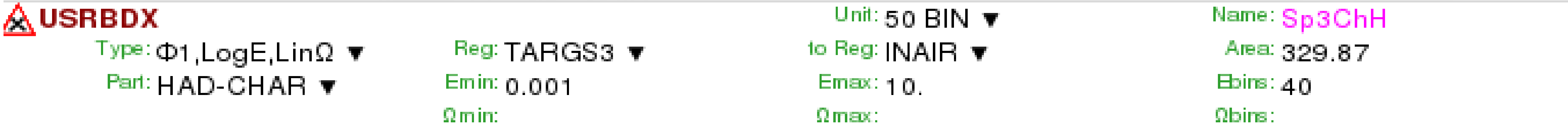
WHAT(1) : the distribution can be fluence or current, one-way or two-ways, according to the value of WHAT(1) (see the manual)
WHAT(2) = particle type to be scored
WHAT(3) = logical output unit
WHAT(4)= first region defining the boundary
WHAT(5)= second region defining the boundary
WHAT(6) = area of the detector in cm^2
SDUM = detector identifier
Continuation card:
WHAT(1)= maximum kinetic energy for scoring (GeV)
WHAT(2)= minimum kinetic energy for scoring (GeV)
WHAT(3) = number of energy intervals
WHAT(4)= maximum solid angle in sr
WHAT(5)= minimum solid angle (if linear angular binning) or solid angle (if logarithmic angular binning)
WHAT(6) = number of angular bins

Example : USRBDX (1)

* in this case post-processed results are single differential (already integrated over the solid angle)

1) Score CHARGED HADRONS at the outer surface of the lead segment (from TARGS3 to INAIR). WHAT(1)=99 means: fluence, one-way only, log. intervals in energy. From 1 MeV to 10 GeV in 40 intervals, and *one angular interval (default)**. WHAT(6) is a normalization factor: setting it equal to the surface area provides results normalized to cm^{-2} (fluence unit) GeV^{-1} sr^{-1}. Output to unformatted unit 50

```
*    +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
* out from lead
USRBDX          99.0  HAD-CHAR      -50.    TARGS3     INAIR   329.87Sp3ChH
USRBDX          10.0     0.001       40.                             &
```



Repeat the same between TARGS1 and TARGS2, and between TARGS2 and TARGS3 (use the right normalization factor!).

Example : USRBDX (2)

* in this case post-processed results are single differential (already integrated over the solid angle)

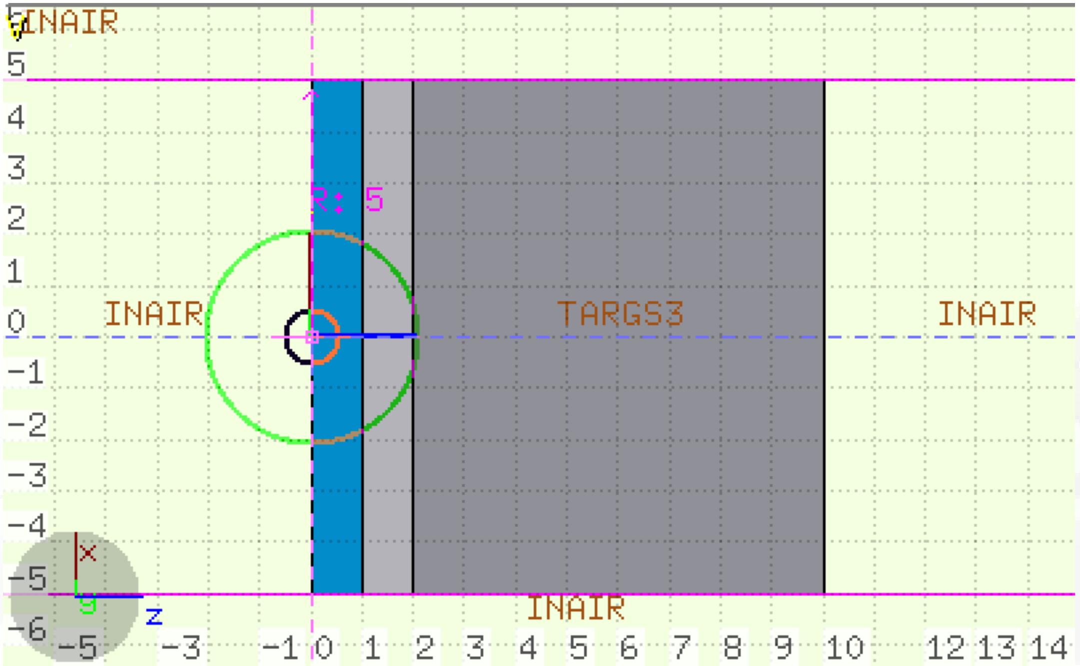
2) Score at the surface between 2nd and 3rd target section, same as before but in 3 angular bins.

```
*    +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
USRBDX          99.0  HAD-CHAR      -54.    TARGS2    TARGS3   78.5398Sp2ChHA
USRBDX          10.0     0.001       40.                           3.0&
```

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.	Ebins: 40
	Ωmin:	Ωmax:	Ωbins: 3

Example : Normalization



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

Area between TARGS2 and TARGS3 = πR_{TARG}^2 = 78.5398
Area between TARGS3 and INAIR = $2\pi R_{TARG} Z_{TARGS3} + \pi R_{TARG}^2$ = 329.87

Standard Postprocessing Programs

The FLUKA prostprocessing program for USRBDX, usxsuw.f, generates files with the extension **_sum.lis** and **_tab.lis**. Example of sum.lis from USRBDX:

```
 Total primaries run:            3000
   Total weight of the primaries run:   3000.00000
Detector n:            1 (          1 )  Sp2ChHA
      (Area:           78.5398026       cmq,
       distr. scored:        218     ,
       from reg.          3  to           4 ,
       one way scoring,
       fluence scoring scoring)

      Tot. resp. (Part/cmq/pr)  1.4218389E-02  +/-   1.486696     %
      ( -->      (Part/pr)      1.116709      +/-   1.486696     % )

  **** Different. Fluxes as a function of energy **** ****      (integrated over solid angle)       ****
……..
  **** Cumulative Fluxes as a function of energy **** ****      (integrated over solid angle)
  ……..
**** Double diff. Fluxes as a function of energy ****
```

User provided the area in what(6), thus normalization is /cm^2

Charged Hadrons

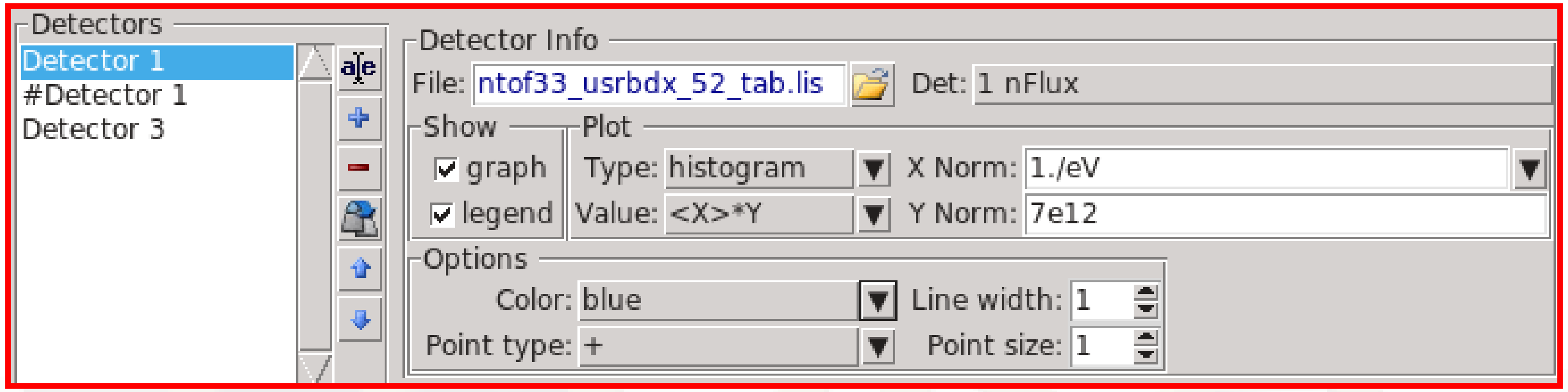
Standard Postprocessing Programs

- Example of tab.lis for USRBDX

```
 # Detector n:          1   Sp2ChHA   (integrated over solid angle)
 # N. of energy intervals        40
   Emin        Emax        Result        Error  (%)
1.000E-02  1.259E-02  5.049E-03  6.420E+01
 1.259E-02  1.585E-02  1.115E-03  6.934E+01
 1.585E-02  1.995E-02  2.826E-03  4.675E+01
 1.995E-02  2.512E-02  2.356E-03  3.866E+01
 2.512E-02  3.162E-02  6.437E-03  2.857E+01
…
# double differential distributions
 # number of solid angle intervals          3
 # Block n:           1     0.00000000     :   2.09439516
1.000E-02  1.259E-02  2.980E-04  9.900E+01
 1.259E-02  1.585E-02  1.981E-04  9.900E+01
 1.585E-02  1.995E-02  3.866E-04  6.700E+01
 1.995E-02  2.512E-02  7.171E-04  3.402E+01
 2.512E-02  3.162E-02  5.544E-04  4.550E+01
```

FLAIR USR-1D Single Differential Plot

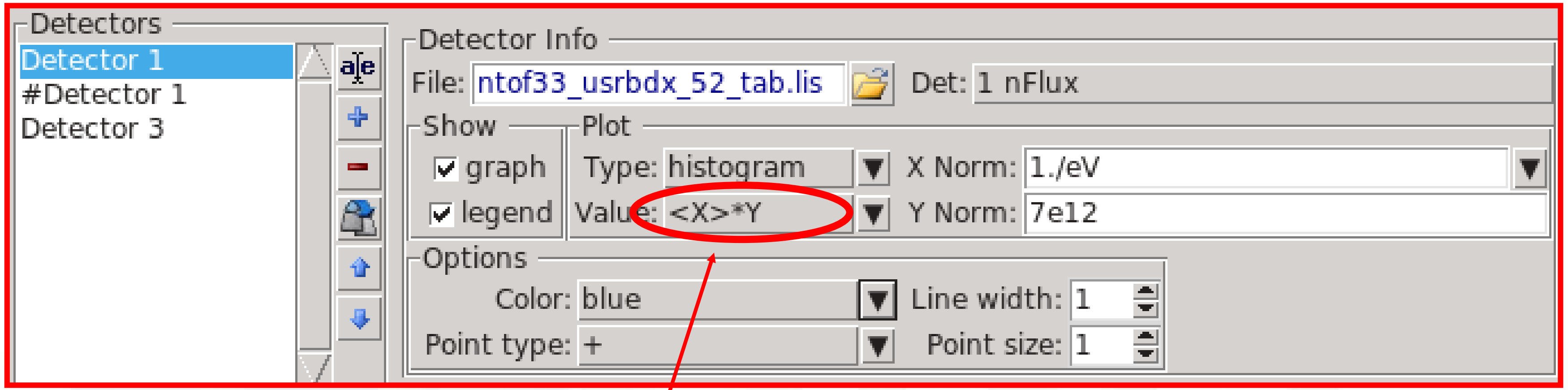
Plot → Add → USR-1D (or using the Wizard buttom)



- USR-1D is able to plot the 1D single differential information from the USRBDX, USRCOLL, USRTRACK and USRYIELD cards (The 2D information is not handled).
- The file type in use should have the extension _tab.lis (generated by the FLUKA data merging tools)
- You can superimpose many scoring output in a single plot.
- Error bars can be plotted (for instance using histerr instead of histogram)

FLAIR USR-1D Single Differential Plot

Plot → Add → USR-1D (or using the Wizard buttom)



WARNING:
use Lethargy plot!!!

Lethargy plots

- What is Lethargy? Why to use it?

Case 1: Linear plot F(x) vs x.
The integral between x_1 and x_2 is

$$I = \int_{x1}^{x2} F(x)dx$$

Comparing the F(x) value in each bin one has a direct, immediate feeling which bins contribute more to the integral.

Lethargy plots

- What is Lethargy? Why to use it?

Case 2: x-logarithmic plot F(x) vs log(x)

$$z = \log(x) \quad , \quad dz = \frac{dx}{x} \quad \Rightarrow \quad dx = x dz$$

Making a change of variable in $I = \int_{x1}^{x2} F(x)dx$ one gets:

$$I = \int_{log(x1)}^{log(x2)} xF(z)dz = \int_{log(x1)}^{log(x2)} xF(\log(x))d(\log(x))$$

$$\neq \int_{log(x1)}^{log(x2)} F(\log(x))d(log(x))$$

Comparing the x*F(log(x)) value in each bin one has a direct, immediate feeling which bins contribute more to the integral.

Lethargy plots

- What is Lethargy? Why to use it?

  - If E=particle energy and N=number of particles, a plot in E*dN vs log(E) (in FLAIR : y*<x> plot option) is called Lethargy plot. It allows giving the correct importance to different energy ranges in the plot:

    i.e. the area of each bin is proportional to the corresponding integral flux, and comparing the bins you have immediately the feeling in which energy bin you have more/less particles.

  - Lethargy plots must be used in general for any particle type with an energy spectrum extended over many orders of magnitude.

  - It is the standard representation for Low Energy Neutrons spectra, also because of the 1/E dependence of moderated n spectra (see lecture on Low-Energy Neutrons).

USRBDX ->The Result

This is true only if the surface area is explicitly given

Evolution of charged hadron spectra at the various surfaces

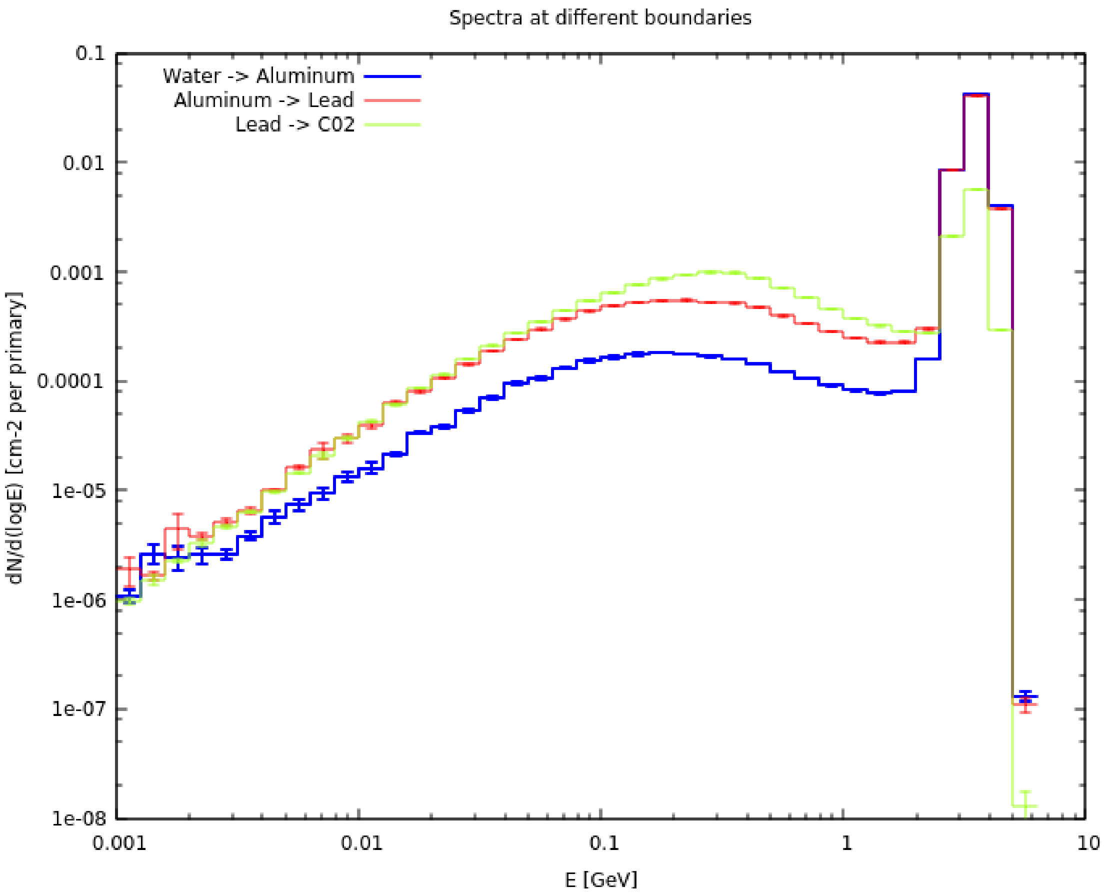
post-processed results are normalized to GeV^{-1} cm^{-2} per primary

From post-processing we get **single** differential spectra since we asked for one angular bin only

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

Value: <X>*Y

Lethargy plot



USRBDX ->The Result

This is true only if the surface area is explicitly given

Evolution of charged hadron spectra at the various surfaces

post-processed results are normalized to GeV^{-1} cm^{-2} per primary

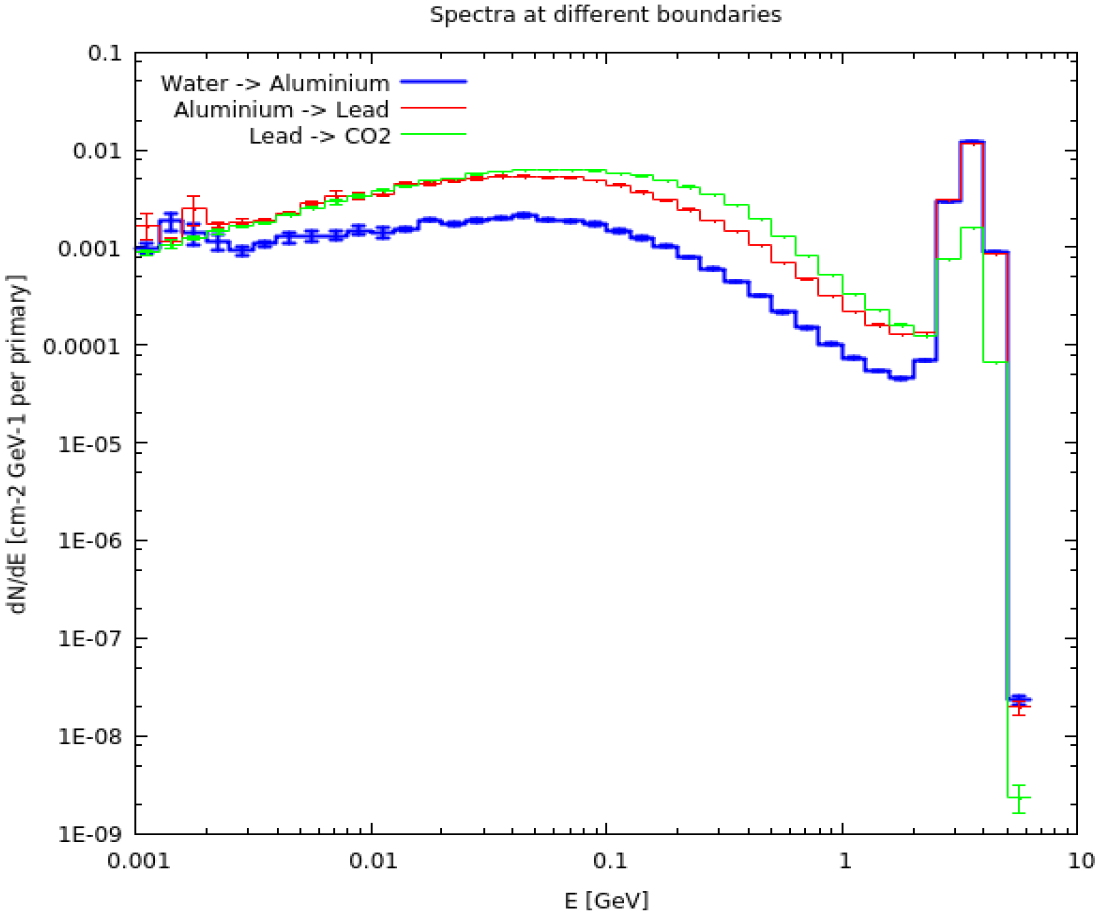
From post-processing we get **single** differential spectra since we asked for one angular bin only

$$y = \frac{dN}{dE}$$

Value: Y

Not Lethargy plot.

The low energy area "seems" to contribute more. This may be misleading… Be careful!



USRBDX ->The Result

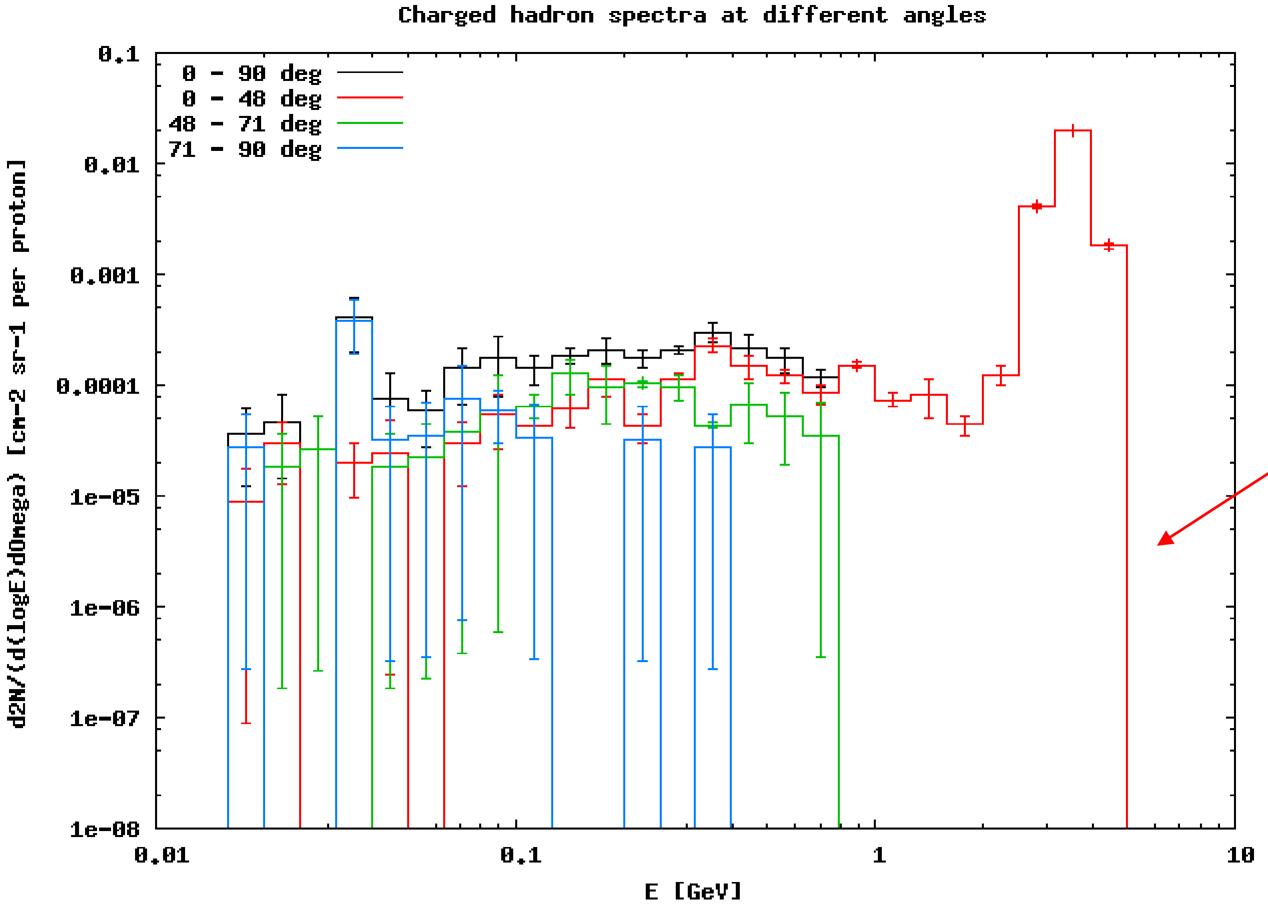
This is true only if the surface area is explicitly given

Double differential charged hadron spectra for consecutive solid angle portions

results are normalized to $GeV^{-1}\ sr^{-1}\ cm^{-2}$ per primary

From post-processing we get **double** differential spectra since we asked for more than one angular bin,

but the angle-integrated spectrum is provided as well on top



Forward is high energy

USRTRACK

- Calculates differential fluence as a function of energy by scoring track-length in a given region. Results are normalized to *GeV^{-1} cm^{-2} per primary* if the region volume is provided (otherwise should be intended as *GeV^{-1} cm per primary*, i.e. differential track-length)

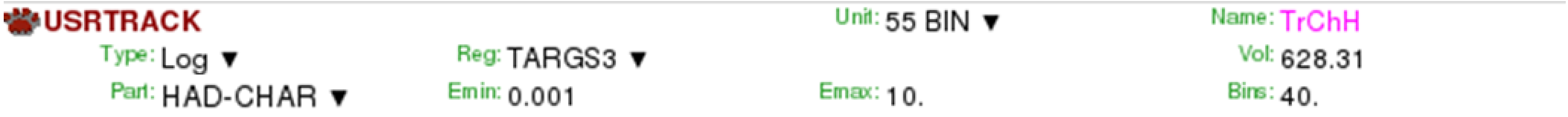
For all SDUMs except EN-NUCL and ENERGY:
WHAT(1) : linear (=1) or logarithmic (=-1) binning energy
WHAT(2) = particle type to be scored
WHAT(3) = logical output unit
WHAT(4)= region defining the detector (if >0) or all regions (if =-1)
WHAT(5)= volume of the detector in cm^3
WHAT(6) = number of energy bins
SDUM = track-length detector identifier
Continuation card:
WHAT(1)= maximum kinetic energy for scoring (GeV)
WHAT(2)= minimum kinetic energy for scoring (GeV)

For SDUM= EN-NUCL: The energy scale will be changed from energy to energy per nucleon. For SDUM= ENERGY: the energy scale will be changed to the default, that is total kinetic energy.

USRTRACK

- Score track-length of charged hadrons in TARGS3, in a logarithmic binning energy (WHAT(1)=-1) using 40 energy bins, between 1 MeV and 10 GeV. Normalize to the region volume in order to have the results in *[GeV^{-1} cm^{-2} per primary]*

```
*   +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
*              log  partype  out.unit    region    volume     #bins
*             Emax     Emin
USRTRACK      -1.0 HAD-CHAR       -55.    TARGS3    628.31       40.TrChH
USRTRACK      10.0    0.001                                          &
```



Remember: USRTRACK scores differential fluence in a region, USRBDX scores fluence or current on a surface, and USRBIN scores e.g. fluence in volumes and gives no differential information.

USRYIELD

- Scores a double-differential particle yield across a boundary surface or at interaction points. Angles wrt beam direction. Only 1 interval in the "second" quantity
- "Energy-like" quantities

Kinetic energy , total momentum , total energy , longitudinal momentum in the lab frame , longitudinal momentum in the c.m.s. frame , LET

- "Angle-like" quantities

Rapidity in the lab frame , rapidity in the c.m.s. frame , pseudorapidity in the lab frame , pseudorapidity in the c.m.s. frame , Feynman-x in the lab frame , Feynman-x in the c.m.s. frame , transverse momentum , transverse mass , polar angle (*) in the lab frame , polar angle (*) in the c.m.s. frame , square transverse momentum , charge , weighted angle in the lab frame , weighted transverse momentum

USRYIELD

WARNING!! calculating a cross section has no meaning in case of a thick target.

- While option USRBDX calculates angular distributions WITH RESPECT TO THE NORMAL to the boundary at the point of crossing, USRYIELD's distributions are calculated WITH RESPECT TO THE BEAM DIRECTION, as defined by BEAMPOS (or a different direction specified with SDUM=BEAMDEF).

WHAT(1) : the two physical quantities with respect to which the double-differential yield is calculated.
WHAT(2) = particle type to be scored
WHAT(3) = logical output unit
WHAT(4)= first region defining the boundary
WHAT(5)= second region defining the boundary
WHAT(6) = normalization factor
SDUM = detector name
Continuation card:
WHAT(1)= upper limit for the first quantity
WHAT(2)= lower limit for the first quantity
WHAT(3) = number of scoring intervals for the first quantity
WHAT(4)= upper limit for the second quantity
WHAT(5)= lower limit for the second quantity
… (see the manual)

USRYIELD

- Score plain double differential yield (continuation card WHAT(6)=3) of pions, with the first quantity being the polar angle (degree) and the second quantity being the kinetic energy (WHAT(1)=124), between TARGS3 and INAIR, between 0 and 180 deg in 18 bins and between 0 and 10 GeV.

```
*    124 = 24 + 1 * 100 => polar angle (in degrees) and kinetic energy
*                                  out.unit      Reg1      Reg2      Norm
*                   Amax      Amin   #Abins      Emax      Emin dbl.differential
*   +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
USRYIELD       124.0  PIONS+-      -57.    TARGS3     INAIR       1.0YieAng
USRYIELD       180.0       0.0      18.      10.0       0.0       3.0&
```

- Only one interval is possible for the second variable, BUT results are normalized as Double Differential (in this case, charged pions GeV^{-1} sr^{-1} per primary)

WARNING!!
Use WHAT(6) = 3 for plain double differential yield, the DEFAULT is plain double-differential cross section !!

Standard Postprocessing Programs

The FLUKA postprocessing program for USRYIELD, usysuw.f, generates files with the extension **_sum.lis** and **_tab.lis**. Example of sum.lis from USRYIELD

automatic conversion from degrees

Detector n: 1 YieAng
(User norm: 1.
sigma: 1. mb
distr. scored: 209 , PIONS+-
from reg. 4 to reg. 5)
linear 1st variable (x1) binning from 0.0000E+00 to 3.1416E+00 18 bins
(1.7453E-01 wide)
2nd variable (x2) ranges from 0.0000E+00 to 1.0000E+01
1st variable (x1) is: Laboratory Angle (radians)
2nd variable (x2) is: Laboratory Kinetic Energy
The scored double differential yield is (normalized per primary particle):
plain d2 N / dx1 dx2 where x1, x2 are the first and second variables

Tot. response (integrated over x1) 2.6339998E-02 +/- 3.883959 %

WARNING!! The Tot. response is NOT integrate over the second quantity !!
in this case it turns out to be *particles/GeV per primary*
(to be multiplied by the energy width interval of 10GeV)

Standard Postprocessing Programs

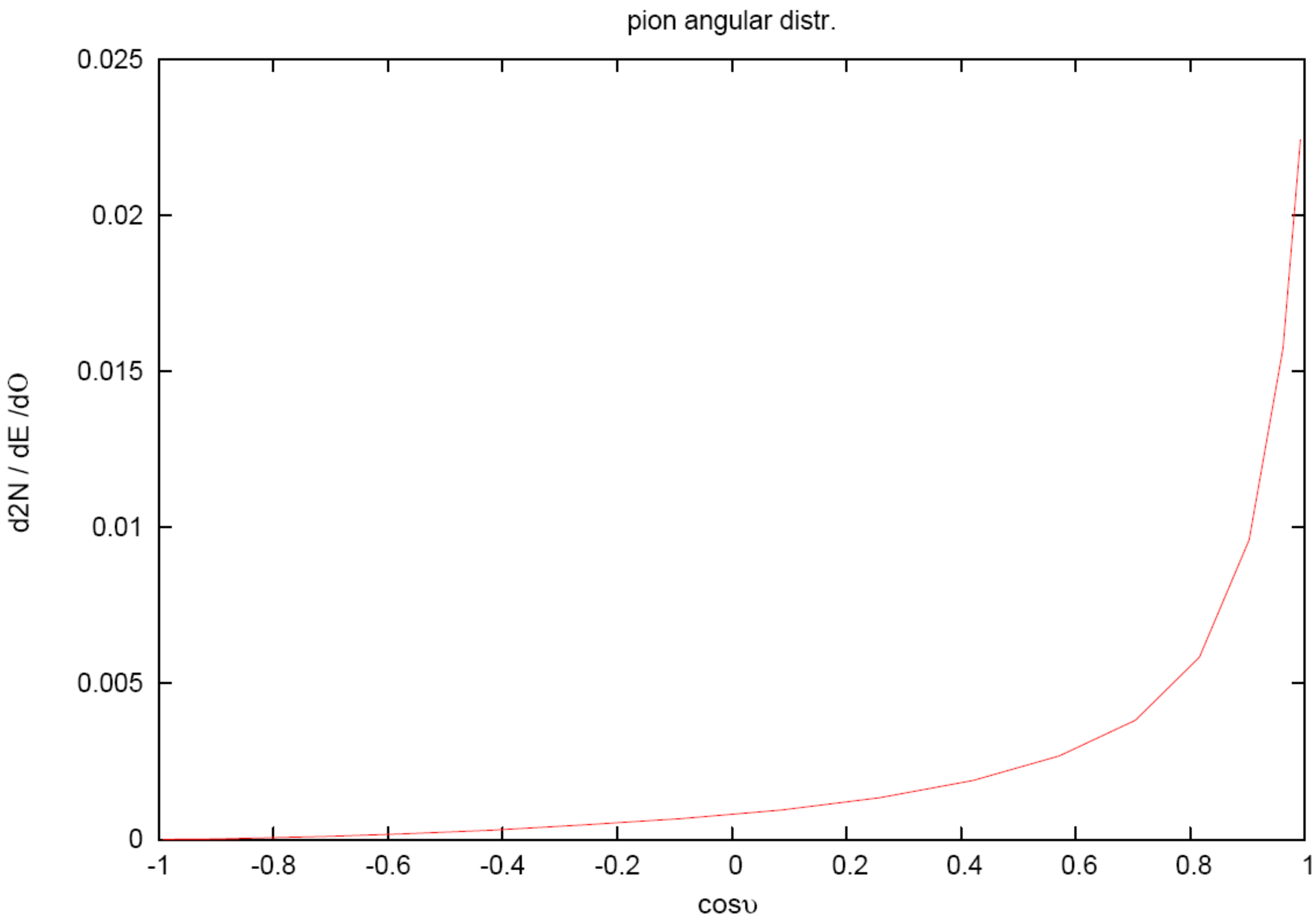
- Example of tab.lis for USRYIELD

```
# Detector n:  1  YieAng
# N. of x1 intervals 18

Thetamin     Thetamax          Result           Error  (%)
0.000000      0.1745329        2.0742605E-02   10.87912
0.1745329     0.3490658        1.4463779E-02   10.65940
0.3490658     0.5235988        9.8084798E-03   7.649231
0.5235988     0.6981317        5.8580171E-03   4.966214
0.6981317     0.8726646        3.8220894E-03   10.60832
0.8726646      1.047198        2.6973977E-03   5.450788
...
```

USRYIELD -> The Result

- pion angular distribution



Bins, units etc

- Results from USRBDX, USRYIELD, USRTRACK, USRCOLL are given as DIFFERENTIAL distributions of fluence in energy, in units of (cm-2) GeV^{-1} per primary. Thus,
- A) results are independent on the chosen binning
- B) to obtain INTEGRAL results (fluence in cm^{-2} PER ENERGY INTERVAL per primary) one must multiply the value of each energy bin by the width of the bin (even for logarithmic binning):

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

- When scoring Neutrons (see lecture), the E bin limits below 20 MeV are automatically set==transport groups limits

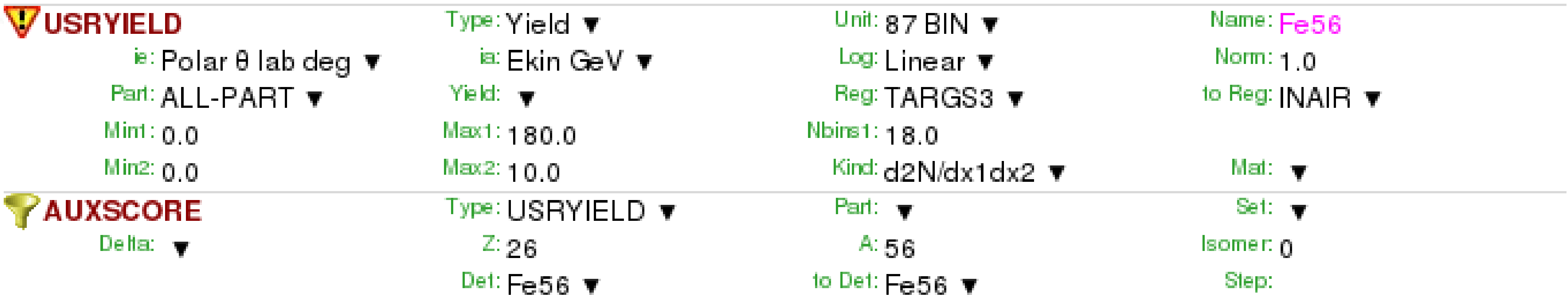
- The normalization is per cm^{-2} ONLY if the user provides the surface area or region volume. FLUKA is not able to calculate areas/volumes
- The same if USRBIN is used by region
- Instead, the normalization for USRBIN on grids is automatically in cm^{-2} (or cm^{-3} for deposited energy etc)

FILTERS : AUXSCORE

There is the possibility to filter the estimators, restricting the scoring to a selected subset of particles.

For instance: : score the yield of 56-Iron ions (very useful: there is no separate name for each ion specie, except light ones. HEAVYION score all isotopes heavier than alpha's together!)

```
*    +    1    +    2    +    3    +    4    +    5    +    6    +    7    +
USRYIELD       124.0  ALL-PART        -87.    TARGS3     INAIR      1.0Fe56
USRYIELD       180.0       0.0         18.      10.0       0.0      3.0&
AUXSCORE    USRYIELD  -5602600.                 Fe56      Fe56
```



The requested ion is coded in what(2) according to its **A**, **Z** and (optionally) isomeric state **m**:

what(2) = - (100***Z** + 100000***A** + **m***100000000)

Z,A,m=0 means all , e.g. -2600 == all Iron isotopes

Warning on AUXSCORE

- To be used with care, or NOT used at all for energy deposition scoring.
- Why? Because **In real world, energy is eventually deposited mostly by electrons only.**
- In Monte Carlo, part of the energy is deposited "by other particles" as continuous energy deposition or point energy deposition, depending on the delta-ray threshold, production threshold, transport threshold (see lecture on transport)
- Any filtering done with AUXSCORE on energy deposition will depend on the adopted thresholds and settings. (see lecture on transport)