Prompt radiation and shielding design

Radiation Protection Topical Course

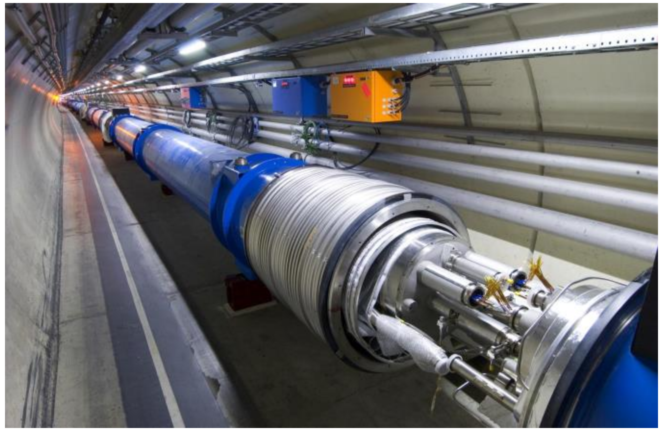
25-27 November 2024, CERN

Outline

- Introduction (**source term**)
  - Sources of high-energy radiation
  - Categories of prompt particles for shielding design
  - Hadrons (neutrons!) and muons
  - Shielding design considerations
- **Geometry/materials**
- **Typical scoring** options for shielding design
  - `USRBIN`
  - `USRTRACK`
  - `AUXSCORE`
- **Physics** settings and simulation **optimization**
  - `LOW-PWXS`
  - Physics settings and thresholds
  - Biasing (`LAM-BIAS`, `BIASING`, `usimbs.f`)
  - Two-step approach (`mgdraw.f`) ← *A bonus track here ;)*
- **Validation** of simulation results (some hints)

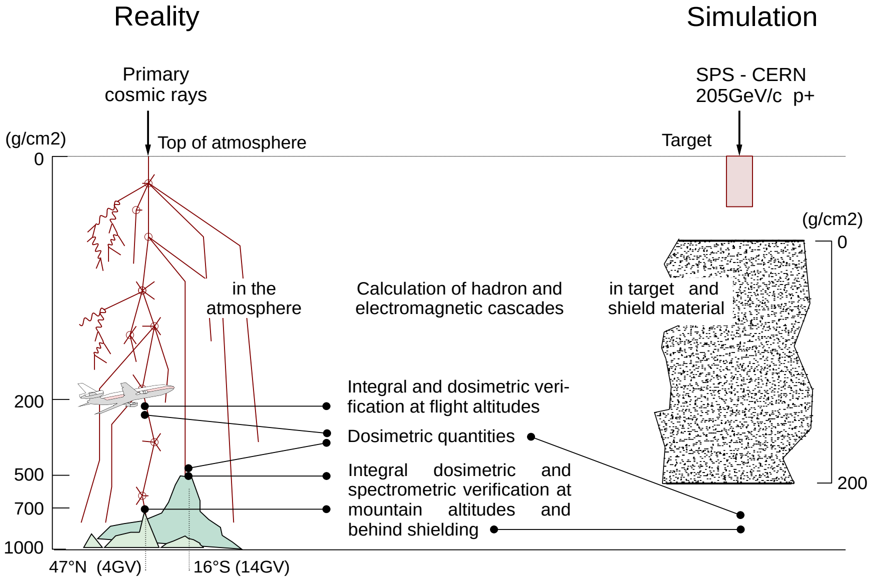
Introduction (source term)

Sources of high-energy radiation



- **Particle accelerators**
  - **Lepton/hadron** accelerators (linacs, synchrotron, cyclotrons…)
  - **Laser driven** accelerators (ELI Beamlines facility…)
- **Cosmic** radiation
  - Changes with altitude/latitude (atmosphere shielding effect, deviation by earth’s magnetic field)
  - Above atmosphere: hadrons and common nuclei
  - At **ground level**: **neutrons**, **muons**, **photons**
  - At **flight altitudes** particle spectrum **similar** to spectrum behind shield of ~200 g/cm^2 of any **high-energy accelerator**
- Concepts of this lecture also apply to
  - Nuclear **fission** reactors
  - Nuclear **fusion** reactors

Neutron energies up to ~14 MeV



[CERF facility](#) at CERN

Categories of prompt particles for shielding design

- Beam particle
  - **Primary beam**: protons, electrons,…
  - To be considered for **radiation safety** (access systems, beam stoppers, beam dumps, etc)
- Prompt radiation
  - **Particle cascade** generated by the primary beam: **neutrons**, **photons**, **pions**…
    - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

    Muons are more penetrating than the primary hadron beam!
    - This phenomenon can trigger **nuclear reactions** that result in **unstable radionuclides** (activation and residual radiation)

- **Radioactive sources** by Anna
- **Activation** by Davide
- **Residual radiation** exposure by Angelo

- Persons (**personnel** and **public**) can be exposed to prompt radiation
  - **Radiation protection assessement** required (based on dose (rate) objectives and limits)
    - Time, distance, source intensity → if those are fixed, then…
    - **Shielding design**!

Hadrons

[Attenuation length of high-energy neutrons through thick concrete shield at CHARM](#)
[Attenuation in iron of neutrons produced by 120 GeV/c hadrons](#)

- **Interaction** with atomic **electrons**
  - Continuous loss of E_k but in numerous **small amounts**
- **Strong interactions** (elastic and inelastic) with **target nuclei**
  - A single **nuclear interaction** transfers much more energy than an electromagnetic interaction (~E_k) although less frequent → the **high-energy particle** is "**removed**"
  - New **high-energy particles** are **created** (spallation reaction)
    - Also as lower energy cascade nucleons, evaporation neutrons, heavy nuclear fragments
  - **Probability** for an interaction by a **high-energy hadron** in a given material can be expressed as the interaction **mean free path** (**mfp**) or **nuclear interaction length** λ [g/cm^2 or cm]
    - mfp tends to appear longer due to secondary high-energy hadrons produced in the shield

***High-energy mfp** in various shielding materials*

Material	λ [g/cm²]	ρ [g/cm³]	mfp [cm]	TVL [cm]
Concrete	101	2.35	43	99
Iron	133	7.4	18	41
Soil	101	1.8	56	128

*These formulas apply to **high-energy** hadrons only*

mfp in g/cm^2

Atomic weight

$$\lambda = 40\ A^{0.3}$$

Dose rate

Source term

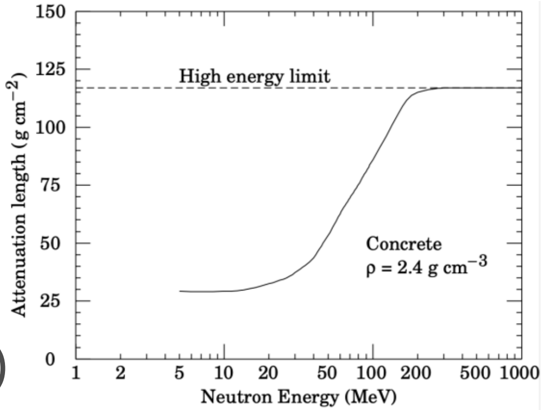
Shield thickness

mfp

Distance between beam-loss point and the estimation point

$$H = H_0\ \frac{1}{r^2}\ e^{-x/\lambda}$$

Something more about neutrons



- Why **neutrons** (which are by the way hadrons!)?
  - **High penetration** into shielding (neutral particles)
  - **Significant** even at very **low energies** (transport down to 10^{-5} eV in FLUKA)
    - For **thermal neutrons**, we speak of **diffusion length**, **L** [cm]
      - Average distance between the place where a neutron is born and the place where it is absorbed
      - In nuclear reactors: reflector thickness ~L
      - Examples: carbon: L ~48 cm, Pb: L~100-150 cm
      - For an infinite medium:

Neutron source rate [n/s]

exp. attenuation related to absportion and scattering

$$\Phi\ (r)\ \approx S_o\,\frac{e^{-kr}}{4\pi D r}$$

1/r dependence (!= 1/r^2 of the formula in the previous slide)

Diffusion length coefficient

  - **Dominate** the **H*(10)** at 90º behind a "thick" shielding at high-energy particle accelerators
    - Let's **not underestimate other particles (muons and photons)**, which, in certain cases, can be the top contributors for the shielding design
- **Attenuation** of **high-energy neutrons** depends on the **effective cross section** for **inelastic reactions** of the shield (probability to undergo a nuclear reaction)

Muons

Particle	Mean lifetime
$\pi^{\pm}$	2.6e-8 s
$k^{\pm}$	1.2e-8 s

Question time

What about the μ decay to remove muons?
- Mean lifetime: 2.2e-6 s ($t_{1/2}$ ~ 1.5e-6 s)
  - Relativistic $t_{1/2}$ ~1.5e-5 s
- Mass : 0.106 GeV/c^2
- Let's suppose $E_{\mu} = 1$ GeV, v_{μ} ~ c, d = 1 km
- How many muons decay?
  - Travel time = 1 km/c = 3e-6 s
  - Decayed = $e^{-\lambda/t}$ = 15%!

- **Production**
  - **Pion** (and kaon) **decay** (before they interact!)
    - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
    - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - Above several hundreds of GeV, other production process (hadron-hadron collisions)
  - In high-energy (electron) accelerators: direct pair-production from photons > 40 GeV
- **Muons rarely interact** with nuclei and **lose energy** by ionisation → issue for shielding!
  - Special attention when determining **shielding requirements** in the **forward direction**
  - **Muon attenuation** in shielding does **not follow** an **exponenational attenuation** law
  - **Ranging out** (profiting of EM energy losses) muons by "**massive**" iron beam dumps/**shielding** (to stop a 450 GeV muon ~1 km of soil required!)
    - High-energy muons lose 1 GeV when travelling through 1.8 m of concrete or 70 cm of iron
  - **Preventing production** of **muons**: early capture (before it decays) of the hadronic parents

Shielding design: considerations 1/2

- **Main aspects** to be considered
  - **Civil engineering**, nearby buildings and geographical features
  - Location, type and strength of primary and secondary radiation sources
  - Shielding purpose (public vs personnel) and **design criteria**
  - **Technical possibilities** and **constraints** (e.g. compatibility with clean rooms – concrete vs granite)
  - “Reasonable” **safety factor** → to include uncertainties/unknowns (will see some later…)

Area of concern	Considerations
Maximum energy	As energy increases new physical process may dominate shielding requirements (e.g. muons)
Intensity	Prompt radiation scale proportionally with source intensity (future upgrades to be taken into account)
Beam losses	Beam instrumentation, radiation monitors…
Layout and shielding	Shielding location, accessibility, skyshine, ducts, labyrinths
Cost!	Material choice, ALARA

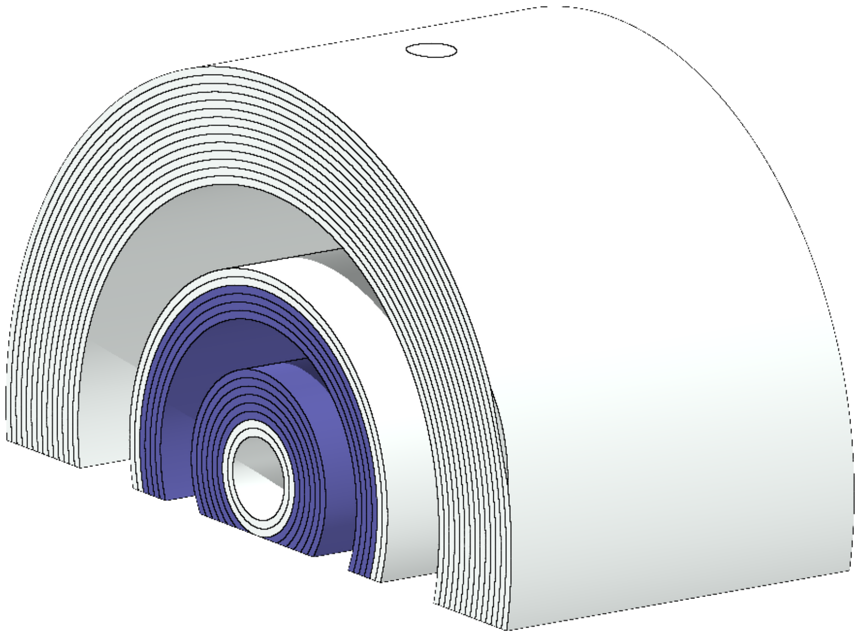
Shielding design: considerations 2/2

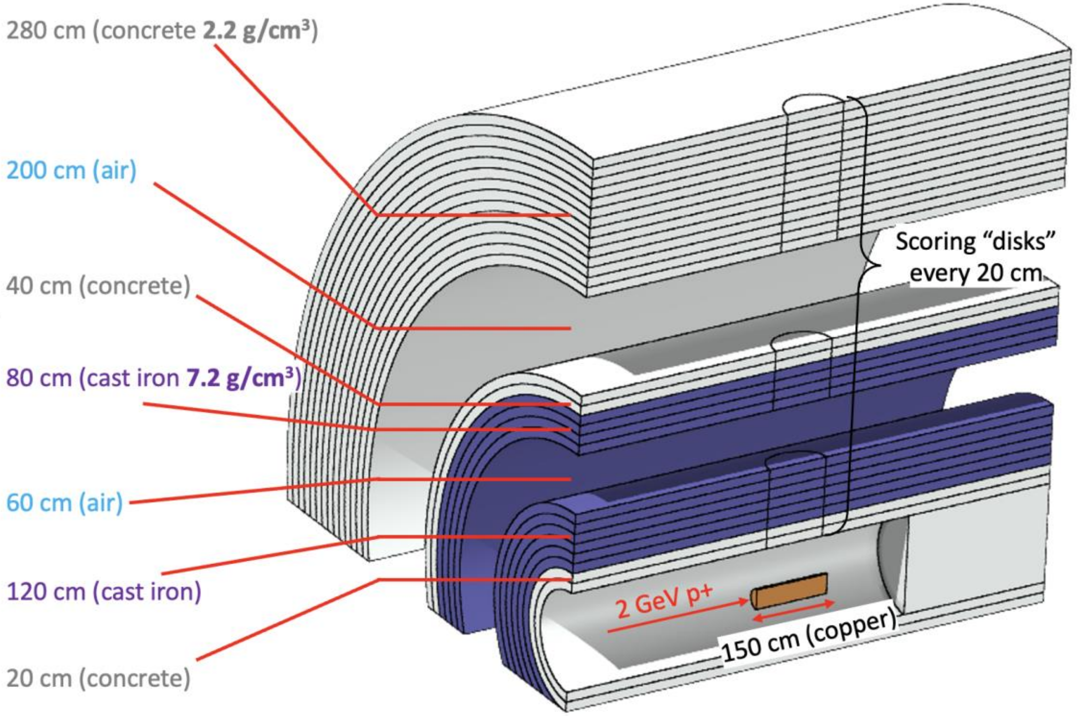
- **Radiation protection** units for **external exposure**
  - RP quantities (**ambient dose equivalent**, H*(10) or **effective dose**, E) are not physical quantities directly simulated
    - FLUKA estimates these quantities based on **particle fluence**
      - Fluence-to-dose conversion coefficients [pSv·cm2] are applied to translate radiation fields into generalized particles
  - **Which unit** to use for a **shielding design**?
    - **Dose limits** are (usually) expressed in terms of **effective dose**, E (**not measurable** in practice)
    - For **design** of **new facilities**, results could be expressed in terms of **effective dose** for direct comparison with limits
    - For **consolidation** of **existing facilities**, there could be an interest to perform calculations in terms of **ambient dose equivalent**, H*(10), to **compare** Monte Carlo simulations **with** available **experimental measurements**
    - In the future **ambient dose, H*,** may become the new reference quantity given its conservative nature (corresponding coefficients are already implemented in FLUKA!)

Geometry and materials

Geometry: how to start…

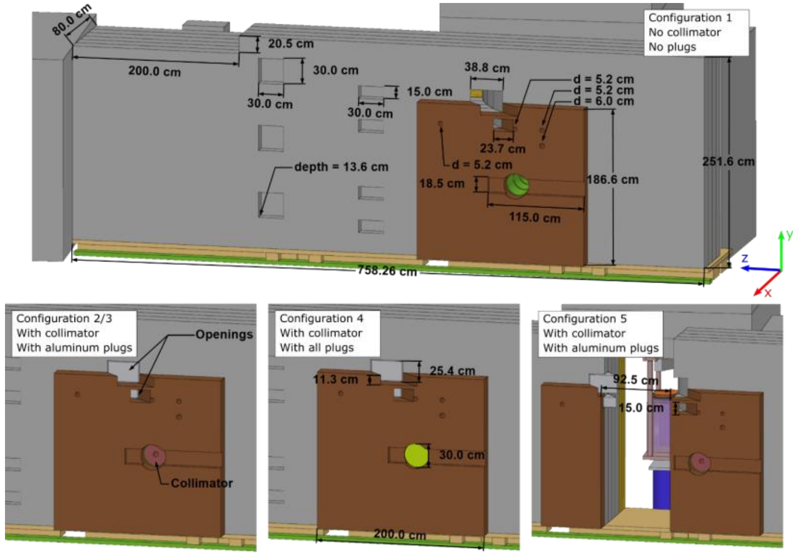
- For **preliminary shielding design**, the geometry does not need to be accurate
  - Use of "**toy models**" (fast to implement, easy to customize to test various solutions/shapes/materials)
    - To be combined with **analytical calculations**

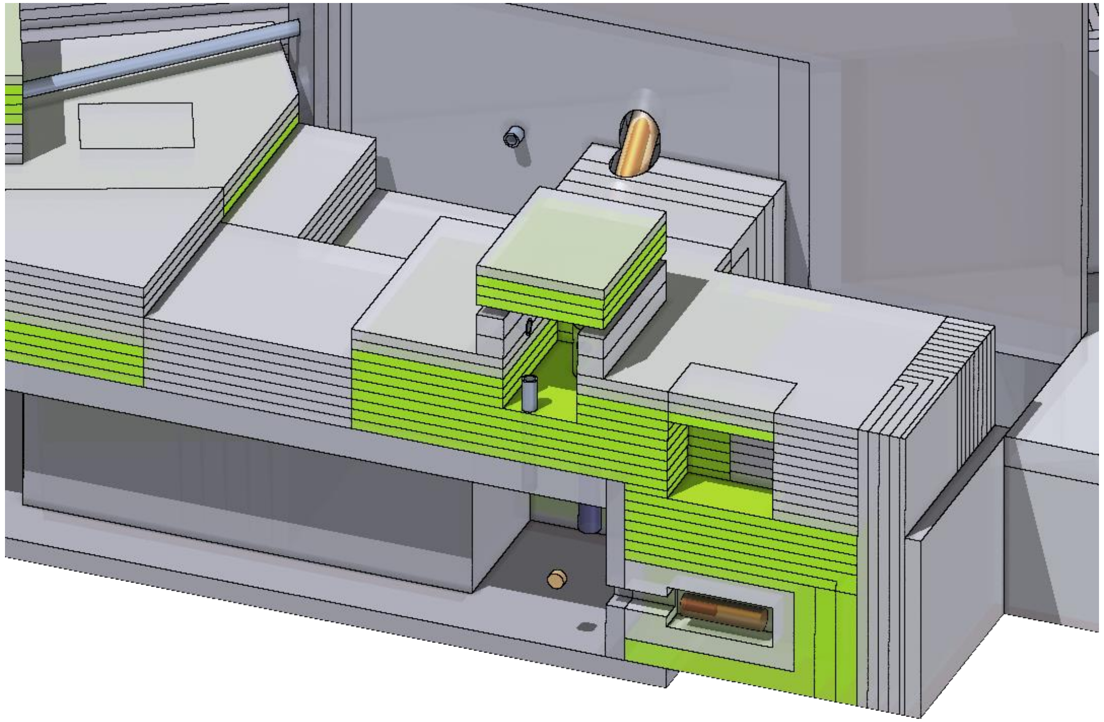




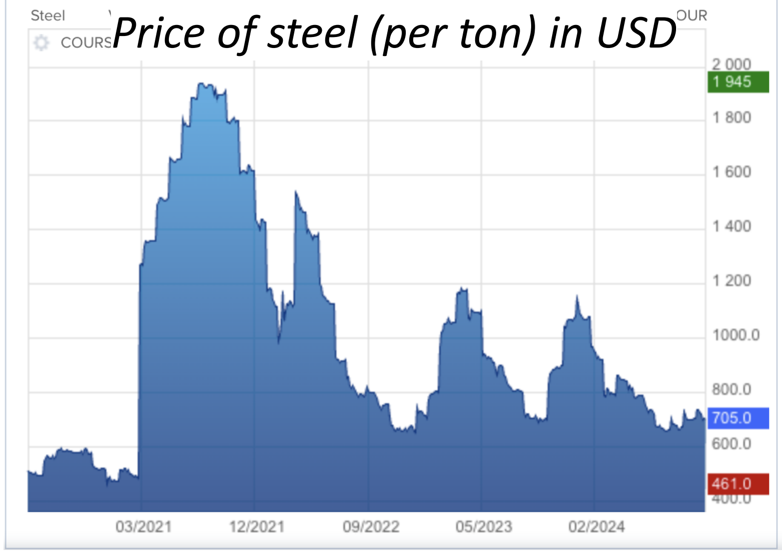
Geometry: …how to finish

- However, at a certain point in the study, a more **realistic model** needs to implemented and **tested**
    - Presence of **ducts/openings**
    - Shielding weaknesses
    - **Space limitations**
    - **Costs** (see later)!
- Close **collaboration** between **RP** and **civil engineering** (and transport team)
    - Feasibility/integration
    - Installation/removal (dismantling aspects)





Materials



Price of steel (per ton) in USD

- Aspects to be considered for **shielding materials**
  - Prompt radiation type (e.g. neutrons vs muons) and energy range (low vs high)
  - **Attenuation length**
  - **Cost** and availability
  - **Residual activation of the shielding material**
    - Soil: environmental impact (leaching effect)
    - Iron: future disposal, accessibility
    - Marble: lower residual activation if compared with concrete
  - Available **space** for installation

Material	Typical density g/cm^3
Concrete	2.2-2.4
Baryte	3.2-3.4
Iron (cast iron, steel, stainless steel)	7.2-7.9
Magnetite	3.9
Polyethylene	0.9-1.0
Water	1.0
Soil	1.8-2.2

Materials

- In **shielding design**, one has to pay attention to:
  - **Chemical composition** (often more relevant for residual activation) of the shielding material, e.g.
    - **Water content** in **concrete**/**soil**
    - **Realistic** vs **ideal concrete blocks** (e.g presence of iron frame)
      - Impact of few percent on attenuation of prompt radiation but may be non-negligible for residual calculations
  - Use of the most appropriate **cross section data set**
  - **Density**: a minor variation could lead to significant change in the H*(10)

Question time

The foreseen shielding thickness to ensure that an area at 90 degree w.r.t to the beam interaction point has been estimate to **400 cm** of concrete (nominal density considered 2.35 g/cm^3)

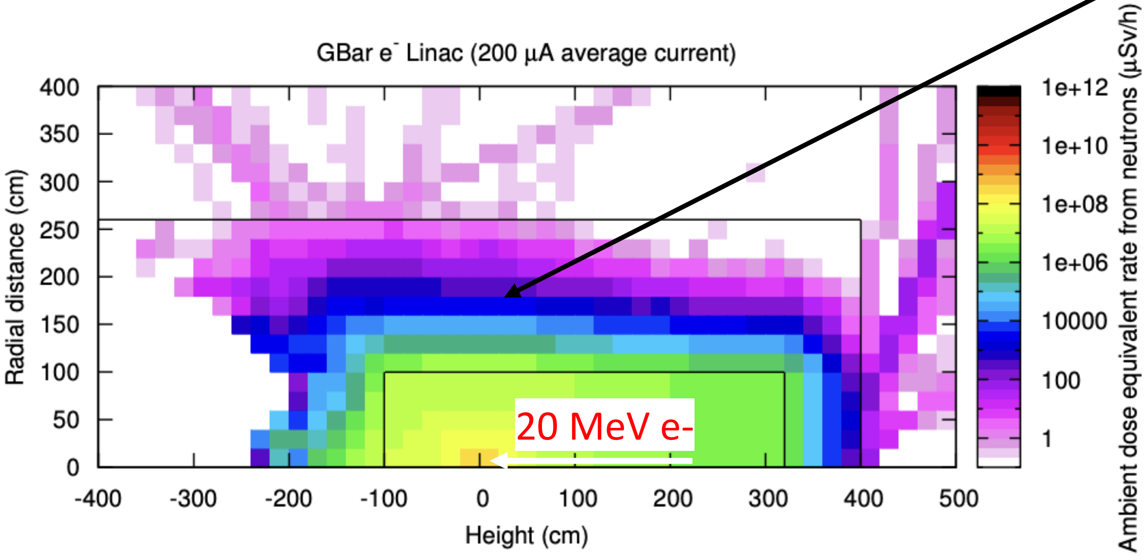
- How many attenuation lenghts?
  - λ_{conc} = 100 g/cm^2 $\rightarrow$ 42.6 cm
  - # λ = 9.3
- The civil engineering team tell us that the final density of the concrete has been measured to be 2.2 g/cm^3 (only 7% less), and ask us if we see any issue…
  - λ_{conc} = 45.5 cm
  - # λ = 8.8 → the dose rate will be a factor of 1.8 higher (exponential law)

Material choice: an example (1/2)

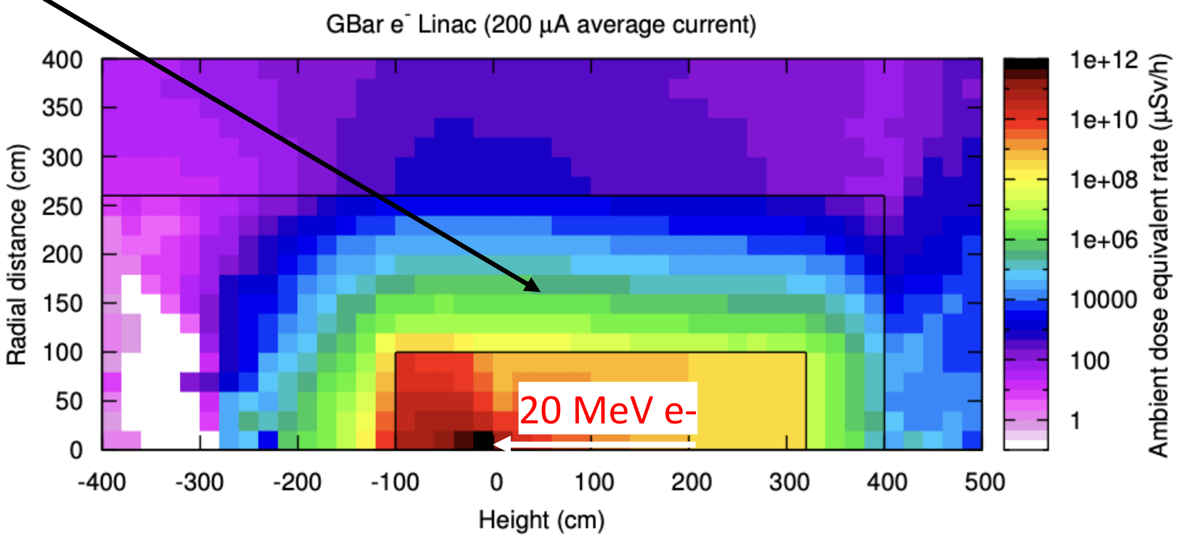
Gbar simplified model (more details during Claudia’s talk and visit)

- **20 MeV electron** onto a thin (2.5 mm) W-target
- Different **shielding configurations** studied

Lateral shielding of 160 cm concrete



H(10) due to **neutrons***

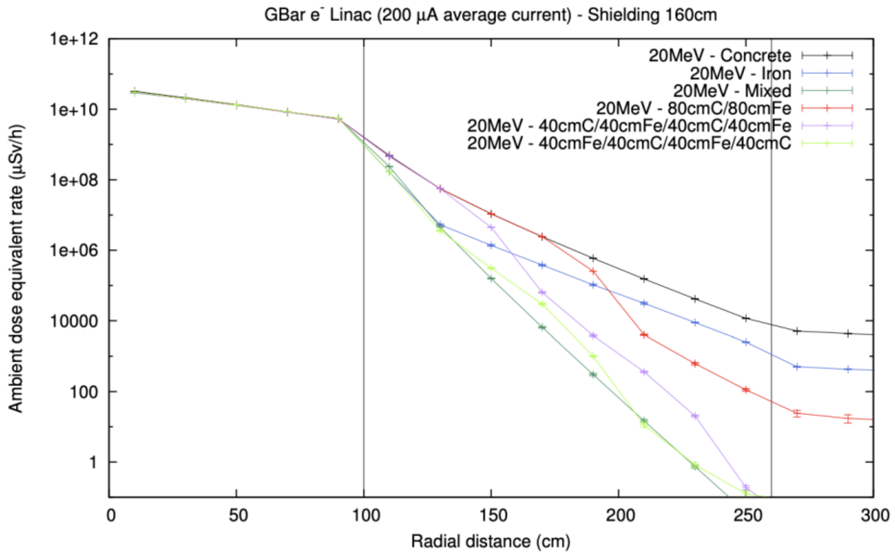


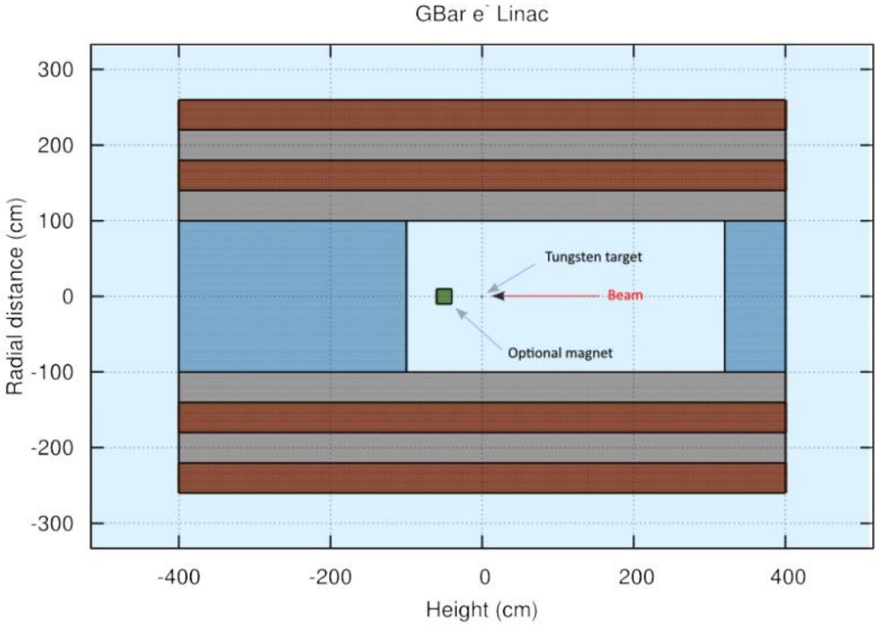
H(10) due to **photons***

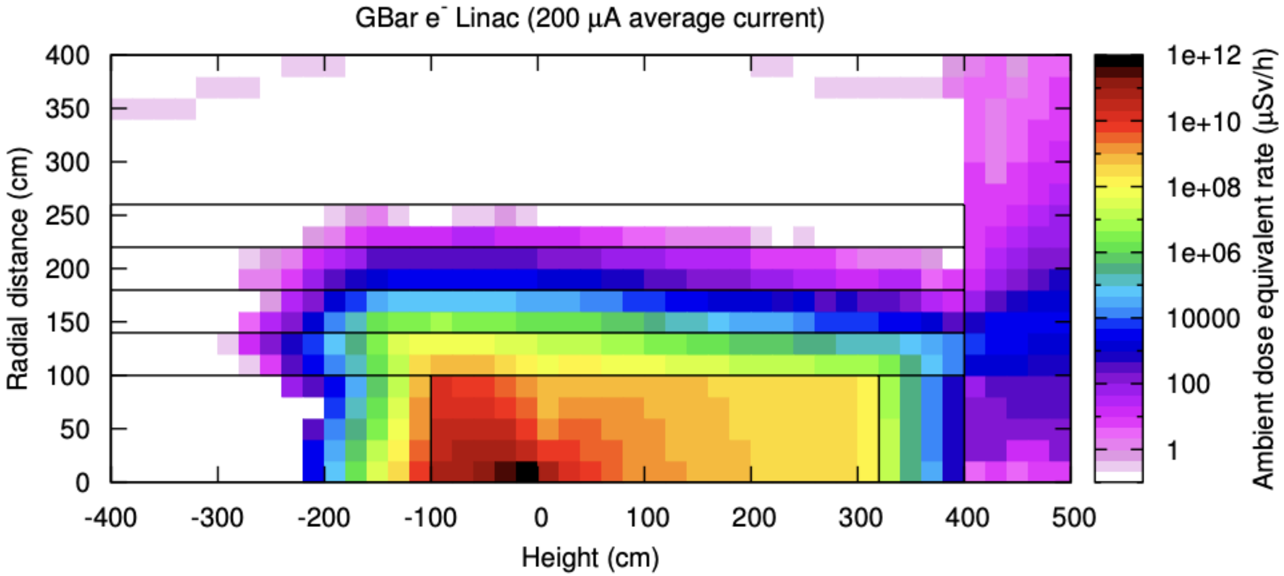
Material choice: an example (2/2)

Gbar simplified model (more details during Claudia’s talk and visit)

- Final configuration retained: a “**sandwhich** of **concrete** and **iron** layers”







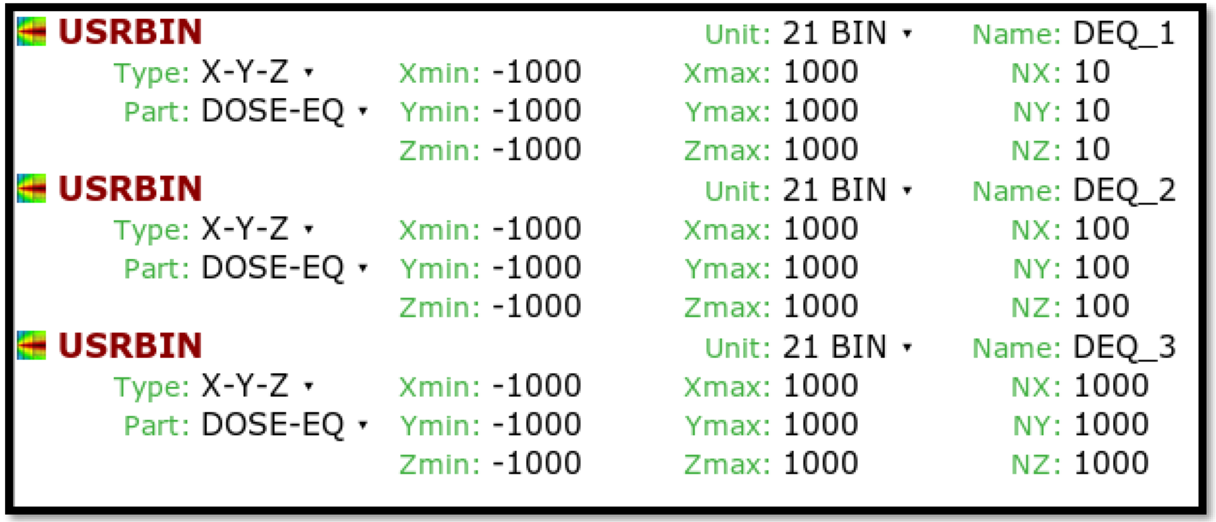
Typical scoring options for shielding design

USRBIN

- **USRBIN**: mesh-based (cartesian vs cylindrical)
  - Since volume of scoring bin in USRBIN mesh is known, **volume normalization** is **automatically applied**
  - **DOSE-EQ**: pSv / primary particle → normalization required (beam intensity) to get results easy to understand and communicate (e.g. in mSv/h or μSv/h)
- **USRBIN**: region-based
  - Volume of scoring region not known to the code
  - **Volume normalization** is **NOT applied → required if you want to have a meaningful dose (rate) → see Chris' lecture about Flair**

Question time

- Which **USRBIN** card (among the three proposed) do you find more meaningful for a shielding design and why?
- What do we do with results from **USRBIN**?



USRBIN Unit: 21 BIN Name: DEQ_1
Type: X-Y-Z Xmin: -1000 Xmax: 1000 NX: 10
Part: DOSE-EQ Ymin: -1000 Ymax: 1000 NY: 10
Zmin: -1000 Zmax: 1000 NZ: 10

USRBIN Unit: 21 BIN Name: DEQ_2
Type: X-Y-Z Xmin: -1000 Xmax: 1000 NX: 100
Part: DOSE-EQ Ymin: -1000 Ymax: 1000 NY: 100
Zmin: -1000 Zmax: 1000 NZ: 100

USRBIN Unit: 21 BIN Name: DEQ_3
Type: X-Y-Z Xmin: -1000 Xmax: 1000 NX: 1000
Part: DOSE-EQ Ymin: -1000 Ymax: 1000 NY: 1000
Zmin: -1000 Zmax: 1000 NZ: 1000

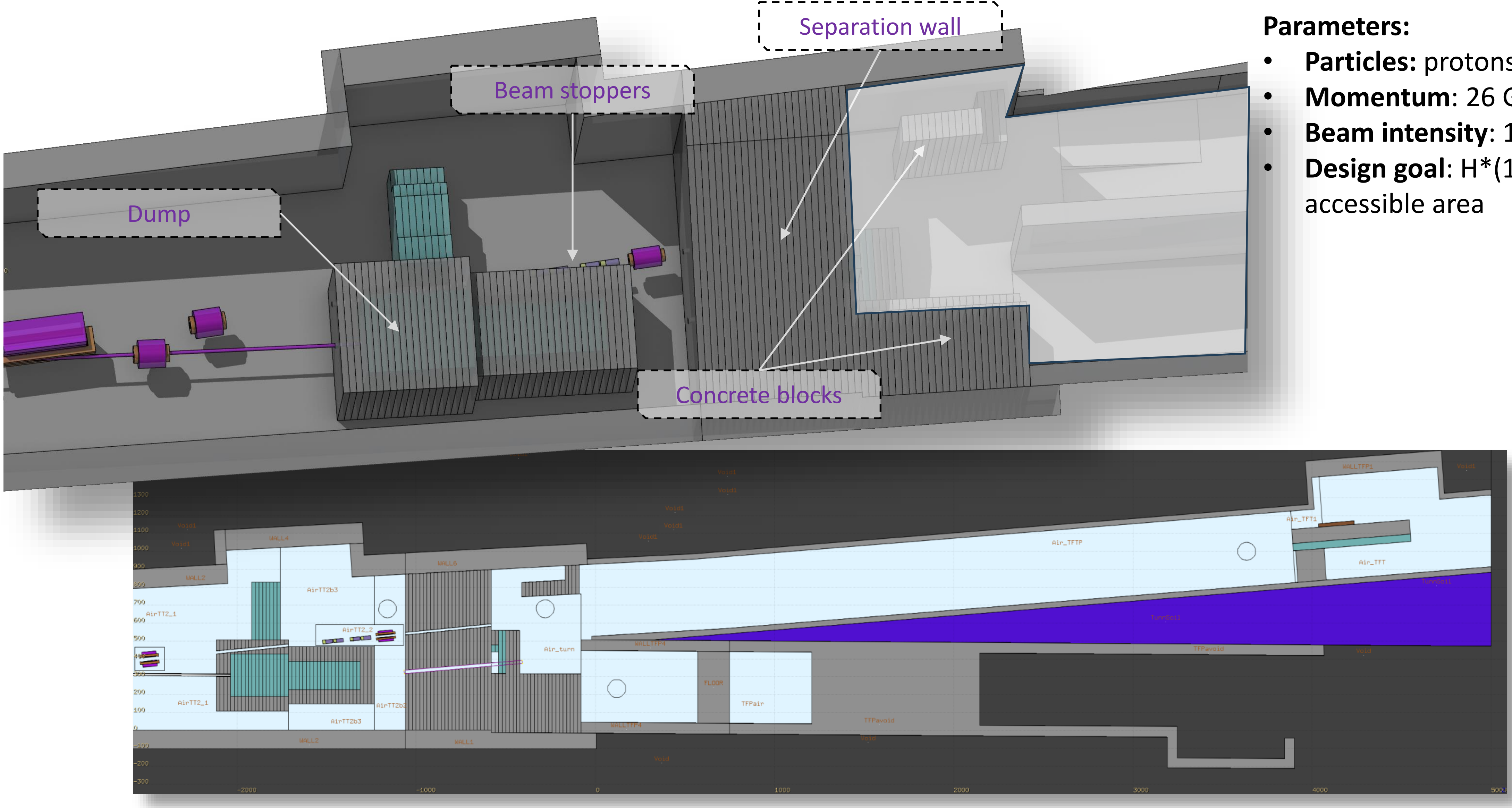
An example 1/2

Goal of the shielding design:

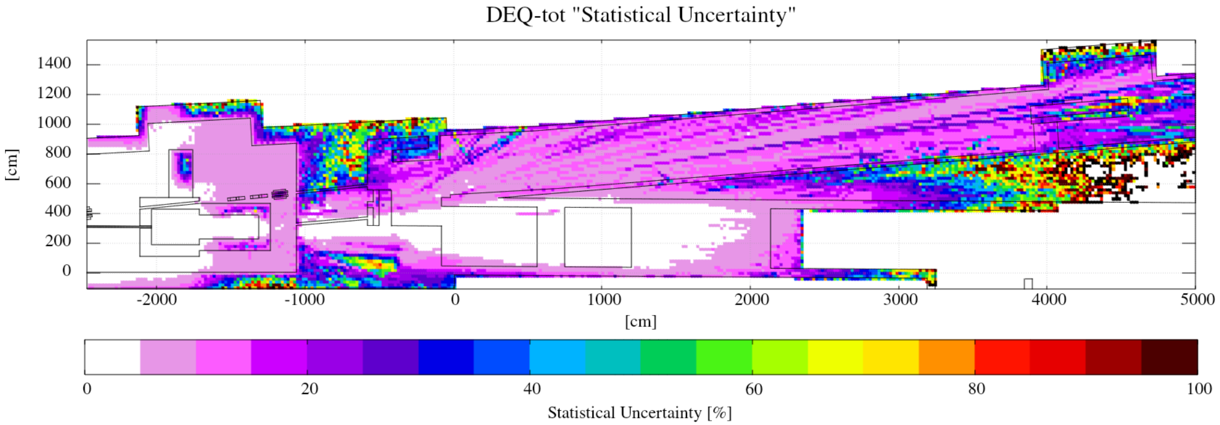
- Can access be granted to the white area when beam is sent to the dump

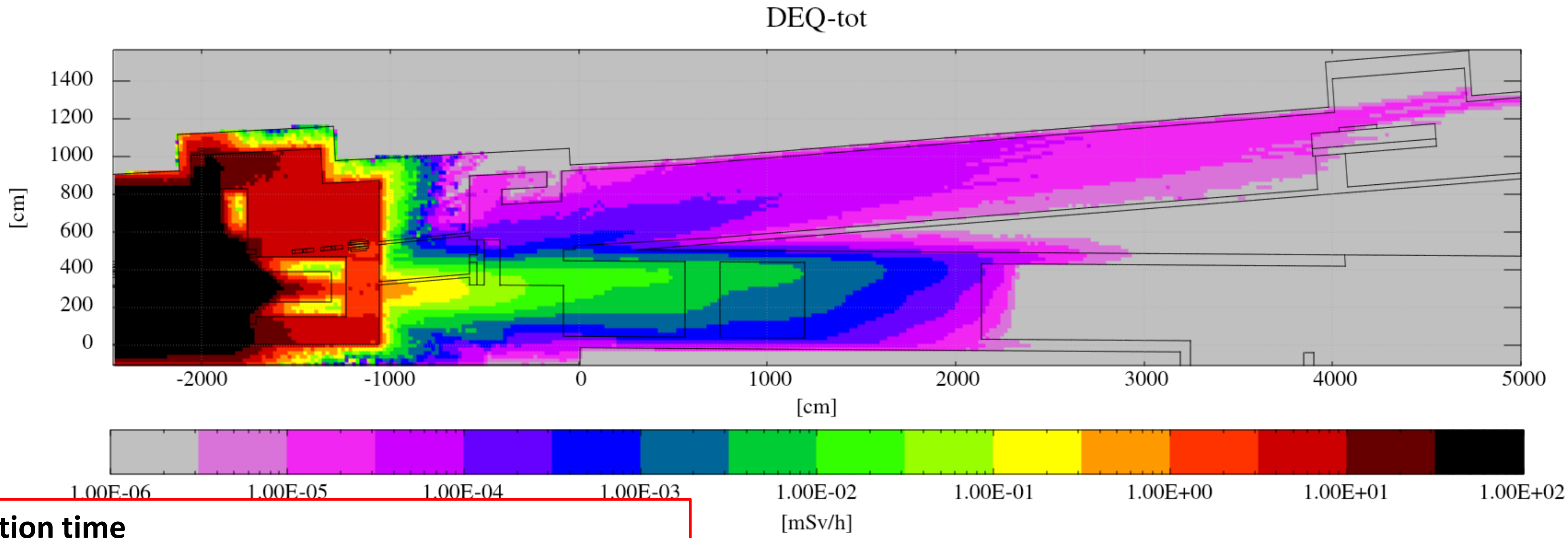
Parameters:

- **Particles:** protons
- **Momentum**: 26 GeV/c
- **Beam intensity**: 1e12 p/s
- **Design goal**: H*(10) < 10 μSv/h in accessible area



USRBIN results

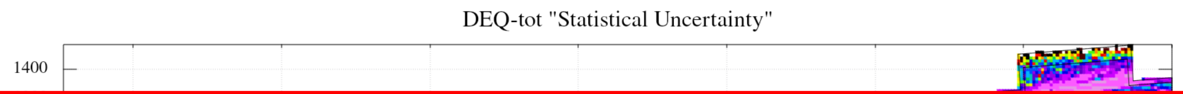


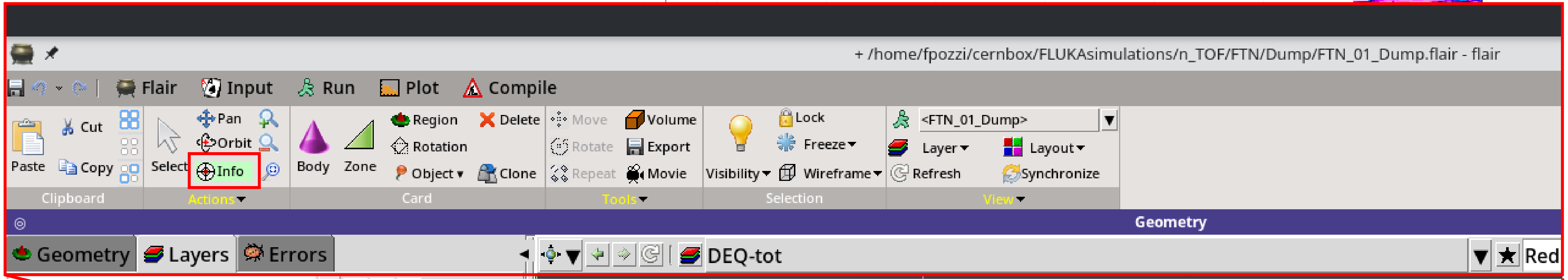


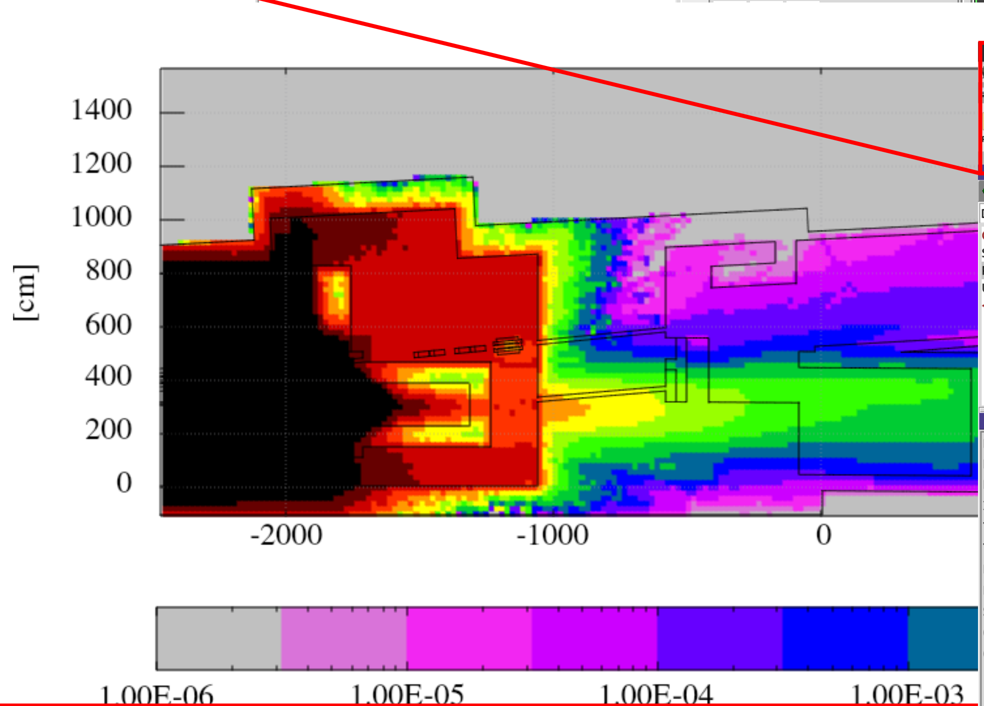
Question time

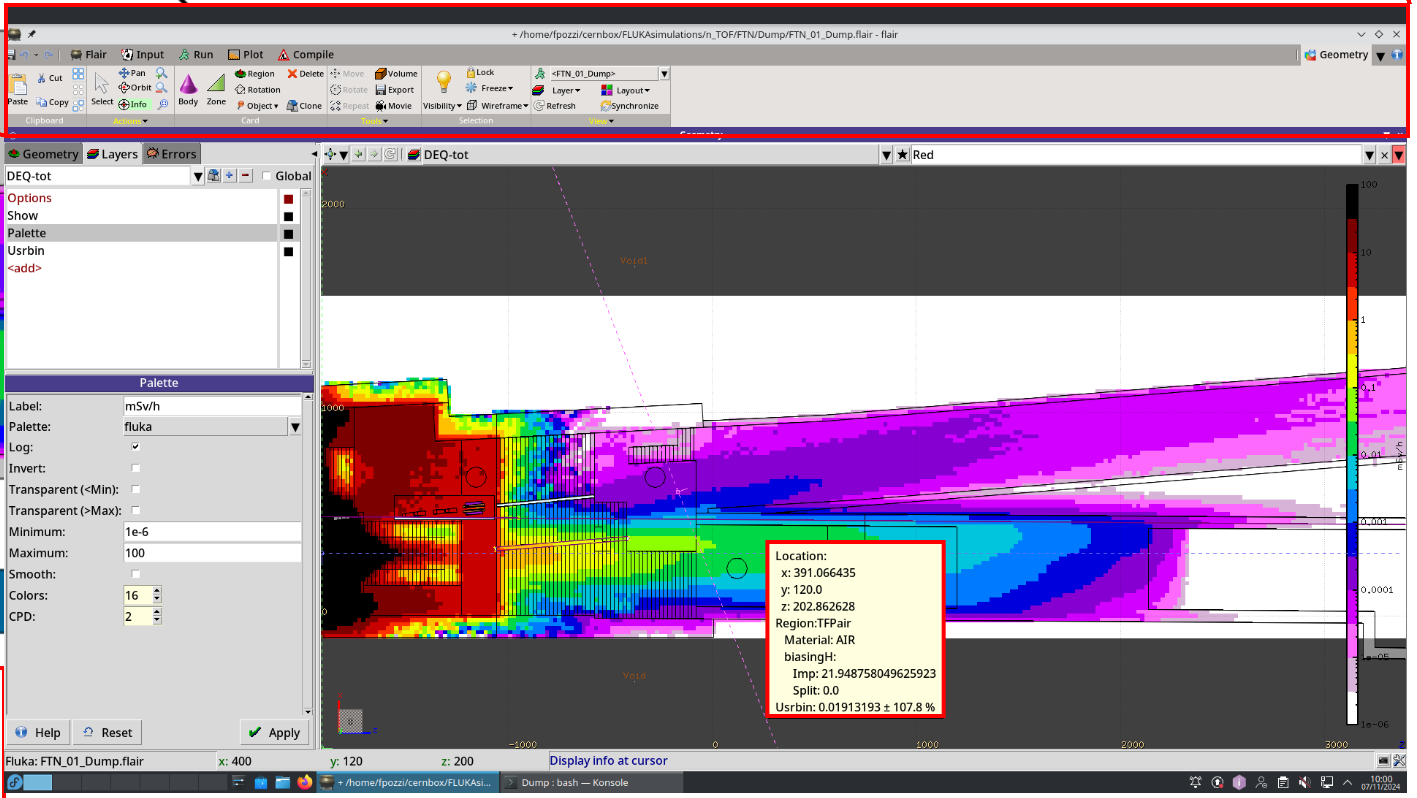
How would you obtain the H*(10) at a given location?

USRBIN results









Label: mSv/h
Palette: fluka
Log: ☑
Invert: ☐
Transparent (<Min): ☐
Transparent (>Max): ☐
Minimum: 1e-6
Maximum: 100
Smooth: ☐
Colors: 16
CPD: 2

```
Location:
  x: 391.066435
  y: 120.0
  z: 202.862628
Region:TFPair
  Material: AIR
  biasingH:
    Imp: 21.948758049625923
    Split: 0.0
Usrbin: 0.01913193 ± 107.8 %
```

Fluka: FTN_01_Dump.flair x: 400 y: 120 z: 200

Question time

How would you obtain the H*(10) at a given location?

USRTRACK

In the next slides we will focus on **DOSE-EQ**, however later in the lecture we will go back to the usefulness of the differential fluence

- **USRTRACK**: region-based
  - To score **DOSE-EQ**
  - To score differential fluence **dΦ/dE** of a given type or family of particles (we come back to this later)

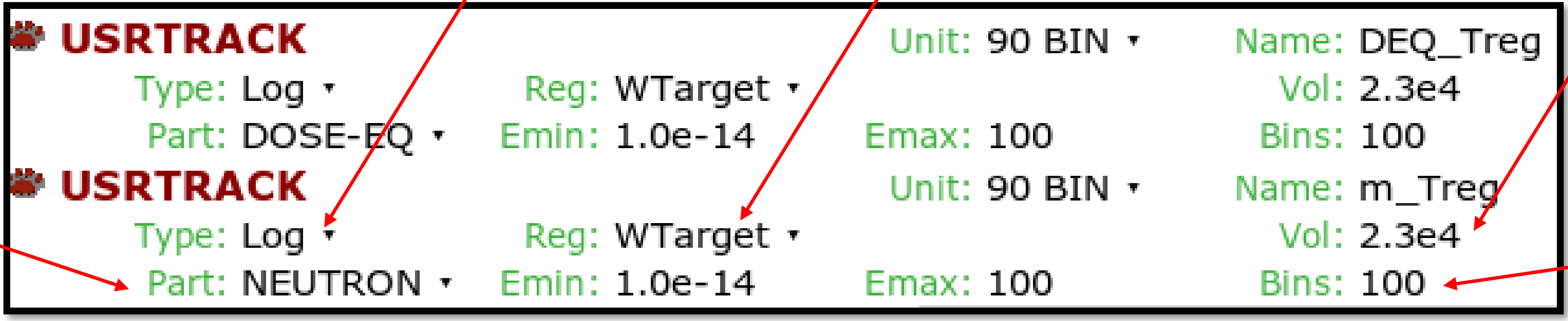
Log binning in energy

Region choice

Volume normalization!

Particle type

100 bins in energy



USRTRACK Unit: 90 BIN ▾ Name: DEQ_Treg
Type: Log ▾ Reg: WTarget ▾ Vol: 2.3e4
Part: DOSE-EQ ▾ Emin: 1.0e-14 Emax: 100 Bins: 100

USRTRACK Unit: 90 BIN ▾ Name: m_Treg
Type: Log ▾ Reg: WTarget ▾ Vol: 2.3e4
Part: NEUTRON ▾ Emin: 1.0e-14 Emax: 100 Bins: 100

- 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

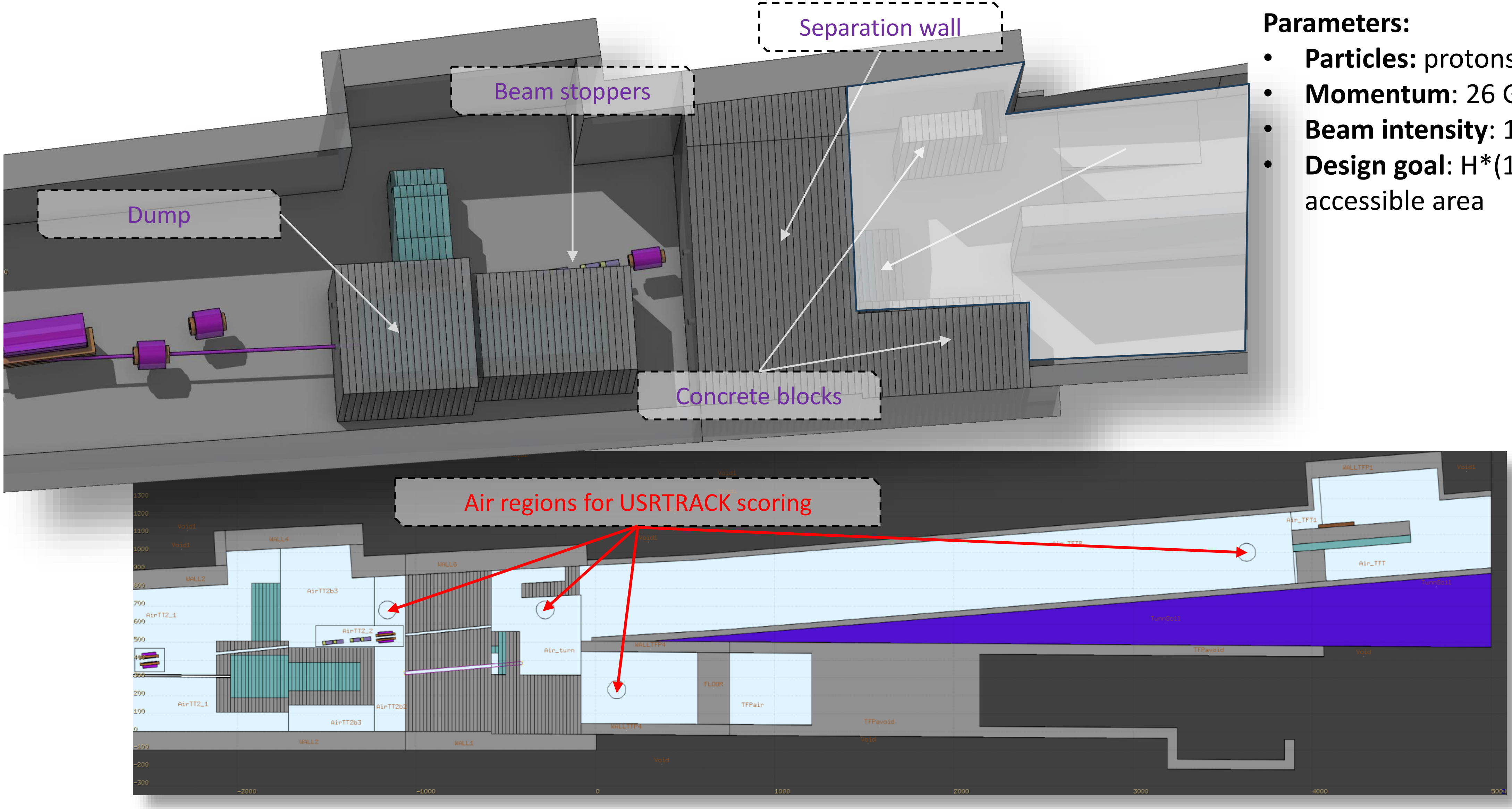
An example 2/2

Goal of the shielding design:

- Can access be granted to the white area when beam is sent to the dump

Parameters:

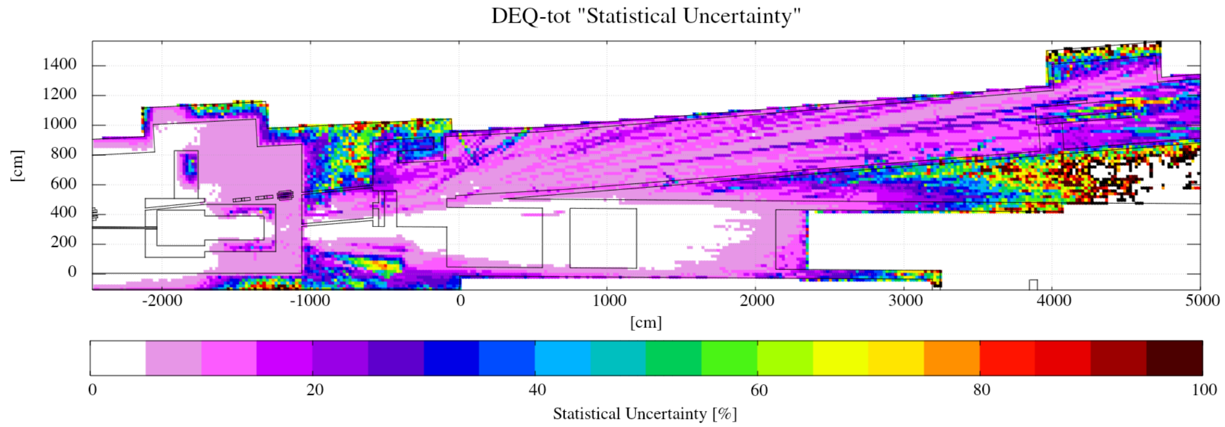
- **Particles:** protons
- **Momentum**: 26 GeV/c
- **Beam intensity**: 1e12 p/s
- **Design goal**: H*(10) < 10 µSv/h in accessible area

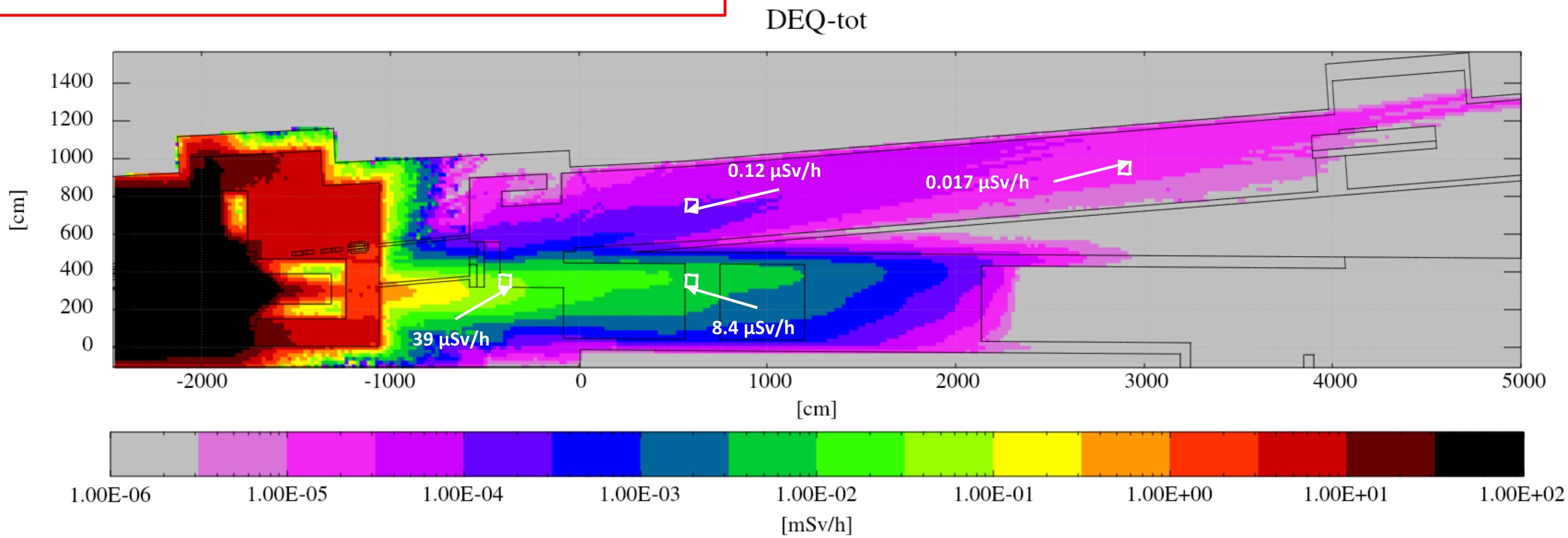


USRBIN + USRTRACK

Question time

- How do we optimize the shielding to reach the design goal?
- What information do we need or can be useful?





AUXSCORE

- allows to **associate** scoring estimators with **dose equivalent conversion factors**
- allows to apply a **filter** within the scoring estimator for a specific generalized particle type

AUXSCORE Type: USRBIN ▾ Part: NEUTRON ▾ Set: AMB74 ▾
Delta Ray: ▾ Det: n_DEQ ▾ to Det: ▾ Step:

Type	**Type of estimator to associate with** drop down list of estimator types (`USRBIN`, `USRTRACK`…)
Part	**Particle or isotope to filter for scoring** Particle or particle family list
Det .. to Det	**Detector range** Drop down list to select detector range of type **Type**
Step	**Step in assigning indices of detector range**
Set	**Conversion factor set for dose equivalent (DOSE-EQ) scoring** Drop down list of available dose conversion sets

Since shielding material/thickness depends (also) on the particle type, the use of this card is very helpful

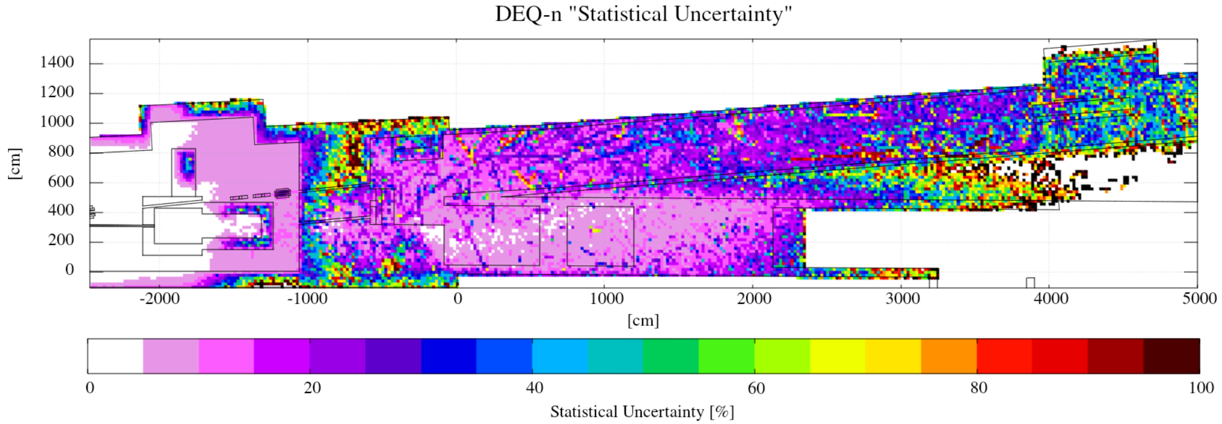
Note: This card can be used for prompt and residual scorings.

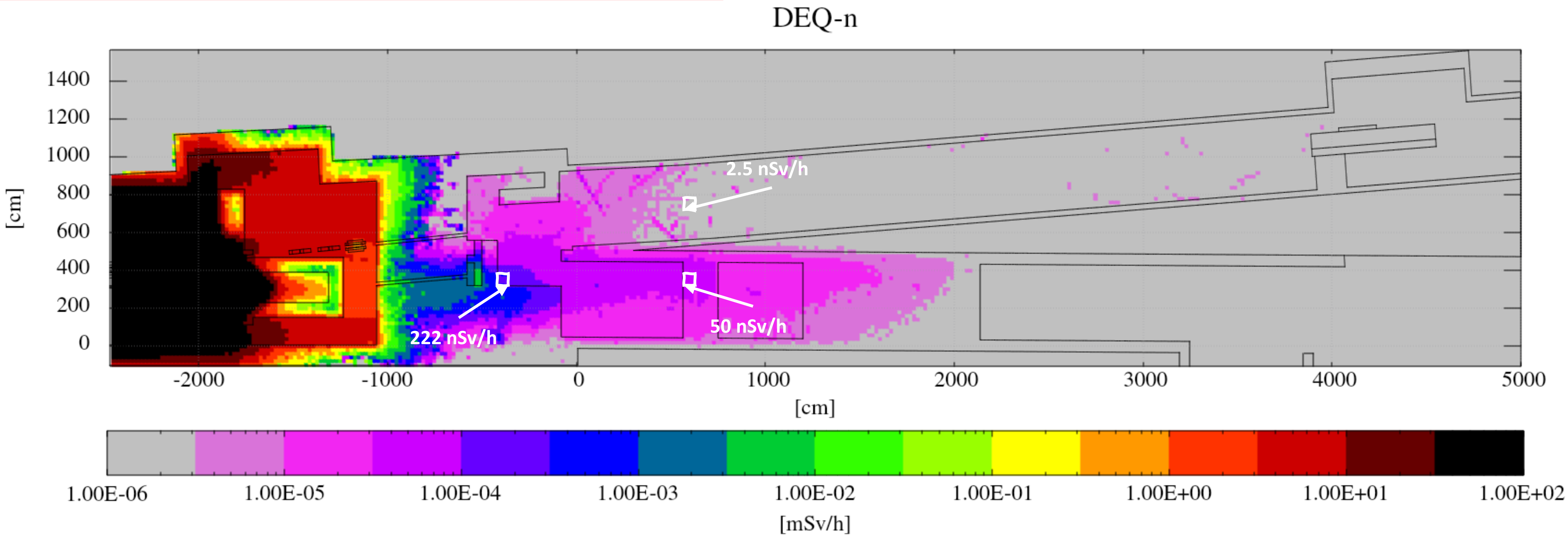
USRBIN + AUXSCORE

- Neutrons

Question time

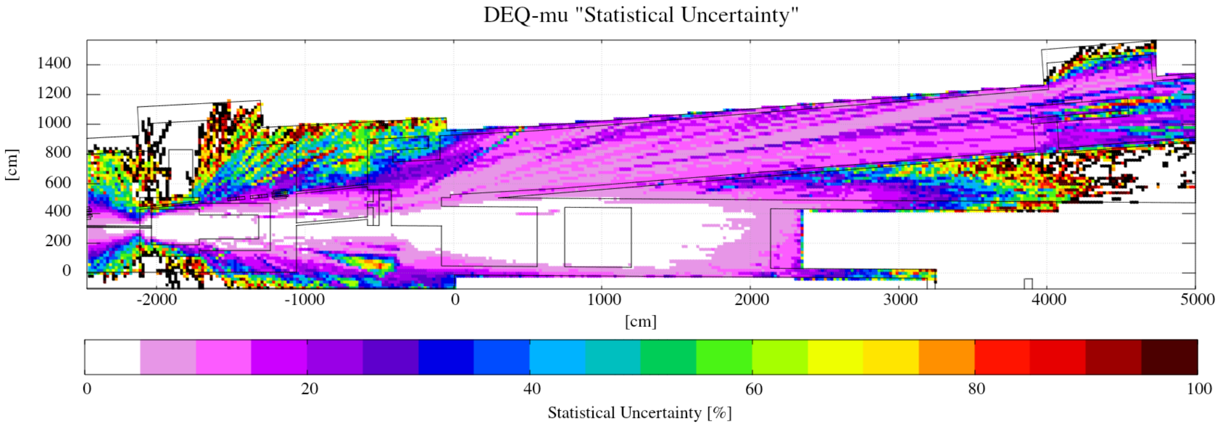
- Surprisingly (or not), the H*(10) is not dominated by neutrons. Which particle then?

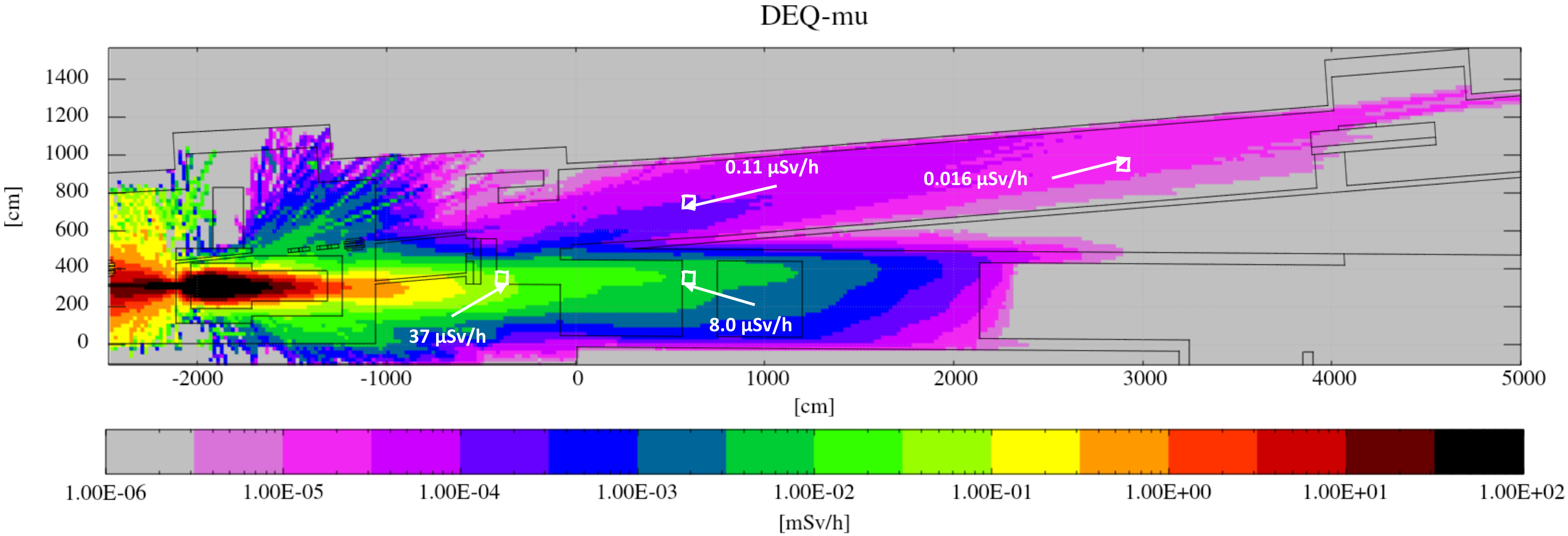




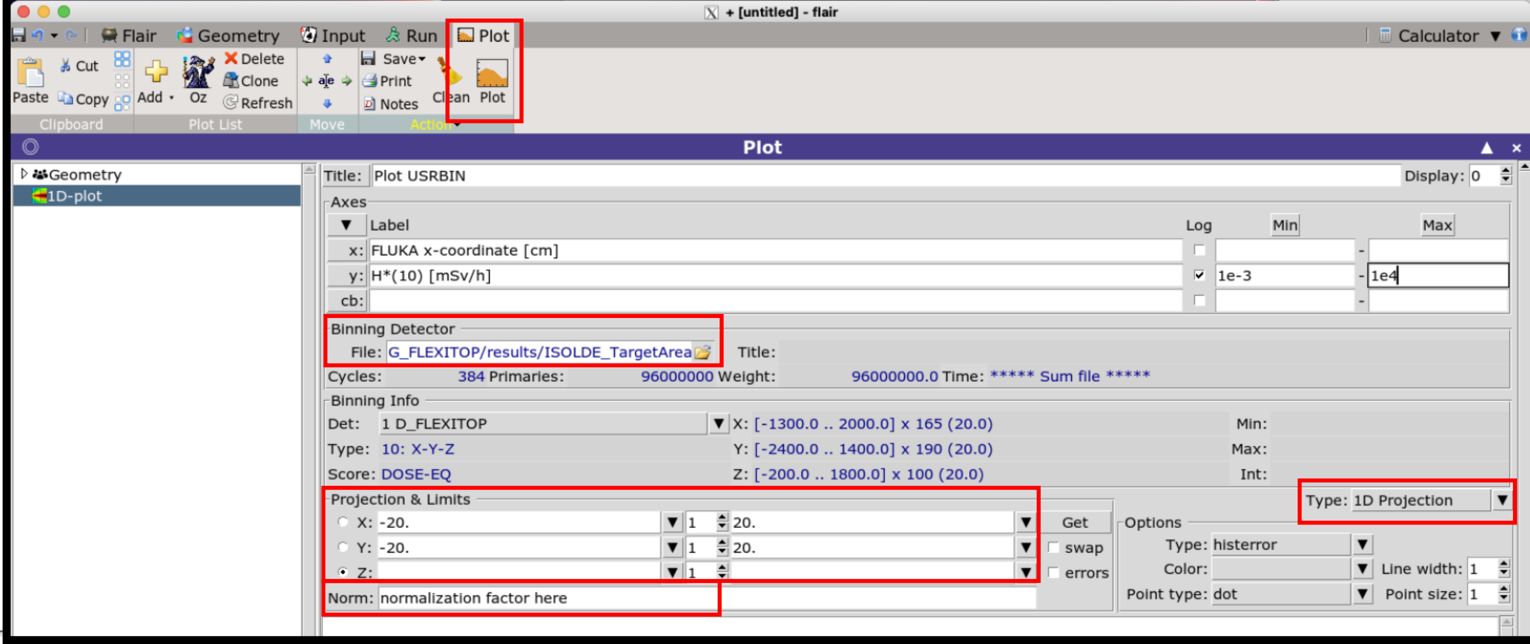
USRBIN + AUXSCORE

- Muons!





USRBIN: 1D-map



Title: Plot USRBIN Display: 0

Axes

Label	Log	Min	Max
x: FLUKA x-coordinate [cm]	☐		
y: H*(10) [mSv/h]	☑	1e-3	1e4
cb:	☐		

Binning Detector

File: G_FLEXITOP/results/ISOLDE_TargetArea Title:

Cycles: 384 Primaries: 96000000 Weight: 96000000.0 Time: ***** Sum file *****

Binning Info

Det: 1 D_FLEXITOP X: [-1300.0 .. 2000.0] x 165 (20.0) Min:

Type: 10: X-Y-Z Y: [-2400.0 .. 1400.0] x 190 (20.0) Max:

Score: DOSE-EQ Z: [-200.0 .. 1800.0] x 100 (20.0) Int:

Type: 1D Projection

Projection & Limits

○ X: -20. 1 20.

○ Y: -20. 1 20.

● Z: 1

Get

☐ swap

☐ errors

Norm: normalization factor here

Options

Type: histerror

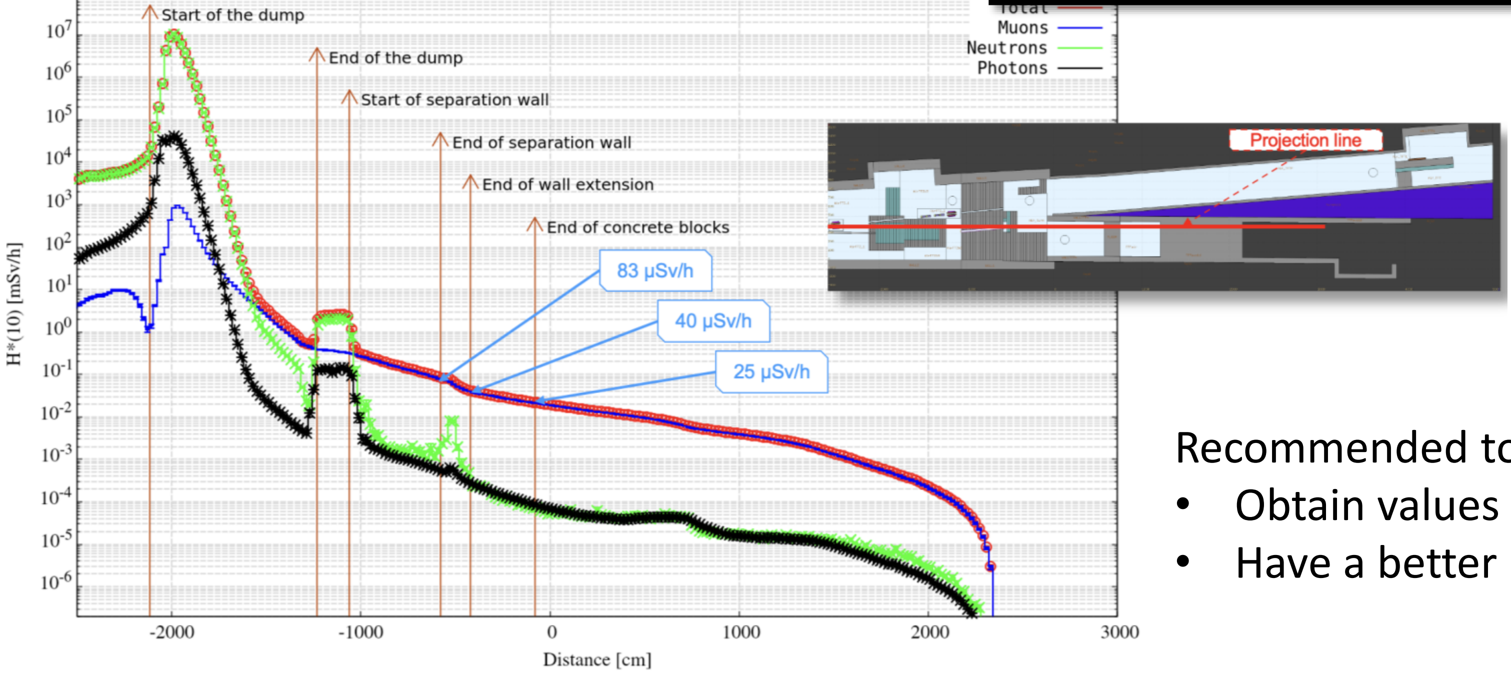
Color:

Point type: dot

Line width: 1

Point size: 1

H*(10) - x = [330;370] cm, y = [100;140] cm



Recommended to explore 1D map to:

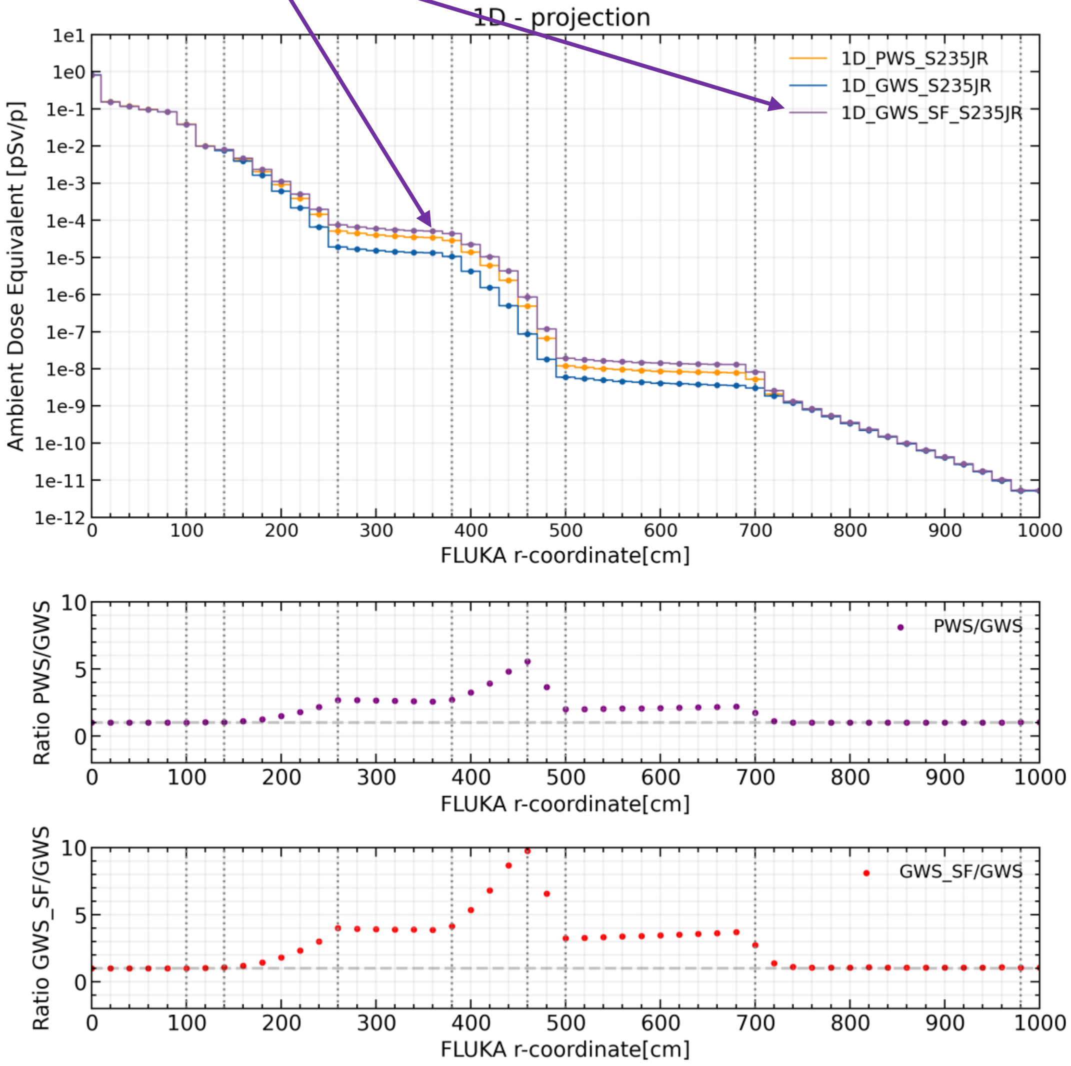
- Obtain values at given distances
- Have a better understanding of the attenuation process

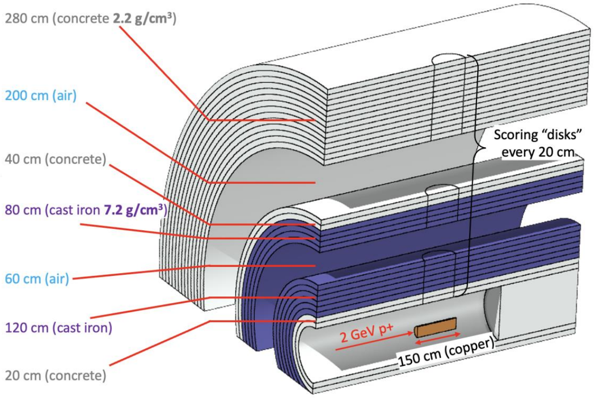
Physics settings and simulation optimization

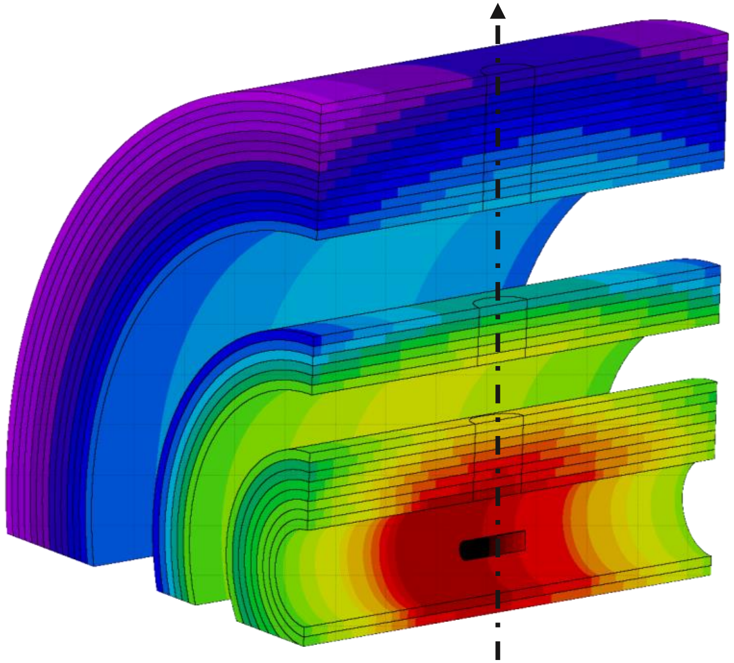
Low-energy neutrons in FLUKA


LOW-MAT Mat: IRON ▾ LowMat: Fe. Natural Iron SelfShielded, 296K ▾

- Low-energy neutrons (< 20 MeV) treatment in FLUKA
  - **`LOW-PWXS`** (point-wise): recommended!
    (properly **take all physical effects into account**)
  - **Group-wise** (energy scale divided in 260 fixed bins):
    coarse but fast
    - Group-wise cross sections available for a series of materials: **`LOW-MAT`** card

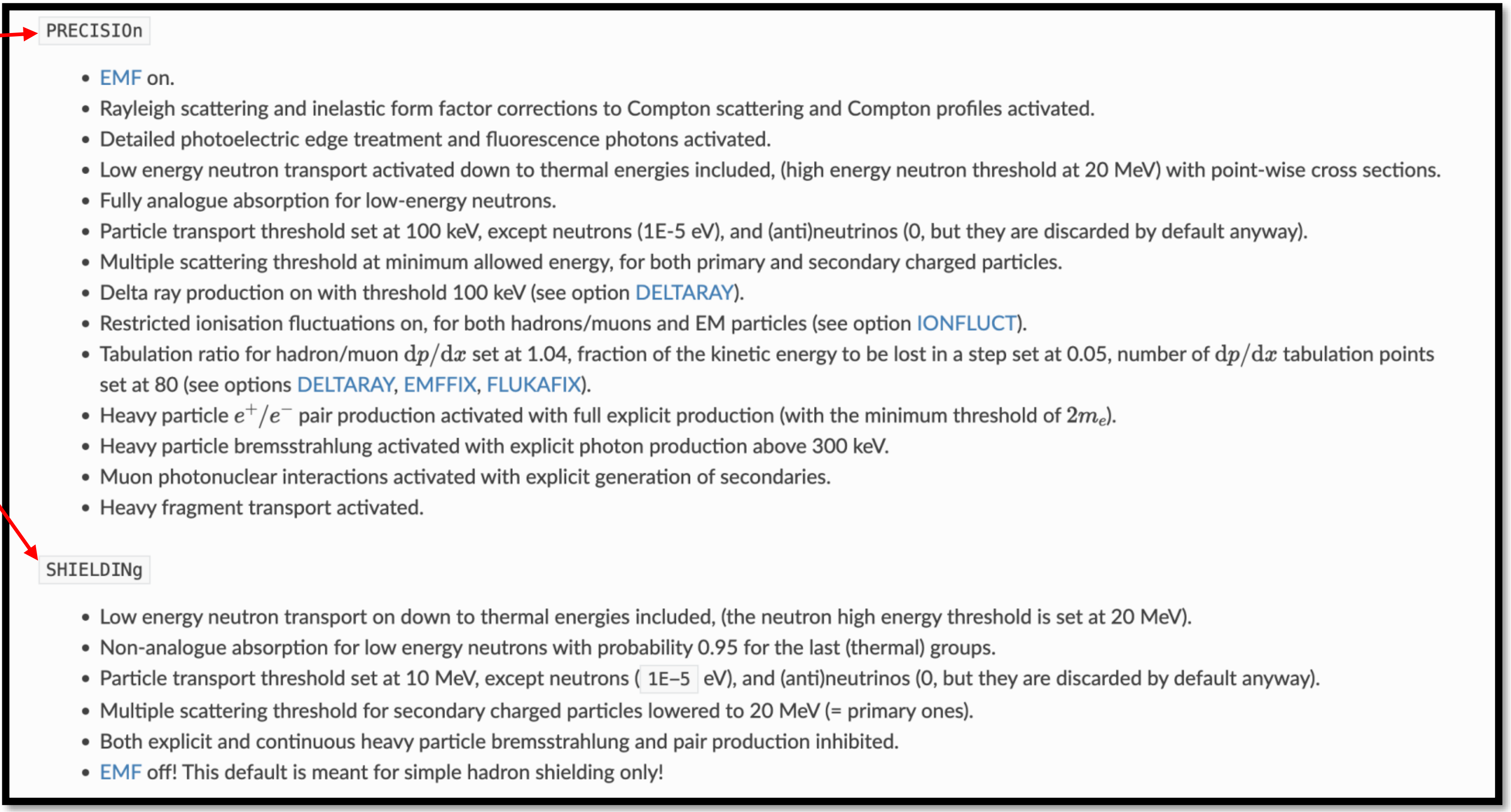






Physics settings

- **`DEFAULTs`**
  - Check **FLUKA manual** to be sure that the **default thresholds** and **physics settings** are **appropriate** for your problem
    - **`PRECISIOn`**
    - **`SHIELDINg`**



`PRECISIOn`

- EMF on.
- Rayleigh scattering and inelastic form factor corrections to Compton scattering and Compton profiles activated.
- Detailed photoelectric edge treatment and fluorescence photons activated.
- Low energy neutron transport activated down to thermal energies included, (high energy neutron threshold at 20 MeV) with point-wise cross sections.
- Fully analogue absorption for low-energy neutrons.
- Particle transport threshold set at 100 keV, except neutrons (1E-5 eV), and (anti)neutrinos (0, but they are discarded by default anyway).
- Multiple scattering threshold at minimum allowed energy, for both primary and secondary charged particles.
- Delta ray production on with threshold 100 keV (see option DELTARAY).
- Restricted ionisation fluctuations on, for both hadrons/muons and EM particles (see option IONFLUCT).
- Tabulation ratio for hadron/muon $\mathrm{d}p/\mathrm{d}x$ set at 1.04, fraction of the kinetic energy to be lost in a step set at 0.05, number of $\mathrm{d}p/\mathrm{d}x$ tabulation points set at 80 (see options DELTARAY, EMFFIX, FLUKAFIX).
- Heavy particle e^+/e^- pair production activated with full explicit production (with the minimum threshold of $2m_e$).
- Heavy particle bremsstrahlung activated with explicit photon production above 300 keV.
- Muon photonuclear interactions activated with explicit generation of secondaries.
- Heavy fragment transport activated.

`SHIELDINg`

- Low energy neutron transport on down to thermal energies included, (the neutron high energy threshold is set at 20 MeV).
- Non-analogue absorption for low energy neutrons with probability 0.95 for the last (thermal) groups.
- Particle transport threshold set at 10 MeV, except neutrons (`1E−5` eV), and (anti)neutrinos (0, but they are discarded by default anyway).
- Multiple scattering threshold for secondary charged particles lowered to 20 MeV (= primary ones).
- Both explicit and continuous heavy particle bremsstrahlung and pair production inhibited.
- EMF off! This default is meant for simple hadron shielding only!

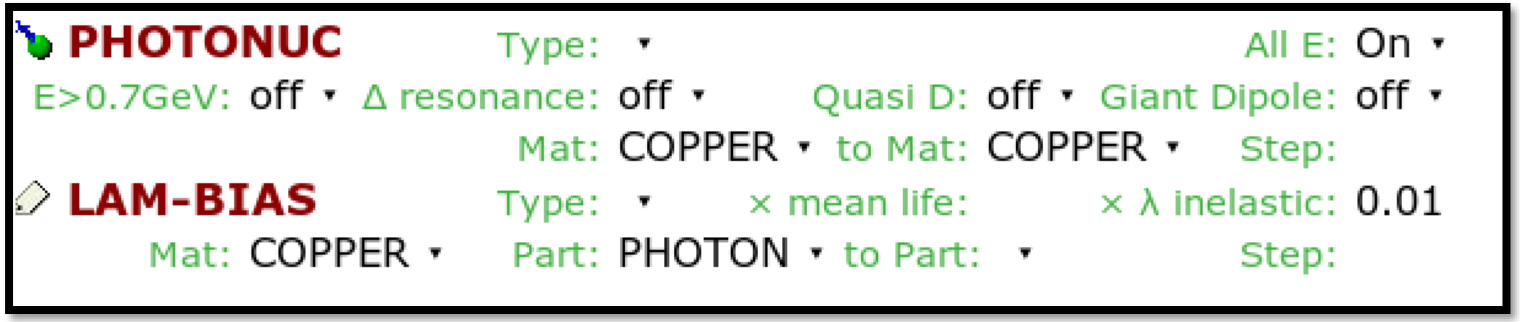
`LOW-PWXS` is the default for **`PRECISIOn`** but **<u>not</u>** for **`SHIELDINg`!**

`PHOTONUC` and muon pair production not ON by default for those two **`DEFAULTs`**

Thresholds

PART-THRES Type: Energy ▾ E: 1e-14
Part: NEUTRON ▾ to Part: ▾ Step:

- Transport thresholds can (shall) be optimized (see **`PART-THR`** and **`EMF`**/**`EMFCUT`**)
  - Thresholds for nuclear reactions from **charged hadrons**: a couple of MeV (**`PART-THR`**)
  - **Neutrons** should be transported down to thermal energies (10^{-5} eV in FLUKA) (**`PART-THR`**)
  - If H*(10) behind a shielding is dominated by neutrons, **EM cascade** can be switched **off** (reduction in CPU time) (**`EMF`**)
  - In, e.g. **high-energy lepton accelerators**, **photonuclear reactions** (not on by default in FLUKA) are relevant (typical threhsolds in the order of few MeV)
    - **`PHOTONUC`**: selected/all energies on a per-material basis
    - **`LAM-BIAS`**: since inelastic scattering lengths for photonuclear interactions can be very long, one can request to shorten the mean free path for this process (e.g. by a factor 50-100)

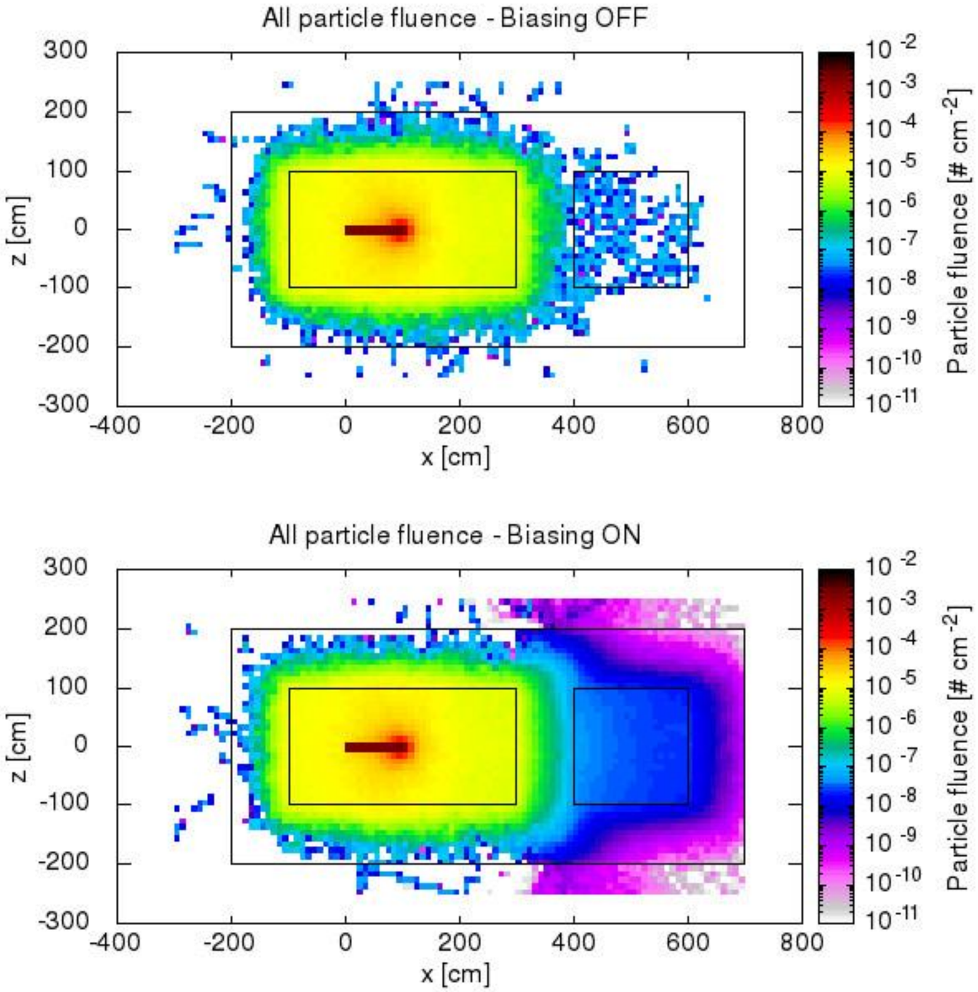


PHOTONUC Type: ▾ All E: On ▾
E>0.7GeV: off ▾ Δ resonance: off ▾ Quasi D: off ▾ Giant Dipole: off ▾
Mat: COPPER ▾ to Mat: COPPER ▾ Step:

LAM-BIAS Type: ▾ × mean life: × λ inelastic: 0.01
Mat: COPPER ▾ Part: PHOTON ▾ to Part: ▾ Step:

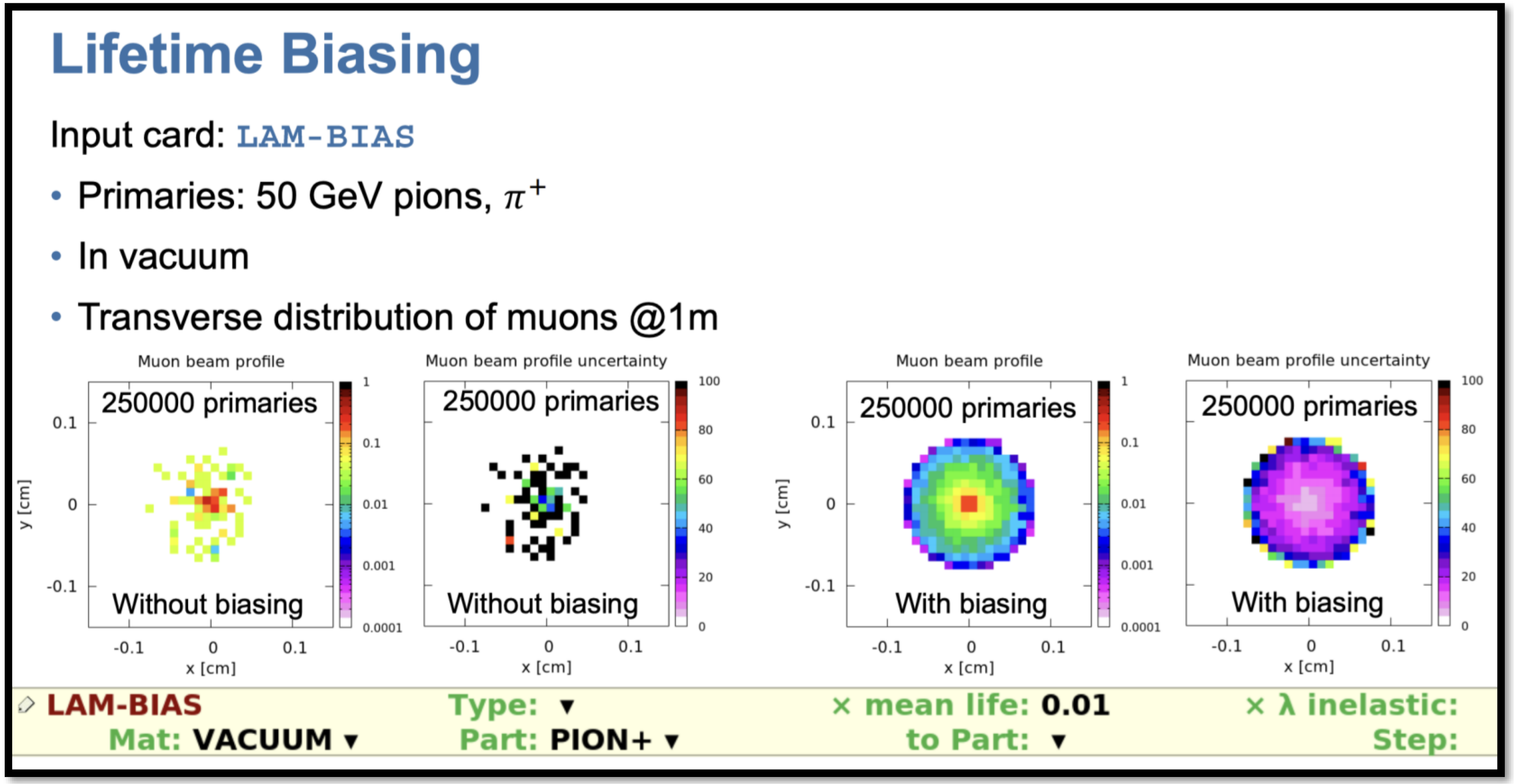
Biasing: a recall

- Several **biasing techniques** (see dedicated FLUKA lectures in beginner and advanced courses for details)
- **Non-biased** Monte Carlo simulation
  - Slow convergence
  - Rare events are "rare"!
- **Biased** Monte Carlo simulation
  - Requires active reasoning and experience
  - User's time to be implemented
- Here, we will speak/use
  - Region Importance Biasing (**`BIASING`**)
  - Mean free path biasing (**`LAM-BIAS`**)
  - Lifetime (**`LAM-BIAS`**)
  - User defined biasing (**`BIASING`** + **`usimbs.f`**)



Lifetime biasing

- Lifetime biasing (`LAM-BIAS`)
  - It could be useful to **enahance** (statistically) the **muon production**
  - Allows to **modify** the **lifetime** of unstable particles by a given factor



Lifetime Biasing

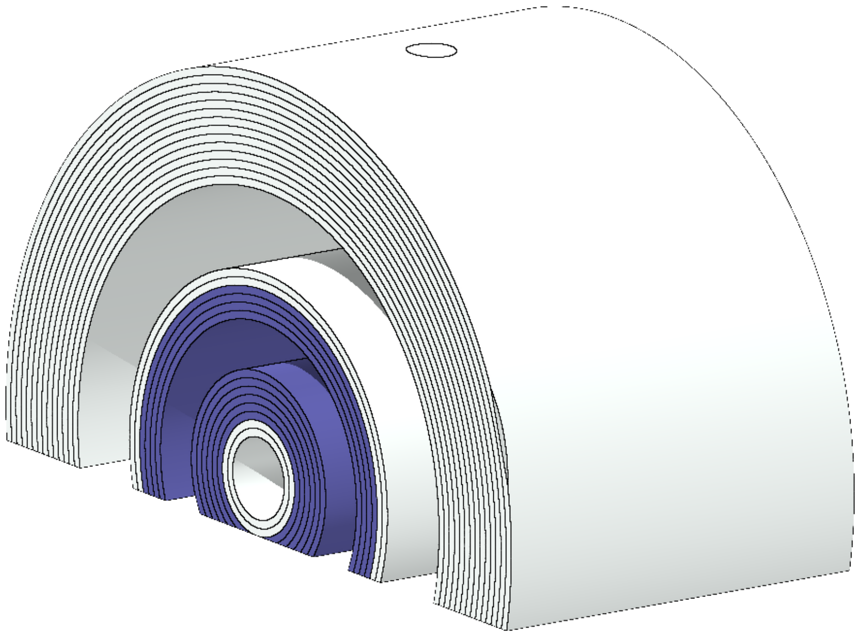
Input card: `LAM-BIAS`

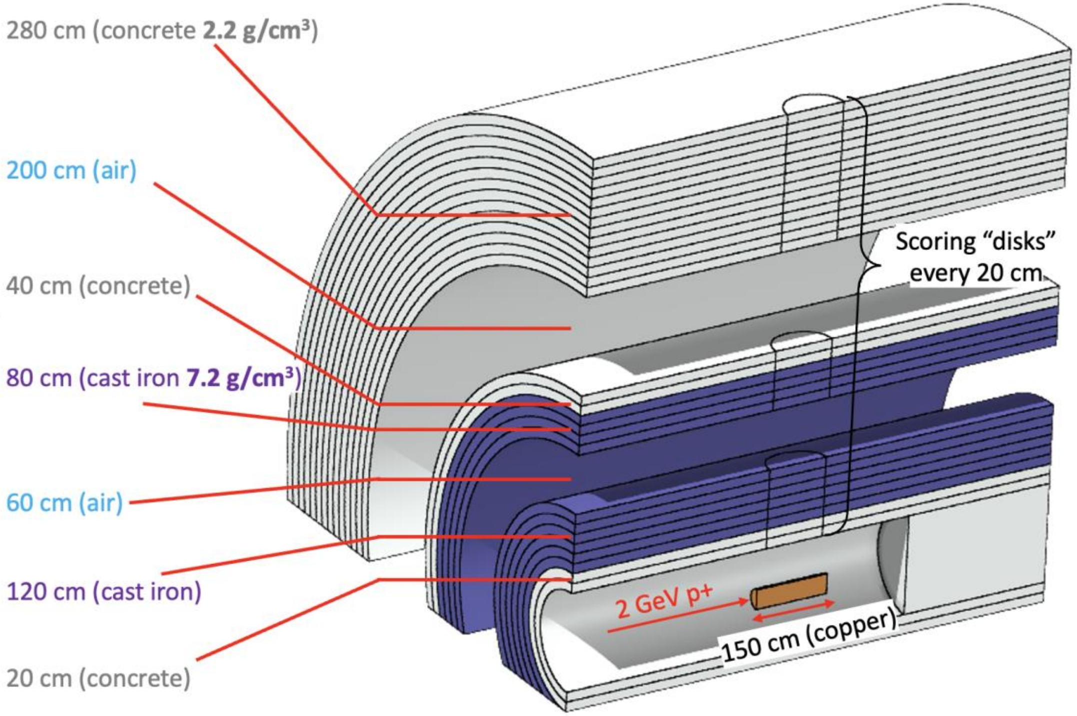
- Primaries: 50 GeV pions, π^+
- In vacuum
- Transverse distribution of muons @1m

LAM-BIAS Type: ▼ × mean life: 0.01 × λ inelastic:
Mat: VACUUM ▼ Part: PION+ ▼ to Part: ▼ Step:

Region importance biasing: a practical case

- Thick shielding problem
  - The example below was used to compare different shielding configurations
  - The analogue simulation could **not converge** in a “reasonable” amount of time
  - Geometry sliced every 20 cm to apply **region importance biasing** (`BIASING` card)

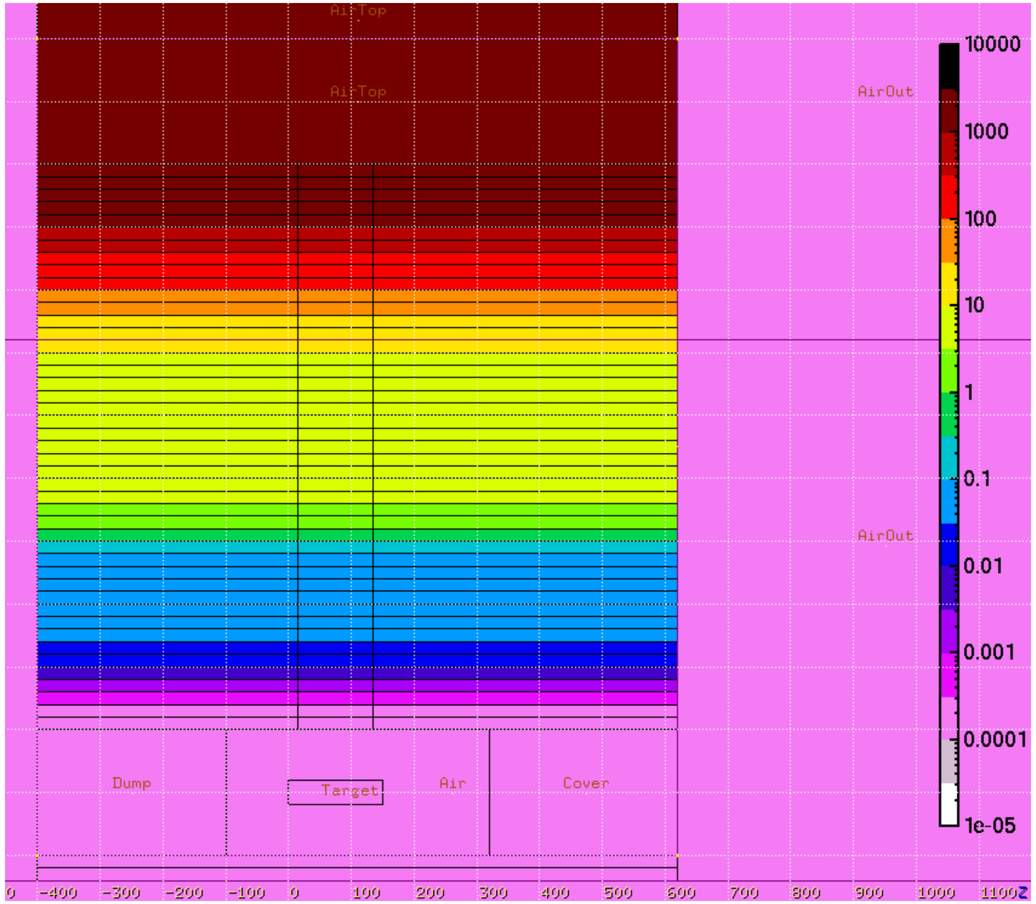


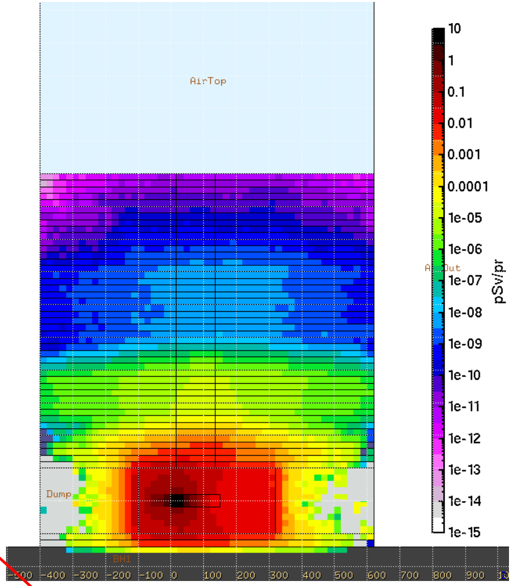


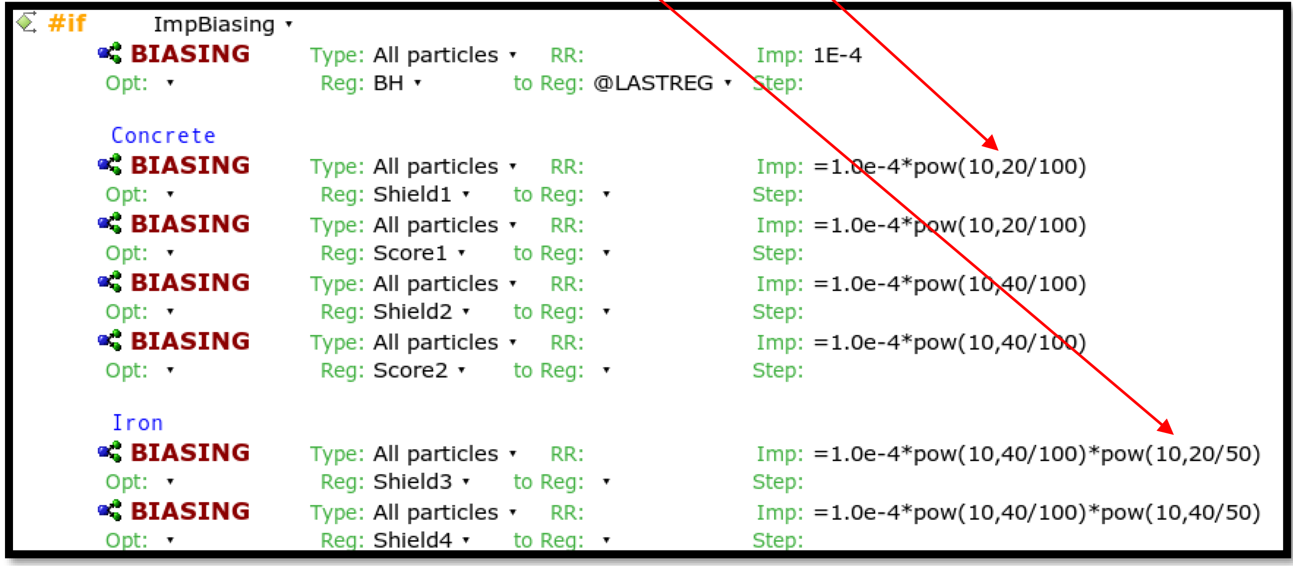
Region importance biasing: a practical case

Importance biasing:

- **Concrete** (2.2 g/cm^3): x10 every **100 cm**
- **Cast iron** (7.2 g/cm^3): x10 every **50 cm**







#if ImpBiasing ▾

BIASING Type: All particles ▾ RR: Imp: 1E-4
Opt: ▾ Reg: BH ▾ to Reg: @LASTREG ▾ Step:

Concrete

BIASING Type: All particles ▾ RR: Imp: =1.0e-4*pow(10,20/100)
Opt: ▾ Reg: Shield1 ▾ to Reg: ▾ Step:

BIASING Type: All particles ▾ RR: Imp: =1.0e-4*pow(10,20/100)
Opt: ▾ Reg: Score1 ▾ to Reg: ▾ Step:

BIASING Type: All particles ▾ RR: Imp: =1.0e-4*pow(10,40/100)
Opt: ▾ Reg: Shield2 ▾ to Reg: ▾ Step:

BIASING Type: All particles ▾ RR: Imp: =1.0e-4*pow(10,40/100)
Opt: ▾ Reg: Score2 ▾ to Reg: ▾ Step:

Iron

BIASING Type: All particles ▾ RR: Imp: =1.0e-4*pow(10,40/100)*pow(10,20/50)
Opt: ▾ Reg: Shield3 ▾ to Reg: ▾ Step:

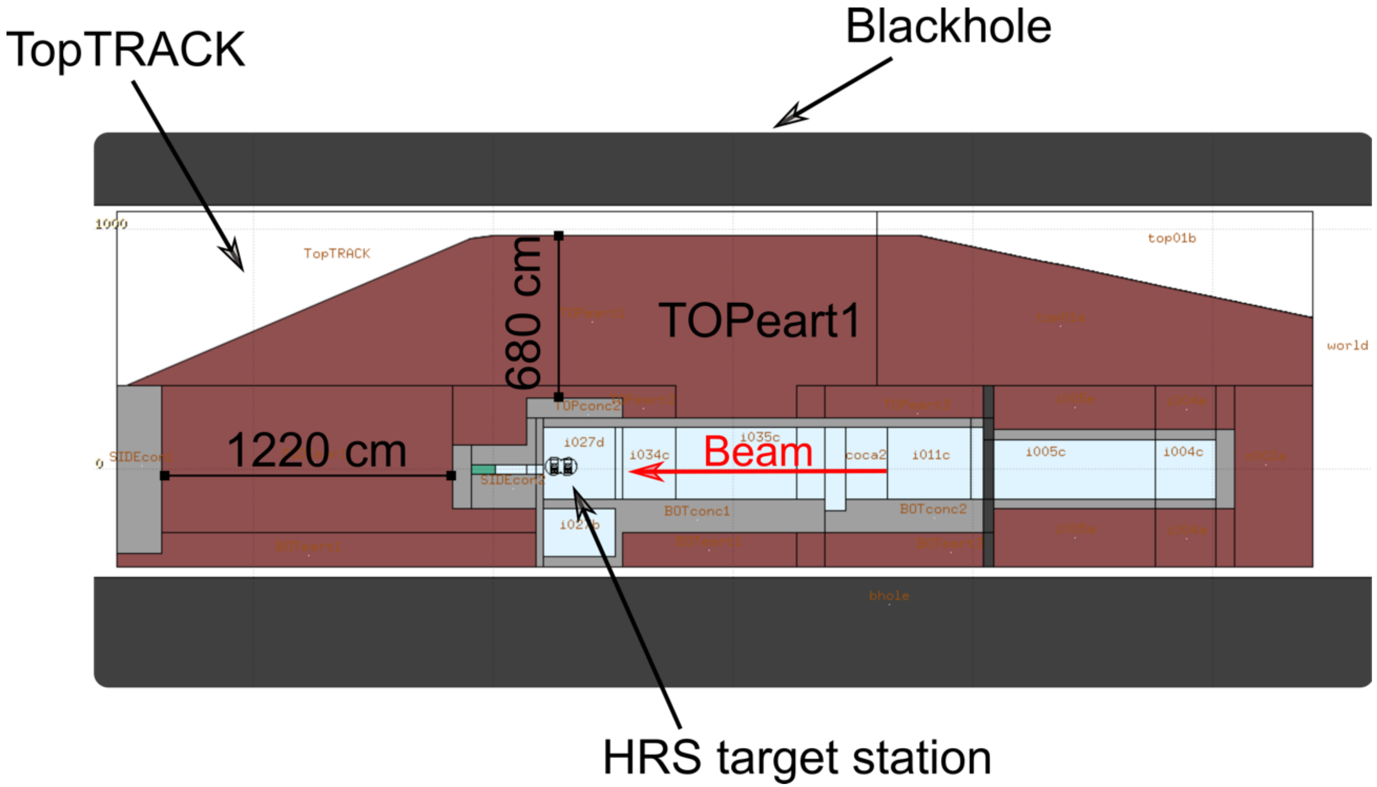
BIASING Type: All particles ▾ RR: Imp: =1.0e-4*pow(10,40/100)*pow(10,40/50)
Opt: ▾ Reg: Shield4 ▾ to Reg: ▾ Step:

`usimbs.f`: a practical case

Goal: simulate the particle spectra and H*(10) outside a thick shielding (concrete + soil)

Parameters

- Beam particles: protons
- Beam energy: 1.4 GeV
- Beam intensity: 1.25e13 p/s

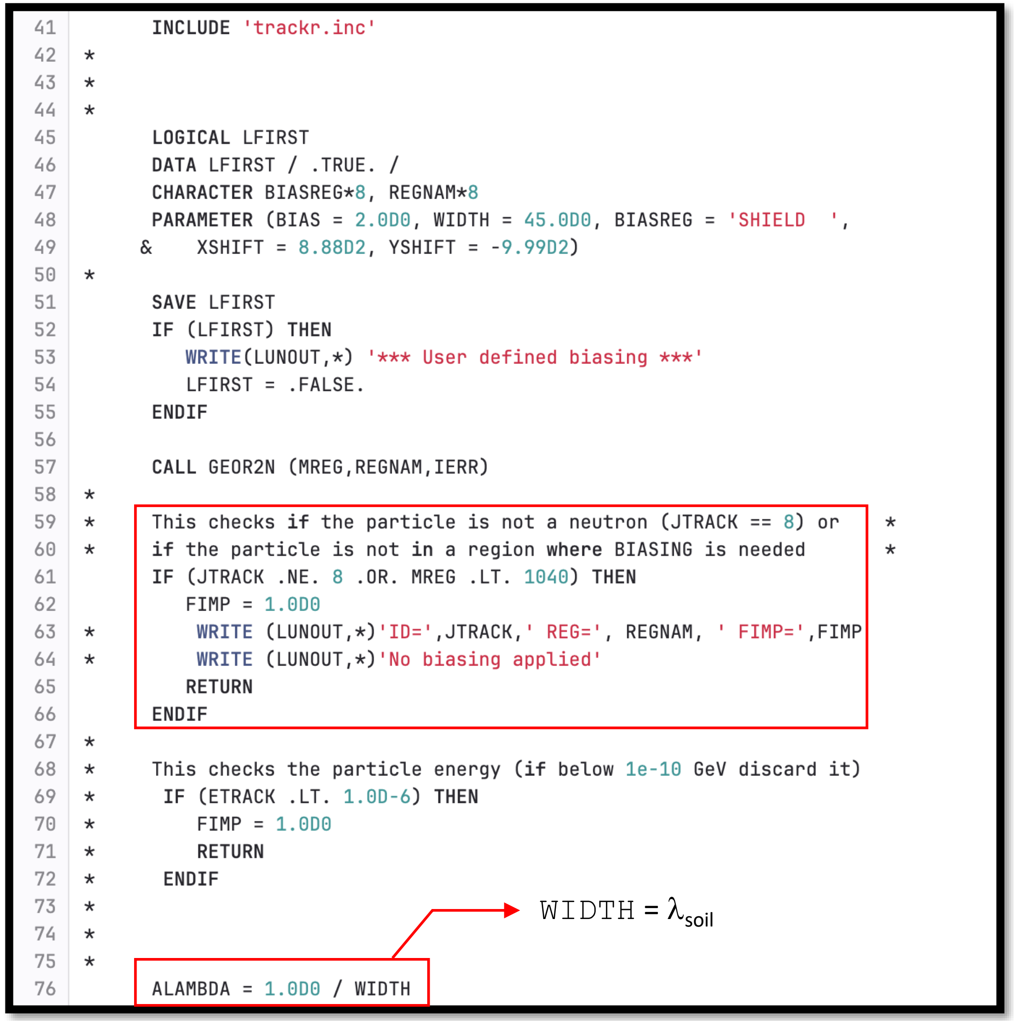


Biasing is required → two options:

- Region importance biasing (`BIASING`)
  - It requires to slice the entire geometry to apply importance factor
- **`usimbs.f`**
  - It requires to program a fortran routine

Guess which option has been chosen?

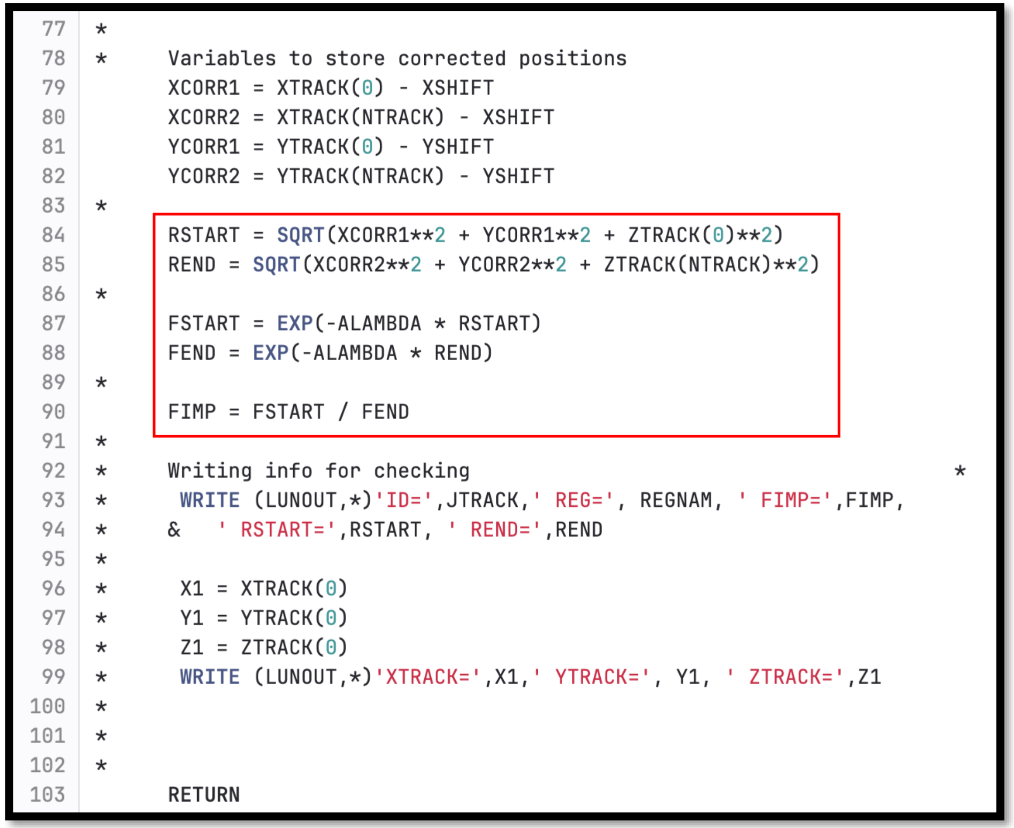
usimbs.f



```
      INCLUDE 'trackr.inc'
*
*
*
      LOGICAL LFIRST
      DATA LFIRST / .TRUE. /
      CHARACTER BIASREG*8, REGNAM*8
      PARAMETER (BIAS = 2.0D0, WIDTH = 45.0D0, BIASREG = 'SHIELD  ',
     &    XSHIFT = 8.88D2, YSHIFT = -9.99D2)
*
      SAVE LFIRST
      IF (LFIRST) THEN
         WRITE(LUNOUT,*) '*** User defined biasing ***'
         LFIRST = .FALSE.
      ENDIF

      CALL GEOR2N (MREG,REGNAM,IERR)
*
*     This checks if the particle is not a neutron (JTRACK == 8) or    *
*     if the particle is not in a region where BIASING is needed       *
      IF (JTRACK .NE. 8 .OR. MREG .LT. 1040) THEN
         FIMP = 1.0D0
*         WRITE (LUNOUT,*)'ID=',JTRACK,' REG=', REGNAM, ' FIMP=',FIMP
*         WRITE (LUNOUT,*)'No biasing applied'
         RETURN
      ENDIF
*
*     This checks the particle energy (if below 1e-10 GeV discard it)
*      IF (ETRACK .LT. 1.0D-6) THEN
*         FIMP = 1.0D0
*         RETURN
*      ENDIF
*
*
*
      ALAMBDA = 1.0D0 / WIDTH
```

WIDTH = λ_{soil}

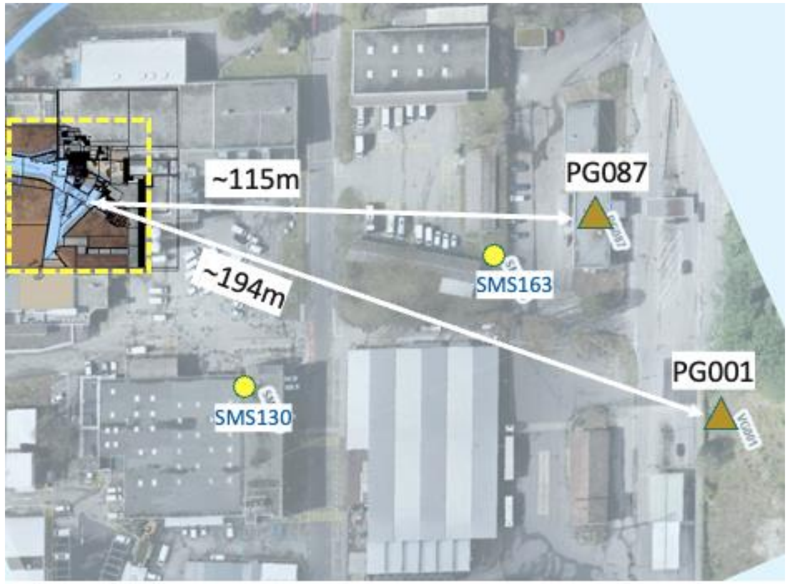


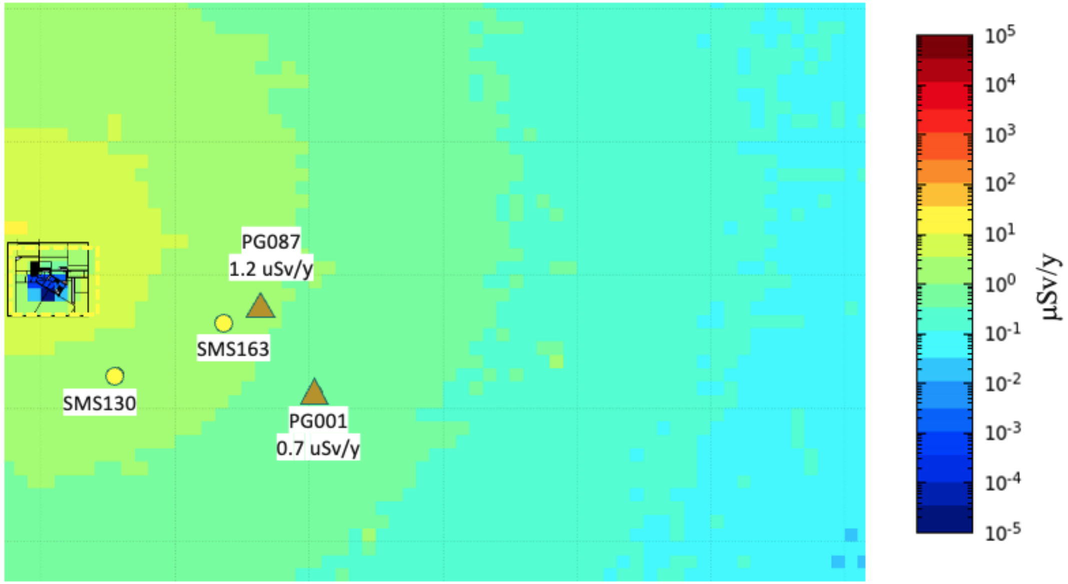
```
*
*     Variables to store corrected positions
      XCORR1 = XTRACK(0) - XSHIFT
      XCORR2 = XTRACK(NTRACK) - XSHIFT
      YCORR1 = YTRACK(0) - YSHIFT
      YCORR2 = YTRACK(NTRACK) - YSHIFT
*
      RSTART = SQRT(XCORR1**2 + YCORR1**2 + ZTRACK(0)**2)
      REND = SQRT(XCORR2**2 + YCORR2**2 + ZTRACK(NTRACK)**2)
*
      FSTART = EXP(-ALAMBDA * RSTART)
      FEND = EXP(-ALAMBDA * REND)
*
      FIMP = FSTART / FEND
*
*     Writing info for checking                                        *
*      WRITE (LUNOUT,*)'ID=',JTRACK,' REG=', REGNAM, ' FIMP=',FIMP,
*     &   ' RSTART=',RSTART, ' REND=',REND
*
*      X1 = XTRACK(0)
*      Y1 = YTRACK(0)
*      Z1 = ZTRACK(0)
*      WRITE (LUNOUT,*)'XTRACK=',X1,' YTRACK=', Y1, ' ZTRACK=',Z1
*
*
*
      RETURN
```

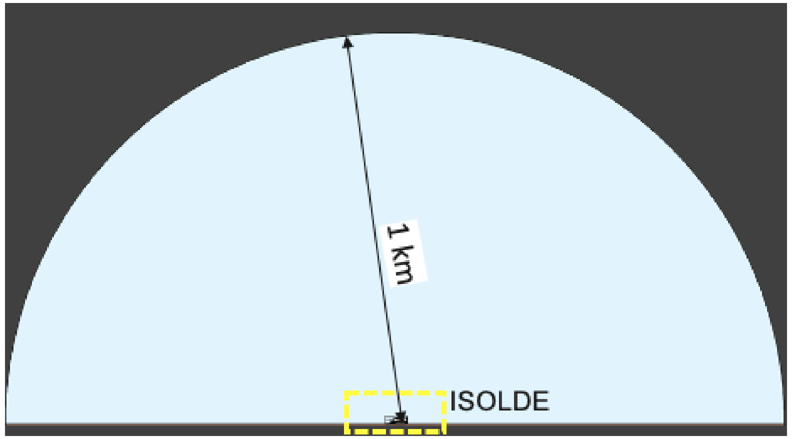
The two-step approach

- A transport problem can be split in **two sequential phases**
  - **Output** quantities **from FLUKA** transport can be re-injected as source of a consecutive FLUKA run
  - **First step**: record all particles (and relevant information) crossing a given boundary (`mgdraw.f`)
  - **Second step**: sample repeatedly source particles from that record (`source.f`)
- This approach can be **very powerful but**…
  - The dumped particles are only a fraction of the full shower (second step consists only of a subset of the full simulation)
  - Results of the second step should be **normalized** with the recorded weight of the first step
  - The user should make sure that **any effect/particle** that could have an impact on the result **has not been missed** (first step shall be representative)
    - **Uncertaintities** are **not propagated** between the first and the second step

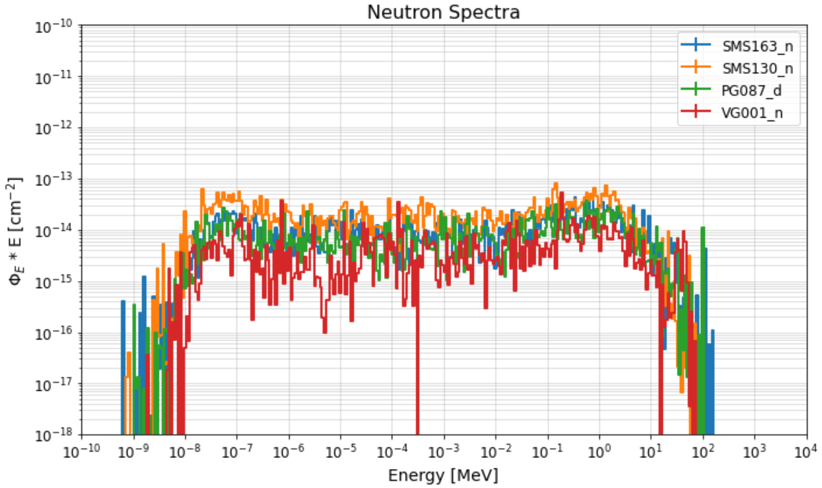
Two-step approach: the skyshine problem





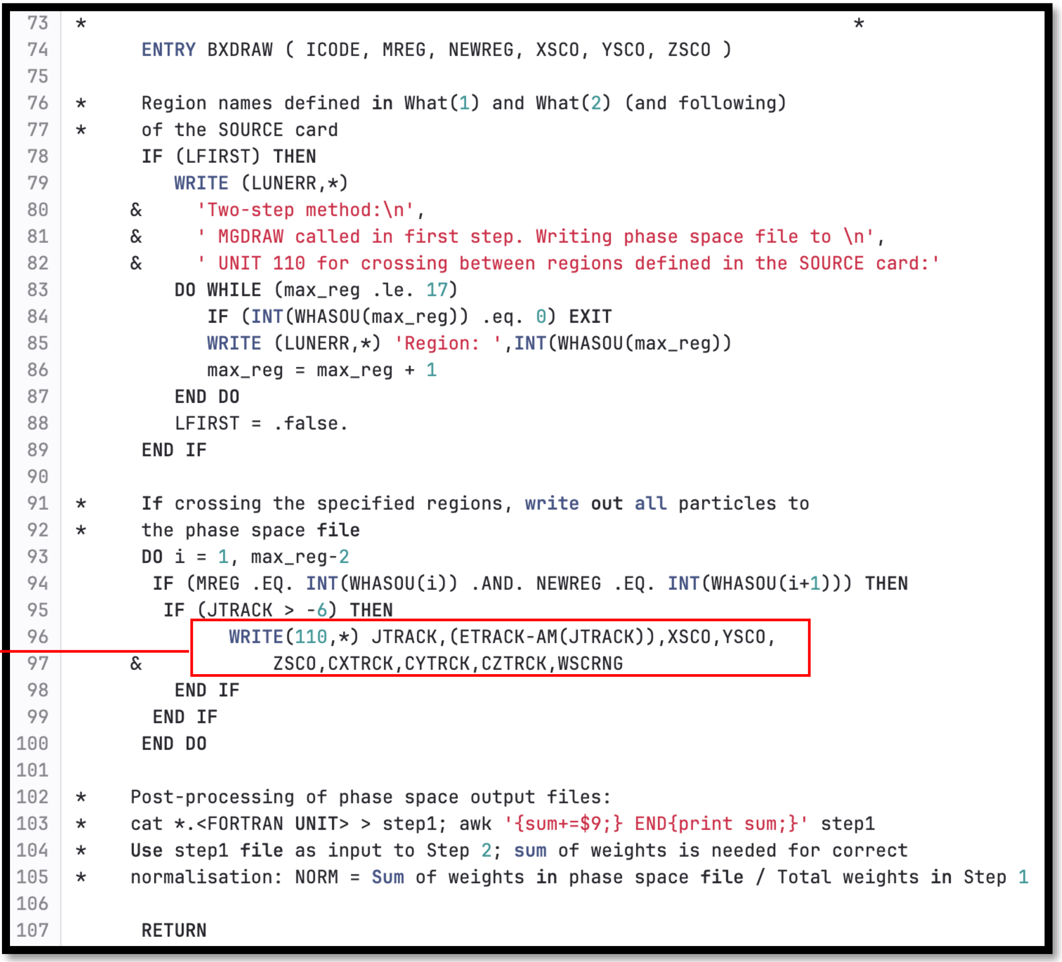


Note: neutron mfp in air is ~850 m



Question time
- USRBIN results look nice. Isn’t ?
- What else we should look at?

`mgdraw.f`: an example



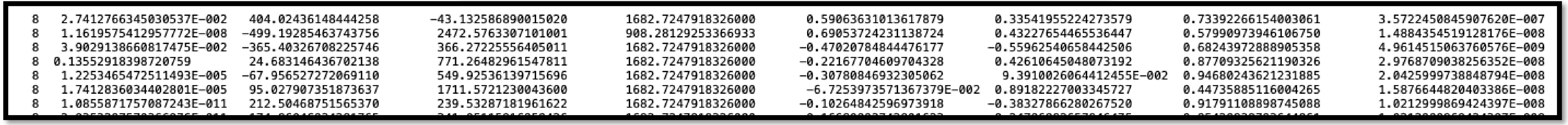
```fortran
*                                                                      *
      ENTRY BXDRAW ( ICODE, MREG, NEWREG, XSCO, YSCO, ZSCO )

*     Region names defined in What(1) and What(2) (and following)
*     of the SOURCE card
      IF (LFIRST) THEN
         WRITE (LUNERR,*)
     &     'Two-step method:\n',
     &     ' MGDRAW called in first step. Writing phase space file to \n',
     &     ' UNIT 110 for crossing between regions defined in the SOURCE card:'
         DO WHILE (max_reg .le. 17)
            IF (INT(WHASOU(max_reg)) .eq. 0) EXIT
            WRITE (LUNERR,*) 'Region: ',INT(WHASOU(max_reg))
            max_reg = max_reg + 1
         END DO
         LFIRST = .false.
      END IF

*     If crossing the specified regions, write out all particles to
*     the phase space file
      DO i = 1, max_reg-2
       IF (MREG .EQ. INT(WHASOU(i)) .AND. NEWREG .EQ. INT(WHASOU(i+1))) THEN
        IF (JTRACK > -6) THEN
          WRITE(110,*) JTRACK,(ETRACK-AM(JTRACK)),XSCO,YSCO,
     &          ZSCO,CXTRCK,CYTRCK,CZTRCK,WSCRNG
         END IF
       END IF
      END DO

*    Post-processing of phase space output files:
*    cat *.<FORTRAN UNIT> > step1; awk '{sum+=$9;} END{print sum;}' step1
*    Use step1 file as input to Step 2; sum of weights is needed for correct
*    normalisation: NORM = Sum of weights in phase space file / Total weights in Step 1

      RETURN
```



```
  8   2.7412766345030537E-002   404.02436148444258       -43.132586890015020       1682.7247918326000       0.59063631013617879       0.33541955224273579       0.73392266154003061       3.5722450845907620E-007
  8   1.1619575412957772E-008  -499.19285463743756       2472.5763307101001        908.28129253366933       0.69053724231138724       0.43227654465536447       0.57990973946106750       1.4884354519128176E-008
  8   3.9029138660817475E-002  -365.40326708225746       366.27225556405011        1682.7247918326000      -0.47020784844476177      -0.55962540658442506       0.68243972888905358       4.9614515063760576E-009
  8  0.13552918398720759        24.683146436702138       771.26482961547811        1682.7247918326000      -0.22167704609704328       0.42610645048073192       0.87709325621190326       2.9768709038256352E-008
  8   1.2253465472511493E-005  -67.956527272069110       549.92536139715696        1682.7247918326000      -0.30780846932305062        9.3910026064412455E-002  0.94680243621231885       2.0425999738848794E-008
  8   1.7412836034402801E-005   95.027907351873637       1711.5721230043600        1682.7247918326000       -6.7253973571367379E-002  0.89182227003345727       0.44735885116004265       1.5876644820403386E-008
  8   1.0855871757087243E-011   212.50468751565370       239.53287181961622        1682.7247918326000      -0.10264842596973918      -0.38327866280267520       0.91791108898745088       1.0212999869424397E-008
```

Bonus track: the automatic importance biasing (`AUTOIMBS` card)

Available in the next FLUKA release!

Automatic importance biasing: basics

- Advantages
  - **Automatizes** the use of importance biasing in combination with weight control
  - Able to solve **penetration & streaming** (e.g. ducts) problems at the same time
  - **Avoid iterative calculations** (for the sake of user friendliness)
- Features
  - User provides **spatial limits** for biasing and the region(s) of interest (**ROI**)
  - At initialization —few seconds to few minutes for typical problems, voxelized maps are created and superimposed to the geometry (**No need to slice geometries**!)
  - At each particle step, the code compute an importance ratio R:
    - R > 1: splitting R < 1: Russian Roulette R = 1: none
  - The ratio is not estimated on fixed importance values
  - Importance **ratios** are **tailored individually for each particle** (particle type, direction, statistical weight, energy, etc.)

Automatic importance biasing: R computation

1. **Direction-based** importance ratio
    - Takes into account the particle direction and evaluates if it is moving in a direction that should be encouraged or discouraged
2. **Population-based** importance ratio
    - Takes into account whether the particle has a statistical weight that makes it sufficiently significant relative to the local particle population
3. **Use** the **minimum** of the two importance ratios
    - Particles moving in a favourable direction with significant weight will be split.
    - Particles traveling in an unfavourable direction may undergo RR.
    - Particles with low statistical significance will undergo RR.

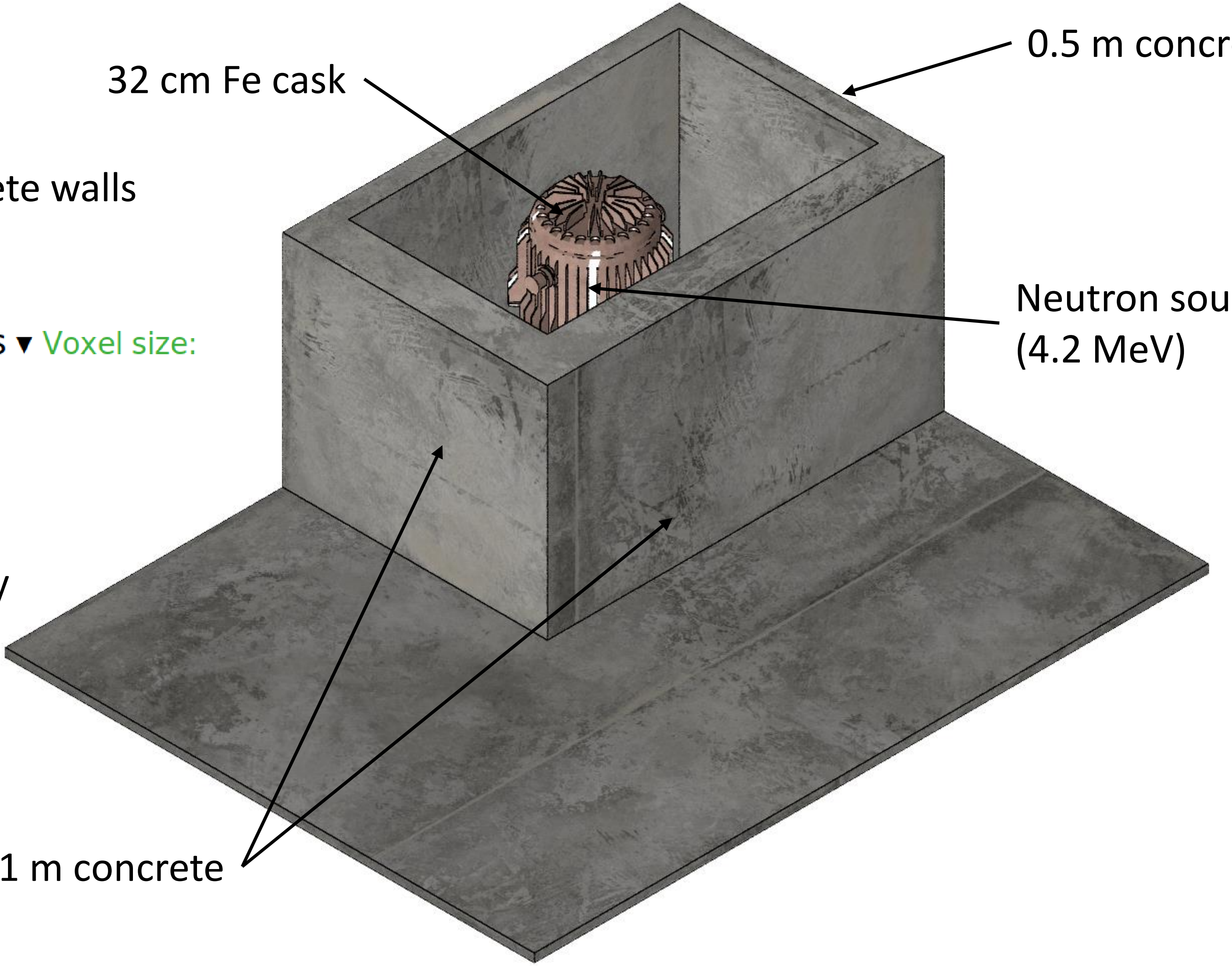
An example

- Transport cask stored within concrete walls
- Neutron source filling the cask

AUTOIMBS Opt: ▼ Spatial limits: bias ▼ Voxel size:
ROI: Air_Outs ▼ ROI: ▼ ROI: ▼ ROI: ▼

Region surrounding the room

Surface enclosing the geometry



32 cm Fe cask

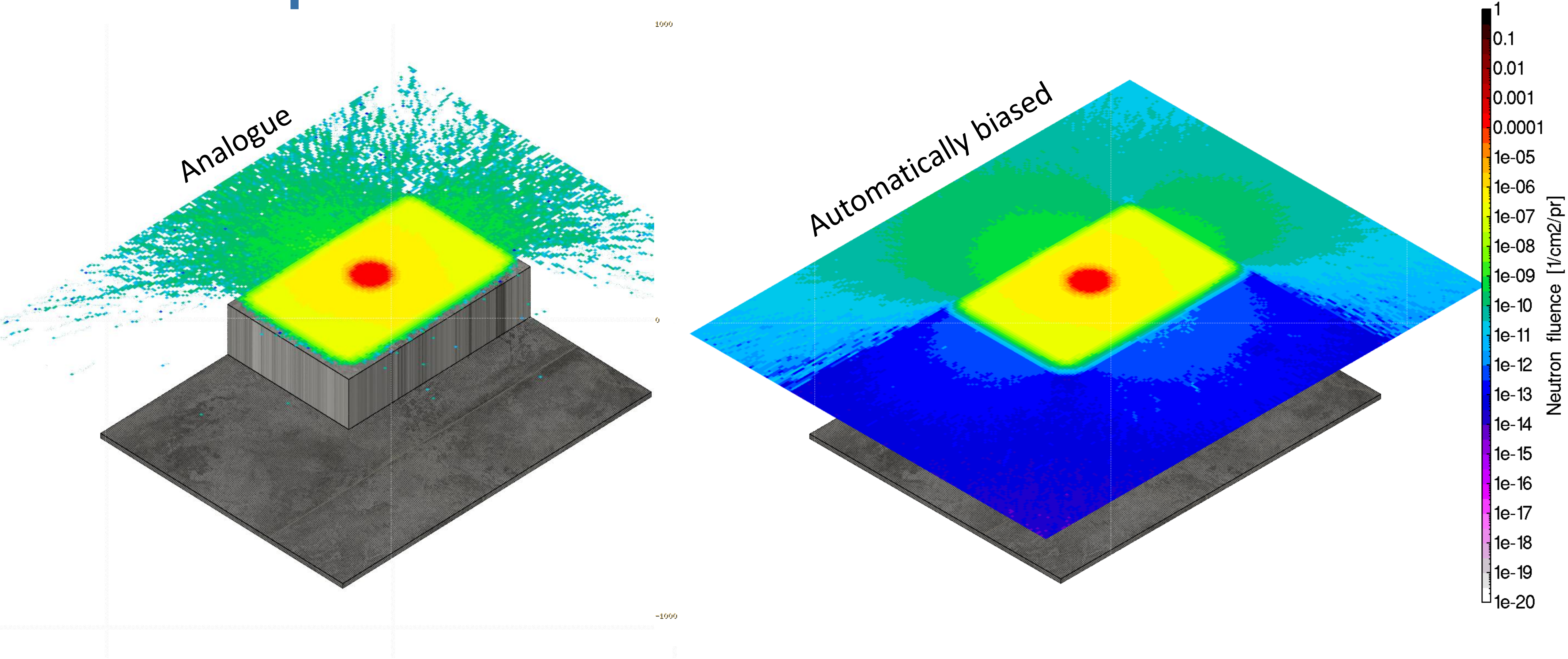
0.5 m concrete

Neutron source
(4.2 MeV)

1 m concrete

Initialization time ~ 150 s

An example



10 CPU.days

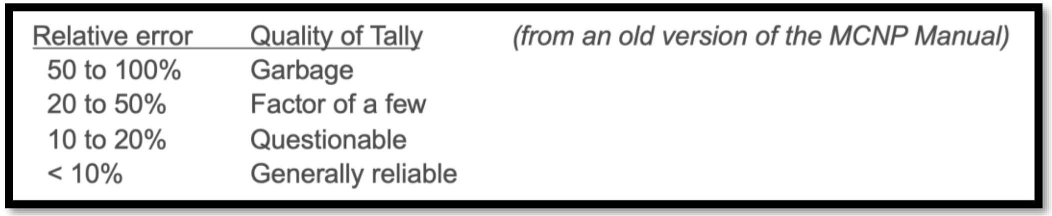
Region vs automatic importance biasing

- If **region importance biasing** cannot solve the problem in one or more runs, then `AUTOIMBS` will not be able to solve it either.
- **Region importance biasing** can be better **tailored** and **optimized**
- `AUTOIMBS` can solve cases that are not solvable by region importance biasing in a single simulations (e.g. competing pathways or disconnected ROIs)
- No matter how complex your geometry is, `AUTOIMBS` can be **set-up** in a **few minutes**
- `AUTOIMBS` is **less error-prone** than region importance biasing (user intervention is simple and minimal)
- Unlike region importance biasing, `AUTOIMBS` can handle **polyhedral geometries**

Validation of simulation results (some hints)

How to validate your shielding calculations

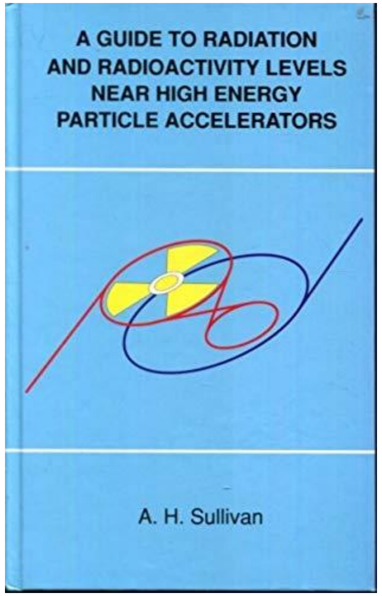
- The question: are my results **meaningful**?



Relative error	Quality of Tally
50 to 100%	Garbage
20 to 50%	Factor of a few
10 to 20%	Questionable
< 10%	Generally reliable

(from an old version of the MCNP Manual)

- Some hints
  - Always check **statistical uncertainty**
  - If possible, **validate your results** (at least in terms of order of magnitude) via **empirical formulas**
  - If available, **compare** simulation results **with radiation measurements**
    - Indeed, this has to be done for the facility commissioning!
  - **Compare** simulation results **with data from similar** (in terms of energy/intensity/power) **facilities**
  - **User experience** (which comes with time)
    - But do not neglect to ask your colleagues to brainstorm and profit from their experience
  - And remember that
    - Mistakes are part of the game

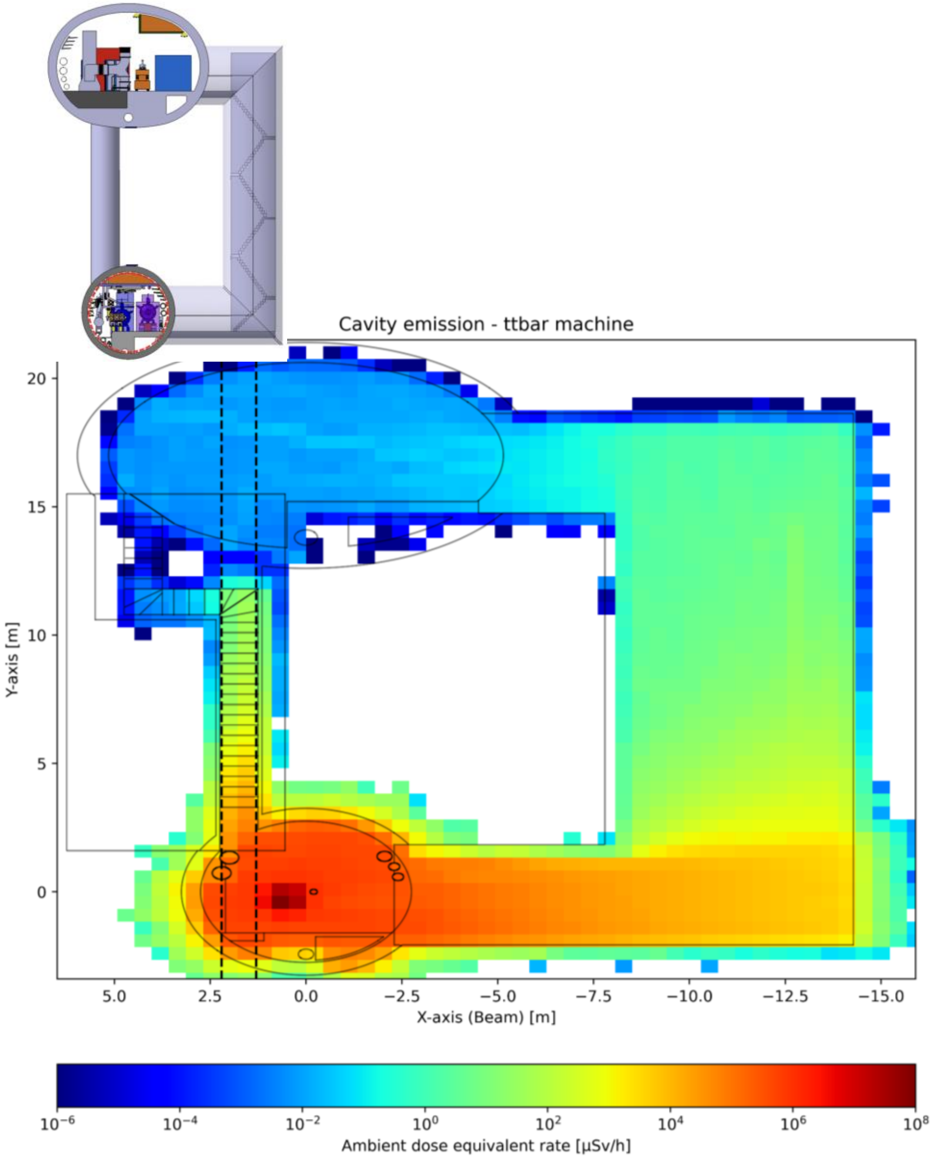


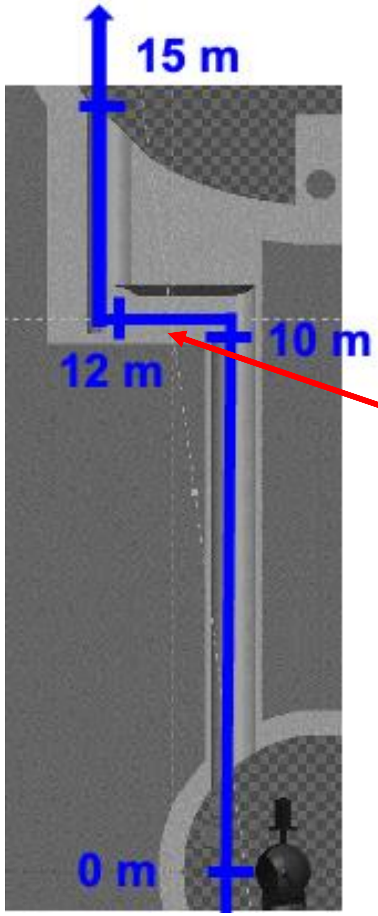
A GUIDE TO RADIATION AND RADIOACTIVITY LEVELS NEAR HIGH ENERGY PARTICLE ACCELERATORS

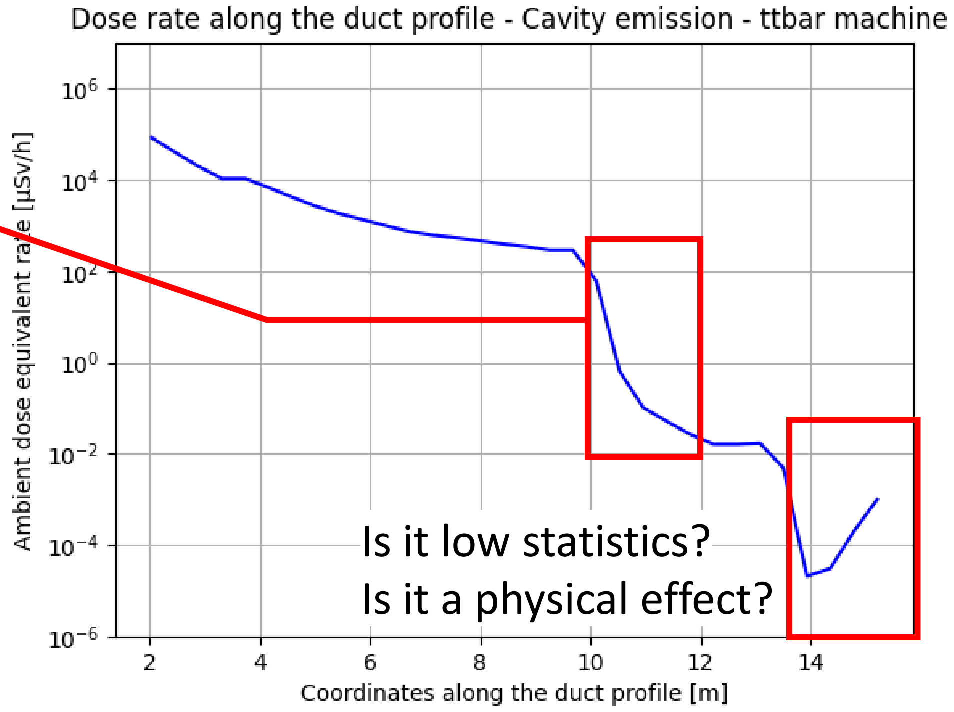
A. H. Sullivan

Result validation: an example

- **10.5 MeV electrons** impinging on the inner surfaces of RF cavities (sampled along the axis of the cryomodule)
- **Prompt radiation**: mainly **photons**







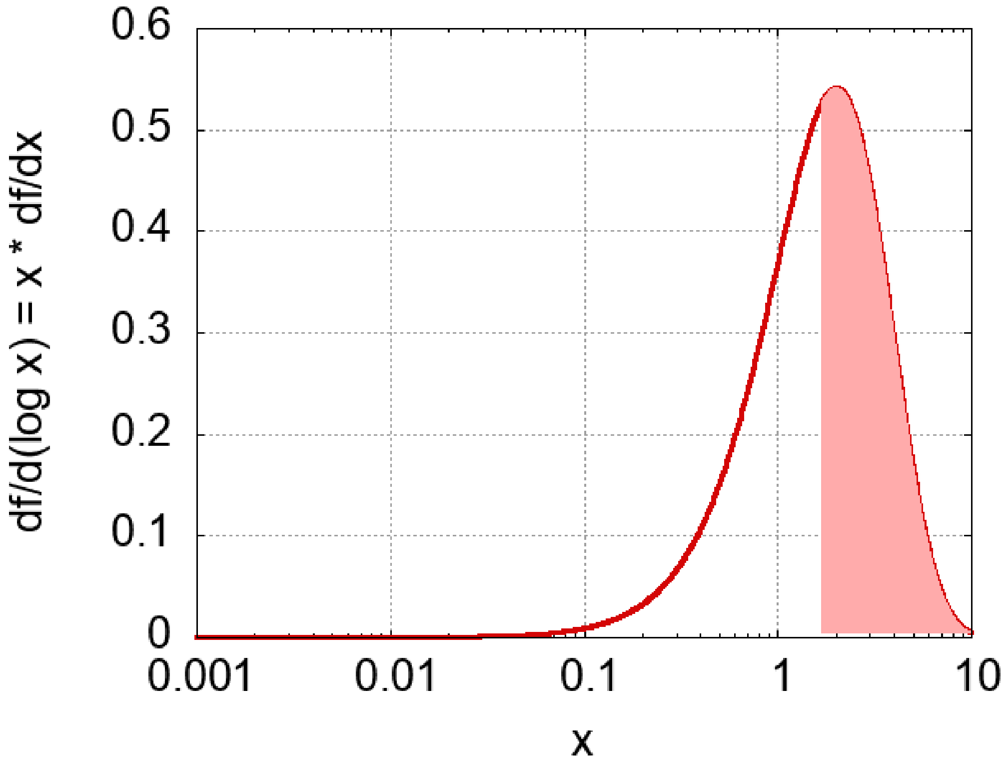
Is it low statistics?

Is it a physical effect?

FLUKA

Recall of… fluence

- $\Phi\,(\boldsymbol{r}, v) = n\,(\boldsymbol{r}, v)\,dl$, $[cm{-}2]$: **fluence**, *i.e.* time integral of the flux density
  - With $n\,(\boldsymbol{r}, v)$ the number of particles, dl the distance travelled
  - Fluence is expressed in **"particles" per cm^2** but in reality represents the **density of particle tracks [cm / cm^3] !**
- Remember when plotting fluence to embrace lethargy units the proper representation of $\frac{df}{d\log(x)}$:

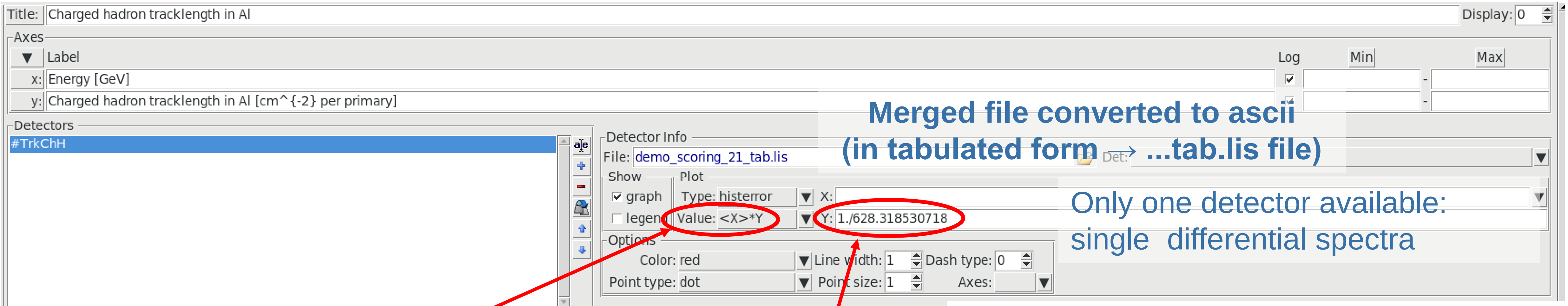


In this representation, integrals are respected

You are now representing information in a faithful way

(NB: taking a logarithmic scale in the vertical axis is harmless)

Plotting – single diff. fluence in volume (USRTRACK)



Title: Charged hadron tracklength in Al

Display: 0

Axes

	Label	Log	Min	Max
x:	Energy [GeV]	☑		
y:	Charged hadron tracklength in Al [cm^{-2} per primary]	☑		

Detectors

#TrkChH

Detector Info

File: demo_scoring_21_tab.lis

Det:

Show

☑ graph

☐ legen

Plot

Type: histerror

Value: <X>*Y

X:

Y: 1./628.318530718

Options

Color: red

Line width: 1

Dash type: 0

Point type: dot

Point size: 1

Axes:

```
set format y '10^{%T}'
set ylabel offset -1
```

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

Value: <X>*Y

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