An overview of FLUKA

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with material from previous lectures by G. Lerner, A. Lechner, F. Salvat Pujol, F. Cerutti

An overview of FLUKA
https://agenda.infn.it/event/51984/

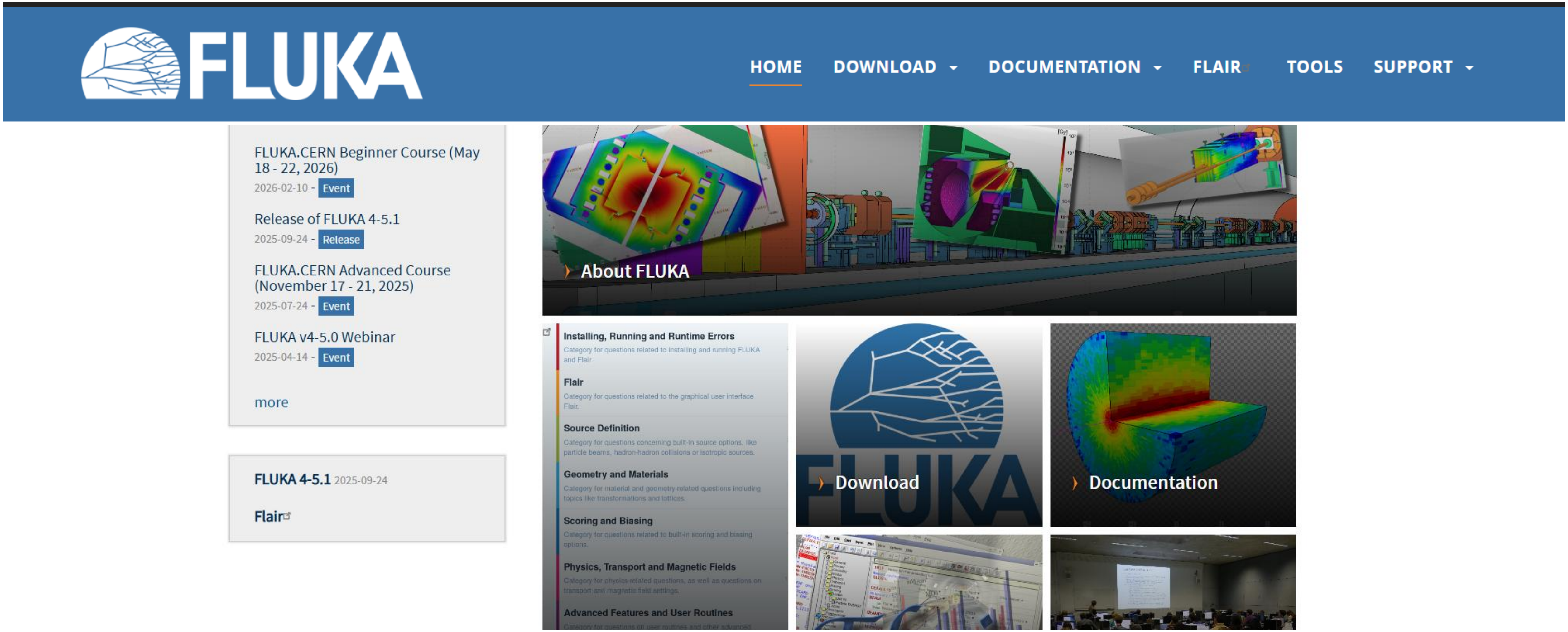
Roma 4/5/2026

Where we come from

- FLUKA was born in the 60s at **CERN** with Johannes Ranft
- It was further developed in the 70s and 80s in a collaboration between **Leipzig University**, **CERN** and **Helsinki University of Technology** for applications, e.g. at CERN's high energy accelerators, and in the 90s with **INFN**, among others for the design of SSC and LHC
- From 2003 until August 2019 maintained and developed under a **CERN & INFN** agreement
- From December 2019, new **CERN** distribution aiming to ensure FLUKA's long-term sustainability and capability to meet the evolving requirements of its user community, welcoming contributions by both established FLUKA contributors as well as new partners within an **international collaboration**.
- Presently a joint development & management team based in the **CERN Accelerators and Technology Sector and Radiation Protection Group and at ELI-Beamlines (Prague) and FNAL,** with contributors from the CERN Research and Computing Sector, JRC-Geel, ANL, BNL, and STFC, is in place.

FLUKA.CERN distribution

https://fluka.cern



Licensing scheme

- **Licenses are free** except for commercial use
- They are granted for **non-military use** only

Registration options	*access to*
FLUKA ***Single User License Agreement***	**binary code**
Affiliates of institutes with a FLUKA ***Institutional License Agreement***	**source code** too
CERN Staff members and Fellows	
Affiliates of institutes which signed the FLUKA ***Memorandum of Understanding***	**development version** (binary and source code)
Companies which purchased a FLUKA ***Commercial License Agreement***	**binary code**

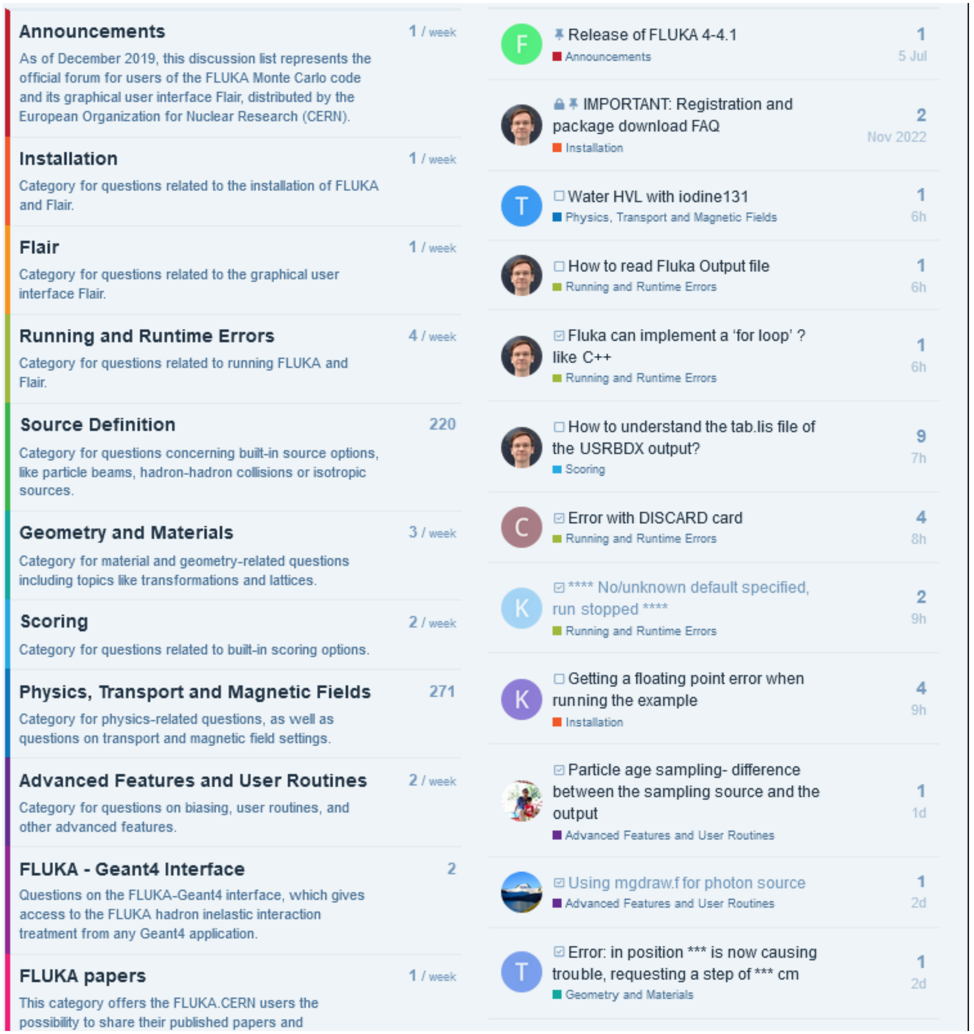
- For **central FLUKA installations on computing clusters** of universities/institutes it is not necessary to obtain an Institutional FLUKA Licence. However, it is mandatory that all FLUKA users register on the *fluka.cern* website and accept the Single User Licence Agreement.

User support

FLUKA user forum

https://cern.ch/fluka-forum

Note: an independent one-time registration is required to be able to participate



FLUKA training

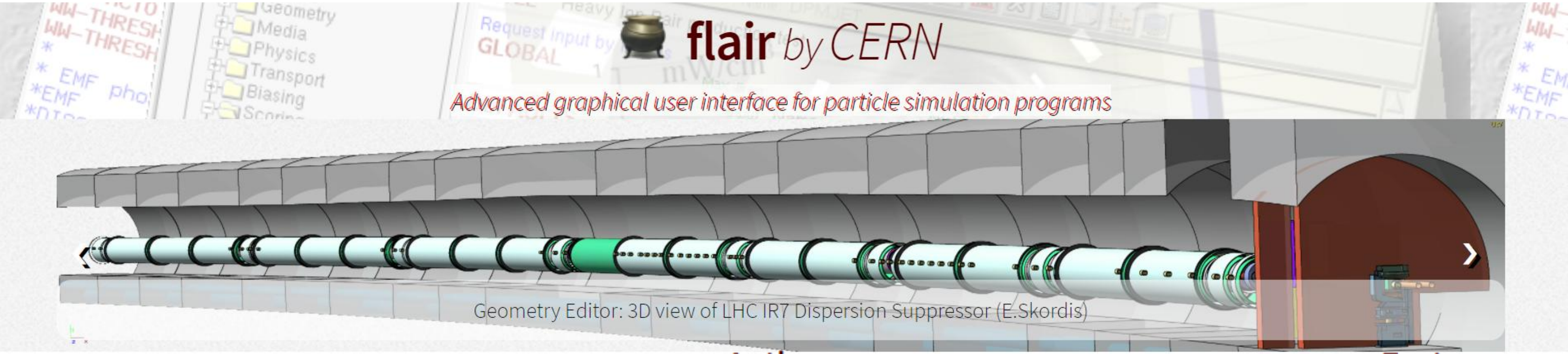
https://indico.cern.ch/category/9178

Beginner and advanced courses are held on a regular basis across the world

The first topical course (on Radiation Protection) was held in November 2024

Flair

https://flair.cern



Authors

authors: Vasilis Vlachoudis *(lead author)*
Christian Theis
Wioletta Kozlowska

Current Version

- Latest version: **3.4-5.2**
- Released on: ***Sat 15-Nov-2025***
- Powered by python**3**, tkinter, gnuplot, pydicom

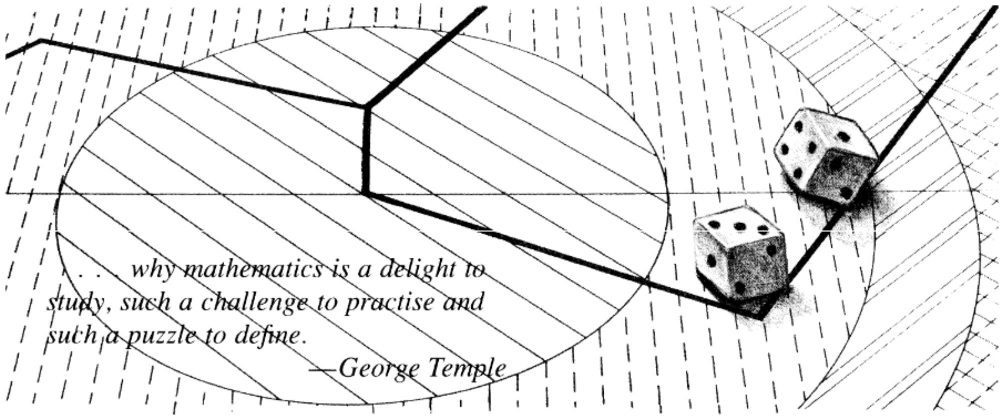
Features

- modern and intuitive design
- Input editor for error free inputs
- Interactive geometry editor, photorealistic ray tracer and debugger
- run and monitor the simulation
- back-end for post-processing of results
- I/O of other simulation formats (MCNPX,GDML,...)
- Medical file importing, DICOM, RT-PLAN,DOSE,...
- extended material library

1. The transport problem

THE BEGINNING *of the* MONTE CARLO METHOD

by N. Metropolis



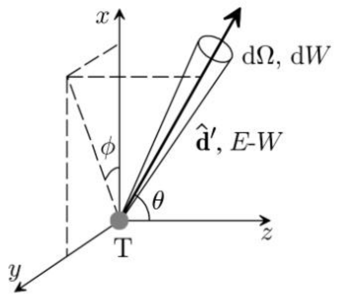
Monte Carlo methods: history

- First experiments by Fermi (~1930) to study neutron diffusion, no publications
- Extensive use for neutronics in nuclear weapons applications. First proposal by Stanislaw Ulam, with contribution by Metropolis and Neumann

The transport problem

Radiation source → Propagation in matter → Scoring

- **Neutrons:** best example (no continous Coulomb scattering)
- … but also other particles (p, $e^{+/-}$, photons, pions, muons etc.)
- Radioactive elements decay



- Interaction described as cross sections: likelihood of interaction per unit quantity of interest (solid angle, energy, ...)

$$\frac{d^2\sigma}{d\Omega\, dW} \equiv \frac{\dot{N}_{count}}{|\mathbf{J}_{inc}|\, d\Omega\, dW}$$

- Any quantity related to the particle fluences, energy deposition or interaction events
- Non trivial problem!

Particle interactions: cross section and mean free path

- Particle-matter interactions are **stochastic processes**, governed by the laws of quantum physics and relativity (i.e., Quantum Field Theory)
- The fundamental quantity of each particle-matter interaction process is the **cross section (σ)**, measured in barn (1b = 10^{-24} cm^2)
- For each particle travelling through matter, we can use it to compute the **mean free path (λ**, in units of length), measuring the **average distance between two interactions**:

$$\lambda = \frac{1}{N\sigma} = \frac{M}{\rho N_A \sigma}$$

- The cross section is a property of the physics process, and it depends exclusively on the characteristics of the initial and final states (i.e., identity and energy of the particles/atoms). Everything else in the above formula is simply there to "count" the target atoms in the volume of interest.

Application: transport problem

- Given a particle density n_0(r,E,Ω,t=0), determine the radiation field of any given particle species, with different energies E, and directions Ω

$$
\begin{aligned}
\int_V \mathrm{d}\boldsymbol{r}\, \frac{\partial n_i(\boldsymbol{r},E,\Omega,t)}{\partial t} = & -\oint_S \mathrm{d}A\, \mathbf{j}(\boldsymbol{r},E,\Omega,t)\cdot\hat{\boldsymbol{a}} && \text{(unscattered particles)}\\
& - N\int_V \mathrm{d}\boldsymbol{r}\, n_i(\boldsymbol{r},E,\Omega,t)v(E)\sigma(E) && \text{(particles scattered out)}\\
& + N\int_V \mathrm{d}\boldsymbol{r}\int \mathrm{d}E'\int \mathrm{d}\Omega'\, n_i(\boldsymbol{r},E',\Omega',t)v(E')\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega''\mathrm{d}W''} && \text{(particles scattered in)}\\
& + N\int_V \mathrm{d}\boldsymbol{r}\int \mathrm{d}E'\int \mathrm{d}\Omega'\, \sum_j n_j(\boldsymbol{r},E',\Omega',t)v(E')\frac{\mathrm{d}\sigma_{\mathrm{sec},i}}{\mathrm{d}\Omega''\mathrm{d}W''} && \text{(production of secondaries)}\\
& + \int_V \mathrm{d}\boldsymbol{r}\, Q_{\mathrm{source}}(\boldsymbol{r},E,\Omega,t) && \text{(source)}
\end{aligned}
$$

$$p(s) = (1/\lambda)\exp(-s/\lambda) \qquad P_i = \sigma_i/\sigma$$

…and charged particles?

$$p(s) = (1/\lambda)\exp(-s/\lambda) \qquad P_i = \sigma_i/\sigma$$

- Coulomb scattering & ionization losses: charged particles lose energy and interact almost continuously
- Typical Monte Carlo solution → **condensed history**:
  - Moliere theory of multiple Coulomb scattering: the cumulated effect of several scattering events is condensed in a distribution
  - Ionization losses (below the δ-ray threshold) distributed on the track length

How to solve the transport problem?

- Several solution strategies for the transport problem:
  - Analytical: only restricted geometries and interaction models
  - Spectral: with symmetries, expand in appropriate basis functions. Restricted cases
  - Numerical quadrature integration: inefficient in high-dimensional integrals
  - Monte Carlo: general, efficient for arbitrary geometries and radiation fields
- Generic Monte Carlo problem: P is a probability measure, g is a function of the random variable

$$I = \int g \, dP \xrightarrow{a.s.} I_n = \frac{1}{n} \sum_{i=1}^{n} g(X_i)$$

1. Sample X_i from the correct distribution (not trivial!) given a pseudo random number
2. Calculate the $g(X_i)$ quantity of interest
3. Obtain the integral as the mean

Application: scoring & estimation

- The typical applications require the scoring of fluence/star related quantities (energy deposition, number of interactions, etc)
- Any physical observable is the average of the contribution of all particles in the field. The estimator chosen is the sample mean, under the assumption that the CLT can be applied
- In FLUKA, the choice made is to adopt a batch analysis (instead of history by history). Assuming N batches, with ni primary particles and average scoring xi in the i-th batch, the estimator and uncertainty are:

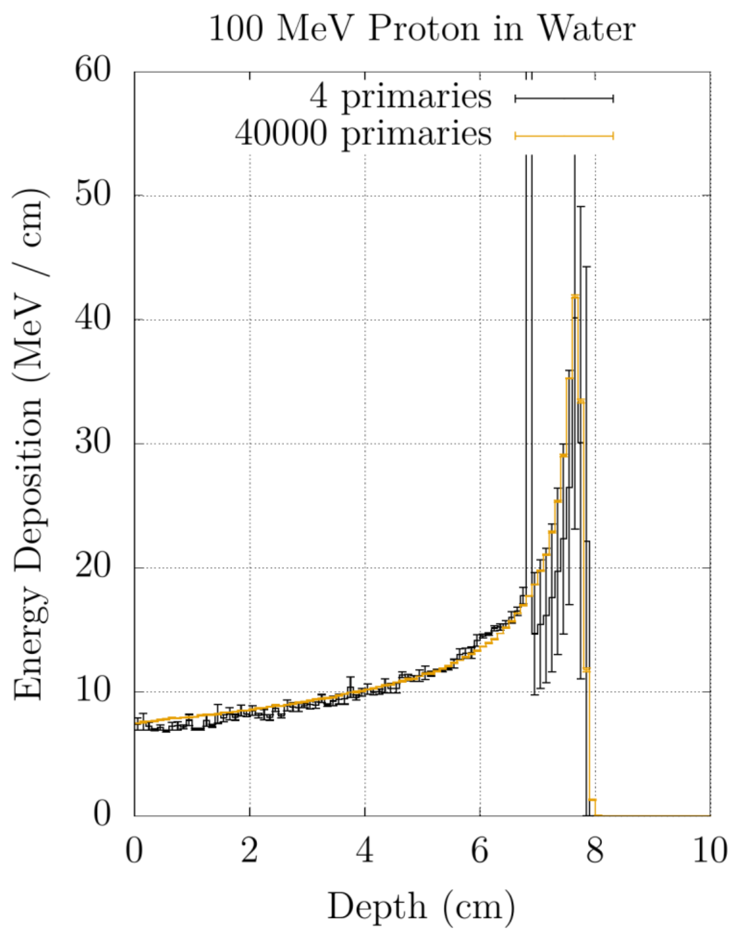
$$x_i = \sum_{j=1}^{n_i} \frac{x_{ij}}{n_i} \quad \begin{cases} \hat{X} = \frac{1}{N} \sum_{i=1}^{N} x_i \\ \sigma^2_{\hat{X}} = \frac{1}{N-1} \left[\frac{\sum_{i=1}^{N} n_i x_i^2}{n} - \left(\frac{\sum_{i=1}^{N} n_i x_i}{n} \right)^2 \right] \end{cases}$$

Uncertainty and statistics

*biasing is an effective alternative solution

- How many primaries? The more, the better*. In general, as rule of thumb:

Relative error	Estimator quality
>50 %	Garbage
20 – 50 %	Order of magnitude
10 – 20 %	Questionable
<10 %	Reliable (generally)



- This does not include systematic errors, such as:
  - Physics
  - Algorithm artifacts
  - Missing (or uncertain) data
  - Material & geometry composition
  - Uncertainty on the source terms (beam losses estimation)

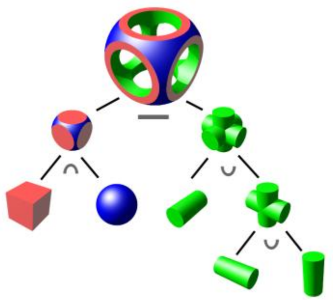
2. Geometries in Monte Carlo

Geometries in Monte Carlo

- When following the particles, the code continuously ask:
  - Where am I?
  - Where am I going?
  - How far can I travel before an interface?
- The geometry implementation in the codes (FLUKA, GEANT, …) needs to be fast and versatile.
- Most recent codes allow to use CAD imported assemblies with tesserated solids

FLUKA: Constructive solid geometry

- Simple and extremely fast
- Employs lattice and replica capabilities



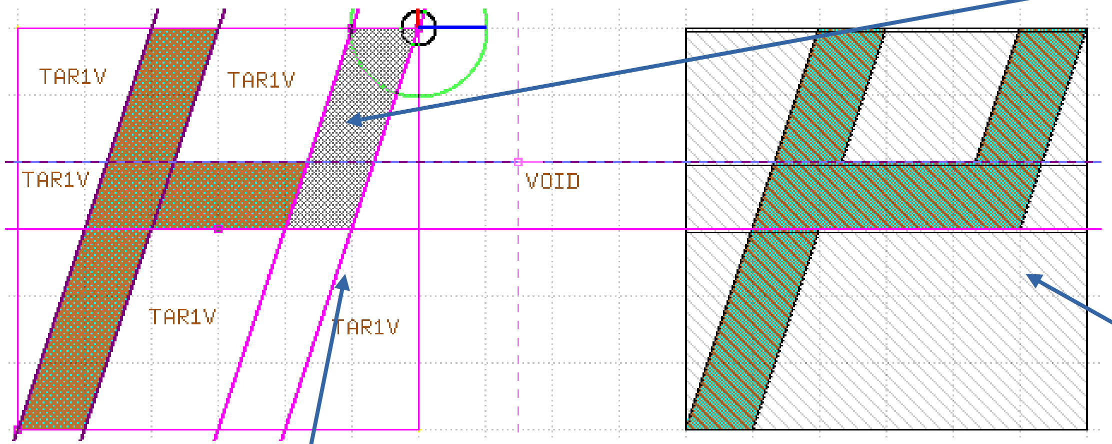
GEANT: Hierarchical

- Each volume has a "mother"
- More complicated to implement ex-novo
- Lot of geometry shapes available

Geometries in FLUKA

- Four fundamental concepts:
  - **Body**: basic geometry object (finite or infinite: planes, spheres, …).
  - **Zone**: sub-region composed by intersection and subtraction of bodies.
  - **Region**: union of zones
  - **Lattices**: duplication of existing regions confined in a container volume

Target
REGION TAR1C   Neigh: 5
expr: +target +po_1 -po_2
| +target +po_1 +po_2 -base_1 +base_2 -po_3
| +target +po_3 -po_4 -base_1



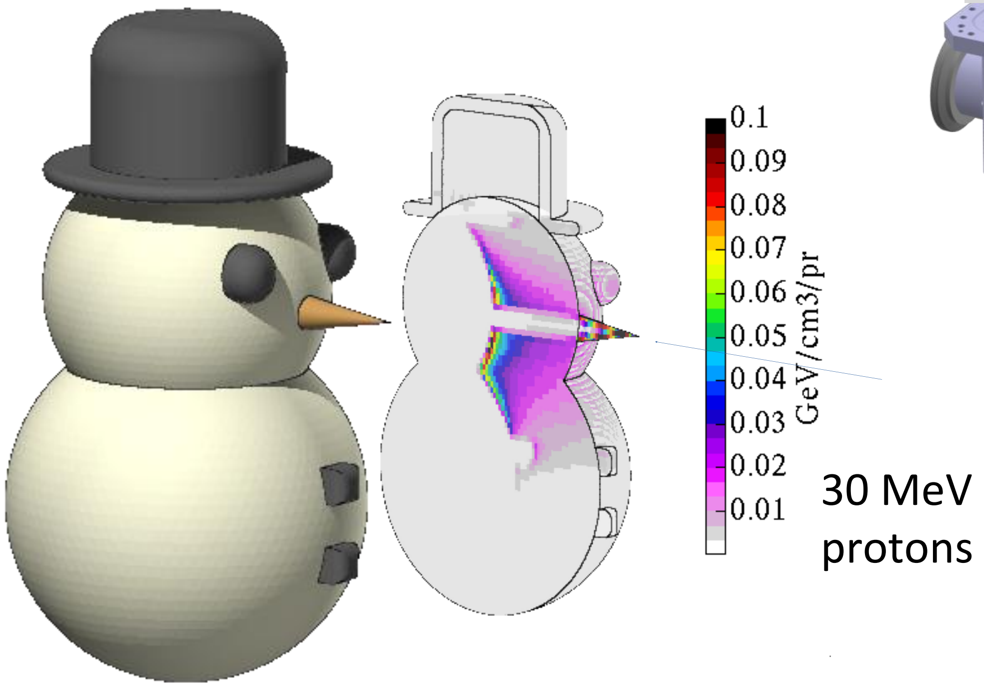
PLA po_4   Nx: 2   Ny: 0   Nz: -6
x: 3   y: 0   z: 3

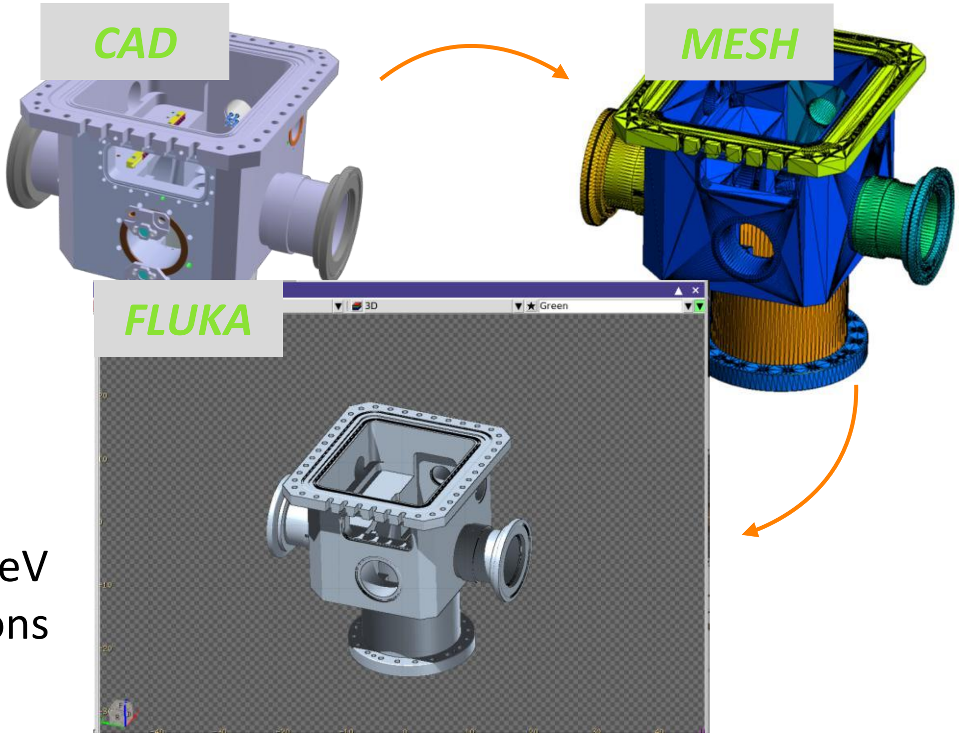
define the transformation for lattice cell Target2
rot.numb.   theta   phi   dx   dy   dz
ROT-DEFINI   Axis: Z ▾   Id: 1   Name: tr
Polar: 0.0   Azm: 0.0
Δx: 0.0   Δy: 0.0   Δz: -10.0

define region TARGRP as a replica, with name Target2, associated to roto-traslation number 1
LATTICE tr ▾   Reg: TARGRP ▾   to Reg: ▾   Step:
Lat: Target2   to Lat: Step:

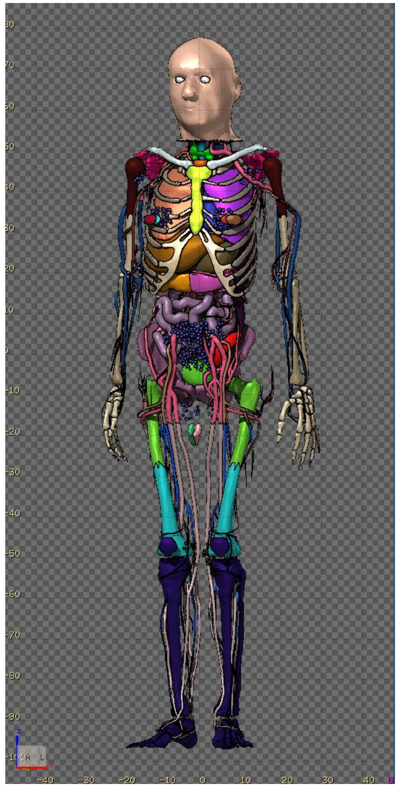
CAD / unstructured meshes

- Geometries can be described also using unstructured meshes:
  - More precise geometry descriptions (including gaps, penetrations, details)
  - ...but more complicated to perform parametric scans (varying a single element in the geometry)



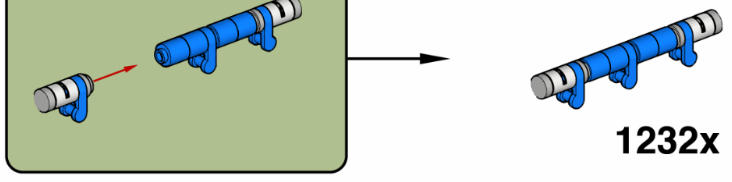


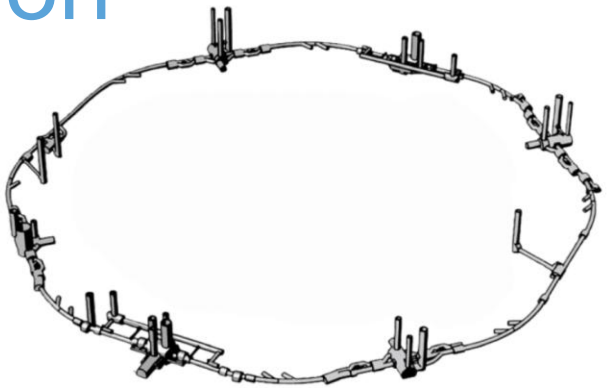
ICRP P145 phantom
(initialization < 10 s)



Linebuilder: a specific accelerator solution

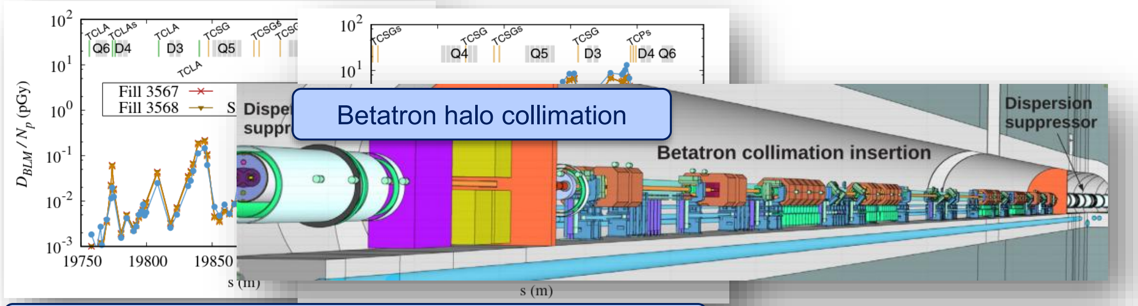
Elementary models + instruction set



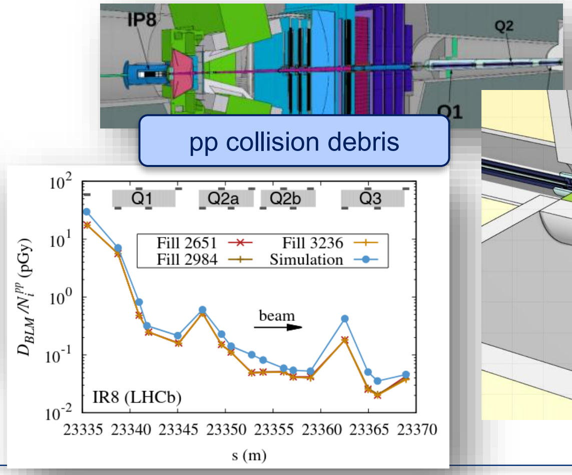


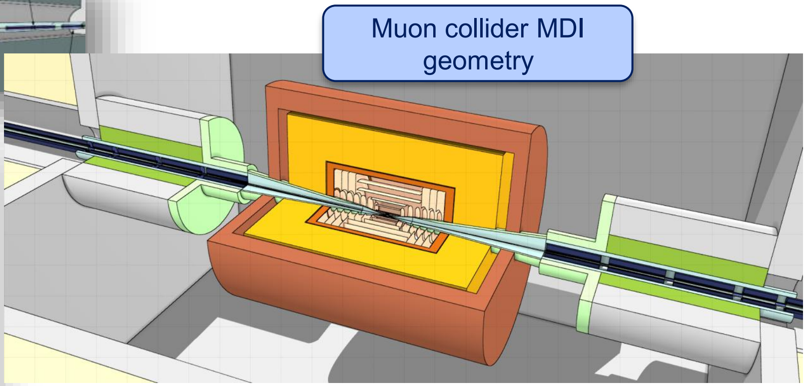
- Together with FEDB (FLUKA Element DataBase), organize all the necessary information for creating complex, modular and detailed geometry
- Build beamlines in 3D
- Automatically handles the scorings (USRBIN)

Now public [here](#)!



A. Lechner et al., Phys. Rev. Accel. Beam (22), 071003, 2019.



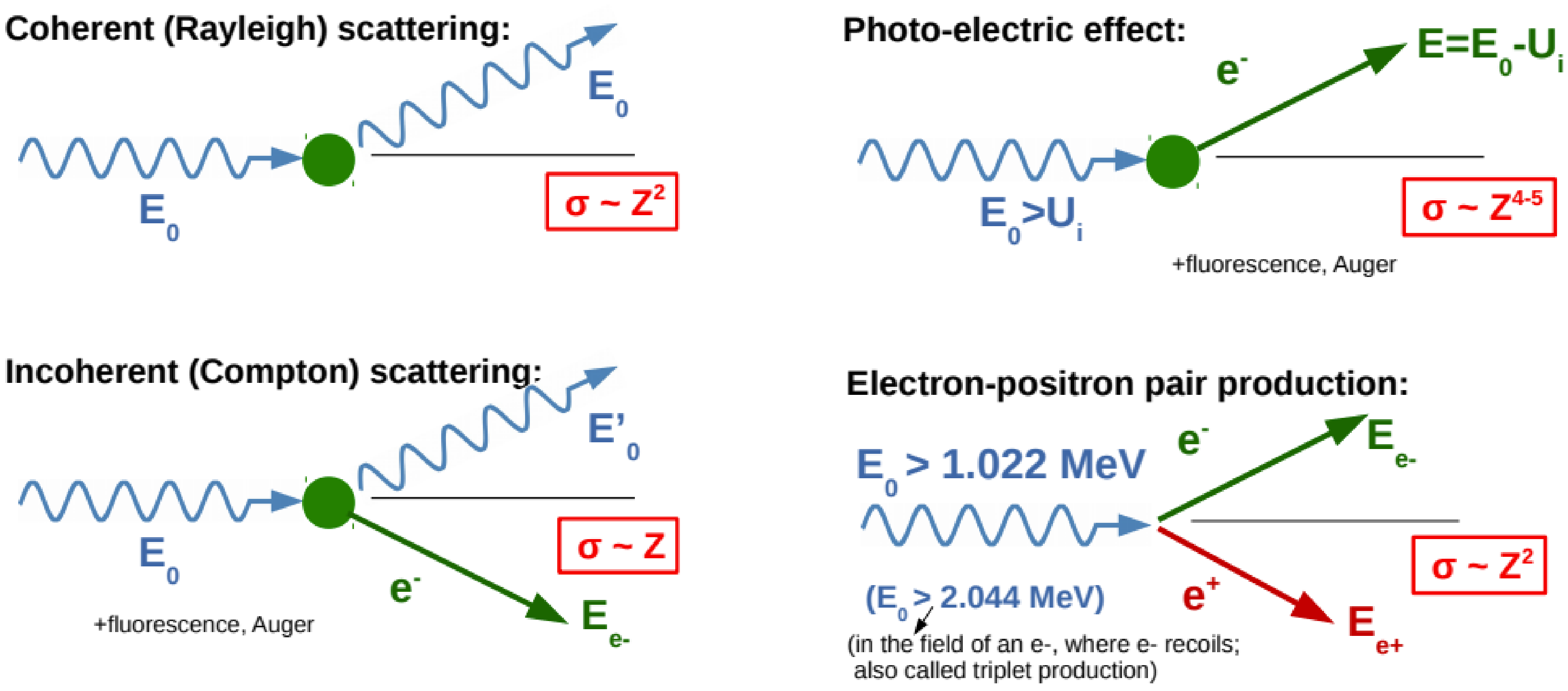


3. Main interaction models

Photon interactions basics

- Photons can be produced by many different mechanisms:
  - Bremsstrahlung emission
  - Gamma de-excitation after nuclear reactions
  - Radiative neutron capture
  - Electron-positron annihilation
  - Particle decay (e.g., π^0)

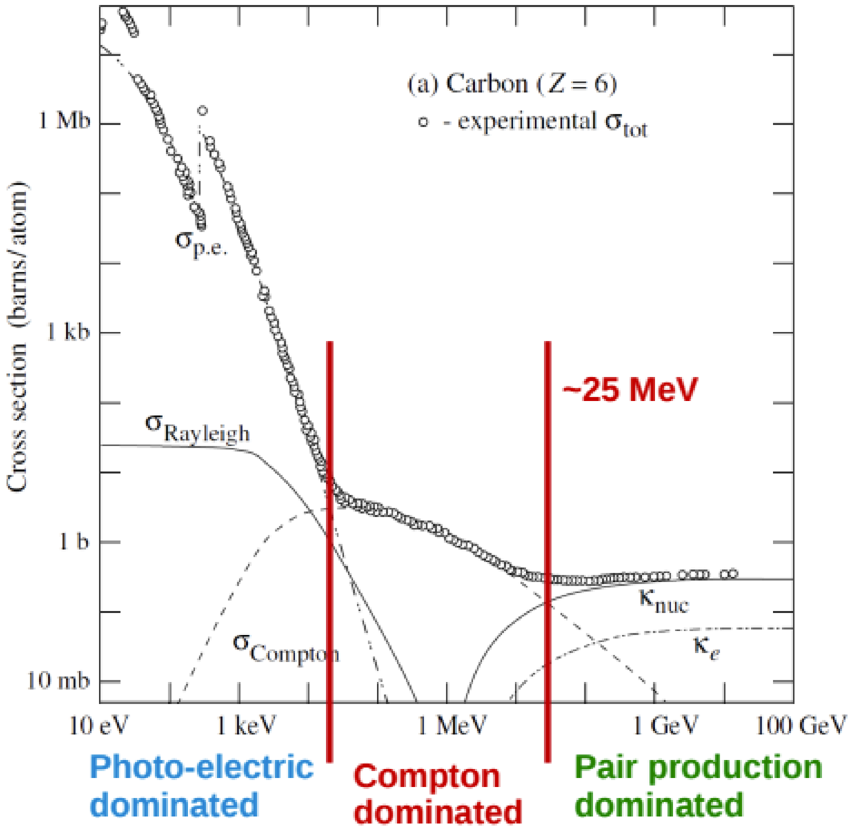
- Their interaction mechanisms vary depending on the photon energy and on the target material:



+ photo-nuclear reactions

Photon interactions cross sections

Figures from: C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).



$\sigma_{p.e.}$ = **Photo-electric effect**

$\sigma_{Rayleigh}$ = **Coherent scattering**

$\sigma_{Compton}$ = **Incoherent scattering**

κ_{nuc} = **Pair production in field of nucleus**

κ_e = **Pair production in field of electron**

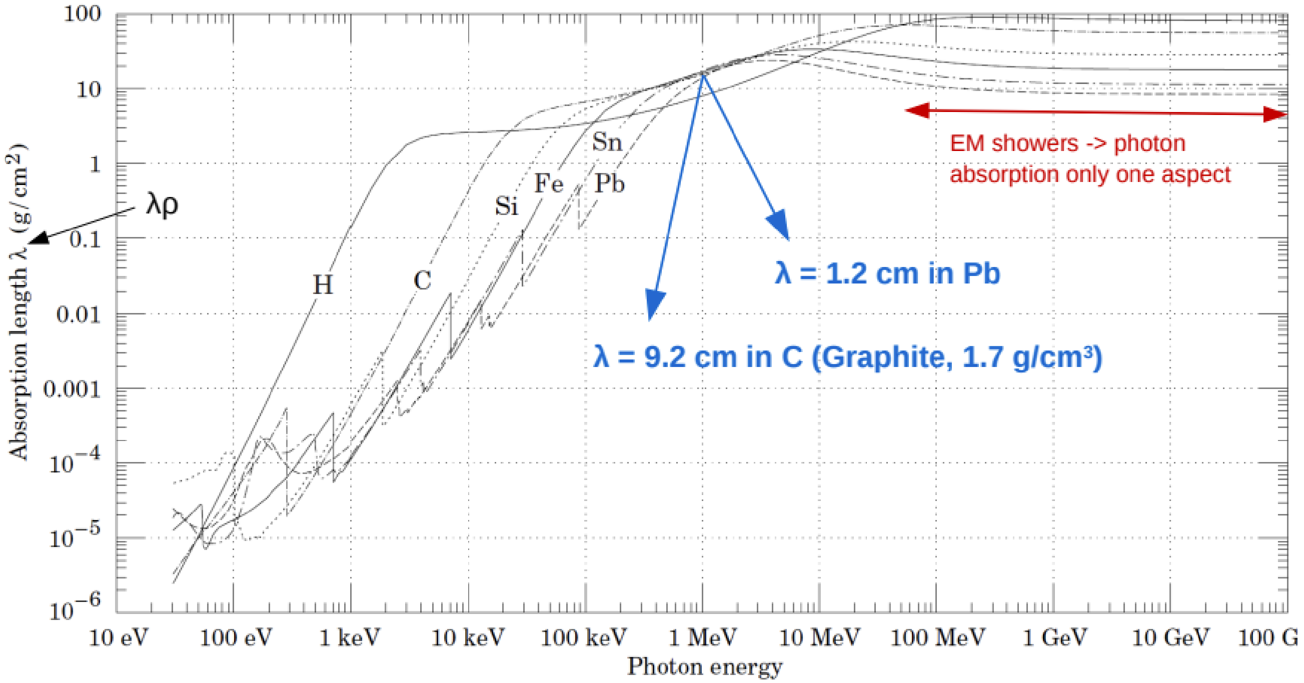
$\sigma_{g.d.r}$ = **Giant Dipole Resonance**

Mass attenuation length $[\frac{mass}{area}]$ **(absorption length)**

$$\lambda\rho = \frac{M}{N_A \sigma_{tot}} \quad \text{where} \quad \sigma_{tot} = \sum_i \sigma_i$$

Mass attenuation coefficient $[\frac{area}{mass}]$

$$\mu_m = \frac{1}{\lambda\rho}$$



Extra: photonuclear reactions (lower cross sections)

Charged particle interactions with electrons and nuclei

Coulomb interactions with atomic electrons

- Leads to the **ionization** (or excitation) of the atoms, with the production of knock-off electrons (δ-rays if high-E)
- Most relevant energy loss mechanism up to:
  - Tens of MeV for $e^{+/-}$
  - Hundreds of GeV or more for $\mu^{+/-}$ and charged hadrons*
- Causes energy deposition in the material → heating

Coulomb interactions with atomic nuclei

- Dominant source of **angular deflections** for charged particles
- The associated energy loss is referred to as Non-Ionizing Energy Loss (NIEL)
- In general, NIEL is less relevant than atomic electron losses, except for low-energy heavy ions

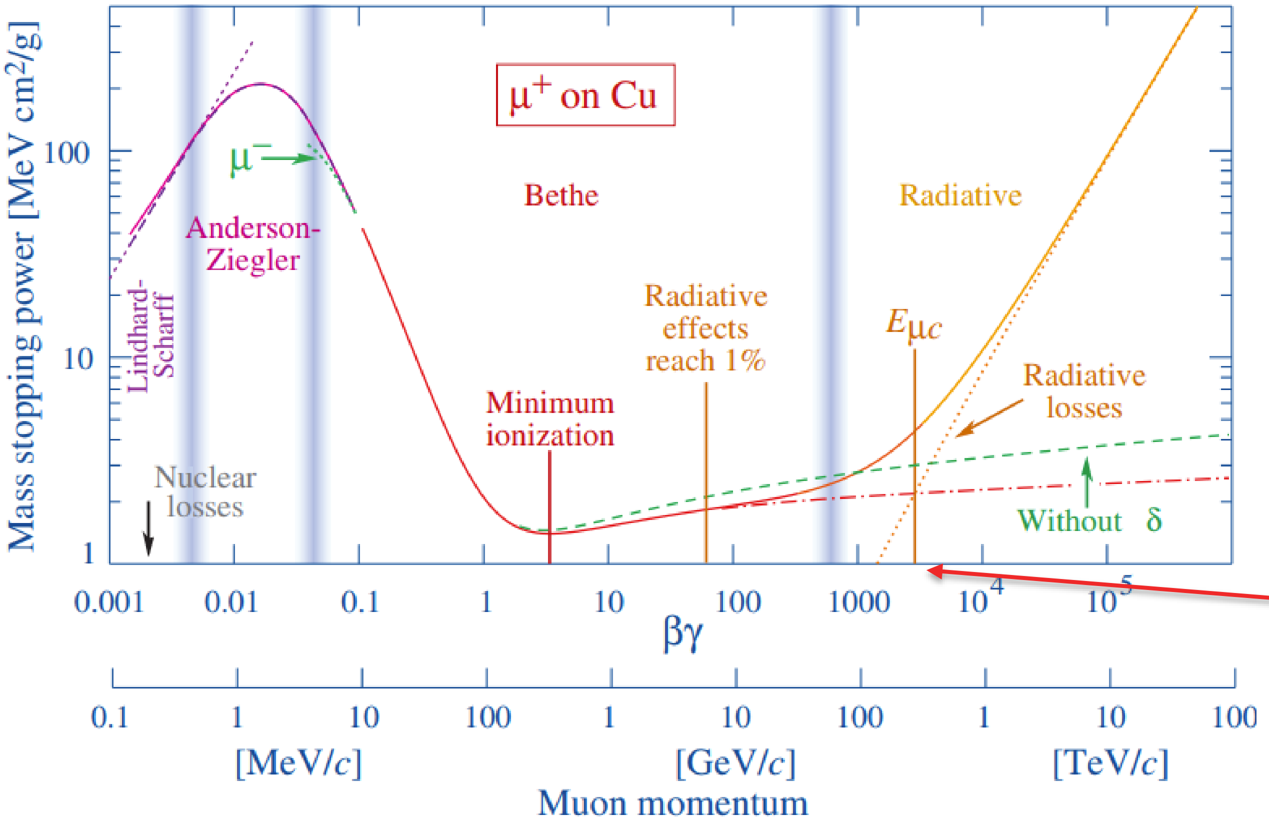
Radiative processes

- Lead to the emission of photons from the interaction between the particle and the field of the atomic nuclei
- Dominant energy loss mechanism for high-energy projectiles*

**for high-energy hadrons, nuclear interactions play a major role in the energy loss mechanisms*

Coulomb interactions with atomic electrons: Bethe formula

Mass stopping power: $\frac{dE}{dx}\frac{1}{\rho}$ *in units* : $\left[\frac{MeV}{cm}\frac{1}{g/cm^3} = \frac{MeV\ cm^2}{g}\right]$



Figures from: C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

- Key equation describing the energy losses via ionization for all charged particles heavier than $e^{+/-}$
- High stopping power at low energies due to high photoelectric cross sections
- Minimum Ionizing Particles (MIP) at $\beta\gamma \approx$ 3-3.5, releasing 1-2 MeV cm^2/g
- Radiative losses dominate at high energy
- At the critical energy E_C, ionization and radiative stopping power are equal:

$$\left.\frac{dE}{dx}(E_c)\right|_{ioni} = \left.\frac{dE}{dx}(E_c)\right|_{rad}$$

- For $e^{+/-}$, E_C is substantially lower

Nuclear interactions: introduction

In nuclear interactions, the strong force plays a major role (but electroweak processes also take place)

ELASTIC INTERACTIONS

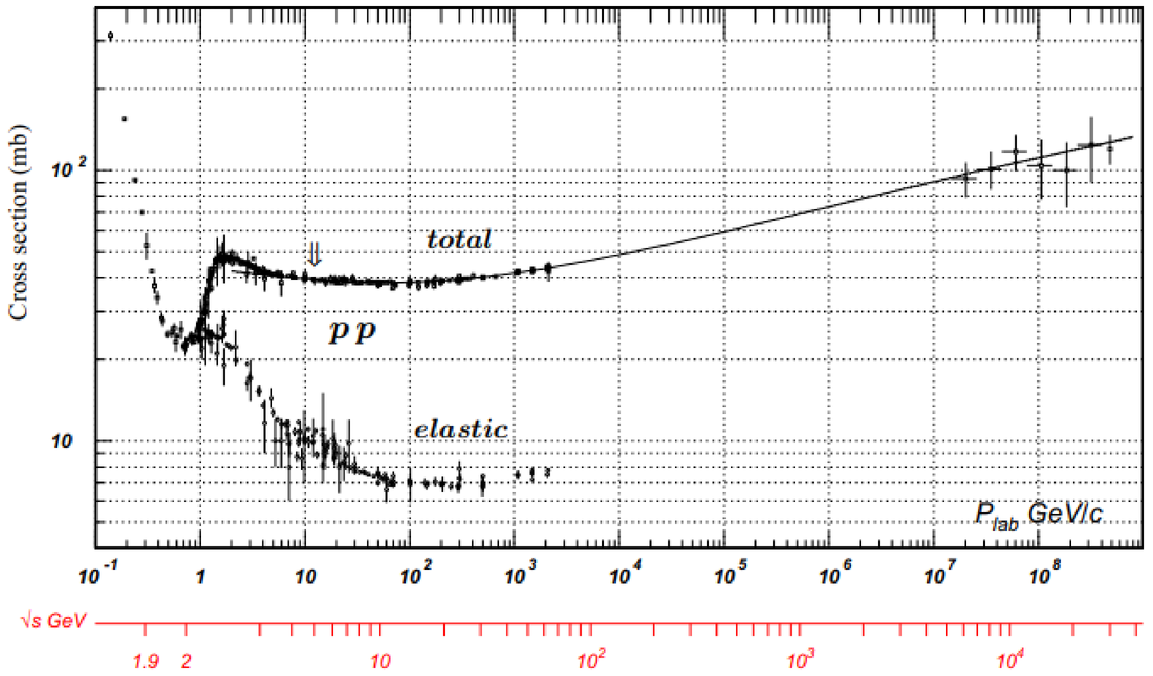
- Do not modify the internal structure of the particles involved in the interaction, i.e., the initial and final states are the same
- They "only" yield energy transfer (including the recoil of target nuclei in projectile-nucleus reactions) and angular deflections
- There are no energy thresholds
- They are highly relevant for neutral projectiles (e.g., neutrons) at low energy. For charged projectiles, they compete with Coulomb scattering.

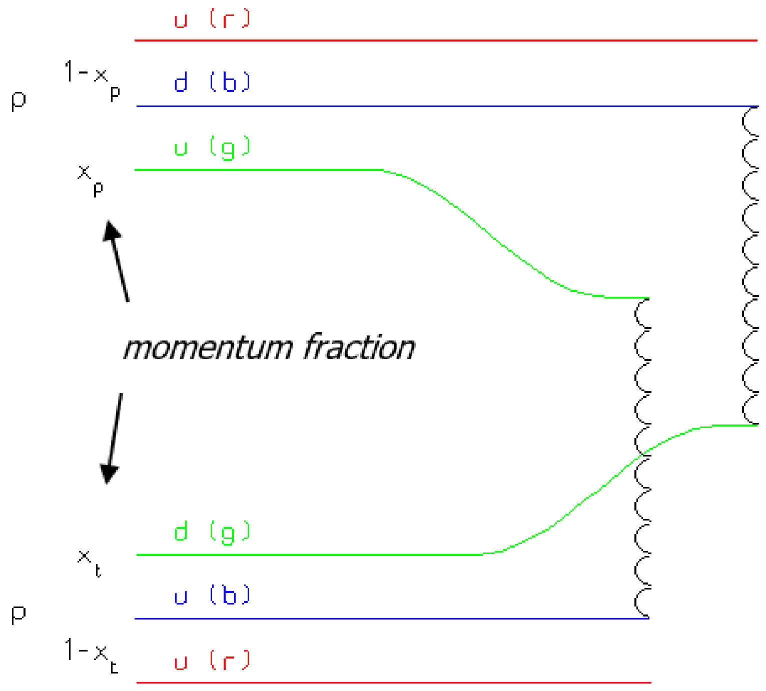
INELASTIC INTERACTIONS

- The internal structure of the particles is modified in the interaction, and/or new particles are produced
- Energy thresholds are usually present, because typically one needs a minimum amount of energy to "break" the incoming particles/nuclei, produce new particles (e.g., pions), and/or excited nuclear states.
- Exception: neutron capture (inelastic interaction with no threshold)

Nuclear interactions: nucleon-nucleon cross sections

- Nucleon-nucleon cross sections are the basis to understand more complex cross sections with nuclei.
- At low energies, elastic interactions are dominant. At intermediate energies, the reactions proceed through intermediate resonant states (e.g., Δ(1232))
- At high energies, the cross section is driven by inelastic processes involving single partons (quarks/gluons), and it reaches a constant value for both pn and pp reactions.

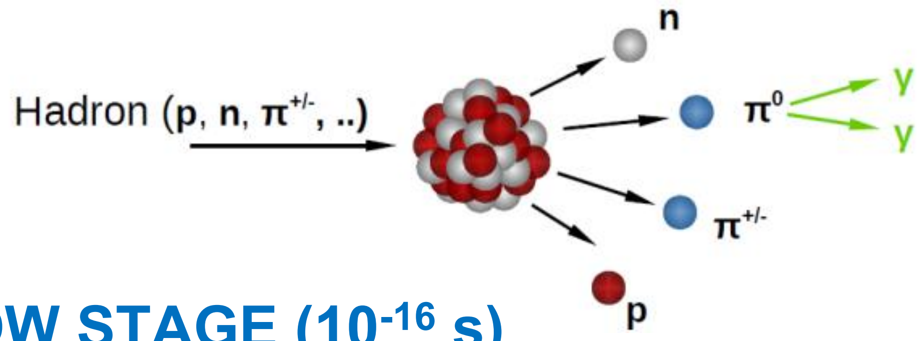




Inelastic hadron-nucleus reactions

FAST STAGE (10^{-22} s)

The projectile interacts with nucleons, producing secondaries (mainly π, but also, other hadrons, γ…) with high multiplicity (≈log[E])

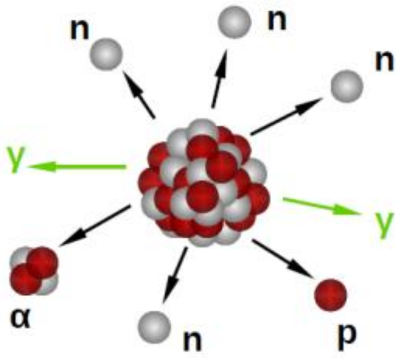


The more energetic secondaries leave the nucleus and develop a **forward-directed hadronic cascade** (see next slides)

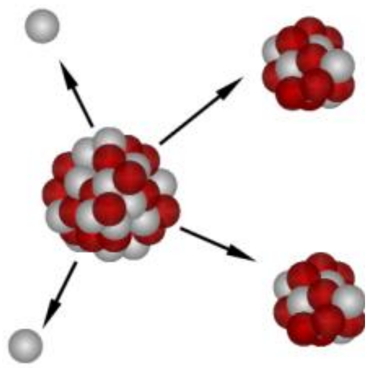
The less energetic secondaries can deposit energy within the nucleus, leaving it into an excited state

SLOW STAGE (10^{-16} s)

MeV-scale light fragments from **evaporation** and photons from **γ-deexcitation**



Heavier fragments from **fission** (when possible)



In summary, one gets:

- An energetic hadronic shower from the fast stage*
- MeV-scale fragments and photons
- Optionally, fission products (that may be radioactive, as the residual nuclei)

*if the projectile has enough energy

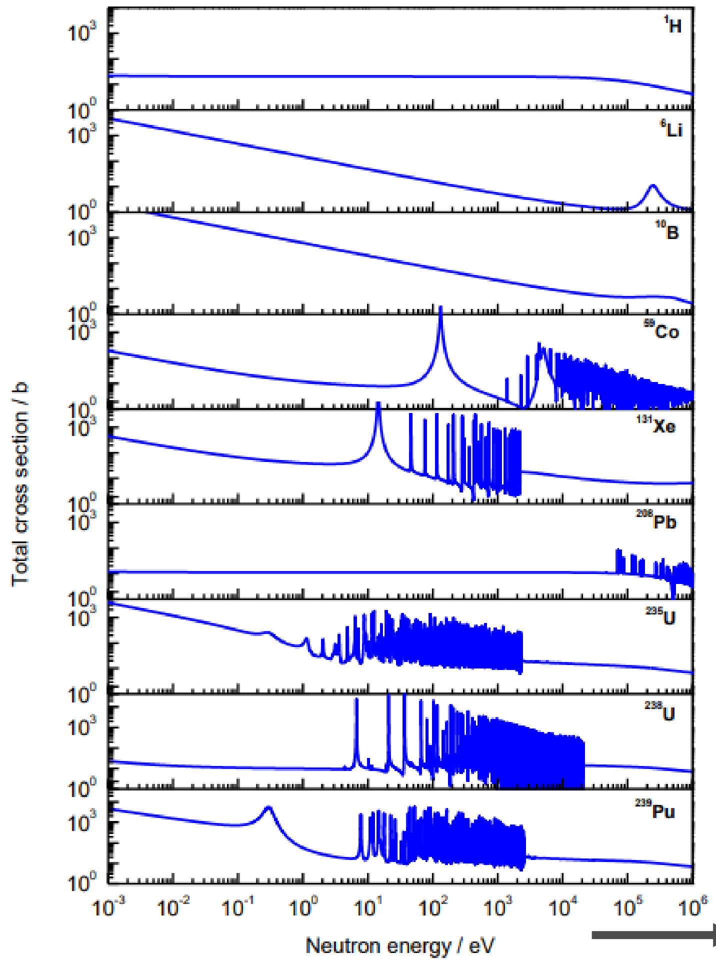
Focus on neutron interactions

- Neutrons are hadrons with unique features:
  - **Long half-life (>10 minutes)** → effectively stable
  - **No charge** → no Coulomb force
- They travel long distances through matter, and they undergo a **moderation** process, i.e., they progressively lose their energy via a sequence of elastic nuclear interactions
- Eventually they can **thermalize**, i.e., their kinetic energy can drop to the thermal scale (≈25 meV at room temperature)

TYPICAL NEUTRON CROSS SECTION PATTERN:

Low-E (≲ eV)*	**eV-MeV range***	**High-E (>MeV)***
σ decreases with E (σ≈1/v), n capture reactions take place	Resonances are present, varying with the target nucleus (difficult to model)	The behaviour becomes similar to the one of the other hadrons

*highly variable with A



Increasing *A*

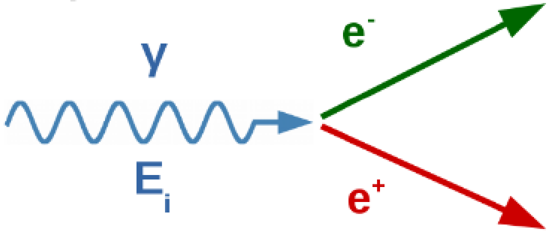
>MeV region not shown

P. Schillebeeckx et al., "Neutron Resonance Spectroscopy for the Characterisation of Materials and Objects", Report EUR 26848 EN (2014)
DOI: 10.2787/98278

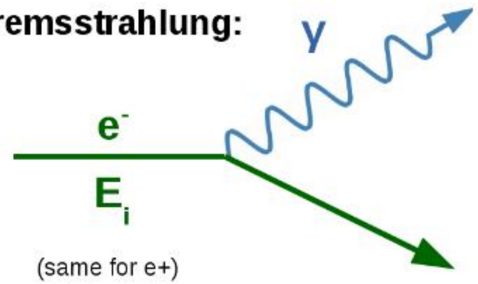
High-energy $e^{+/-}$, γ: electromagnetic (EM) showers

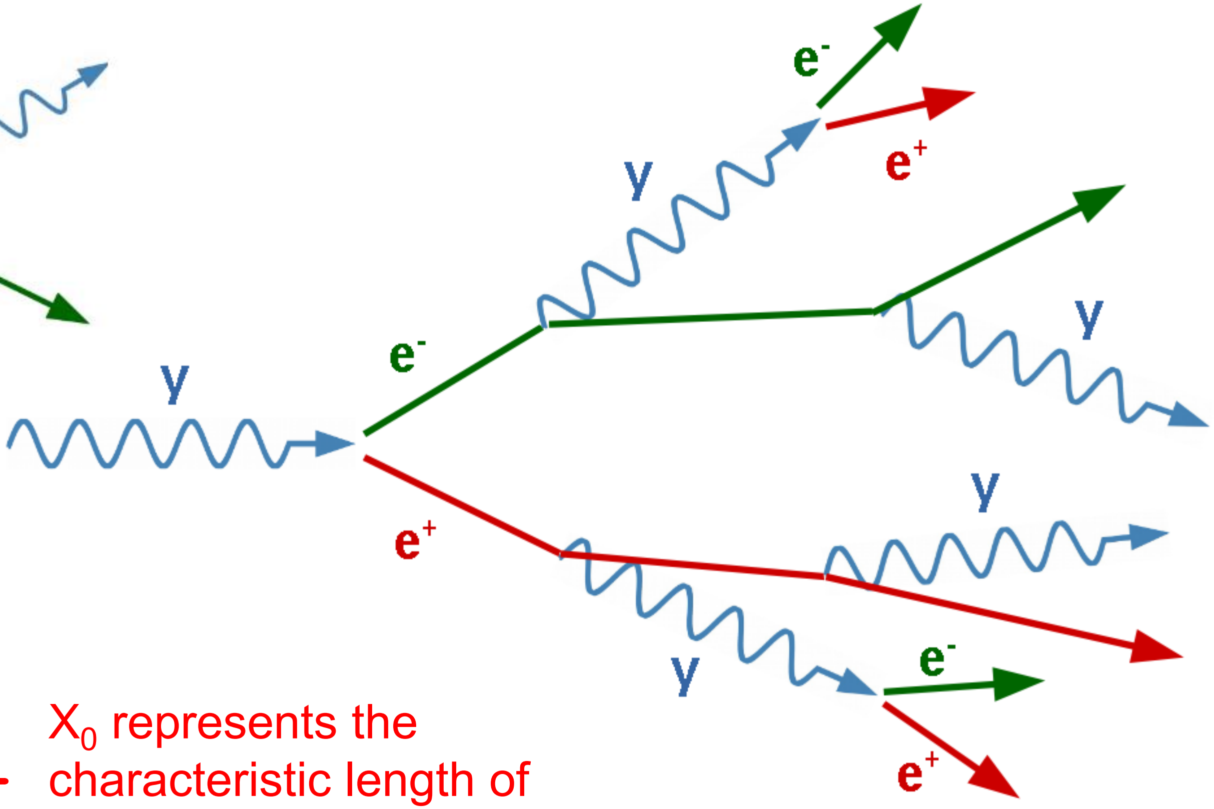
- When the projectiles are above the previously introduced critical energy E_C, the dominant interaction mechanisms in matter are:

Pair production:



Bremsstrahlung:





- An **electromagnetic shower (or cascade)** develops, where the above processes are repeated until the produced particles fall below E_C

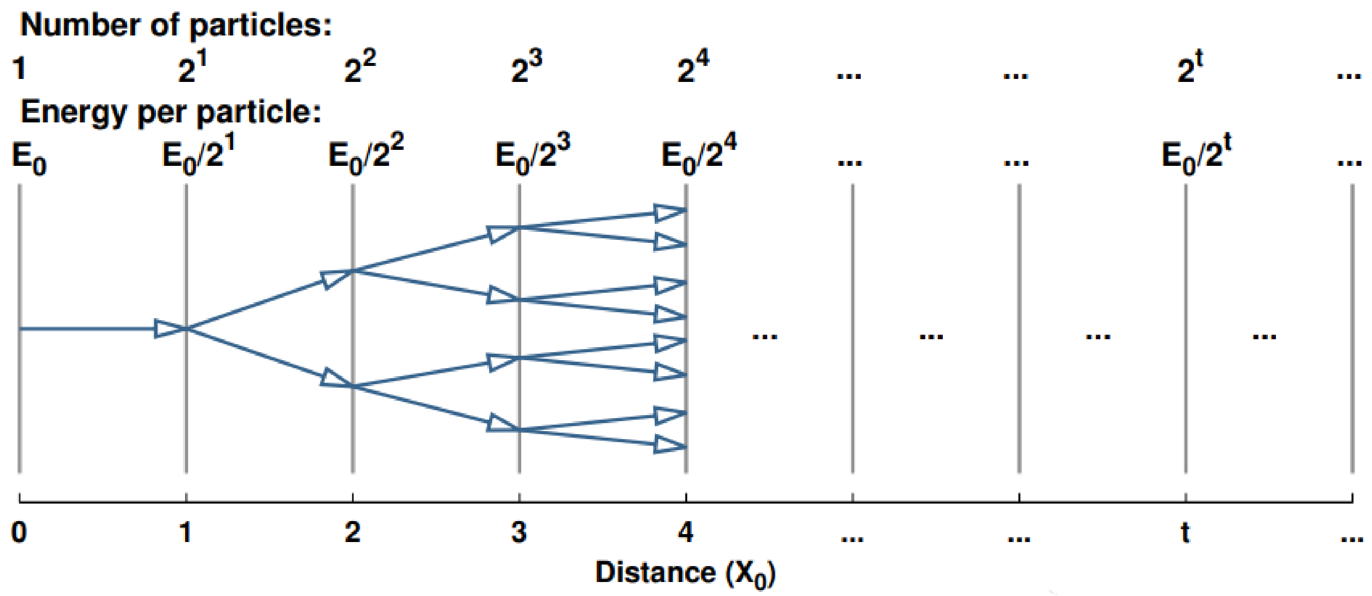
- The key parameter is the **radiation length X_0:**
  - Mean distance over which the energy of $e^{+/-}$ is reduced to 1/e
  - 7/9 of the photon Bremsstrahlung mean free path

X_0 represents the characteristic length of the EM shower steps

Note: neutrons can also appear (with relatively low abundance) from photonuclear reactions

EM showers: key features and energy deposition

EM shower evolution vs depth, in units of X_0 ($t = z/X_0$):



- Maximum number of particles at depth t_{max}:

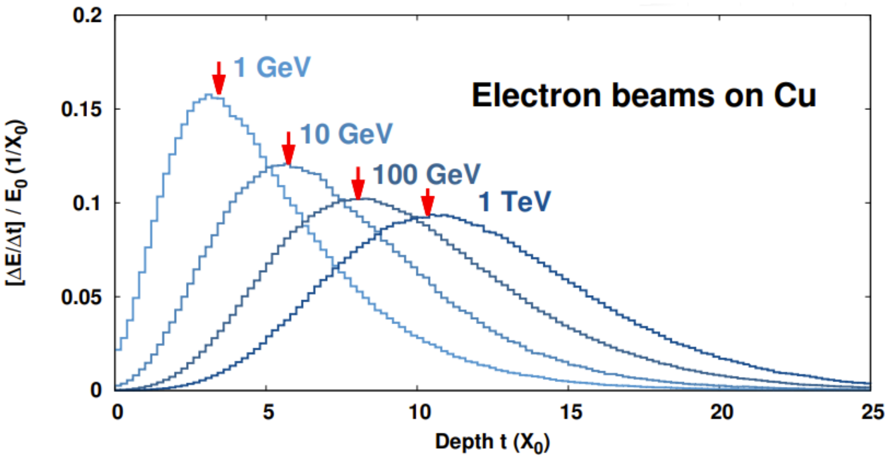
$$t_{max} \propto \ln\left(\frac{E_0}{E_C}\right)$$

(typically a few X_0 depending on projectile energy and material)

- The peak energy deposition in the target material (important to assess the impact of the shower!) is typically right before t_{max}

X_0 by material, where $\frac{X_0}{\rho} \propto \frac{A}{Z^2}$

Material	*Z*	Density	X_0
Graphite	6	2.21 g/cm^3	19.32 cm
Al	13	2.699 g/cm^3	8.90 cm
Fe	26	7.874 g/cm^3	1.76 cm
Cu	29	8.96 g/cm^3	1.44 cm
W	74	19.30 g/cm^3	0.35 cm
Pb	82	11.35 g/cm^3	0.56 cm

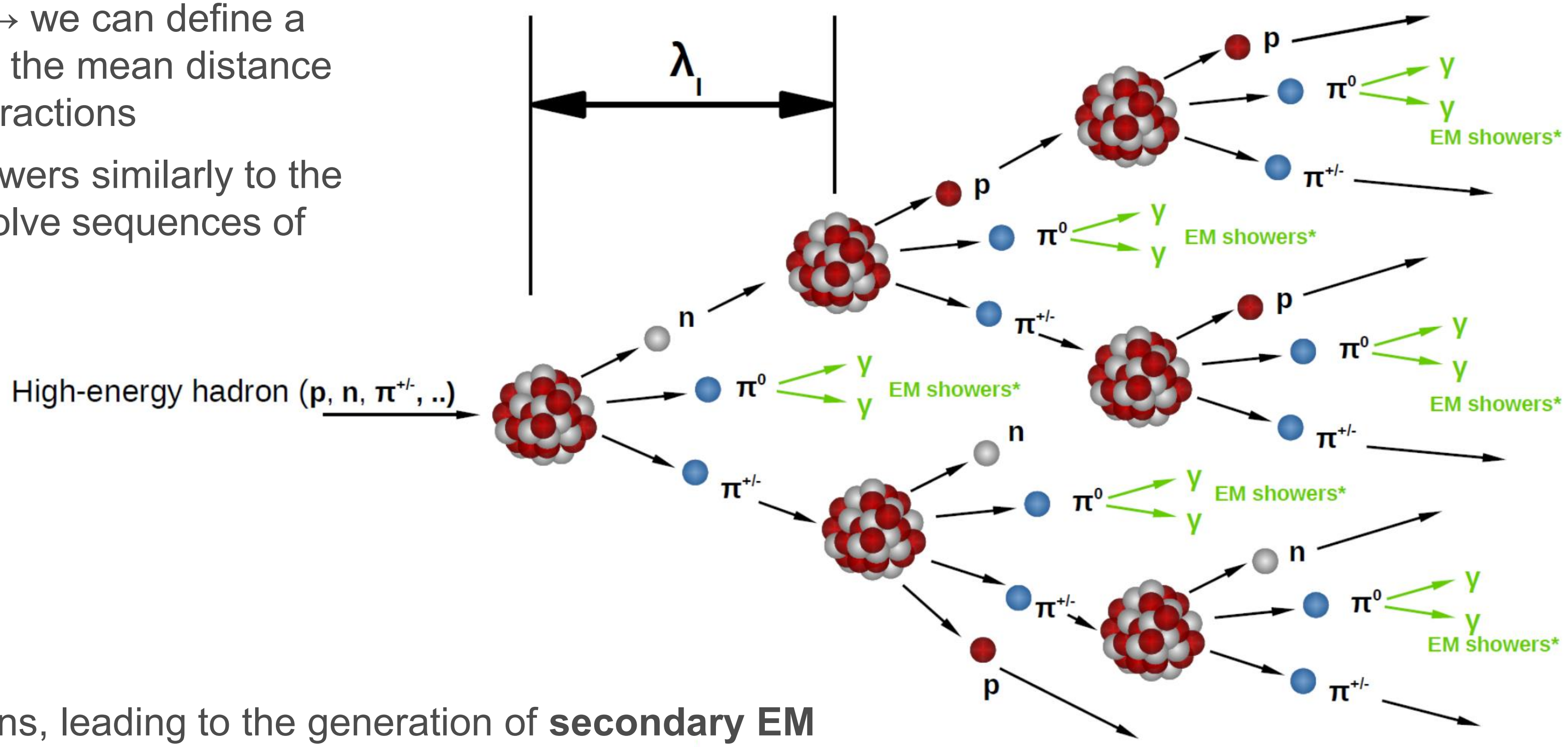


Hadronic showers

Mat	Z	Density	X_0	λ_I
C	6	2.2 g/cm^3	21.4 cm	37.3 cm
Al	13	2.7 g/cm^3	8.90 cm	35.4 cm
Fe	26	7.8 g/cm^3	1.76 cm	15.1 cm
Cu	29	8.96 g/cm^3	1.44 cm	13.9 cm
W	74	19.3 g/cm^3	0.35 cm	8.9 cm
Pb	82	11.4 g/cm^3	0.56 cm	15.7 cm

Source: FLUKA, λ_I for 7 TeV protons

- We have seen that the interaction cross section of high energy hadrons tends to stabilize → we can define a **nuclear interaction length λ_I**, i.e., the mean distance travelled between two inelastic interactions
- High energy hadrons generate showers similarly to the electromagnetic ones, but they involve sequences of hadronic interactions
- λ_I is the key parameter of hadronic showers and it's typically longer than X_0
- The particle content of hadronic showers is richer compared to EM ones



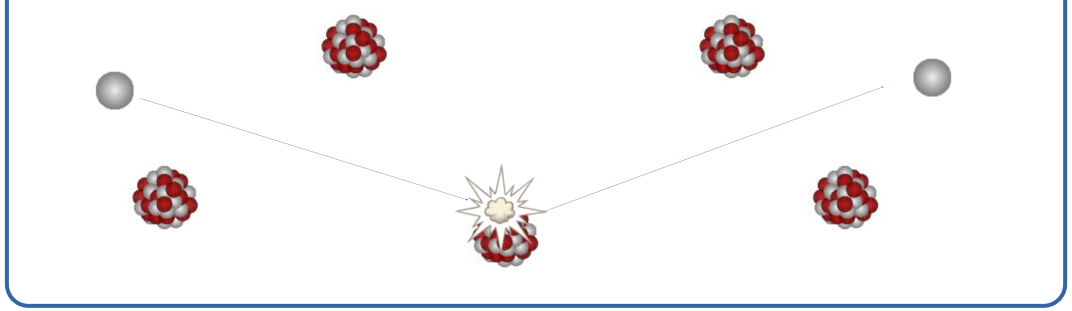
- Neutral pions decay into two photons, leading to the generation of **secondary EM showers** within the hadronic shower itself!
- The fraction of energy that goes into EM particles varies stochastically between showers

4. FLUKA main capabilities

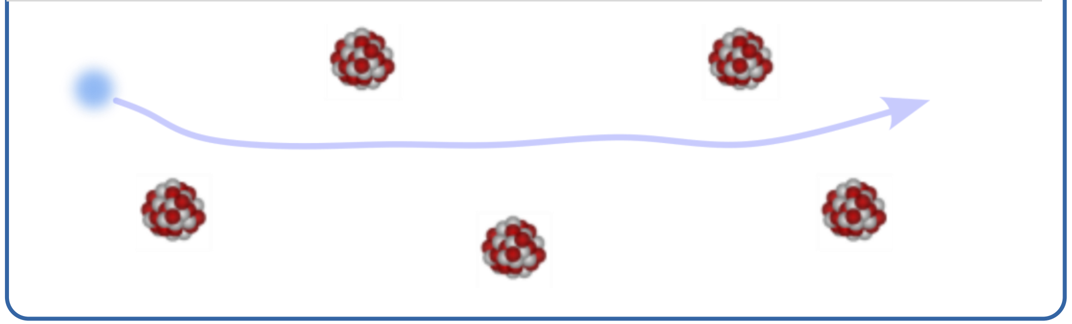
Physical processes: continuous and discrete

- Main assumption: particle scattering occurs on a single target
- Typical inter-atomic distances are ~1Å. MC simulation of electron transport << 100 eV is generally questionable

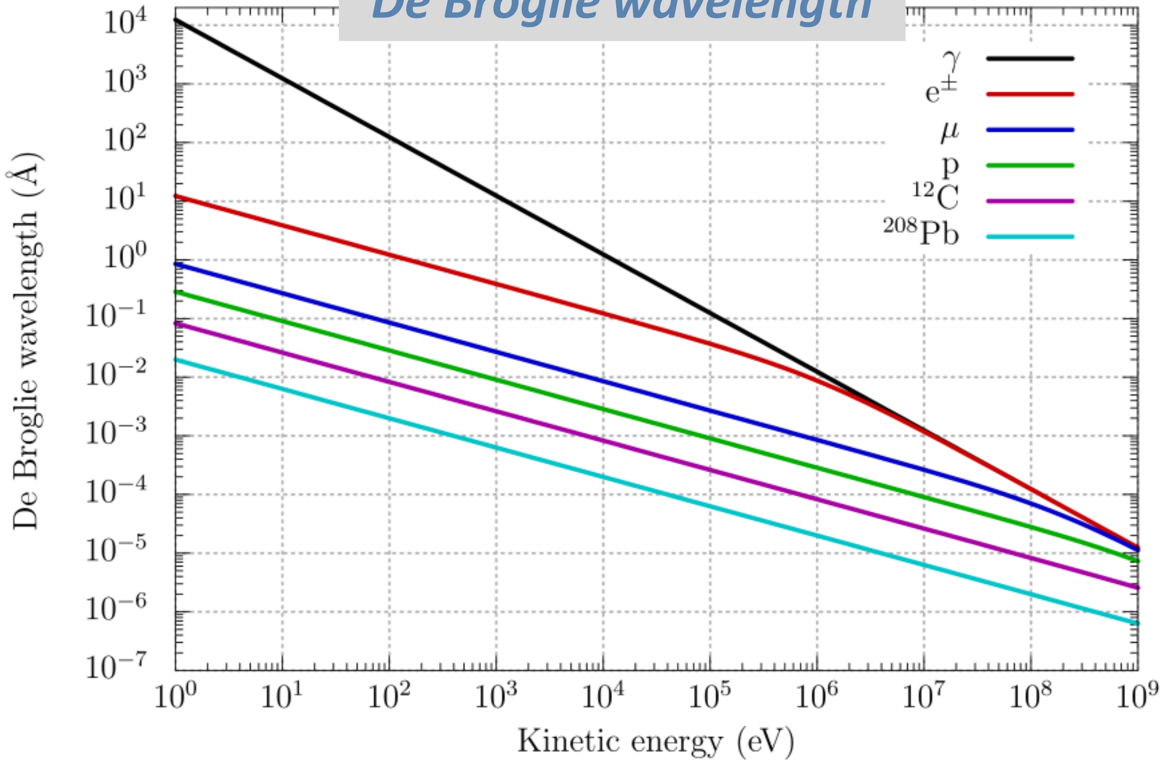
Discrete processes: simple!



Coulomb scattering & ionization: continuous



De Broglie wavelength

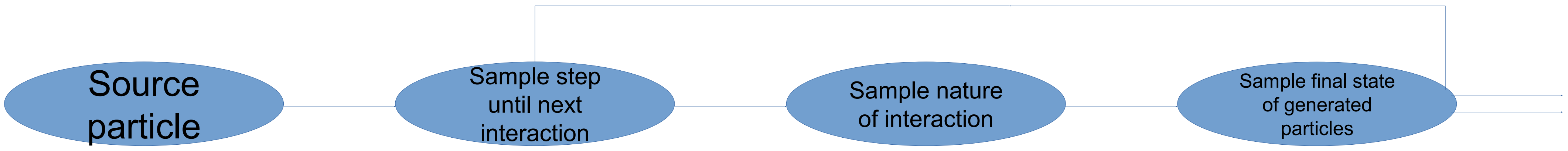


Physical processes: continuous and discrete

Main discrete interaction mechanisms

- hadron-hadron and hadron-nucleus interactions
- nucleus-nucleus interactions (including deuterons)
- photon interactions (>100 eV)
- electron interactions (> 1 keV; including electronuclear)
- muon interactions (including photonuclear)
- neutrino interactions
- low-energy (<20 MeV) neutron point-wise interactions
- particle decay
- synchrotron radiation emission

Simple algorithm: the particles are unaffected between interactions



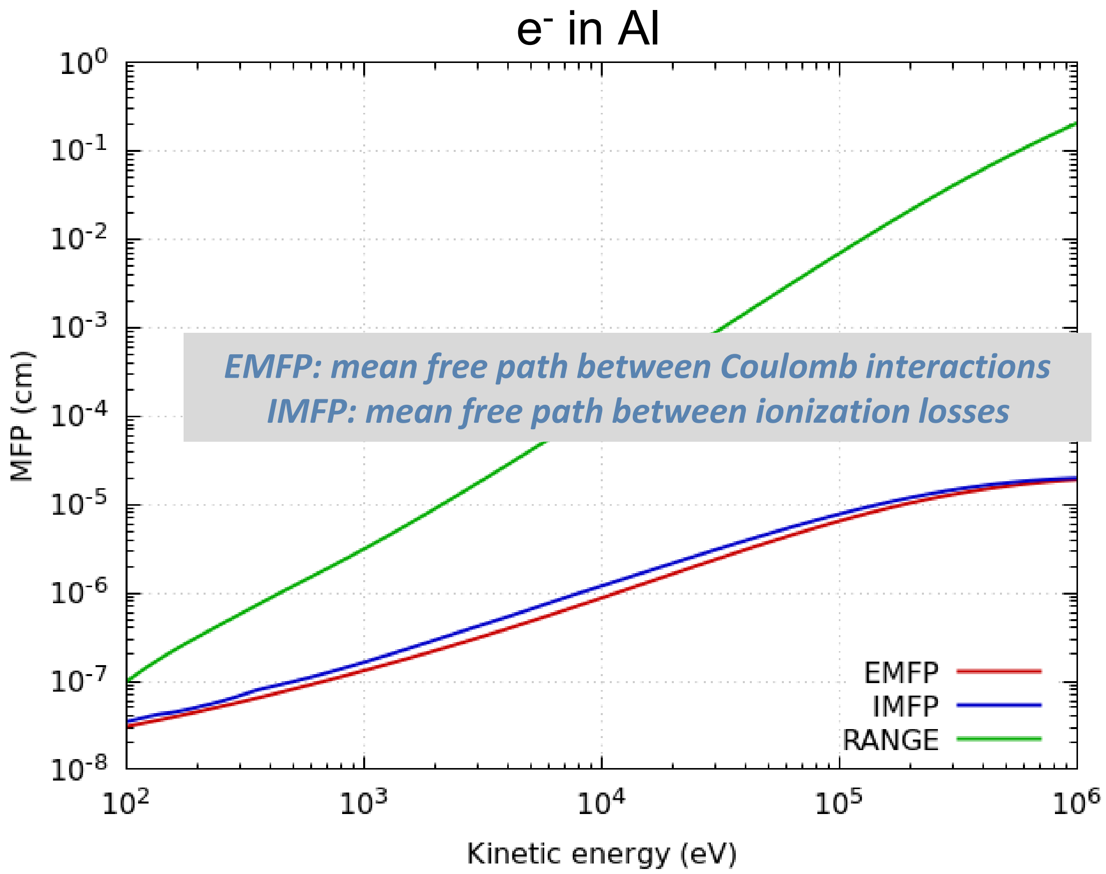
$$p(s) = (1/\lambda)\exp\left(-s/\lambda\right)$$

$$P_i = \sigma_i/\sigma$$

Physical processes: continuous

- Elastic scattering of charged particles o target atoms (**Coulomb scattering**)
- **Collisions of charged particles with targ** along the particle step

1 MeV e^- ≈ 10^4 interactions

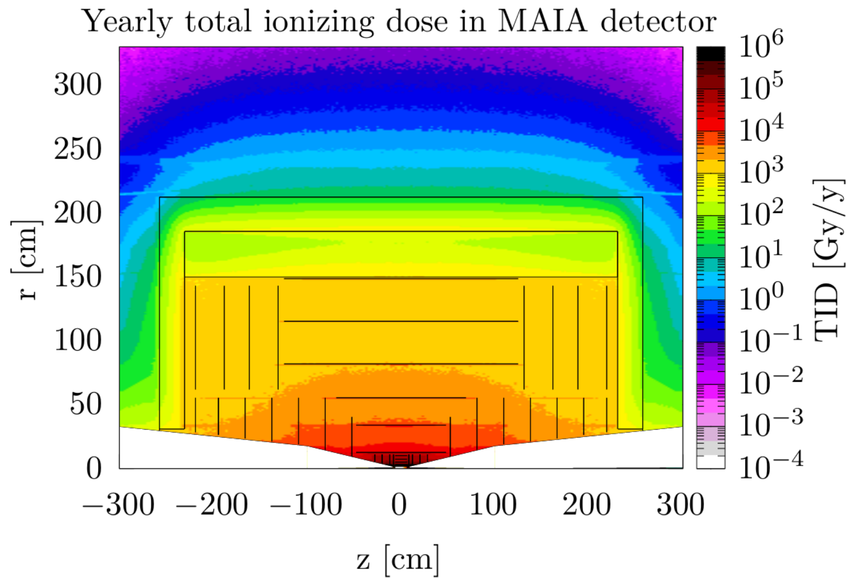


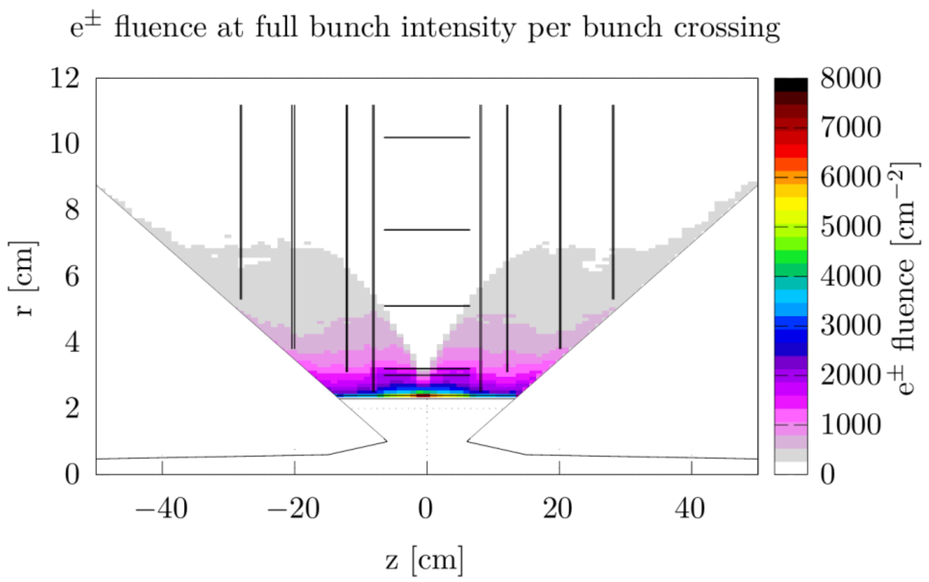
- Typical solutions: condensed history for ionization losses, and Molière theory for multiple Coulomb scattering

- **Warning**: in residual gas or thin geometries (few elastic collisions) single Coulomb scattering shall be adopted

Scoring & estimators

- The result of the Monte Carlo experiment is called **estimator**. The main types used in the MDI are:
  - Star like quantities: energy deposition, **ionizing dose**, displacement damage
  - Fluence like quantities: **$e^{+/-}$ fluence**, 1 MeV n eq. in Si
  - Double differential distribution (angle/energy) of particles crossing a boundary
  - Particle spectra in volumes
- When the full phase-space is required to transmit information, the data are stored in particle lists



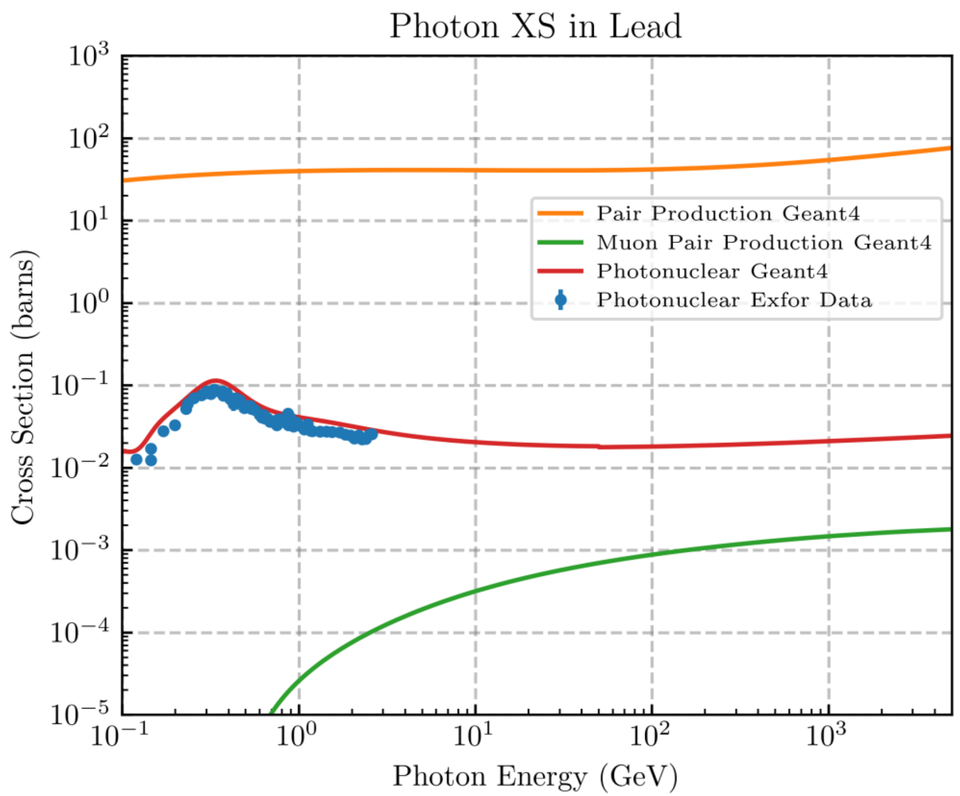


Biasing

- Biasing is a **variance reduction technique** which distort distribution to minimize the variance.

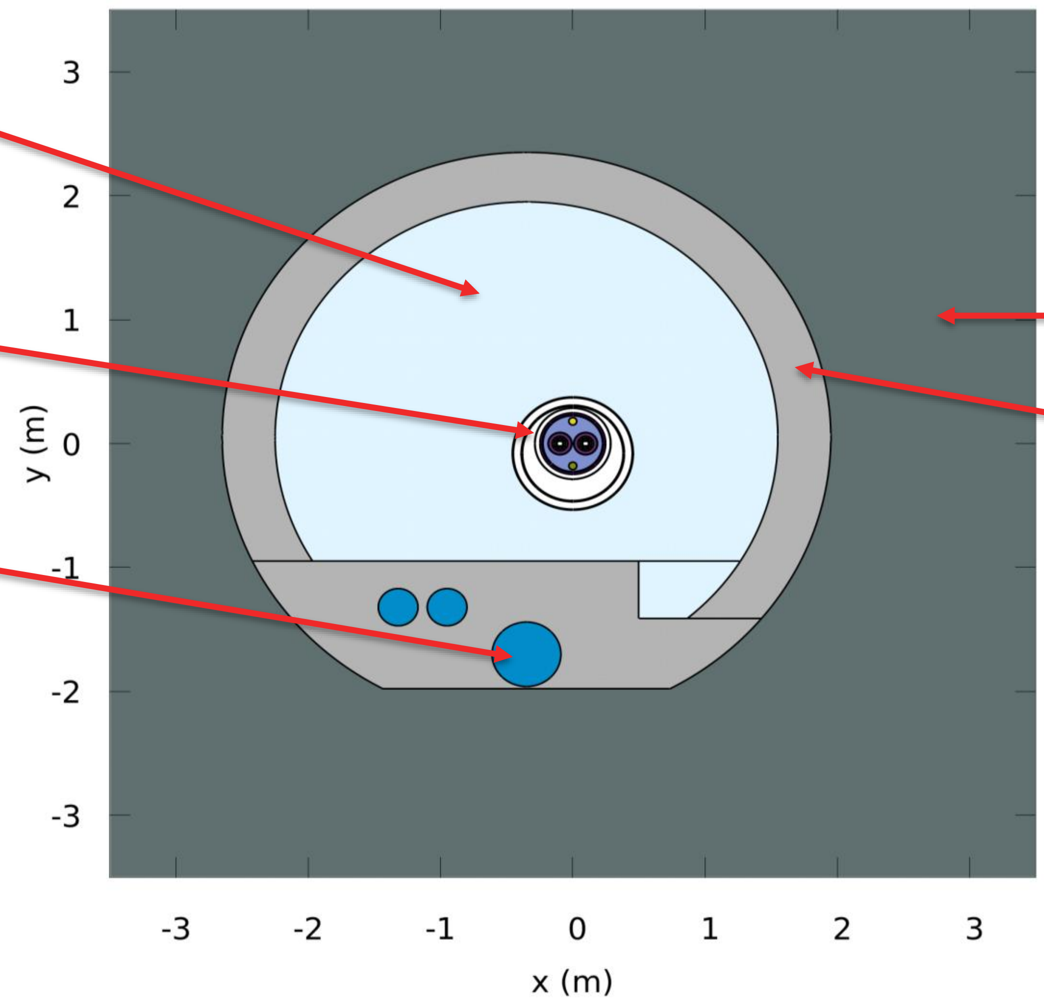
Figure of merit: $\sigma^2 t$

- Among the various techniques, the most important ones are:
  - **Region importance biasing**: applied when a particle crosses a boundary between two region with different importance
  - **Mean free path**: the cross sections are scaled by a factor to enhance the rare interactions



5. Radiation Quantities

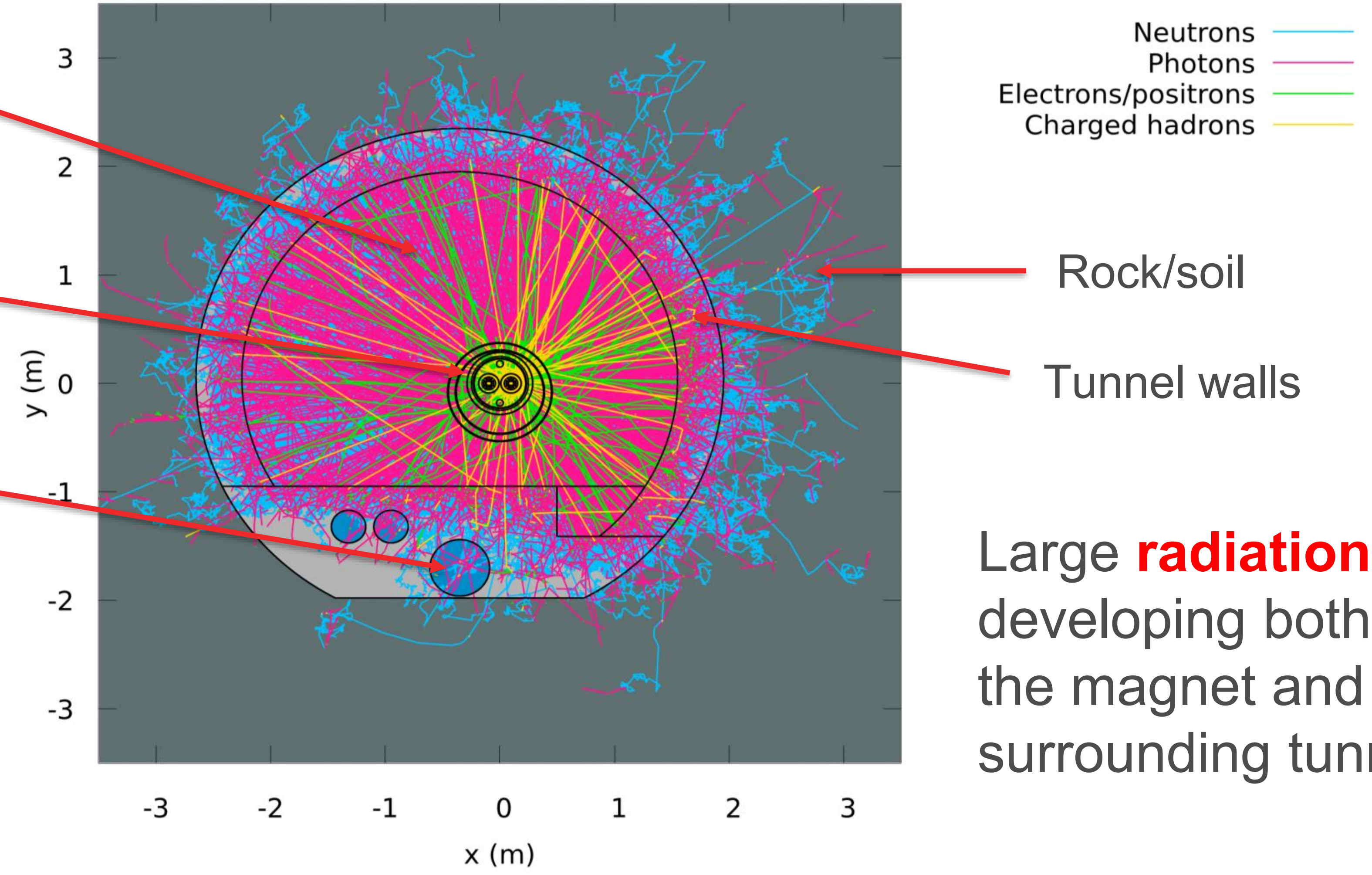
What happens in case of LHC beam losses?



FLUKA geometry: section (x-y) of the LHC tunnel showing a dipole magnet

Considering again **a single 450 GeV proton** that interacts with an LHC magnet

What happens in case of LHC beam losses?



FLUKA geometry: section (x-y) of the LHC tunnel showing a dipole magnet

Large **radiation shower** developing both within the magnet and in the surrounding tunnel!

Accidental loss: historical example from SPS (2004)

- In the pre-LHC phase, an incident occurred at the SPS during the extraction of an LHC-like beam **(450 GeV protons, $3.4 \cdot 10^{13}$ p, 2.5 MJ)**
- Major damage to the vacuum chamber, requiring a magnet replacement (weeks of downtime)

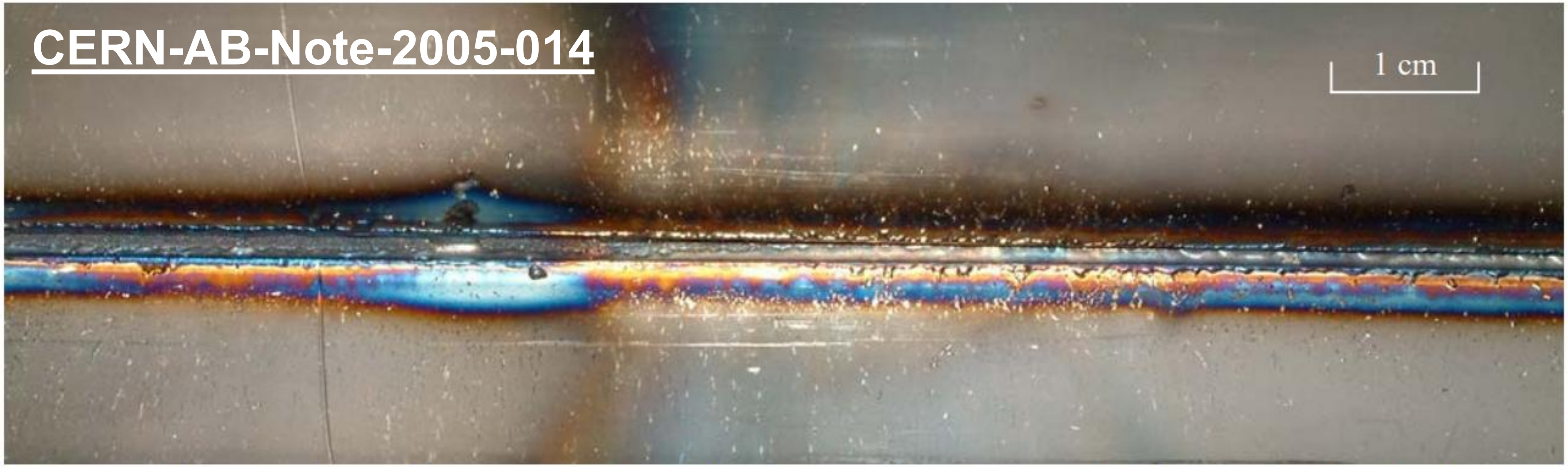


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

Energy deposition in SC magnets: quenches

- Maximum temperature increase that LHC dipole coils can sustain without losing their superconducting (SC) state:

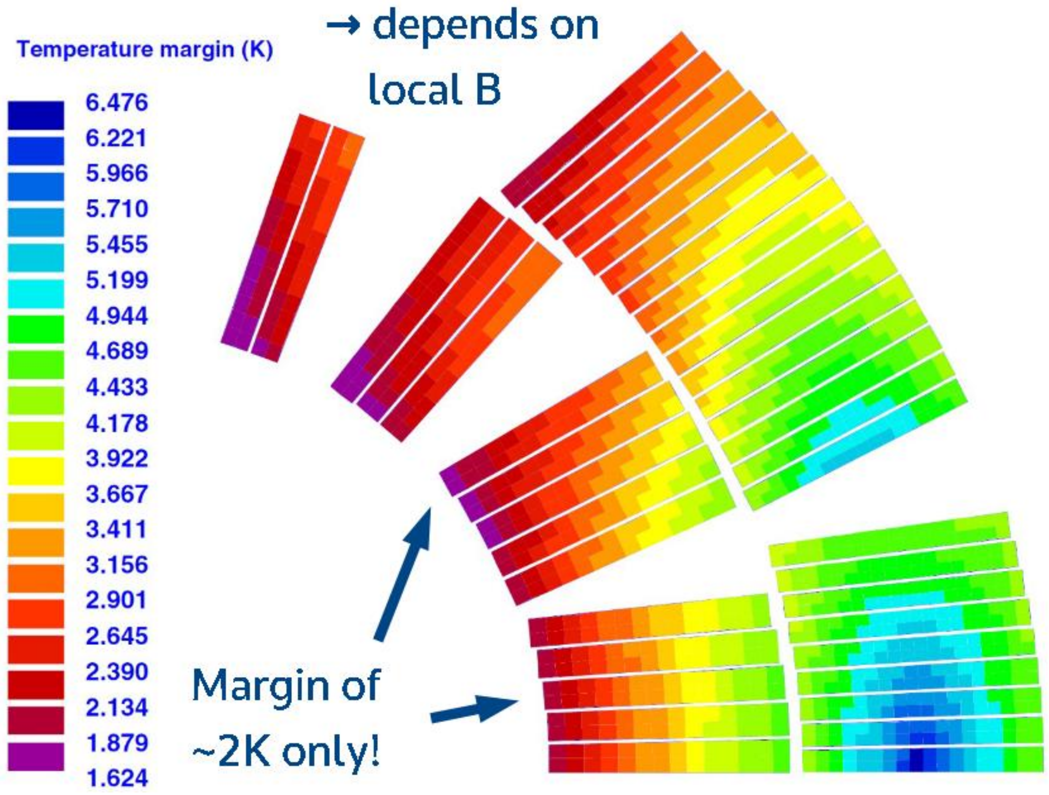


Figure of merit: Heat deposition

- There are regions where the margin is a mere increase of 2 K
- An instantaneous energy deposition of **O(mJ/cm³)** can lead to a quench
- After a quench, it can take ~1/2 day to recover (cryogenics)
- Systems are in place to protect SC magnets from quenching

Material degradation from TID

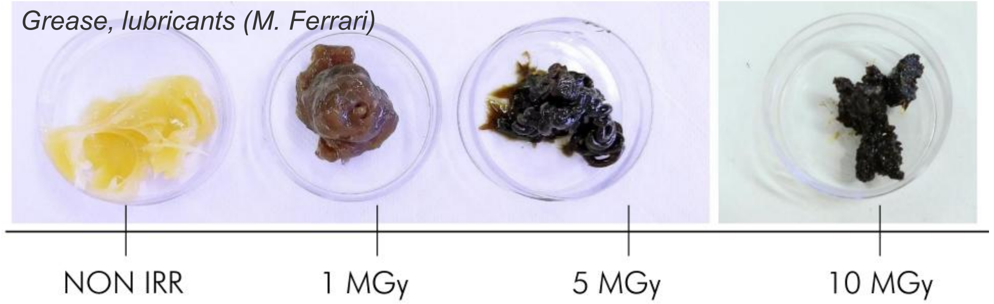
- A key observable linked to energy deposition is the **Total Ionizing Dose (TID)**, i.e., the energy deposition per unit material mass:

  $TID = E_{dep}/M$, in units of Gy = J/kg

- TID can alter the mechanical, electrical, and optical material properties of **organic materials**, compromising the integrity and the functioning of the accelerator equipment
- Damage to magnets coils and insulation is particularly critical, but TID affects also cables, lubricants, etc.

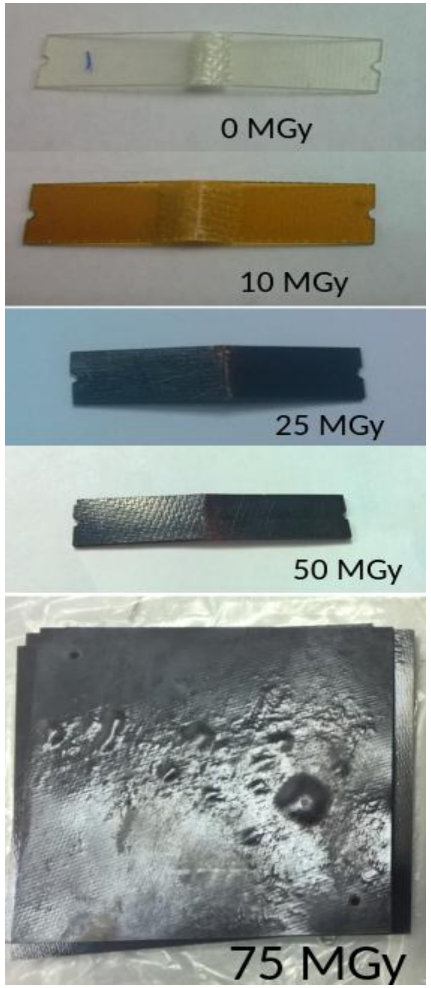
Figure of merit: Dose

Grease, lubricants (M. Ferrari)



LEP damage to cables and magnet insulation ([NIM B](NIM B))

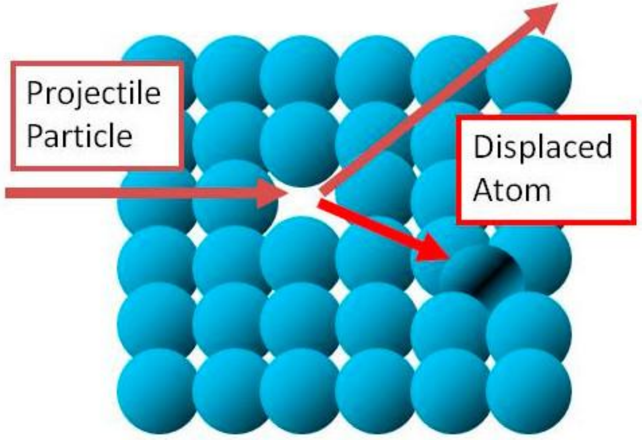
Magnet insulation (P. Fessia)



Displacement Damage (DD) and DPA

- **Non-Ionizing Energy Loss (NIEL)** can cause material damage by displacing atoms from their reference position in the lattice
- Quantified by the **Displacement Per Atom (DPA):**

  Number of atomic displacements from the reference position in the lattice (e.g., DPA=0.1 means that ~10% of the atoms have been displaced)
- Relevant for radiation damage studies to superconductors, with interesting cross-disciplinary links (e.g., fusion magnets)



A. Lechner

	SC type	Radiation source	Shielding inserts (Δr)	Scenario	DPA-NRT	Ionizing dose
HL-LHC final focus quadrupoles	Nb_3Sn	Proton-proton collision debris	1.6 cm W-alloy	3000 fb^{-1} (10 years)	$1.5x10^{-4}$	20-30 MGy
FCC-hh final focus quadrupoles	Nb_3Sn / REBCO	Proton-proton collision debris	4 cm W-alloy	30 ab^{-1} (20 years)	**$4\text{-}5x10^{-3}$**	60-80 MGy
Muon Collider (10 TeV) arc magnets	Nb_3Sn / REBCO	Muon decay	3 cm W-alloy	10 ab^{-1} (5 years)	$5x10^{-5}$	20 MGy
Muon Collider target solenoid	REBCO	Proton beam on target	**35 cm W-alloy +H20+BC layer**	10 ab^{-1} (5 years)	**$5x10^{-3}$**	50 MGy

Displacement Damage (DD) and DPA

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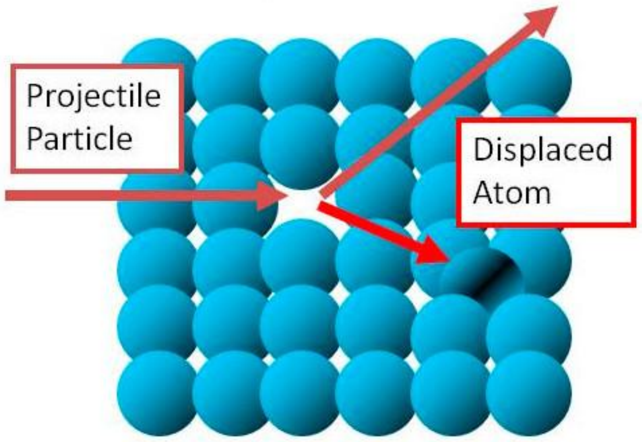
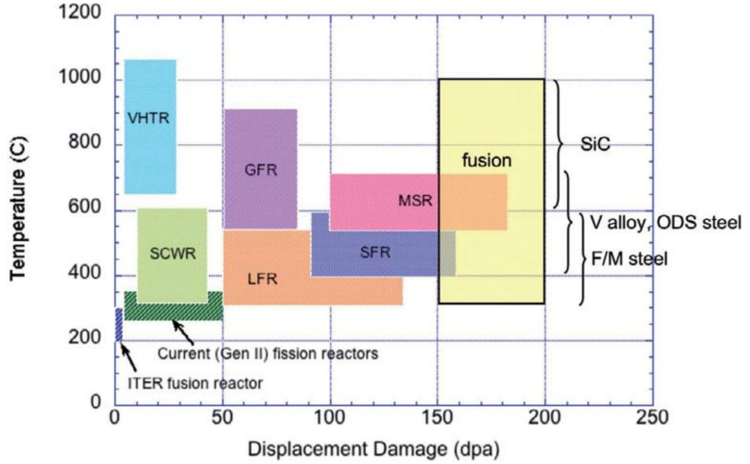


Not only colliders!

- 10^{-3} DPA → Loss of superconductivity
- 0.1 DPA → Loss of thermal conductivity
- ~1 DPA → Embrittlement and hardening
- ~10 DPA → Swelling



Structural materials for fission & fusion energy. Steven J. Zinkle, Jeremy T. Busby

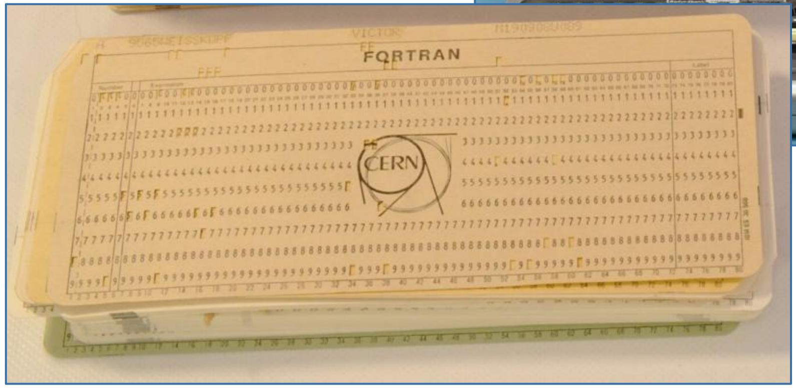
How (and why) FLUKA?

The “naked” inputfile

- FLUKA’s story began a long time ago (1970s)…

  …no graphical interfaces, input and output via text file

- Input files:
  - can be very long > 50k lines
  - based on “cards”: .inp file
  - Each card has 1 name, 6 values (called WHATs), 1 string (called SDUM)



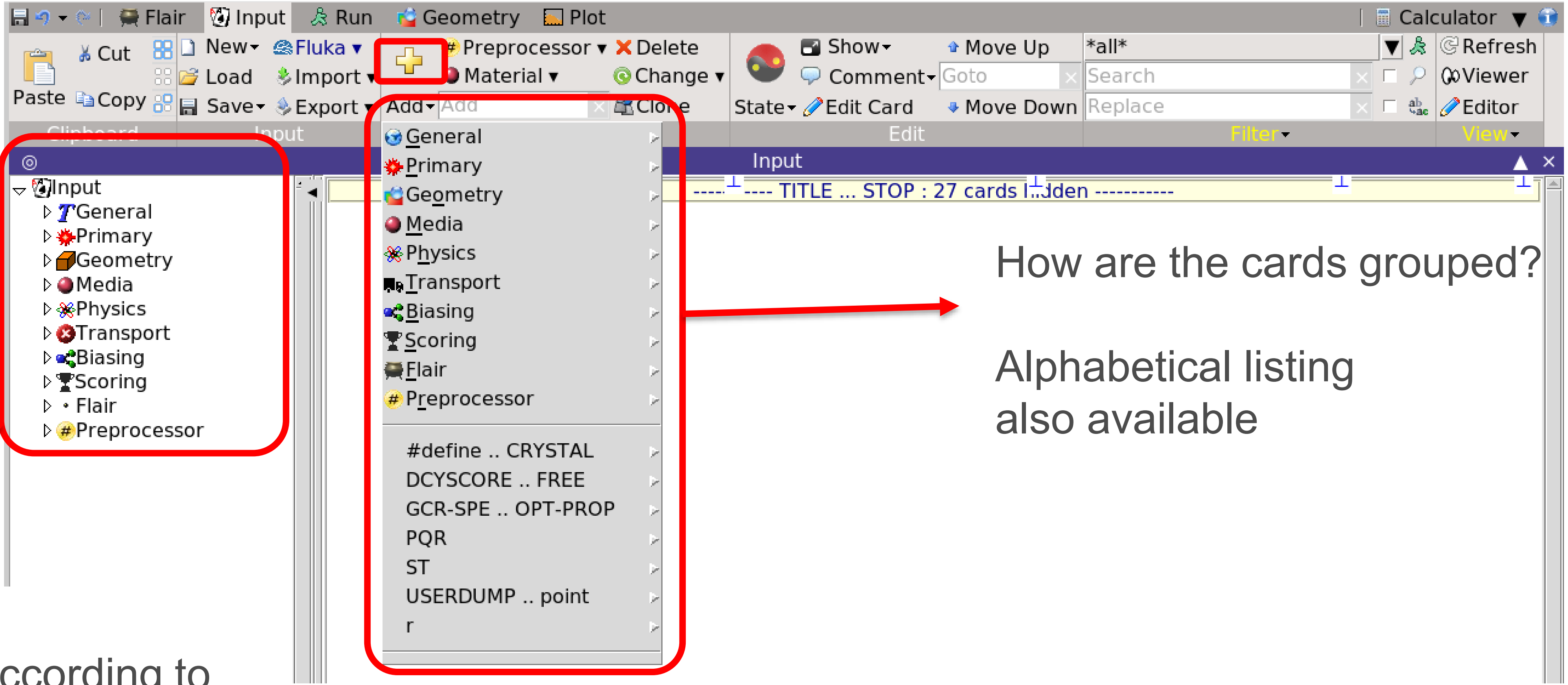

```
BEAMPOS       4750.5     130.0     4866.5                                NEGATIVE
BEAM            -0.4       0.2        5.0      1.E-4      1.E-4          ELECTRON
```

Card name	WHAT(1)	WHAT(2)	WHAT(3)	WHAT(4)	WHAT(5)	WHAT(6)	SDUM

Flair: the GUI

Flair ≠ FLUKA

- In 2006, Flair was born! It is a layer between the user and FLUKA



How are the cards grouped?

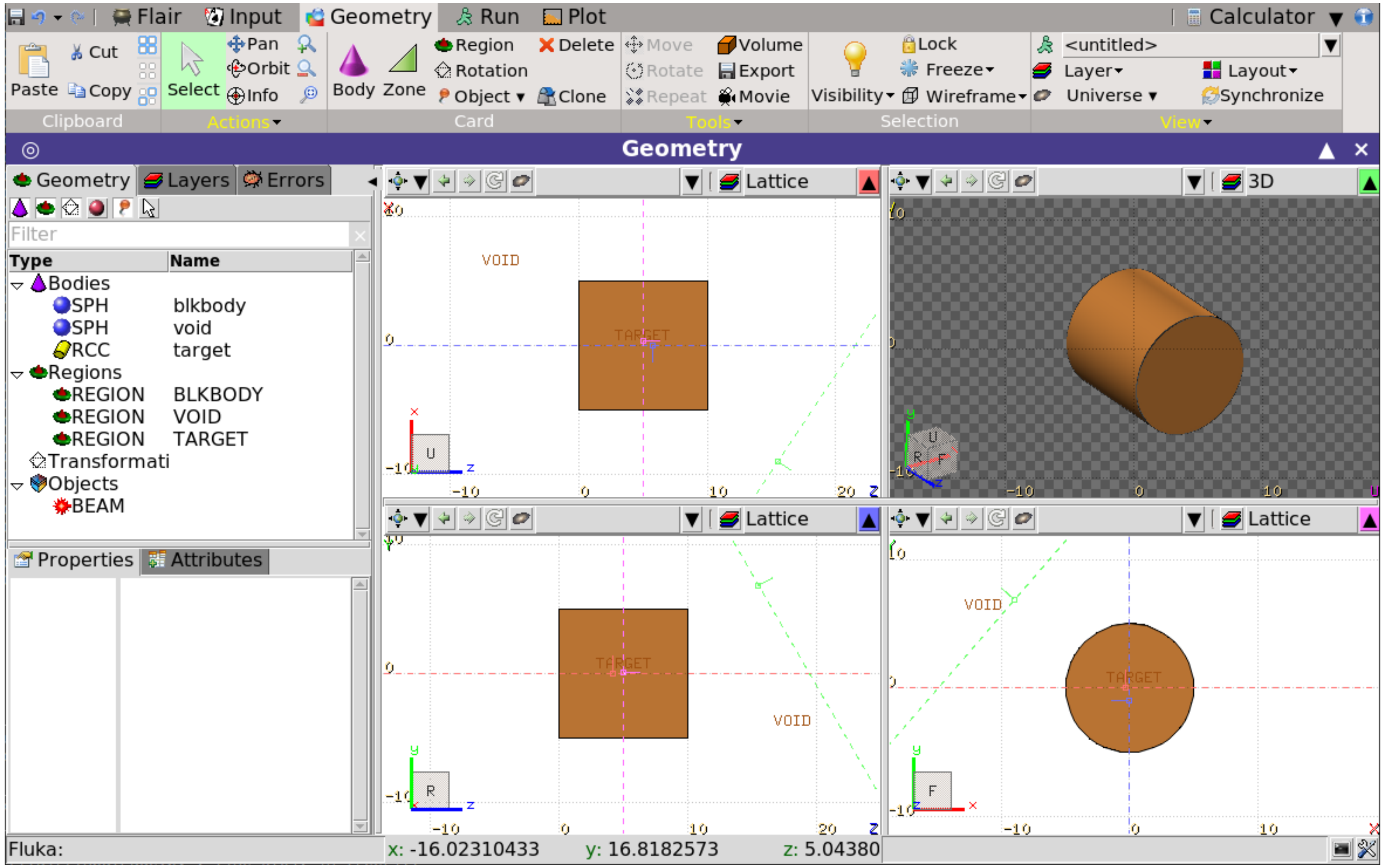
Alphabetical listing also available

Input file tree
Cards grouped according to their “field of action”

Flair: the GUI

Flair ≠ FLUKA

- In 2006, Flair was born! It is a layer between the user and FLUKA



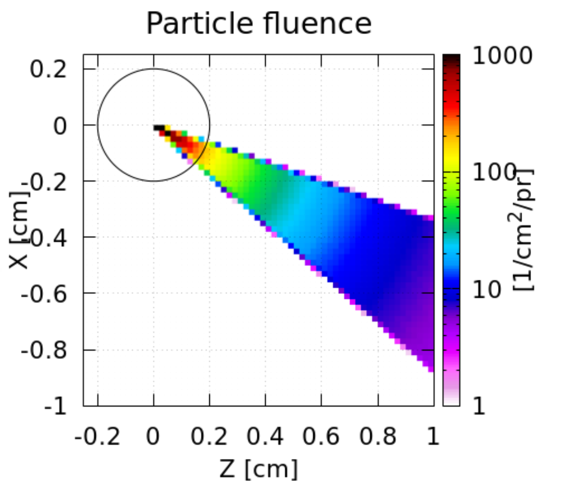
Online geometry view and editing!

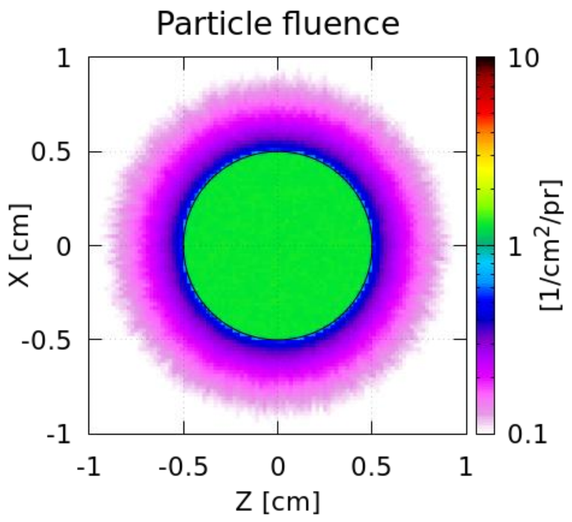
Many other advantages such as:

1. Parametric scan capability
2. Automatic postprocessing
3. Plotting

(Some) possible sources of radiation

- The basic sources FLUKA considers are:
  - Beam-like: one or multiple beams starting from fixes positions
  - Volumetric: uniformly distributed in volumes
- Special sources available in FLUKA
  - Colliding beams
  - Cosmic rays
  - USRBIN source
- … or program your own custom sources (Source routine)!





Geometry and materials

- FLUKA employs a combinatorial geometry (described few slides ago…)
- Materials are assumed homogeneous (except for crystals!) → only the stoichiometry and the density matter
- A set of base elements and compounds is provided by standard. It includes:
  - **VACUUM** → obvious definition (electric field is allowed only here!)
  - **BLCKHOLE** → particles are stopped. This must surround your whole geometry

Element definition

MATERIAL Boron-10 #: ρ: 2.34
Z: 5 Am: A: 10 dE/dx: ▾
MATERIAL Boron-11 #: ρ: 2.34
Z: 5 Am: A: 11 dE/dx: ▾

Compound definition

Butane C4_H10
MATERIAL BUTANE #: ρ: 0.0024934
Z: Am: A: dE/dx: ▾
COMPOUND BUTANE ▾ Mix: Mass ▾ Elements: 1..3 ▾
f1: 0.173408 M1: HYDROGEN ▾ f2: 0.826592 M2: CARBON ▾
f3: M3: ▾

Physics & transport

- FLUKA is not a toolkit
- Users can select the lower energy thresholds for production and transports
- Some interaction are not on by default (e.g. photonuclear). If needed, they need to be requested

```
PHOTONUC    Type: ▾    All E: On ▾
E>0.7GeV: off ▾ Δ resonance: off ▾ Quasi D: off ▾ Giant Dipole: off ▾
      Mat: BLCKHOLE ▾ to Mat: @LASTMAT ▾ Step: 1
```

- The production (and tracking) of low energy electrons and photons is one of the most CPU expensive tasks. Users should set the lowest value compatible with their simulation

```
EMFCUT    Type: PROD-CUT ▾
     e-e+ Threshold: Kinetic ▾ e-e+ Ekin: 1e-05 γ: 1e-6
Fudgem: 1e-5 Mat: ALUMINUM ▾ to Mat: ALUMINUM ▾ Step:
```

```
DELTARAY    E thres: 1e-5 # Log dp/dx:  Log width dp/dx:
Print: NOPRINT ▾ Mat: ALUMINUM ▾ to Mat: ALUMINUM ▾ Step:
```

Basic idea: put transport threshold at energy such that the range is smaller than the bin length

FLUKA scoring

What?

Energy deposition and derivatives (dose), fluence or current versus energy, angle or other kinematic variables, time, DPA, residual activity…

Where?

In regions, across boundaries, on region-independent grids

When?

At the end of each cycle or at each event

Output?

Saved in `[inputname]nnn_fort.##` files,
where `nnn` is the cycle number & `##` is the logical unit number chosen by the user

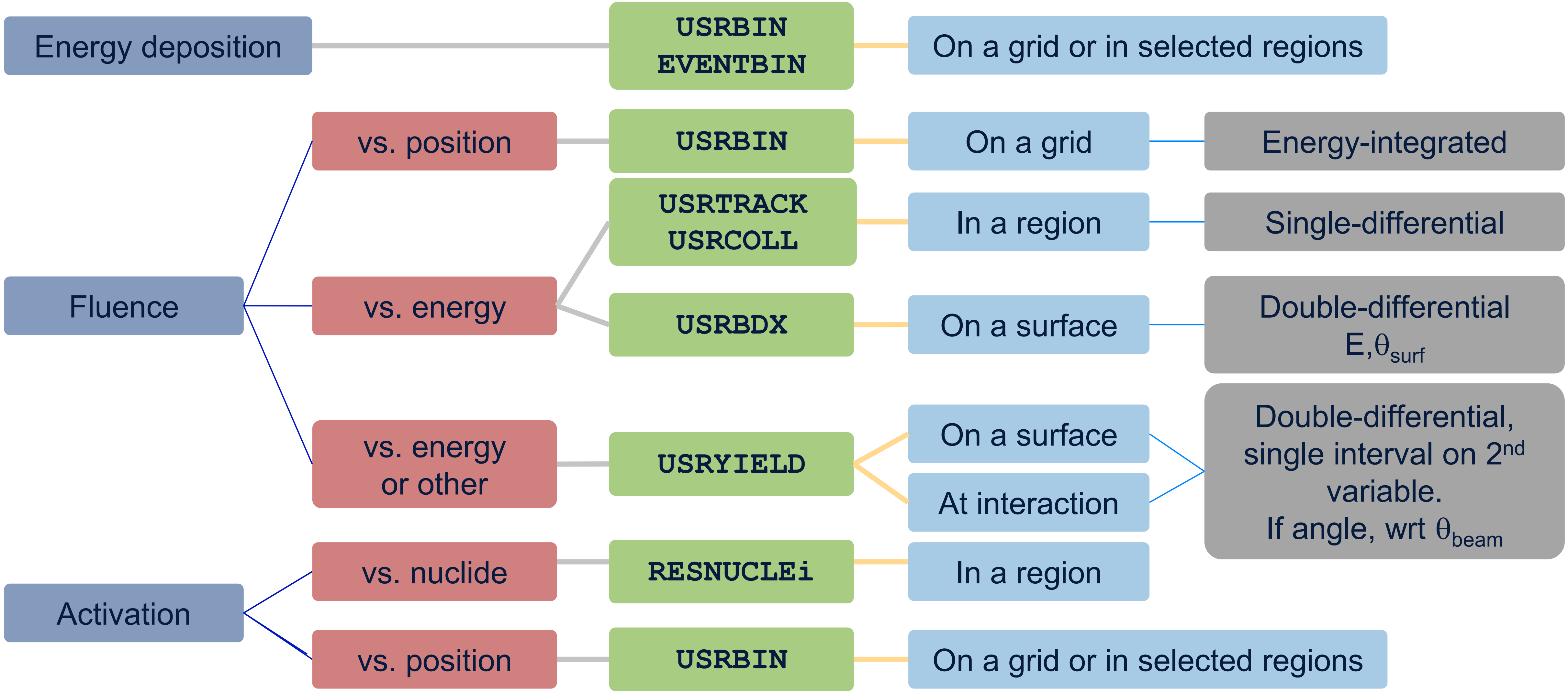
Results?

Post-processing utilities merge cycles, calculate average and rms, provide data files for plotting. Available via **Flair**

Results normalised **per primary**

User code needed for processing of custom scoring!

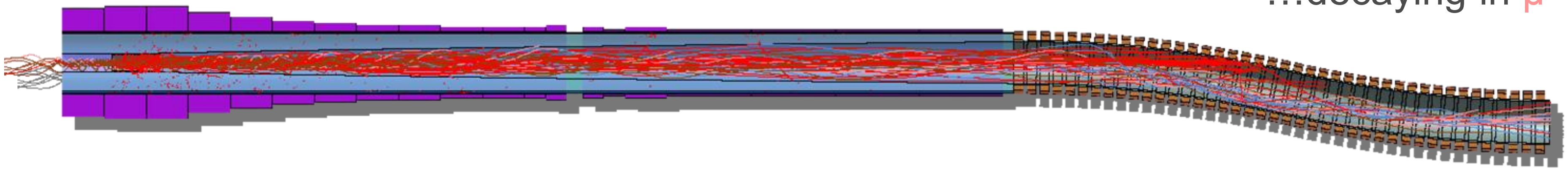
FLUKA scoring



Some case studies

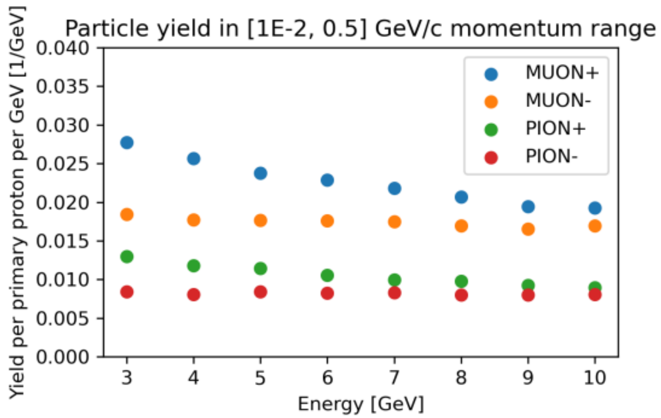
Muon collider: target

…decaying in μ+ and μ-

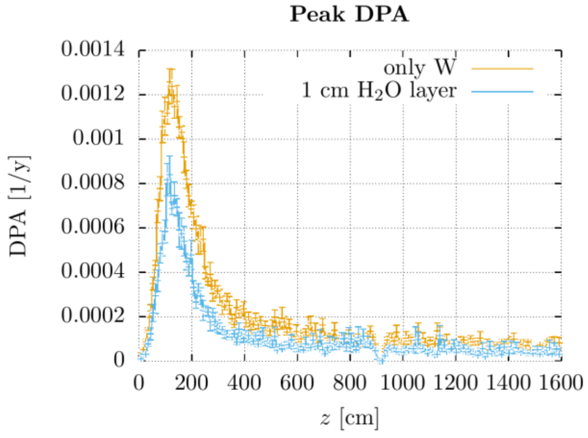


p impacting on a target, producing π^{+-}

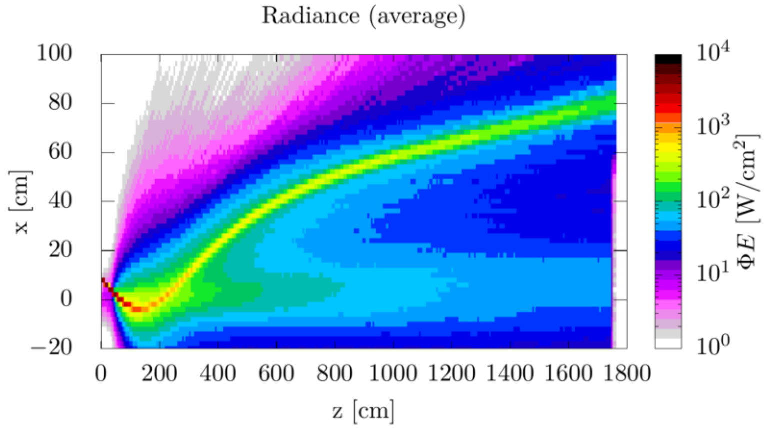
Muon yields



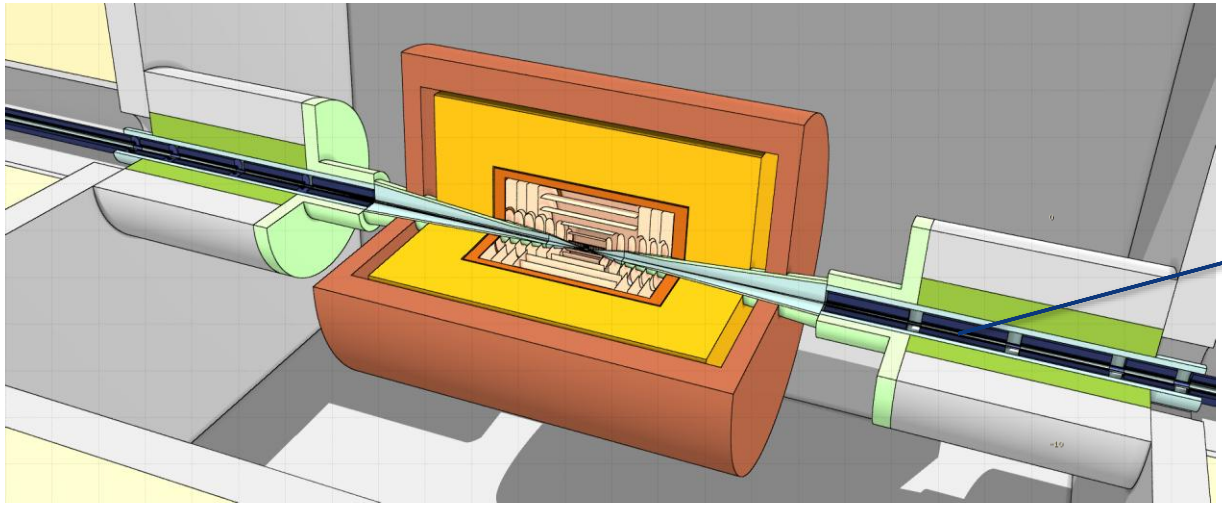
Radiation damage in superconducting solenoid

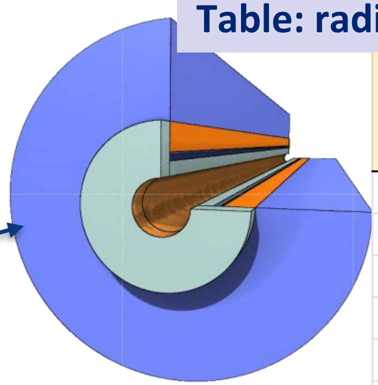


Tentative extraction (spent proton beam)



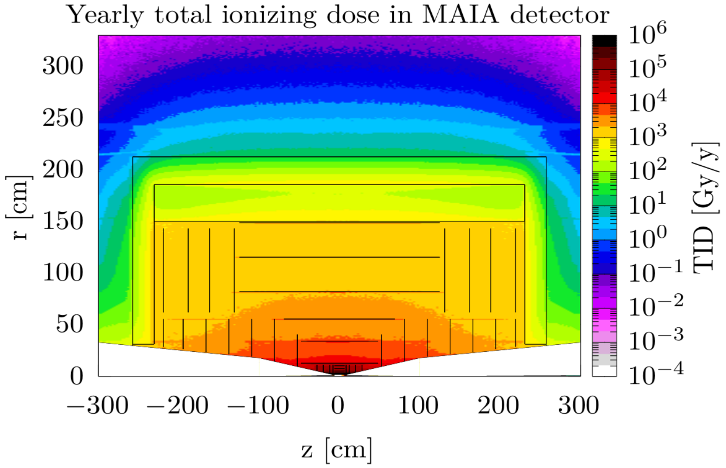
Muon collider: detectors

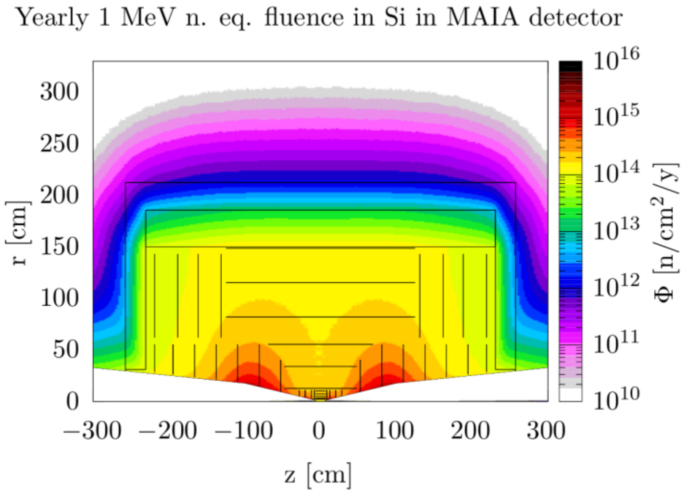




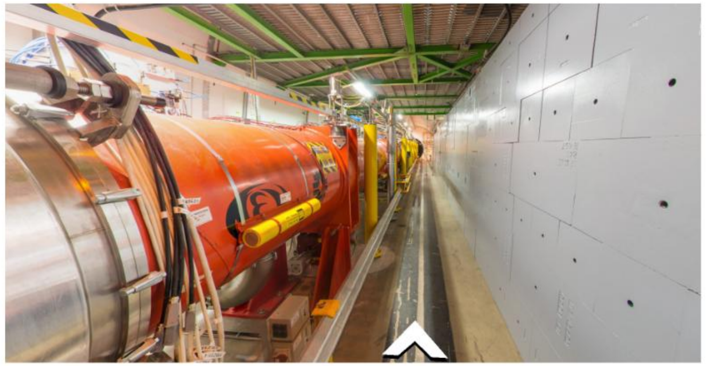
Name	L [m]	Shield thickness [cm]	Coil aperture (radius) [cm]	Peak TID [MGy/y]
IB2	6	4.53	16	1.3
IB1	10	4.53	16	3.1
IB3	6	4.53	16	4.9
IQF2	6	2.53	14	7.7
IQF2_1	6	2.53	13.3	4.6
IQD1	9	2.53	14.5	1.1
IQD1_1	9	2.53	14.5	3.7
IQF1B	2	2.53	10.2	6.4
IQF1A	3	2.53	8.6	3.6
IQF1	3	2.53	7	3.5

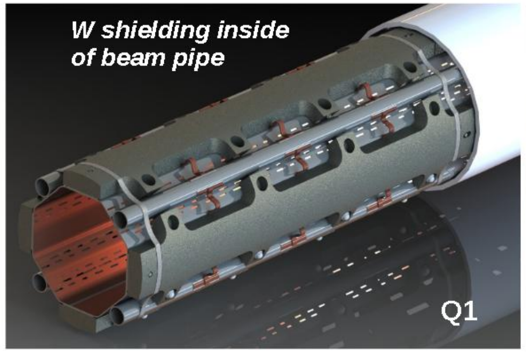
Table: radiation load for each magnet in the final focus

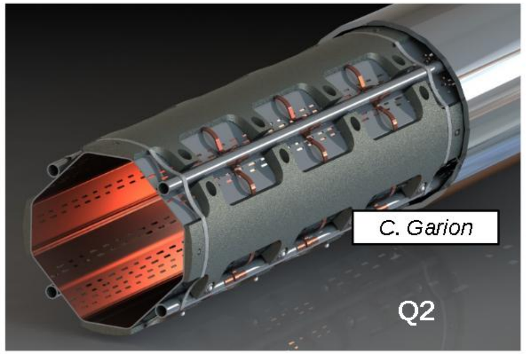




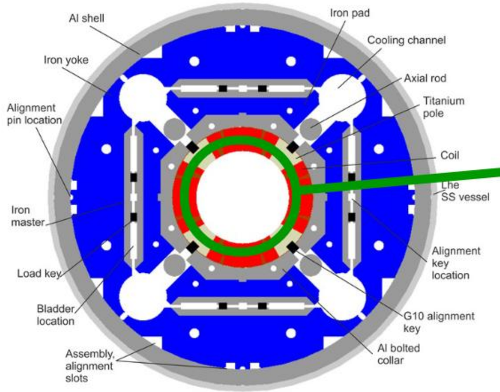
Inner triplet W shielding for HL-LHC

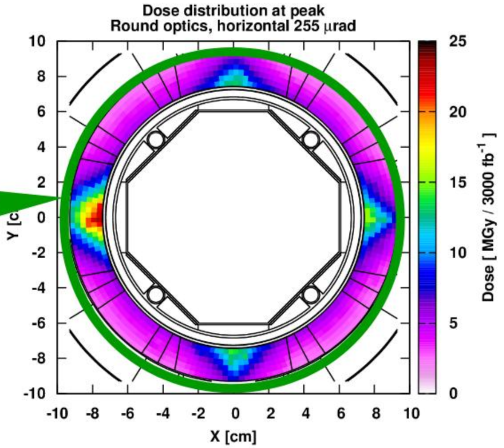






HL-LHC upgrade:





Charged hadrons → captured by strong magnetic field in triplet!

Key element during design → shielding:
→ avoid quenches
→ avoid that magnet fails due to long-term radiation damage

Dose < 30 MGy

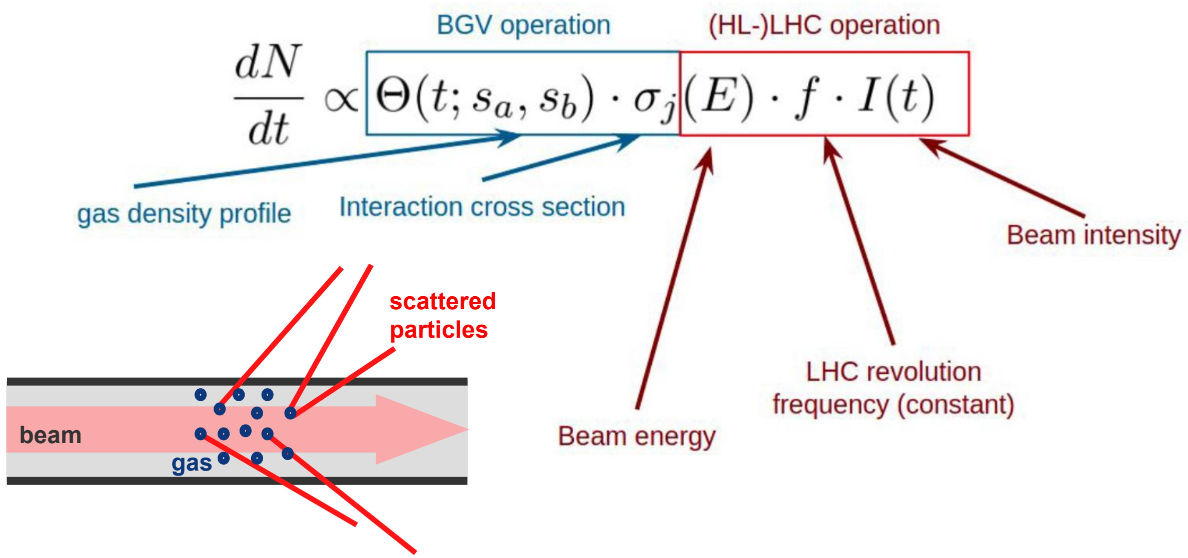
A. Tsinganis, F. Cerutti

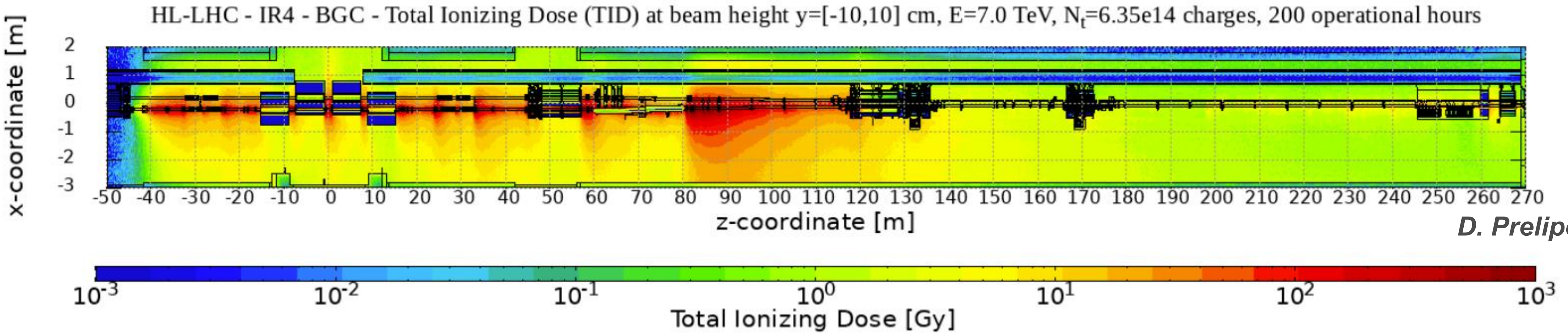
Beam loss / radiation source → MC simulation → Mitigation strategy

Beam-gas collisions in LHC

- Despite the vacuum system, the beam can interact with residual gases, causing radiation showers
- There are also beam instruments that exploit local injections of gas to perform specific measurements (e.g., Beam Gas Curtain monitor) causing local showers with higher intensity

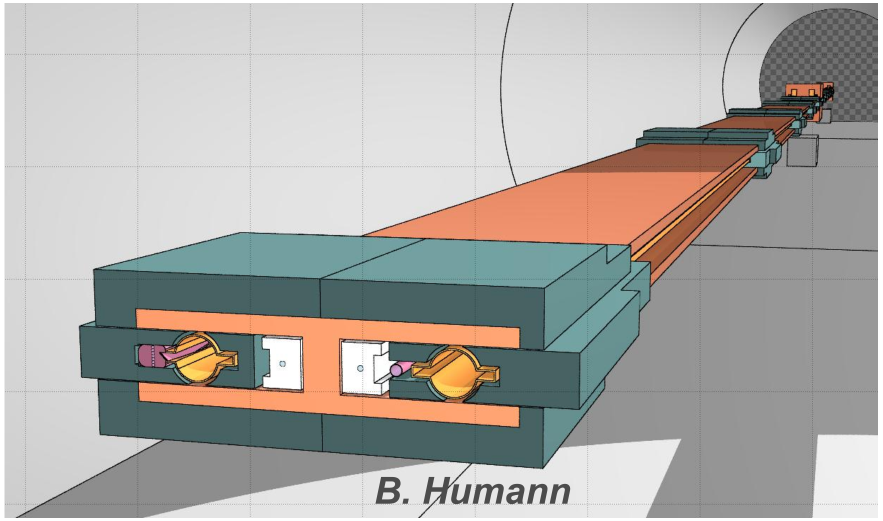
$$\frac{dN}{dt} \propto \Theta(t; s_a, s_b) \cdot \sigma_j(E) \cdot f \cdot I(t)$$



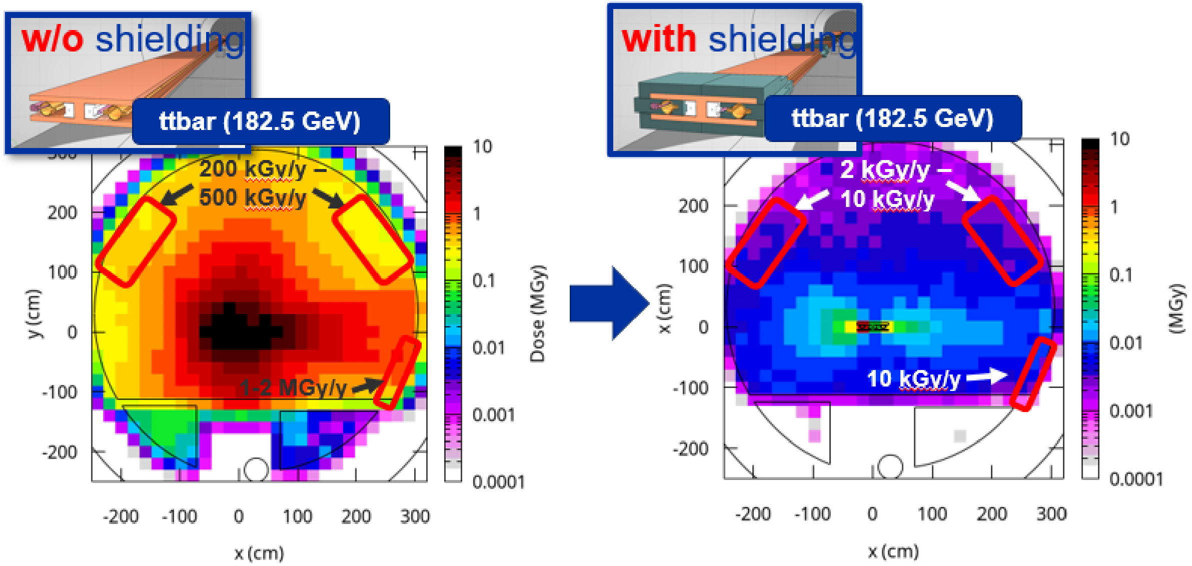


D. Prelipcean

FCC-ee dipole shielding



- SR photons are intercepted by photon stoppers all around the FCC-ee arcs
- For the high-energy beam modes (with higher SR E_c) massive shielding is required to mitigate the resulting radiation levels in the tunnel
  → shielding is an important (and expensive) design element for the FCC-ee!



- Baseline material: Pb94Sb6 (10.88 g/cm^3)
- W-alloys (17-19 g/cm^3) discarded for cost reasons

Shielding material for full ring (arcs)	
Shielding weight per stopper	400 kg
Photon stoppers per 20 m dipole	10 (5 per beam)
# dipoles	2840
Total weight	11360 tons

Other applications (selection)

- **High-energy physics & accelerators**: beam-induced background (BIB), energy deposition in magnets and detectors, machine protection, system design (collimation, beam dump, etc.)
- **Radiation protection**: dose calculations, shielding optimization for accelerators and facilities, residual activation and environmental impact studies
- **Medical physics**: proton and heavy-ion therapy simulations, patient dose distributions, treatment planning verification, radiobiology studies
- **Space & aerospace**: cosmic ray interactions, astronaut dose assessment, spacecraft shielding design, single-event effects in electronics
- **Nuclear engineering & activation**: radionuclide production, material activation, decay heat, waste and transmutation studies
- **Detector design & experiments**: background estimation, radiation damage to the detectors
- **Industrial & applied physics**: radiation effects on electronics (SEE, TID), irradiation facilities, sterilization, non-destructive testing and material analysis

Thank you for your attention!