WP8: Development of SEE simulation capabilities with Monte Carlo particle transport codes

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https://indico.cern.ch/e/radnext-2023

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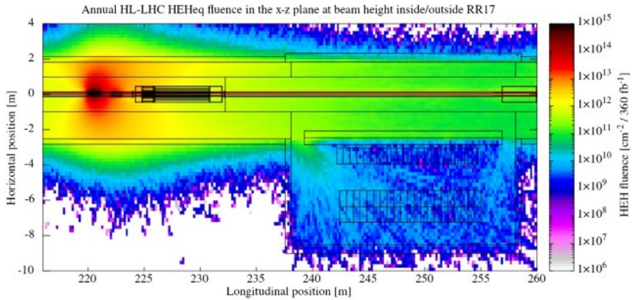
Outline

- FLUKA.CERN – Introduction
- Geant4 – Introduction
- The G4SEE toolkit – Introduction
  - Capabilities & Architecture
  - Validation with neutrons
  - SEU cross-section estimation
  - User support & community
- Next step: Integration of G4SEE into FLUKA
- Validation of FLUKA SEE module / G4SEE

FLUKA.CERN

More info on https://fluka.cern

- **Multi-purpose Monte Carlo particle transport simulation code** developed by the FLUKA collaboration based at CERN [1]
- **Primarily for radiation environments**, heavily used for CERN accelerator incl. (HL-)LHC environments, but also for medical (hadrontherapy) applications
- **Mostly FORTRAN** code, migration to C++
- **Closed source**, academic single user and commercial licenses
- **SEE scoring capabilities are limited**, e.g. biased (non-analog MC) single events can only be simulated using a custom-made user routine [2], which is not part of FLUKA
  ⇒ **RADNEXT WP8 Task 8.6** (Integration of SEE event-by-event scoring in FLUKA)
- **Users are limited to set/change the physics**, validation is the responsibility of developers
- Flair, an **advanced general GUI for FLUKA**



[1] C. Ahdida et al.: New Capabilities of the FLUKA Multi-Purpose Code, [link]
[2] R. García Alía: Radiation Fields in High Energy Accelerators and their impact on Single Event Effects, PhD thesis, [link]

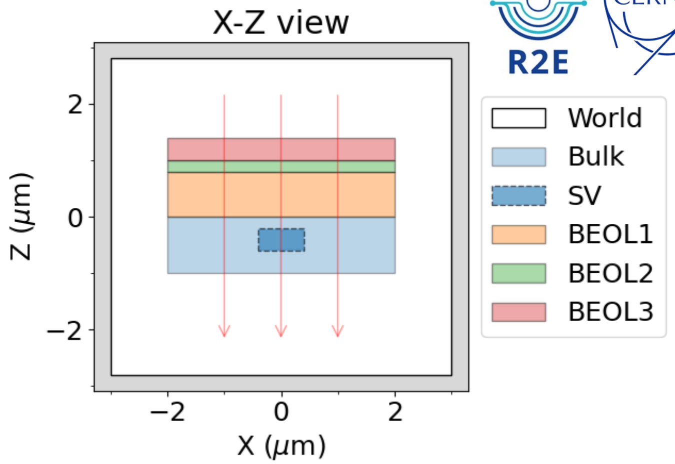
Geant4

More info on https://cern.ch/geant4

- **Multi-purpose Monte Carlo particle transport simulation framework** developed by the Geant4 collaboration world-wide based at CERN
- **Both for detector response and radiation environments**, heavily used by CERN experiments (ATLAS, CMS, etc.), but also for space and medical applications
- It is a **C++ library**, enabling the development of Gean4-based applications
- **Free and fully open-source**
- **Various SEE scoring capabilities**: biased (non-analog MC) single events can be simulated, all the secondaries particle data can be obtained
- **Users and app. developers are free to set/change the physics**, validation is the responsibility of both the Gean4 and application developers, as well as the users
- **No general GUI**, only macro (text) files as input

G4SEE toolkit for SEE simulations

- G4SEE is a **Geant4-based Monte Carlo Single Event Effect** (SEE) simulation toolkit is being developed since 2020 by CERN R2E project [3]
- Direct and indirect **energy deposition scoring** in a micro-metric, user-defined sensitive volume ⇒ SEE cross-section estimation
- **Focusing primarily on SEEs**, while remaining as general as possible ⇒ **user friendly** I/O interfaces
- **Free and open-source** ⇒ available for the whole radiation effects community for a wide variety of use cases

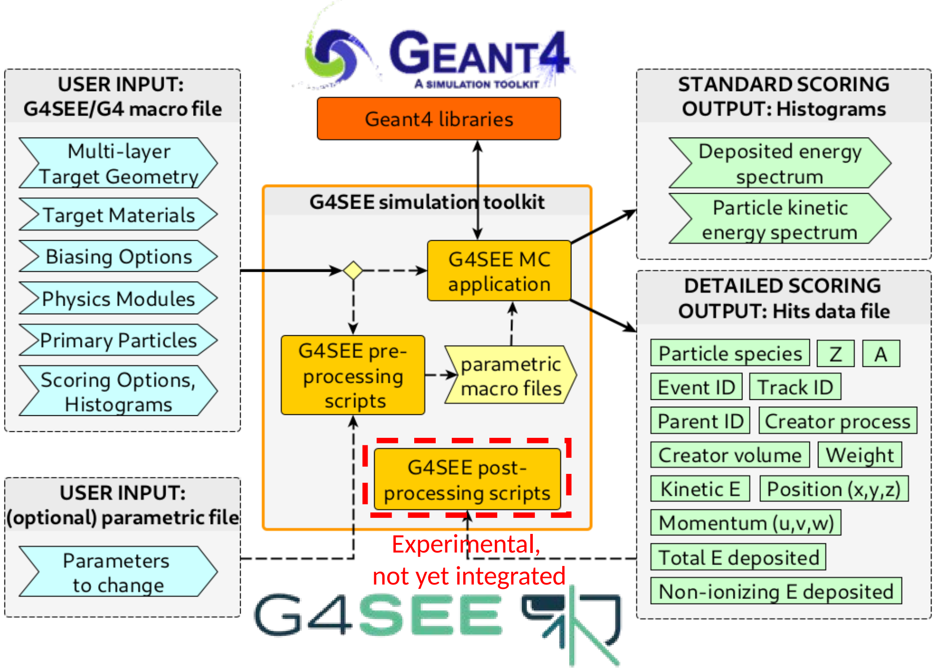


Multi-layer, micro-metric geometry used in a G4SEE simulation to obtain energy deposition in Sensitive Volume (SV) inside Bulk and below Back End Of Line (BEOL) layers

[3] Dávid Lucsányi *et al.*, "G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements", in *IEEE TNS*, [link]

G4SEE Capabilities & Architecture

- **Not just a tool, but a toolkit:** Core Geant4 application, with pre- and post-processing Python scripts
- Extracting **low-level information and quantities** relevant for SEEs, **event-by-event** and **particle-by-particle**, based on the needs of users
- Primary motivation and use cases so far were **neutron and proton induced SEEs** (most relevant at CERN mixed-field accelerator environments)



High-level architecture of the G4SSE toolkit with user inputs and outputs (ASCII files), and the two types of scoring mechanisms

G4SEE Validation with neutrons – Raw output data

event	particle	weight	Z	A	track	parent	E_kin	process	volume	E_dep	counts
377	alpha	1.055e-03	2	4	2	1	3.8826e+00	b(neutronInelastic)	Sensitive	2.5712e-02	1
377	Mg25	1.055e-03	12	25	3	1	1.5530e+00	b(neutronInelastic)	Sensitive	2.4899e-02	1
377	g(e-)	nan	0	0	-1	nan	nan	ionIoni	Sensitive	5.4009e-03	5
490	neutron	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.9415e+00	b(neutronInelastic)	Sensitive	0	1
490	Si28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.4732e-01	b(neutronInelastic)	Sensitive	1.2955e-01	1
490	gamma	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.7778e+00	b(neutronInelastic)	Sensitive	0	1
732	O16	[illegible]	8	16	2	1	1.0890e+00	b(hadElastic)	Oxide	1.3268e-01	1
914	gamma	1.057e-03	0	0	4	1	4.8919e+00	b(neutronInelastic)	Bulk	0	1
914	gamma	1.057e-03	0	0	5	1	1.7790e+00	b(neutronInelastic)	Bulk	0	1
1212	neutron	1.077e-03	0	1	2	1	5.2899e+00	b(neutronInelastic)	Bulk	0	1
1257	O16	1.048e-03	8	16	3	1	1.2290e-01	b(neutronInelastic)	Oxide	9.4224e-02	1
1342	neutron	1.072e-03	0	1	2	1	3.9277e-01	b(neutronInelastic)	Sensitive	0	1
1342	gamma	1.072e-03	0	0	3	1	5.1945e+00	b(neutronInelastic)	Sensitive	0	1
1342	gamma	1.072e-03	0	0	4	1	1.4963e+00	b(neutronInelastic)	Sensitive	0	1
1342	gamma	1.072e-03	0	0	5	1	4.7253e-01	b(neutronInelastic)	Sensitive	0	1
1342	Si30	1.072e-03	14	30	6	1	3.3550e-01	b(neutronInelastic)	Sensitive	1.3925e-01	1
1428	O16	1.050e-03	8	16	3	1	5.6249e-02	b(neutronInelastic)	Oxide	4.4397e-02	1
1536	Si28	1.066e-03	14	28	2	1	4.7965e-02	b(hadElastic)	Sensitive	4.7965e-02	1
1565	Al28	1.067e-03	13	28	3	1	4.7900e-01	b(neutronInelastic)	Bulk	1.6775e-01	1
1605	neutron	1.053e-03	0	1	2	1	6.0902e+00	b(neutronInelastic)	Sensitive	0	1
1605	Si28	1.053e-03	14	28	3	1	2.3035e-01	b(neutronInelastic)	Sensitive	1.2189e-01	1
1605	gamma	1.053e-03	0	0	4	1	1.7730e+00	b(neutronInelastic)	Sensitive	0	1
1984	neutron	1.055e-03	0	1	2	1	6.0284e+00	b(neutronInelastic)	Sensitive	0	1
1984	Si28	1.055e-03	14	28	3	1	2.0772e-01	b(neutronInelastic)	Sensitive	1.6477e-01	1
1984	gamma	1.055e-03	0	0	4	1	1.7703e+00	b(neutronInelastic)	Sensitive	0	1
1993	Si28	1.054e-03	14	28	3	1	3.6548e-01	b(neutronInelastic)	Bulk	1.9489e-01	1
1993	gamma	1.054e-03	0	0	4	1	3.2000e+00	b(neutronInelastic)	Bulk	0	1
1993	gamma	1.054e-03	[illegible]	[illegible]	[illegible]	[illegible]	1.7790e+00	b(neutronInelastic)	Bulk	0	1
1993	g(gamma)	nan	[illegible]	[illegible]	[illegible]	[illegible]	nan	b(neutronInelastic)	Bulk	0	1
2044	Si28	1.072e-03	[illegible]	[illegible]	[illegible]	[illegible]	7.3092e-02	b(hadElastic)	Bulk	0	1
2176	proton	1.066e-03	1	1	2	1	3.3008e+00	b(neutronInelastic)	Sensitive	4.8202e-03	1
2176	Al28	1.066e-03	13	28	3	1	7.5380e-01	b(neutronInelastic)	Sensitive	4.1540e-02	1
2176	g(gamma)	nan	0	0	-1	nan	nan	b(neutronInelastic)	Sensitive	0	1
2559	proton	1.063e-03	1	1	2	1	2.6926e+00	b(neutronInelastic)	Sensitive	2.4314e-03	1
2559	Al28	1.063e-03	13	28	3	1	3.8967e-01	b(neutronInelastic)	Sensitive	8.7722e-02	1
2559	gamma	1.063e-03	0	0	4	1	9.8268e-01	b(neutronInelastic)	Sensitive	0	1
2559	g(e-)	nan	0	0	-1	nan	nan	hIoni	Sensitive	3.9645e-03	3
2559	g(gamma)	nan	0	0	-2	nan	nan	b(neutronInelastic)	Sensitive	0	1

$n + {}^{28}Si \Rightarrow {}^{25}Mg + \alpha + 5e^-$

$n + {}^{28}Si \Rightarrow {}^{28}Al + p$

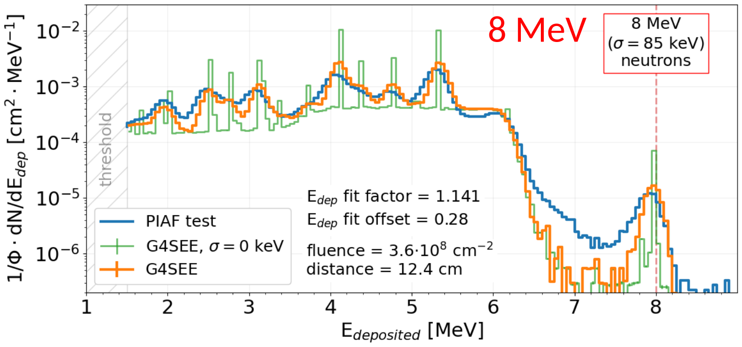
Mono-energetic fast neutrons impacting a Si component producing various secondary particle species.

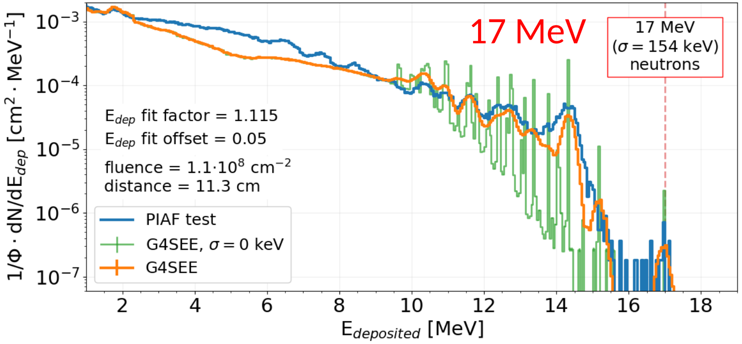
*The **detailed scoring** output file containing information of **individual particles** (or optionally groups of e^-, e^+ and γ particles) **scored inside the sensitive volume**.*

Further post-processing and analysis needed (for this a script will be added to a future release of the toolkit).

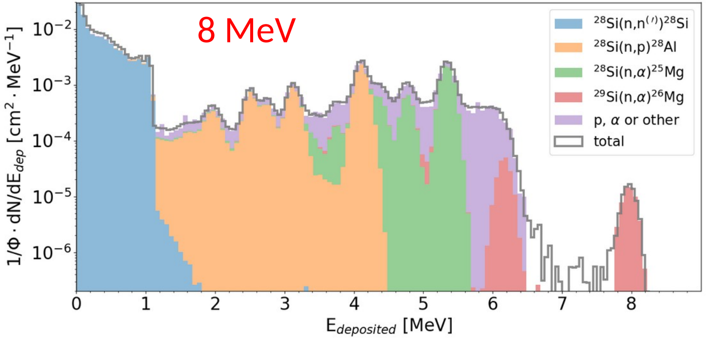
G4SEE Validation with neutrons – Some results

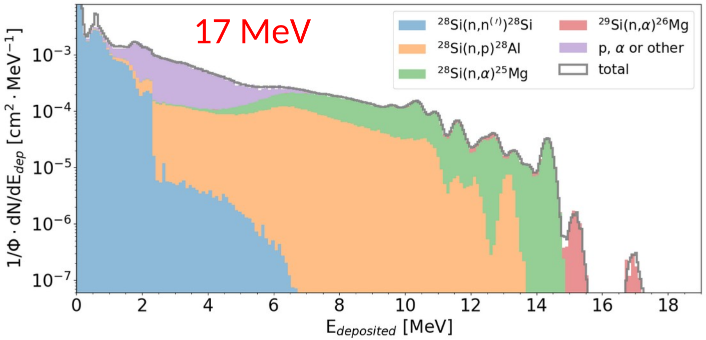
with STANDARD SCORING





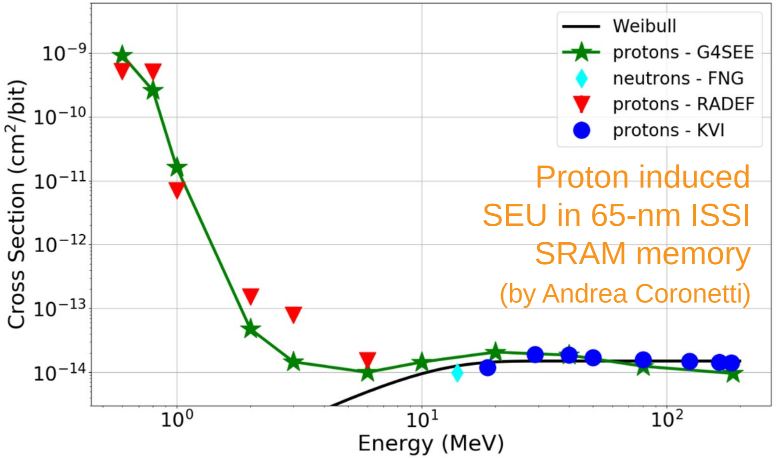
with DETAILED SCORING



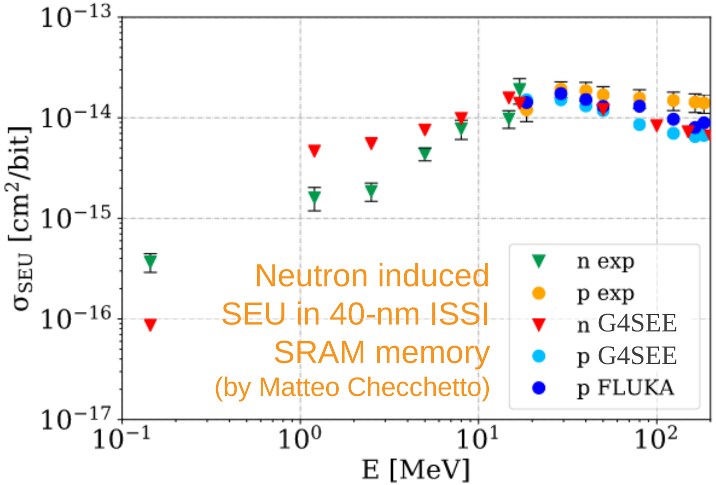


Left: *Comparison of energy deposition distributions by mono-energetic neutrons in Si diode detector [3];*
Right: *Contribution of the most frequent nuclear reactions to the E_{dep} distributions [3]*

SEU cross-section estimation with G4SEE



Simulated and experimental cross-sections of ***proton induced SEUs*** *in 65-nm ISSI SRAM as function of beam energy [4]*

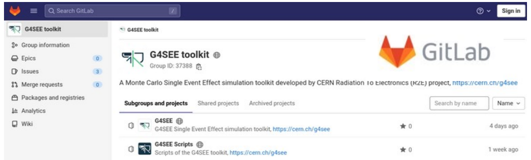


Simulated and experimental cross-sections of ***neutron and proton induced SEUs*** *in 40-nm ISSI SRAM as function of beam energy [5]*

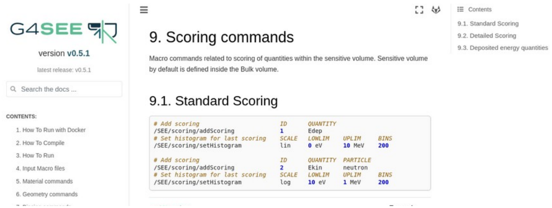
[4] Andrea Coronetti *et al.*, "Proton direct ionization upsets at tens of MeV", in *IEEE TNS*, 2022, [link]
[5] Matteo Cecchetto *et al.*, "0.1–10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments", in *IEEE TNS*, vol. 68, no. 5, May 2021, [link]

G4SEE User support & community

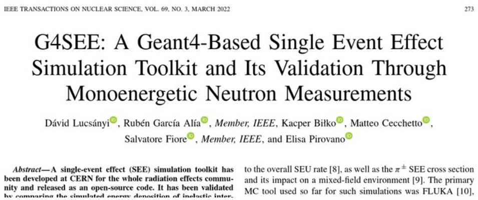
Website: g4see.web.cern.ch



Source code (GitLab): gitlab.cern.ch/g4see



Online docs: g4see-docs.web.cern.ch



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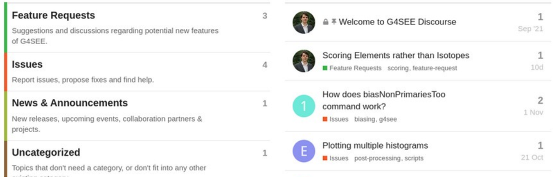
G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements

Dávid Lucsányi, Rubén García Alía, *Member, IEEE*, Kacper Biłko, Matteo Cecchetto, Salvatore Fiore, *Member, IEEE*, and Elisa Pirovano

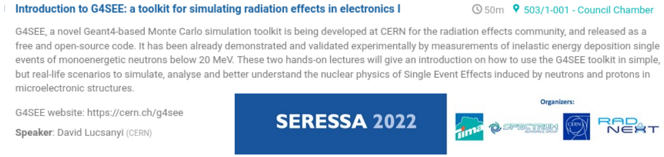
Abstract—A single-event effect (SEE) simulation toolkit has been developed at CERN for the whole radiation effects community and released as an open-source code. It has been validated ...

to the overall SEU rate [8], as well as the $\pi^{\pm}$ SEE cross section and its impact on a mixed-field environment [9]. The primary MC tool used so far for such simulations was FLUKA [10],

Open-access paper: DOI link



User Forum: g4see-forum.web.cern.ch



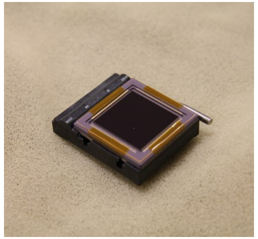
Lectures at SERESSA 2022: Indico page

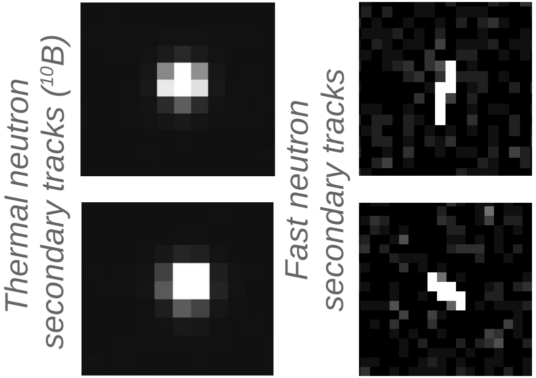
Next step: Integration of G4SEE into FLUKA

- The *Moira* code is being developed by the FLUKA collaboration, which **will become the next (5th) major release of FLUKA.CERN**
  - **Moira is a Geant4 application implemented in C++**, but with FLUKA physics models, scoring and other features, fully compatible with the Flair GUI
- **Progressive integration of G4SEE features into Moira** starts now, while the **G4SEE toolkit will also remain a stand-alone, open-source toolkit**
  - This activity is **supported by FLUKA developers at CERN**
  - **New features in FLUKA 5:** Scoring of single events with biasing; Obtaining all secondary particle data; Particle grouping in output, Post-processing scripts, etc.
  - **New features in G4SEE:** Scoring in arbitrary number of SVs, Complex 3D geometries (importing GDML files), Flair GUI, etc.
  - During integration some features will be duplicated, some will be only available in Moira, until FLUKA 5 will be released (probably as open-source code)

Validation of FLUKA SEE module / G4SEE

- **Cross-validation** between different codes and versions (G4SEE, FLUKA 4, FLUKA 5)
- Comparisons between FLUKA and Geant4 physics models
- **Proton, neutron (and later heavy ion) test campaigns** are planned to validate simulation results by measuring/scoring event-by-event energy deposition in micro-metric sensitive volumes:
  - 1D Energy distribution of deposited energy
  - 2D Spatial distribution of deposited energy
  - **COTS CMOS Active Pixel Sensors** as DUT with small pixel pitches (2 and 11 µm)


COTS CMOS APS



These activities will be part of

- **Task 8.6 (Integration of SEE event-by-event scoring in FLUKA)**, and related
- **Milestone M8.3 (Validation of FLUKA SEE module)** by June 2024 (T_0 + 36m)

Thanks for your attention!

Questions?