Impact of high-Z materials on electronic component hardness assurance in a mixed-radiation field

PH-ESE Electronics Seminar

Rubén García Alía, EN-STI-EET, R2E project

www.cern.ch

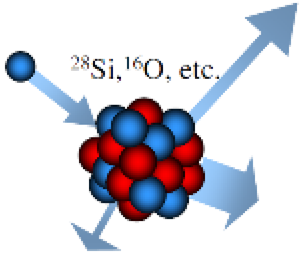
Abstract

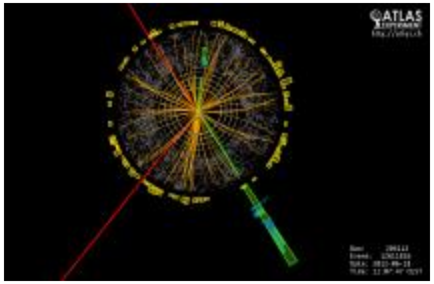
- The use of Commercial-Of-The-Shelf (**COTS**) electronic components in the high energy accelerator context requires **characterizing** their response to **radiation effects**
- Such a characterization is typically performed using one or several test beams which only cover a **small subset** of the particle species and energies present in the operational environment
- In this seminar, we will describe the standard approach used to derive operational failure rates from test results, focusing on the effect of the strong energy dependency introduced by the presence of **high-Z materials** near the component's sensitive region

Presentation Outline

Context

- **Radiation fields** are present in the accelerator and its surroundings
- LHC systems host commercial electronic components (**COTS**) and are located near the accelerator (i.e. exposed to radiation)
- Radiation effects negatively impact the **LHC availability** through beam dumps and reparation time
- The **R2E project** was created to reduce the impact of radiation effects on the LHC performance





Motivation

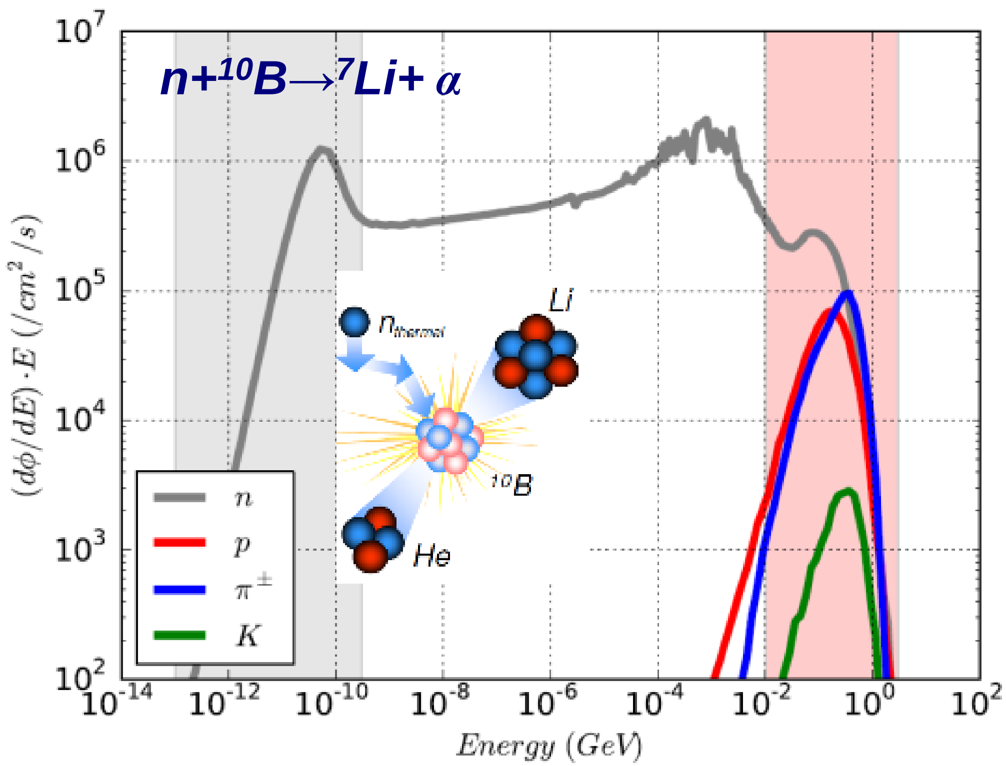
- SEE characterization for LHC applications is typically performed in monoenergetic proton cyclotron test facilities (e.g. PSI, with protons up to 230 MeV)
- The LHC operational environment includes a broad range of particles (of which **hadrons** are the relevant species for SEE induction) and energies and is known as a **mixed-field**
- Therefore, in order to link the experimental and operational contexts, the dependency of the failure probability (i.e. **cross section**) with the particle type and energy needs to be well understood

Accelerator vs. Experiment approach

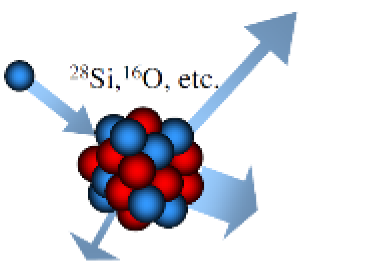
- In the LHC experiment context, critical electronic components are **radiation hardened by design** (ASICs, etc.), though COTS are also partially used
- In the LHC accelerator, **commercial components** (COTS) are used to built customized systems
- The radiation environment and basic transistor elements are similar/common to both domains

Example of LHC spectra

- LHC tunnel-like lethargy energy spectrum
- Broad range of particles, energies and interactions that generate products capable of inducing SEEs

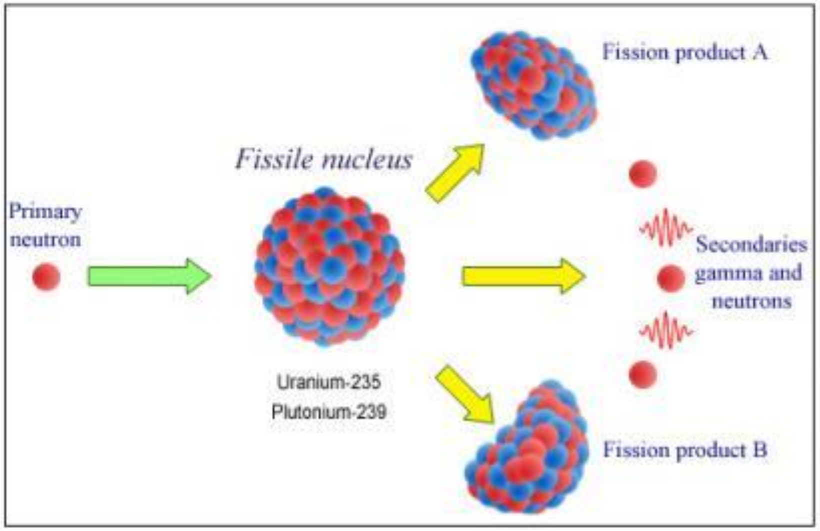


$n+^{28}Si \rightarrow ^{25}Mg+\alpha$
$\rightarrow ^{28}Al+p$
$\rightarrow ^{27}Al+d$
$\rightarrow ^{24}Mg+n+\alpha$
$\rightarrow ^{26}Mg+^{3}He$
…



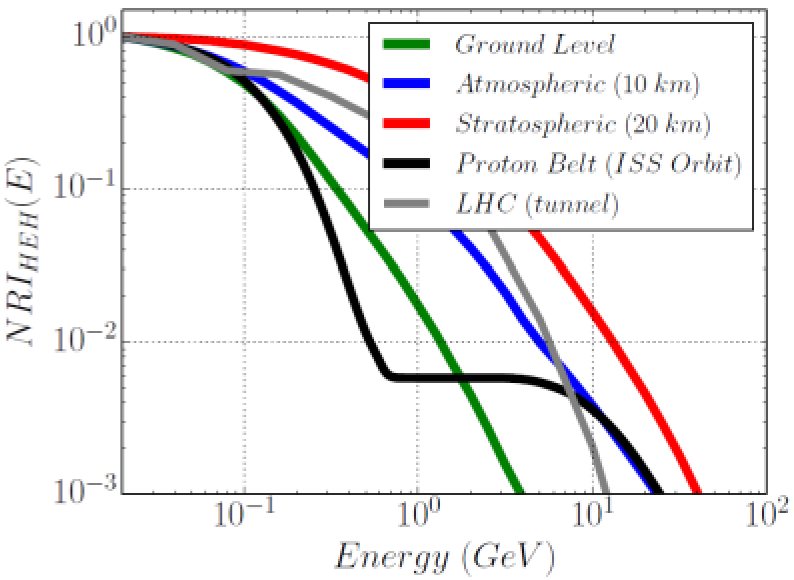
Fission vs. spallation

- In a **spallation** reaction, most of the energy is transferred to the light fragments
- In a **fission** reaction, the binding energy of the nucleus is transferred to the fragments, which therefore have larger energies than heavy spallation fragments



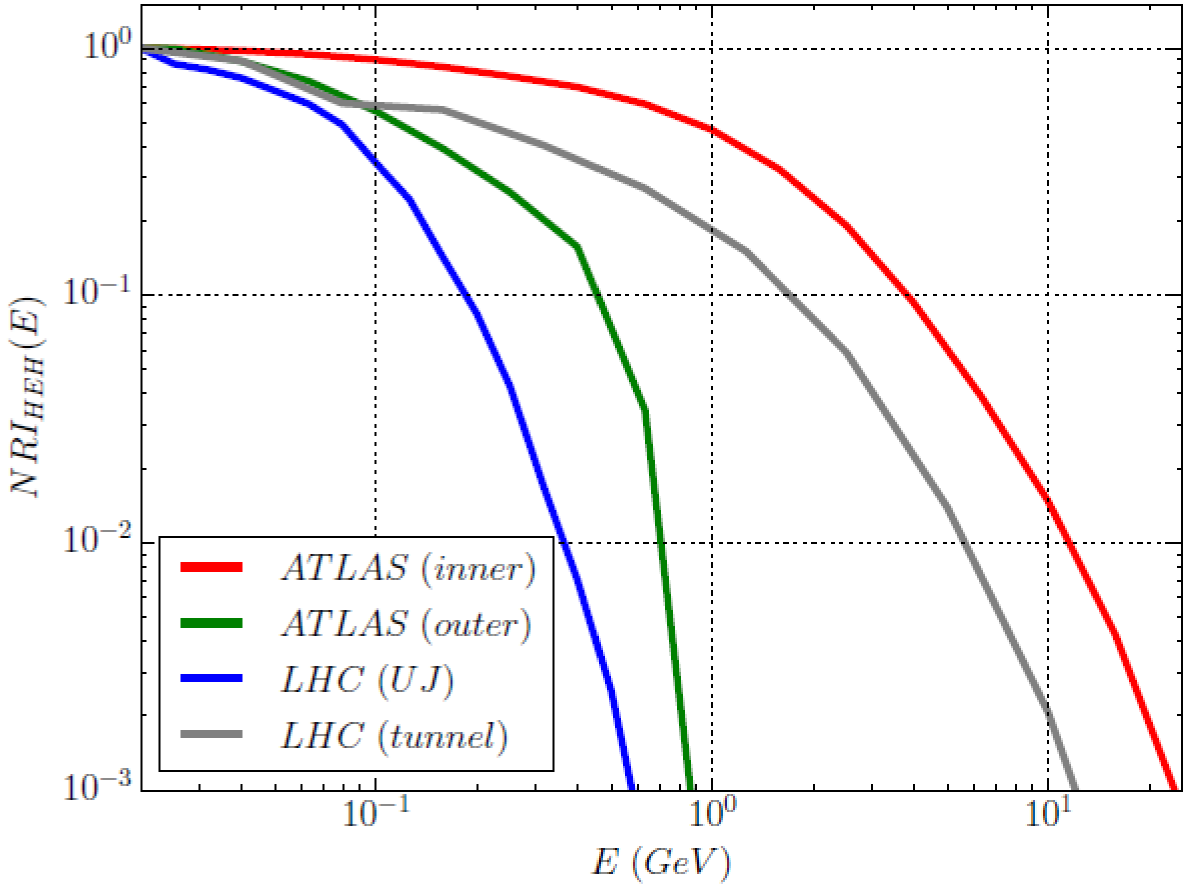
Spectral hardness

- *The Normalized Reverse Integral (NRI)* is used to quantify the **hardness** of an environment and is defined as the proportion of **HEH** (hadrons above 20 MeV) above an energy *E*
- $NRI(H_{50\%}) = 0.5$



Env.	$H_{50\%}$
LHC UJ	80 MeV
Ground Level	80 MeV
Polar Orbit	100 MeV
LHC RR	180 MeV
LHC tunnel	370 MeV
20 km alt.	500 MeV
LHC Exp.	1.5 GeV

LHC experiment environment



Inner: R ~20 cm, between the 3rd barrel layer and pixel support tube, ~89% of HEH flux is pions

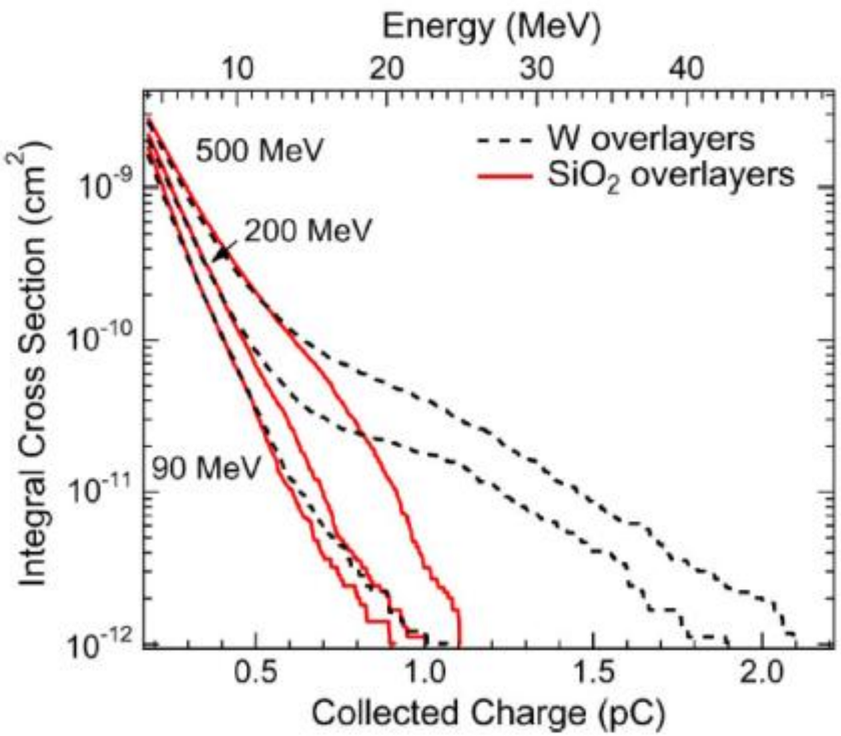
Outer: Muon barrel outer (BO). R ~ 1025 cm

(Courtesy: Charles C. Young from ATLAS)

Effect of tungsten on energy deposition

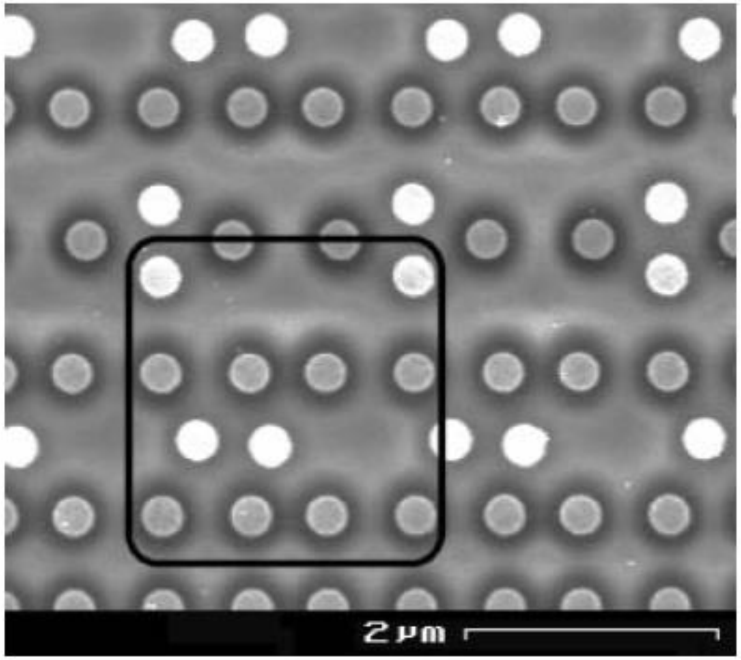
14
Si
28.085

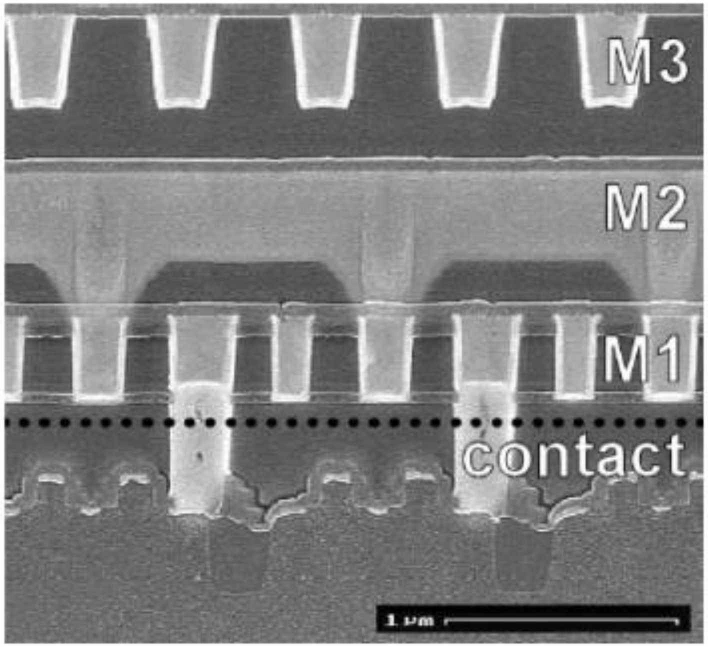
74
W
183.84



Simulated deposited energy as a function of energy and material, "The Effect of High-Z Materials on Proton-Induced Charge Collection", M. A. Clemens et al, IEEE TNS, 2010

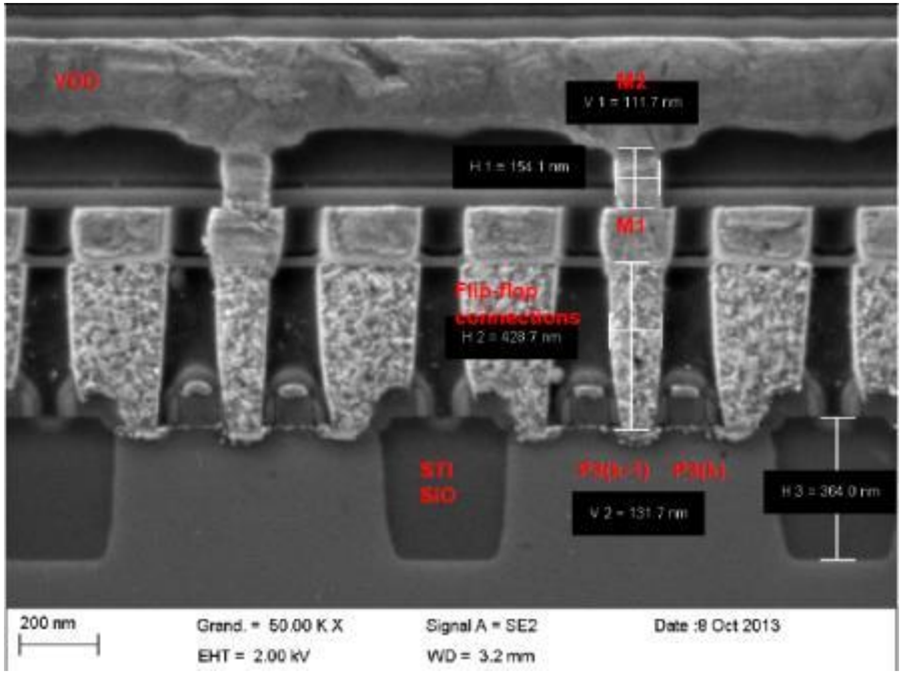
Tungsten in SRAM cell





130 nm technology in "Advanced electrical analysis of embedded memory cells using Atomic Force Probing" (M. Gruetzner, Microelectronics Reliability)

Tungsten in SRAM cell (II)



Recent CERN SEM inspection (through THALES) of a 65 nm commercial SRAM also using tungsten plugs

Presentation Outline

Context and Motivation

Tools and Approach

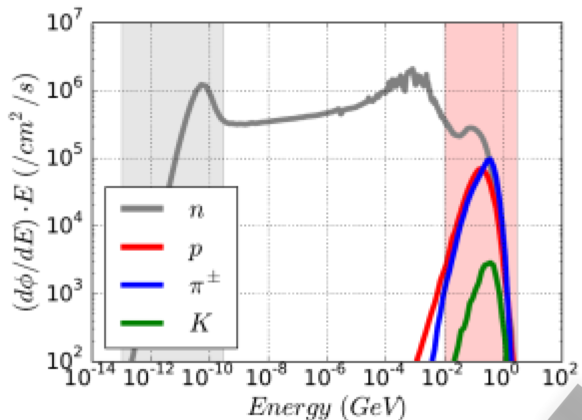
- SEE rate calculation
- Testing
- Simulations

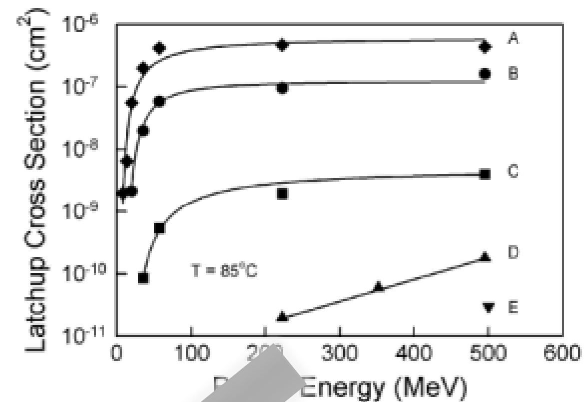
SEE Results: Experiments and Calculations

Applications and Conclusions

SEE rate estimation

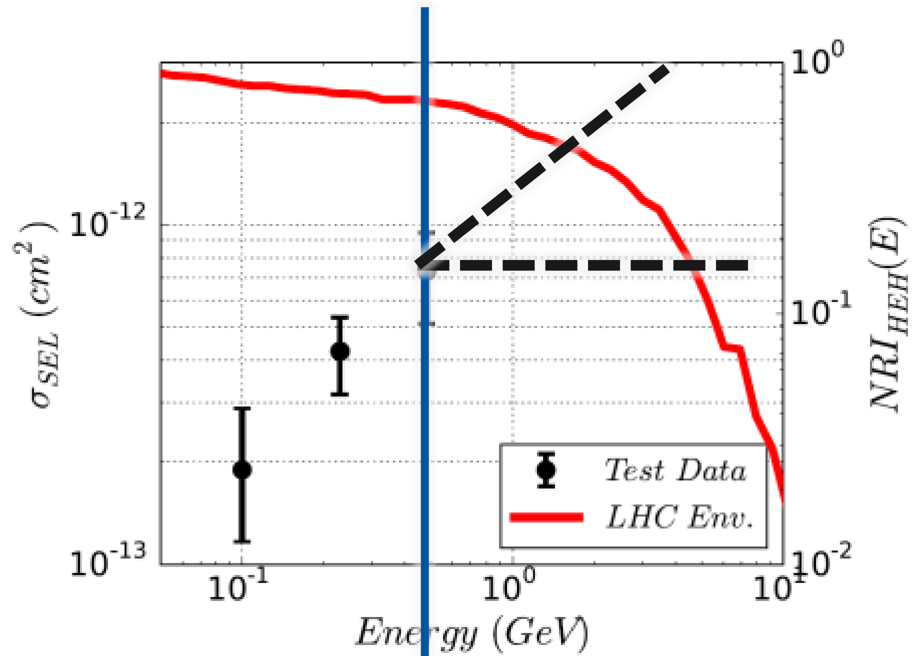
- **Radiation environment**
  - Defined by particle energy spectra
  - Obtained through benchmarked simulations
- **Device response**
  - Represented in the form of a cross section as a function of energy
  - Obtained experimentally





$$N_{failures} = \sum_i \int \frac{d\phi_i(E)}{dE}\sigma_i(E)dE$$

SEE rate estimation (II)

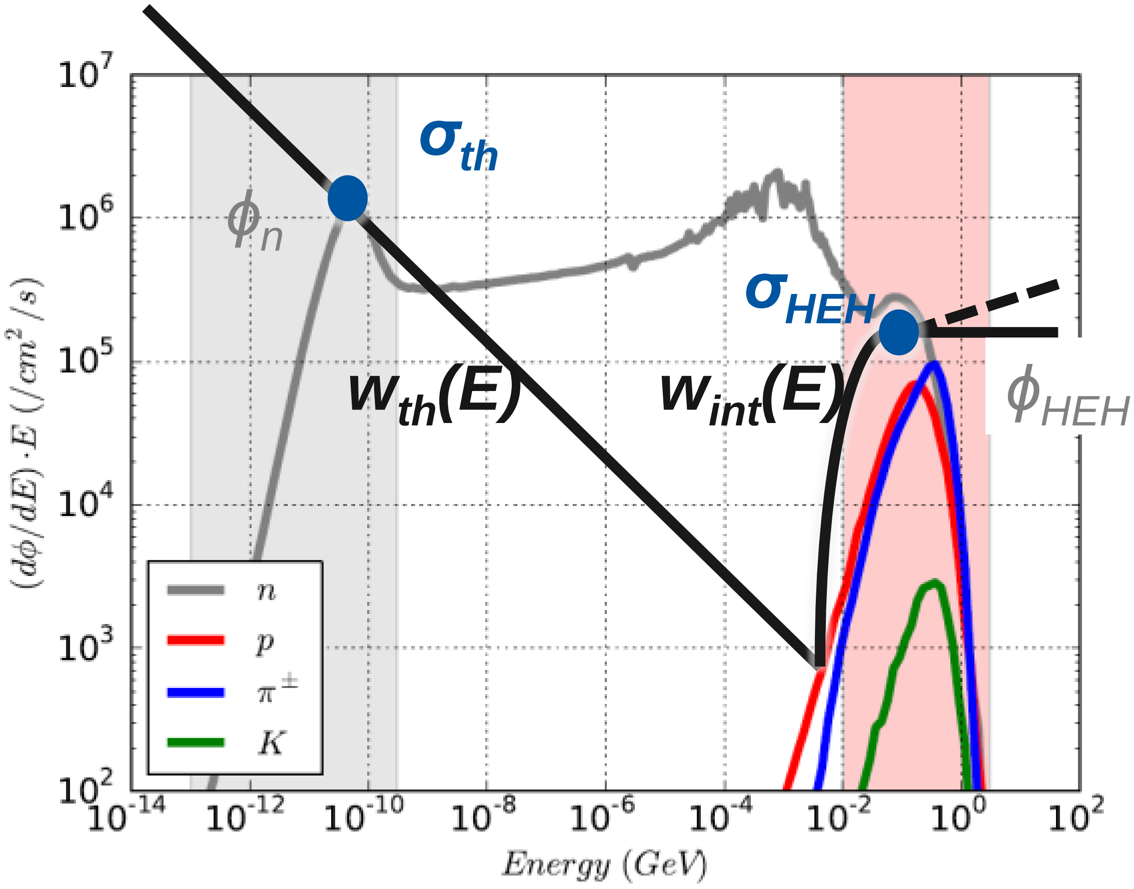


~70% of spectrum above maximum test energy

$$N_{failures} = \sum_i \int \frac{d\phi_i(E)}{dE} \sigma_i(E) dE$$

- As a standard approach, the full integration phase space (in particle type and energy) cannot be covered experimentally
- Therefore, **assumptions** need to be made regarding the SEE cross section dependence with energy and particle type

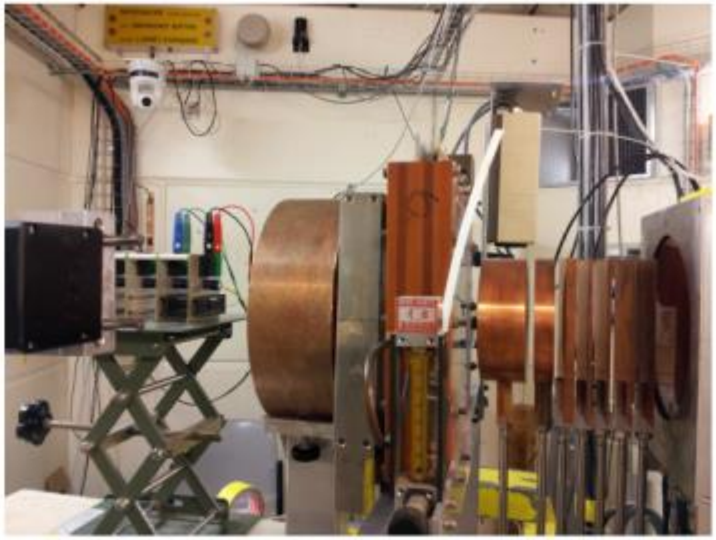
HEH approach



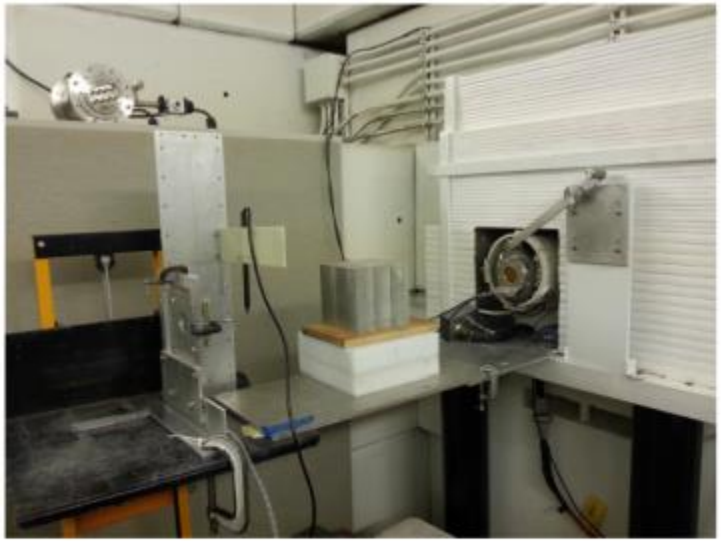
- Thermal neutron and HEH contributions
- HEH approach assumption: the SEE cross section saturates above **20 MeV**
- *Can this be generally applied for the LHC? If not, can we quantify the* ***risk*** *of a possible cross section increase?*

Monoenergetic tests

- (Proton) beam accelerated in a cyclotron and extracted at a certain energy (typically several hundred MeV)
- Beam energy can be reduced through degraders
- Important to identify contribution of particles and energies



230 MeV beam at PSI



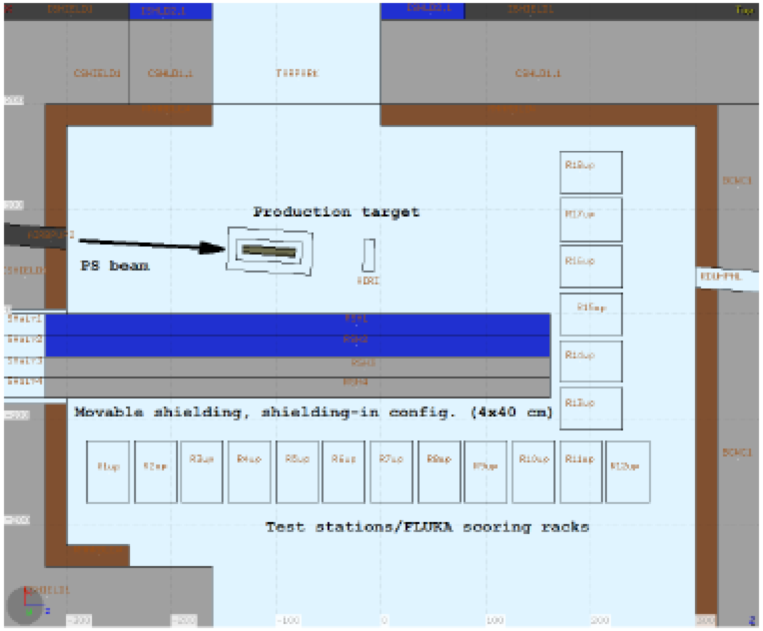
480 MeV beam at TRIUMF

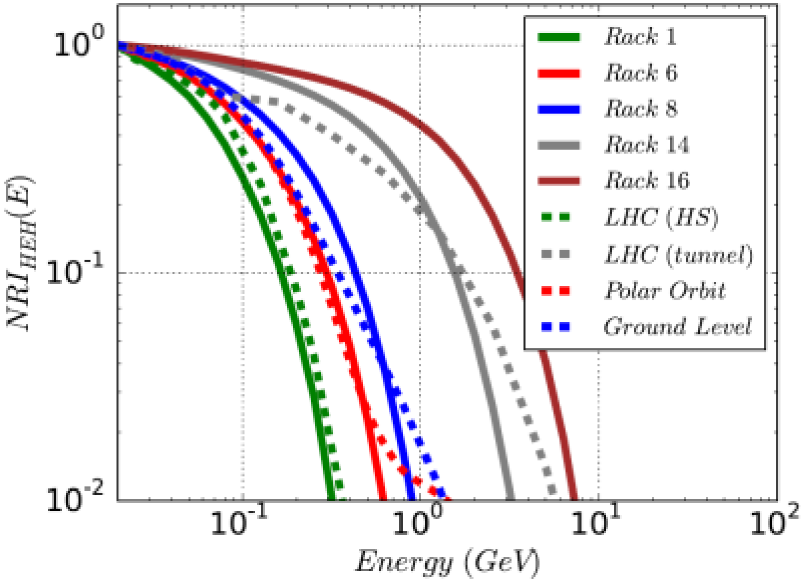
Mixed-field tests

- High energy (proton) beam interacts with target, generating a secondary **mixed-field** with a strong hadronic component (mainly neutrons, protons and pions)
- Used to reproduce environments such as the atmospheric or high-energy accelerator
- Mixed-field composition, intensity and energy distribution strongly depends on:
  - Proton energy
  - Target material and size
  - Test location (angle with respect to beam, shielding elements, etc.)

CHARM facility

- 24 GeV proton beam on 50 cm copper (or aluminium) target
- Multiple possible **configurations** combining target, position and shielding and yielding spectra representative of different operational environments (LHC, space, ground-level, etc.)



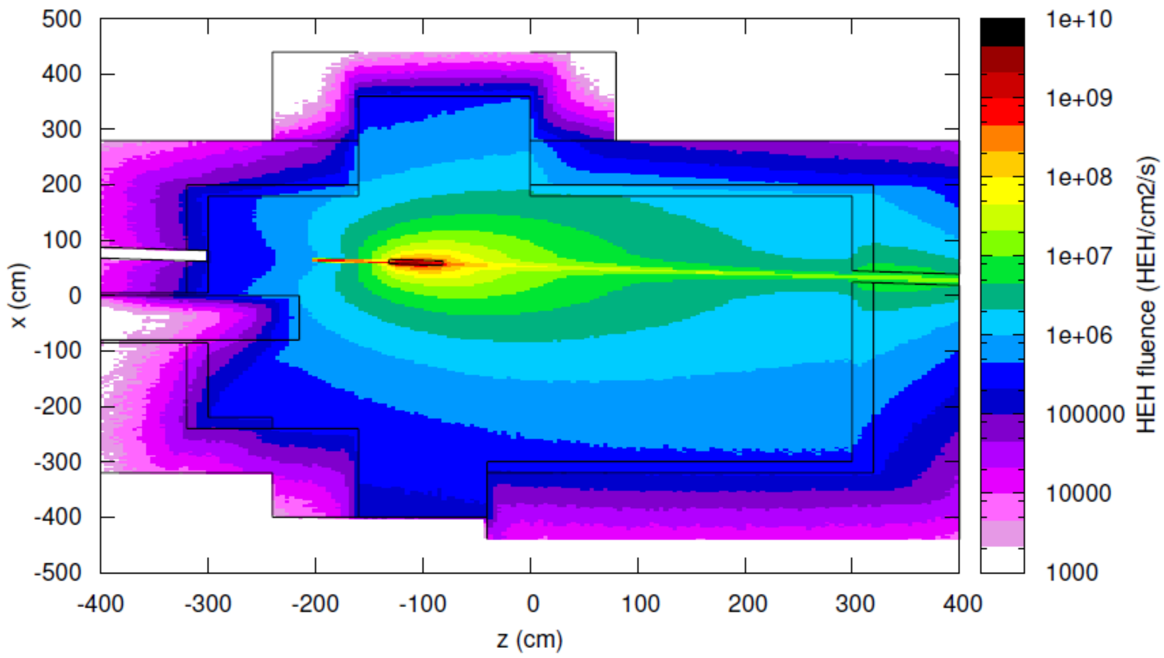


SEE Simulations using FLUKA

- A **Monte Carlo** transport code is a means of performing a mathematical experiment
- The radiation source, geometry and detectors are defined as an **input**. The program performs the transport and interaction of the radiation field with the geometry, and the detector results are yielded as an **output**
- **FLUKA** is a broadly benchmarked Monte Carlo code with a wide range of applications: accelerator shielding, medical physics, Cosmic Ray studies, etc.
- In the SEE context, simulations typically involve two steps: the calculation of the radiation field and its interaction with the electronic component

Mixed-field simulation

- Definition of the beam, the geometry, the scoring elements (detectors) and the physics settings
- Output example: 2D map of HEH flux at CHARM



Presentation Outline

Context and Motivation

Tools and Approach

SEE Results: Experiments and Calculations
- Soft Errors (SEU)
- Hard Errors (SEL)

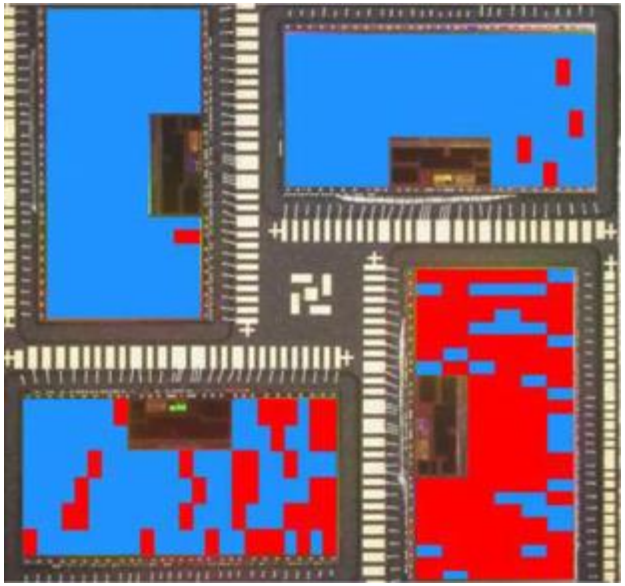
Applications and Conclusions

SEU Measurements and Simulations

- **SEUs** are soft errors that can lead to data corruption or system malfunctions if occurring in configuration memories
- Typically, they can be mitigated in different ways at system level (redundancies, etc.)
- The SEU sensitivity tends to increase with the scaling of CMOS technology
- SEUs in components can also be used as a means of **monitoring** a beam or radiation field

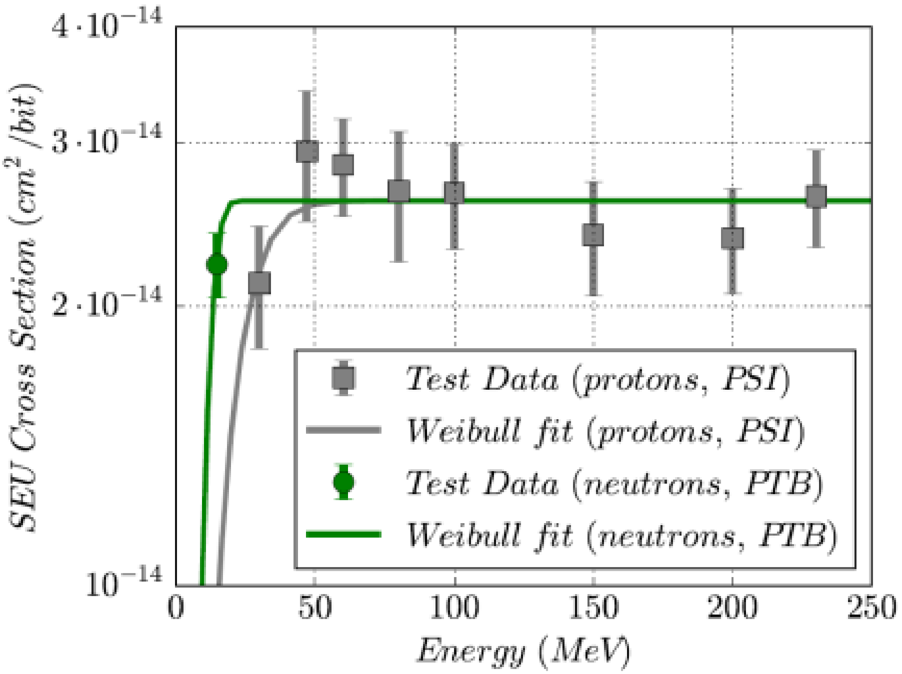
ESA SEU Monitor

- Based on a commercial 250 nm 16 Mbit SRAM
- Developed and tested by ESA as a means of cross-calibrating beams at test facilities
- Total number of SEUs and physical distribution



ESA SEU Monitor Test Results

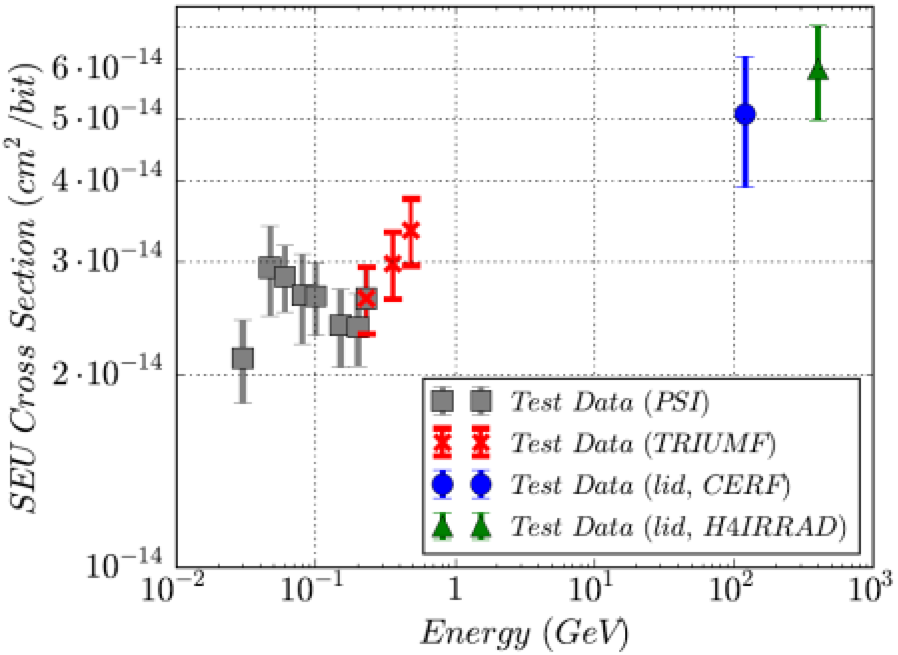
- Proton SEU cross section in the 30-230 MeV range (PSI)



- Cross section compatible with SRAMs of similar technologies
- Fall-off at 30 MeV, bump around 50 MeV, and fairly **constant** up to 230 MeV
- Lid effect at 30 MeV
- Test data from different facilities (TSL, KVI) is compatible

ESA SEU Monitor Test Results (II)

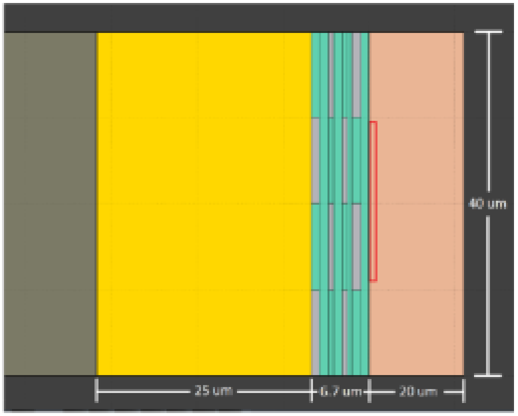
- Measurement in the 230-480 MeV range at **TRIUMF**
- In-beam measurements at **CERF** (120 GeV, 60% π^+ , 35% p, 5% K^{+}) and **H4IRRAD** (400 GeV protons)



- Cross section increase with respect to 230 MeV:
  - **30%** at TRIUMF
  - Factor **2.0** at CERF and **2.3** at H4IRRAD

ESA SEU Monitor simulations

- **Simulation motivation**: calibrate SEU model to standard test data and extend it to the full particle and energy phase space
- **RPP model**:
  - 0.25 μm^3 sensitive volume (SV), consistent with 250 nm technology
  - **Detailed** description of device architecture, as well as the interaction and transport physics (in FLUKA, with customized scoring routine)
  - **Simplified** representation of device response: an SEU will occur if the charge deposited in the sensitive volume exceeds a certain critical value



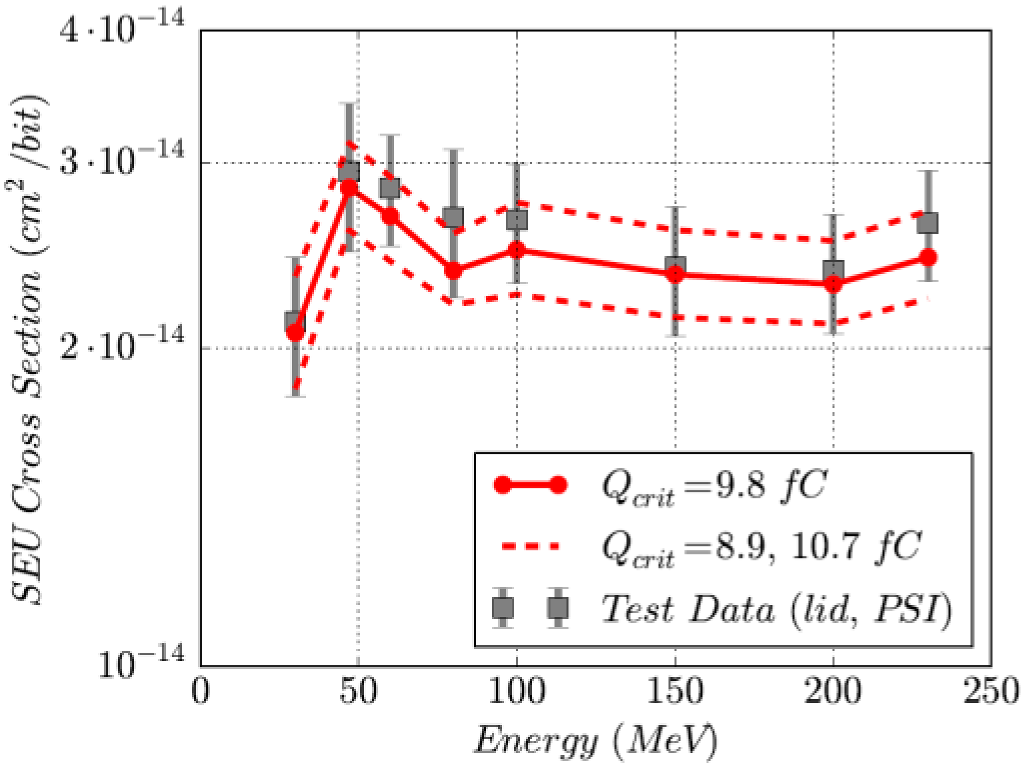
Simulation parameters:

- Sensitive volume and device architecture (technological inputs**)**
- Critical charge (fitted to experimental data)

Semi-empiric RPP model

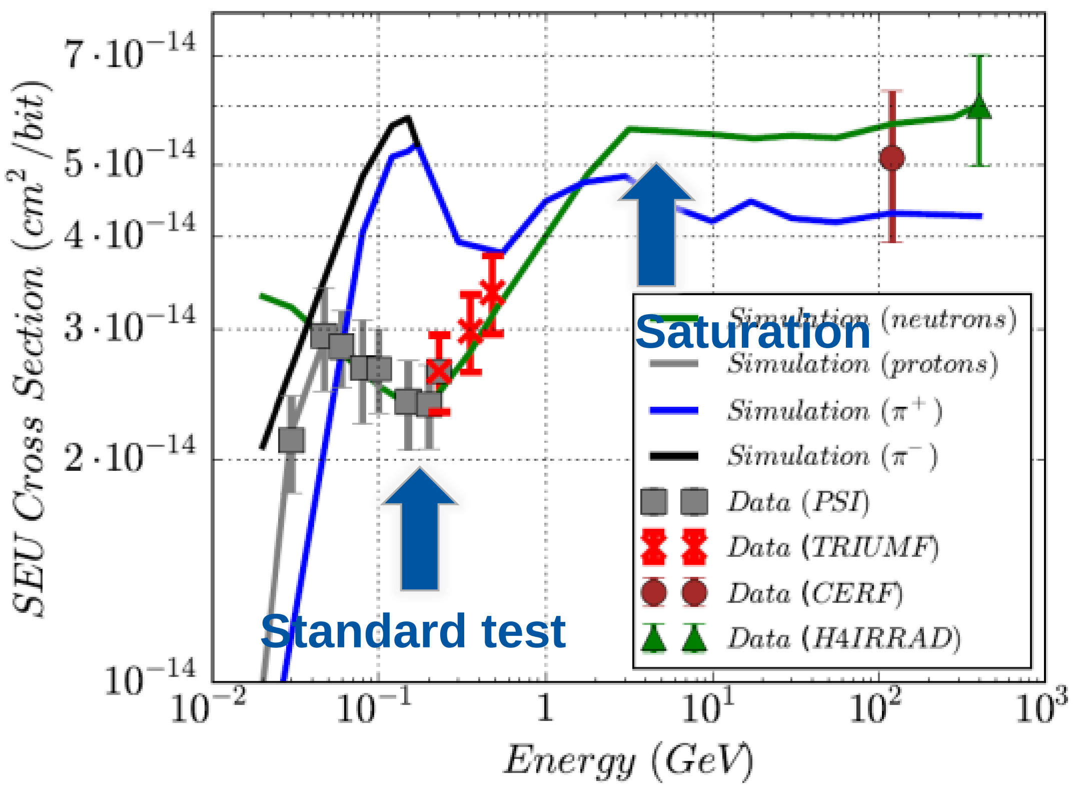
ESA SEU Monitor simulations (III)

$$\sigma(E) = \frac{\int_{Ec}^{\infty} p\,(E, E_{dep})dE_{dep}}{\phi}$$



- Best fit of the **critical charge** to the test data is **9.8 fC**
- In **good agreement** with literature values for 250 nm tech.
- Reproduces dependency in full energy range

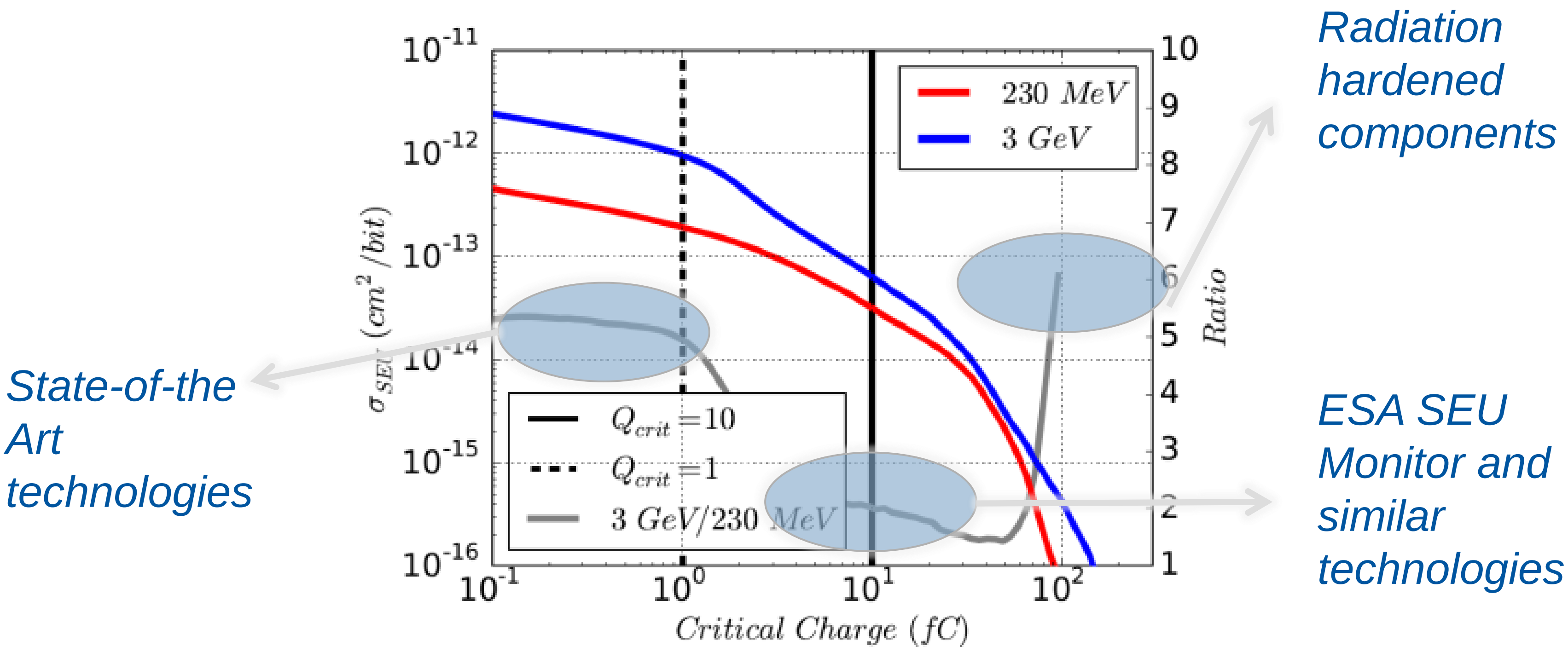
ESA SEU Monitor simulations (IV)



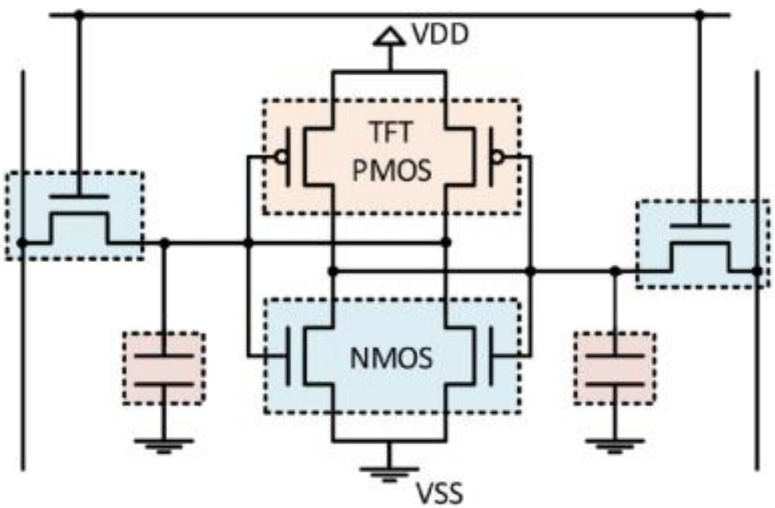
- Use of the model to calculated SEU cross section for particles and energies not accessible in standard facilities
- Expected cross section increase **compatible** with measurements
  - Expected **pion resonance** around 150 MeV

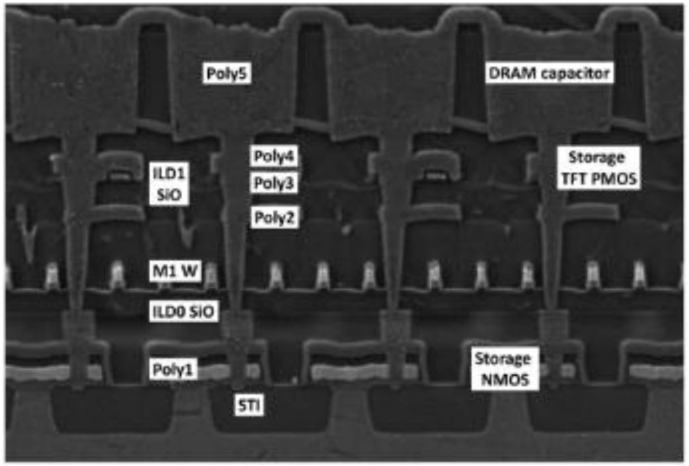
Effect of critical charge

- The **cross section increase** with energy is expected to be larger for more sensitive components as well as rad-hard devices



Effect of critical charge (II)



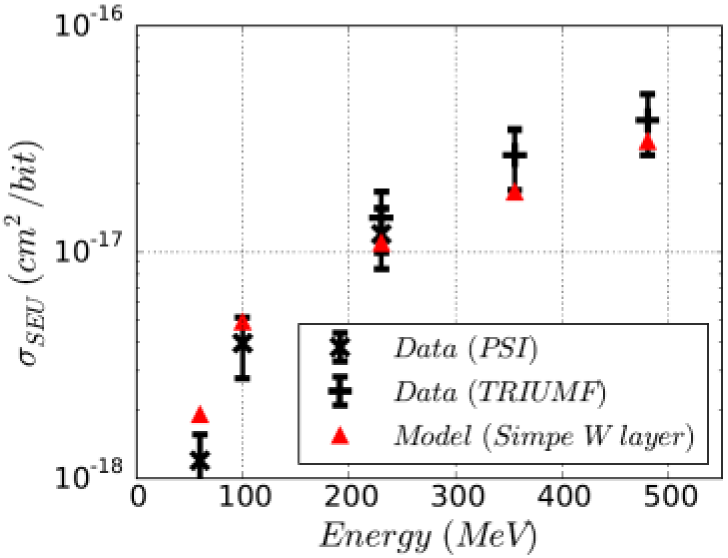


Commercial SEU-hardened SRAM memory to be used in FGCLite project for LHC

"The Effect of Proton Energy on SEU Cross Section of a 16Mbit TFT PMOS SRAM with DRAM Capacitors" S. Uznanski et al., IEEE TNS (2014)

Effect of critical charge (III)

- Similar experimental and calculation analysis for **rad-hard SRAM**
- Factor **~10** cross increase expected between standard test energy and saturation



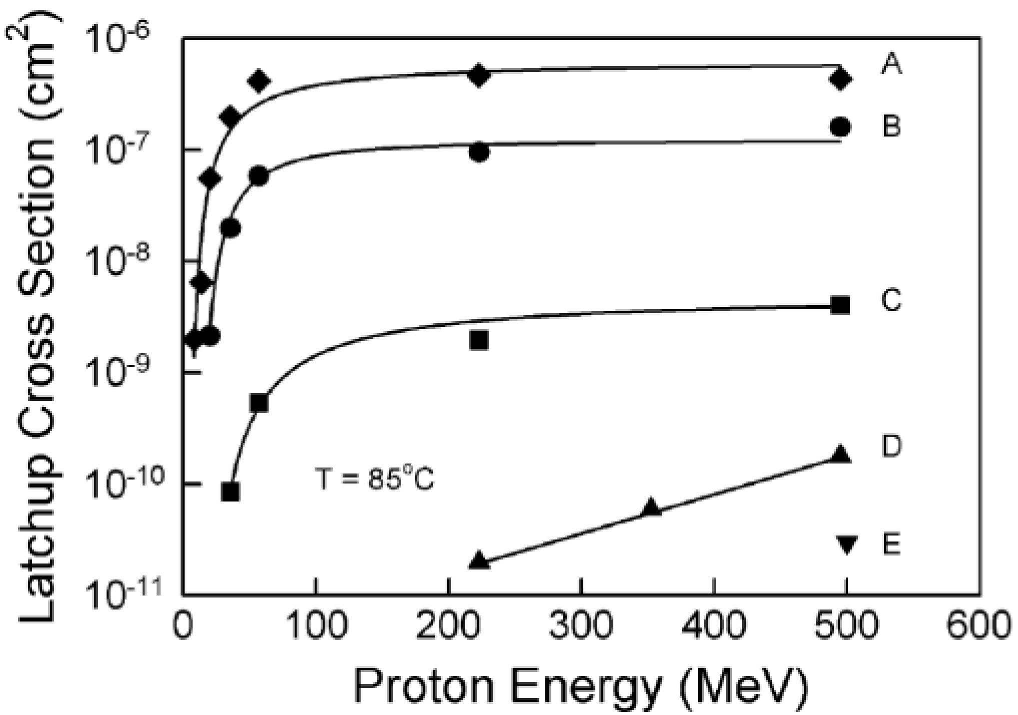
Impact on mixed-field SEU rate

- For an **LHC tunnel** environment, the ESA Monitor SEU rate is expected to be **~40% larger** than what is derived from the HEH approach
- Therefore, impact in terms of **operation** is **modest** (especially when considering uncertainly sources such as the description of the radiation environment or the sensitivity spread of the device)
- However, for **monitoring purposes** (i.e. CHARM) this difference is highly relevant, therefore the energy dependence and spectral hardness need to be carefully considered in this case
- For **state-of-the-art** technologies and **hardened** components, the cross section increase and its impact on the mixed-field SEU rate is expected to be **more severe**

SEL Measurements and Simulations

- **SEL** are potentially **destructive** failures that in the LHC context can result in the malfunction of a system and a beam dump
- SEL affects a broad range of microelectronic devices (essentially those with **CMOS** structure)
- Unlike in the case of space systems, SEL can be tolerated in an LHC system design (trade-off with electronic performance needs to be analysed)
- Therefore, understanding the SEL response in the high energy accelerator mixed-field is essential for **radiation impact evaluation**

SEL Measurements and Simulations (II)

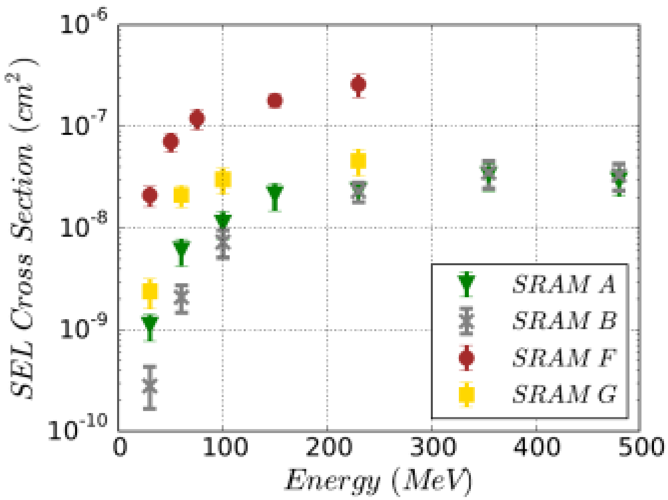


Schwank et al., IEEE TNS, VOL. 52, NO. 6, DEC.2005

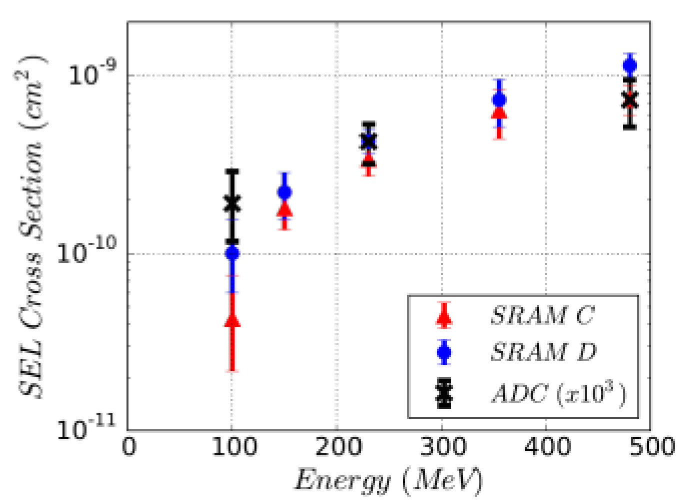
- Six **commercial SRAMs** (130-200 nm tech.) and a commercial **ADC** (300 nm tech.) were selected as a **test sample**
- The objective was to determine their SEL cross section dependence with energy

SEL test results

- Proton tests of SEL component sample at PSI (30-230 MeV) and TRIUMF (230-480 MeV)
- Commercial SRAMs in the 150-200 nm technology interval



High sensitivity components: **saturated** behaviour above ~150 MeV



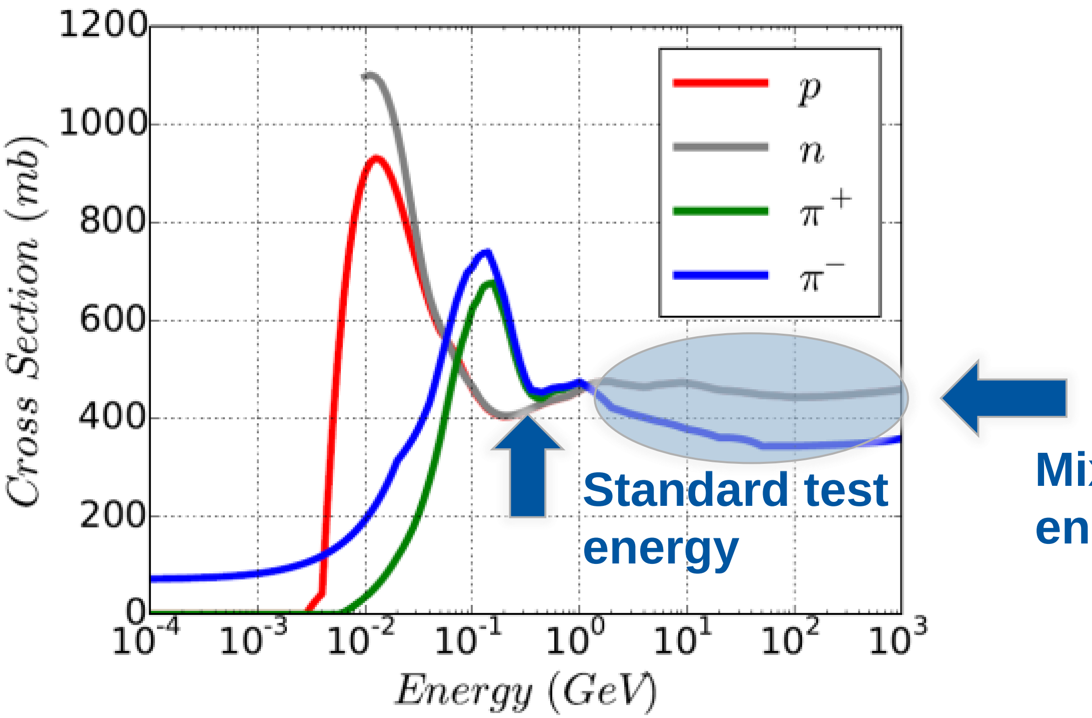
Low sensitivity components: cross section **increase** up to maximum energy tested

SEL simulations

- As can be found in the literature, the SEL cross section increase in the several hundred MeV range is attributed to **high-Z** material **fission** fragments
- **Tungsten** is broadly used in integrated circuits as a connector between the metallization layers closest to the active zone and M0 and the polysilicon level
- Therefore, in order to understand the energy dependence, it is important to analyse the proton-tungsten **fission cross section** and the fission fragment properties

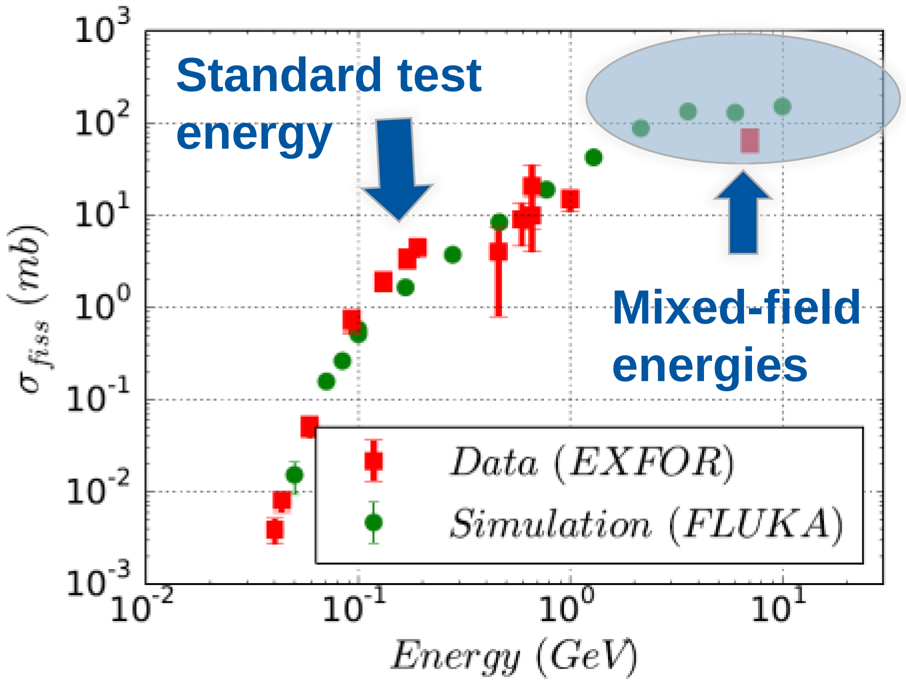
SEL simulations (II)

- Hadron reaction cross section in **silicon**: **saturated** above ~100 MeV



SEL simulations (III)

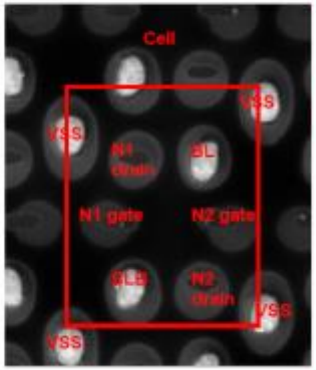
- Proton induced **fission cross section** in tungsten

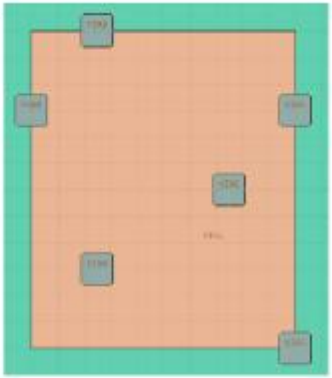


- Consistent with experimental data
- Large increase between 230 MeV and saturation at ~3 GeV (factor **~35**)

SEL simulation (IV)

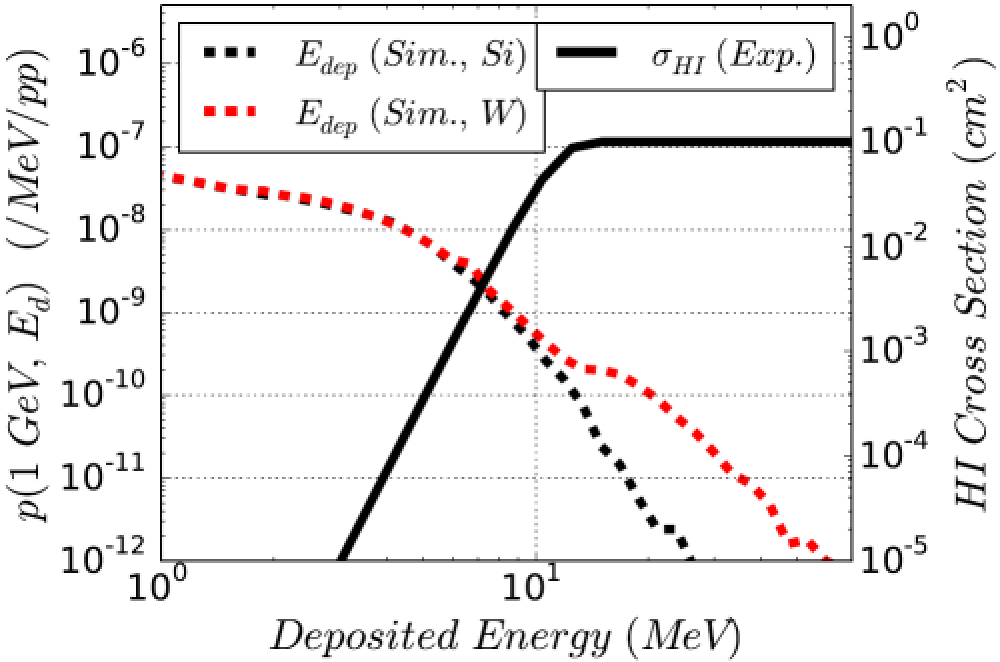
- Previous models fail to predict the proton SEL cross section and its dependence with energy
- In this thesis, a model is introduced taking into account:
  - A **more realistic SV geometry** (based on laser inspections available in the literature)
  - The presence of **high-Z materials** near the SV





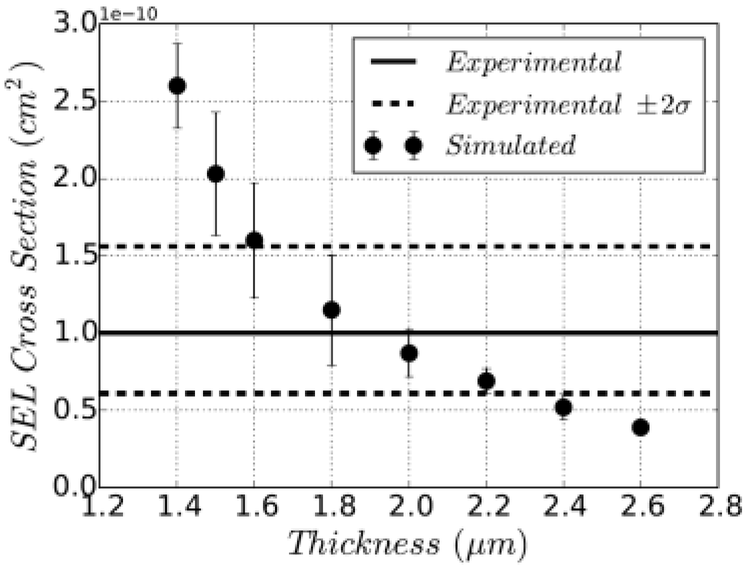
SEL simulations (V)

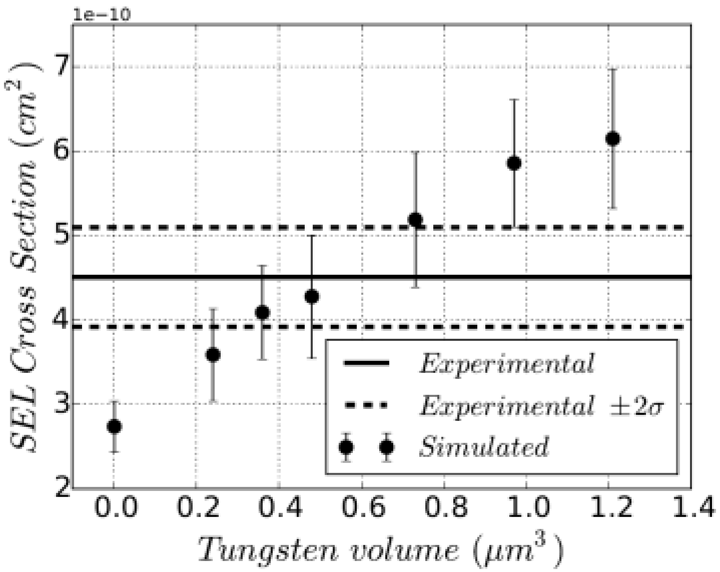
- Semi-empirical model approach: (i) convolving (**simulated**) event-by-event energy deposition distribution and (**experimental**) HI response



SEL simulations (VI)

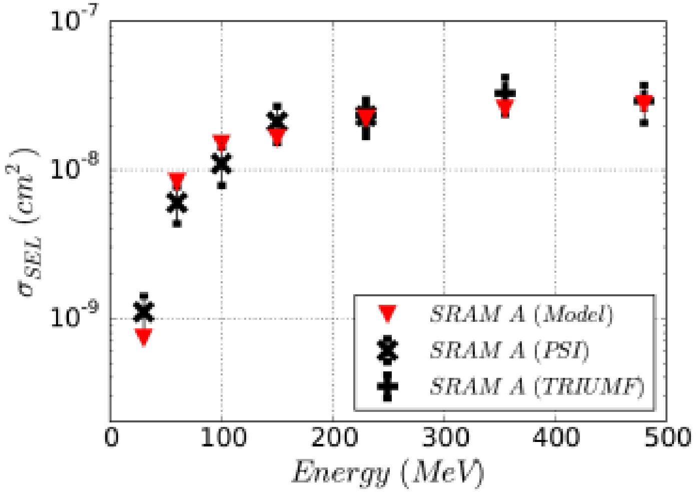
- Semi-empirical model approach: (ii) Fitting **SV thickness** and **tungsten volume** parameters to experimental data in the 100-230 MeV range



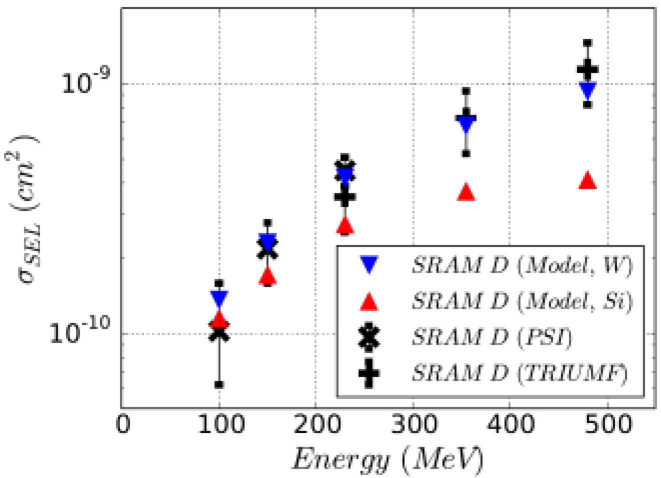


SEL simulations (VII)

- Calibrated model can be used to estimate the SEL cross section for different particles and energies
- **Tungsten** volume has a significant **impact** on the calculated cross section above 100 MeV

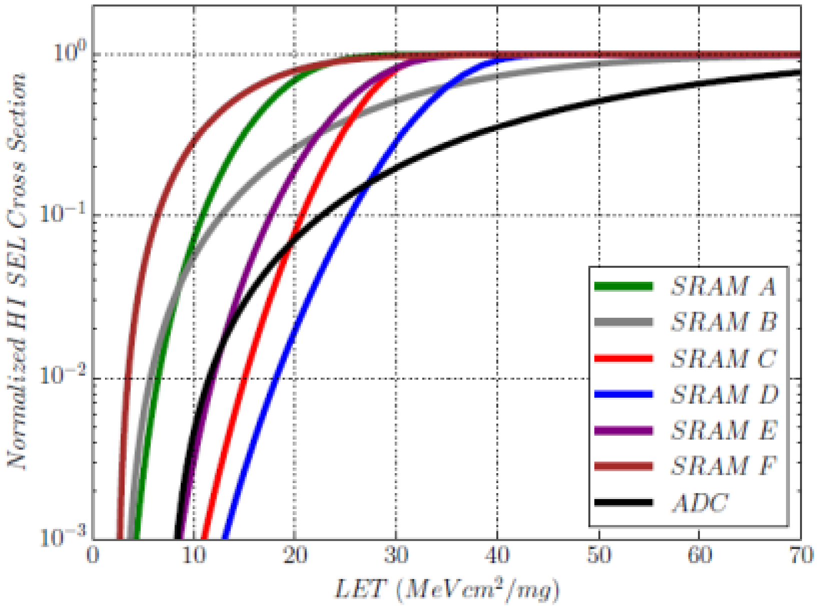


High sensitivity (LET$_{1\%}$ = 5.9 MeVcm^2/mg)



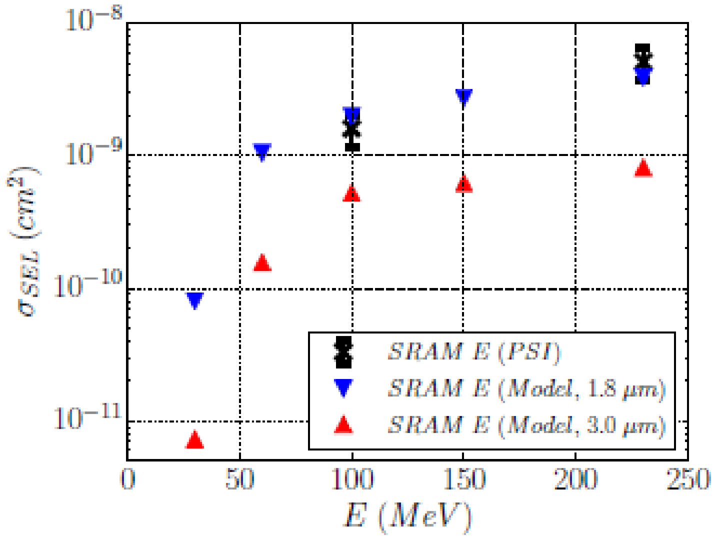
Low sensitivity (LET$_{1\%}$ = 18 MeVcm^2/mg)

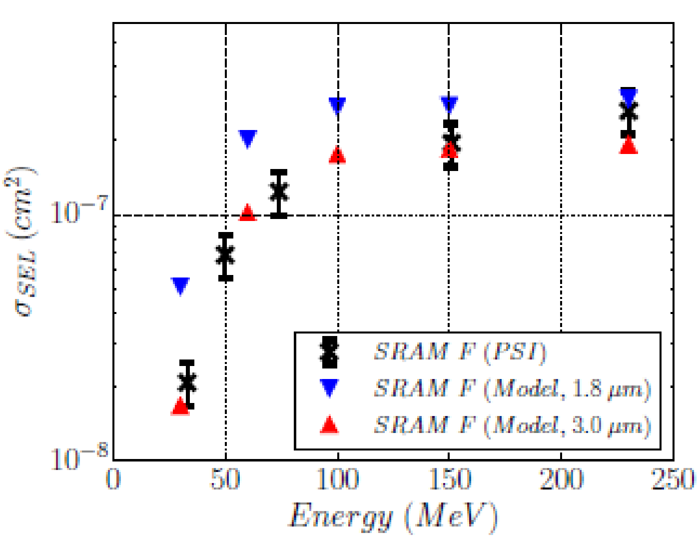
Using the model as a predictive tool



- For SRAMs E and F, the heavy ion cross section was known from previous published tests

Using the model as a predictive tool (II)





- The model is successful in predicting the proton cross section range for a thickness interval of 1.8-3 µm (realistic for the 150 nm technology according to laser studies)

SEL simulation conclusions

- The semi-empirical SEL model is successful in reproducing **energy dependence** up to 480 MeV for the different SRAMs considered
- The predicted **tungsten volume** for SRAMs C and D in good agreement with what was later determined through a SEM inspection
- When using the model as a predictive tool (i.e. no proton data available) the corresponding estimated interval was in good agreement with the measurement
- The model can therefore be used to determine the impact of the SEL cross section increase with energy on the **LHC failure rate**

Presentation Outline

Context and Motivation

Tools and Approach

SEE Results: Experiments and Calculations

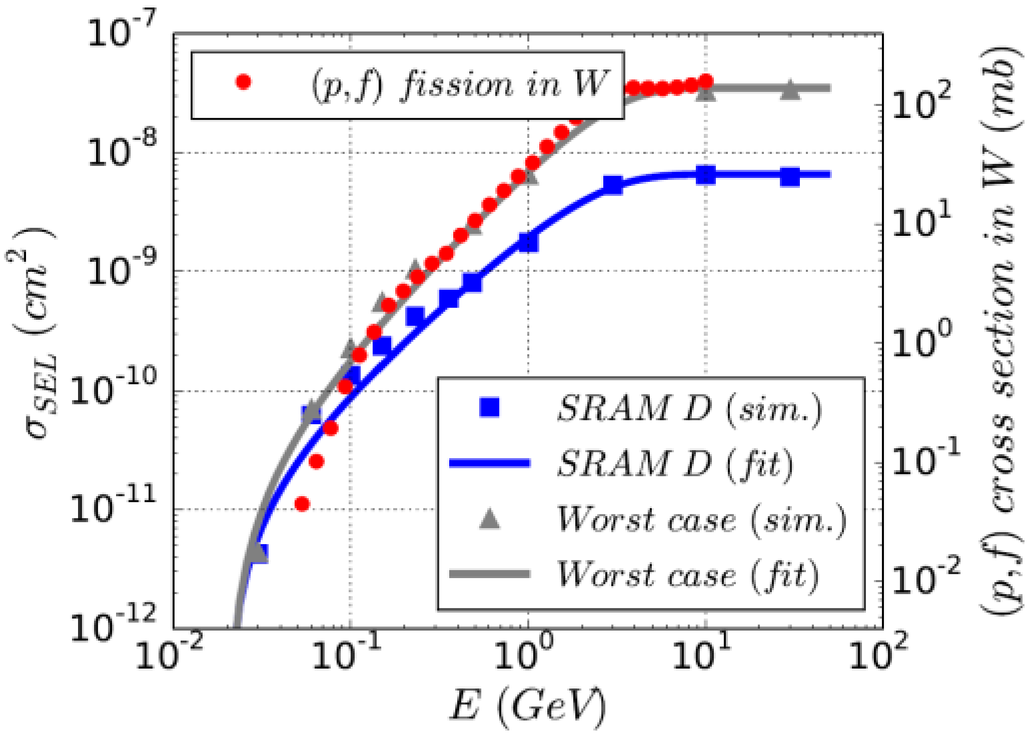
Applications and Conclusions

Implications on the High Energy Environment SEE rate

- The model presented above can be used to estimate the SEL cross section for energies larger than those typically reached at standard cyclotron facilities (e.g. 230 MeV for CERN groups at PSI) but still relevant in the accelerator environment
- This dependency can then be folded with the operational environment spectra in order to retrieve the **estimated SEE rate**
- Results can the be compared with those extracted from the HEH approximation (i.e. assuming the 230 MeV cross section)

Model-based SEE rate calculations

- Calculated cross section for SRAM D and a worst-case model (fully tungsten-dominated)

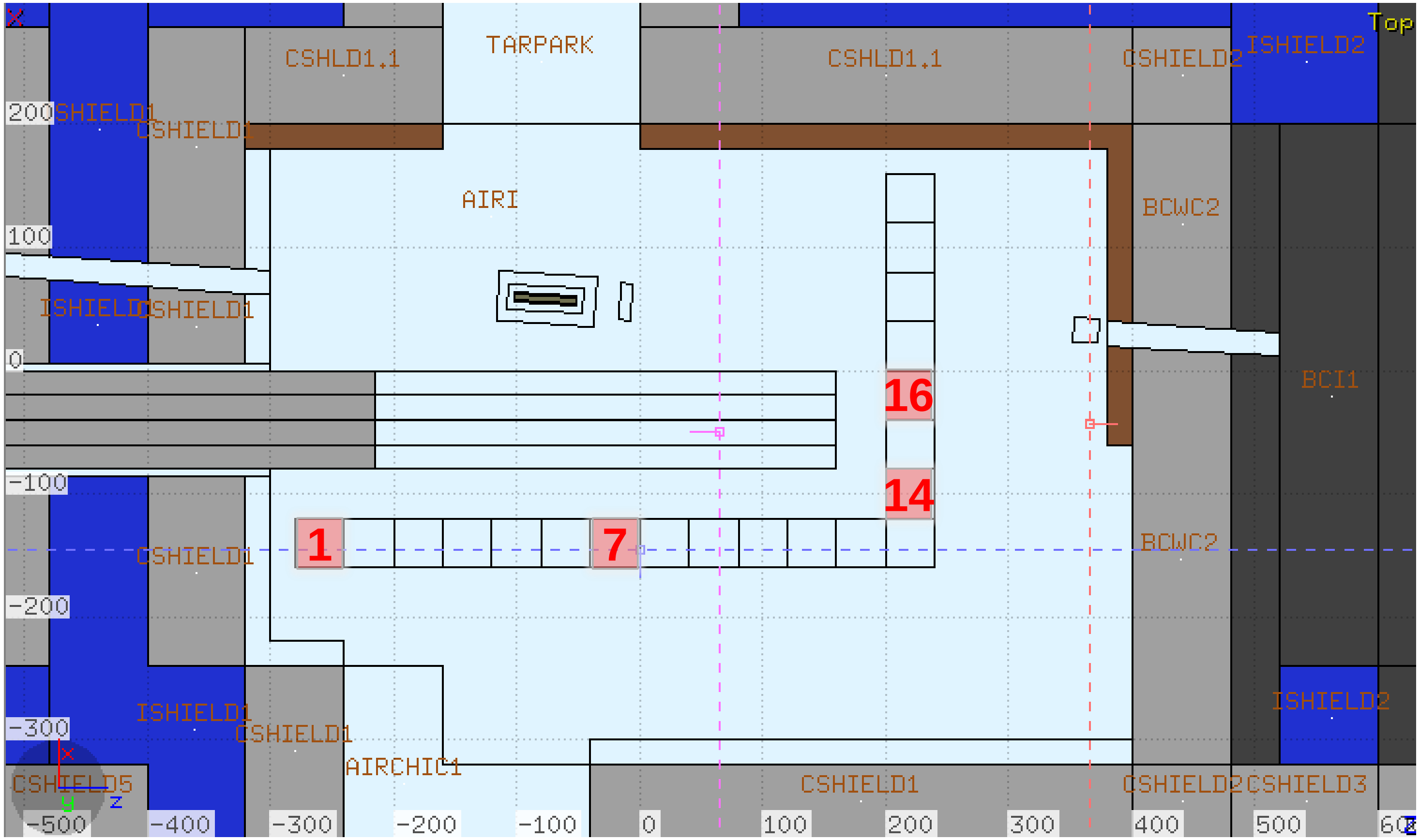


Model-based SEE rate calculations (II)

- **Estimated SEL rate** for models of SRAM A (**saturated**), SRAM D (strong **energy dependence**) and worst-case, relative to the **HEH approach** result

Env.	$H_{50\%}$ (MeV)	SRAM A (LET_{th}=	SRAM D	Worst-case
VESUVIO	50	0.39	0.20	0.19
Atm, 375m	80	0.71	0.68	1.0
LHC HS	80	0.57	0.28	0.29
Polar Orbit	100	0.62	0.64	0.73
LHC LS	180	0.81	1.2	1.9
LHC tunnel	370	1.0	**2.7**	**4.8**
Atm, 20 km	500	1.0	**3.5**	**6.9**
LHC exp.	1500	1.4	**5.6**	**12**

CHARM test locations



CHARM hardness energies and test results

Test Location	$H_{50\%}$	$\sigma_{SRAM\ C}$ (cm^2/device)	$\sigma_{SRAM\ A}$ (cm^2/device)
Monoenergetic	230 MeV	3.4e-10	2.3e-8
CHARM, 1	75 MeV	5.0e-11 (0.15)	9.2e-9 (0.40)
CHARM, 7	120 MeV	2.0e-10 (0.59)	-
CHARM, 14	310 MeV	6.1e-10 **(1.8)**	1.5e-8 (0.65)
CHARM, 16	800 MeV	1.7e-9 **(5.0)**	-

$H_{50\%}$ for LHC tunnel spectrum example = 370 MeV
$H_{50\%}$ for LHC experiment example = 1.5 GeV

Ongoing analysis – preliminary results

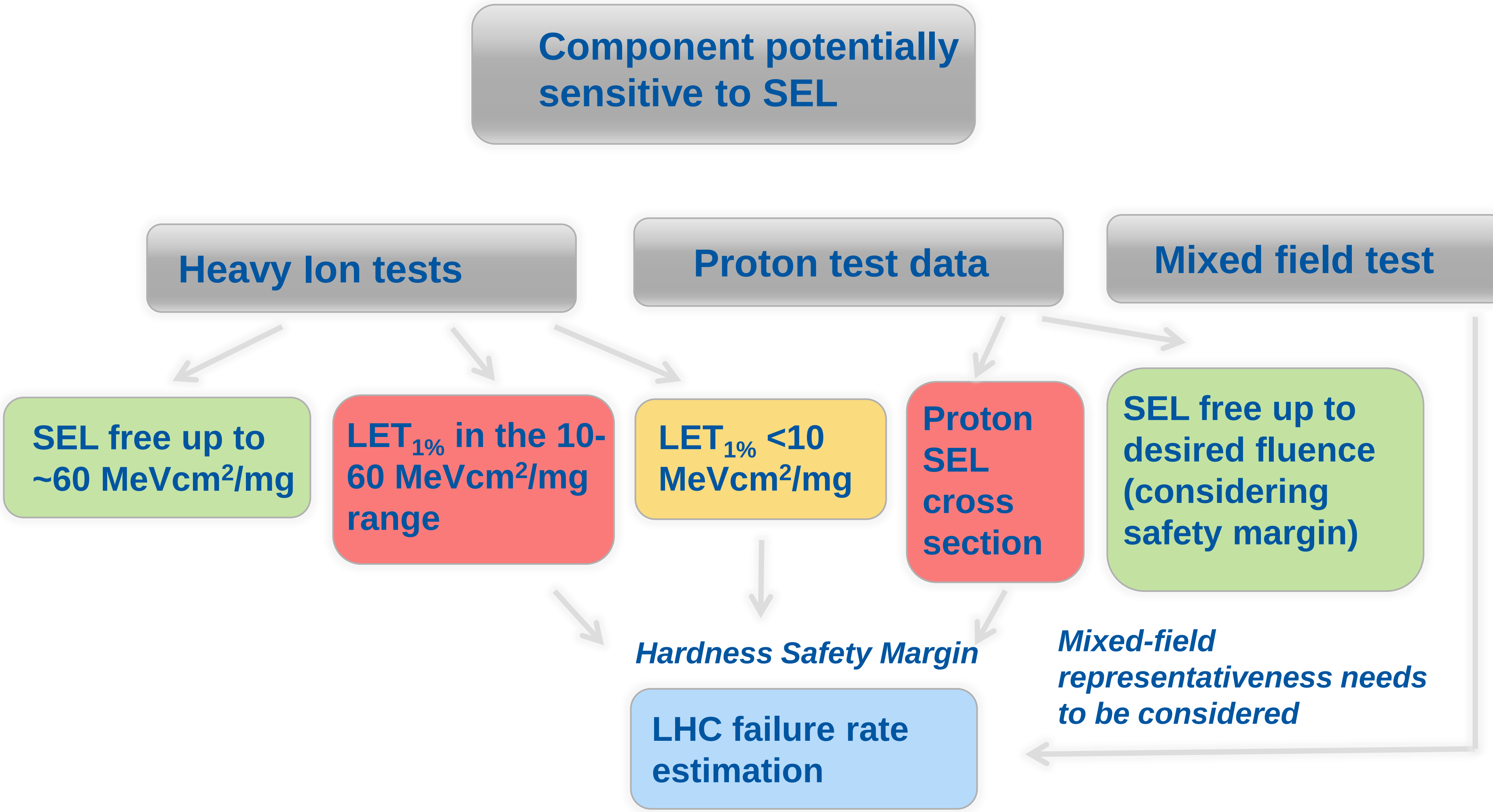
Hardness safety margin

- Therefore, there is a **risk** that components tested at 230 MeV and used in highly energetic environments will have a **significantly larger SEE rate** than what is expected by the HEH approximation
- **Safety margins** depending on the operational environment hardness are therefore to be applied in order to quantify this potential risk
- Components with high LET onsets, tungsten near the SV and a strong energy dependency below 230 MeV are suspicious of having a tungsten-dominated cross section
- If the test energy is lower than 230 MeV, the risk factors to be considered are larger

Main Conclusions

- The LHC mixed-field radiation environment is of a complex nature, involving a broad range of particles and energies
- The impact on the energy dependence with respect to the standard HEH approach was quantified for a wide variety of components and environments. The main results with respect to the HEH approach (based on 230 MeV) are:
  - A **40%** increase in the SEU rate for the ESA Monitor in an LHC tunnel context
  - Up to a **factor 5** in the SEL rate for a worst-case dependency
- Therefore, the respective **safety margins** should be applied in the LHC context in order to account for the risk related to the highly energetic environment

SEL test implications



Outlook

- Based on the work here presented, further research can be carried out in different lines:
  - Investigating the effect of the **angular incidence** on the different SRAM SEL test sample and identifying possible silicon/tungsten differences
  - Extending the mixed-field SEE impact to **power components** and state-of-the-art CMOS technologies
  - **Benchmarking** the predicted SEL failure rates as a function of spectral hardness at CHARM
  - Application of the models to estimate the high-Z material impact on **deep space missions**
  - Identifying the **limitations** of the SEU and SEL models and including more realistic descriptions of the electrical mechanisms

List of Publications

"SEL Cross Section Energy Dependence Impact on the High Energy Accelerator Failure" ***Main author, IEEE TNS, presented at NSREC 2014***

"Energy Dependence of Tungsten-Dominated SEL Cross Sections" ***Main author, IEEE TNS***

"SEE Measurements and Simulations Using Mono-Energetic GeV-Energy Hadron Beams" ***Main author, IEEE TNS, presented at NSREC 2013***

"SEU Measurements and Simulations in a Mixed Field Environment" ***Main author, IEEE TNS, presented at RADECS 2012***

"Qualification and Characterization of SRAM Memories Used as Radiation Sensors in the LHC," ***Co-author, presented at NSREC 2014, IEEE TNS***

"A New RadMon Version for the LHC and its Injection Lines," ***Co-author, presented at NSREC 2014, IEEE TNS***

"The Effect of Proton Energy on SEU Cross Section of a 16 Mbit TFT PMOS SRAM with DRAM Capacitors," ***Co-author, presented at NSREC 2014, IEEE TNS***

"Compendium of Radiation-Induced Effects for Candidate Particle Accelerator Electronics," ***Co-author, presented at NSREC 2013 data workshop, IEEE TNS***