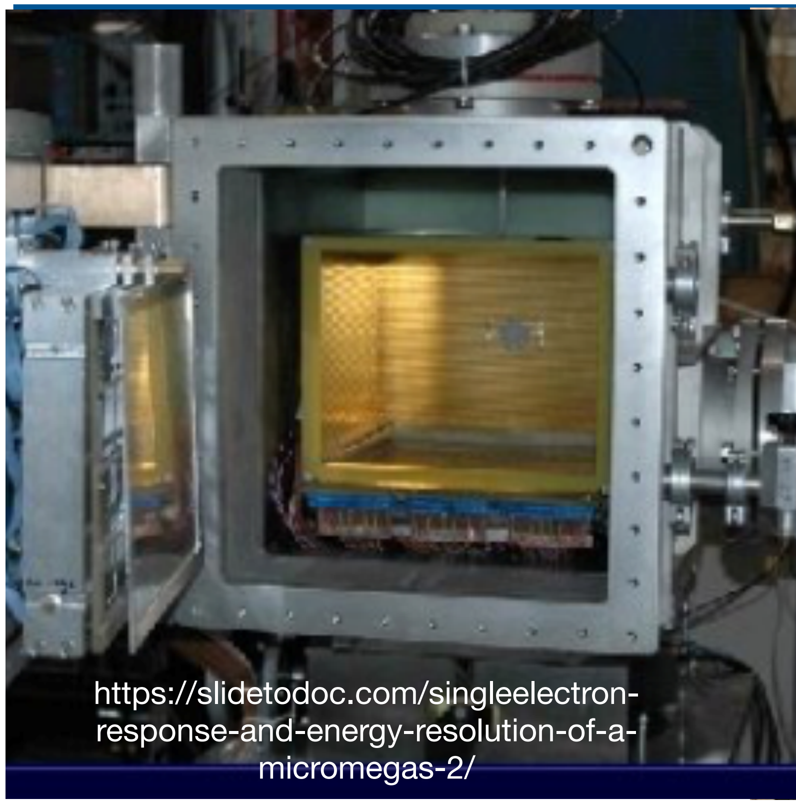
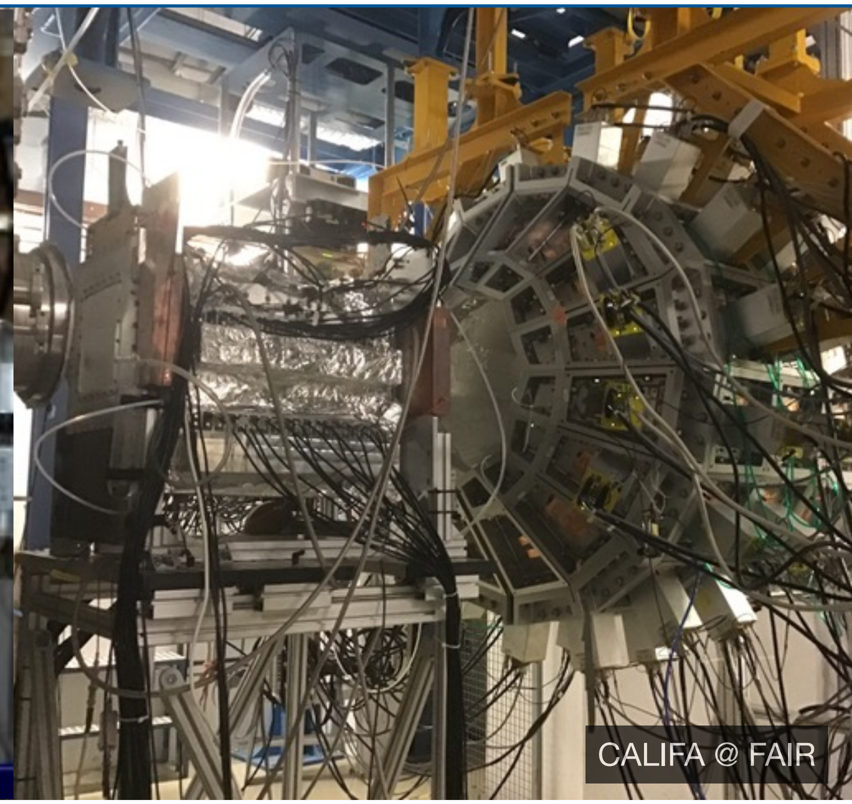
Detector and Physics simulations

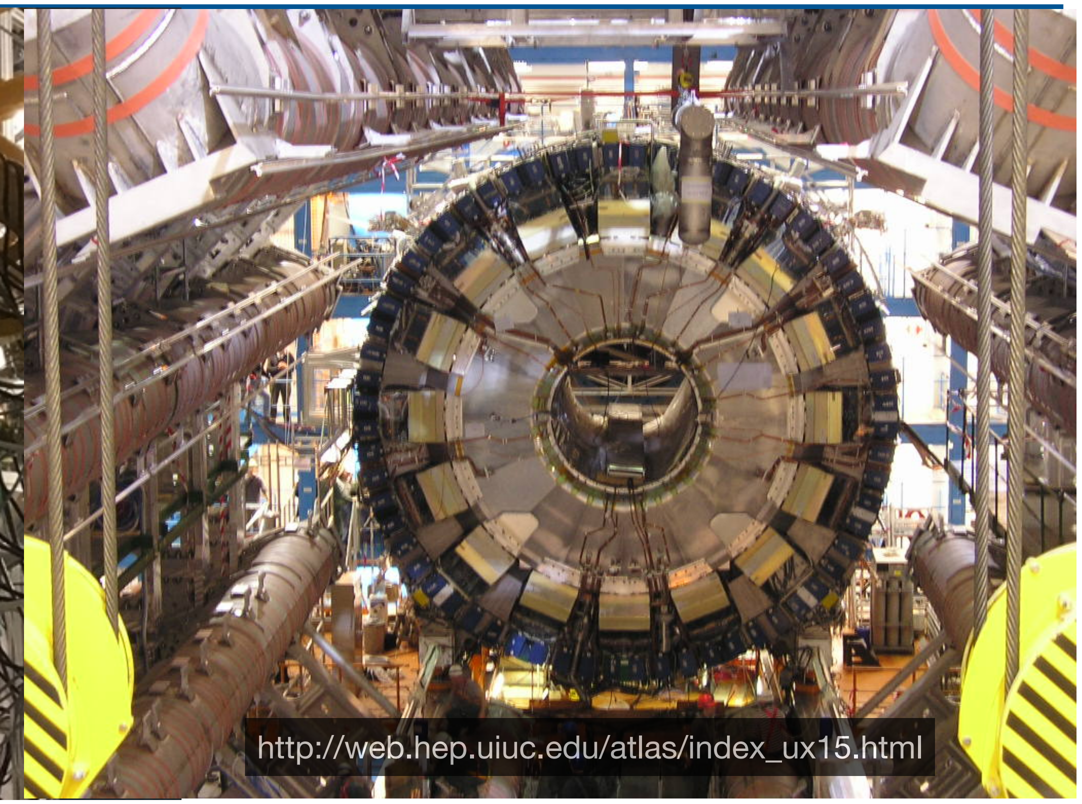
Pamela Teubig
NUC-RIA and Dosimetry

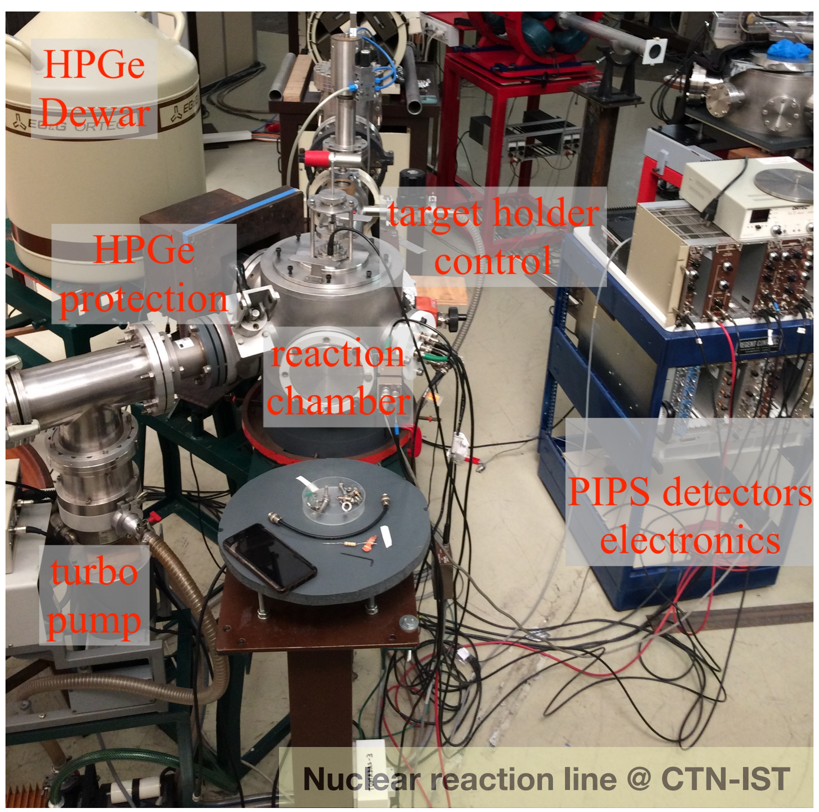
Background cover: Simulation theory by Muse

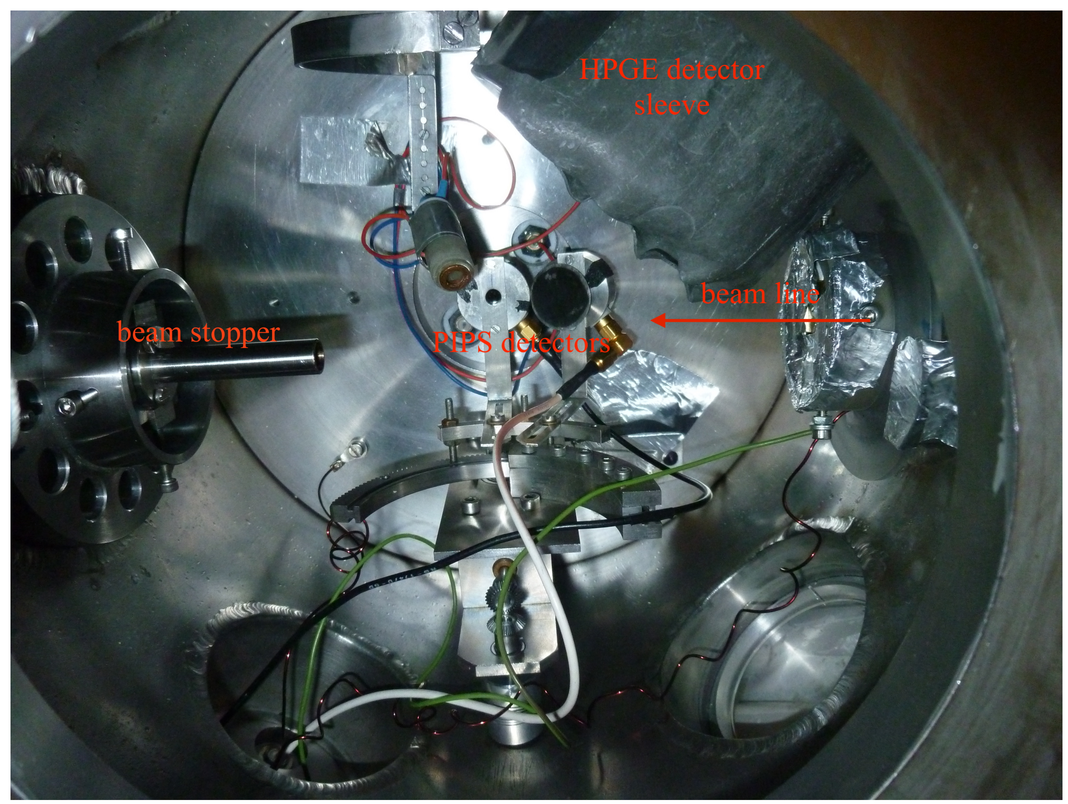
What is a detector?



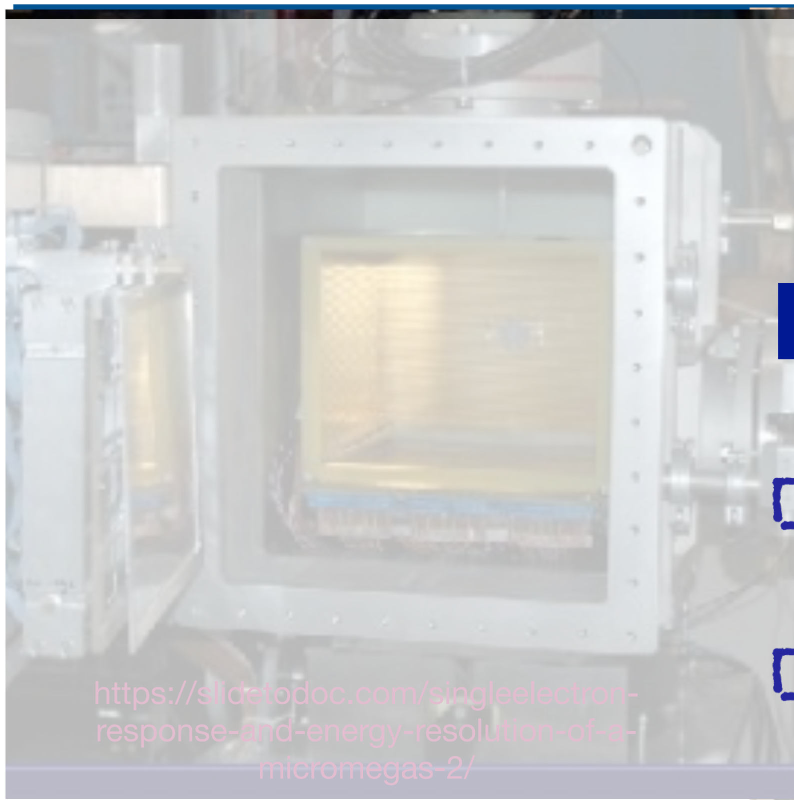


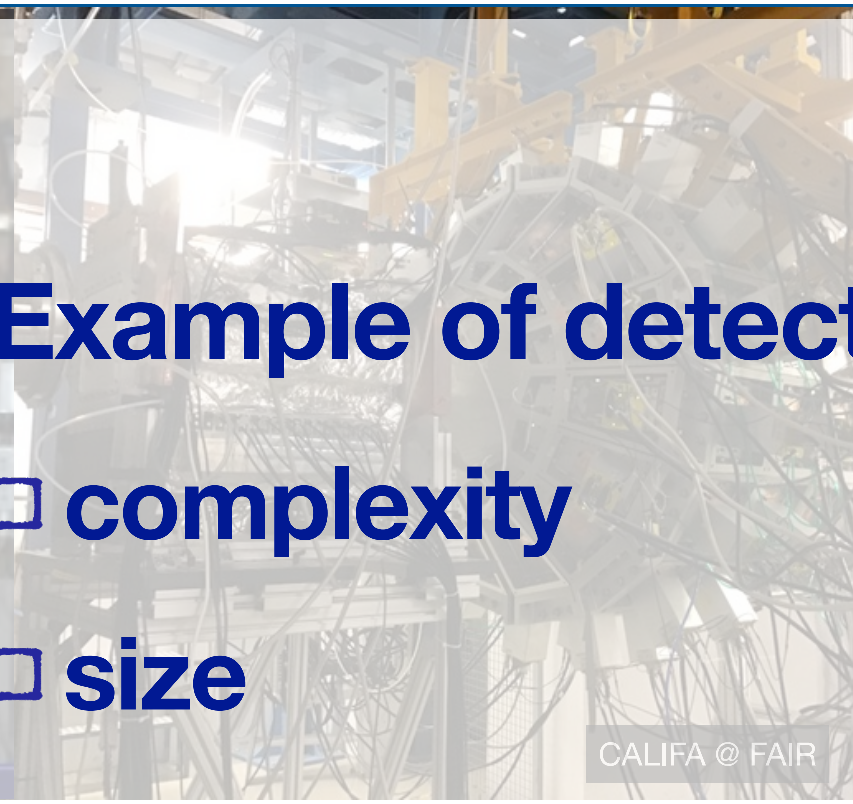






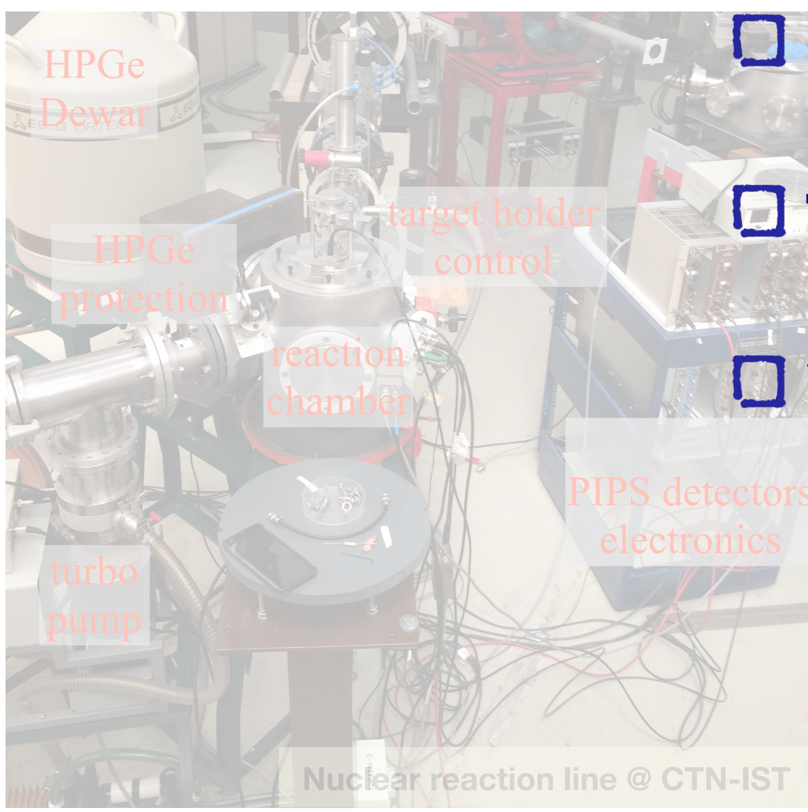
What is a detector?



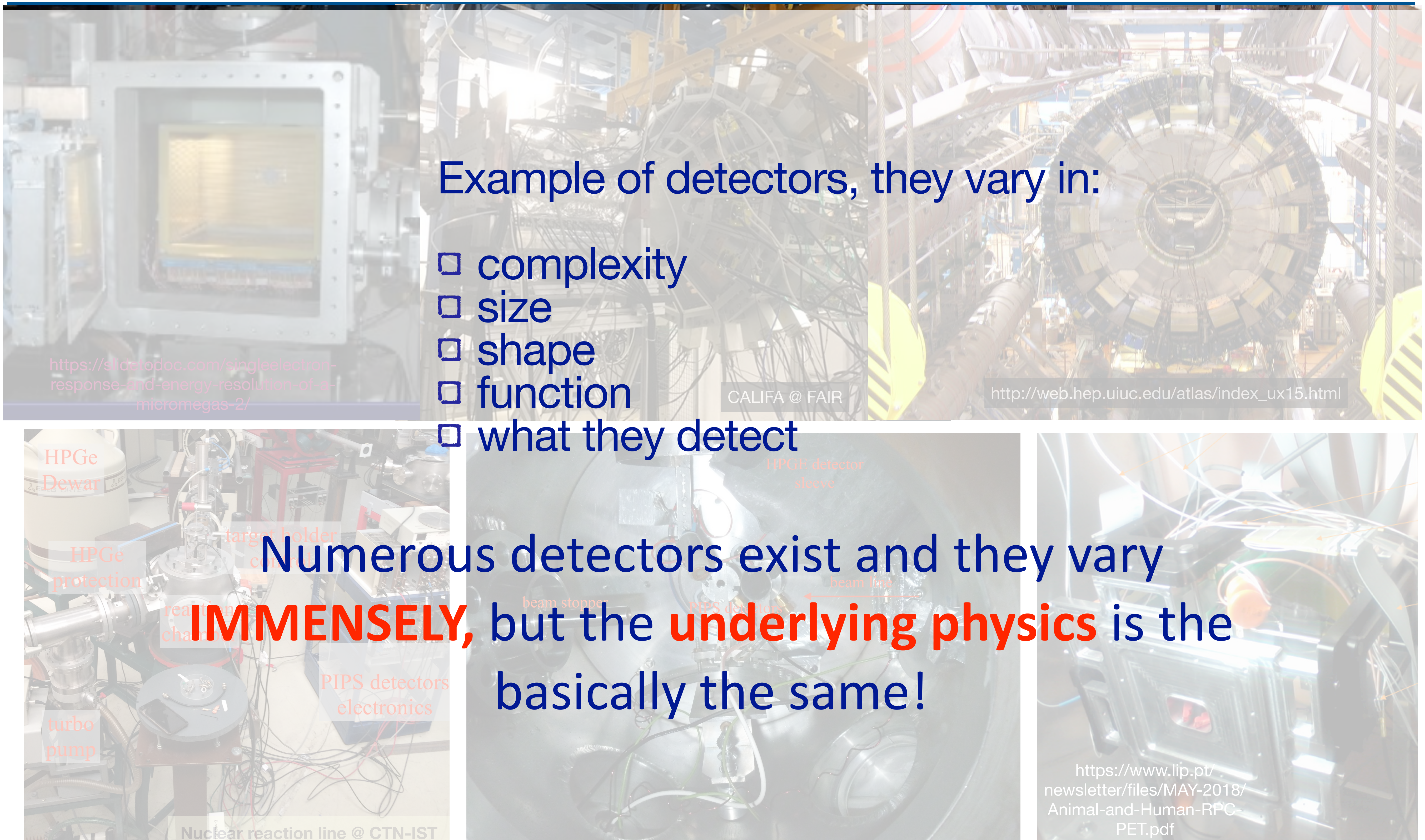


Example of detectors, they vary in:

- complexity
- size
- shape
- function
- what they detect



What is a detector?



Example of detectors, they vary in:

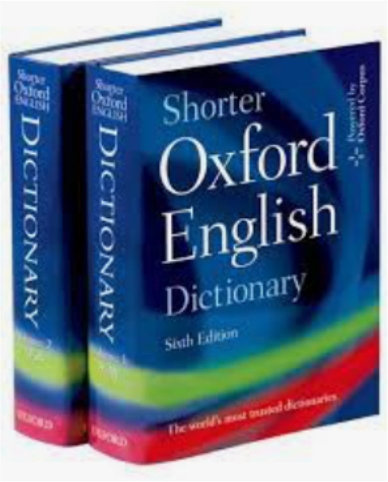
- complexity
- size
- shape
- function
- what they detect

Numerous detectors exist and they vary **IMMENSELY**, but the **underlying physics** is the basically the same!

What are the application area?

- Nuclear physics
- High energy physics (HEP)
- Astrophysics
- Space engineering
- Medical physics
- Environmental application
- Industrial applications

Simulation - what is it?



simulation

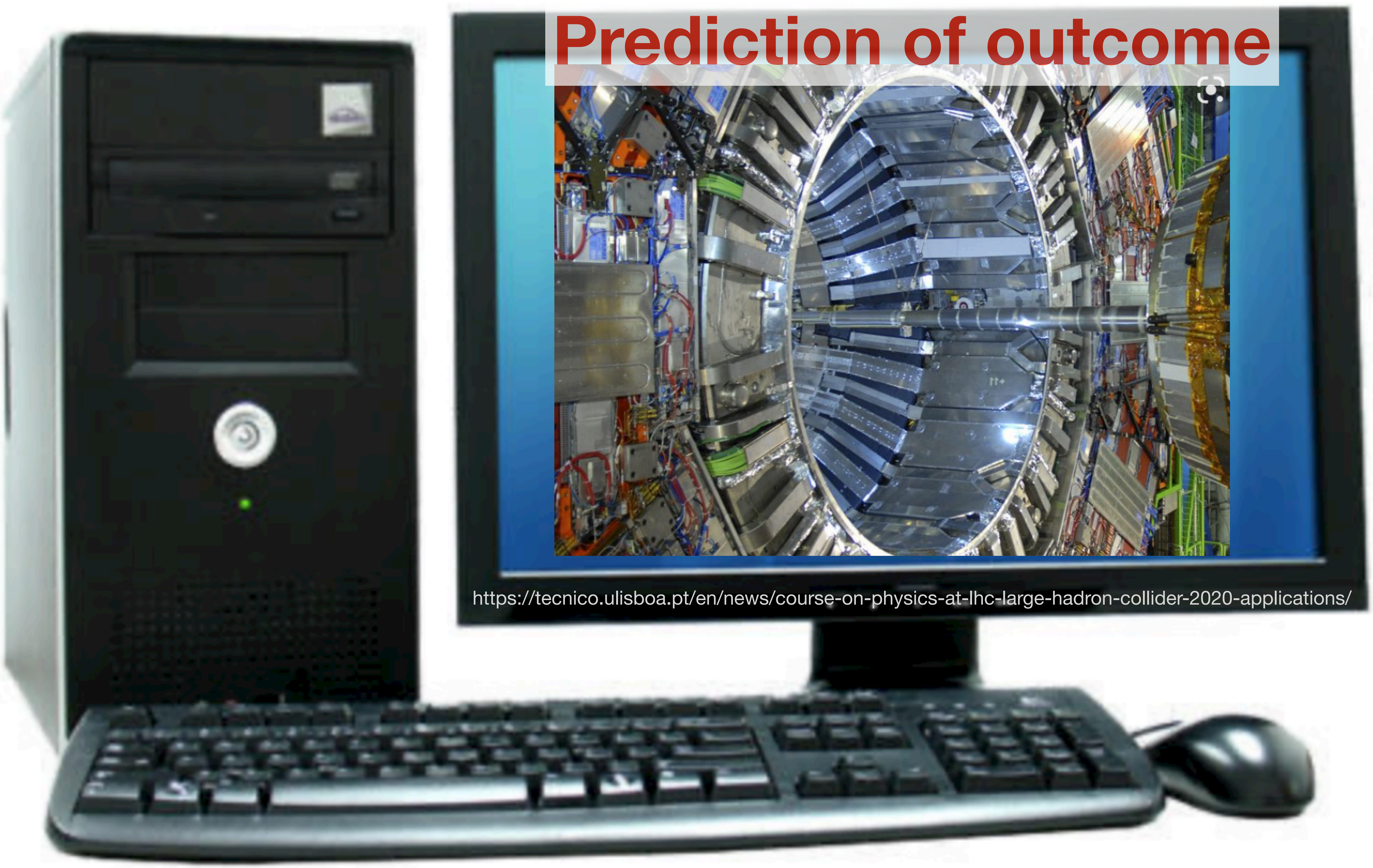
/sɪmjuːˈleɪʃ(ə)n/

noun

imitation of a situation or process.
"simulation of blood flowing through arteries and veins"

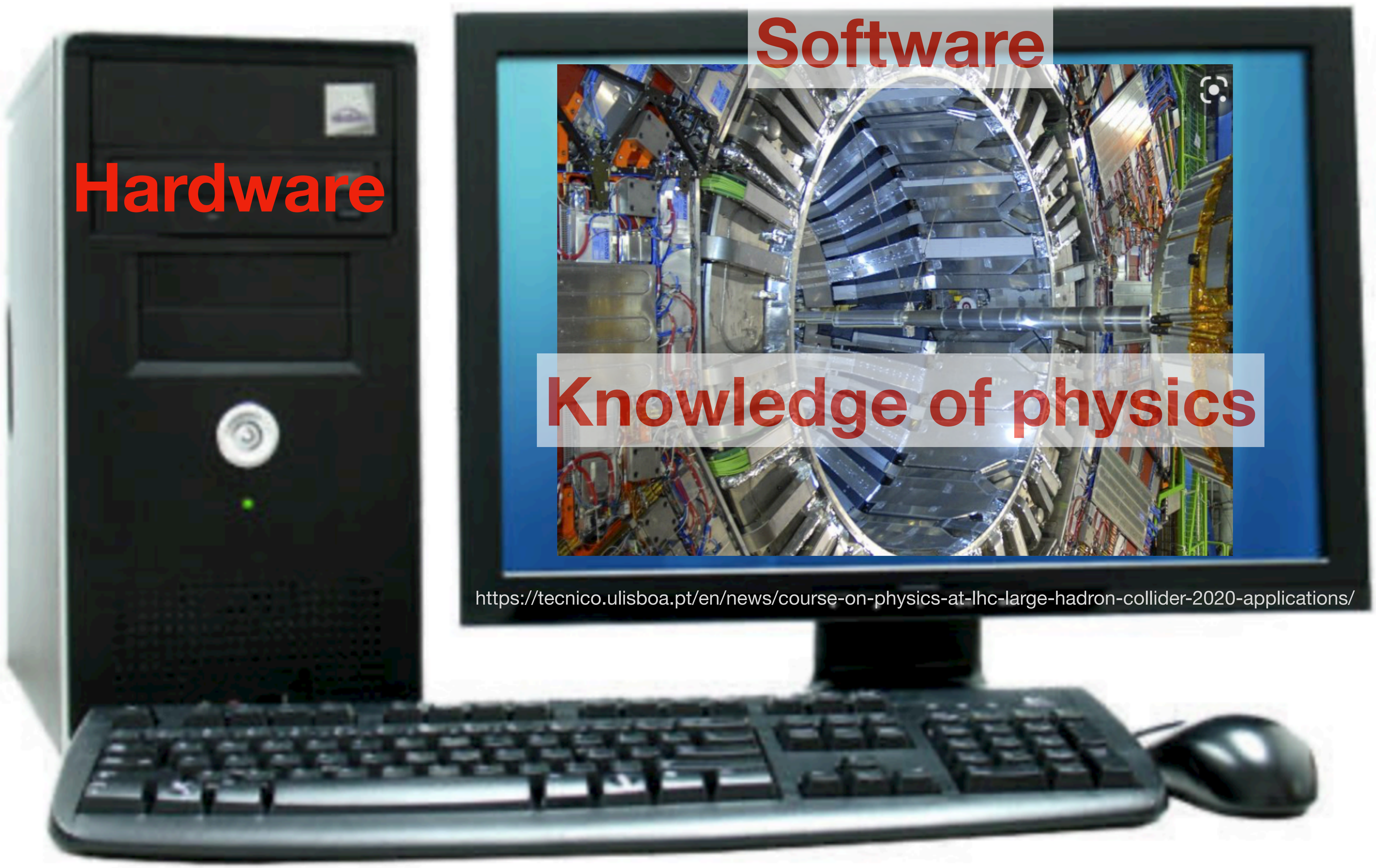
- the action of pretending; deception.
  "clever simulation that's good enough to trick you"
- the production of a computer model of something, especially for the purpose of study.
  "the method was tested by computer simulation"

What do we need?



https://tecnico.ulisboa.pt/en/news/course-on-physics-at-lhc-large-hadron-collider-2020-applications/

What do we need?



Simulation

Essential tool in nuclear and particle physics

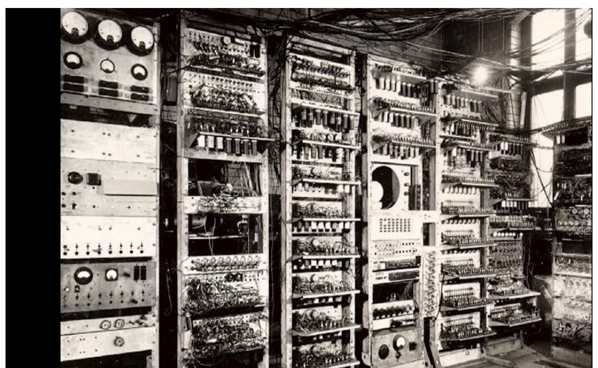
Function:

- Design new detectors
- Analysis of our data
- Benchmarking
- Development of new analysis tools or optimise analysis
- Simulation of new physics models

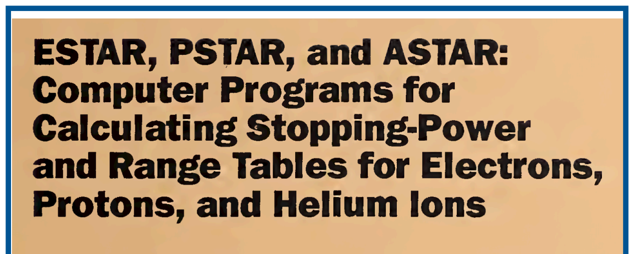
General **Monte Carlo (MC)** Codes exit

MC methods for radiation transport

Random photo of the Monte Carlo casino



http://hotcore.info/kareff-07079.html



ESTAR, PSTAR, and ASTAR: Computer Programs for Calculating Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions

https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nistir4999.pdf

- **John von Neumann** and **Stanislaw Ulam** in 1945 (https://library.lanl.gov/cgi-bin/getfile?00326866.pdf)
- **Nick Metropolis** (1948) converted the style of programming using **ENIAC** as described by J. v. Neumann
- **M. J. Berger** and **S. M. Seltzer** (1963) developed the ETRAN code (coupled electron-photon transport (https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir82-2550.pdf))
- **Probability density function** (pdf)

Sophisticated available MC codes

http://www.fluka.org/fluka.php

https://geant4.web.cern.ch

https://mcnp.lanl.gov

http://pypenelope.sourceforge.net

Detector MC:

- Geant,
- Fluka
- Geant4

Radiation MC:

- Fluka,
- Penelope
- Mars,
- Geant4,
- MCNP

Signal generation:

- Garfield

https://garfield.web.cern.ch/garfield/

Available MC codes

http://www.fluka.org/fluka.php

https://geant4.web.cern.ch

https://mcnp.lanl.gov

http://pypenelope.sourceforge.net

Detector MC:
- ☐ Geant,
- ☐ Fluka
- ☑ **Geant4**

Radiation MC:
- ☐ Fluka,
- ☐ Penelope
- ☐ Mars,
- ☑ **Geant4**,
- ☐ MCNP/MCNPX

Signal generation:
- ☐ Garfield

https://garfield.web.cern.ch/garfield/

Geant4: simulation of the passage of particles through matter

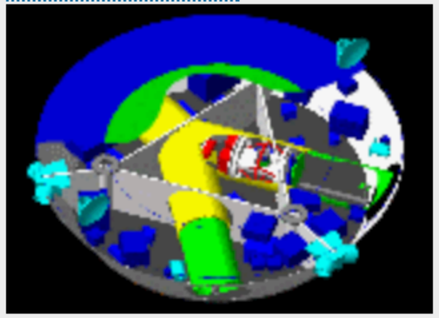
Overview

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The three main reference papers for Geant4 are published in Nuclear Instruments and Methods in Physics Research A 506 (2003) 250-303 , IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278 and Nuclear Instruments and Methods in Physics Research A 835 (2016) 186-225 .

Applications

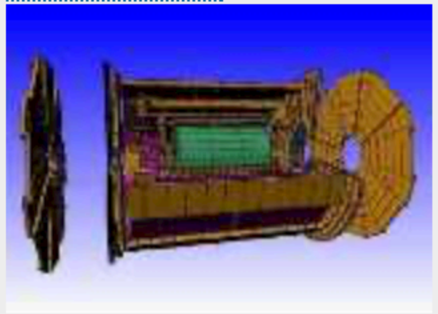
A sampling of applications, technology transfer and other uses of Geant4

User Support



Getting started, guides and information for users and developers

Publications



Validation of Geant4, results from experiments and publications

Collaboration

Who we are: collaborating institutions, members, organization and legal information

https://geant4.web.cern.ch

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 506, Issue 3, 1 July 2003, Pages 250-303

GEANT4—a simulation toolkit

L. Peralta, (J. Perl), …. B. Tomé

Geant4 Developments and Applications

J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce Dubois, M. Asai, G. Barrand, R. Capra, S. Chauvie, R. Chytracek, G. A. P. Cirrone, G. Cooperman, G. Cosmo, G. Cuttone, G. G. Daquino, M. Donszelmann, M. Dressel, G. Folger, F. Foppiano, J. Generowicz, V. Grichine, S. Guatelli, P. Gumplinger, A. Heikkinen, I. Hrivnacova, A. Howard, S. Incerti, V. Ivanchenko, T. Johnson, F. Jones, T. Koi, R. Kokoulin, M. Kossov, H. Kurashige, V. Lara, S. Larsson, F. Lei, O. Link, F. Longo, M. Maire, A. Mantero, B. Mascialino, I. McLaren, P. Mendez Lorenzo, K. Minamimoto, K. Murakami, P. Nieminen, L. Pandola, S. Parlati, L. Peralta, J. Perl, A. Pfeiffer, M. G. Pia, A. Ribon, P. Rodrigues, G. Russo, S. Sadilov, G. Santin, T. Sasaki, D. Smith, N. Starkov, S. Tanaka, E. Tcherniaev, B. Tomé, A. Trindade, P. Truscott, L. Urban, M. Verderi, A. Walkden, J. P. Wellisch, D. C. Williams, D. Wright, and H. Yoshida

10.1109/TNS.2006.869826

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 835, 1 November 2016, Pages 186-225

Recent developments in GEANT4

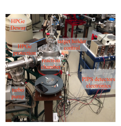
J. Allison [a, b], K. Amako [c, a], J. Apostolakis [d], P. Arce [e], M. Asai [f], T. Aso [g], E. Bagli [h], A. Bagulya [i], S. Banerjee [j], G. Barrand [k], B.R. Beck [l], A.G. Bogdanov [m], D. Brandt [n], J.M.C. Brown [o], H. Burkhardt [d], Ph. Canal [j], D. Cano-Ott [p], S. Chauvie [q] … H. Yoshida [bs, a]

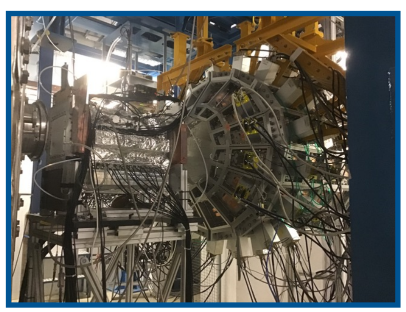
[bj] LIP-Lisboa/IST, Av. Elias Garcia, 14-1, 1000-149 Lisboa, Portugal

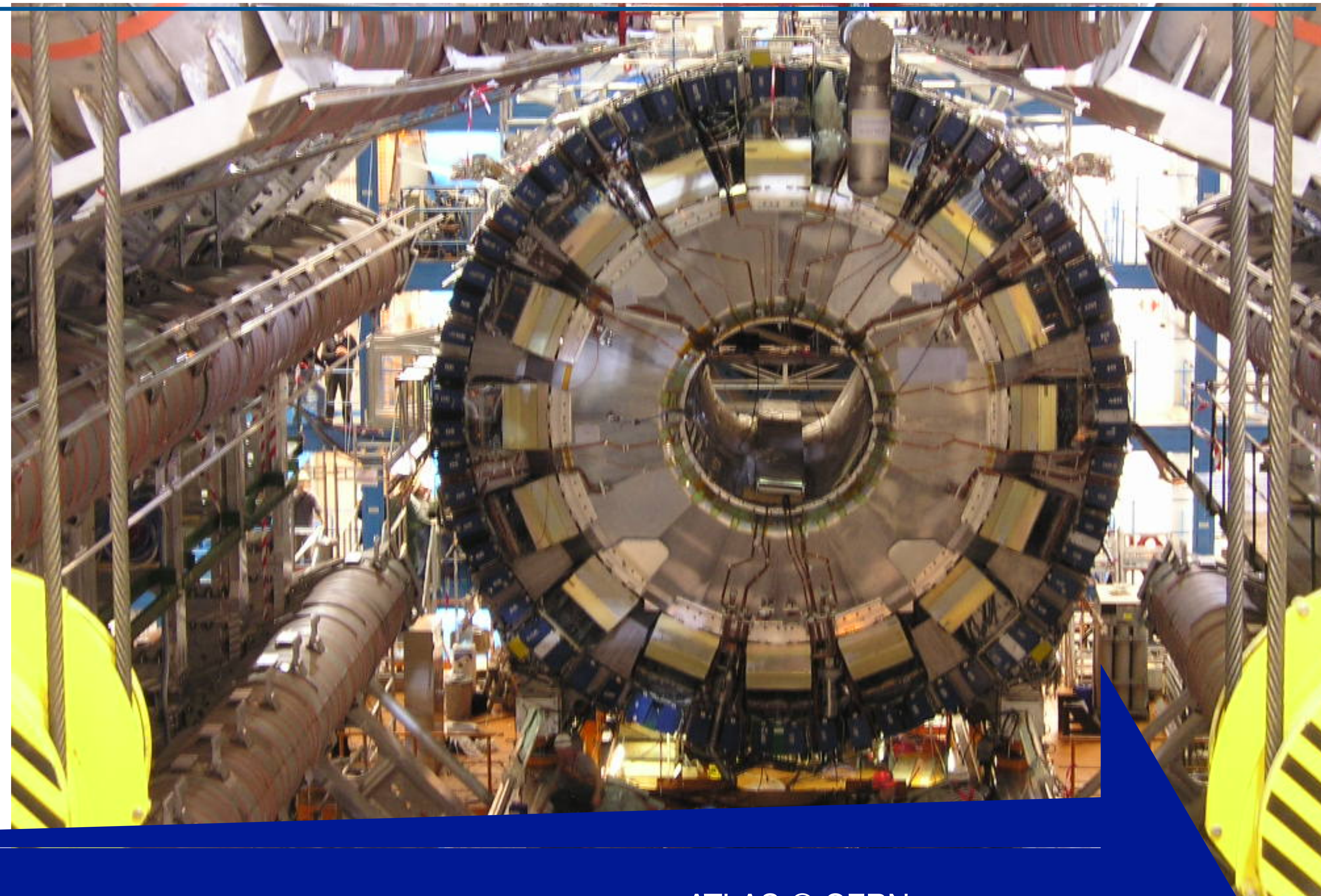
10.1016/j.nima.2016.06.125

Simulation can be done…

NOT to scale!
JUST a quick idea!





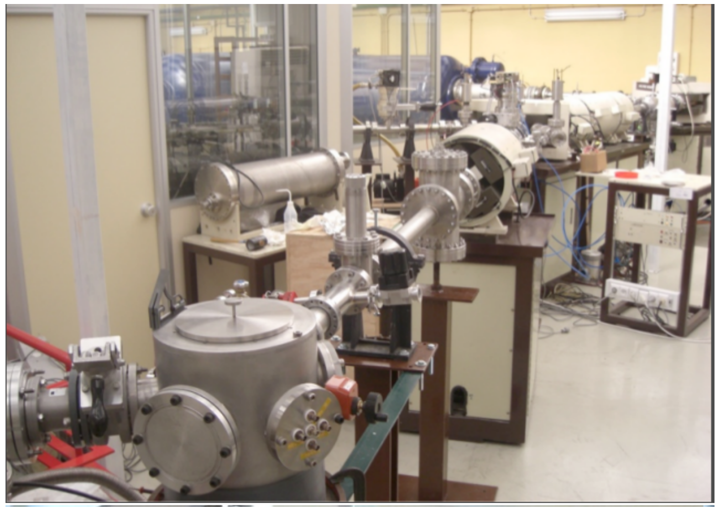


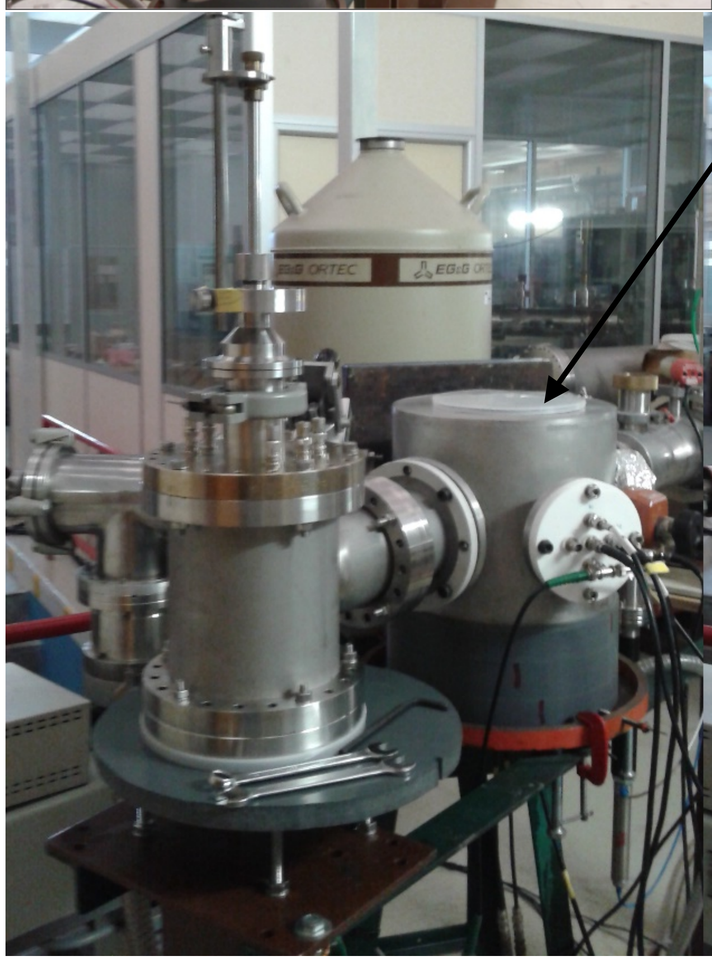
CTN-IST:
nuclear reaction line

CALIFA @FAIR

ATLAS @ CERN

Experimental setup at CTN-IST





- Nuclear reaction line @ CTN-IST

Describe the physical world

Reaction chamber
HPGe Detector

Detector Geometry

- Construct all necessary material
- Define shapes/ solids
- Construct and place volumes
  - Define sensitive and non-sensitive volumes
  - Define visual attributes of the detector

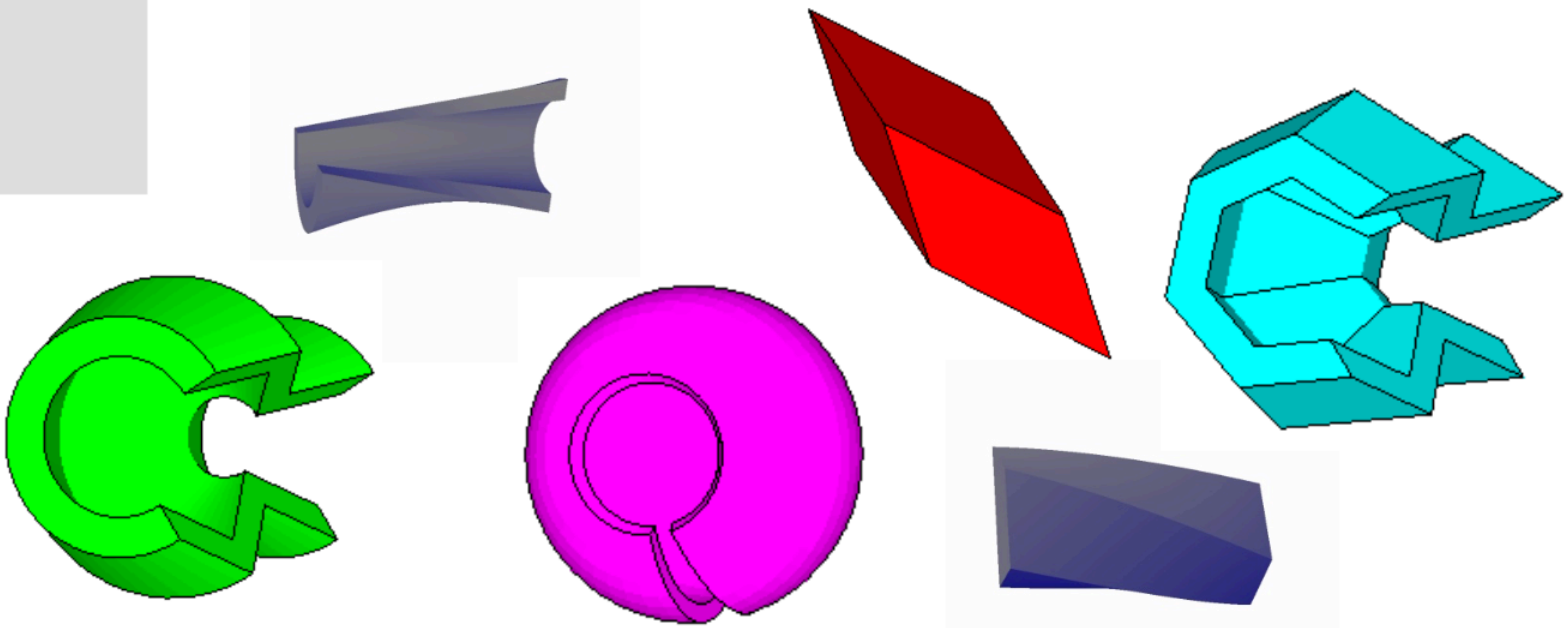
Experimental setup at CTN-IST

Three conceptual layers

- **Solid (G4VSolid Class Reference)**
  - shape (simple shapes)
  - size

Step 1:
create the geometrical object

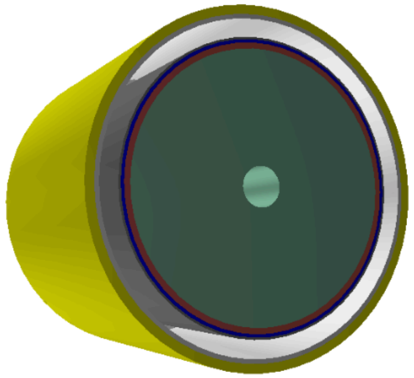
```
G4Tubs(const G4String& pName,
             G4double  pRMin,
             G4double  pRMax,
             G4double  pDz,
             G4double  pSPhi,
             G4double  pDPhi)
```



Experimental setup at CTN-IST

Three conceptual layers

- ☑ **Solid**
  - shape
  - size
- ☐ **Logical volume**
  - daughter physical volume,
  - material,
  - sensitivity,
  - user limits
    - (e.g.max step length, max number of steps, min kinetic energy left, etc.)

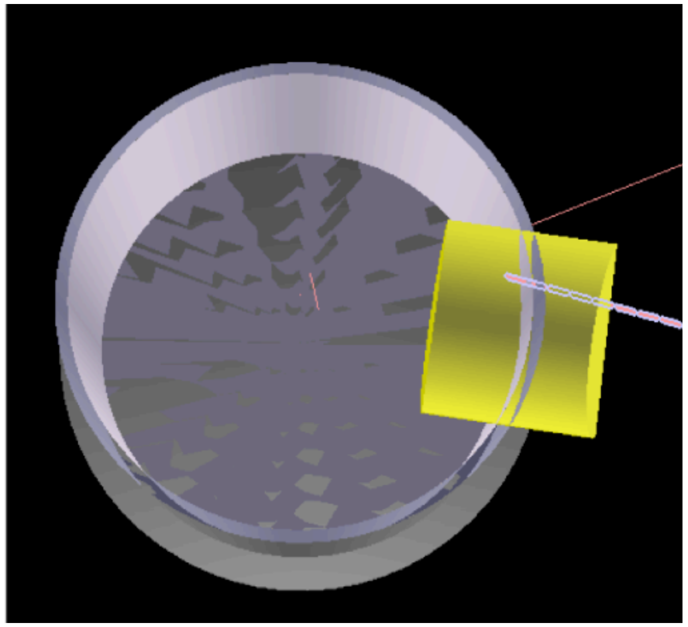


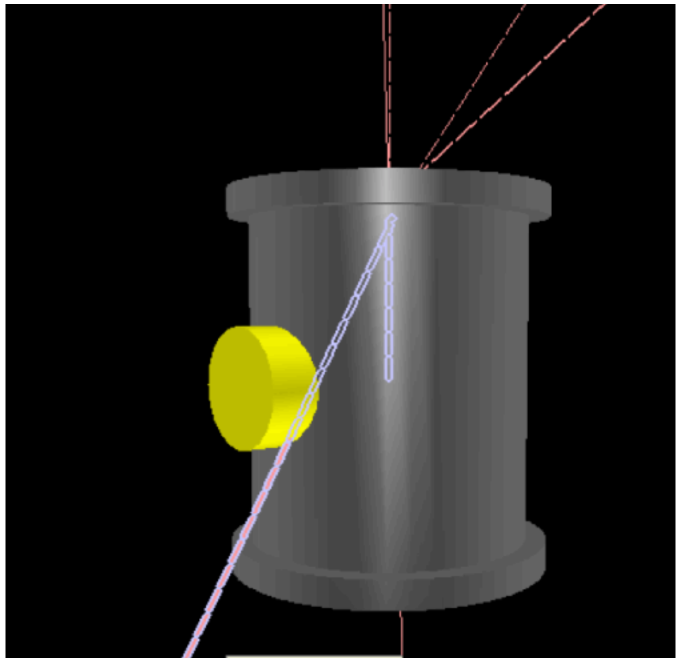
Step 1:
create the geometrical object

Step 2:
Assign properties

E. Galiana Baldó

Experimental setup at CTN-IST





Three conceptual layers

- ☑ **Solid**
  - shape
  - size
- ☑ **Logical volume**
  - daughter physical volume,
  - material,
  - sensitivity,
  - user limits
- ☐ **Physical volume**
  - position
  - rotation

Step 1: create the geometrical object

Step 2: Assign properties

Step 3: Place in world co-or system

Attention: Overlapping and confinement in mother space!

Interaction with detector material

Hadronic, Electromagnetic, and Weak interaction

- Photon:
- Pair production, Compton scattering, photoelectric effect
- All charged particles:
- Ionization / δ-rays, multiple scattering
- Electron / positron
- Bremsstrahlung, annihilation (e^+)
- Hadron:
- Hadronic interactions
-

hadrons (elastic, inelastic, capture, fission, radioactive decay, photo- nuclear, lepton-nuclear,...)

Physic list choice

Physics List Guide

The Physics List is one of the three mandatory user classes of the GEANT4 toolkit. In this class all GEANT4 particles and their interaction processes should be instantiated. This class should inherit from the base class `G4VUserPhysicsList` and should be given to G4RunManager:

```
G4MTRunManager* runManager = new G4MTRunManager;
runManager->SetUserInitialization(physicsList);
```

There are "**packaged**" physics lists available

- Probably you will be interested in the "reference physics lists"
- Option exists to create a customised physics lists (needs to be validated)

https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsListGuide/html/physicslistguide.html

https://geant4.web.cern.ch/node/1731

And many more ….

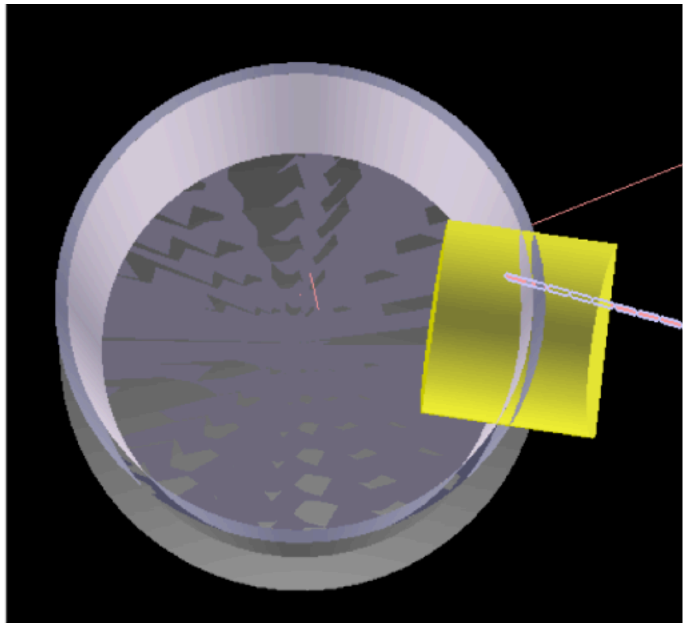
Physic list choice: examples

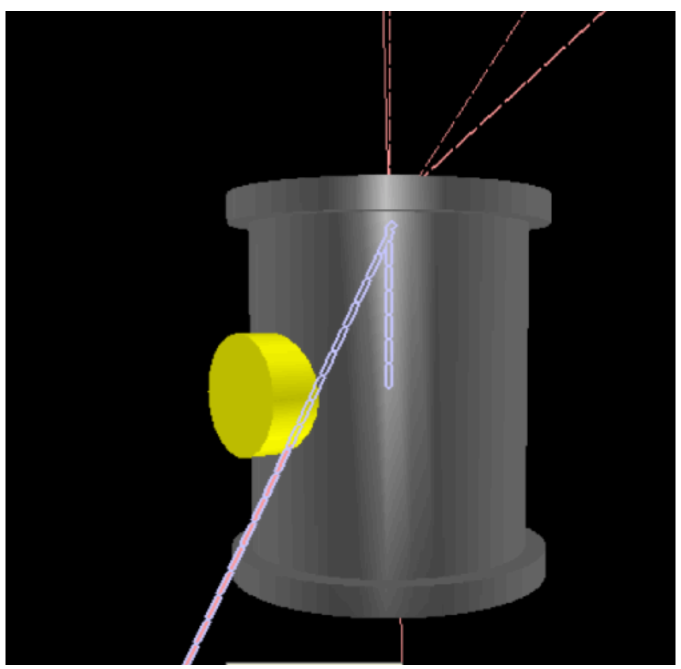
Be careful in the choice of physics lists!

- **Some Hadronic options:**
  - “QGS” Quark Gluon String model (> ~15 GeV)
  - “FTF” FRITIOF String model (> ~5 GeV)
  - “BIC” Binary Cascade model (< ~10 GeV)
  - “BERT” Bertini Cascade model (< ~10 GeV)
  - “P” `G4Precompound` model used for de-excitation
  - “HP” High Precision neutron model (< ~20 MeV)
- **Some EM options:**
  - No suffix: standard EM i.e. the default `G4EmStandardPhysics` constructor
  - “EMV” `G4EmStandardPhysics_option1` CTR: HEP, fast but less precise
  - “EMY” `G4EmStandardPhysics_option3` CTR: medical, space sci., precise
  - “EMZ” `G4EmStandardPhysics_option4` CTR: most precise EM physics
- **Name decoding:** String(s)_Cascade_Neutron_EM
- **The complete list of pre-packaged physics list with detailed description can be found in the documentation (“*Guide for Physics Lists*”):**

http://geant4.web.cern.ch/geant4/support/proc_mod_catalog/ physics_lists/referencePL.shtml

Event Generator





Event generators (Gun)

- Particle type
- Particle kinematics
  - energy
  - Direction
  - Other (charge, polarity)
  - Number of particles generated per event

G4Ion Table

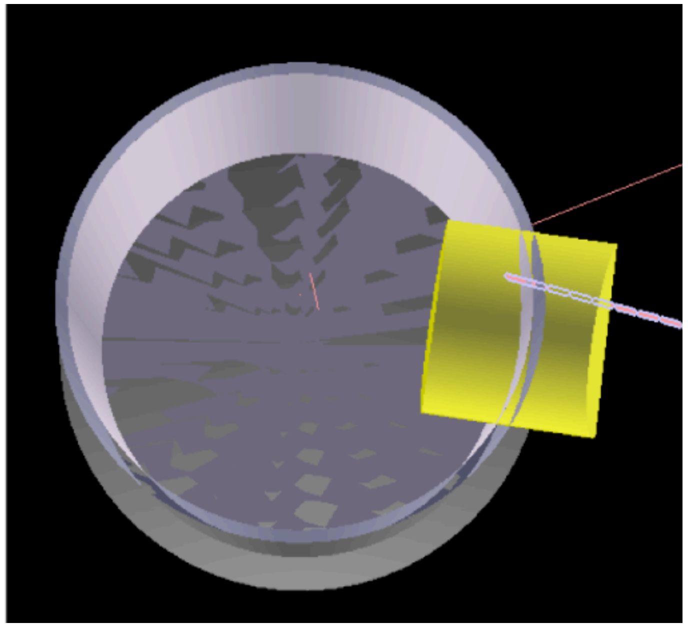
ASCII file input

Pythia, Fritiof using the Lund fragmentation model

HERWIG, HERWIG ++ is an alternative system

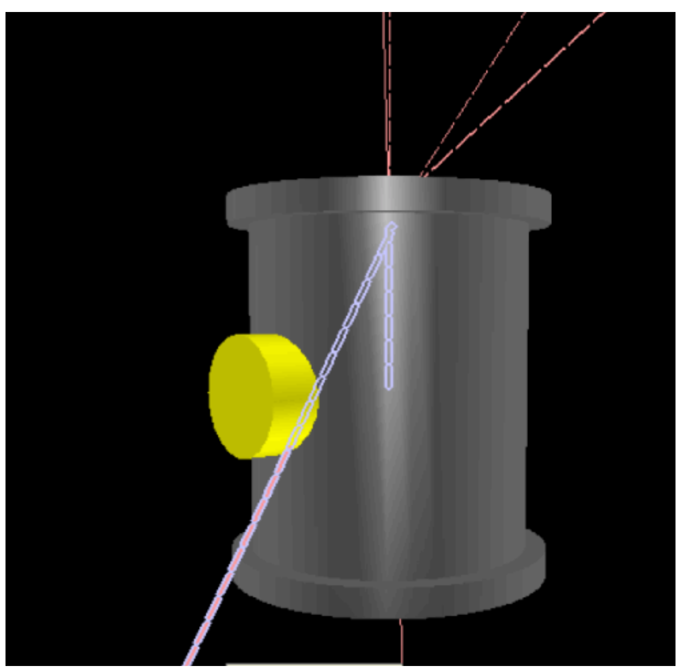
For HEP: https://arxiv.org/pdf/2203.11110.pdf

Hits registration



Event hit

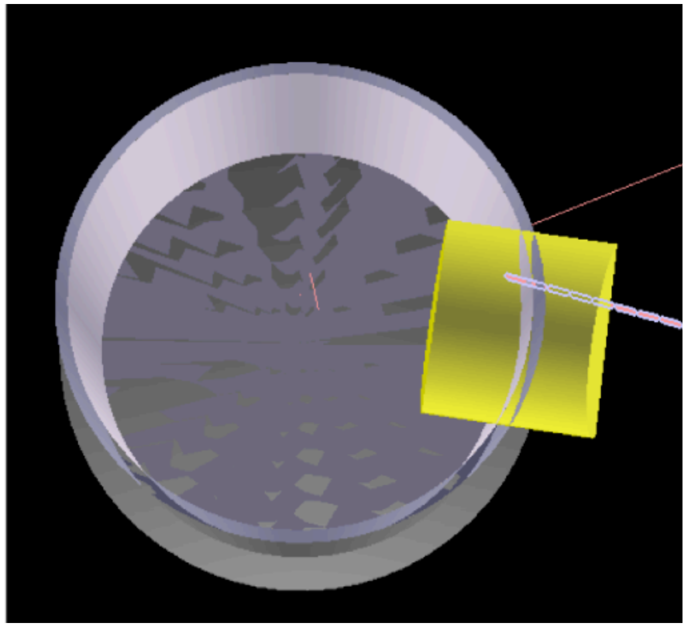
- Particle type
- Particle kinematics
  - energy
  - Direction
  - Multiplicity

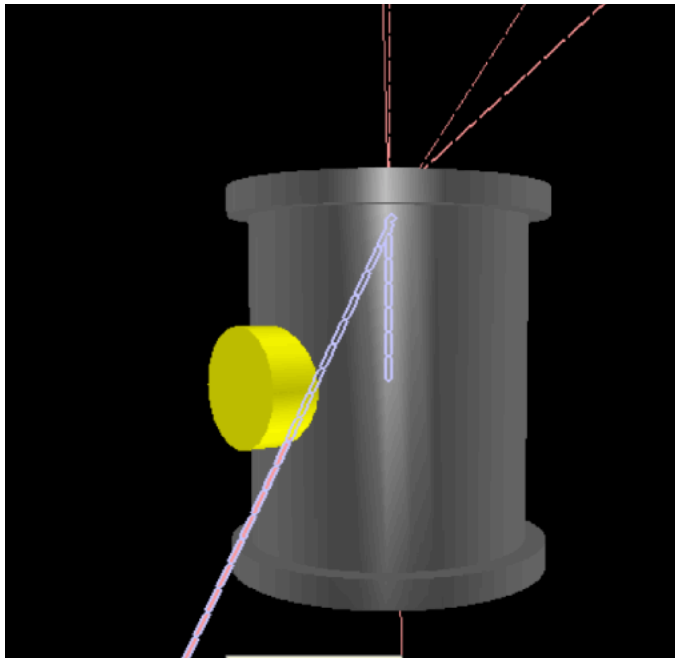


One event is simulated to the end!

Analysis via ROOT Data Analysis Framework

Avoid these pitfalls and be aware





Learn to walk before you run…

- **Check the volumes**
- **Small number of events**
- **Energy: one step at a time**
- **Check your out put: Does it make sense?**

Detector simulation tools are limited by several factors:

Available and known **accuracy** of measurements utilised and tunes or validation of the **physics models**

Particular **x-sections**

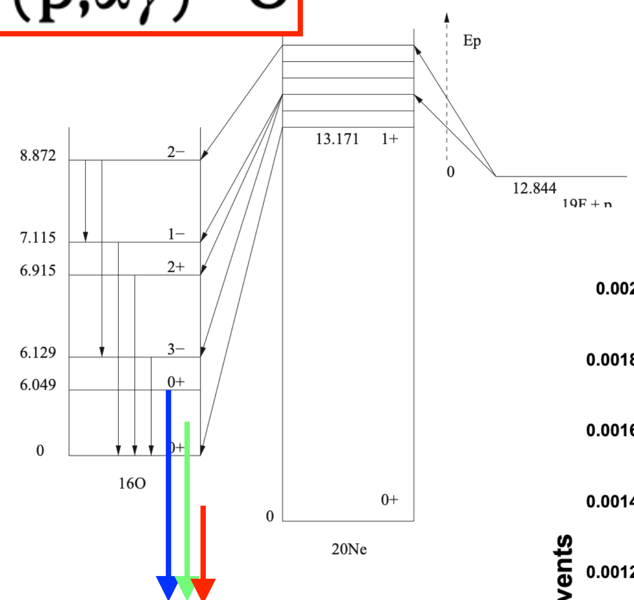
Computational speed

Example: Cross section

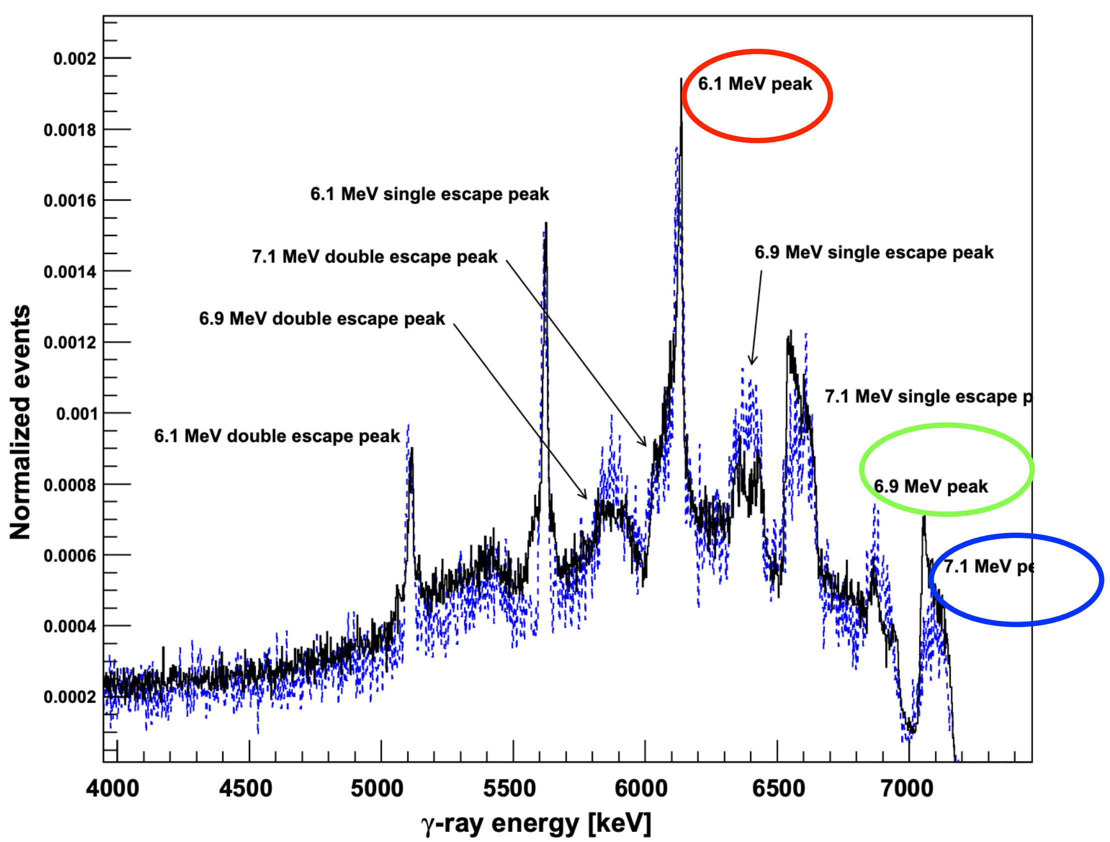
Cross sections for proton induced high energy γ-ray emission (PIGE) in reaction $^{19}F(p,\alpha\gamma)^{16}O$ at incident proton energies between 1.5 and 4 MeV

Nuclear Instruments and Methods in Physics Research B 381 (2016) 110–113

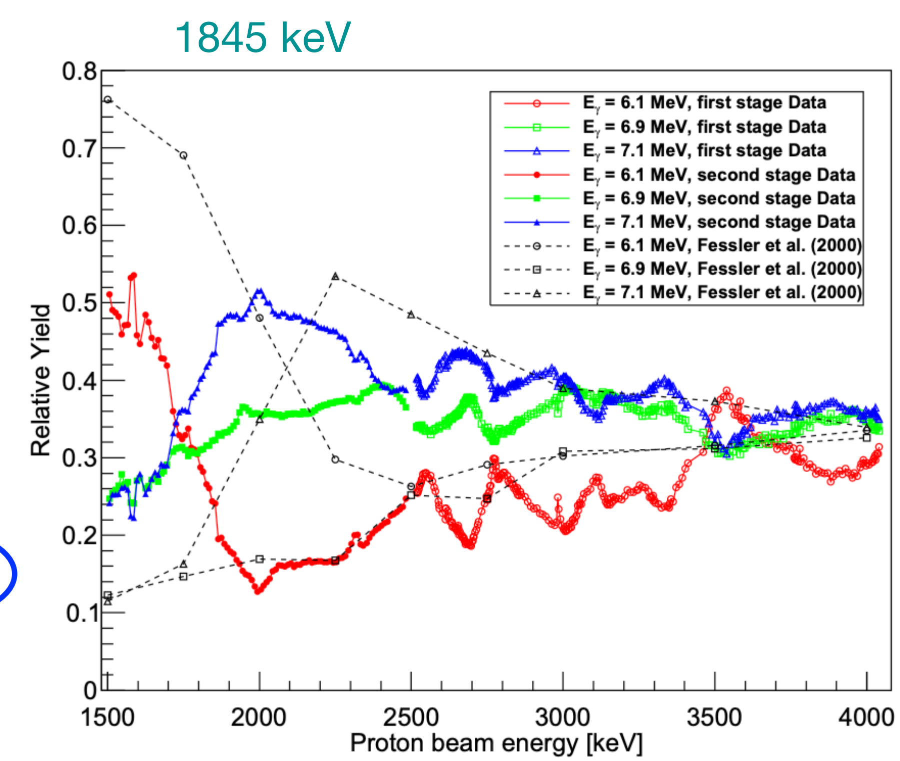
$^{19}F(p,\alpha\gamma)^{16}O$



Spectra @ 1845 keV

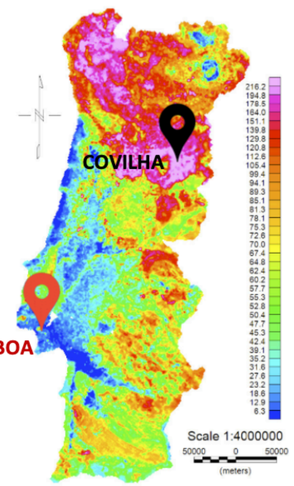


Resonance picture



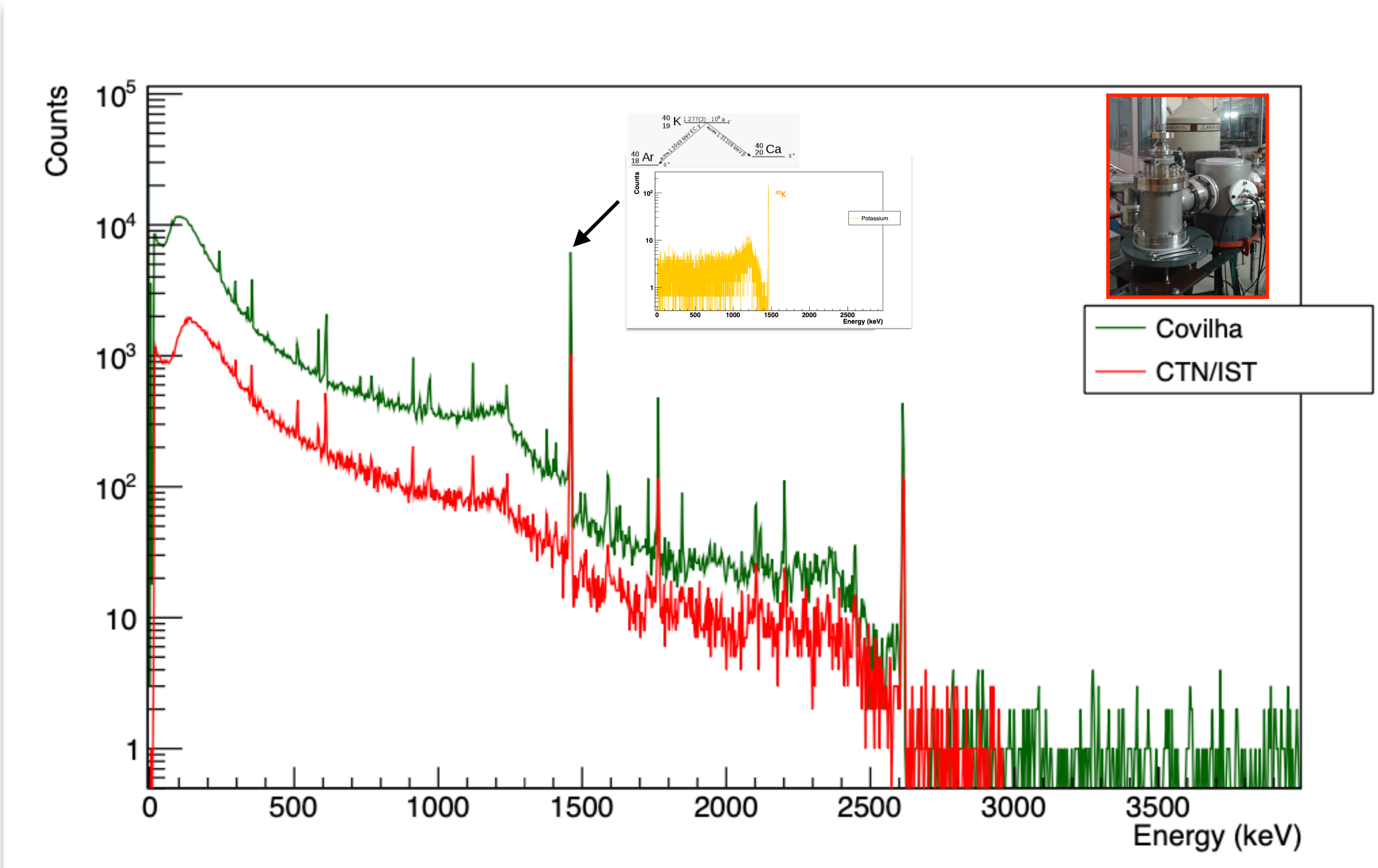
Dr. Pablo Cabanelas Eire, IGFAE (USC)

Example: background radiation



Radiometric map of Portugal.
EuroGeoSurveys, Newsletter 12, page 8,October (2013)

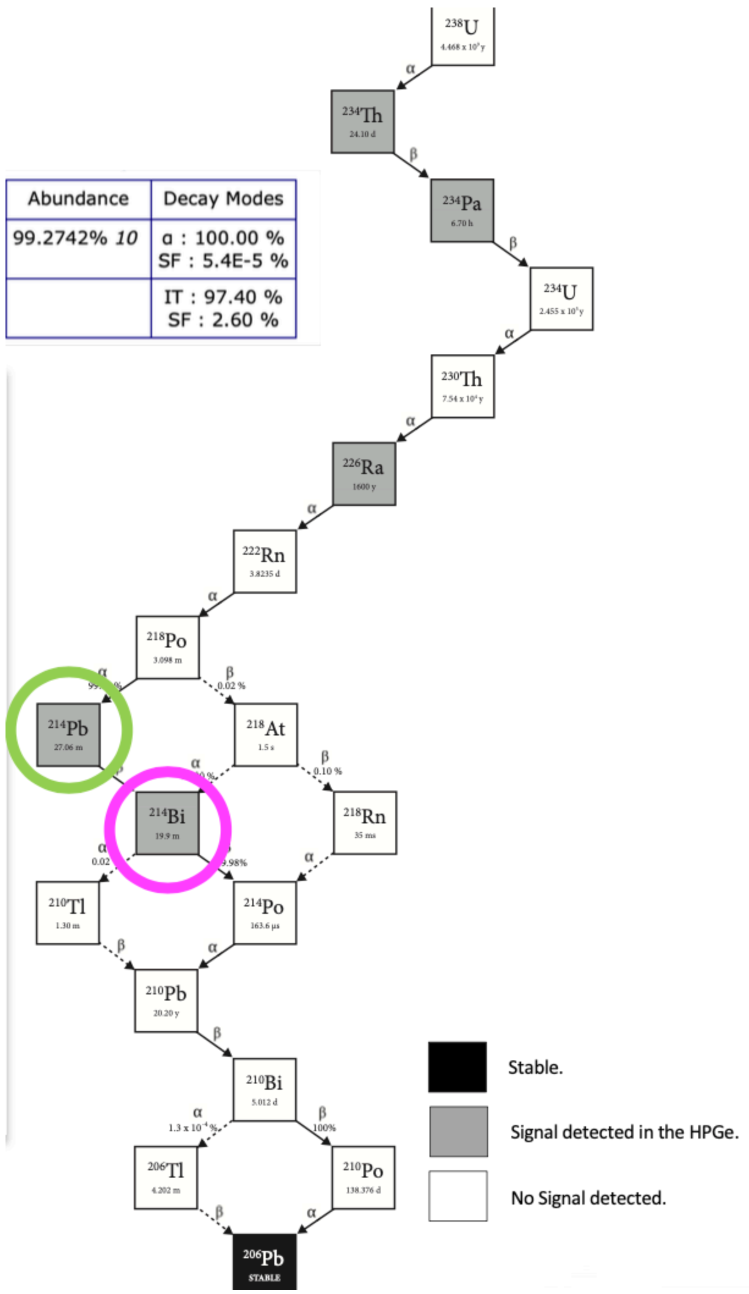
Gamma yield simulators

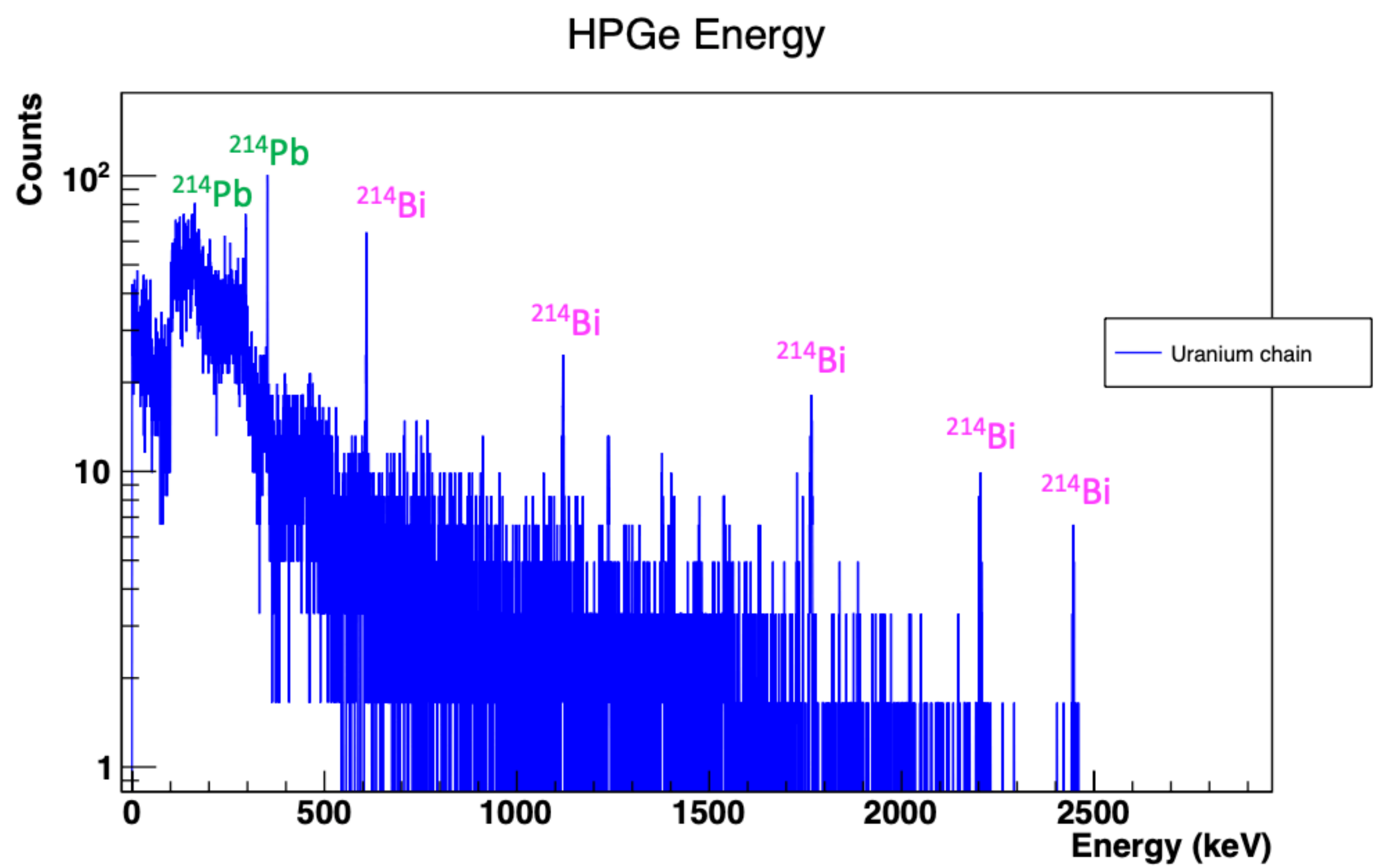


Work by E. Galiana

Example: background radiation

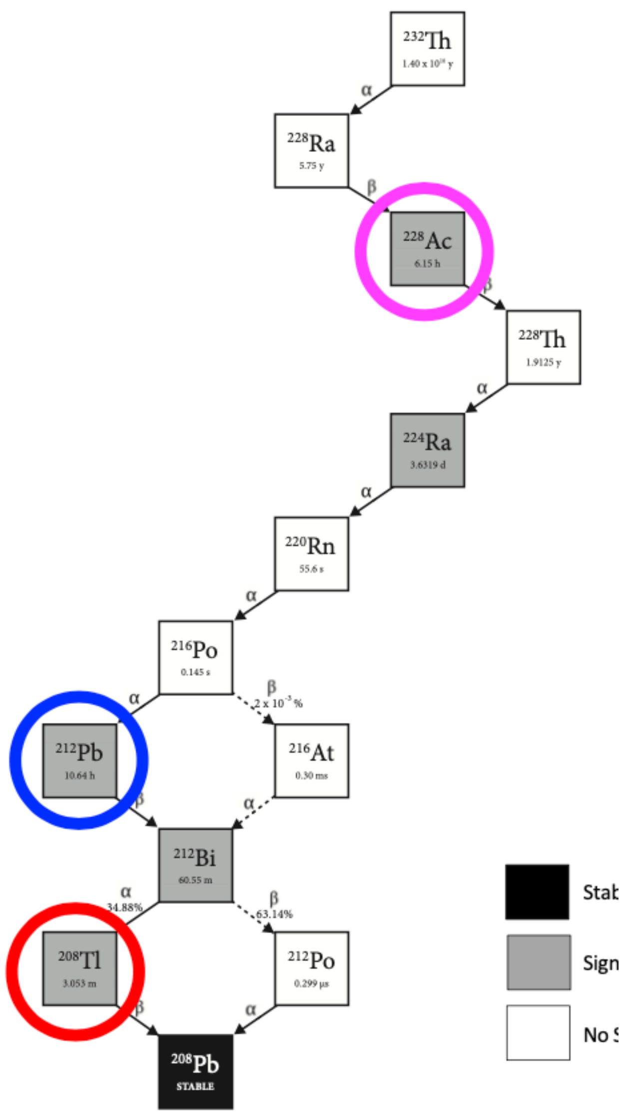
Uranium generator

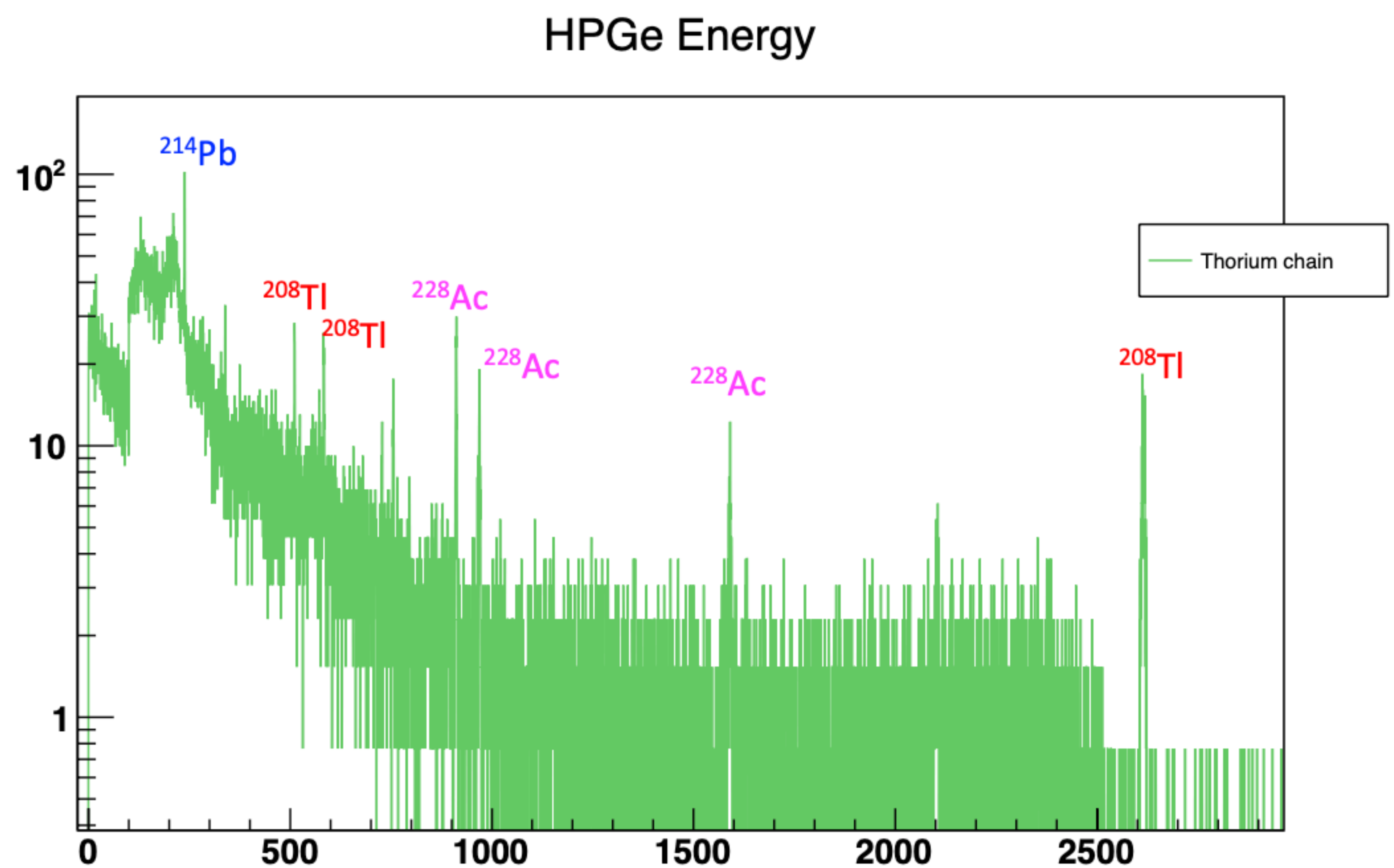




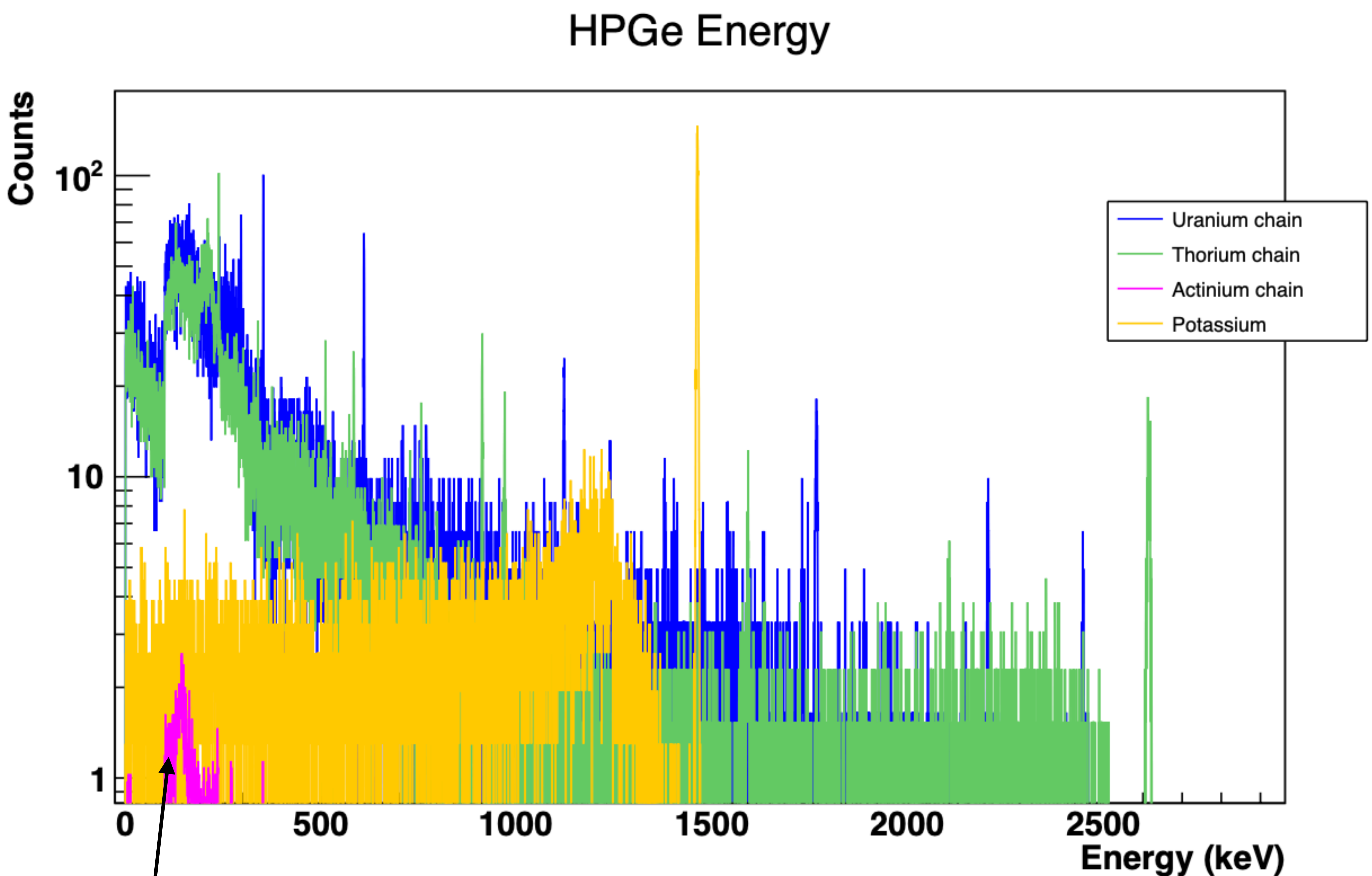
Example: background radiation

Thorium generator





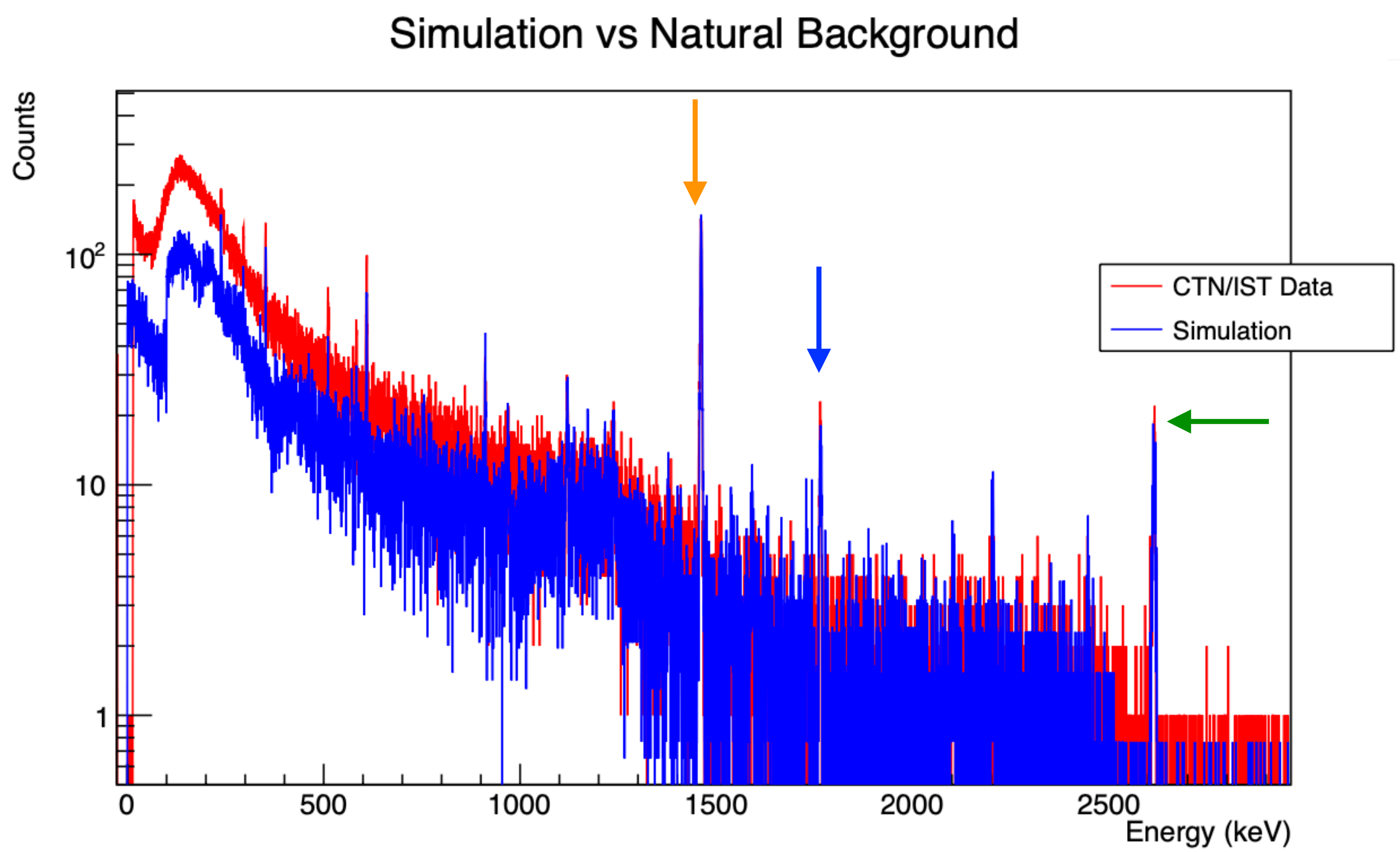
Example: weighted background radiation

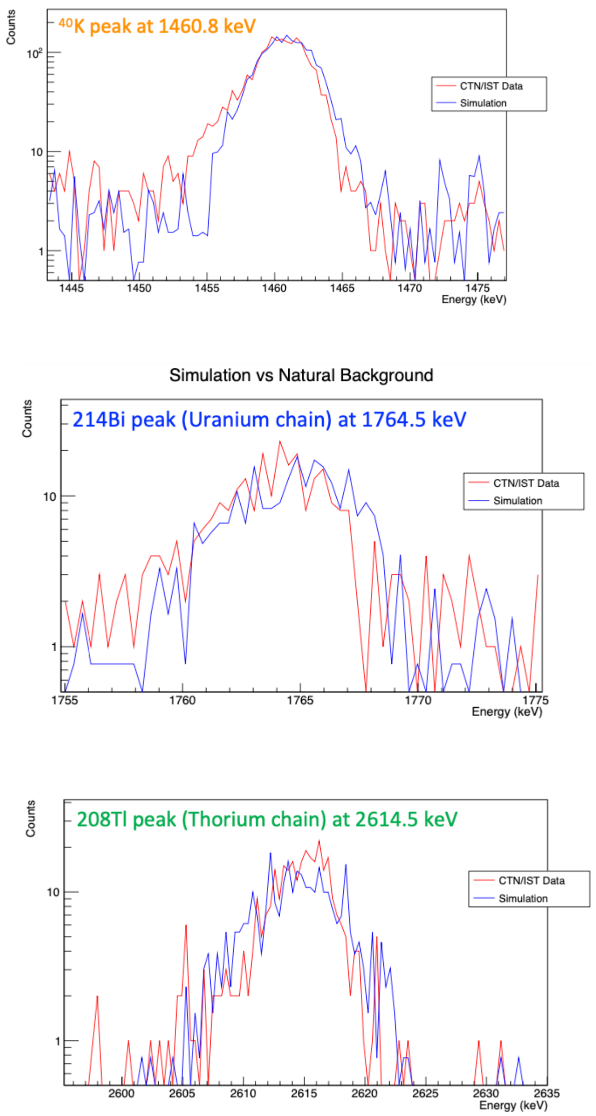


^{235}U (actinium chain) @ 187 keV

Example: background radiation

Very good approximation !

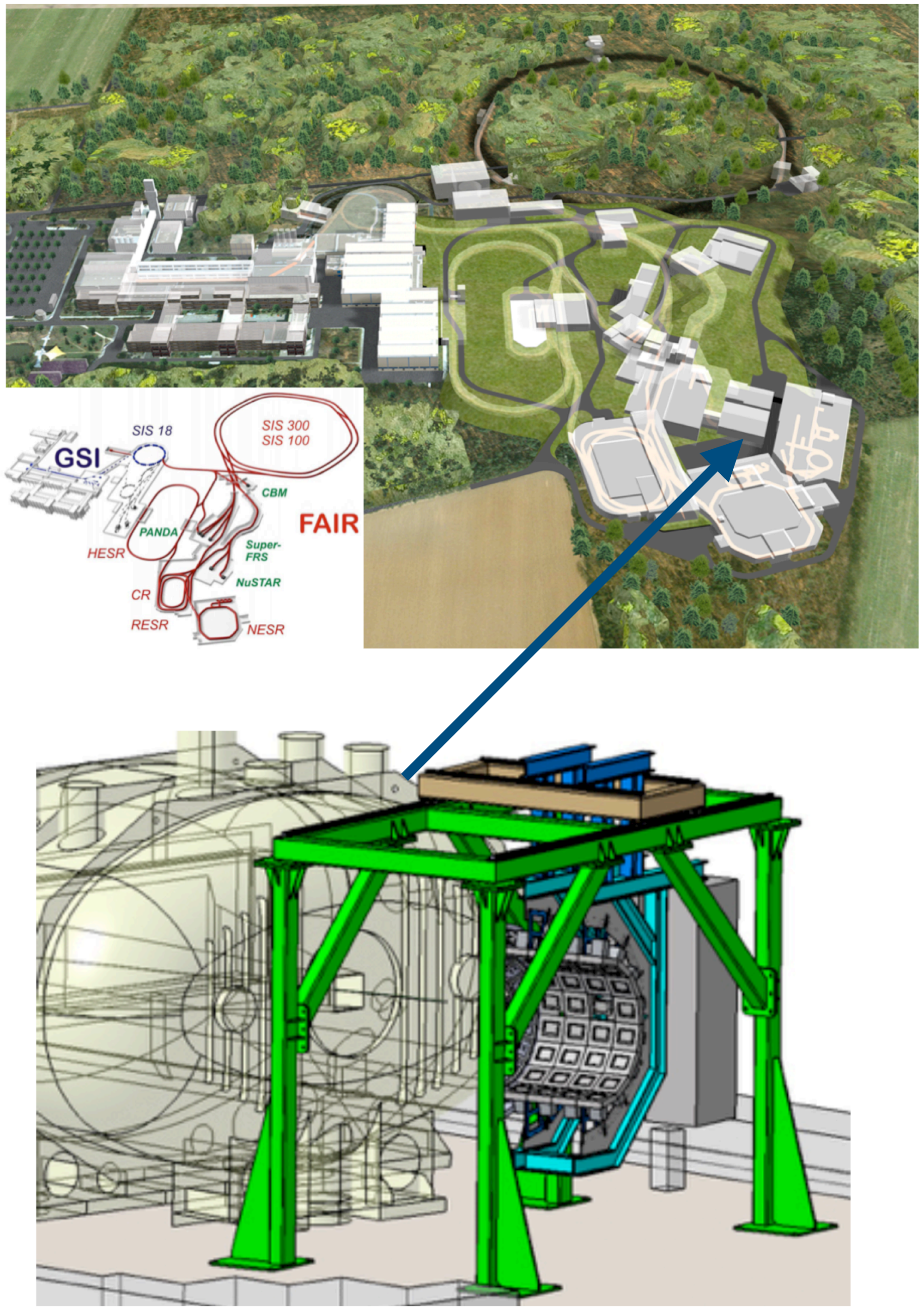


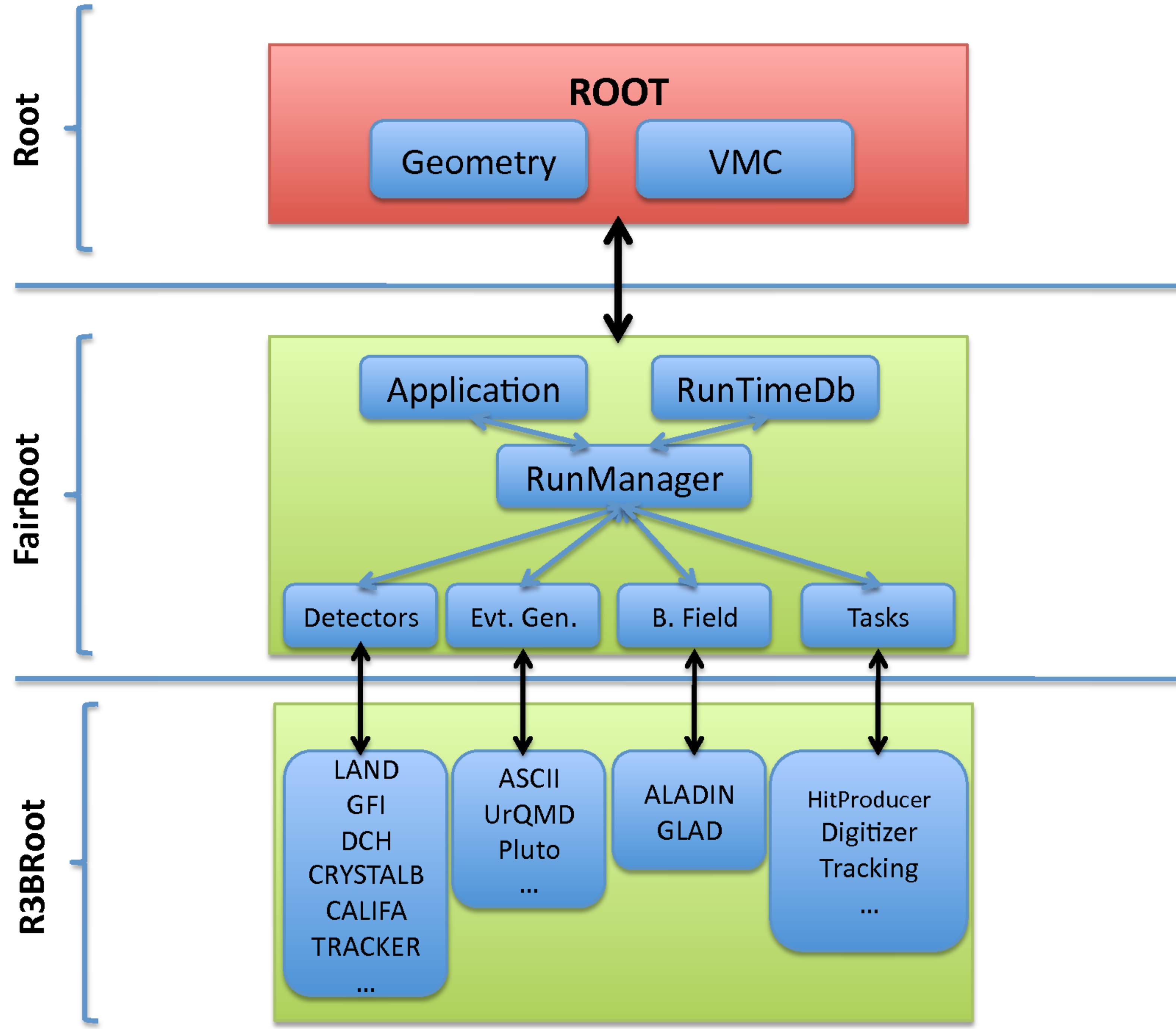


In the lower end of the energy spectrum:

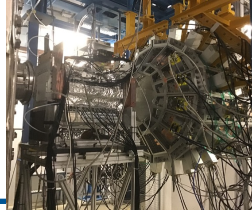
- Cosmic showers have not been included (Geant4 library - Cry)
- Radon: 222Rn may accumulate in close rooms including its daughters (^{216}Pb and ^{214}Bi)

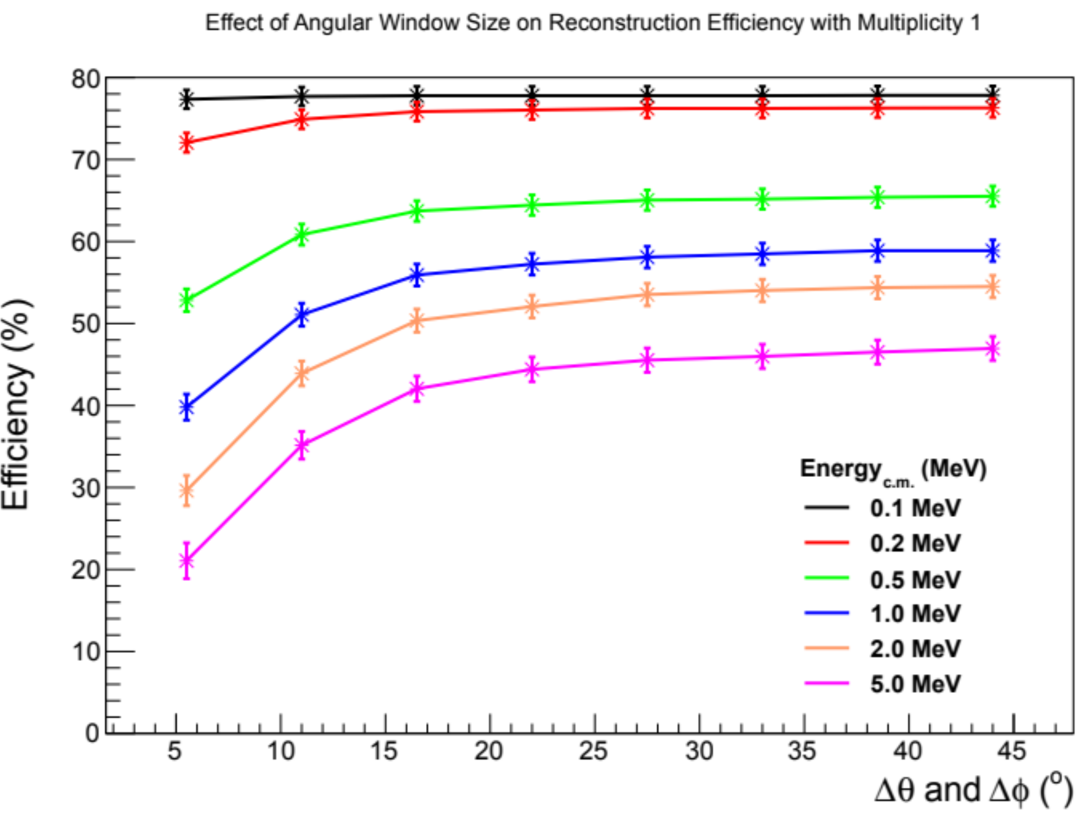
Virtual MC


SIS 18
GSI
SIS 300
SIS 100
CBM
FAIR
PANDA
HESR
Super-FRS
NuSTAR
CR
RESR
NESR


Root
ROOT
Geometry
VMC
FairRoot
Application
RunTimeDb
RunManager
Detectors
Evt. Gen.
B. Field
Tasks
R3BRoot
LAND
GFI
DCH
CRYSTALB
CALIFA
TRACKER
…
ASCII
UrQMD
Pluto
…
ALADIN
GLAD
HitProducer
Digitizer
Tracking
…

Simulation re-cycled & multi-purpose



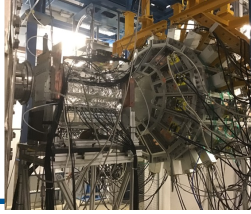


H. Álvarez-Pol, *et al.* NIMB (2014) 767:453-466.

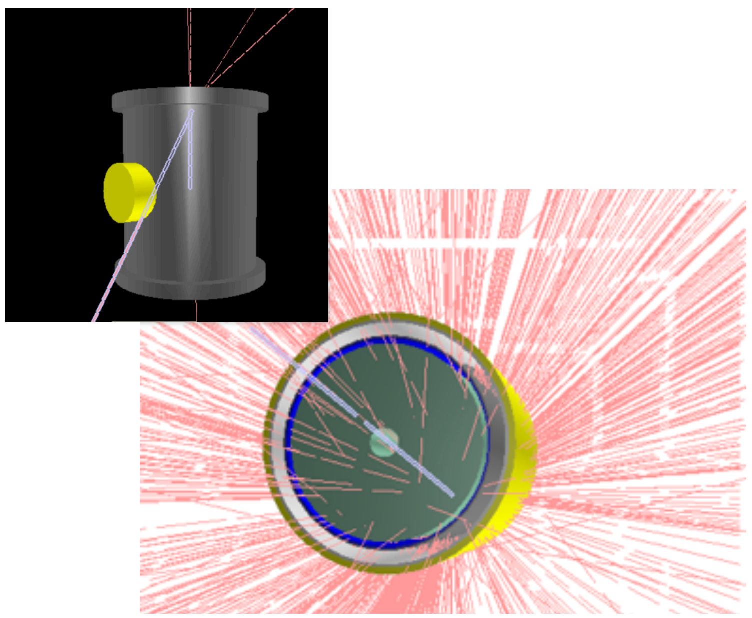
TDR CALIFA barrel
https://fair-center.eu/fileadmin/fair/publications_exp/CALIFA_BARREL_TDR_web.pdf

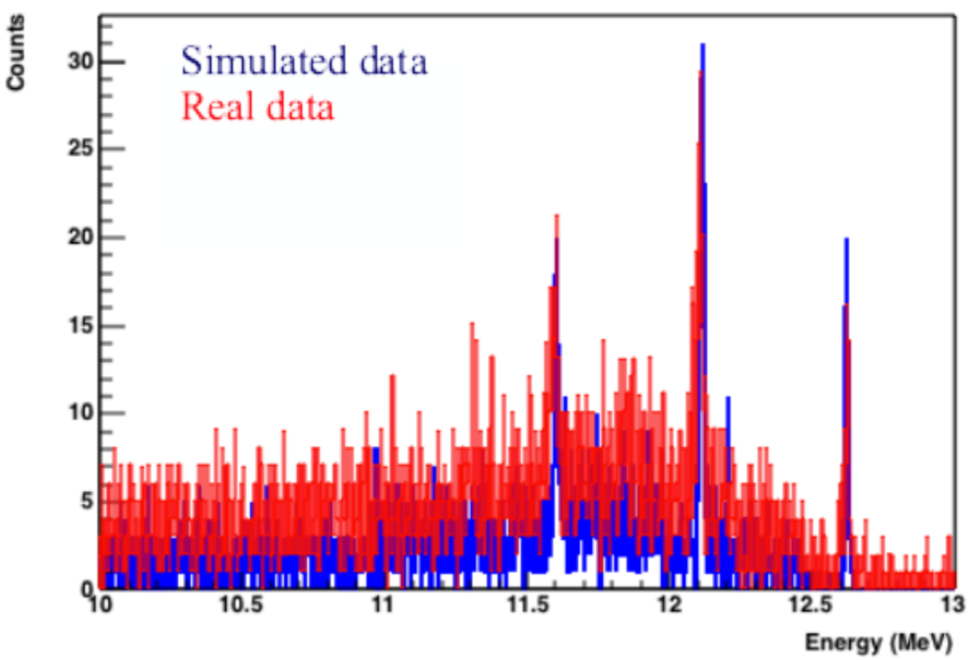
- **Development of prototypes**
- **TDR**
- Bench marking prototypes (smaller facilities & test beams)
- Understanding the performance and development of models
- Data analysis phase
- Development of algorithms
- Proposal submissions

Bench marking prototypes @ smaller facilities



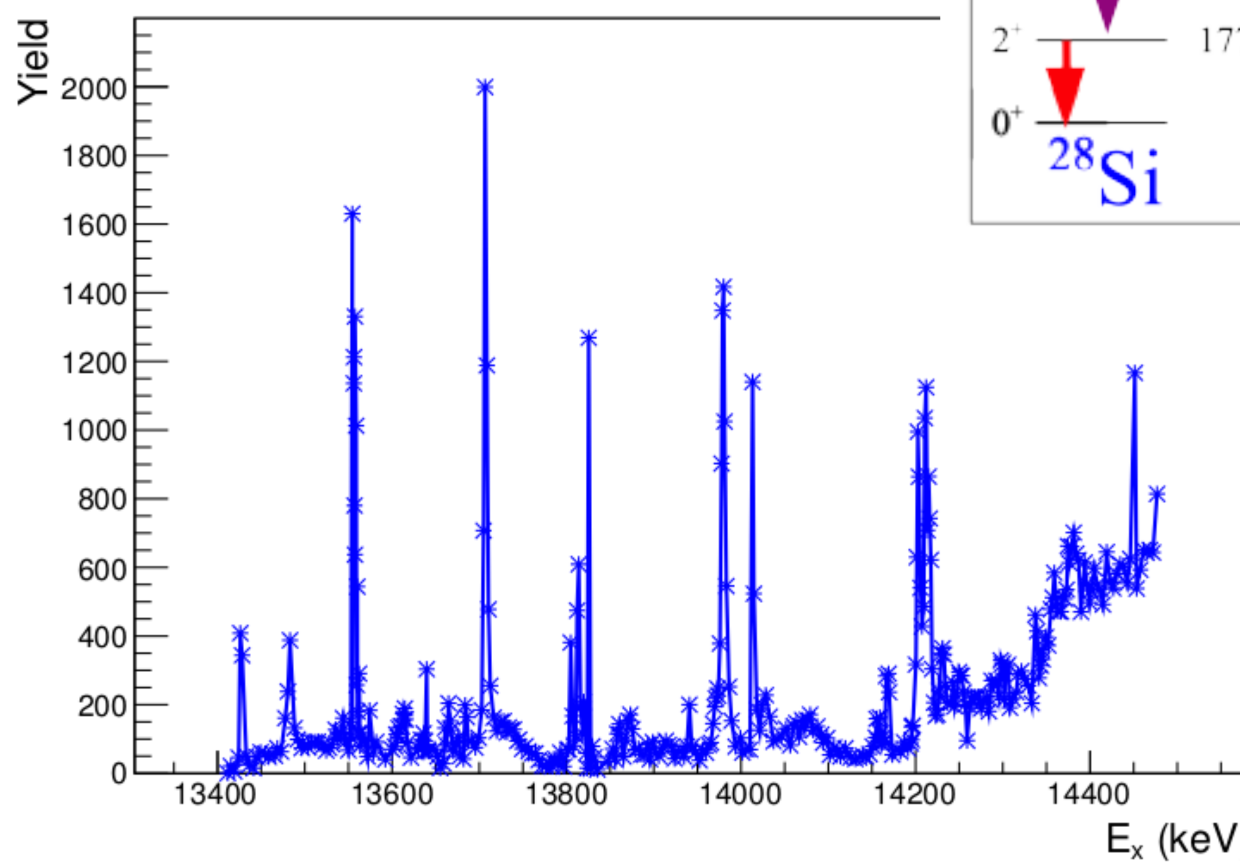
^{28}Si resonance (14399 keV) was simulated

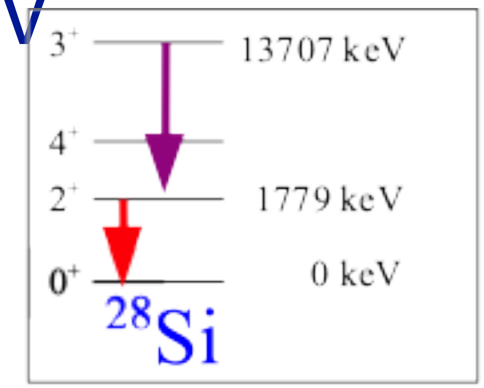




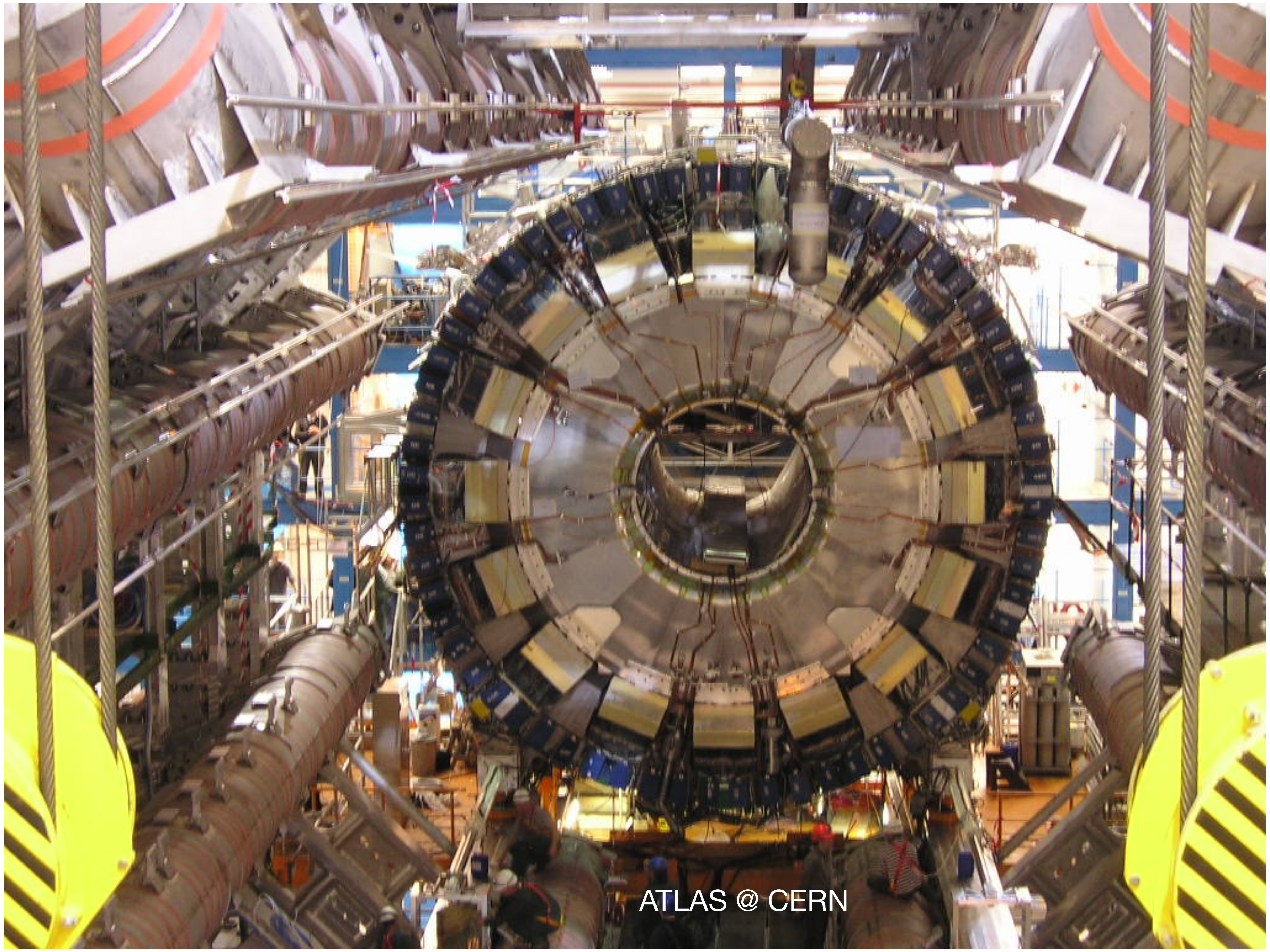
^{27}Al(p,γ)^{28}Si

Q-value 11.585 MeV

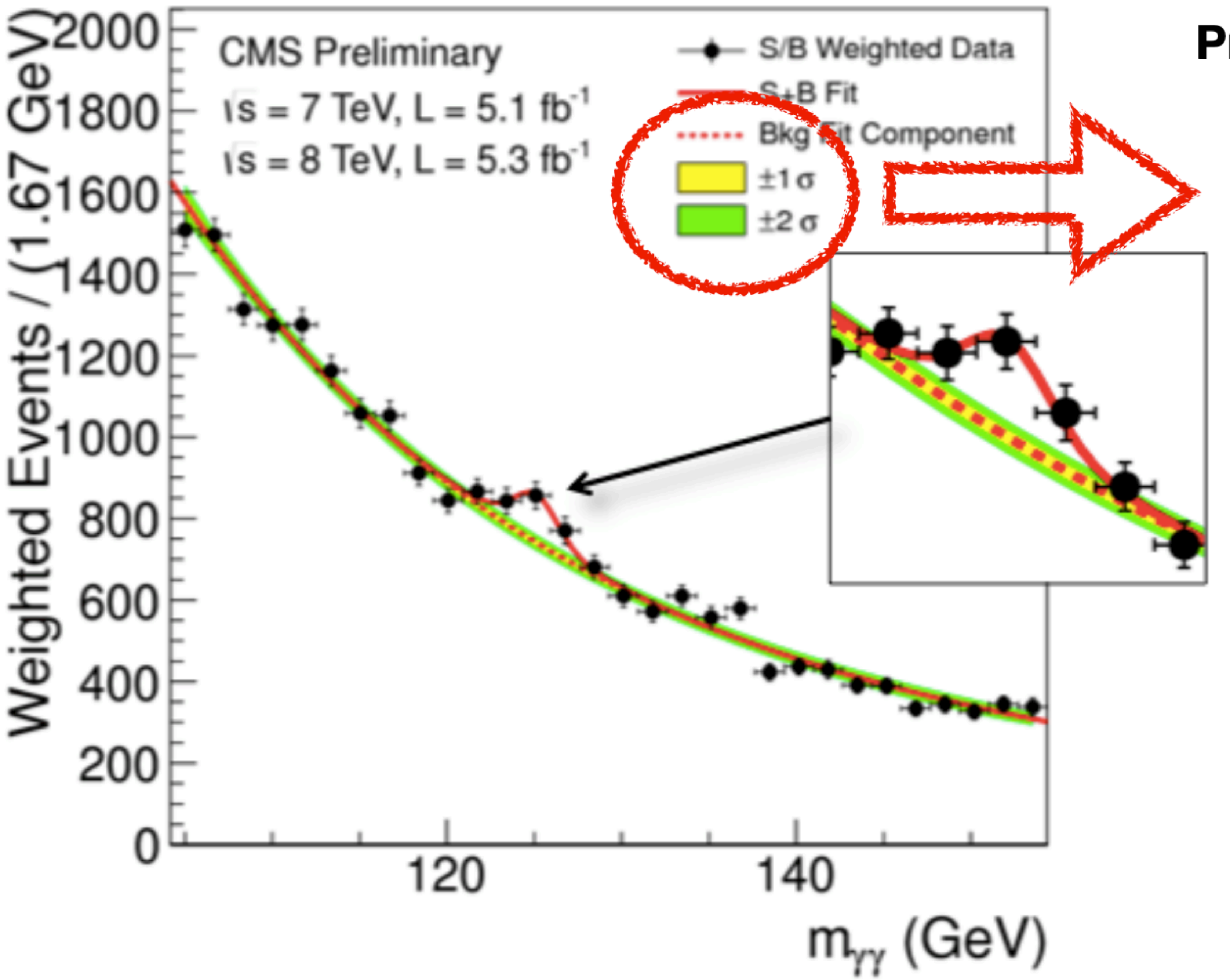




Success stories



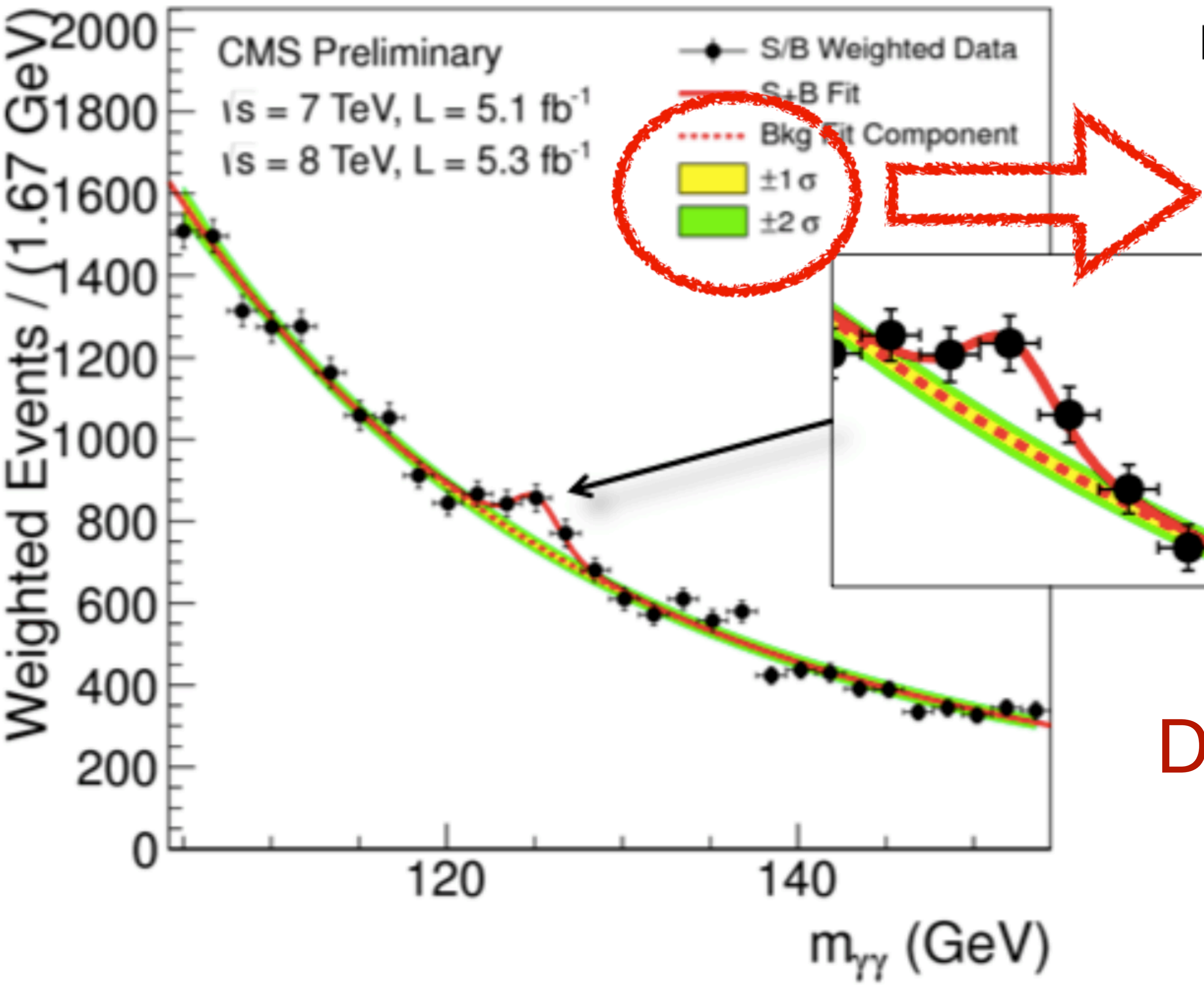
Success stories



Precisely simulated background :

- **Simulation of pp collisions;**
- **Simulation of detector response;**

Nobel prize in Physics



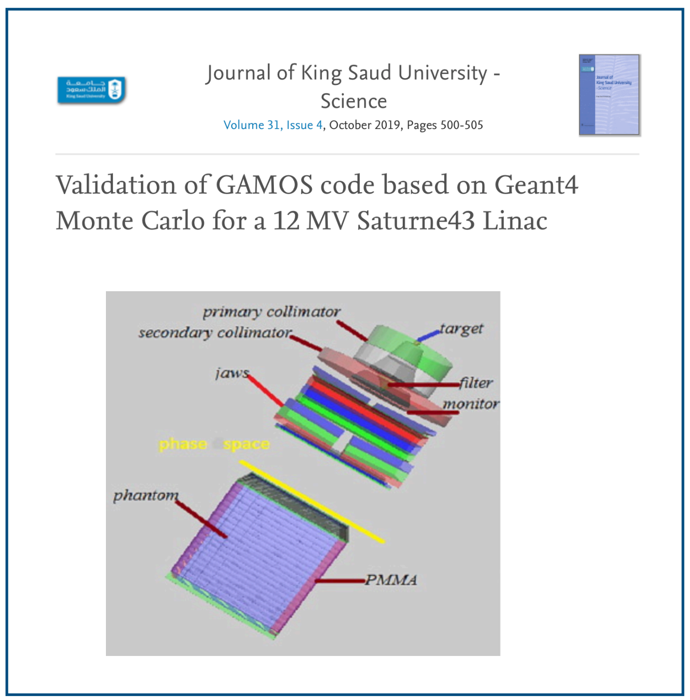
Precisely simulated background :

Discovery of the Higgs Boson!

Specialised packages

GAMOS

Geant4-based architecture for **medicine** orientated simulations

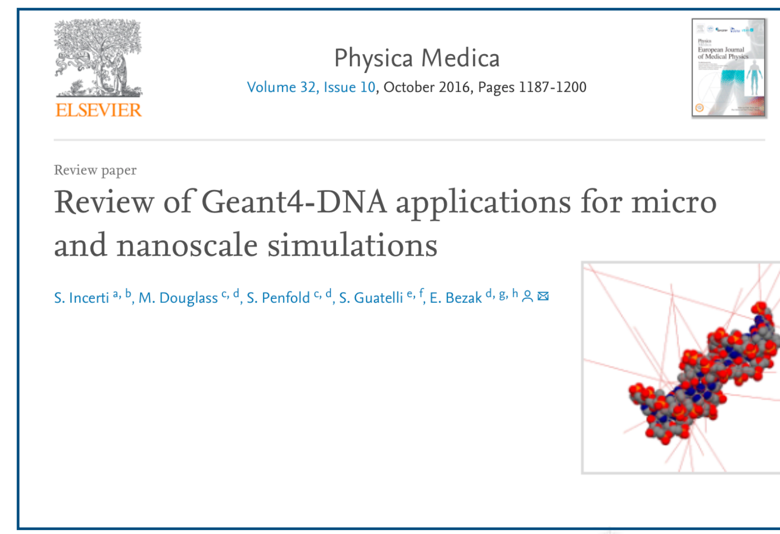

Journal of King Saud University - Science
Volume 31, Issue 4, October 2019, Pages 500-505

Validation of GAMOS code based on Geant4 Monte Carlo for a 12 MV Saturne43 Linac

Center for Energy, Environmental and Technological Research

GEANT4-DNA

Geant4 extension simulation related to **biochemistry** and **DNA**

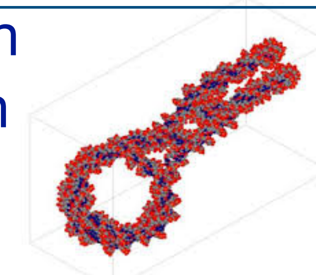

Physica Medica
Volume 32, Issue 10, October 2016, Pages 1187-1200

Review paper

Review of Geant4-DNA applications for micro and nanoscale simulations

S. Incerti [a, b], M. Douglass [c, d], S. Penfold [c, d], S. Guatelli [e, f], E. Bezak [d, g, h]

Developed an interface with the **protein data bank**



https://arxiv.org/pdf/0910.5684.pdf

http://geant4-dna.in2p3.fr/styled-3/styled-8/index.html

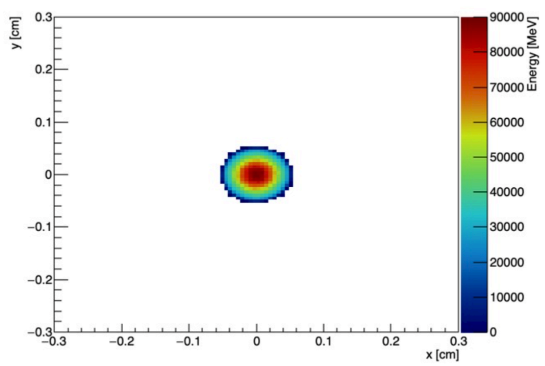
Specialised packages

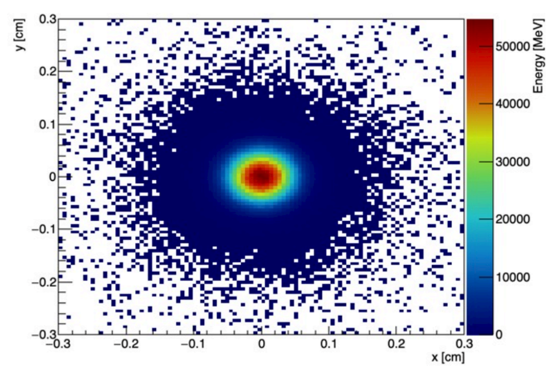
Tool for particle simulation

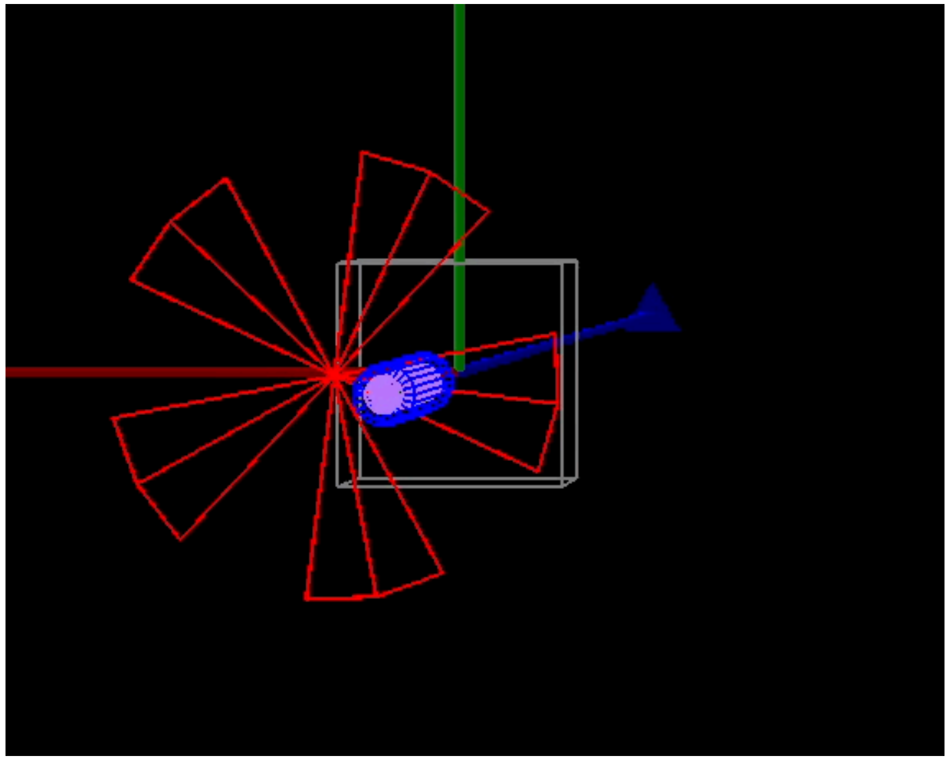
http://www.topasmc.org

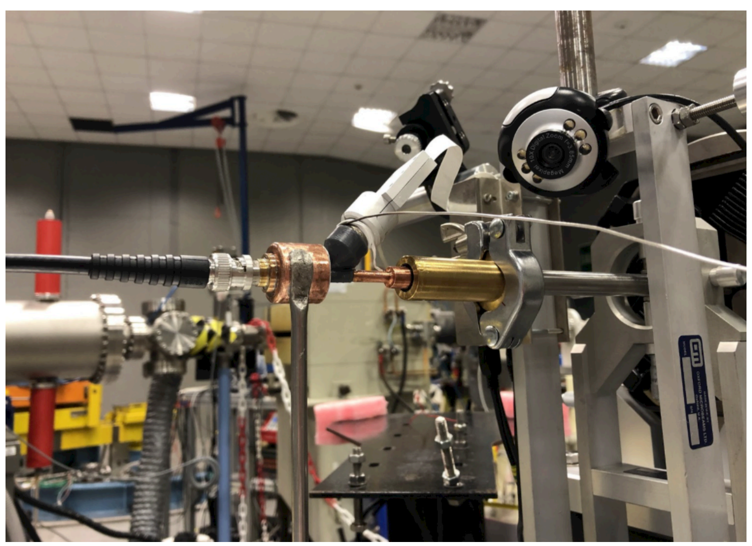
NATIONAL CANCER INSTITUTE
Informatics Technology for Cancer Research

Development of a Standard Methodology for Online Dose Calculations in Air



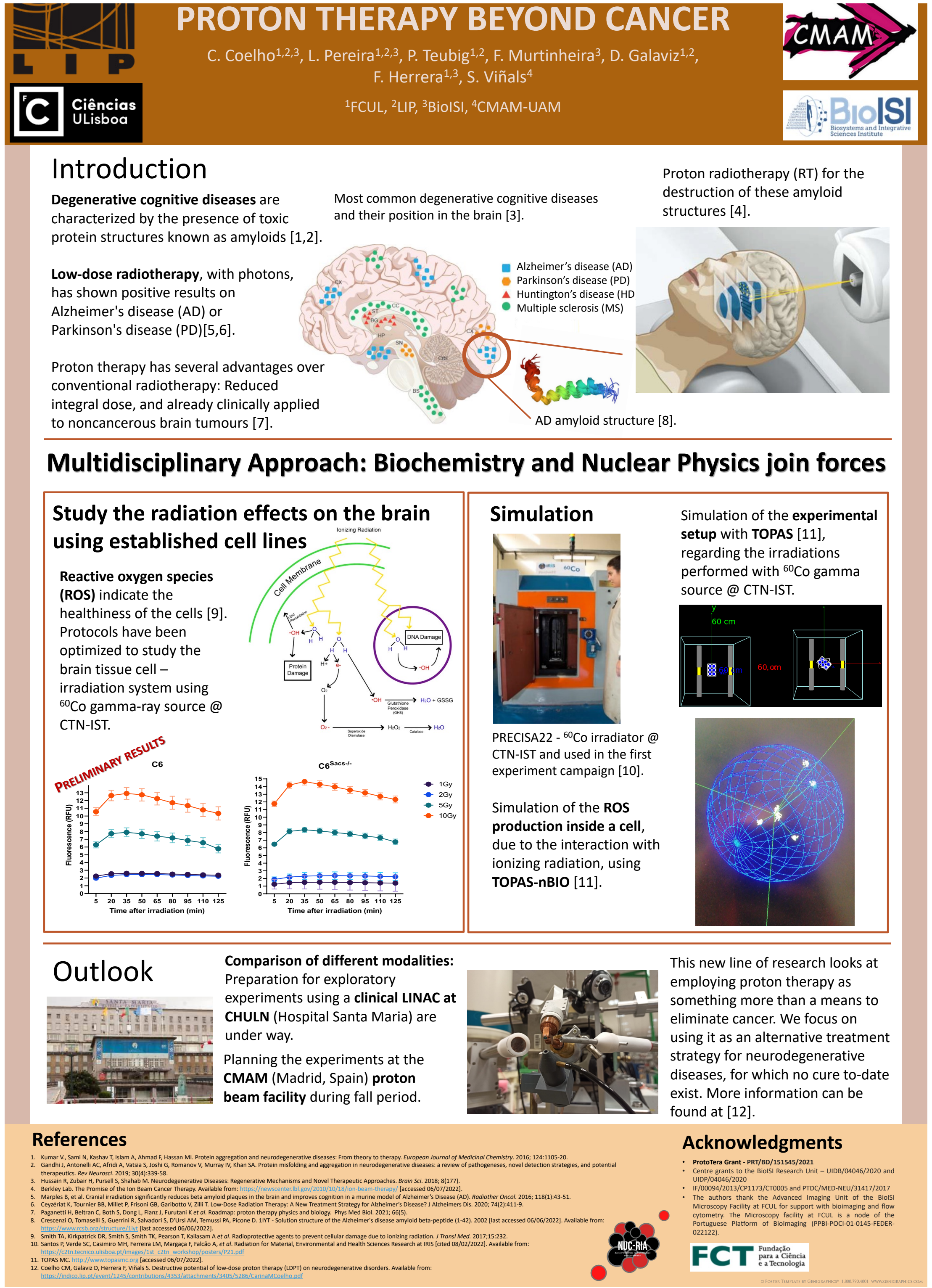


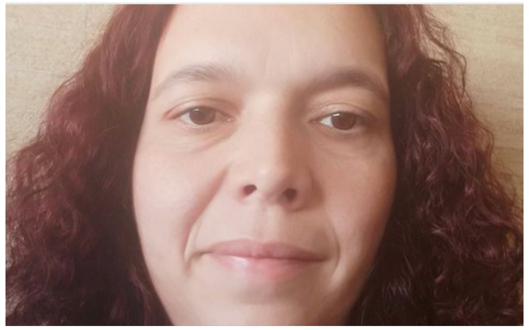




Work by R. Pestana **C. Felgueiras**

Specialised packages





Acknowledgements

R3B
califa
GEANT4 A SIMULATION TOOLKIT
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LIBPhys-UNL
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
TÉCNICO LISBOA
Ciências ULisboa
TUM TECHNISCHE UNIVERSITÄT MÜNCHEN

Thank you!

Questions?

REPÚBLICA PORTUGUESA
FCT Fundação para a Ciência e a Tecnologia