GROOT: A novel Geant4 and ROOT Monte Carlo tool for nuclear physics

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(ELI-NP)

Outline

- ELI-NP and ELISSA
- Nuclear Astrophysics with gamma beams
- MC: *photonuclear* physics in Geant4?
- MC simulation tool
- Physics cases and results
- Final remarks

ELI-NP & Nuclear Astrophysics

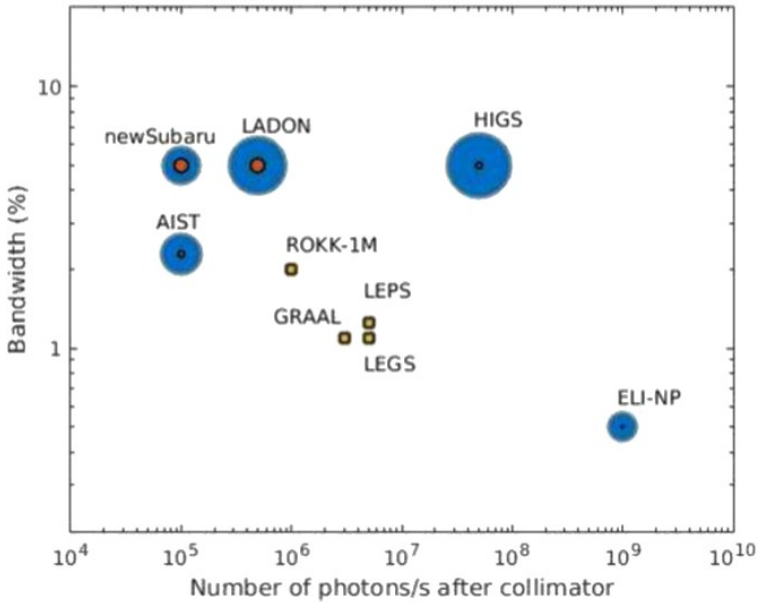


Table 1. The parameters of the gamma beams at ELI-NP Gamma Beam System (GBS).

Gamma beam parameters	Value
Energy [MeV]	0.2-19.5
Spectral density [photons/s/eV]	$>0.5 \cdot 10^3$
Bandwidth [%]	$\leqslant 0.5$
Peak brilliance [photons/s·mm^2·mrad^2·0.1% bdw]	10^{20}–10^{23}
Pulse length rms [ps]	0.7-1.5
Linear polarization [%]	>95
Macro repetition rate [Hz]	100
Number of pulses/macropulse	32
Pulse-to-pulse separation [ns]	16

- **Big Bang Nucleosinthesys and Li-problem**

^{7}Li(γ,t)^{4}He reaction

- **Si-burning in stars and presupernova phase**

^{24}Mg(γ,α)^{20}Ne reaction

^{28}Si(γ,p)^{27}Al reaction

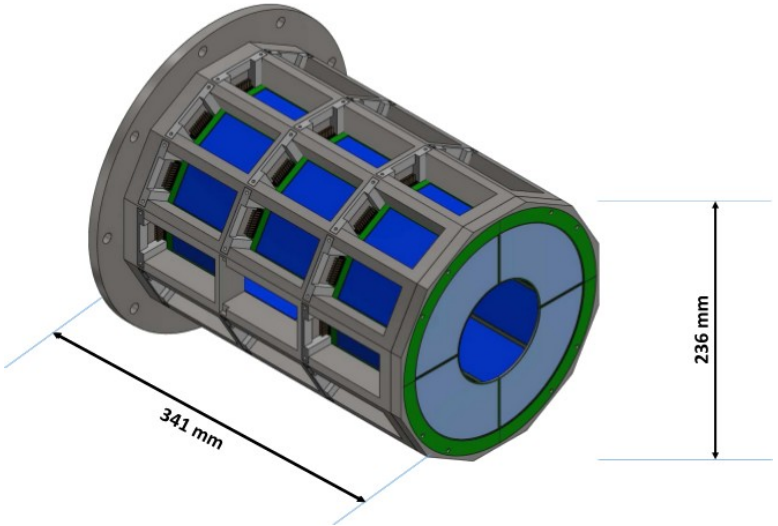
- **p-process (production of proton rich nuclei)**

^{96}Ru(γ,α)^{92}Mo reaction

^{74}Se(γ,p)^{73}As reaction

Nuclear Physics

Extreme Light Infrastructure Silicon Strip Array



- 3 rings of 12 position-sensitive X3 silicon-strip detectors (minus 1)
  Energy resolution (FWHM) ~ 0.3%
  Angular resolution 1 mm or ~ 0.4 deg
- 2 end cap detectors made up of 4 QQQ3 DSSSD
  Energy resolution (FWHM) ~ 0.3%
  Angular resolution 3 mm or ~ 0.8 deg

[1] O. Tesileanu et al., 2016 Charged particle detection at ELI-NP, Rom. Rep. Phys. 68 S699
[2] M. La Cognata et al., 2017 Journal of Instrumentation 12 C03079

Nuclear Physics

Photonuclear Astrophysics

- to perform accurate measurements of (small) cross sections of nuclear reactions
- inverse photo-disintegration reactions with low background measurements
- different systematic uncertainties than charge-particle induced reactions at low energies of astrophysical interest

It is important to evaluate the background

Nuclear Physics

MC simulations

- Estimate the gamma-induced e.m. background (*analysis started by G.A.P. Cirrone, F. Romano, A. Tramontana & M. La Cognata @ LNS*)
- Estimate the full background of photonuclear reactions and the detector's resolution effect
- Optimization of the detector geometry
- Estimate the event rate (provided that we have reliable cross-section calculations) or calculate the minimum cross-section we can measure because of the background

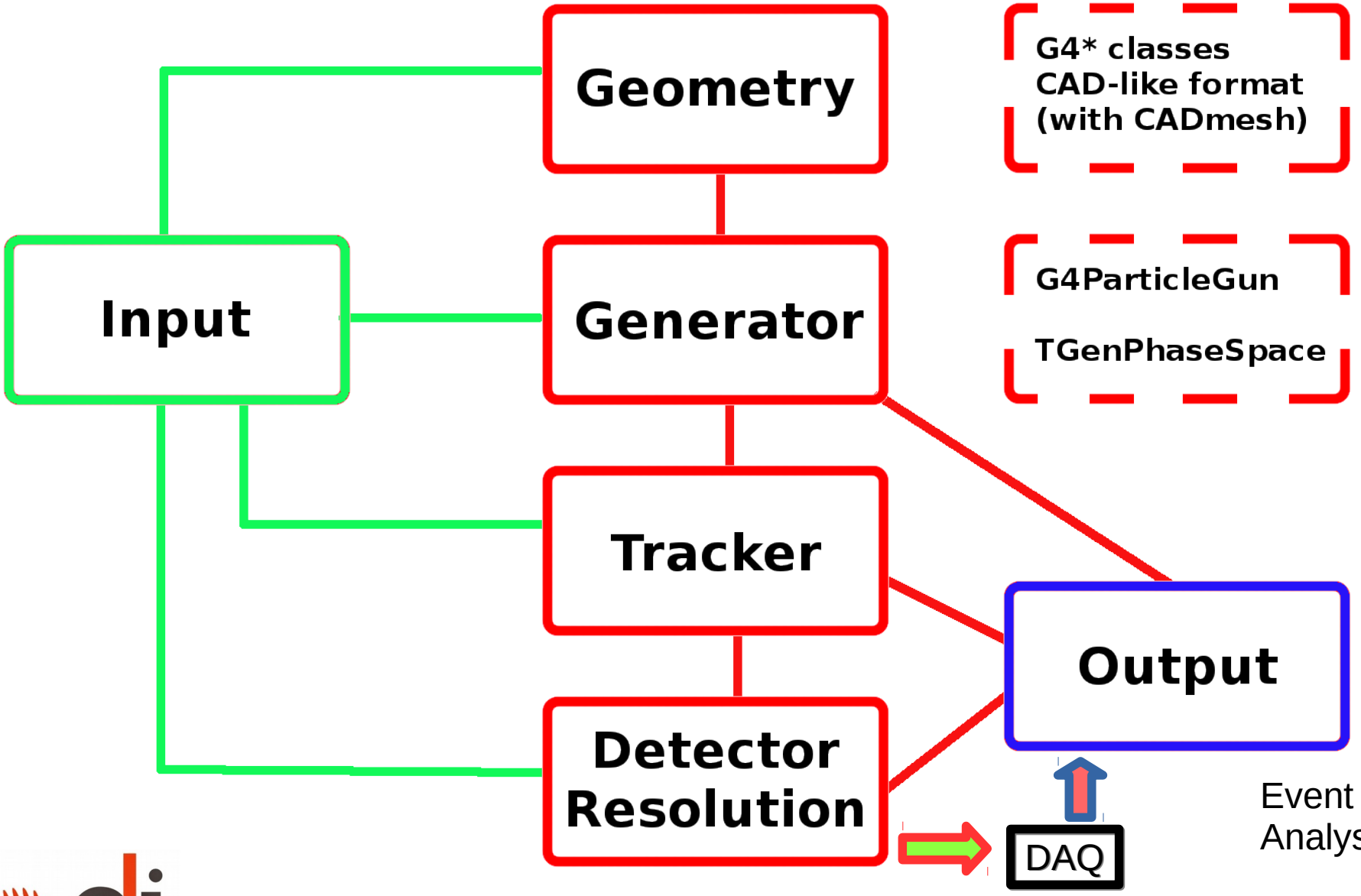
Nuclear Physics

Photonuclear reactions in Geant4

- Photonuclear reactions are not validated at low energies
- Need for external event generator → ROOT TGenPhaseSpace class generates n-body events (based on CERNLIB GENBOD)
- post-run event-weighting → CPU-time saving + no interference with G4 Em physics
- Background and signal treated separately

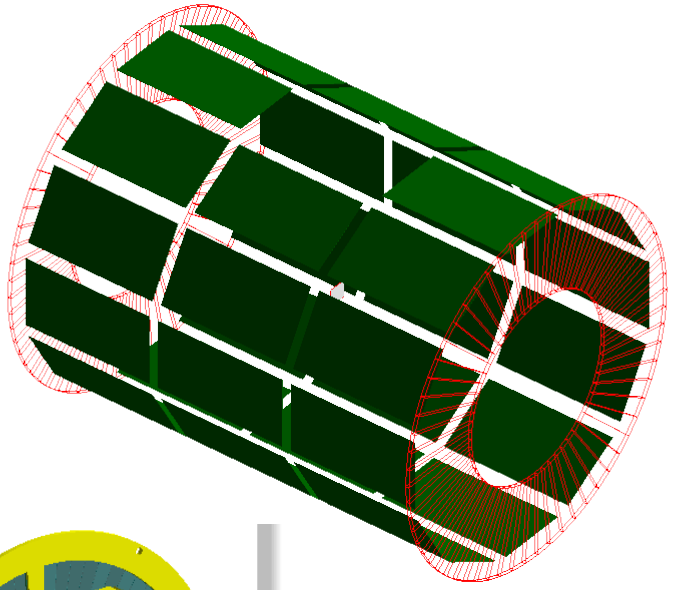
Nuclear Physics

The code

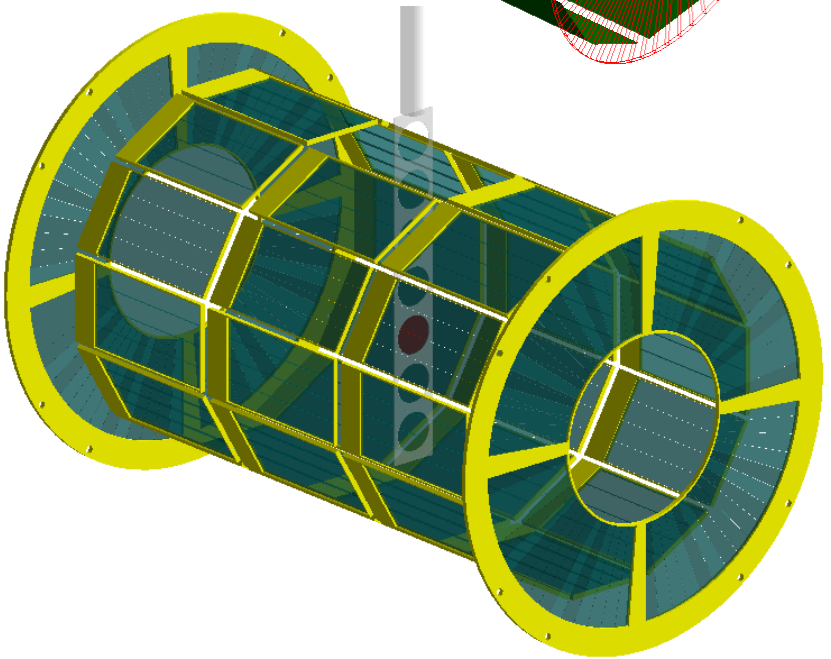

Geometry
G4* classes
CAD-like format
(with CADmesh)
Input
Generator
G4ParticleGun
TGenPhaseSpace
Tracker
Output
Detector
Resolution
DAQ
Event Weight..
Analysis..

The Geometry

CLASSIC:
G4Box, G4Tubs,... classes
(provide your own DetectorConstruction file)

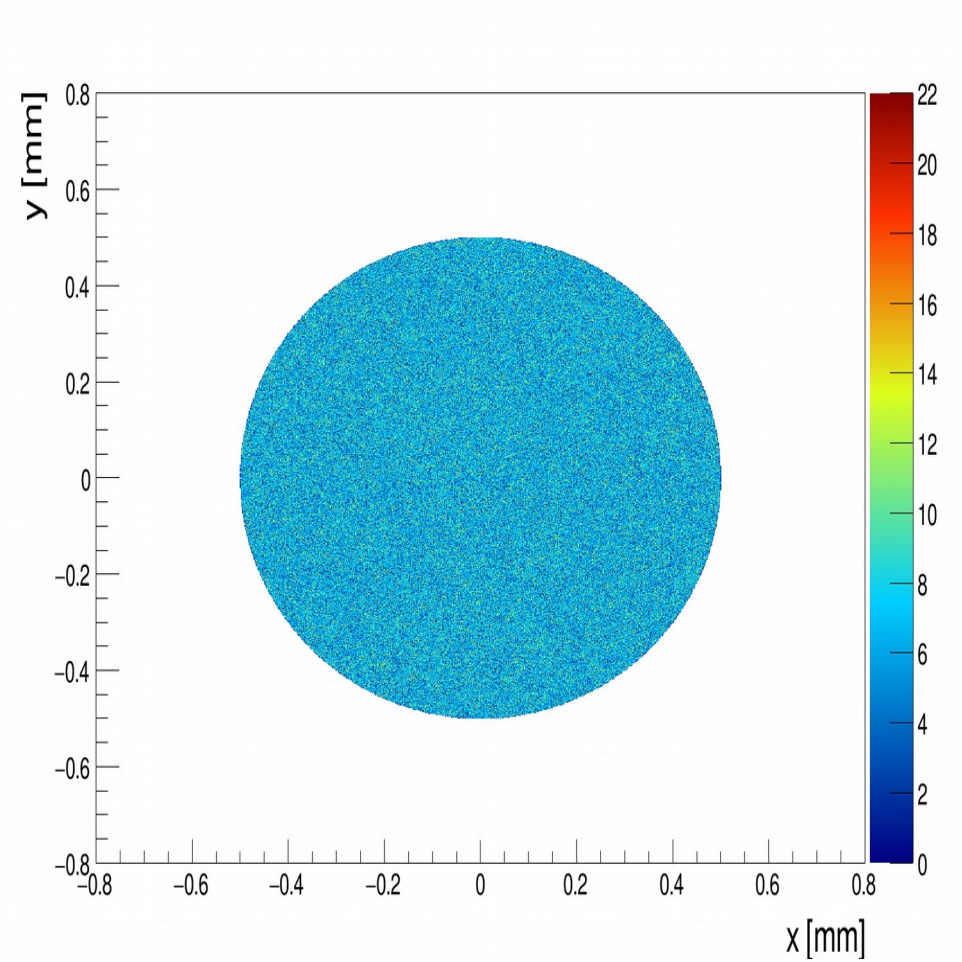


ADVANCED:
STL format (converted from CAD-like file) through dynamic definition of CADmesh* objects



The Event Generator

<u>electromagnetic (background):</u>
G4ParticleGun with adjustable beam profile
Tested, validated, widely used.

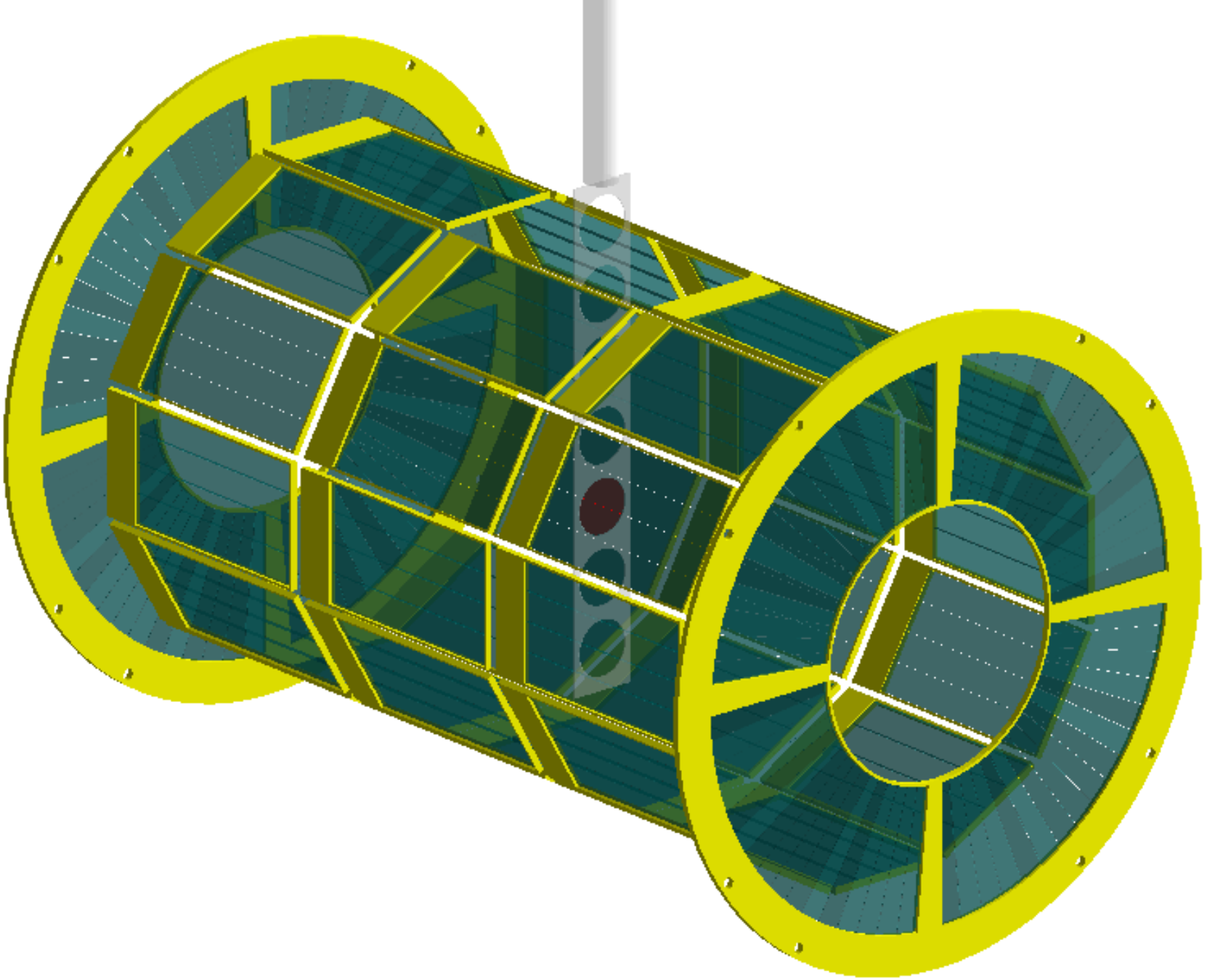


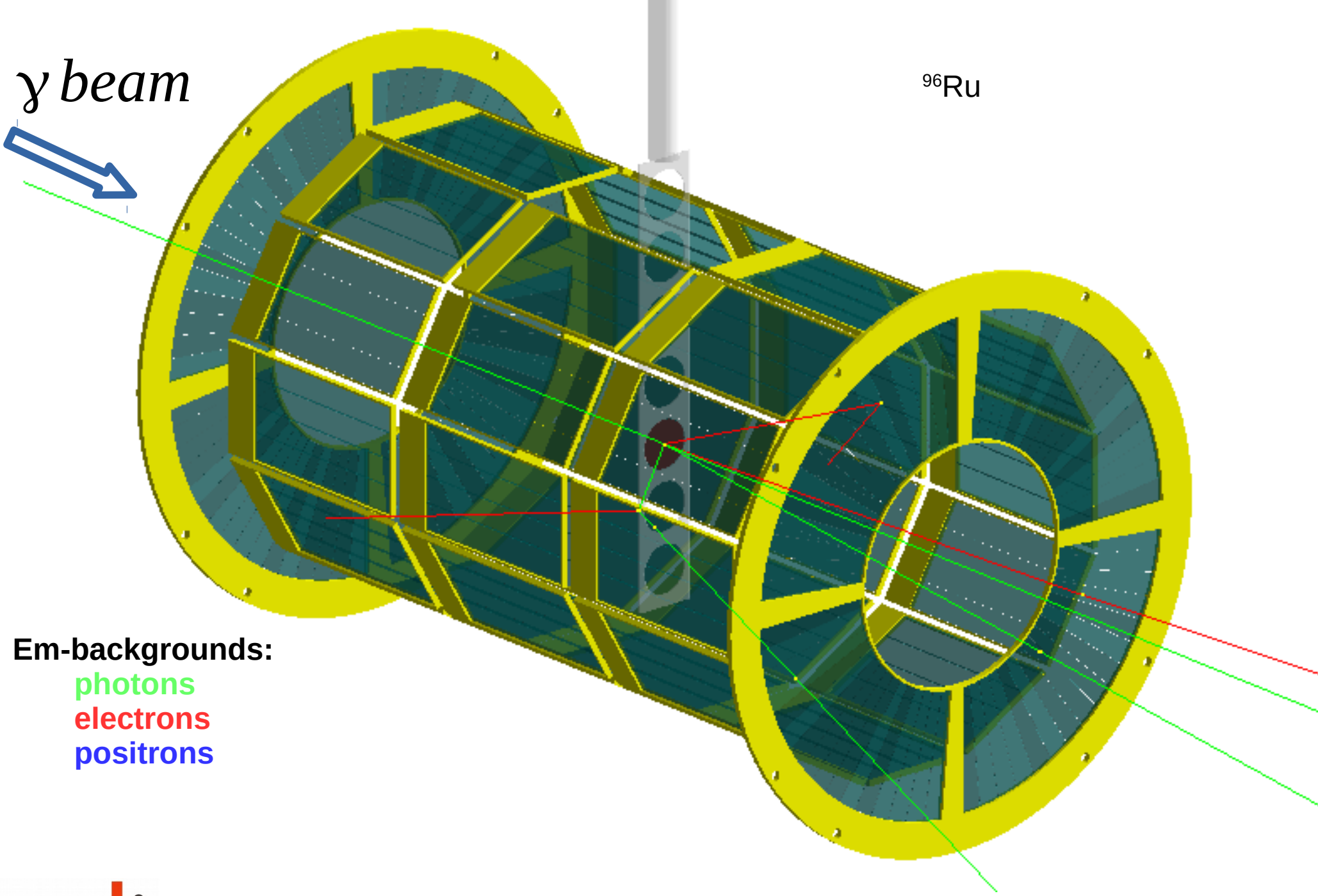
<u>(photo-)nuclear reactions:</u>
TLorentzVectors defining the beam/target particles/nuclei.
Custom beam profile.
Tested, validated, used.
MUST declare the ejectile masses → you can simulate only one (photo-)nuclear reaction at a time

Nuclear Physics

The Tracker and the resolution

- Tracking fully relies on Geant4 G4EmStandardPhysics_option3(), G4EmStandardPhysics_option4(),..
- Energy resolution is currently applied as a custom function (e.g.: a Gaussian function with energy-dependent FWHM). To be optimized for external users..
- electronic noise to be implemented (GET? standard? ..)



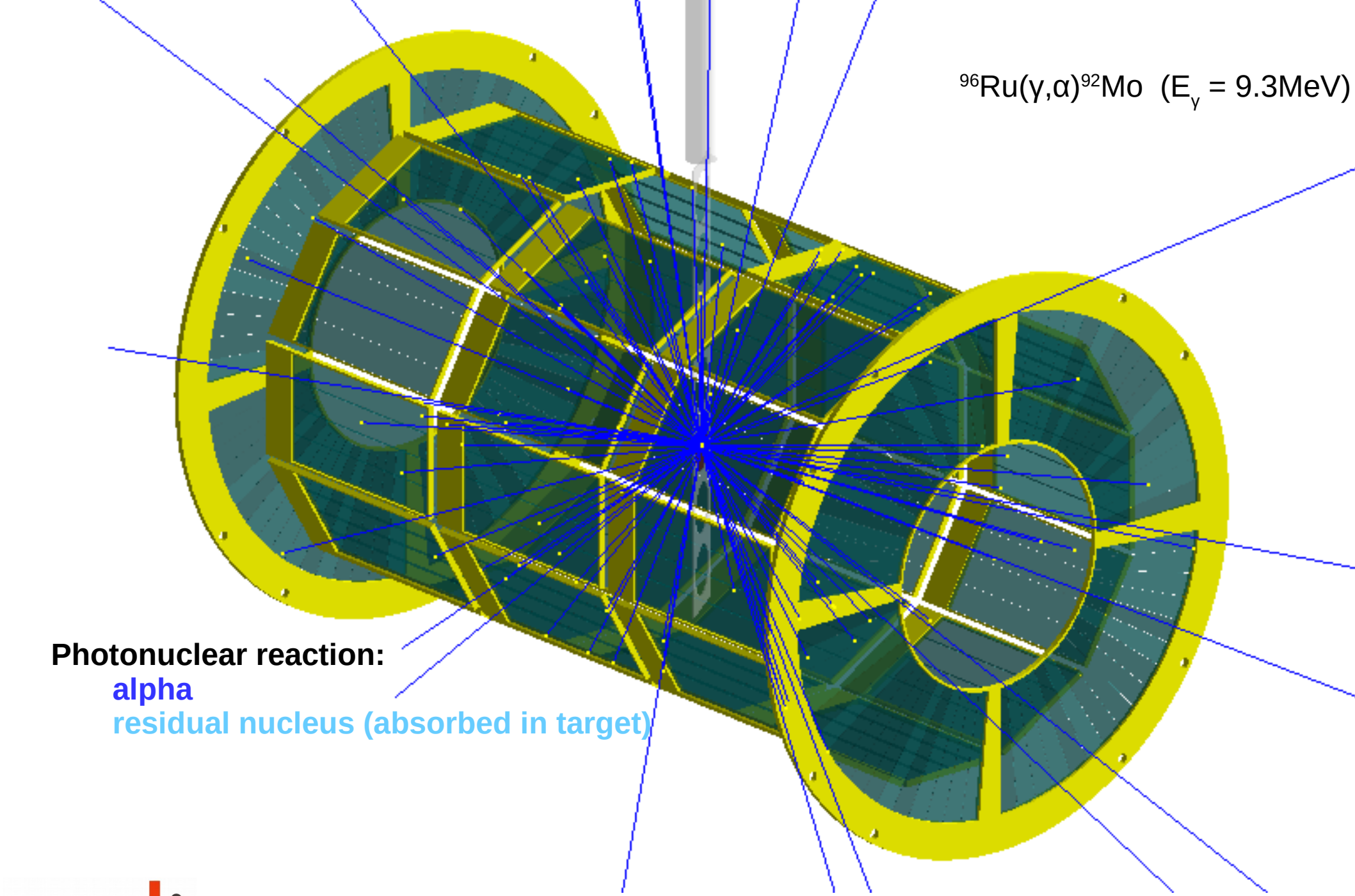


Em-backgrounds:

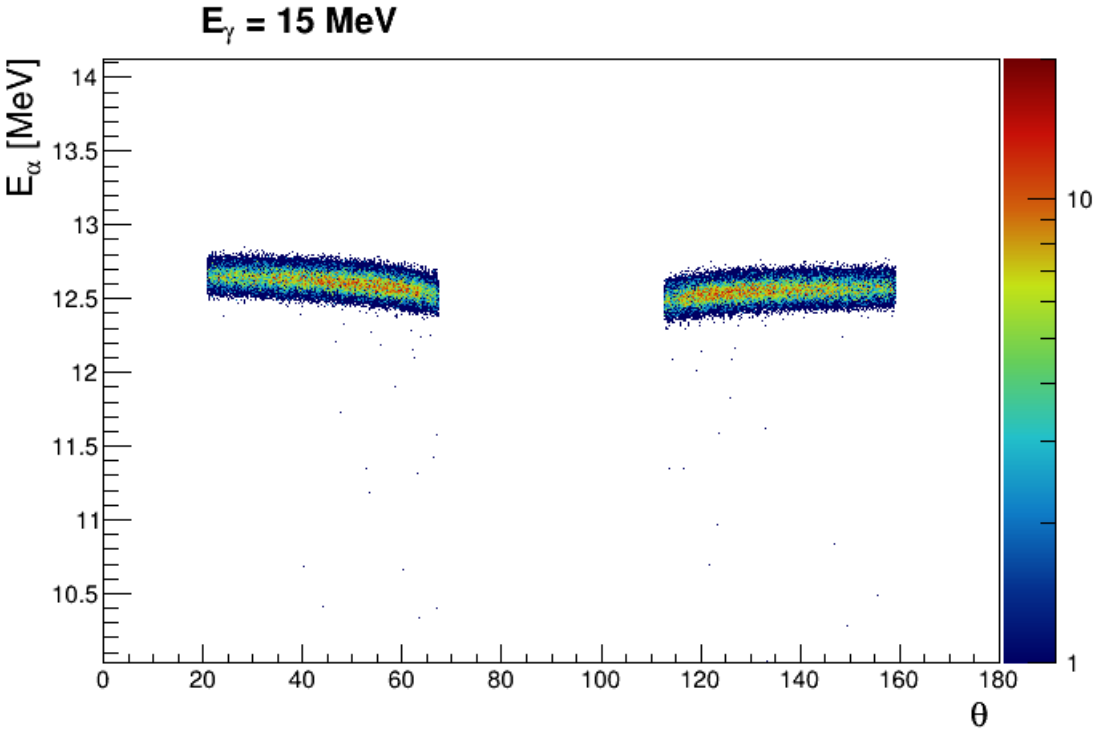
photons

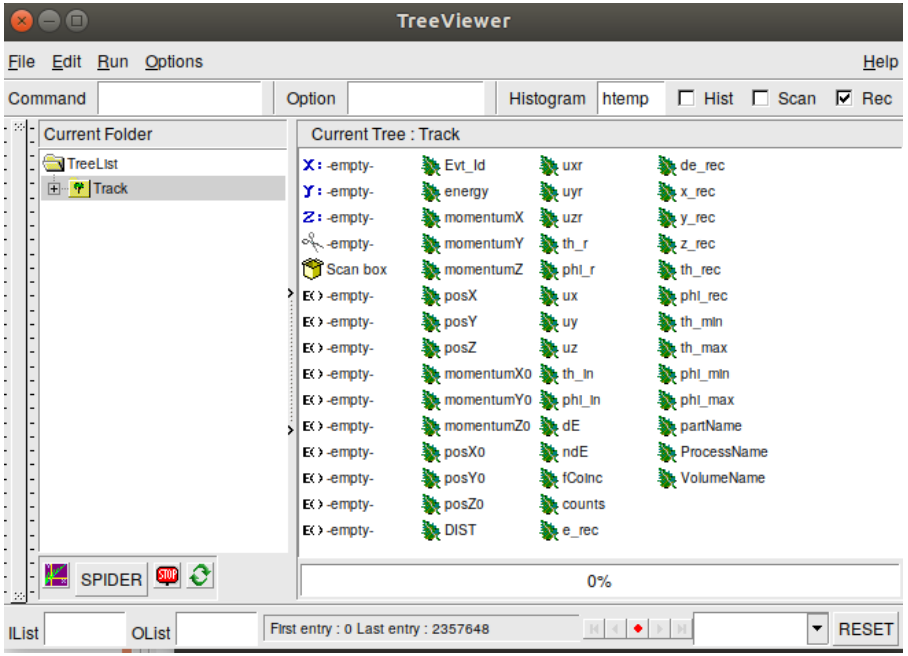
electrons

positrons


$^{96}Ru(\gamma,\alpha)^{92}Mo$ (E_γ = 9.3MeV)
Photonuclear reaction:
alpha
residual nucleus (absorbed in target)

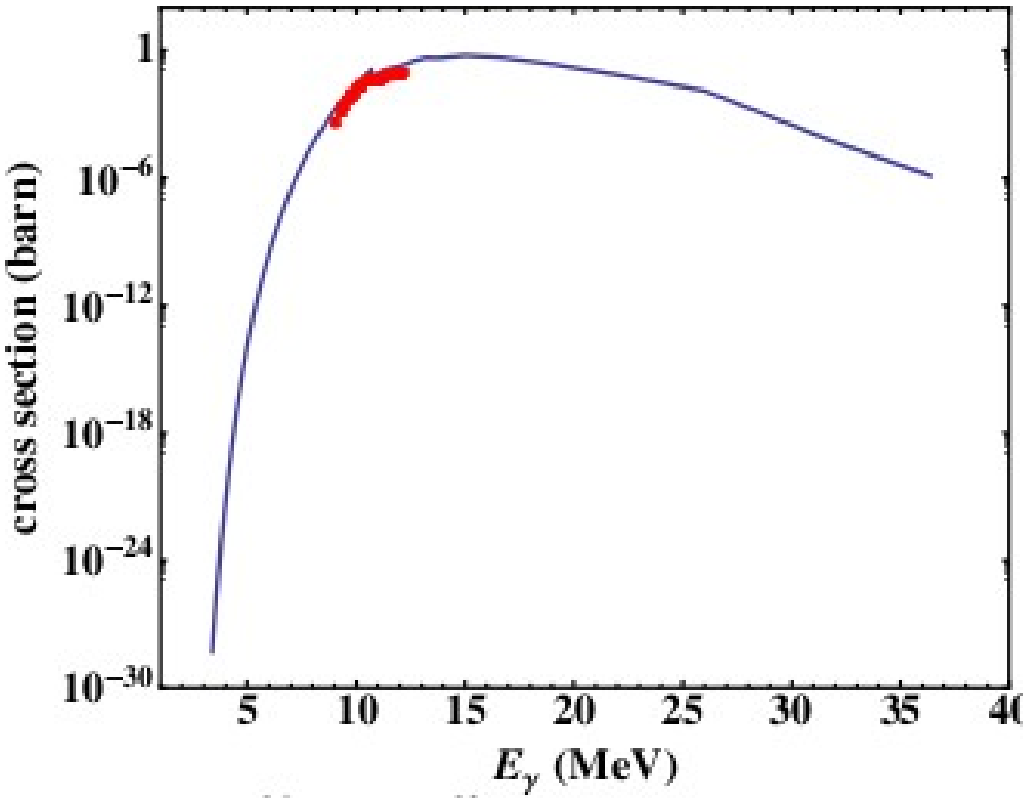
Output

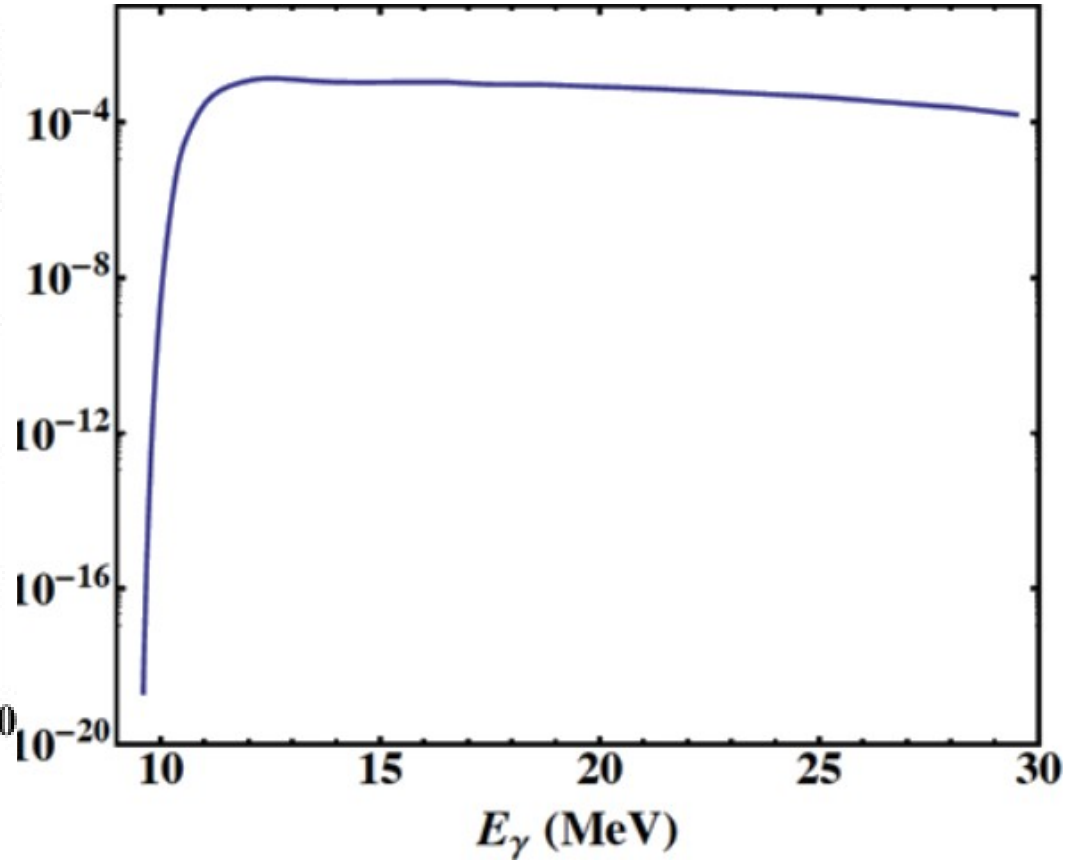

E_γ = 15 MeV
E_α [MeV]
14
13.5
13
12.5
12
11.5
11
10.5
0
20
40
60
80
100
120
140
160
180
θ
10
1


TreeViewer
File Edit Run Options Help
Command
Option
Histogram htemp
Hist
Scan
Rec
Current Folder
TreeList
Track
Current Tree : Track
X: -empty-
Y: -empty-
Z: -empty-
-empty-
Scan box
Evt_Id
energy
momentumX
momentumY
momentumZ
posX
posY
posZ
momentumX0
momentumY0
momentumZ0
posX0
posY0
posZ0
DIST
uxr
uyr
uzr
th_r
phi_r
ux
uy
uz
th_in
phi_in
dE
ndE
fCoInc
counts
e_rec
de_rec
x_rec
y_rec
z_rec
th_rec
phi_rec
th_min
th_max
phi_min
phi_max
partName
ProcessName
VolumeName
SPIDER
0%
IList
OList
First entry : 0 Last entry : 2357648
RESET

Event weight

(Hauser-Feshbach)





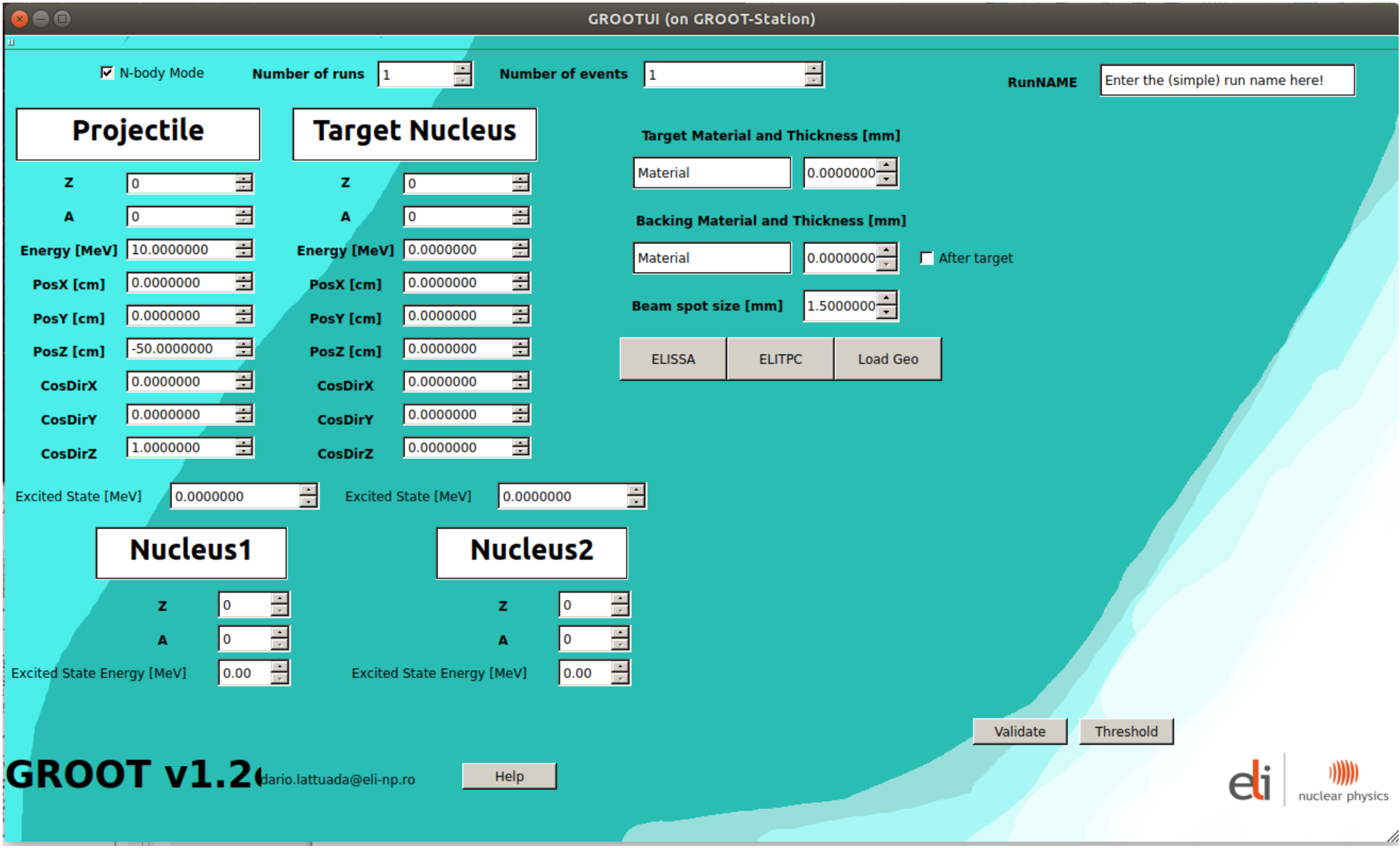
Expected Rate: 6.6×10^5 events/ day

$^{96}Ru(\gamma,\alpha)^{92}Mo$ (E_γ = 9.3MeV)

Expected Rate: 3×10^4 events/ day

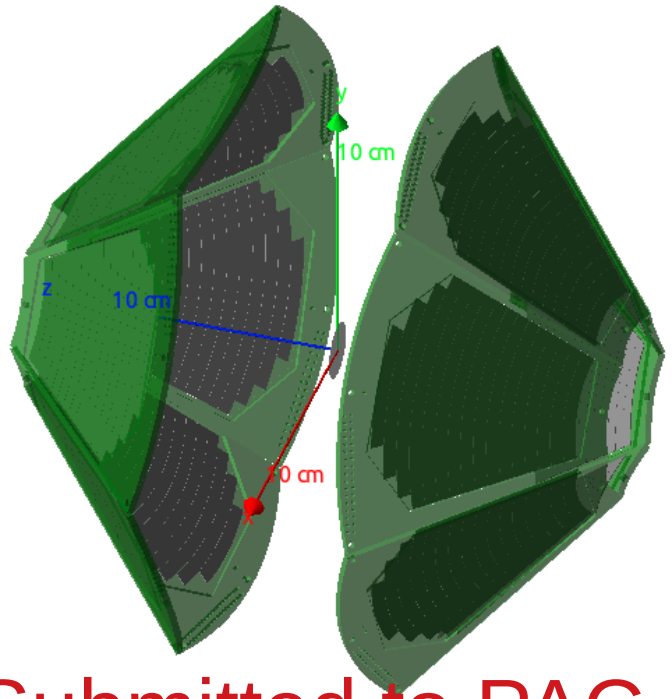
$^{24}Mg(\gamma,\alpha)^{20}Ne$ (E_γ = 11 MeV)

Nuclear Physics

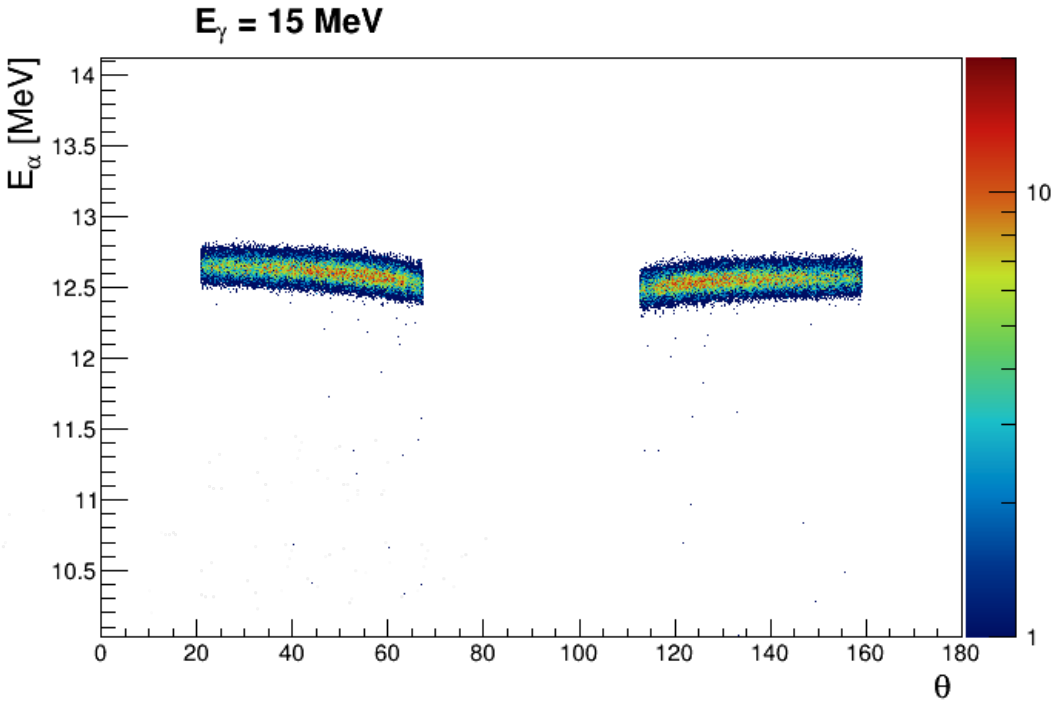

GROOTUI (on GROOT-Station)
N-body Mode
Number of runs
1
Number of events
1
RunNAME
Enter the (simple) run name here!
Projectile
Target Nucleus
Z
A
Energy [MeV]
PosX [cm]
PosY [cm]
PosZ [cm]
CosDirX
CosDirY
CosDirZ
10.0000000
-50.0000000
1.0000000
0.0000000
Target Material and Thickness [mm]
Material
0.0000000
Backing Material and Thickness [mm]
After target
Beam spot size [mm]
1.5000000
ELISSA
ELITPC
Load Geo
Excited State [MeV]
Nucleus1
Nucleus2
Excited State Energy [MeV]
0.00
Validate
Threshold
GROOT v1.2
dario.lattuada@eli-np.ro
Help
nuclear physics

HIgS proposal: The photodisintegration of ^{112}Sn in the astrophysical p-process

^{112}Sn(γ,α) and ^{112}Sn(γ,p) @ $E_γ$ = 11-20 MeV



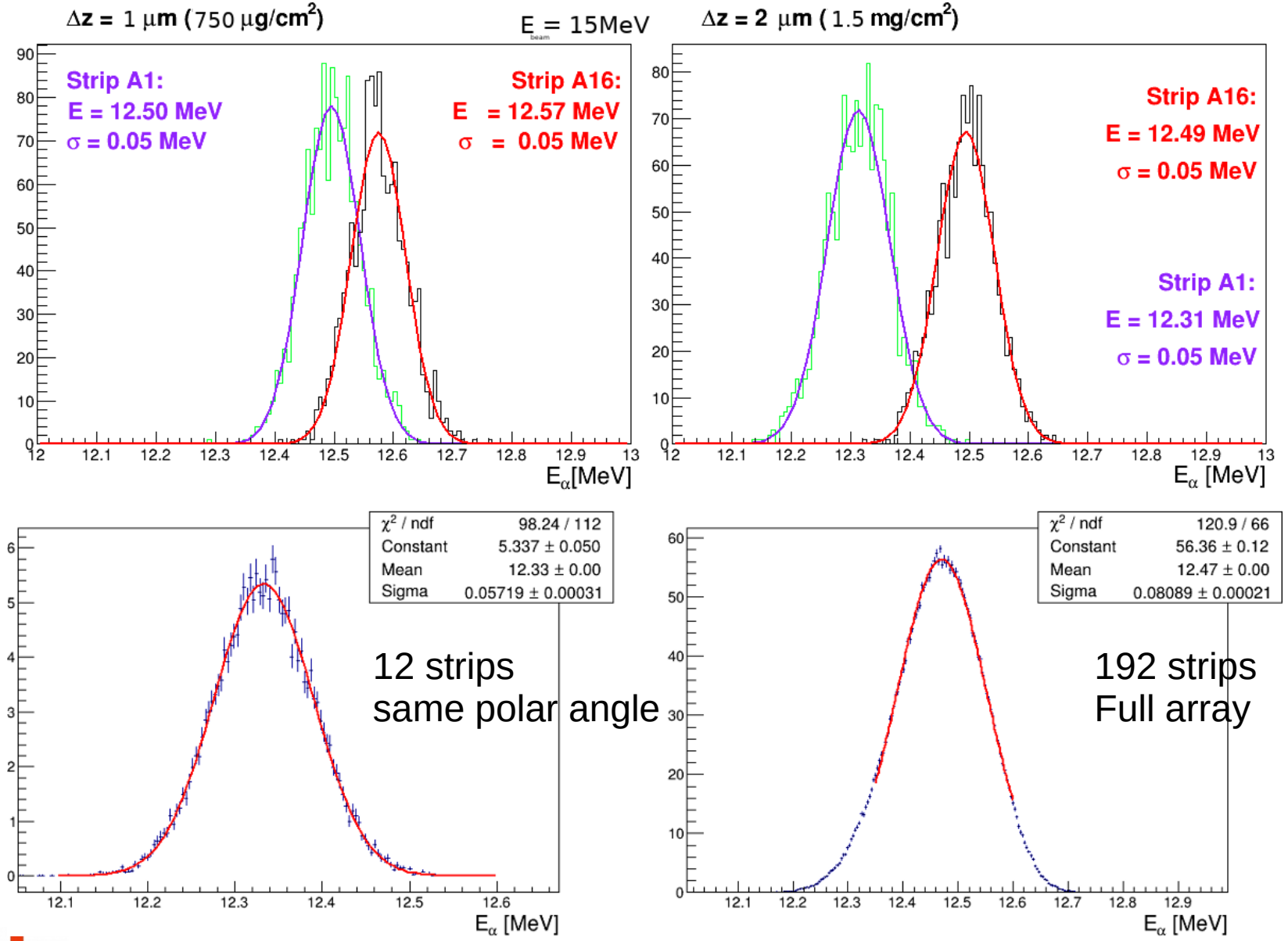
Submitted to PAC (March 2019)



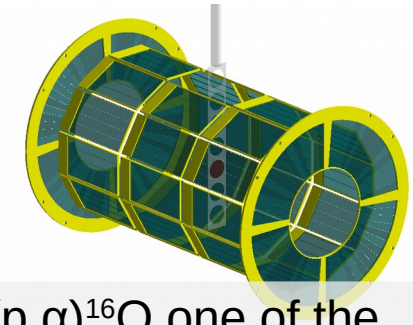
- ^{112}Sn synthetized by the p-process
- α -OMP
- inverse reaction ^{108}Cd (α, γ) ^{112}Sn is important
- No direct measurements
- Only (γ, p) @ 13+ MeV in 1971

Nuclear Physics

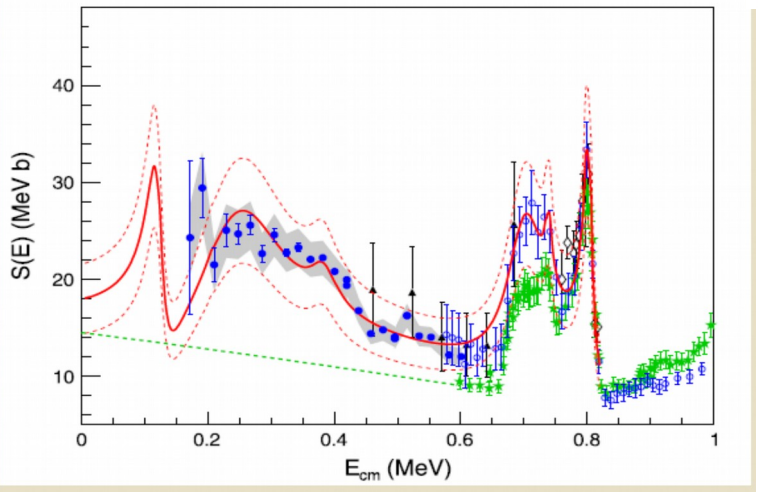
The photodisintegration of ^{112}Sn in the astrophysical p-process



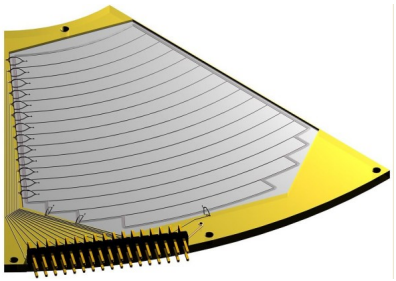
ELISSApi Experiment @ LNS-INFN

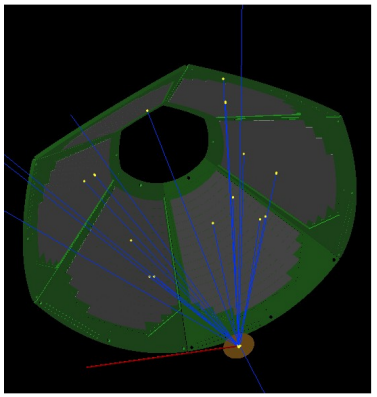


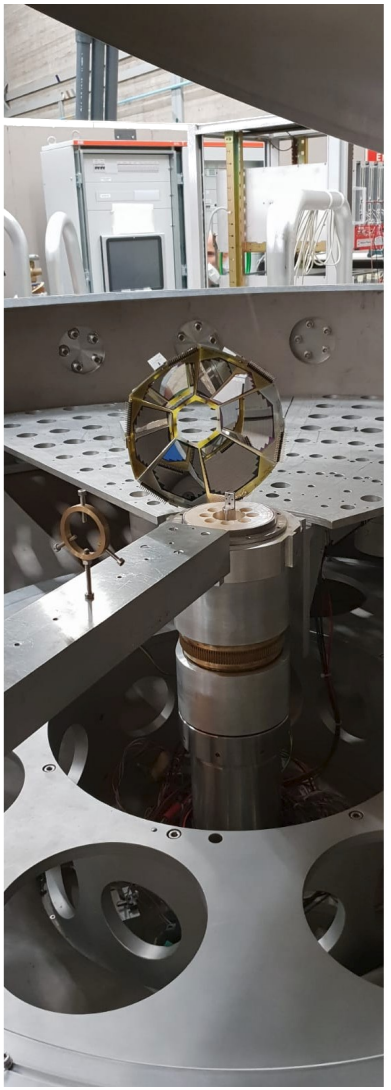
$^{19}F(p,\alpha)^{16}O$ one of the primary destruction channels in fluorine nucleosynthesis in AGB stars
^{19}F beam (9-18.5MeV) on CH_2 targets at LNS Tandem

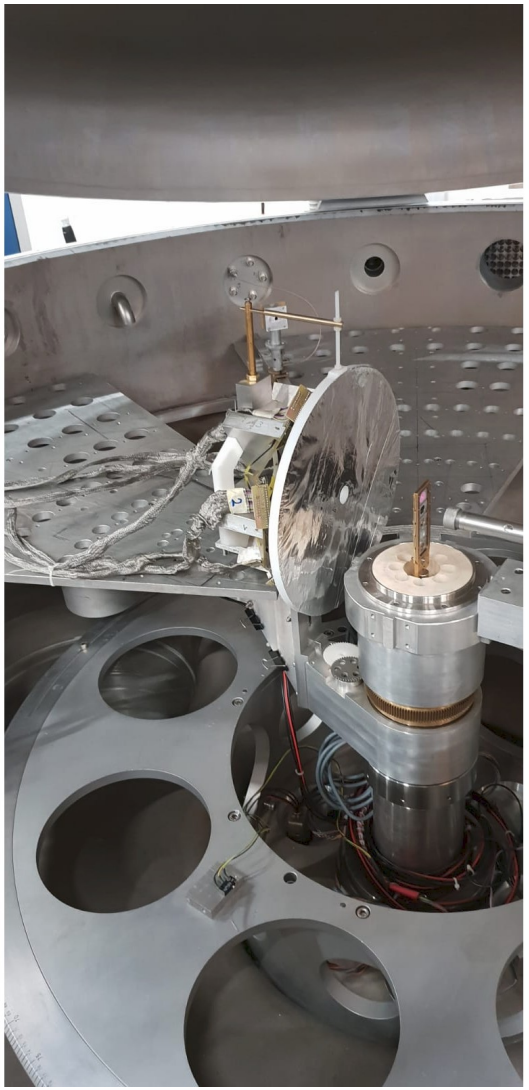


2 weeks before the experiment:
NO ELISSA
.. ok then
SIDAR (LHASA)



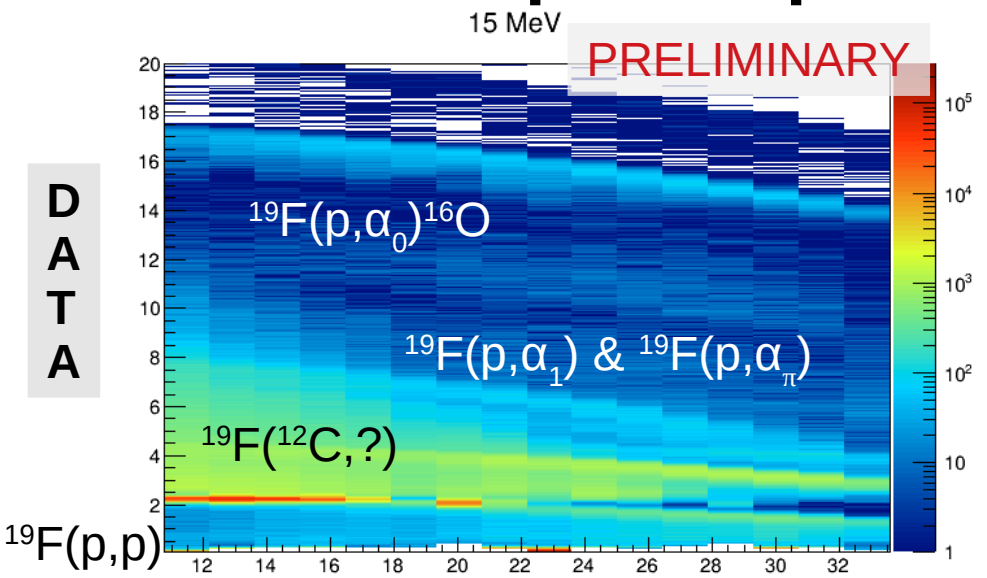


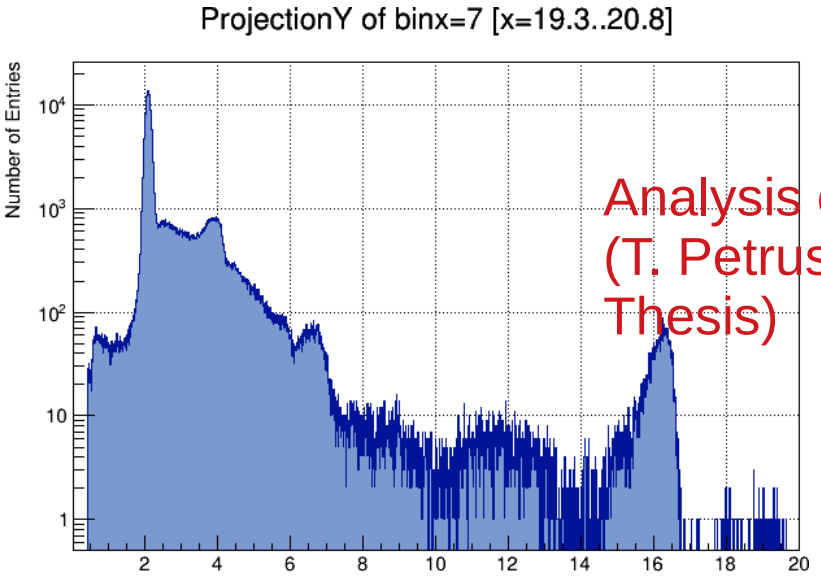




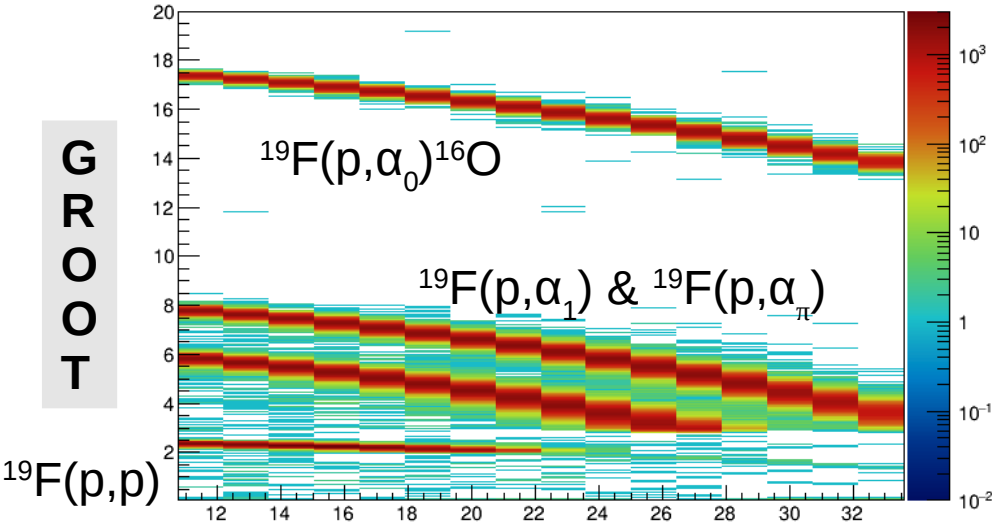
Nuclear Physics

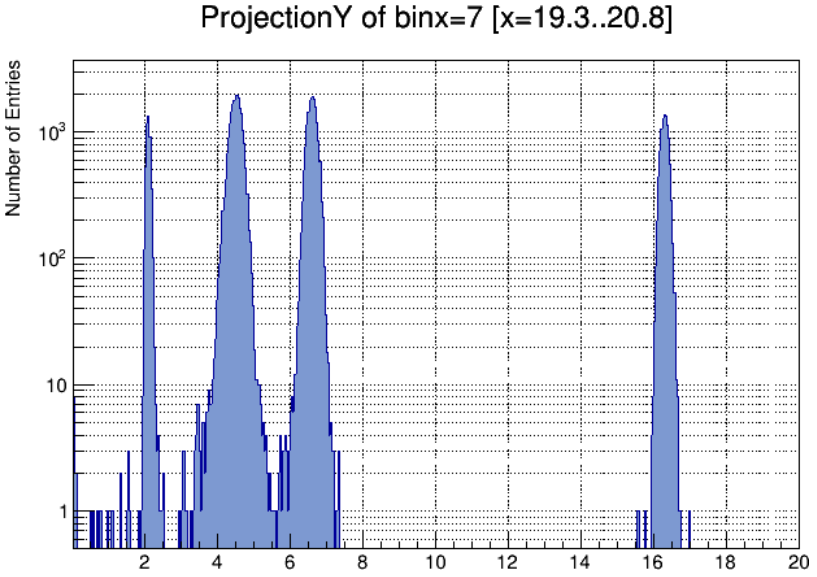
ELISSApi Experiment @ LNS-INFN





Analysis ongoing (T. Petruse, PhD Thesis)





^{19}F(p,α$_2$) absent

Conclusions & future development

- ELISSA is designed to provide insights on nuclear reactions of great astrophysical relevance
- A Geant4&ROOT-based tool for nuclear physics is under development to be mainly used as reference software by ELI-NP facility users with focus on SD (but other detectors and setups are foreseen, scintillators first).
- Electromagnetic background and nuclear reactions have been evaluated with MC simulations for many experiments

- Finalize GUI, detector resolution, hits and DAQ,… write the manuscript...

Nuclear Physics

Final (requested) remarks

- problems related to /items missed in /improvements for Geant4?
  - ✗ n-body event generator for non-validated / unknown / VERY LOW cross-sections in nuclear physics
  - ✗ clarity on *Hadronic Physics, models and CS..* (maybe it's just me)
  - ✗ *The night is dark and full of segfaults..*
- message to the Geant4 developer team?
  - ✔ thank you for the maintenance, development and forum support!
  - ✔ we need collaborators and validation

- **Geant4: A Simulation toolkit** - Geant4 Collaboration (Agostinelli, S. et al.), Nucl.Instrum.Meth. A506 (2003) 250-303 SLAC-PUB-9350, FERMILAB-PUB-03-339
- **ROOT - An Object Oriented Data Analysis Framework** - Rene Brun and Fons Rademakers, Proceedings AIHENP'96 Workshop, Lausanne, Sep. 1996, Nucl. Inst. & Meth. in Phys. Res. A 389 (1997) 81-86. http://root.cern.ch/
- **A CAD Interface for Geant4 -** Poole, C. M. and Cornelius, I. and Trapp, J. V. and Langton, C. M., Australasian Physical & Engineering Science in Medicine, September 2012, DOI = 10.1007/s13246-012-0159-8, http://www.springerlink.com/content/u563877422284578
- **A fast and complete GEANT4 and ROOT Object-Oriented Toolkit: GROOT** - Lattuada, D., Balabanski, D.L., Chesnevskaya, S., Costa, M., Crucillà, V., Guardo, G.L., La Cognata, M., Matei, C., Pizzone, R.G., Romano, S., Spitaleri, C., Tumino, A., Xu, Y., EPJ Web of Conferences, 165, art. no. 01034. DOI: 10.1051/epjconf/201716501034
- **A Geant4-based Monte Carlo Tool for Nuclear Astrophysics** - Lattuada, D., La Cognata, M., Anzalone, A., Balabanski, D.L., Chesnevskaya, S., Costa, M., Crucillà, V., Guardo, G.L., Gulino, M., Matei, C., Pizzone, R.G., Romano, S., Spitaleri, C., Tumino, A., Xu, Y., EPJ Web of Conferences, 184, art. no. 02008. DOI: 10.1051/epjconf/2018184020008

Thank you

Nuclear Astrophysics group at ELI-NP

D. L. Balabanski, C. Matei, G.L. Guardo, D. Lattuada, T. Petruse, Y. Xu & C. Cordun (University of Bucharest)

AsFiN group (et al.) at LNS-INFN

C. Spitaleri, M. La Cognata, R.G. Pizzone, M. Costa, (G.L. Guardo, D. Lattuada)

Backup slides

Competitive double gamma experiment

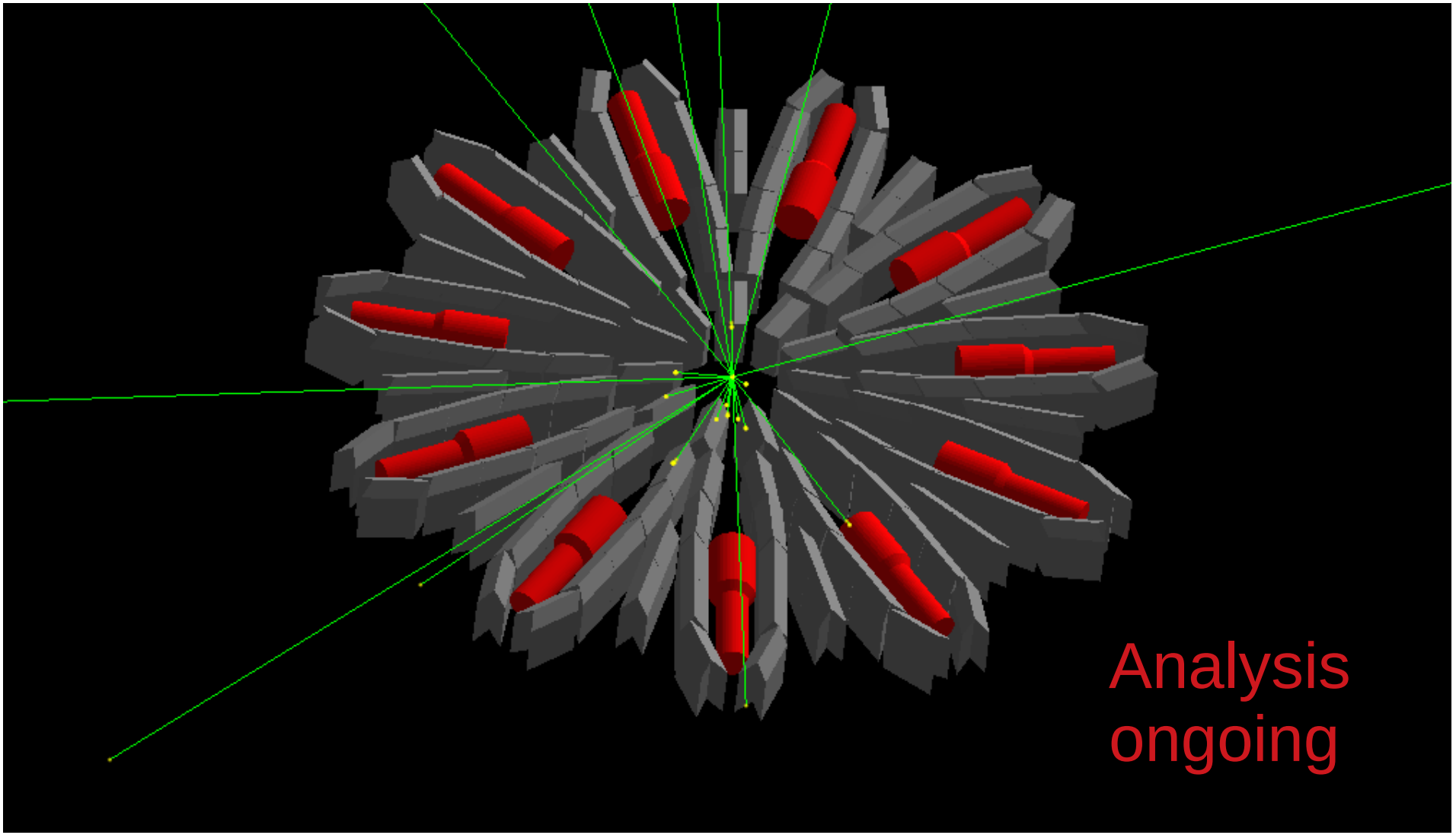


Table 16.13: Energy Levels of ^{16}O [a]

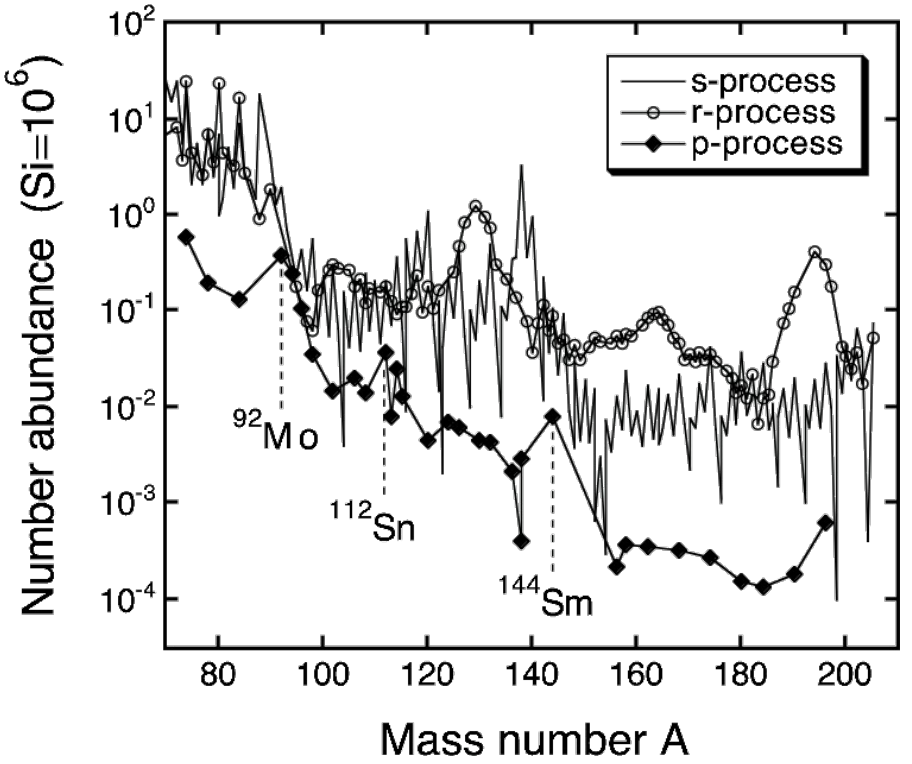
E_x (MeV ± keV)	$J^\pi; T$	K^π	$\Gamma_{c.m.}$ or τ_m (keV)	Decay
0	$0^+; 0$		stable	
6.0494 ± 1.0	$0^+; 0$	0^+	$\tau_m = 96 \pm 7$ psec	π
6.9171 ± 0.6	$2^+; 0$	0^+	$\tau_m = 6.78 \pm 0.19$ fsec	γ
7.11685 ± 0.14	$1^-; 0$		$\tau_m = 12.0 \pm 0.7$ fsec	γ
8.8719 ± 0.5	$2^-; 0$		$\tau_m = 180 \pm 16$ fsec	γ, α
9.585 ± 11	$1^-; 0$	0^-	$\Gamma = 420 \pm 20$	γ, α
9.8445 ± 0.5	$2^+; 0$	2^+ [b]	0.625 ± 0.100	γ, α
10.356 ± 3	$4^+; 0$	0^+	26 ± 3	γ, α

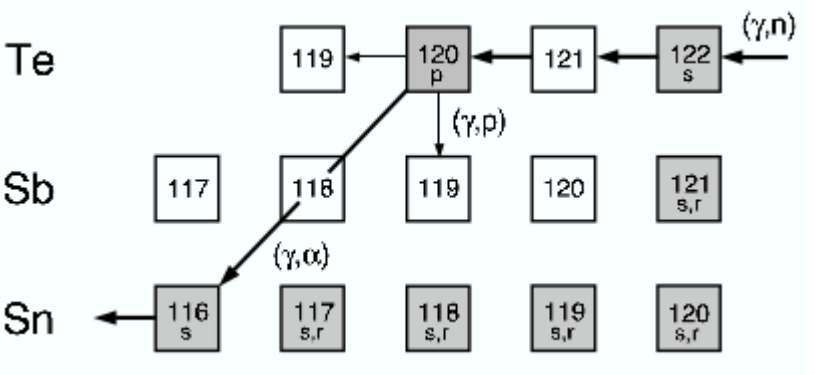
p-process

- proton-rich nuclei with A ≥ 74
- less abundant typically by factors of ten to one thousand than the other isotopes of the same element
- (p,γ) reactions inefficient
- s- and r-nuclei serve as seeds
- suggested to occur in type II supernovae, when the shock wave passes through the O–Ne-rich layer of a massive star @ T≈2–3GK

ELISSA for studying reactions on nuclei intervening in the p-process

^{74}Se, ^{78}Kr, ^{84}Sr, ^{92}Mo, ^{96}Ru, ..





Nuclear Physics