A GEANT4-based simulation of cosmic ray's background and secondary beams analysis for nuBDX-mini experiment

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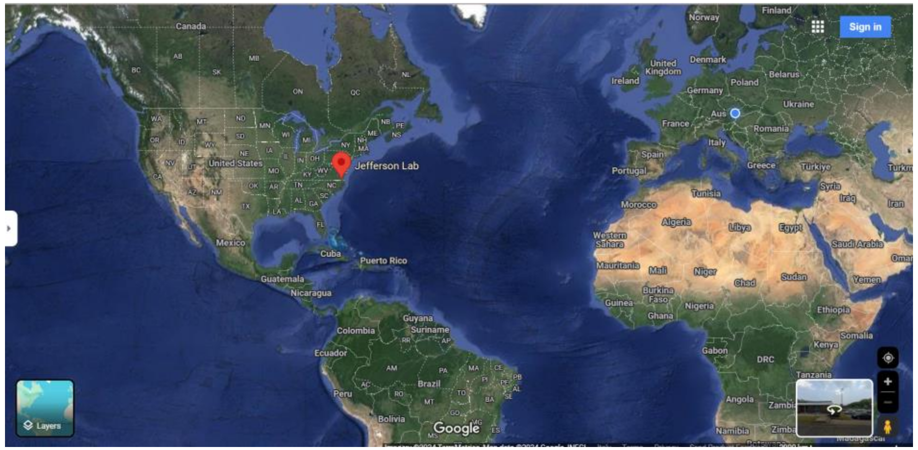
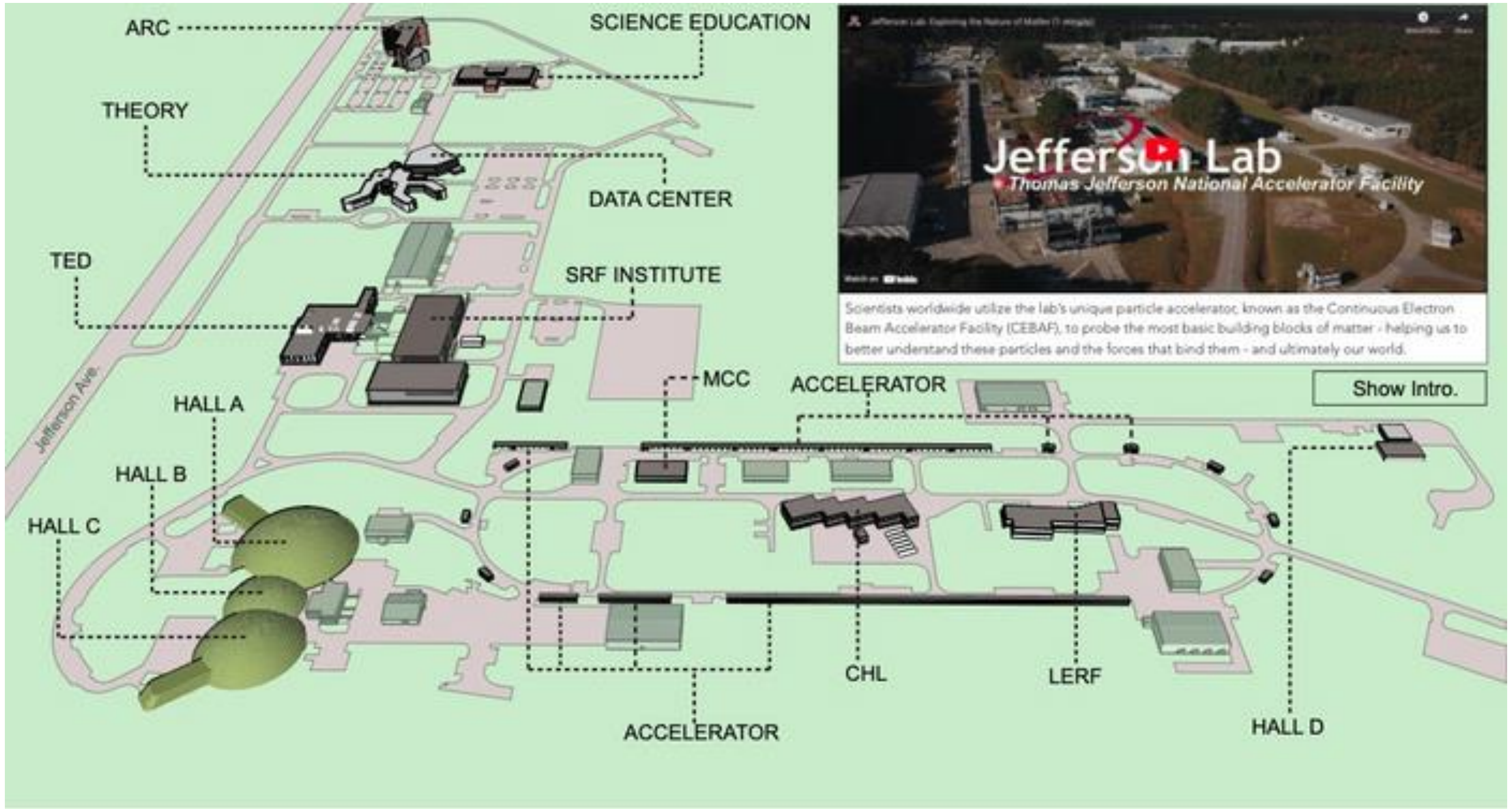
Jefferson Lab accelerator facility

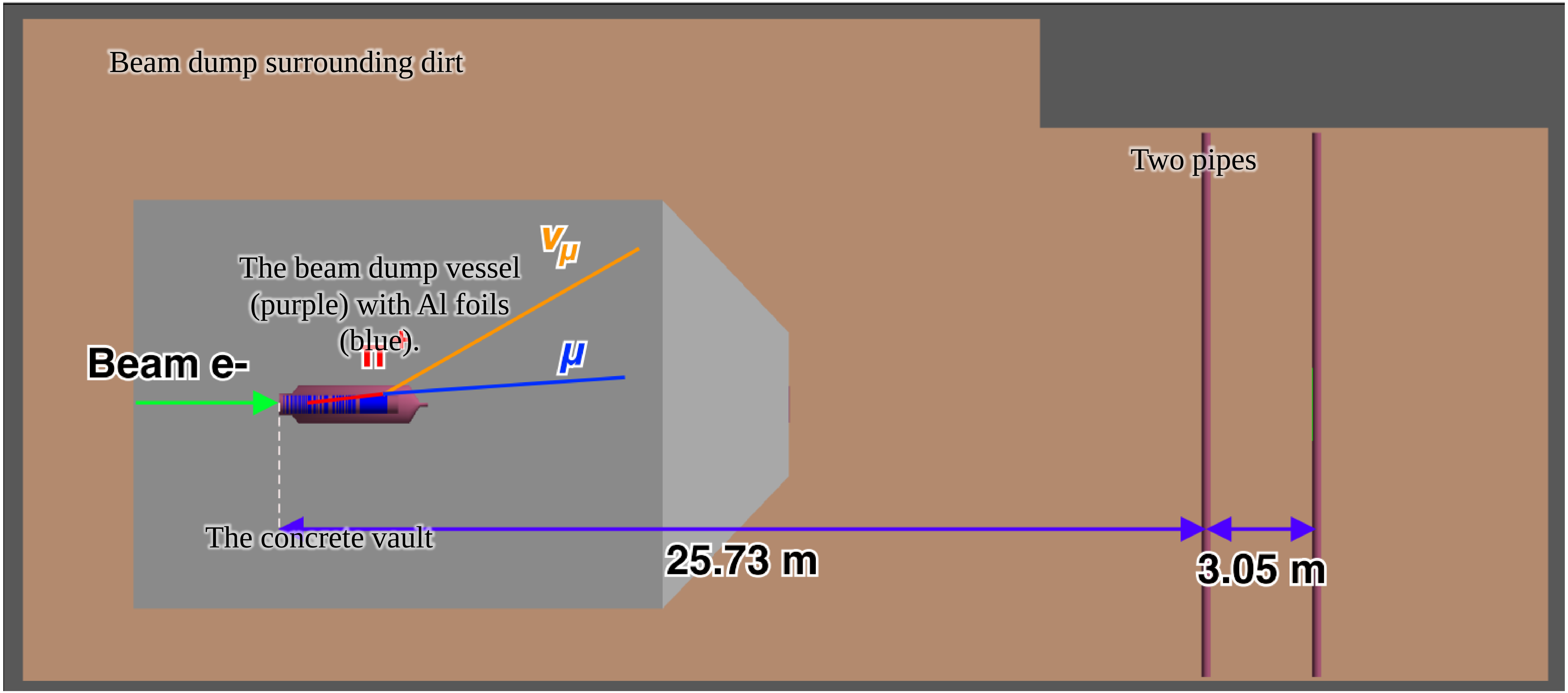
- Thomas Jefferson National Accelerator Facility is a U.S. Department of Energy Office of Science national laboratory. Scientists worldwide utilize the lab’s unique particle accelerator, known as the Continuous Electron Beam Accelerator Facility (CEBAF).
- Energy beam is up to 11 GeV (planning upgrade to 22 GeV)
- Current of 75 uA --> 10^{22} electron on target per year





Scientists worldwide utilize the lab's unique particle accelerator, known as the Continuous Electron Beam Accelerator Facility (CEBAF), to probe the most basic building blocks of matter - helping us to better understand these particles and the forces that bind them - and ultimately our world.

GEMC application: secondary beams analysis



Beam dump geometry implemented in GEMC

Secondary neutrino beam

- Fission reactors and proton accelerators are currently the main source of neutrino beams. The reactors produce electron-type antineutrinos from fission fragment beta decay and are widely used in low-energy (~MeV) experiments. In accelerators, high-energy protons hit a target to generate short-lived hadrons (mainly π± and K ±) that successively either decay in flight (DIF) or decay at rest (DAR) into neutrinos. DAR neutrinos, mainly produced by spallation neutron sources [35], show an isotropic spatial distribution with an energy spectrum depending on the decay:
  - $\pi^+ \longrightarrow \mu^+ + \nu_\mu$
    $E_\nu \sim 29.8$ MeV,
    almost monochromatic;
  - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
    E_ν in the range 0–52.8 MeV;
  - $K+ \longrightarrow \mu^+ + \nu_\mu$
    $E_\nu \sim 236$ MeV,
    almost monochromatic.
  - DAR neutrinos can be used to studying coherent elastic neutrino-nucleus scattering (CEvNS). This process, predicted a long time ago, has been only recently observed and is a leading candidate for the study of non-standard (BSM) neutrino interactions

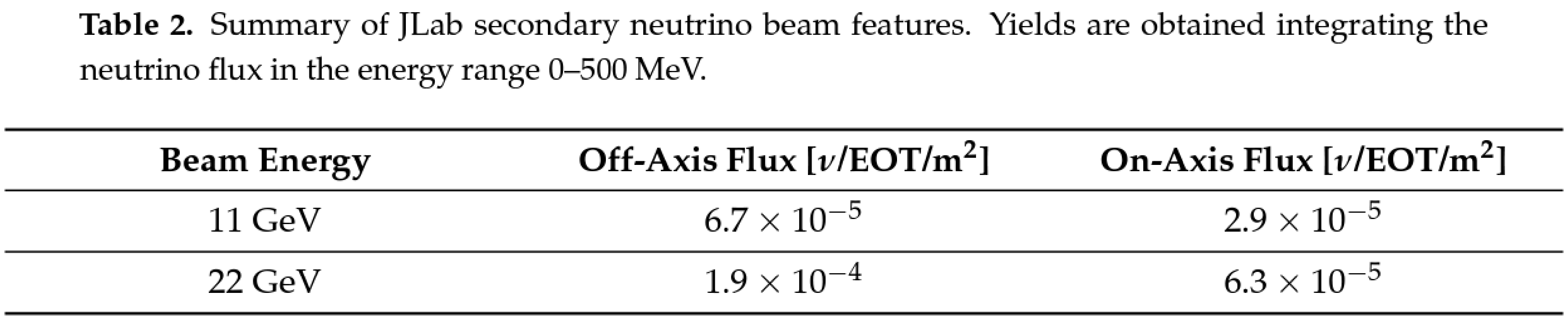
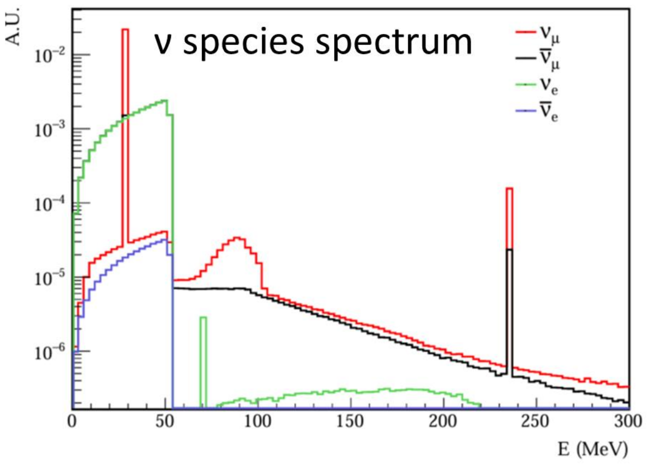
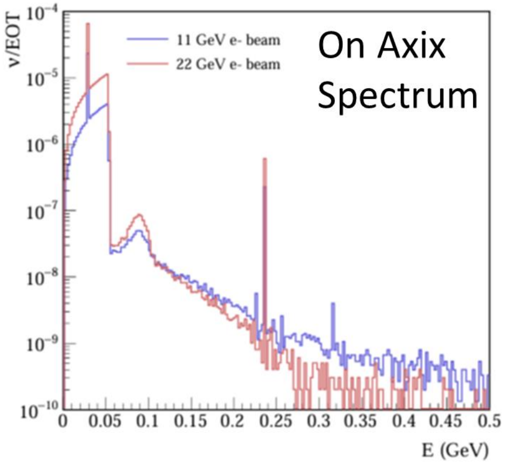
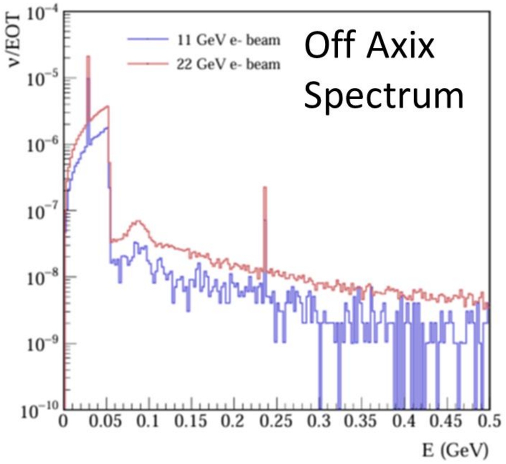


Table 2. Summary of JLab secondary neutrino beam features. Yields are obtained integrating the neutrino flux in the energy range 0–500 MeV.

Beam Energy	Off-Axis Flux [ν/EOT/m^2]	On-Axis Flux [ν/EOT/m^2]
11 GeV	6.7×10^{-5}	2.9×10^{-5}
22 GeV	1.9×10^{-4}	6.3×10^{-5}







GEMC (GEant4 Monte Carlo)

What is gemc?

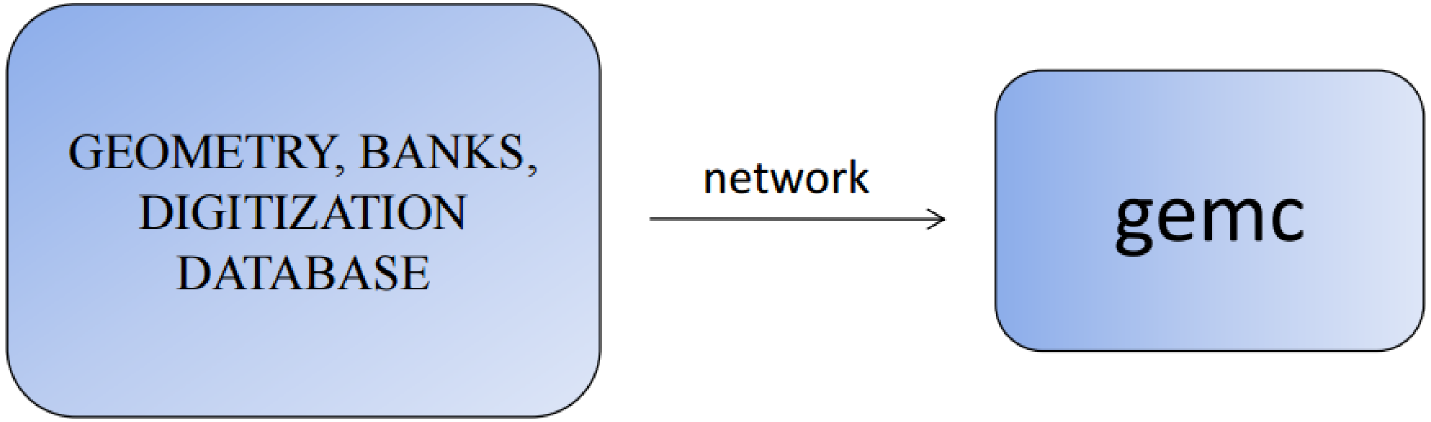
Gemc is a C++ program that simulates particles through matter using the GEANT4 libraries.

Gemc reads as “input”:

Geometry
Materials
Magnetic fields
Hit process, digitalization routines
Bank definitions
Input/output formats

$\left\{ \right.$ *stored in external database*
can be "plugged in" *without*:
knowing geant4 or C++
touching the code
recompiling (*i.e.* only geometry file))

Gemc can import models from CAD and GDML

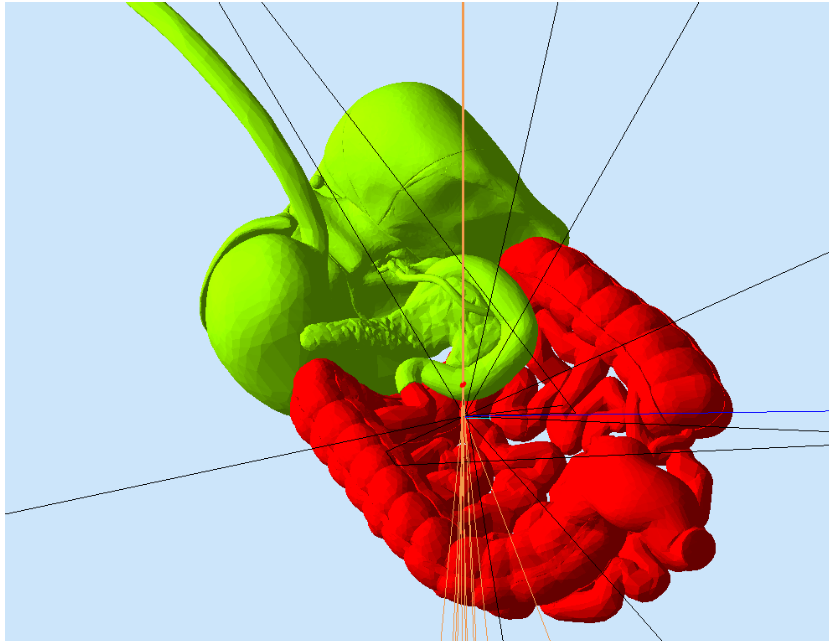


GEOMETRY, BANKS, DIGITIZATION DATABASE

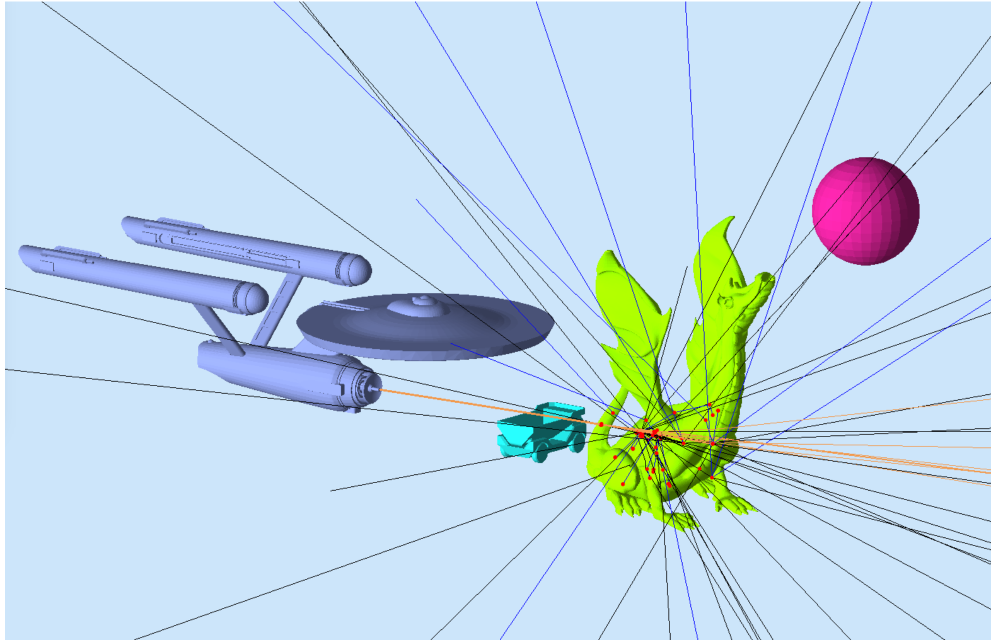
network

gemc

Users can build or import from cad complex setups with minimal programming knowledge



The upper gastrointestinal system is modelled in CAD. It can be imported in GEMC and made it sensitive so that radiation doses can be measured.



The mighty USS Enterprise NCC 1701-A (CAD) can be used to shoot protons torpedos at a dragon (CAD) while a GDML sphere is watching.

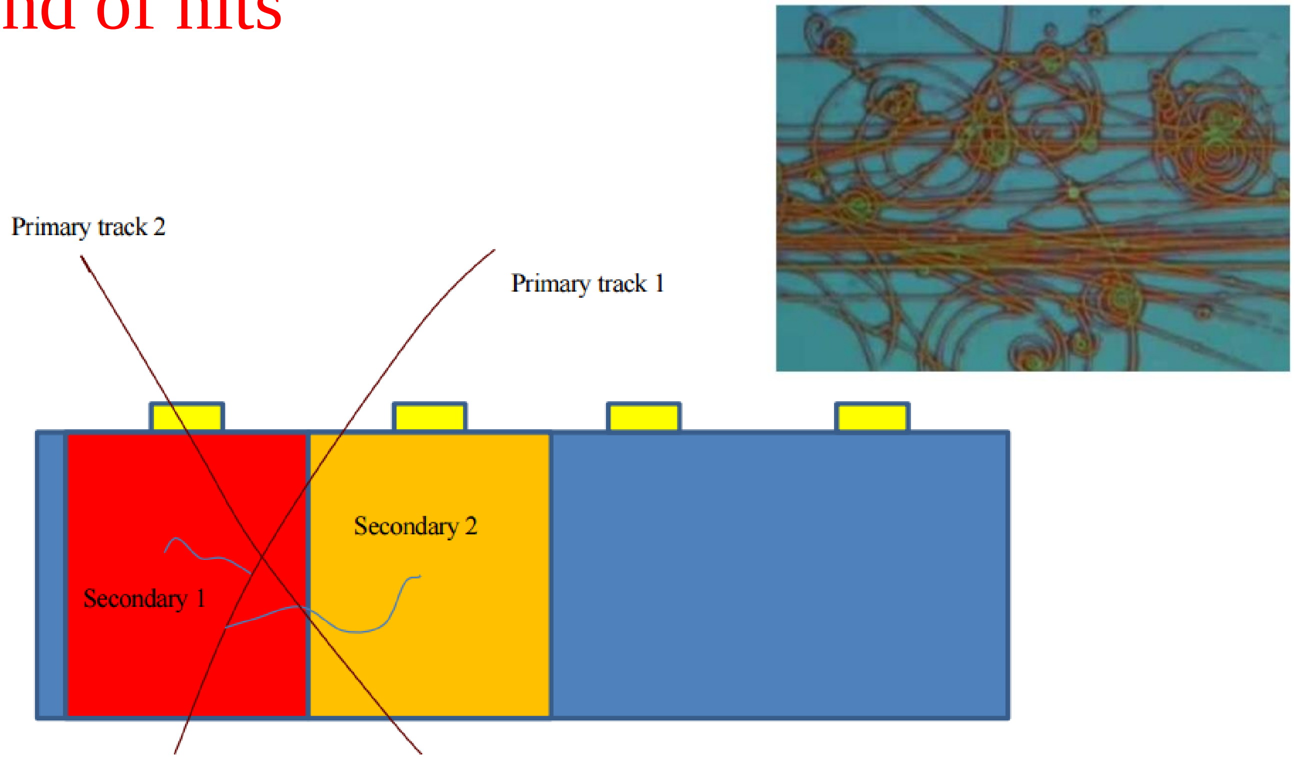
Hit types Databases

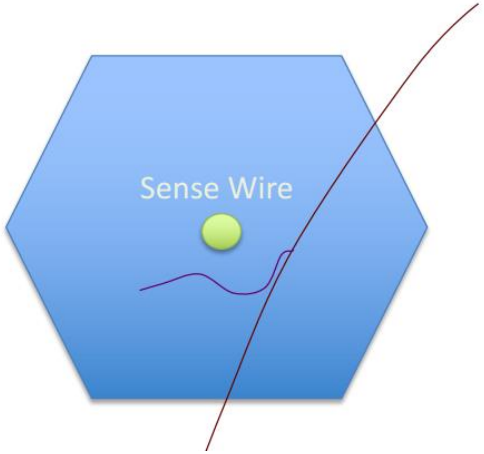
3 kind of hits

1. “Flux” type: every track has its own hit. useful for counting purposes (i.e. how many protons pass through the detector, etc.)

2. Time Window ADC: all hits (separate tracks too) in the same time window for a particular detector will be added to a single hit

3. Time Window TDC: the first signal within the detector time window will give the TDC



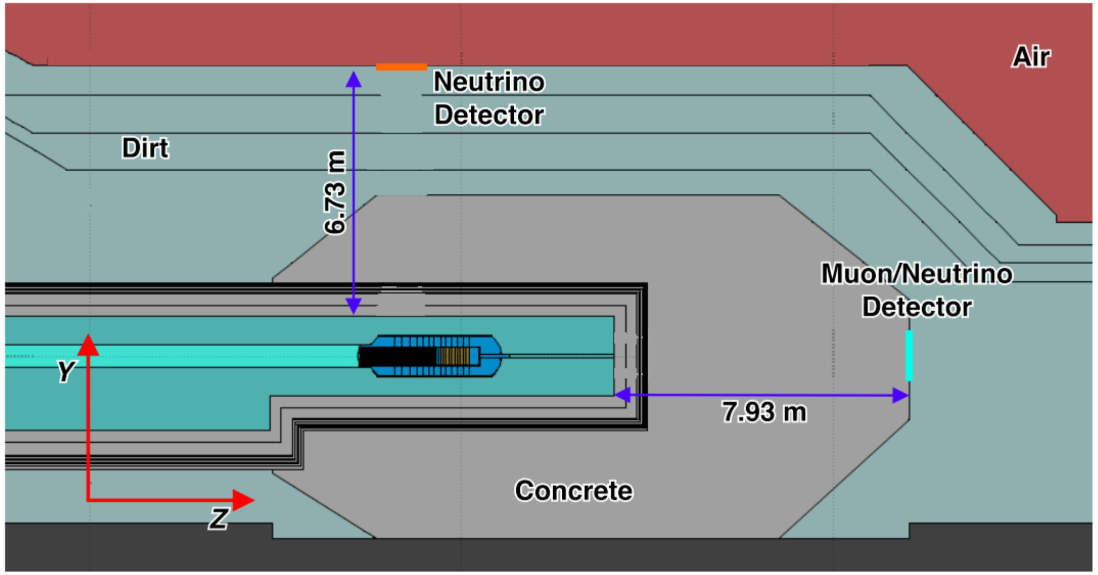


GEMC application: secondary beams analysis

FLUKA was used to simulate the interaction of the primary electron beam with the Hall-A beam dump and the propagation of muons and neutrinos through concrete and dirt to reach a hypothetical downstream detector.

The input parameters used to run the program include all physics processes and a tuned set of biasing weights. As a reference, we considered a run time of one-year corresponding to $\sim 10^{22}$ EOT.

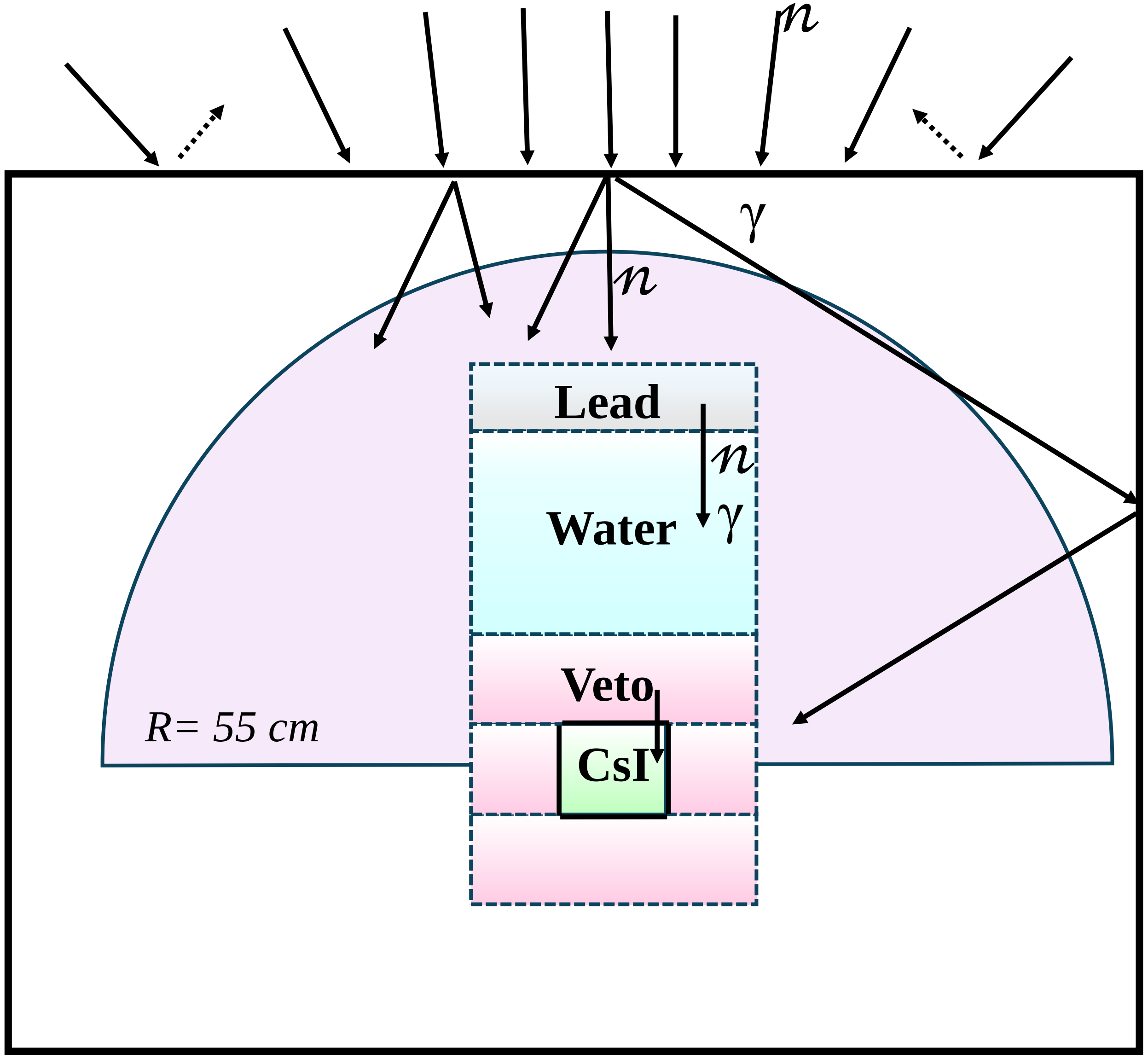
Final beam features obtained with FLUKA simulations (particle ID, vertex and momentum) were fed to GEMC.



Cross section of the Jlab Hall-A beam dump geometry with the two flux-detectors used in the simulations to evaluate the flux of secondary particles. A hypothetical neutrino detector (orange) located perpendicular to the beam dump. Aluminium disks of beam dump inner core are shown in yellow. A muon / neutrino detector (light blue) located just after concrete vault downstream of the beam dump.

Gemc application. Cosmic rays' radiation

Energy range	$^{neutrons}/_{cm^2 s}$	$^{neutrons}/_{m^2 day}$	*neutrons generated*
1 meV-1 eV	$2 \cdot 10^{-3}$	$1{,}64 \cdot 10^{6}$	$2 \cdot 10^{6}$
1 eV- 1keV	$1{,}43 \cdot 10^{-2}$	$1{,}17 \cdot 10^{7}$	$2 \cdot 10^{7}$
1keV-1MeV	$1{,}43 \cdot 10^{-2}$	$1{,}17 \cdot 10^{7}$	$2 \cdot 10^{7}$
1-2 MeV	$1{,}43 \cdot 10^{-3}$	$1{,}18 \cdot 10^{6}$	$2 \cdot 10^{6}$
2MeV- 100MeV	$3{,}06 \cdot 10^{-3}$	$2{,}51 \cdot 10^{6}$	$3 \cdot 10^{6}$
100-1000MeV	$1{,}54 \cdot 10^{-3}$	$1{,}27 \cdot 10^{6}$	$2 \cdot 10^{6}$
1GeV-10GeV	$7{,}8 \cdot 10^{-5}$	$6{,}4 \cdot 10^{4}$	$7 \cdot 10^{4}$
Total	$3{,}67 \cdot 10^{-2}$	$3{,}01 \cdot 10^{7}$	$5 \cdot 10^{7}$



Calculate hits from cosmic neutrons not distinguishable from neutrinos.

Conditions: E_{dep}= 10-200 keV

Coincidence between veto and crystal more than 5 µs

Tasks:

Reduce the number of nonremovable hits

Minimize the thickness of layers (with preference to active shielding)

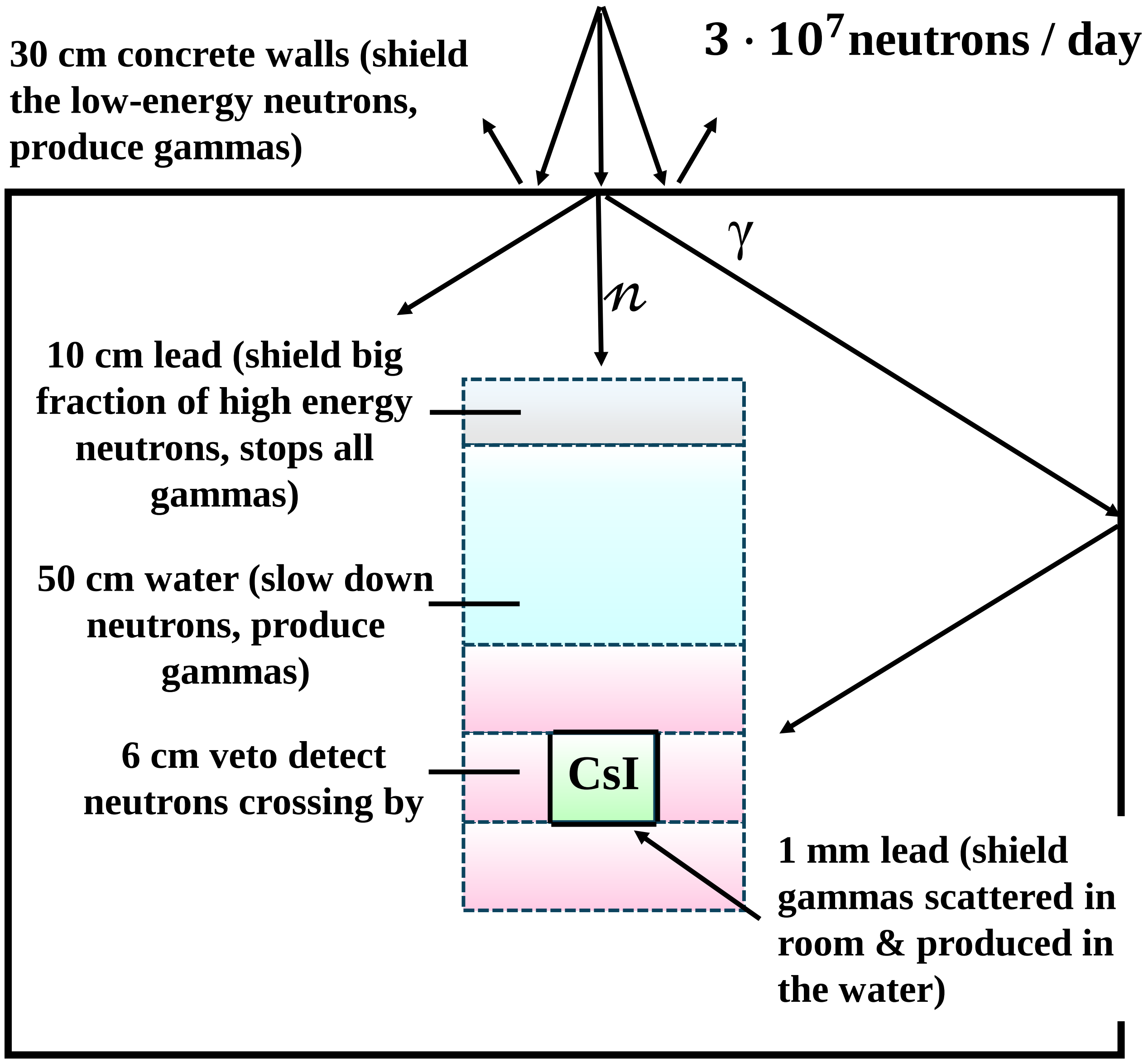
Shielding design

thr 1 MeV	Neutron single hit in crystal	Gamma single hit in crystal	Neutrons outside 5 μs coincidence	Gammas outside 5 μs coincidence	**hits not removable expected in a day**
1cm Pb	1832	37	420	89	**1510**
1cm Al	1816	38	401	92	**1493**
10cmLead 50cmWater	832	166	165	98	**804**
50cmWater 10cmLead	1042	364	30	41	**708**

1 cm of lead (aluminium etc.) around crystal shields almost all gammas but increase neutron number.

Composition	Total hits not removable in a day
6cm Veto 50 cm water 10 cm lead	1722
6cm Veto 50 cm water 5 cm lead	1832
1mm lead, 6cm Veto, 5cm lead 50cm water	936
1 mm lead 6cm Veto 55 cm lead	490

1 mm of lead around crystal works well for shielding gammas and not producing neutrons.
The minimum of not removable hits for now is 490 / day



$3 \cdot 10^7$ neutrons / day

30 cm concrete walls (shield the low-energy neutrons, produce gammas)

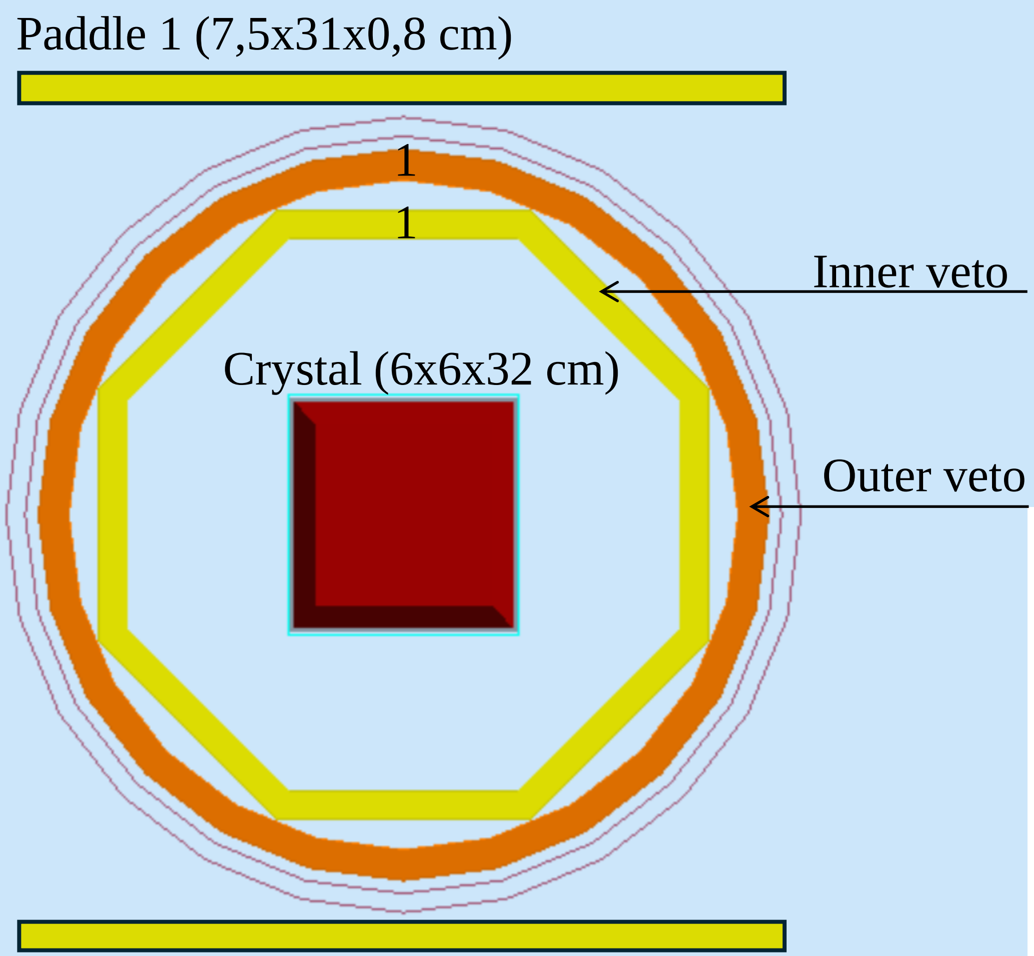
10 cm lead (shield big fraction of high energy neutrons, stops all gammas)

50 cm water (slow down neutrons, produce gammas)

6 cm veto detect neutrons crossing by

1 mm lead (shield gammas scattered in room & produced in the water)

Preparation for the experiment

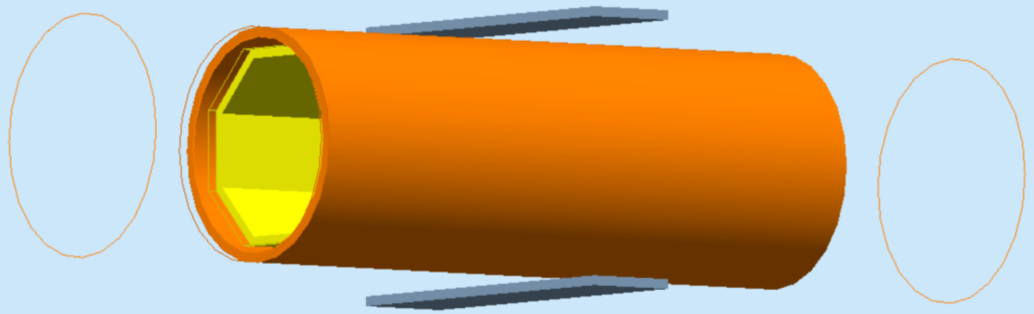


Paddle 1 (7,5x31x0,8 cm)

Inner veto

Crystal (6x6x32 cm)

Outer veto



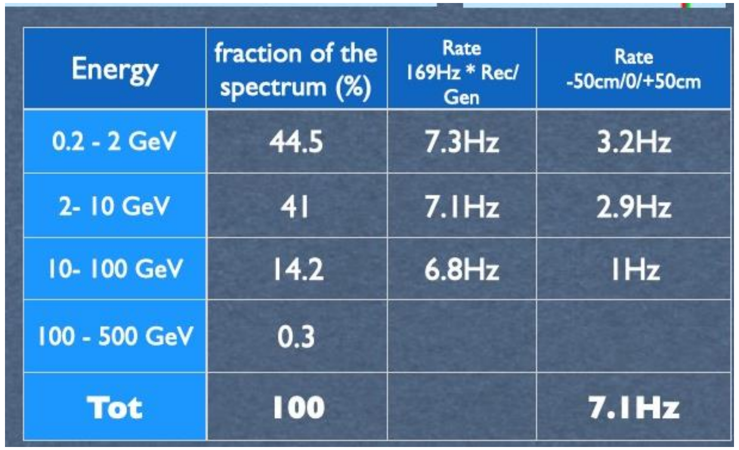
Muon rates for crystal and paddle

Energy ranges	Events generated	Fraction of the spectrum, %	Flux, $1/cm^2 \cdot s$	Events detected in paddle	Events detected in crystal	Rate in paddle, 1/s	Rate in crystal, 1/s
200MeV-2Gev	9,02E+06	44,5	0,4717	132270	139.264	1,530	1,61
2GeV-10GeV	8,31E+06	41	0,4346	119910	132.446	1,387	1,53
10-100 GeV	2,88E+06	14,2	0,15052	37744	45314	0,436	0,52
100-500 GeV	6,08E+04	0,4	0,00318	621	905	0,007	0,001
Total	**2,03E+07**	**100**	**1,06**	**290’545**	**317’929**	**3,36**	**3,58**

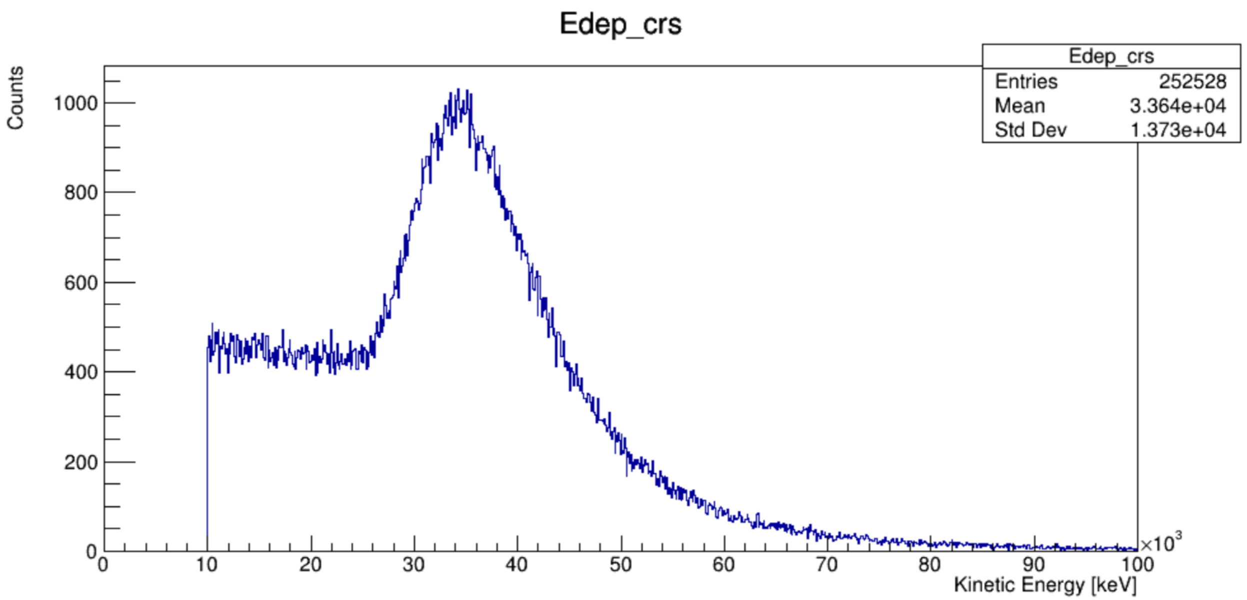
$$Theoretical\ rate = \frac{1,06}{60}\,[muons/s\,cm^2] \cdot surface[cm^2]$$

Theoretical rate	
Crystal	**3,4**
Single paddle	**4,1**

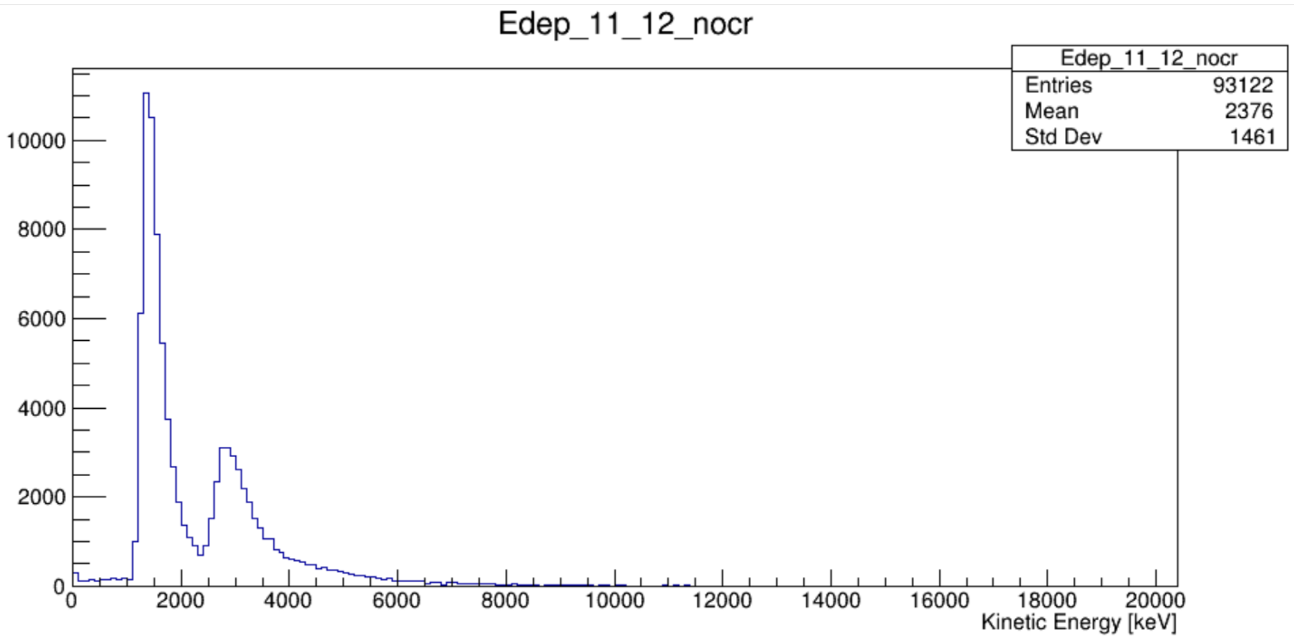
- *Flux · cosmic surface = 234,49 Hz*
- *Muon flux = 1,06 muons/min cm^2*
- *Crystal surface = 32*6 = 192 cm^2*
- *Paddle surface = 31*7,5 = 232,5 cm^2*



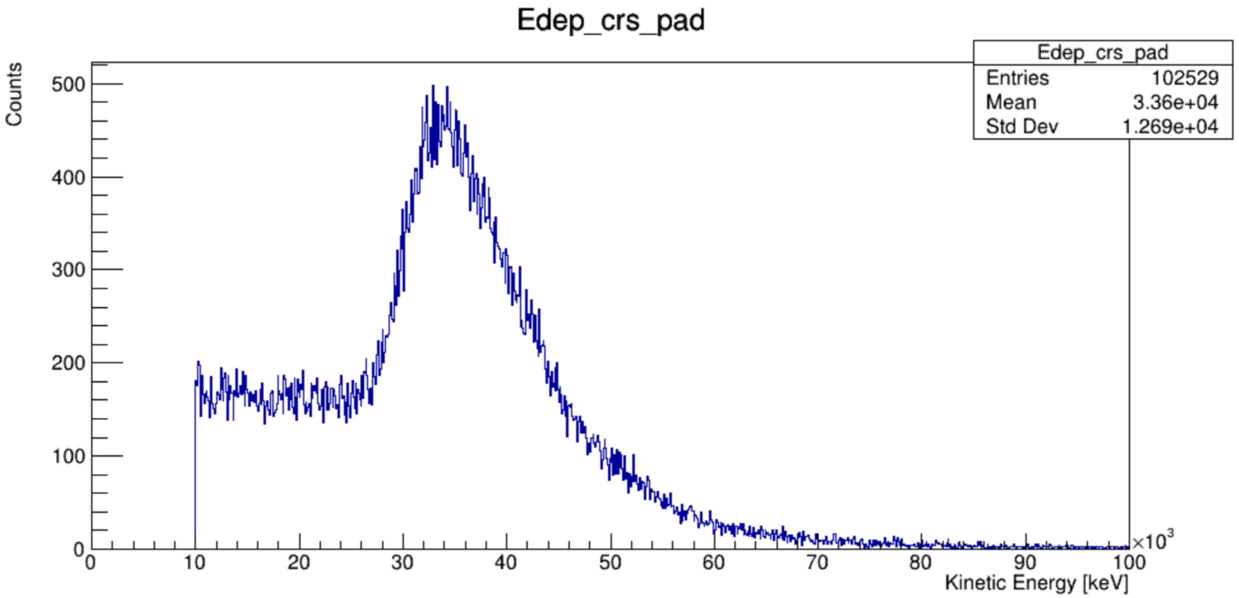
Energy	fraction of the spectrum (%)	Rate 169Hz * Rec/ Gen	Rate -50cm/0/+50cm
0.2 - 2 GeV	44.5	7.3Hz	3.2Hz
2- 10 GeV	41	7.1Hz	2.9Hz
10- 100 GeV	14.2	6.8Hz	1Hz
100 - 500 GeV	0.3		
Tot	**100**		**7.1Hz**



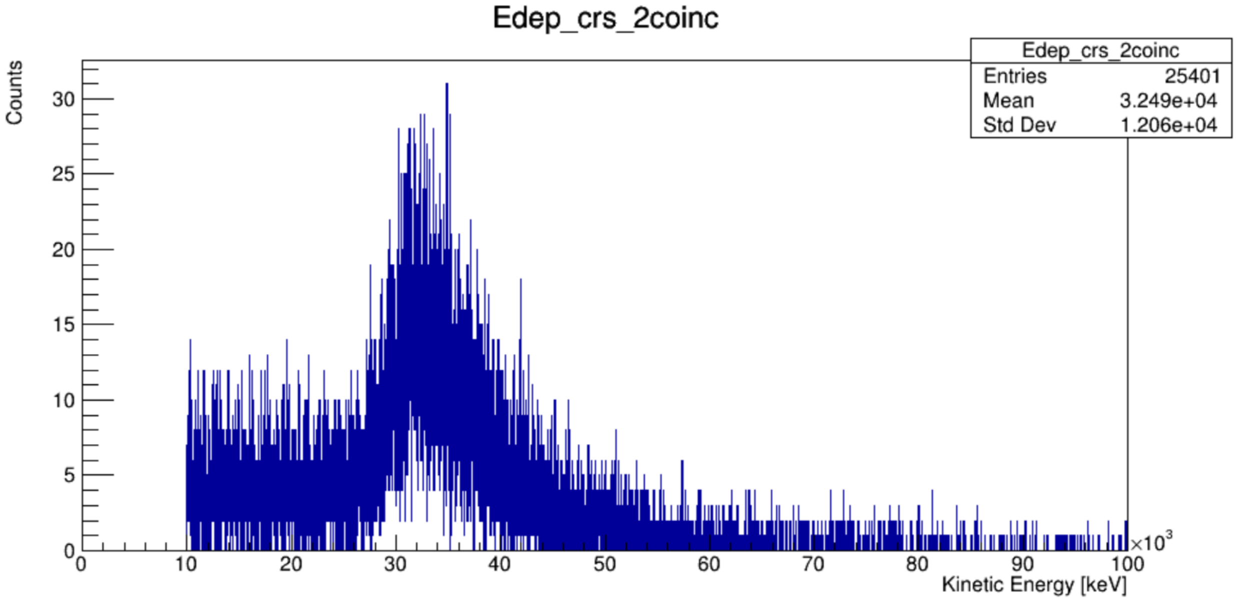
Energy deposited in crystal



Energy deposited for both paddles in coincidence

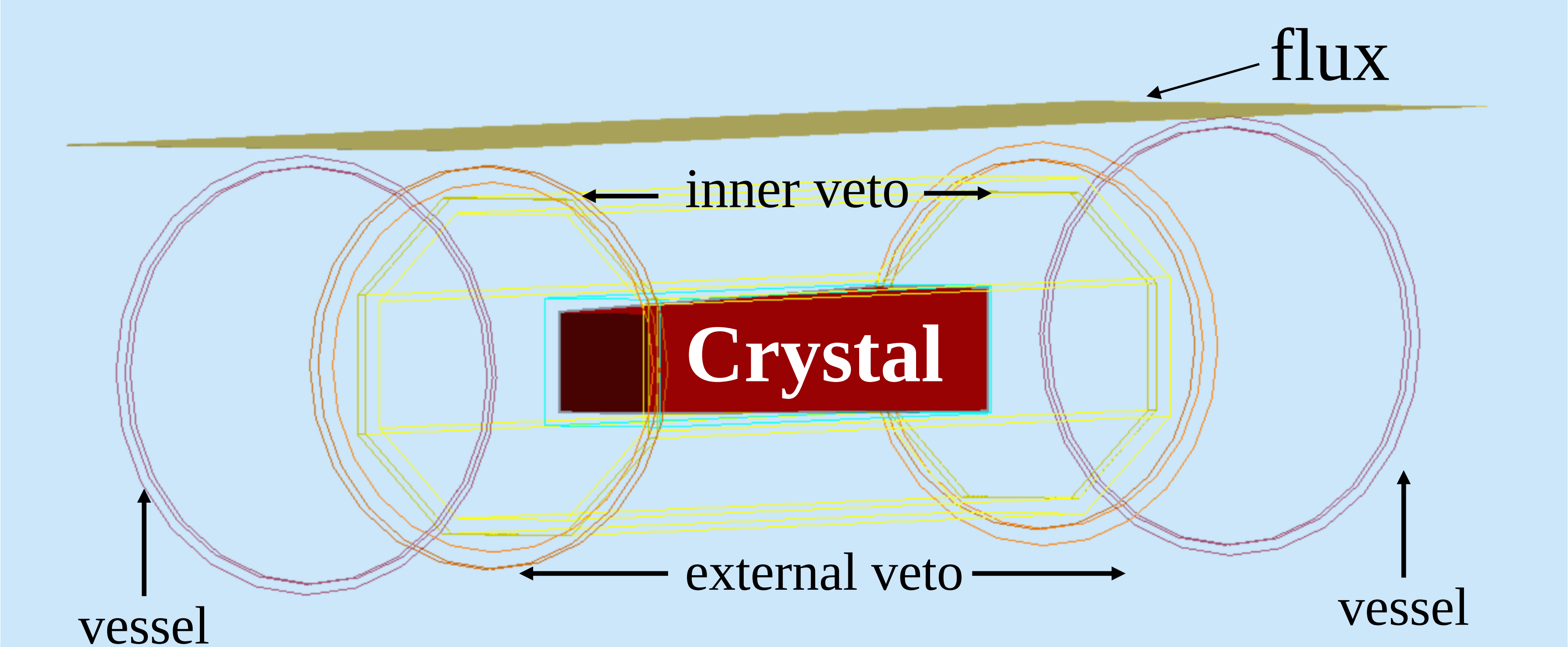


Energy deposited for crystal and one paddle in coincidence



Energy deposited for both paddles and crystal in coincidence

Preparation for the experiment


flux

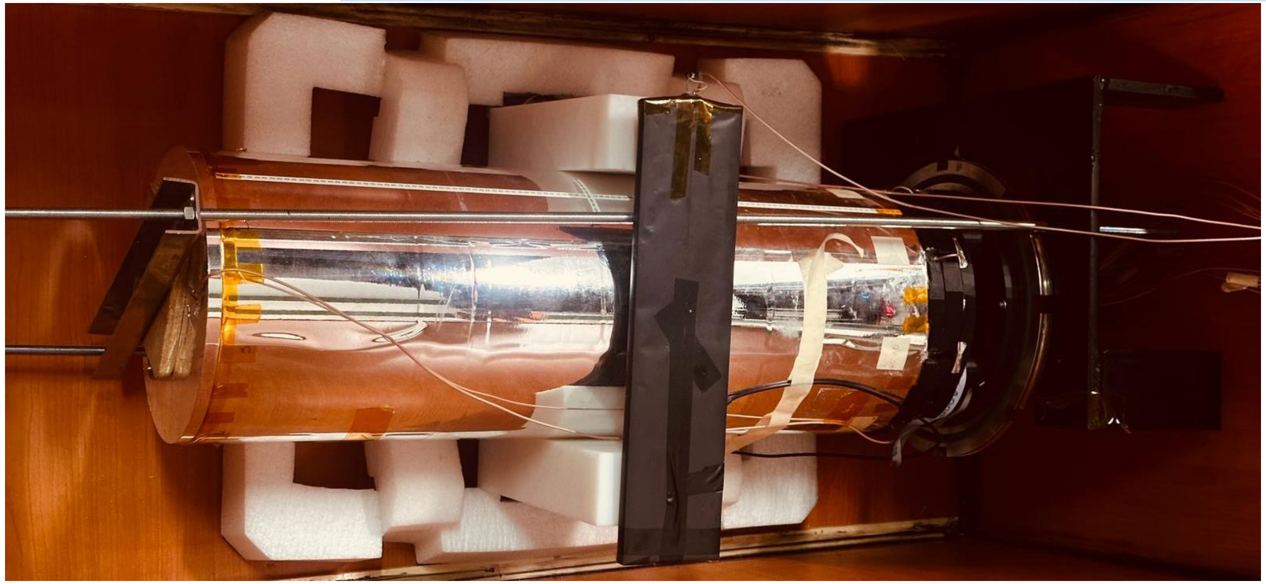
inner veto

Crystal

external veto

vessel

vessel



Conclusions

- **Gemc as a Geant4 framework can be used for detail experiment description.**
- **It has full geant4 capabilities**
- **Easy intuitive interface**
- **Application in high-intensity beam experiments as well as cosmic radiation shielding design**

Thank you for attention