Preliminary Results

Matteo Palermo

Sino-German GDT Cooperation Symposium 2015, Ringberg Castle

On behalf of the GeDet group
Max-Planck-Institut für Physik, München

Outline

- **Why MINIDEX**
- Preliminary studies
- Setup description and installation
- Analysis and (preliminary) results
- Future upgrades
- Summary & Outlook

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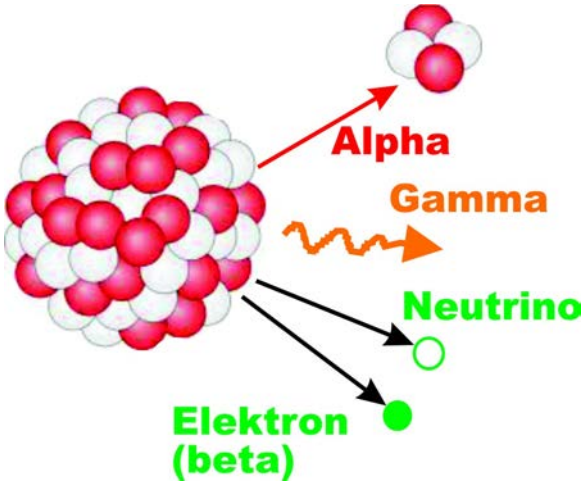
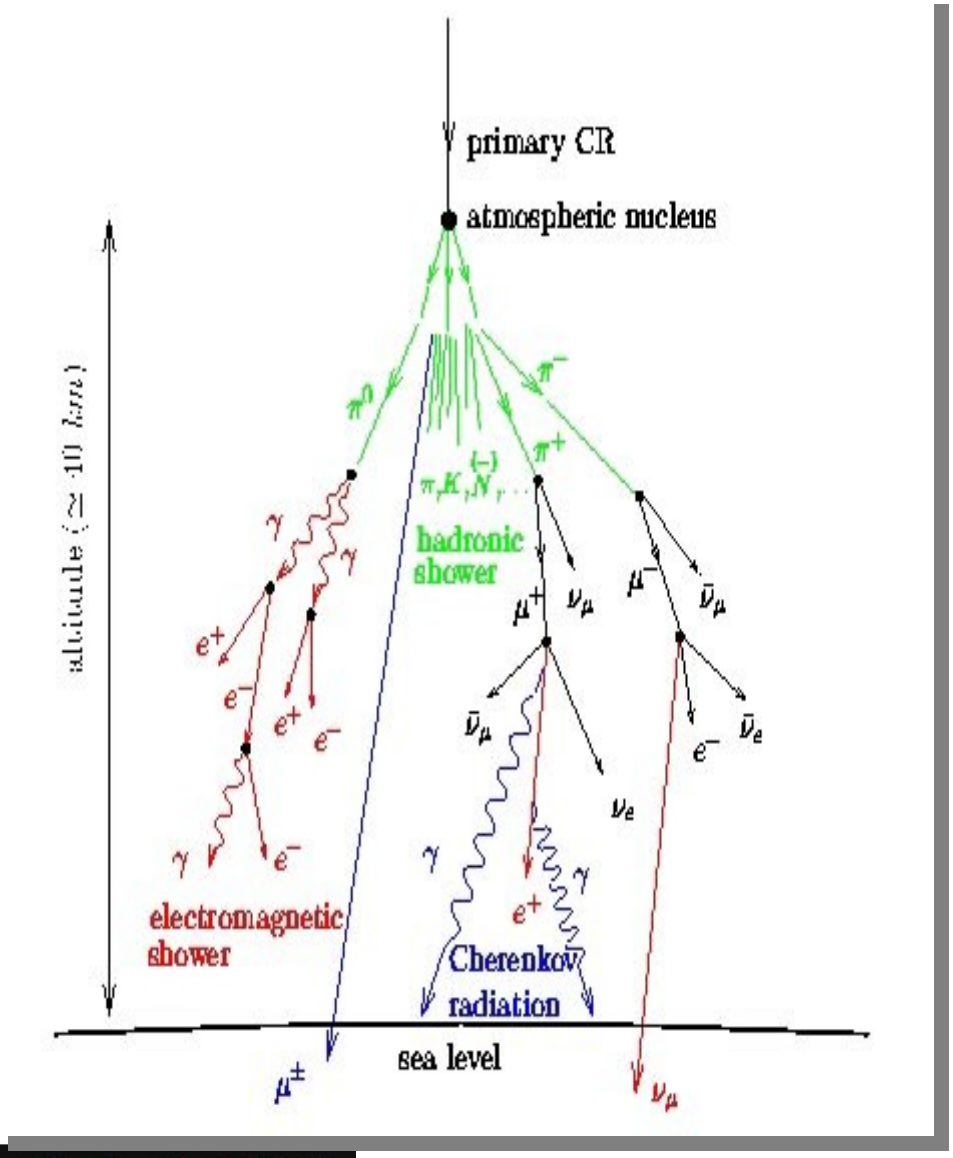
Why Muon-Induced?

- **Three different sources:**
  - Intrinsic detector radioactivity
  - Environmental Natural radioactivity
  - Cosmic Rays-induced showers (μ and ν-induced)



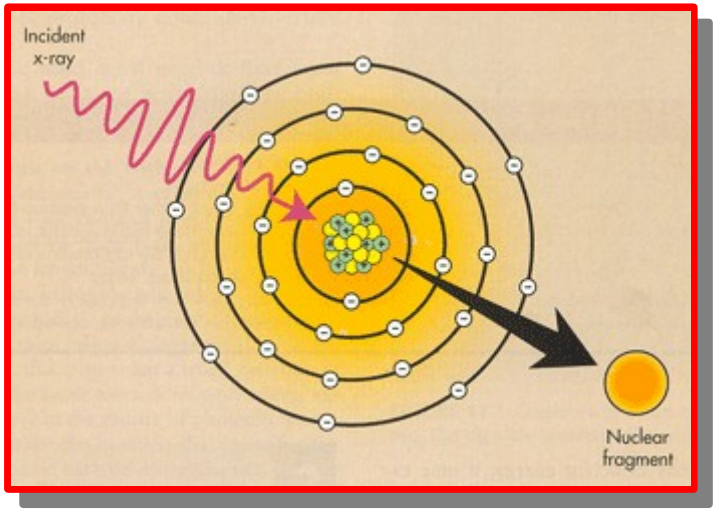
- **Two different components:**
  - Charged → easy to veto
  - Neutral → high shielding power is required (neutron, gammas)

Cosmic Rays Shower



Production mechanism:

- **Photodisintegration**

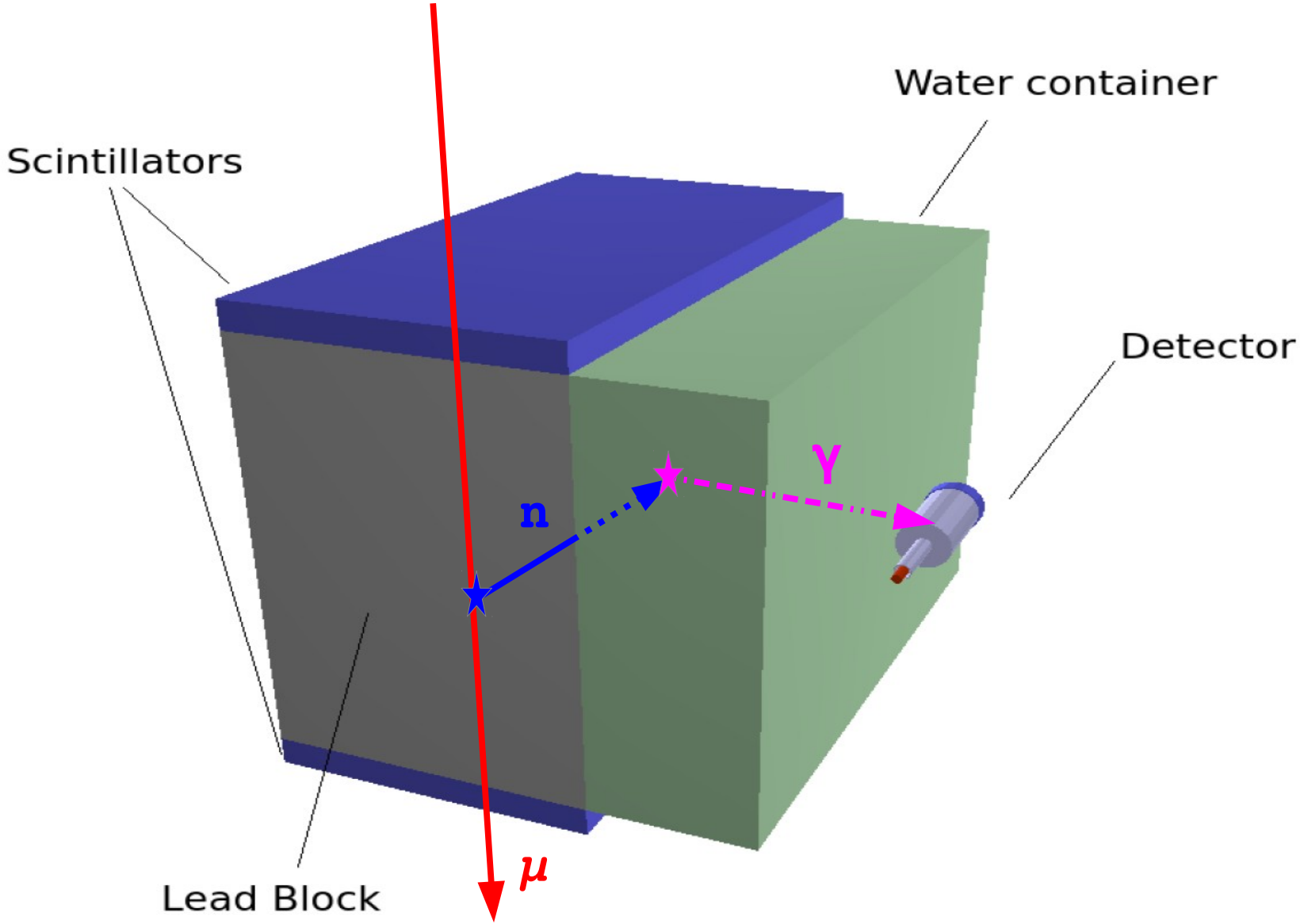


Why MINIDEX?

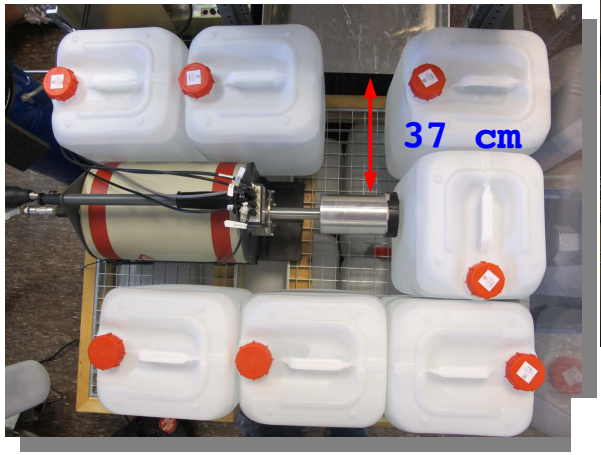
Perform a measurement to test the reliability of our Monte Carlo (MaGe)

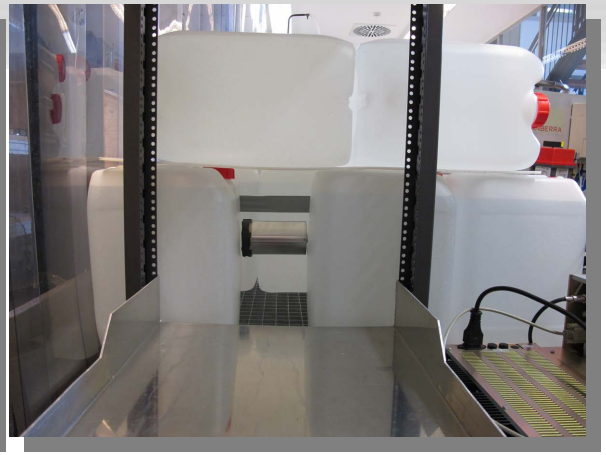
- **Neutrons production (μ-induced)**
- **Neutrons transportation**
- **Thermal capture** (in this case)
- **...**

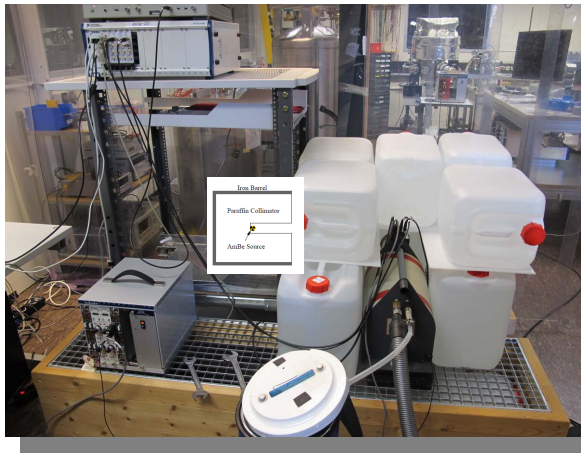
A Simple Setup: the working principle

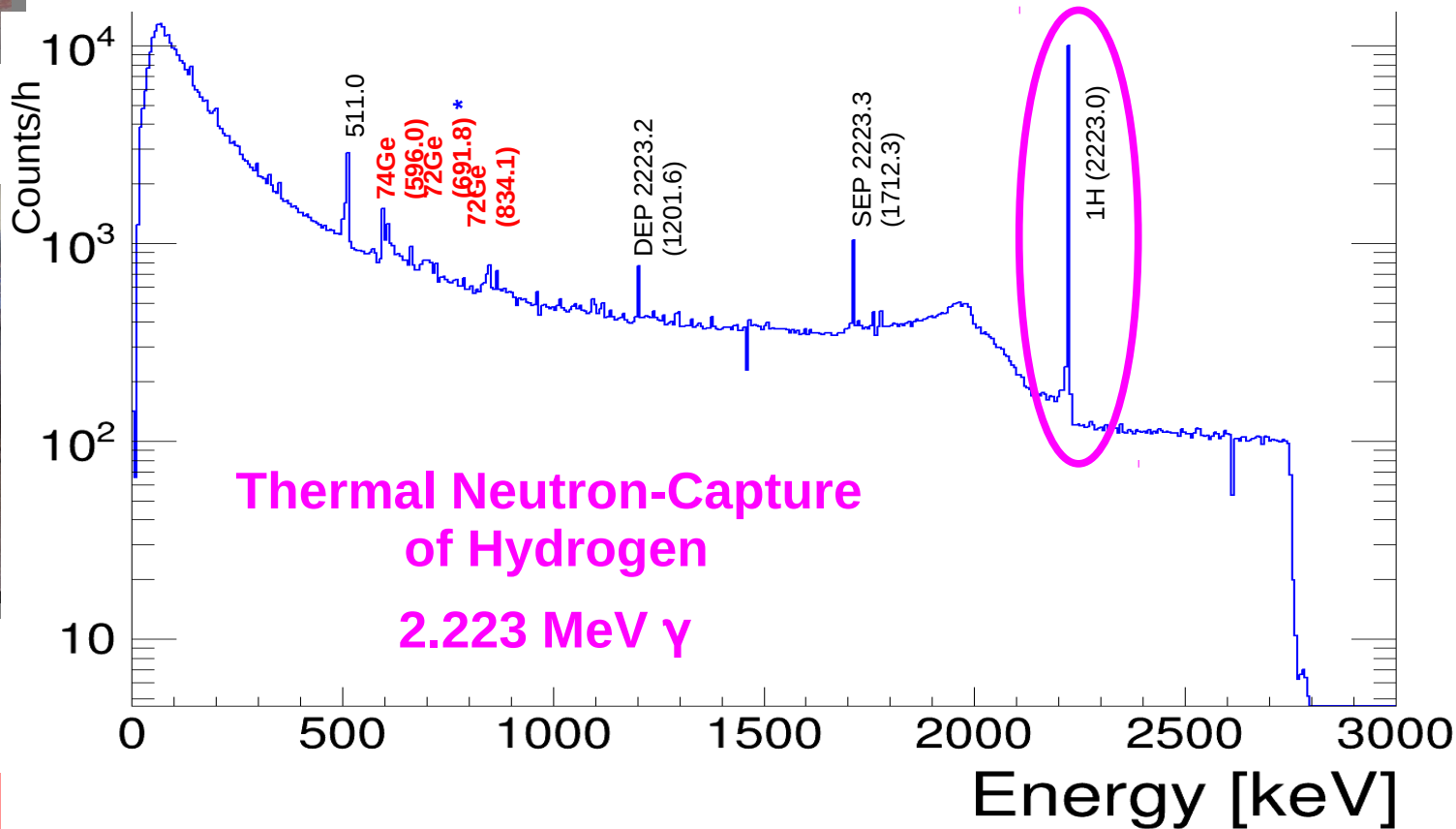


Why neutron-gamma conversion?









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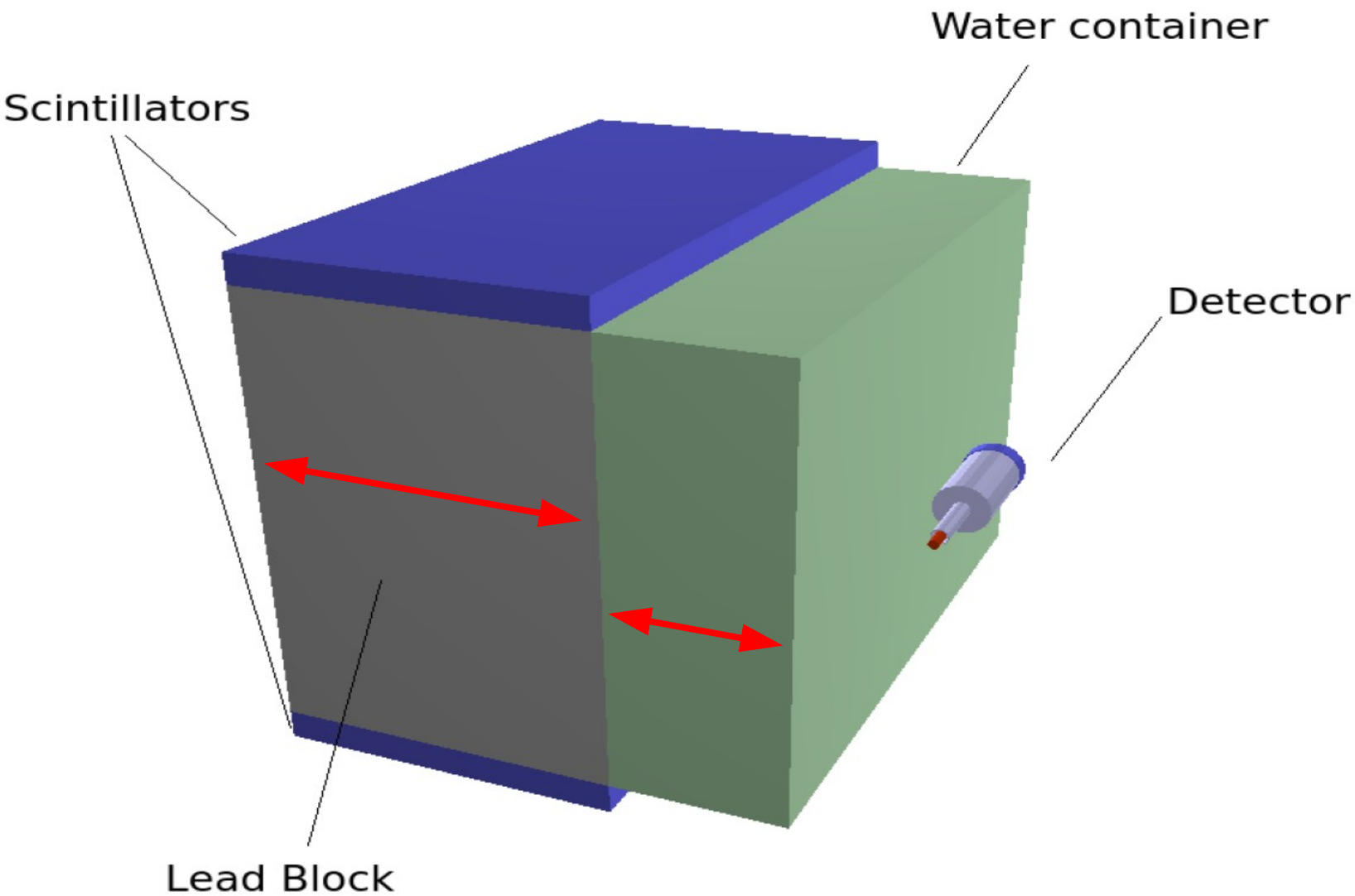
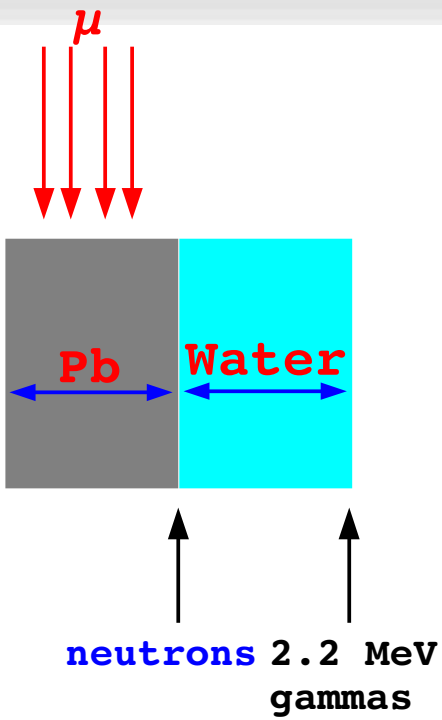
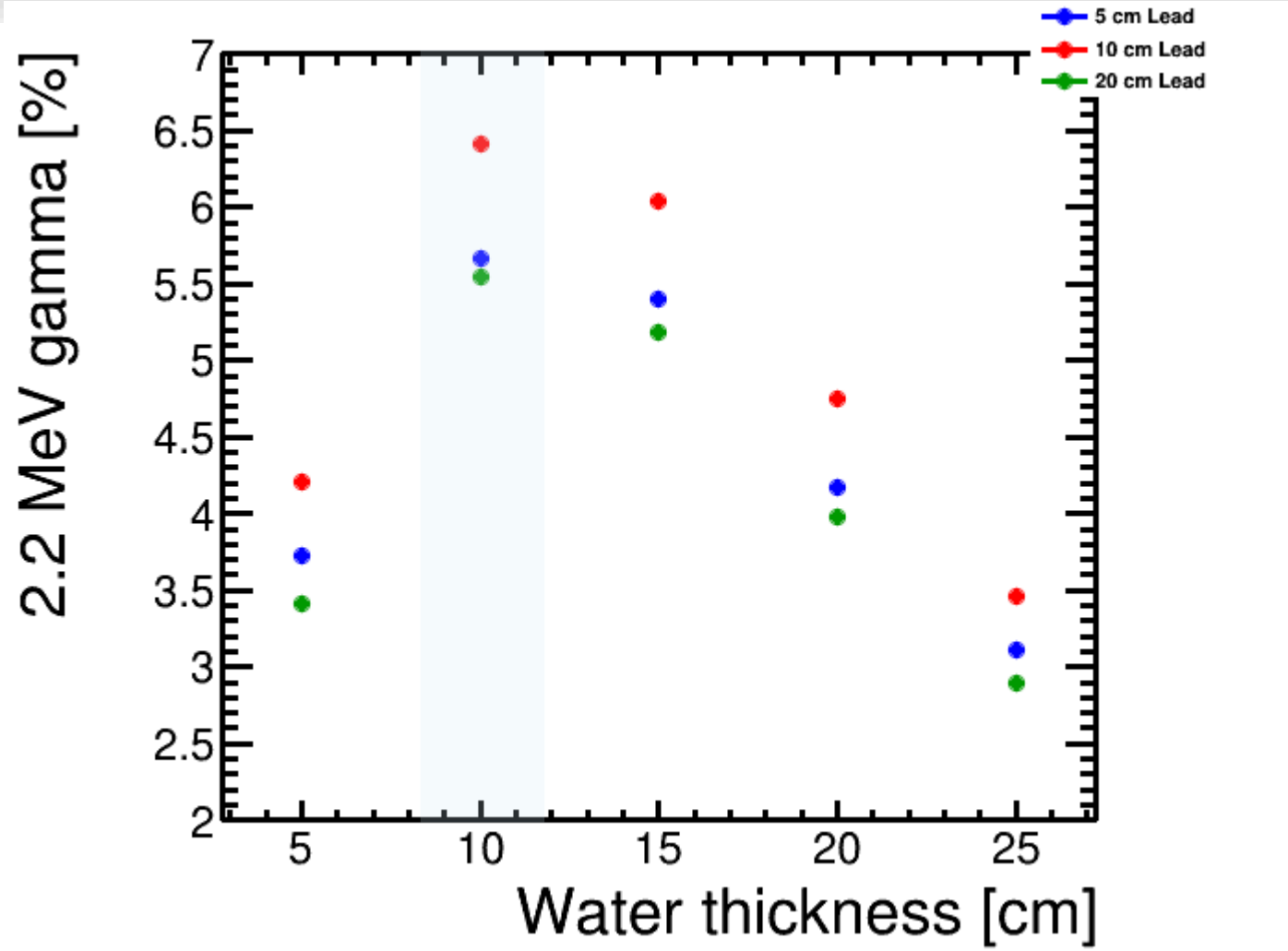
Lead and Water Sizes Optimization



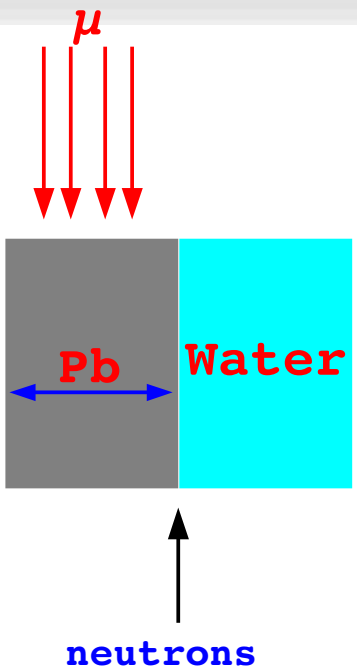
Water Thickness Optimization

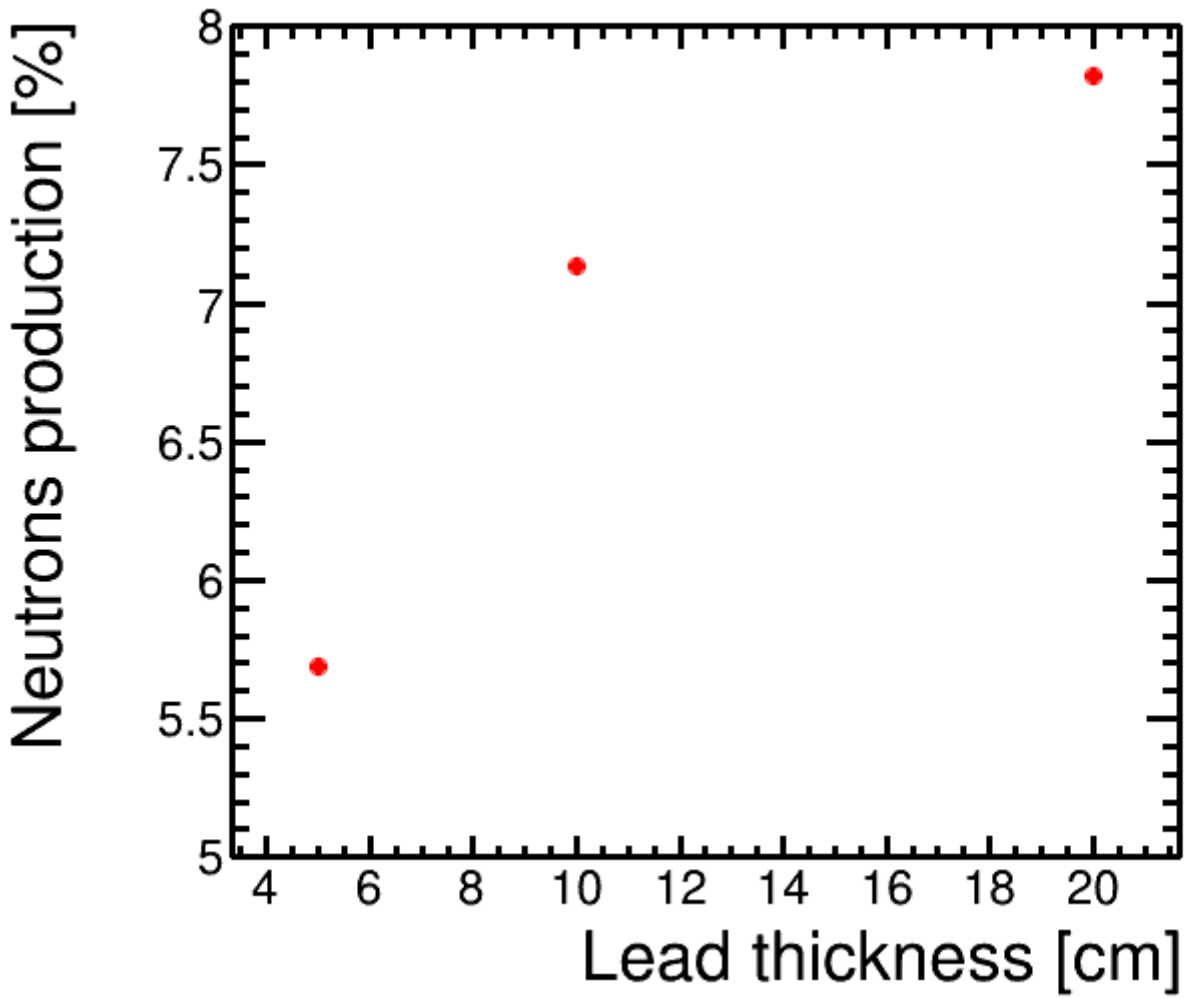




10 cm of Water is best in terms of 2.2 MeV gamma production

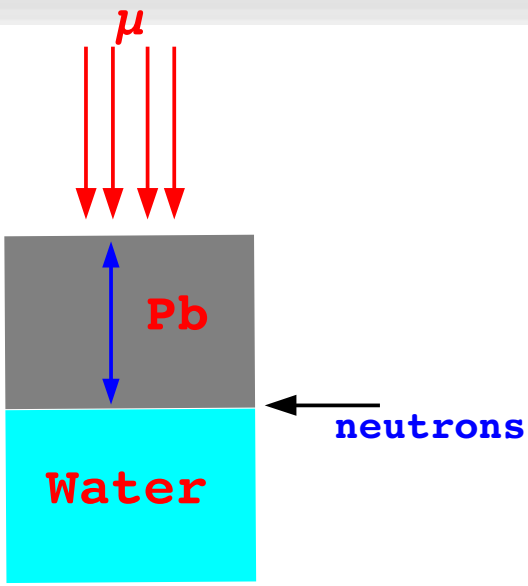
Lateral Lead Thickness Optimization

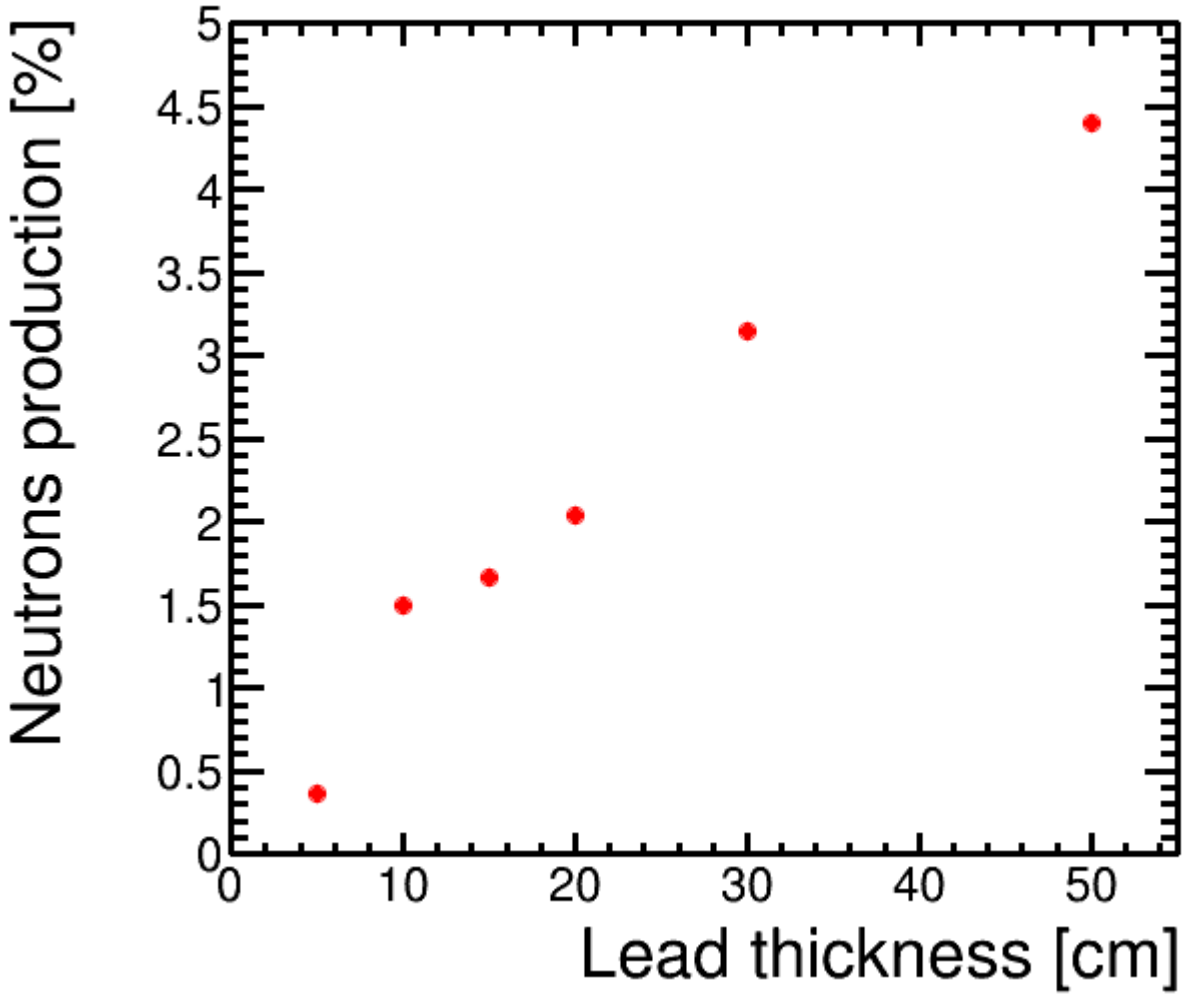




As expected, the more Lead the better

Top Lead Thickness Optimization





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MINIDEX: Equipment

- **Two Pulse-Tube Extended Range HP Germanium detectors (Canberra)**

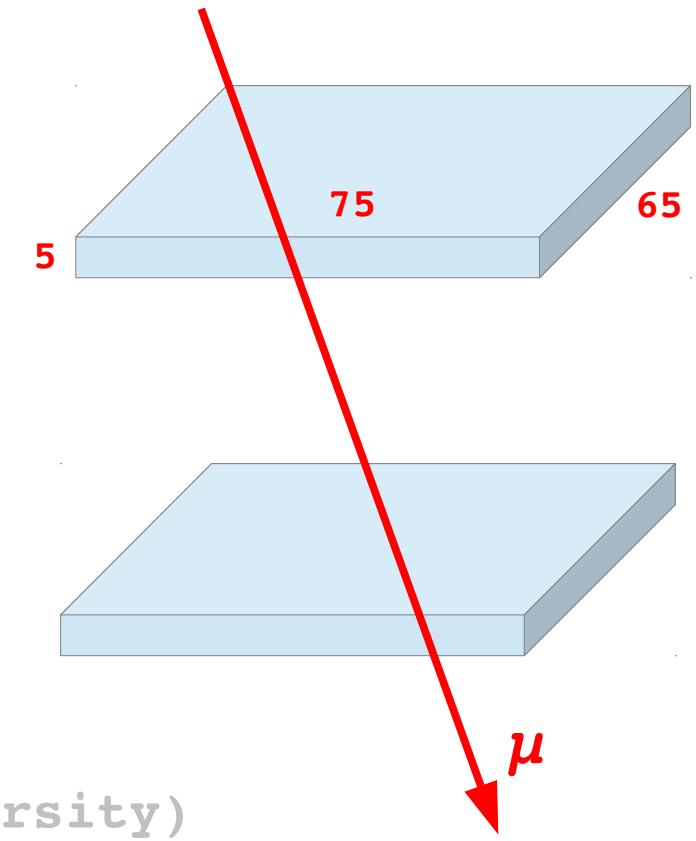
- **Plastic scintillators:**
  - **2x 5x75x65 cm3 (Saint-Gobain)**
  - **4x 5x55x10 cm3 (Saint-Gobain)**
  - **2x 0.7x126x20 cm3 (Tuebingen)**

- **Lead and Water**

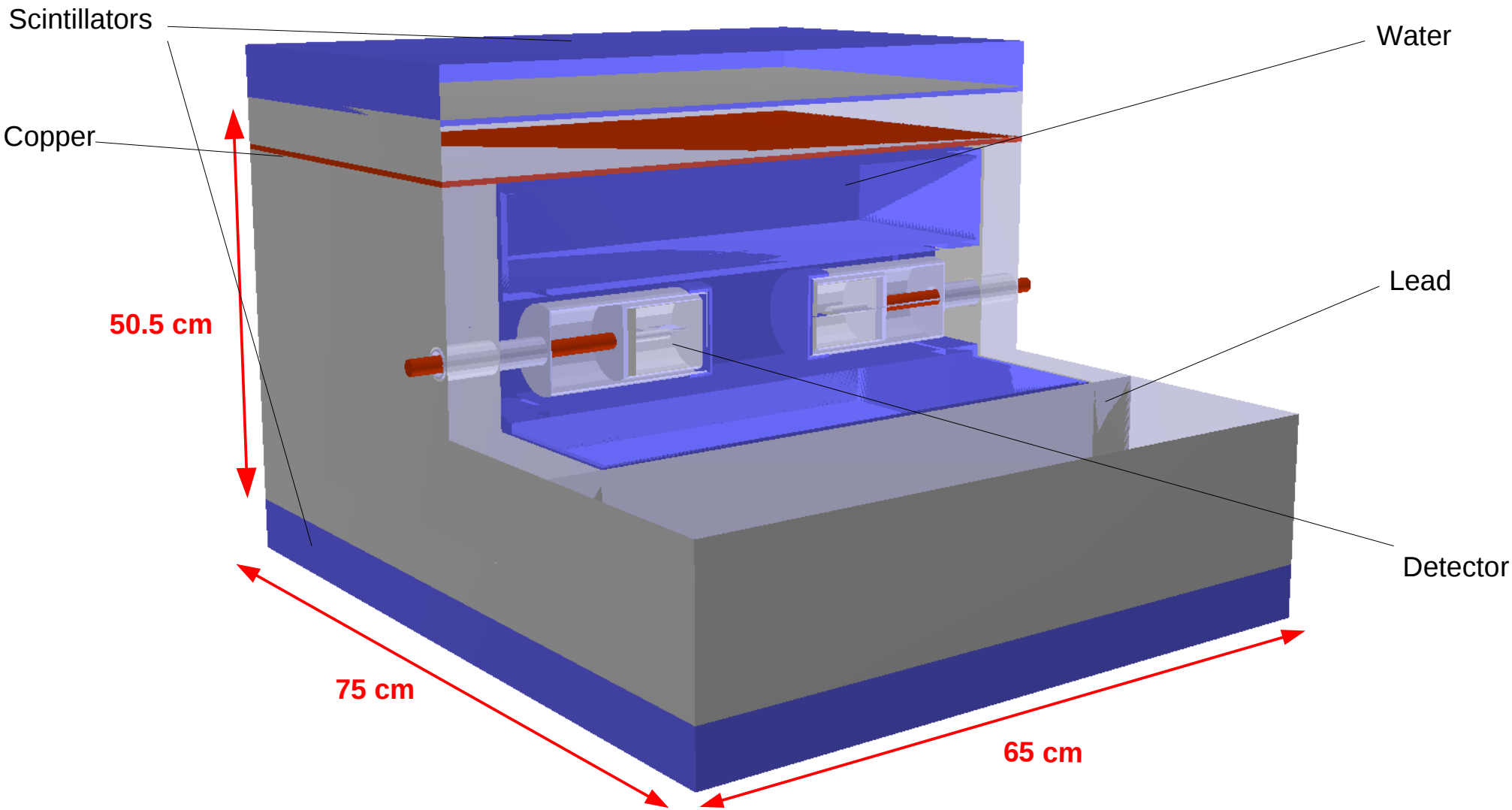
- **DAQ: SIS3316-DT Fast-ADC (Struck)**
(for details: http://www.struck.de/sis3316.html)

- **Fast Neutron Detector (Tsinghua University)**

- **Additional Electronics:**
https://github.com/mppmu/minidex/wiki/Electronics



MINIDEX: Geometry



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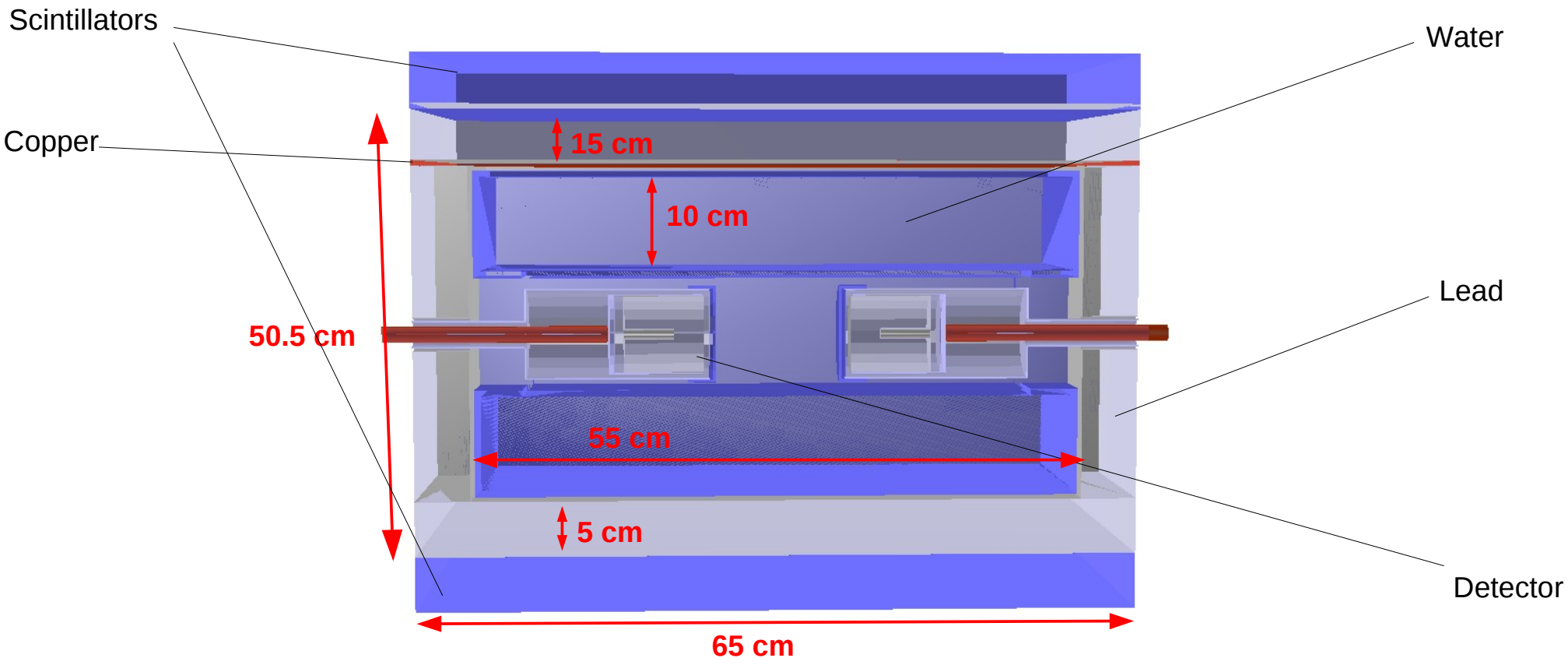

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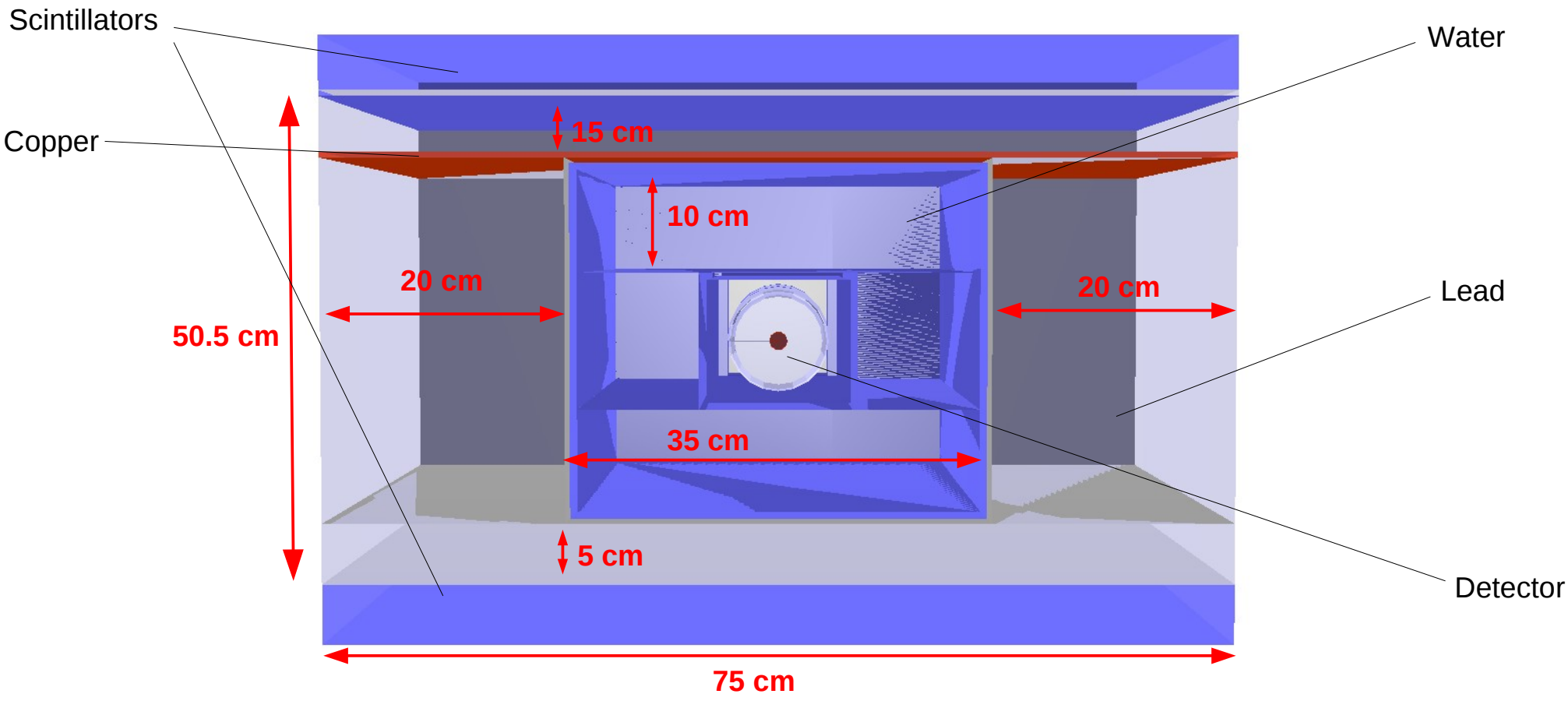

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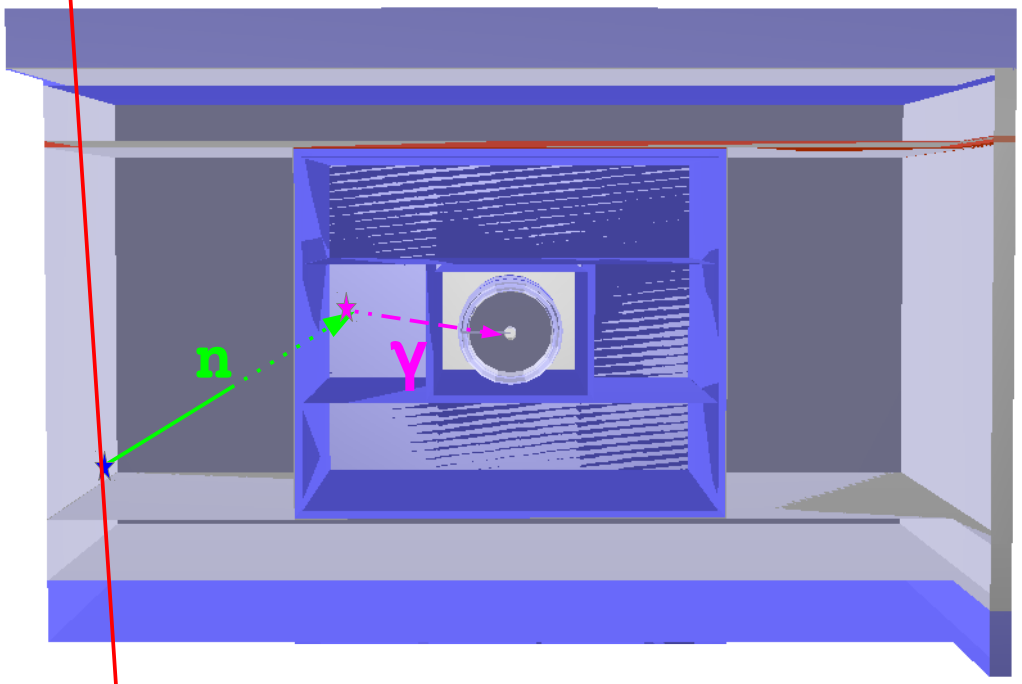
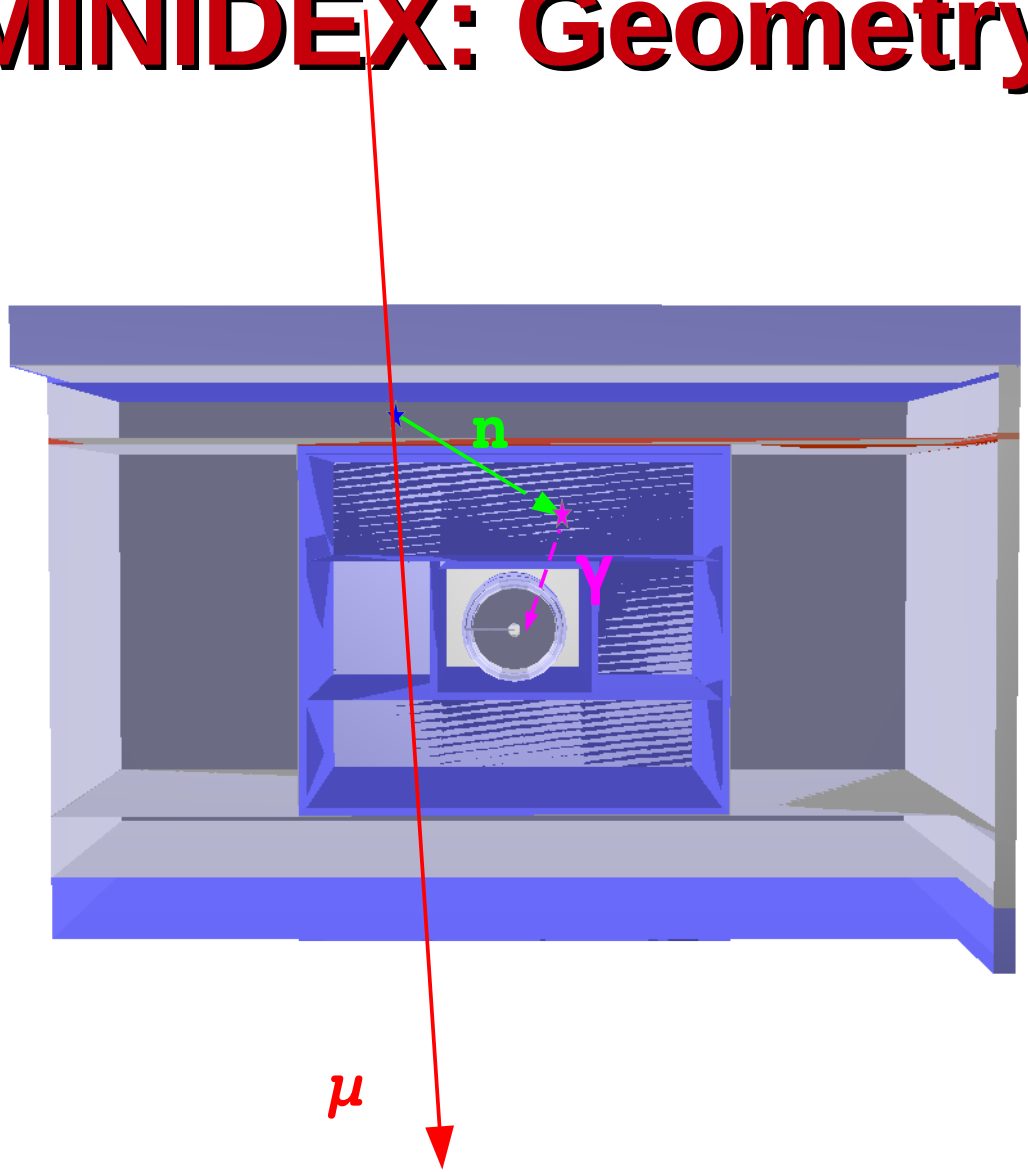


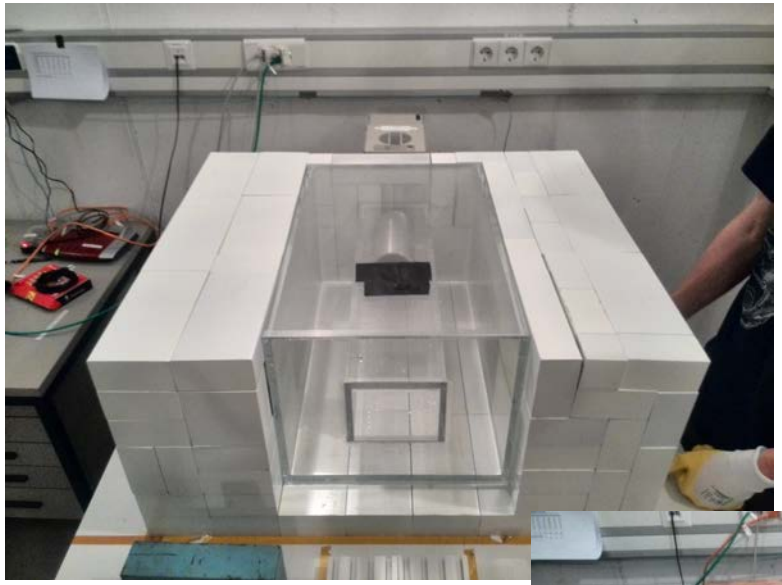
μ

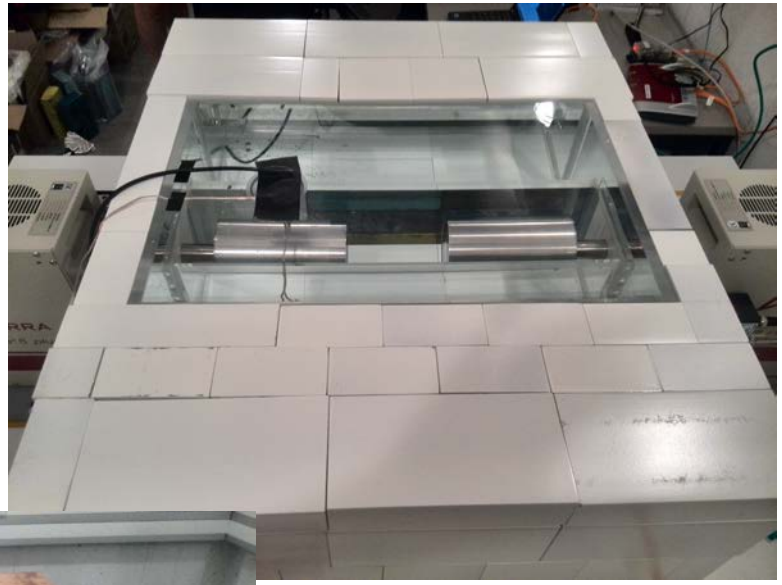
MINIDEX: Geometry

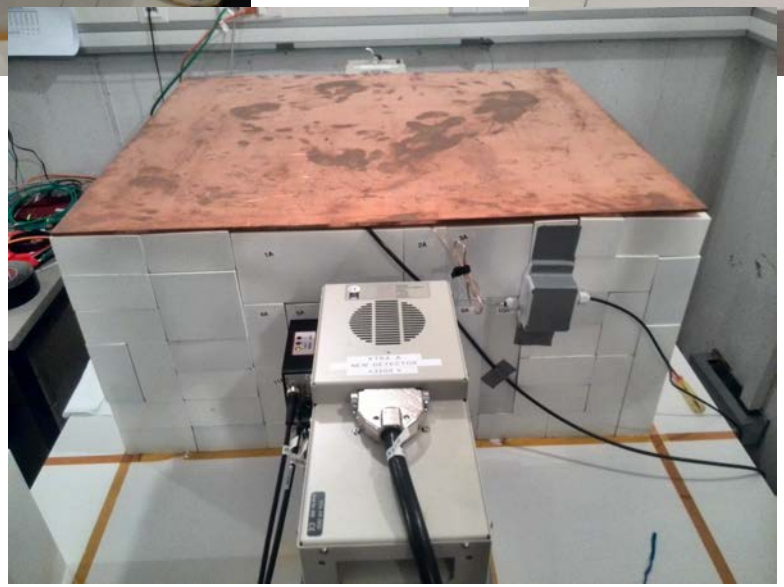


MINIDEX: installation

Tübingen Underground Lab







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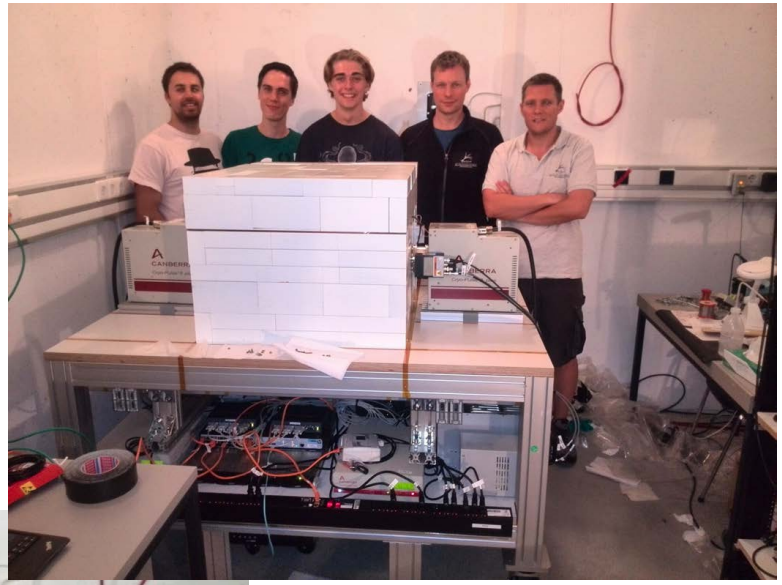
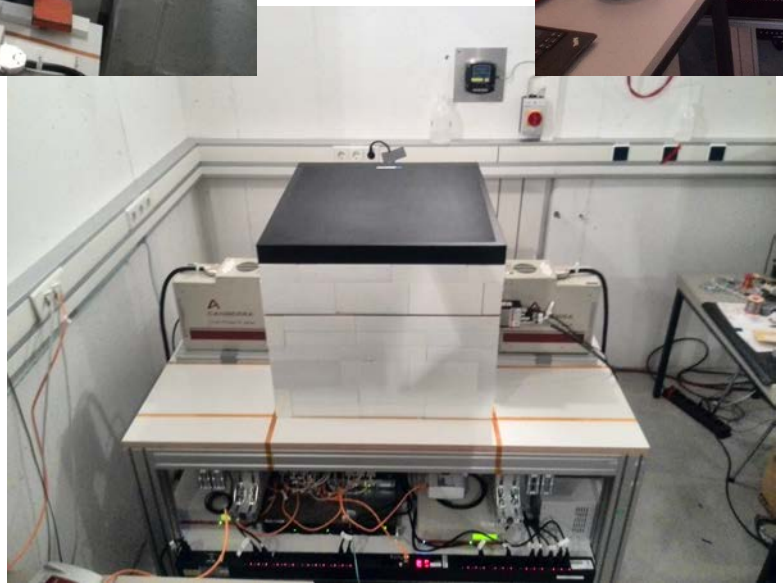
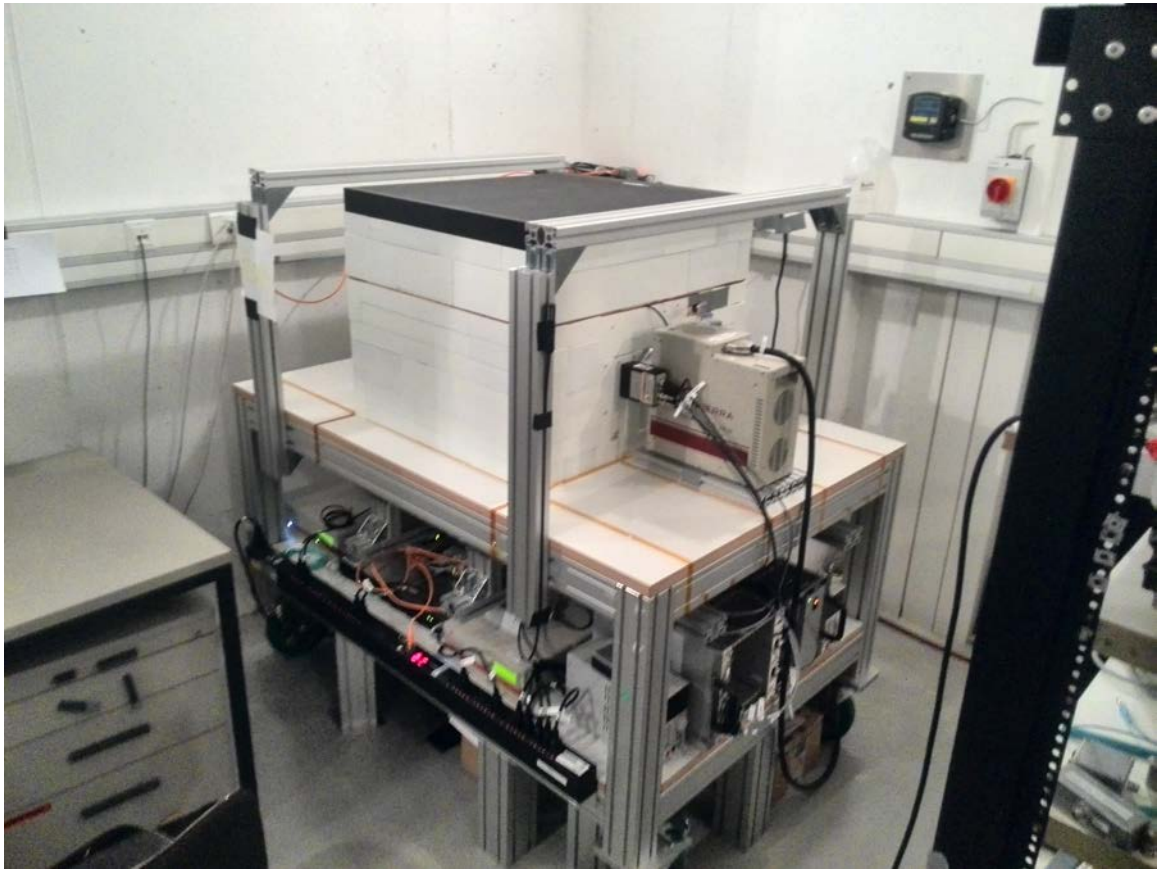




MINIDEX: Run 1

Tübingen Underground Lab

- **MINIDEX Run 1:**
  - **Started on July, the 15th ,2015**
  - **Still ongoing**



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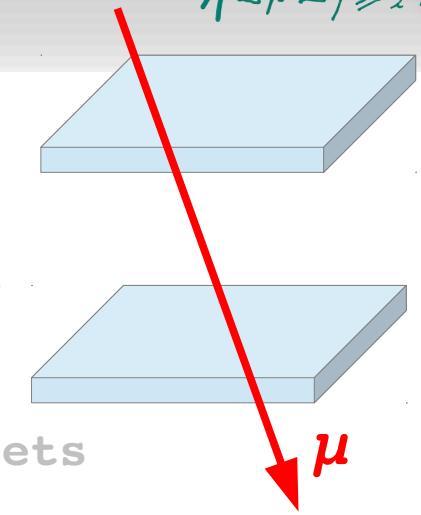
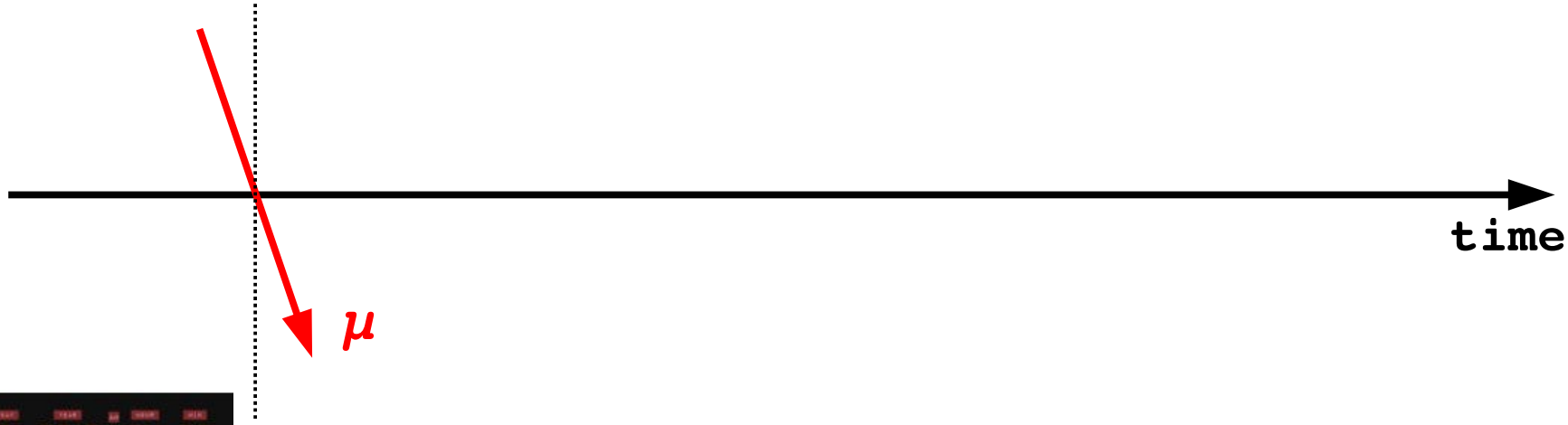
Analysis Strategy



- **Define a muon-event (trigger)**
- Open a Time Window (Twin) right after the muon-trigger to look at the Ge-Dets
- Count the number of 2.2 MeV gamma events into the Ge-Dets
  - INSIDE the Twin → S+B
  - OUTSIDE the Twin → B
- Evaluate the S/B ratio for different Twin



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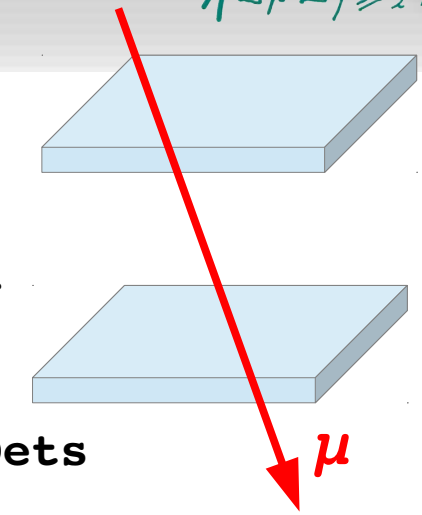

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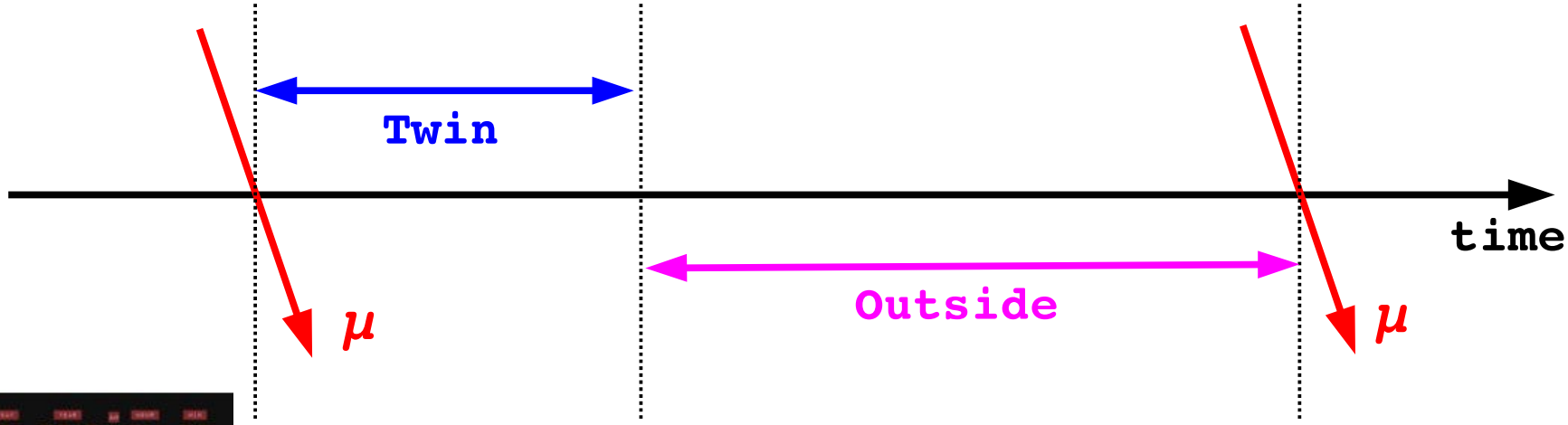

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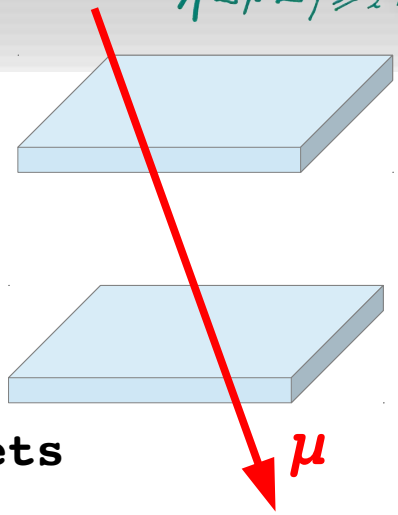

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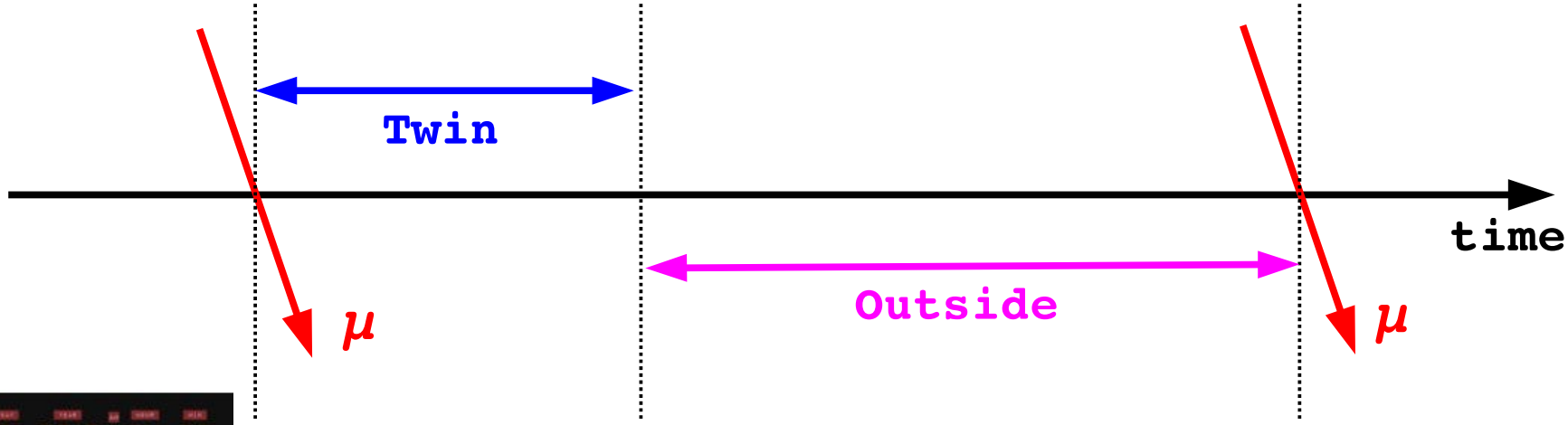
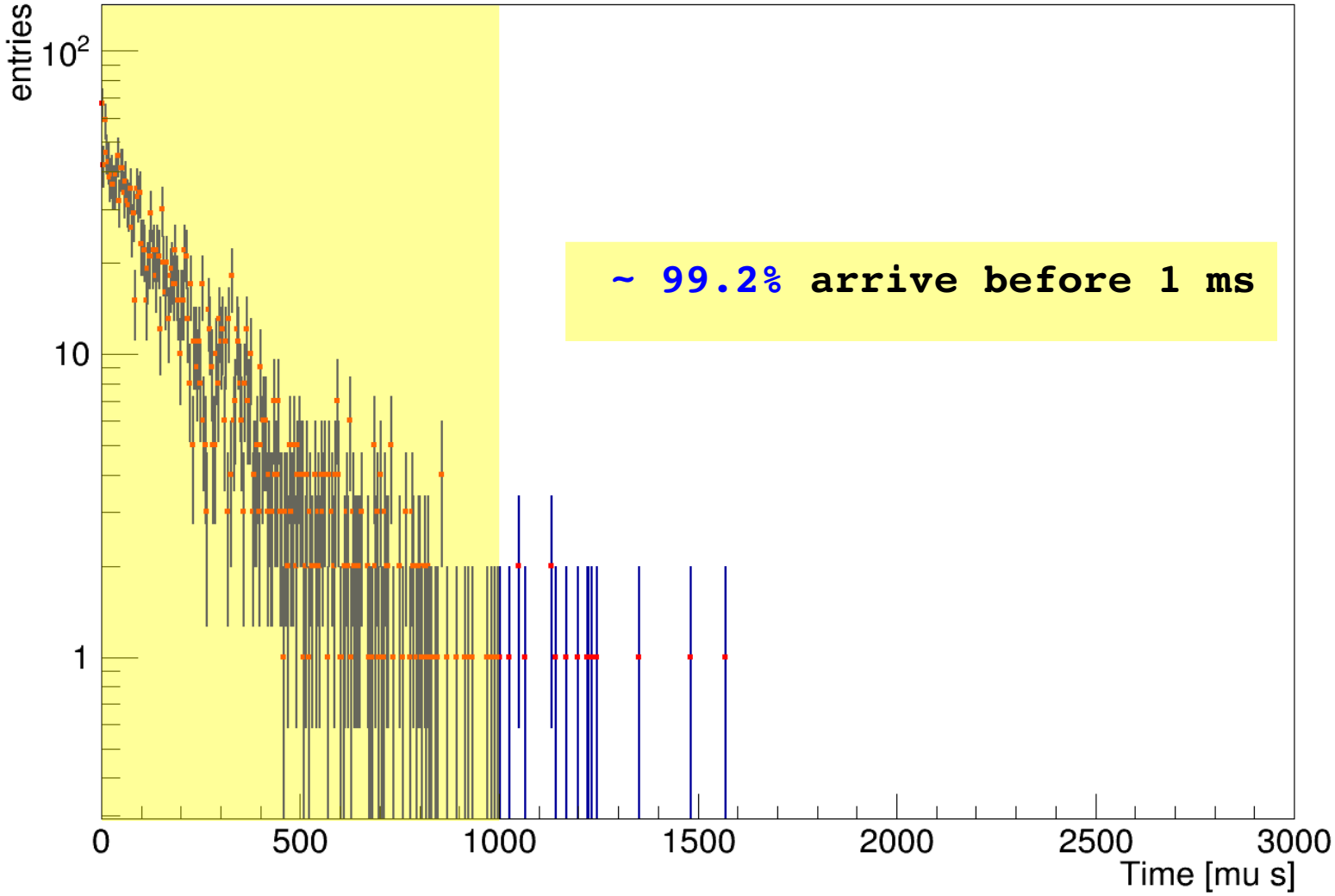


2.2MeV γ Time Distribution INCOMING @ GeDet

- Test the time structure behavior in the MC



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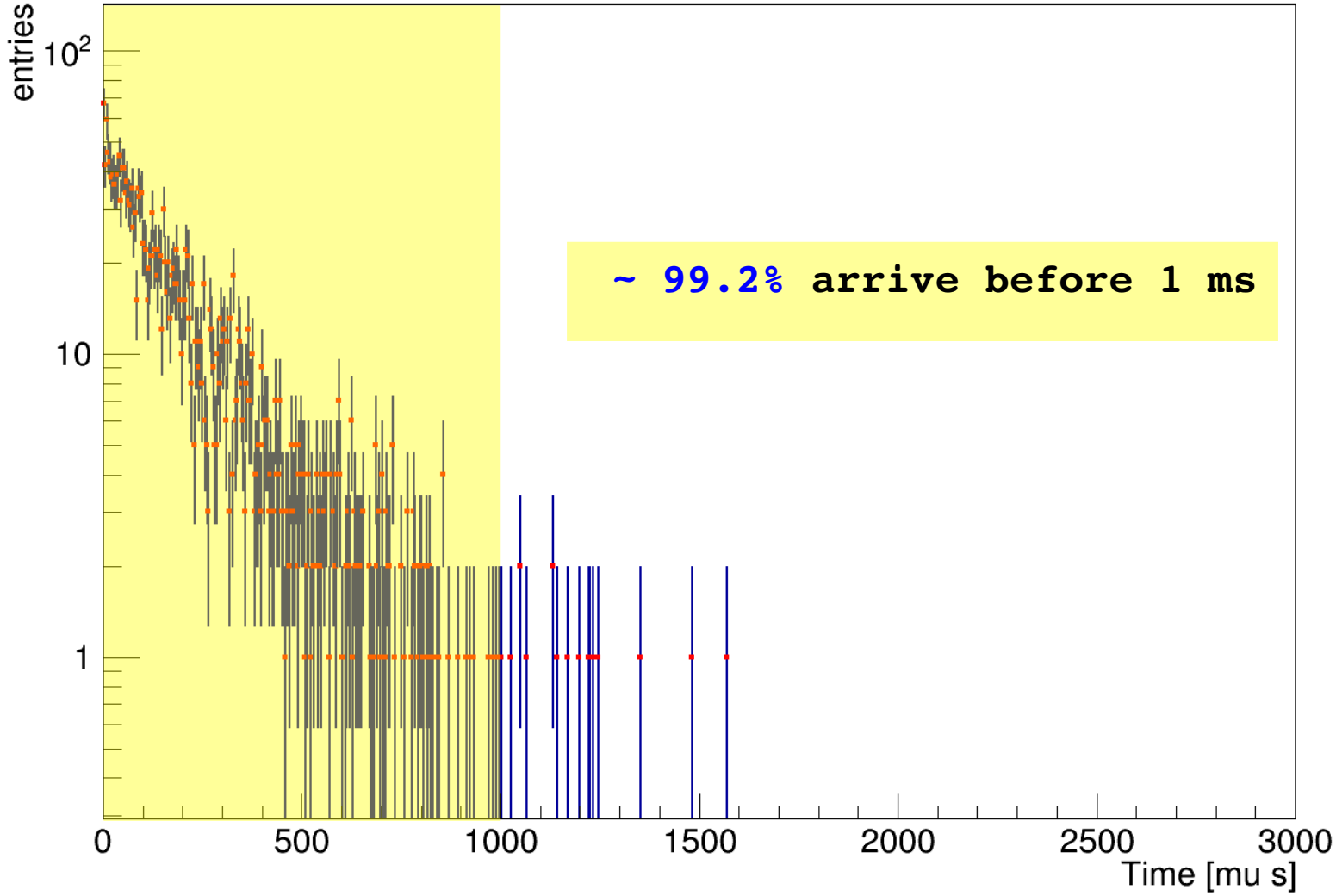
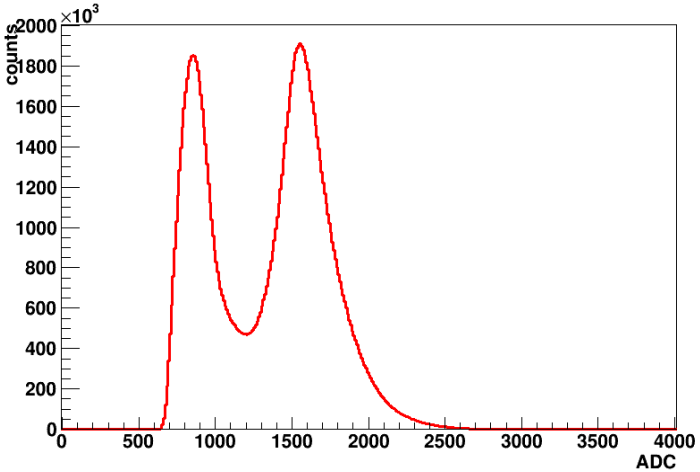
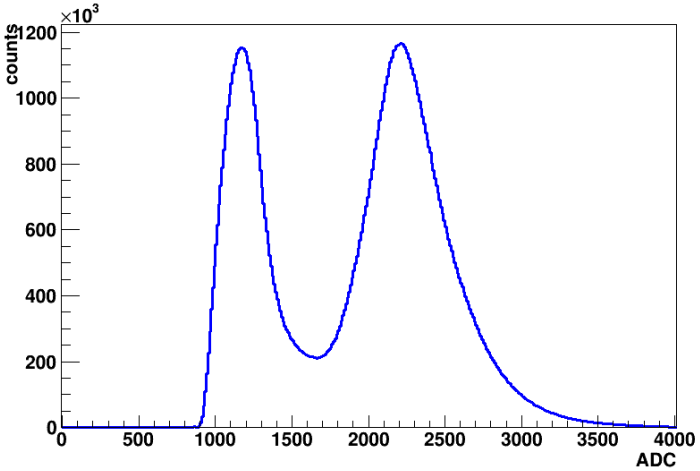
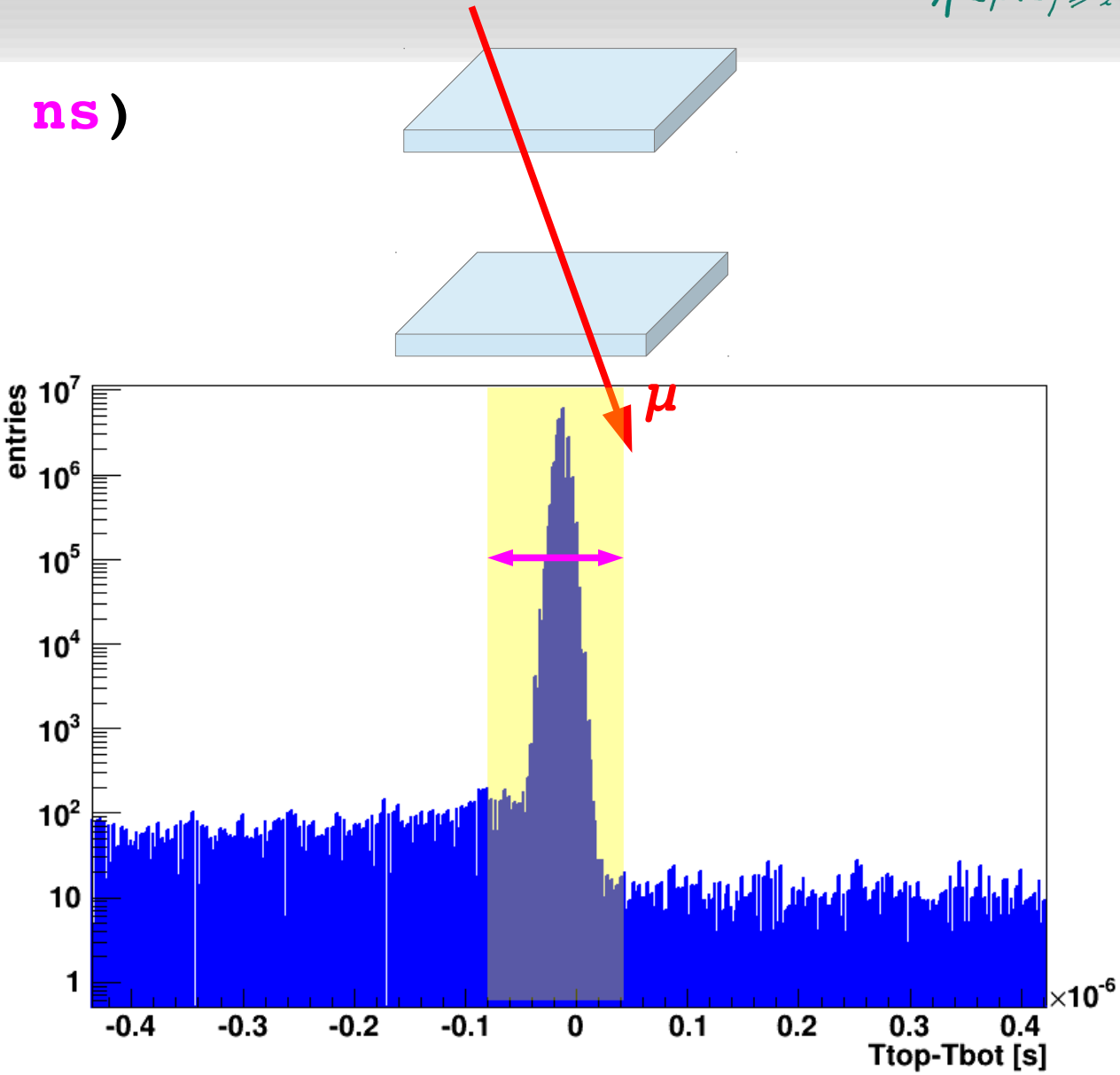


Trigger

- Only time cut (60 ns)
- No Energy cut







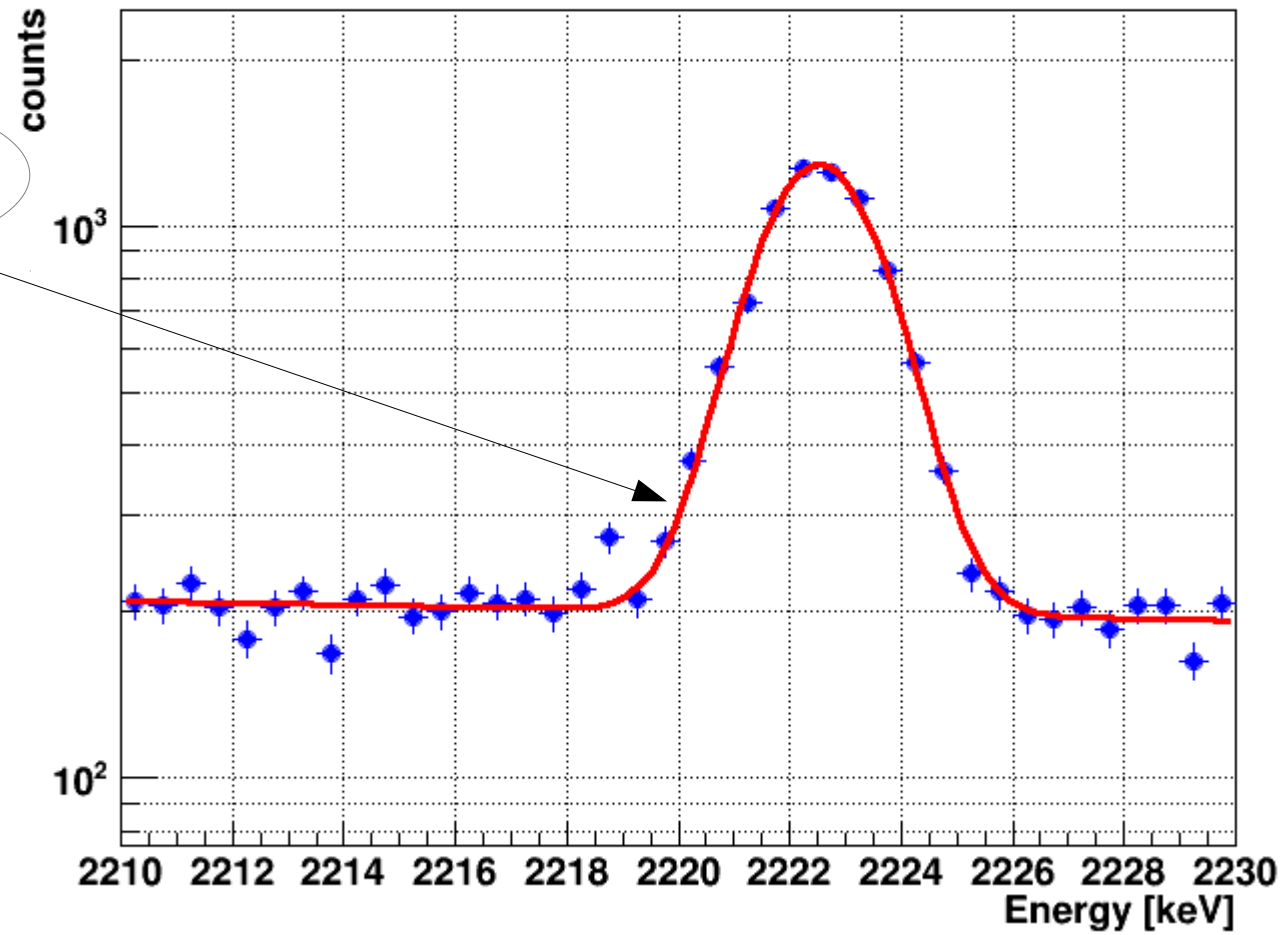
Count the 2.2 MeV gammas

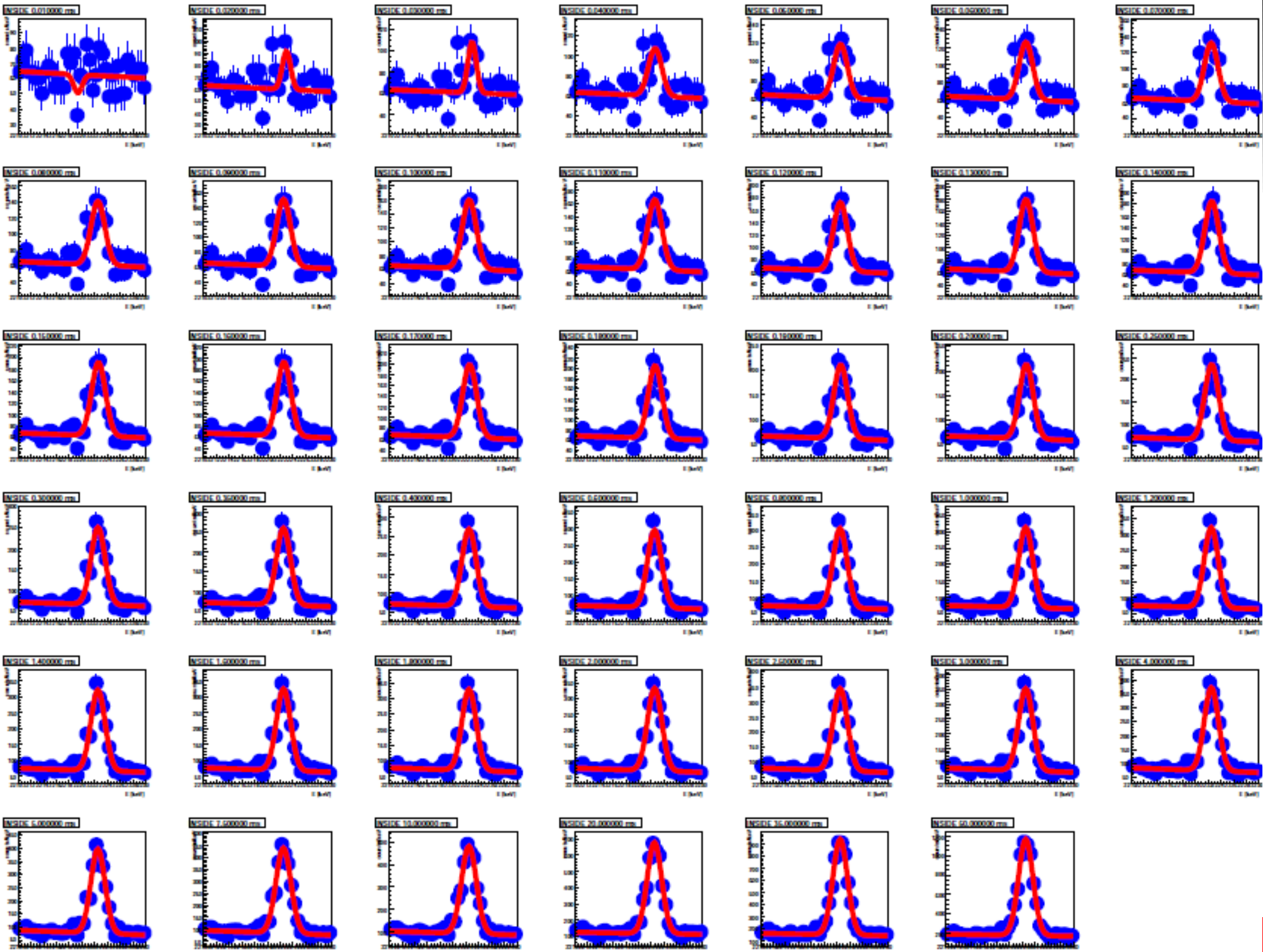
- **Two methods used:** (→ Systematic Uncertainties)
  - **FIT method**

Gaus + poll

FWHM mean

Counts(±1.8*FWHM)





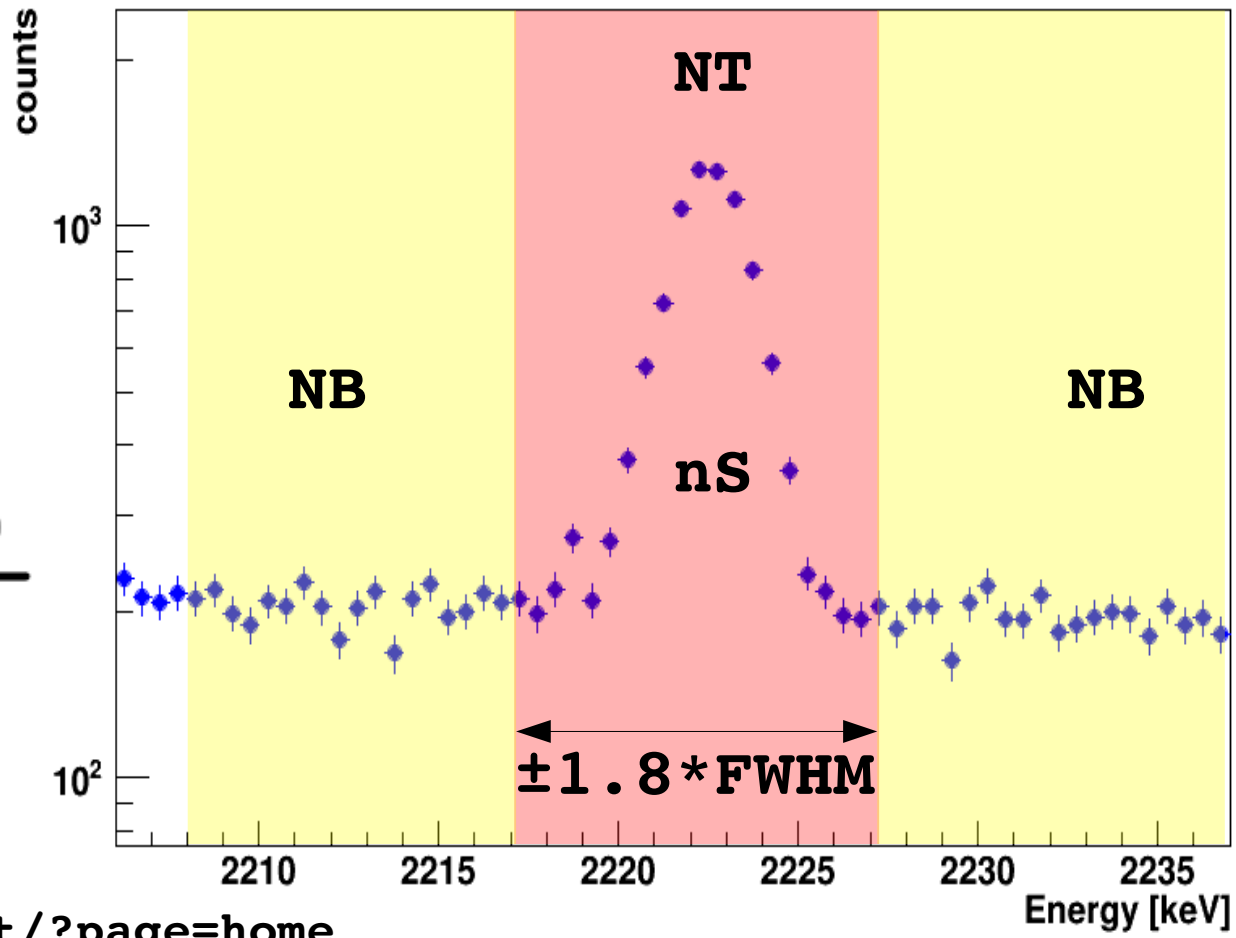
Count the 2.2 MeV gammas

- **Two methods used:** (→ Systematic Uncertainties)

  - **BAT method**

Bayesian Analysis Toolkit

$$P(A|B) = \frac{P(B|A)\ P(A)}{P(B)}$$



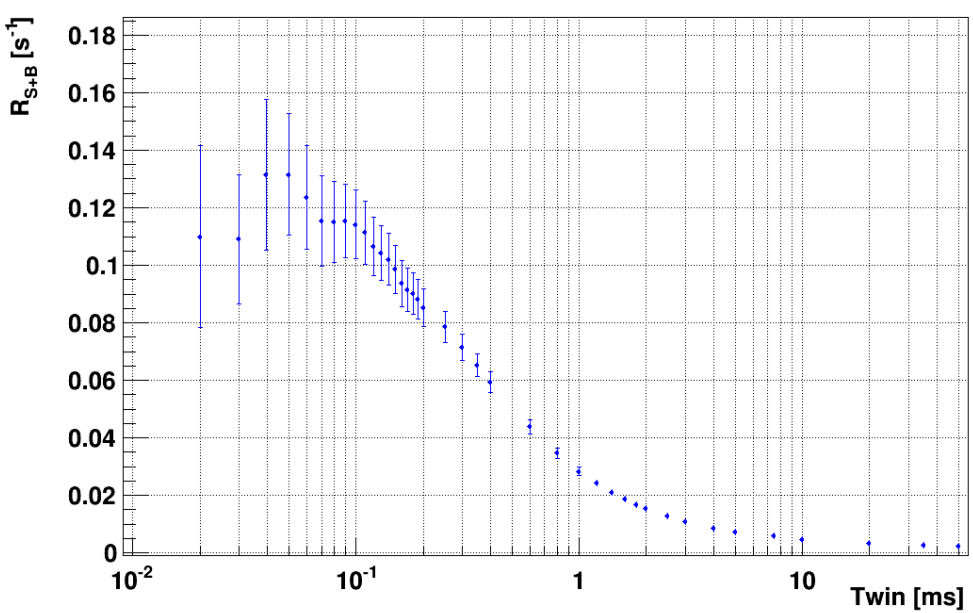
https://www.mppmu.mpg.de/bat/?page=home

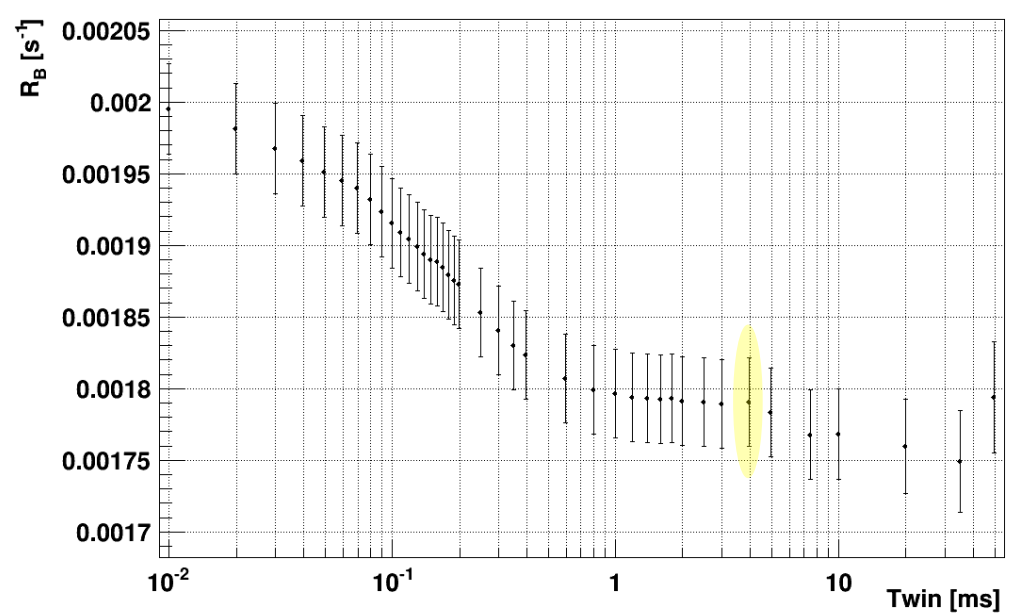
S/B ratio

$$\rho_{S/B} = \frac{R_{S+B} - R_B}{R_B}$$

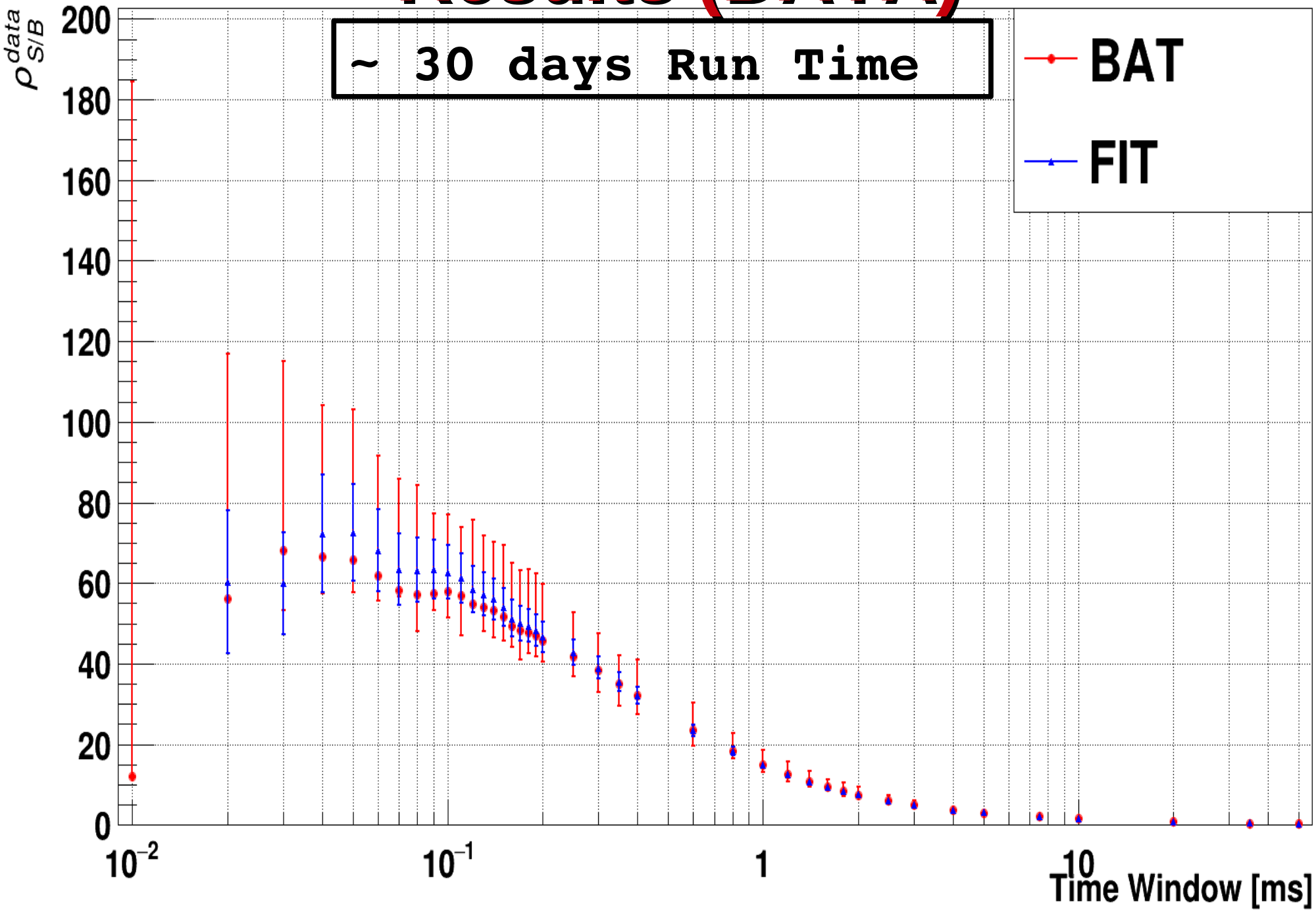
$$R_{S+B} = \frac{N_{inside}}{N_{trig} \cdot T_{win}}$$

$$R_B = \left[\frac{N_{outside}}{RT - (N_{trig} \cdot T_{win})} \right]_{T_{win}=4ms}$$

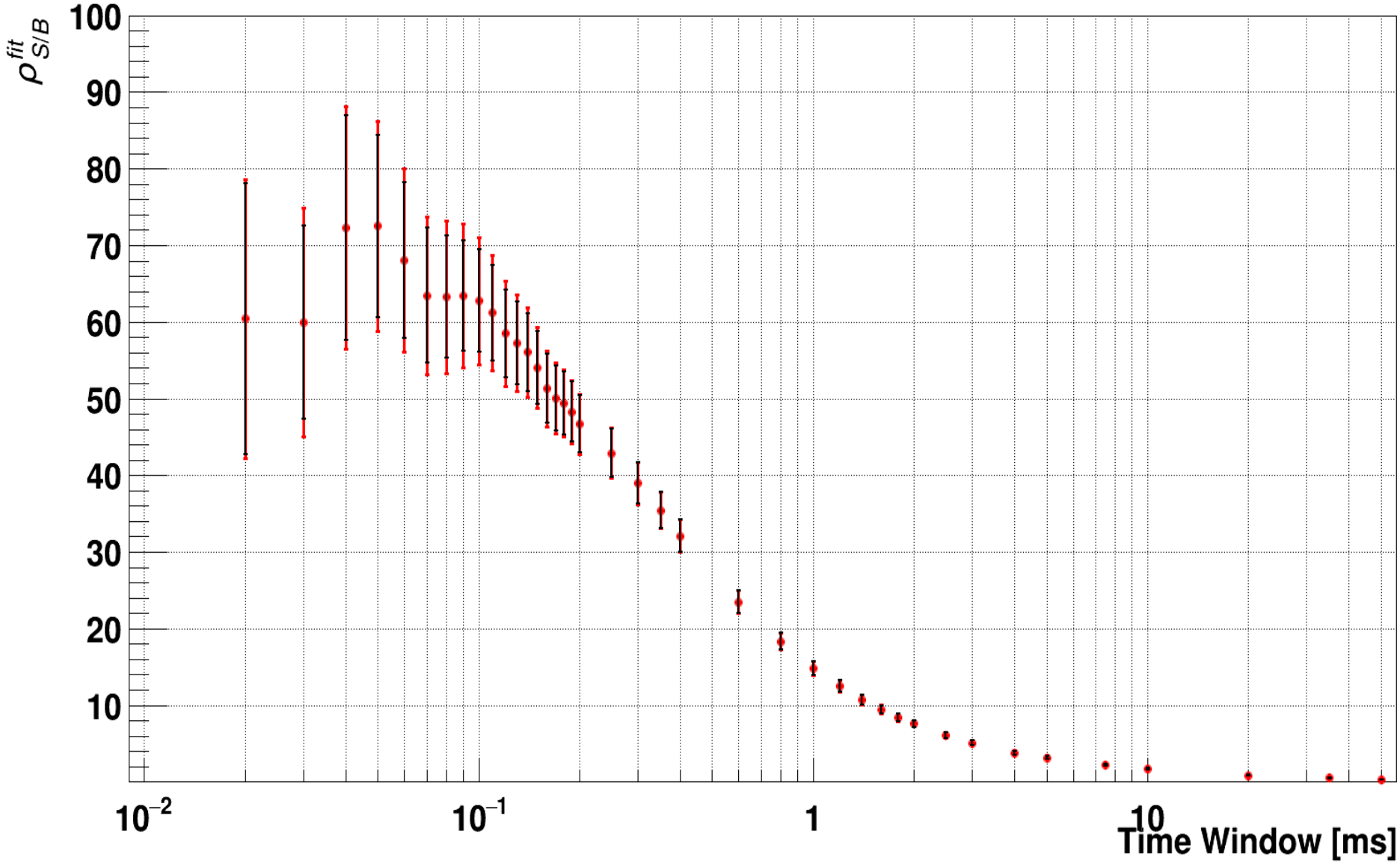




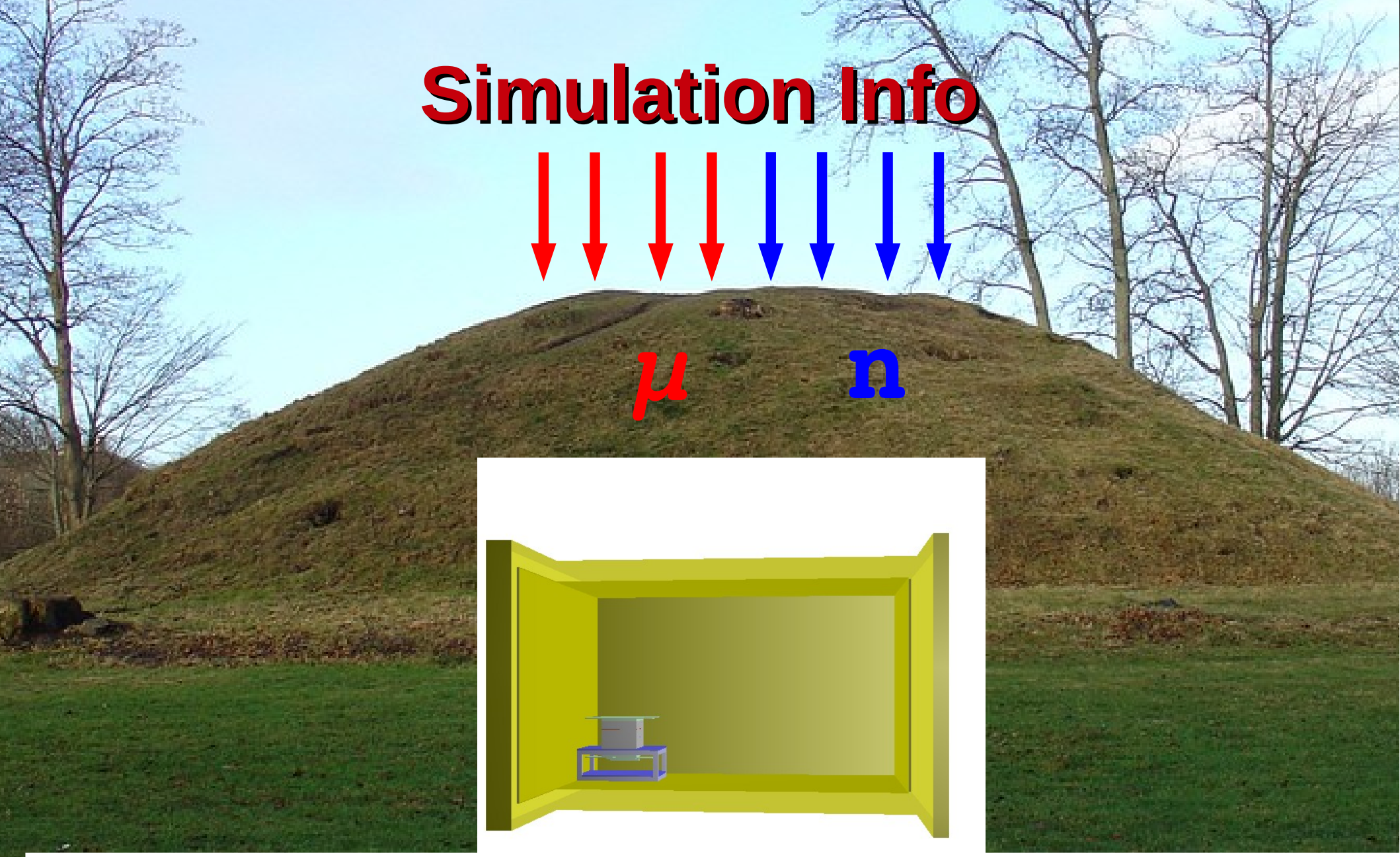
Results (DATA)



Results (DATA)



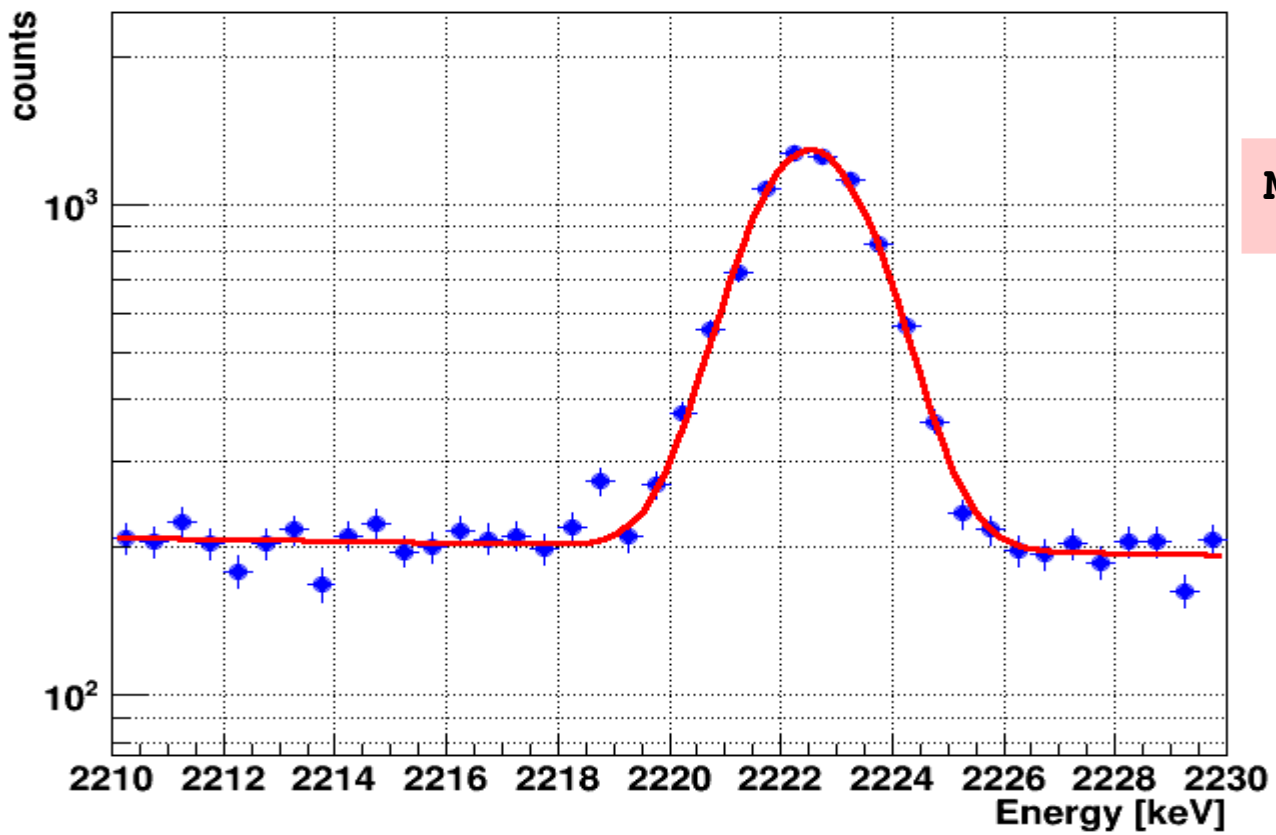
Simulation Info



BUT NO environmental radioactivity!!

Correction Factors

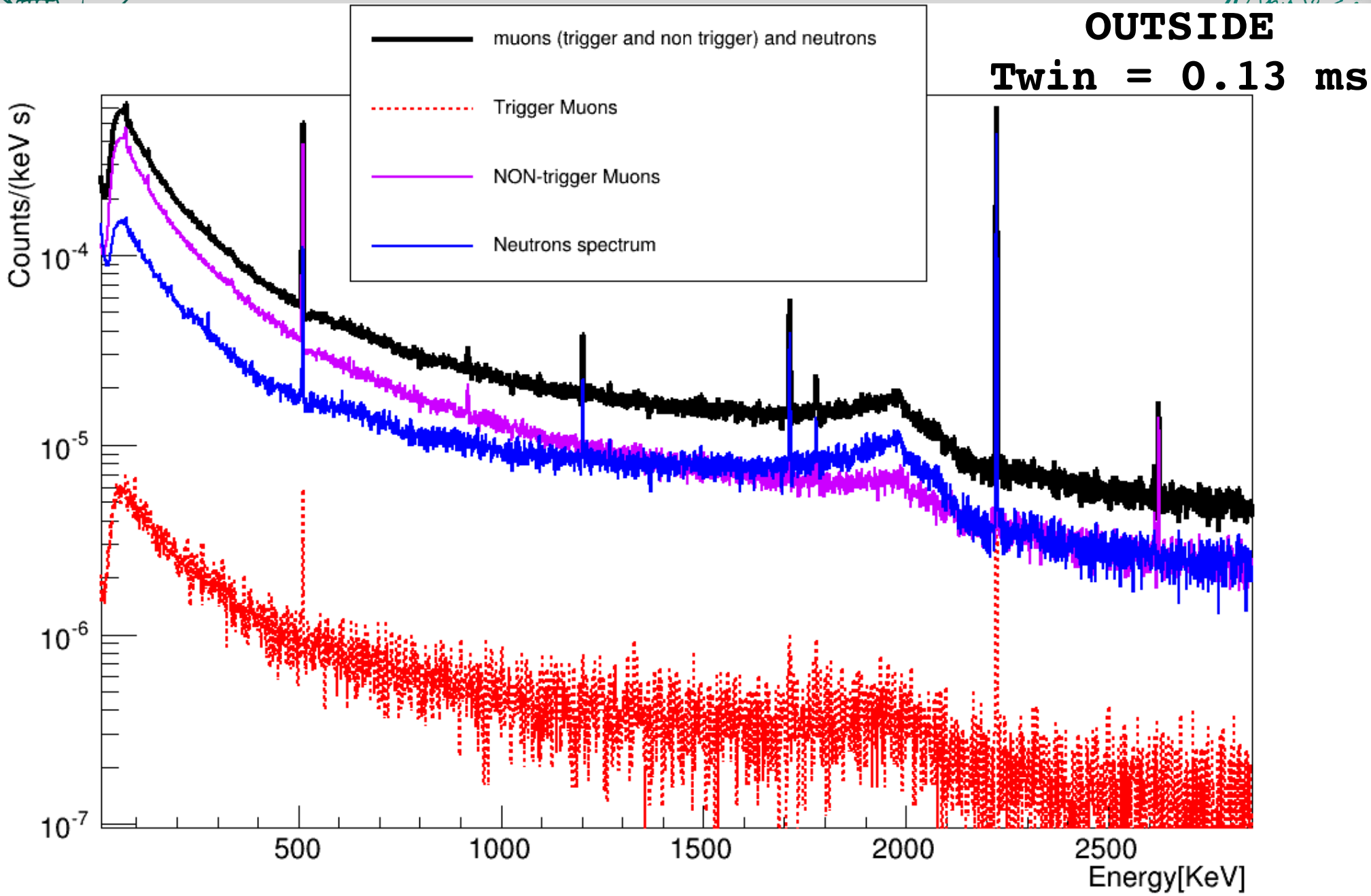
$$\begin{cases} (R_S + R_{NOT-trig\mu} + R_{neutrons})_{DATA} = A \cdot (R_S + R_{NOT-trig\mu})_{MC} + B \cdot (R_{neutrons})_{MC} \\ (R_{NOT-trig\mu} + R_{neutrons})_{DATA} = A \cdot (R_{NOT-trig\mu})_{MC} + B \cdot (R_{neutrons})_{MC} \end{cases}$$



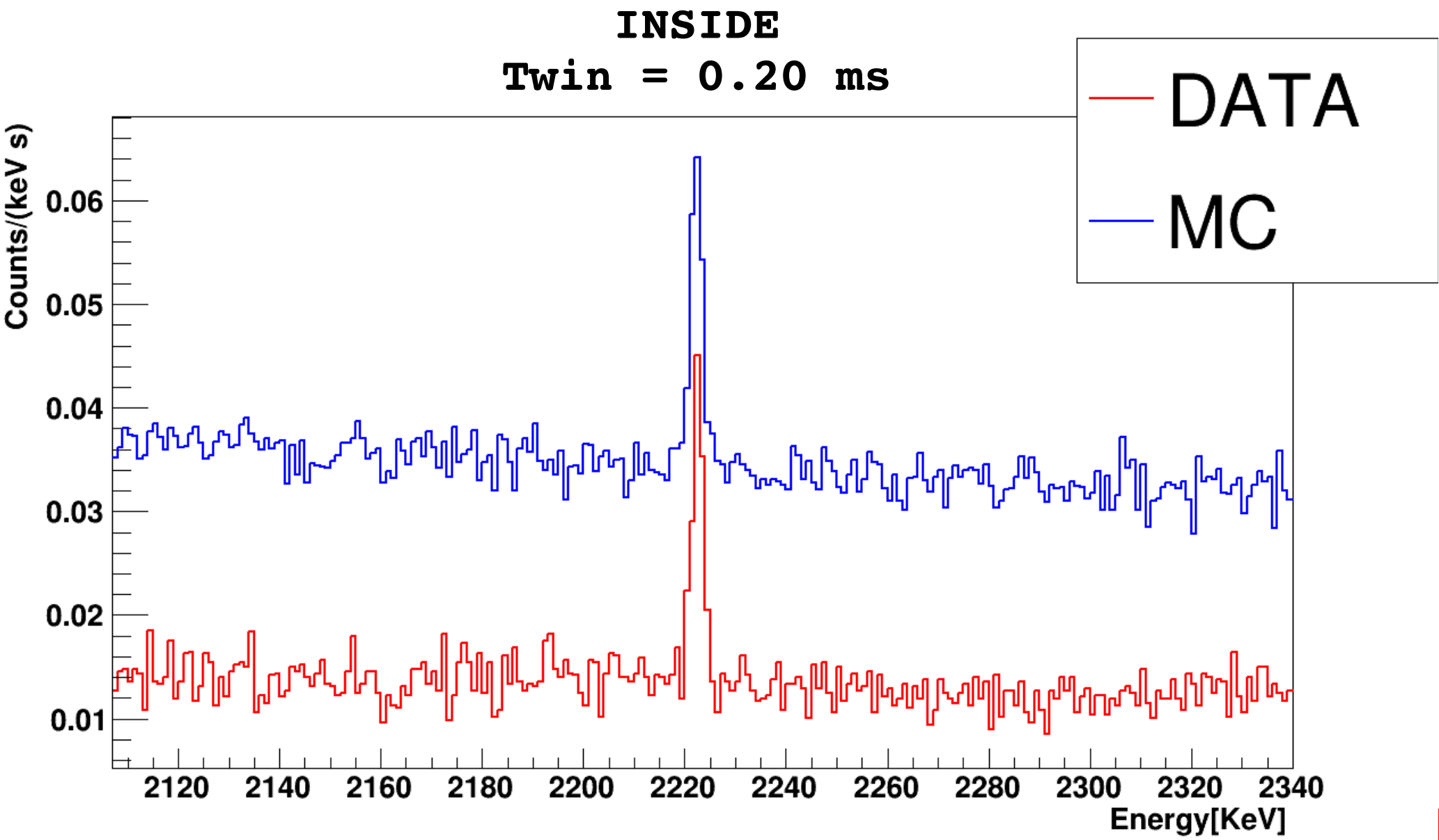
Neutron component

Muon component

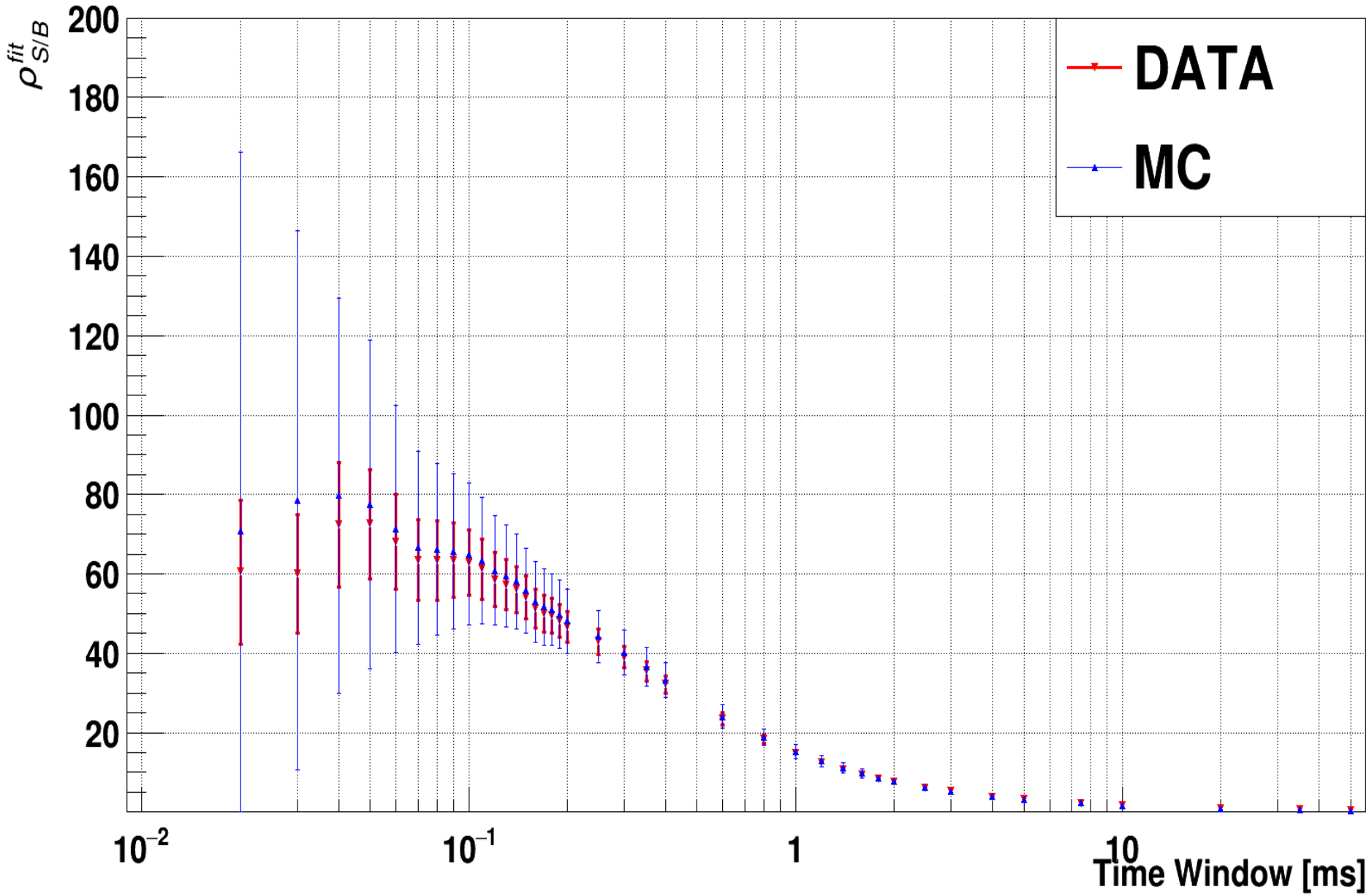
Simulated Spectra



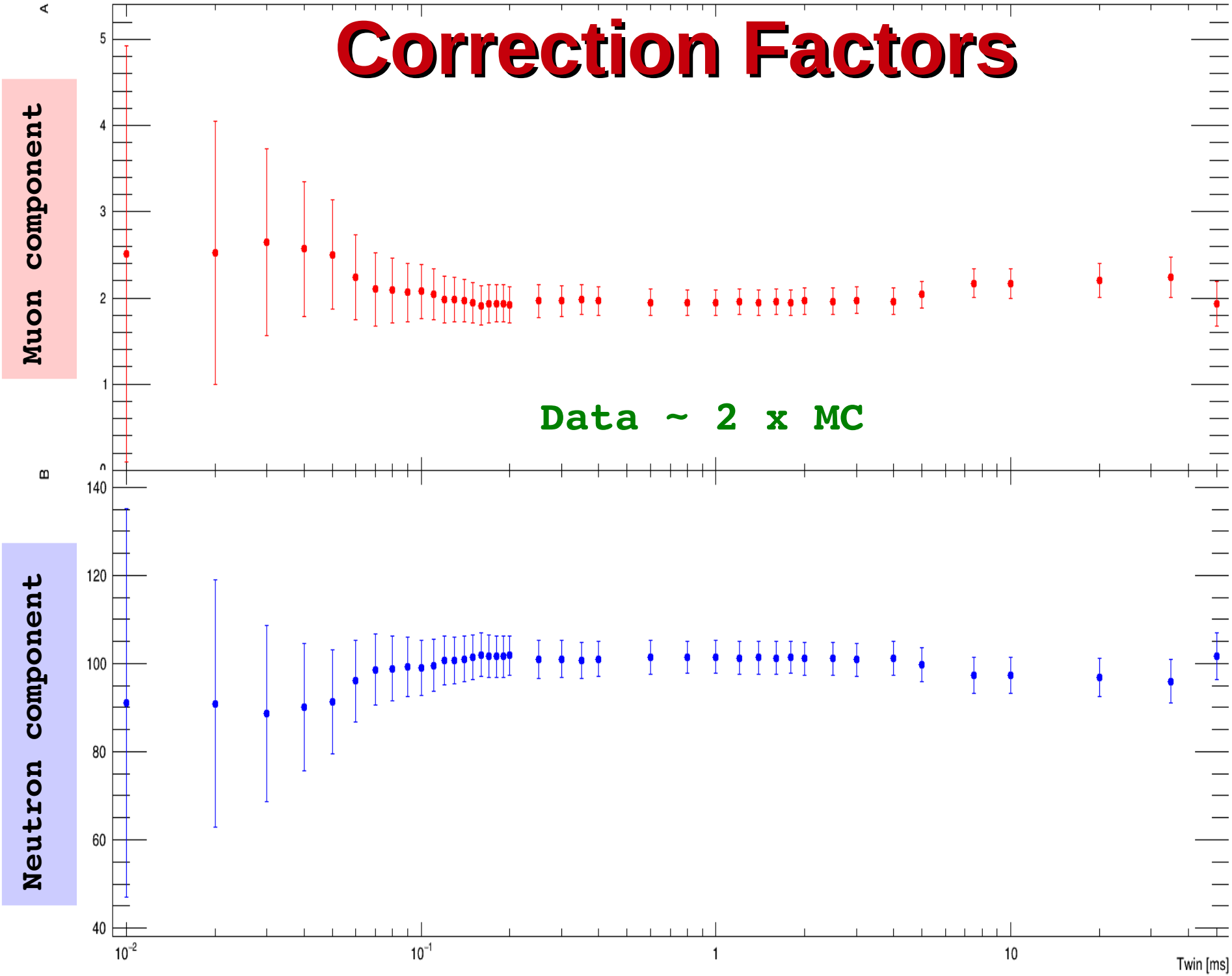
DATA-MC comparison



DATA-MC comparison



Correction Factors

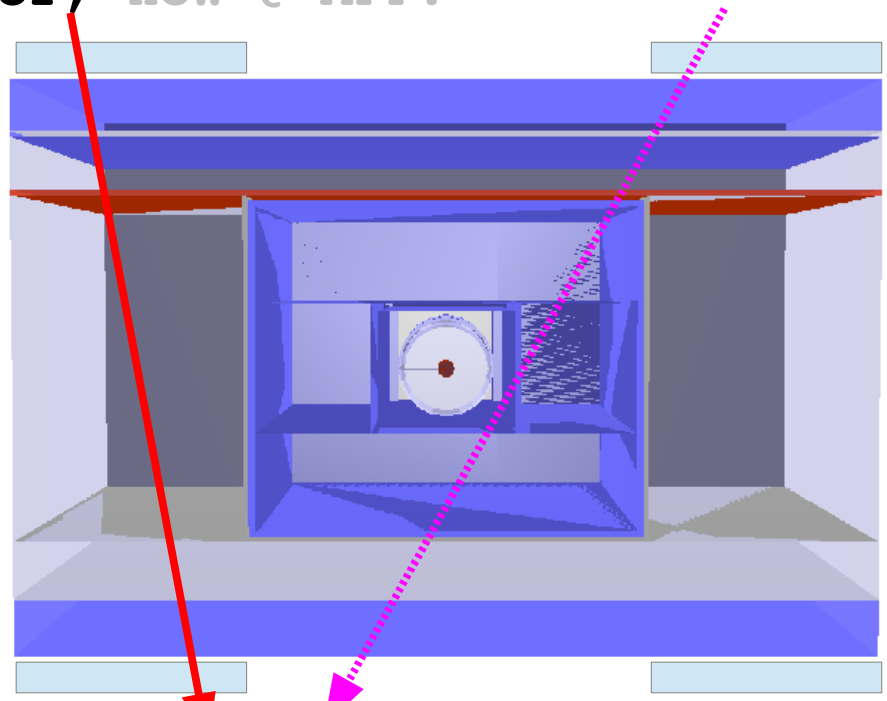


Outline

- Why MINIDEX
- Preliminary studies
- Setup description and installation
- Analysis and (preliminary) results
- **Future upgrades**
- Summary & Outlook

Future Upgrades

- Replace the big scintillators (higher eff.)
- Add 4x 5x75x20 cm3 (Saint-Gobain)
- Integrate a Fast Neutron Detector, now @ MPP? (Wang Li, Tsinghua University)



- Probe other materials (concrete, steel, soil ..)

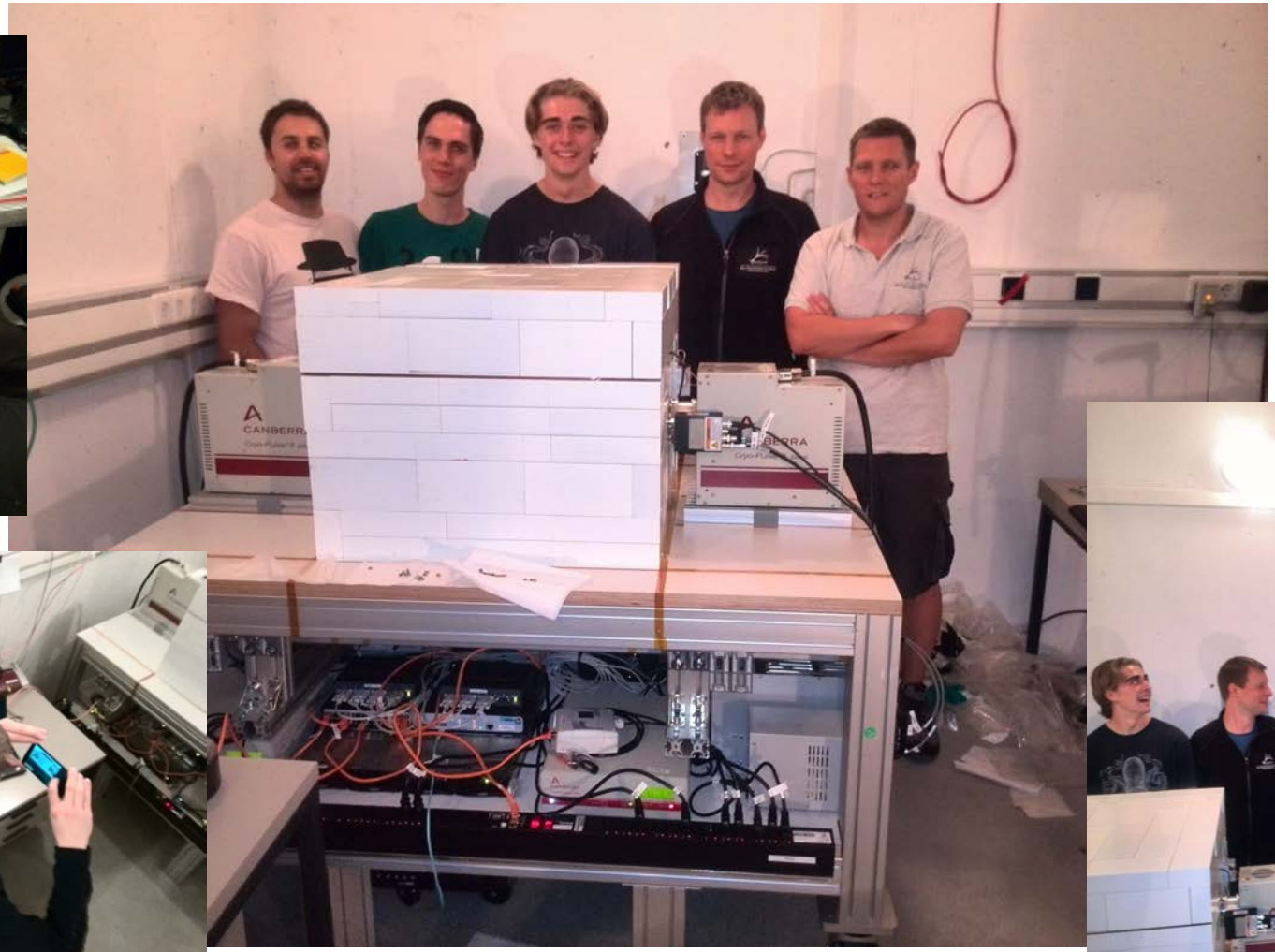
Outline

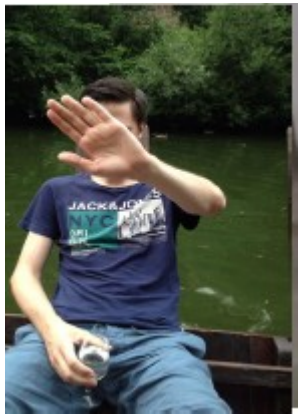
- Why MINIDEX
- Preliminary studies
- Setup description and installation
- Analysis and (preliminary) results
- Future upgrades
- **Summary & Outlook**

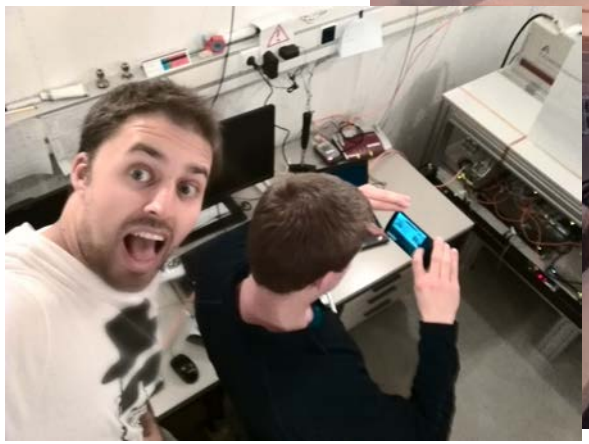
Summary & Outlook

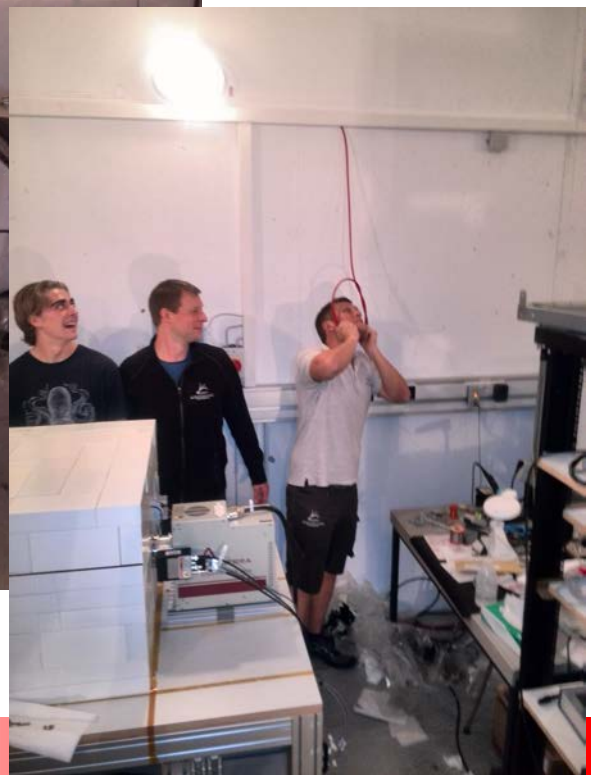
- **Summary:**
  - Simple and relatively cheap setup
  - MINIDEX Run 1 has started (ongoing)
  - Visibile pattern (already after 1 month)
  - MC reproduces well the time structure behavior
  - Two times more signal in the data ?
- **Outlook:**
  - Include the environmental bkg. in the MC
  - Upgrades:
    - New scintillators
      - → cleaner data samples
      - → higher efficiency → bkg. reduction power
    - Fast Neutron Detector (Wang Li)
  - Probe different materials ?

Thank You

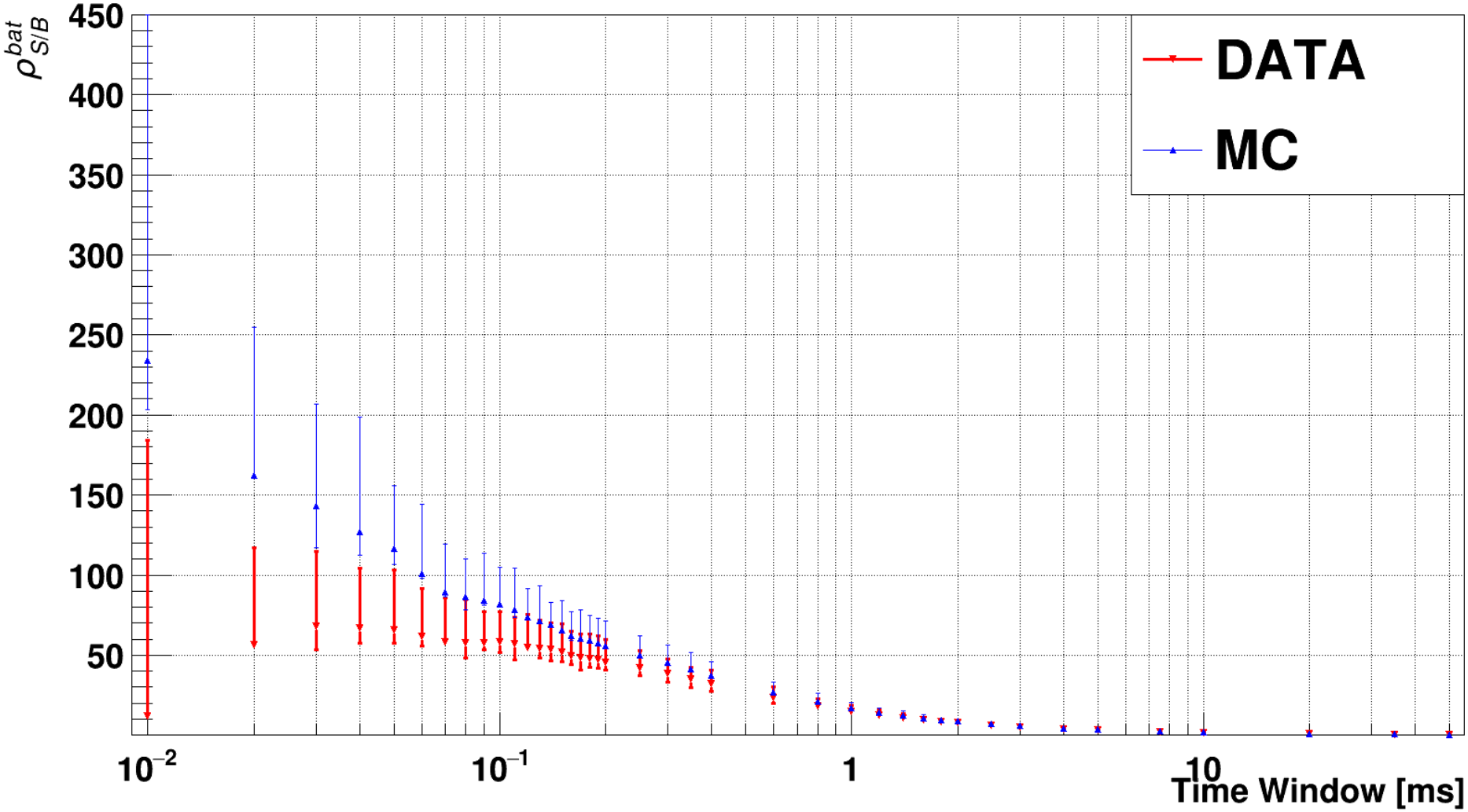


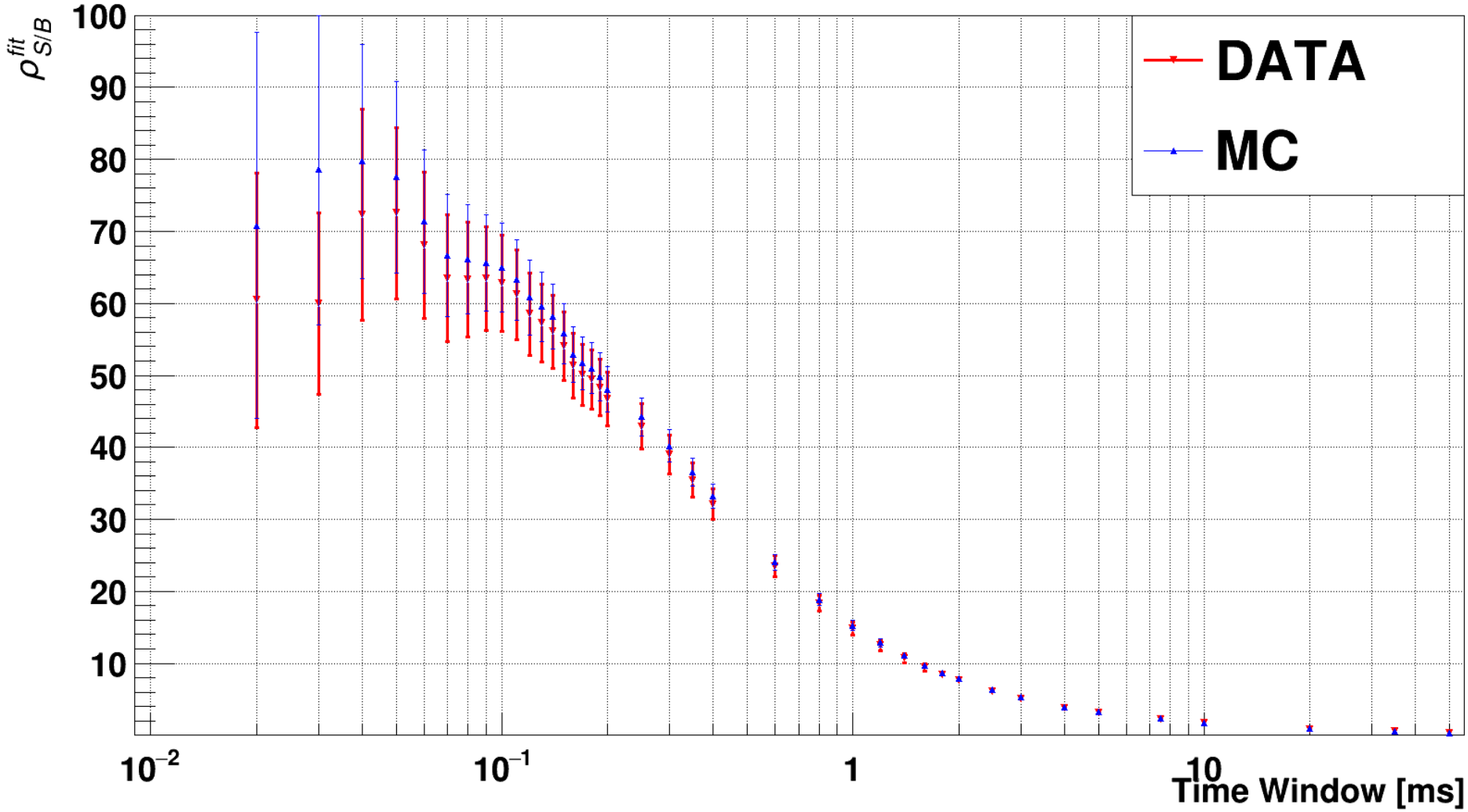


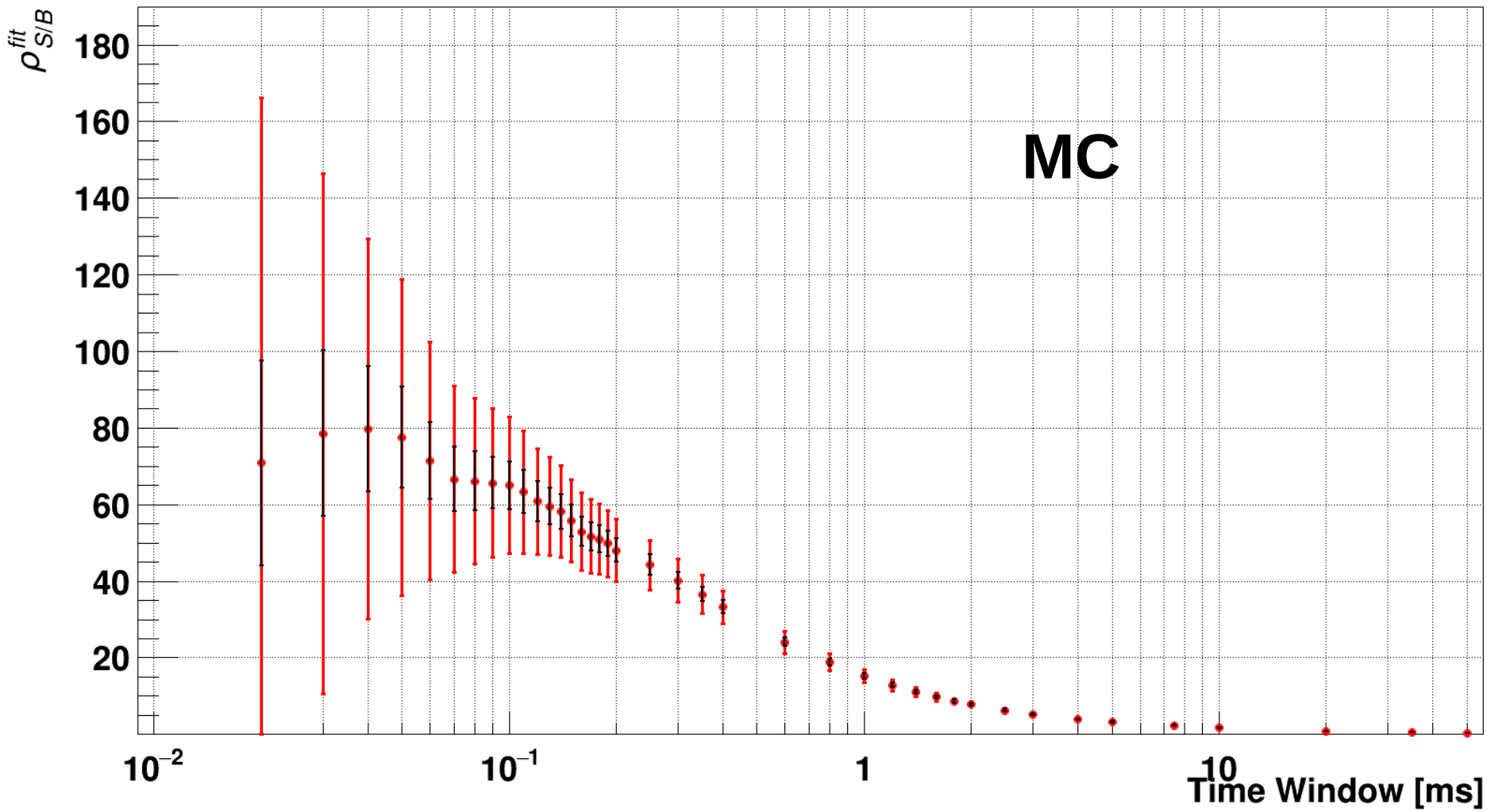


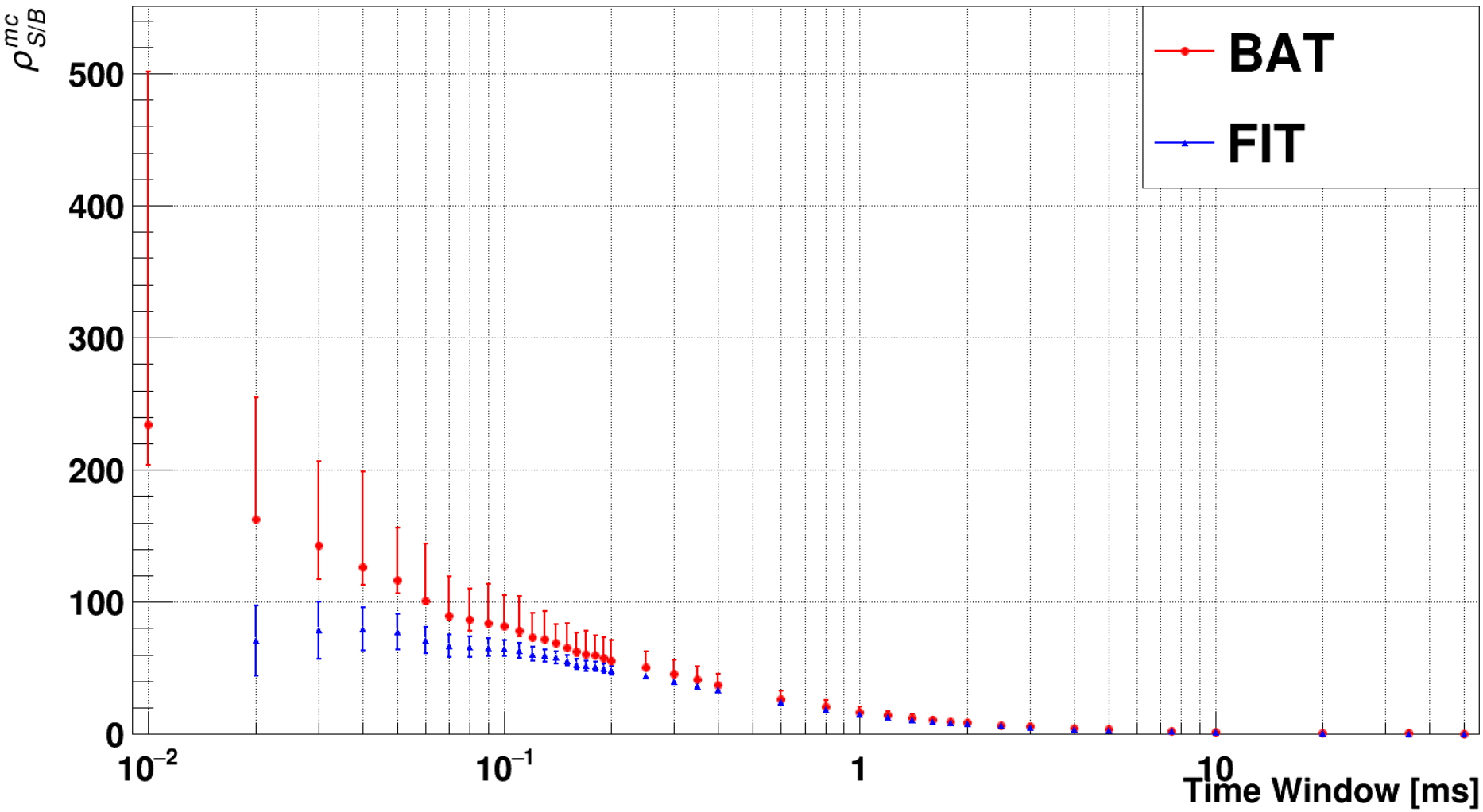


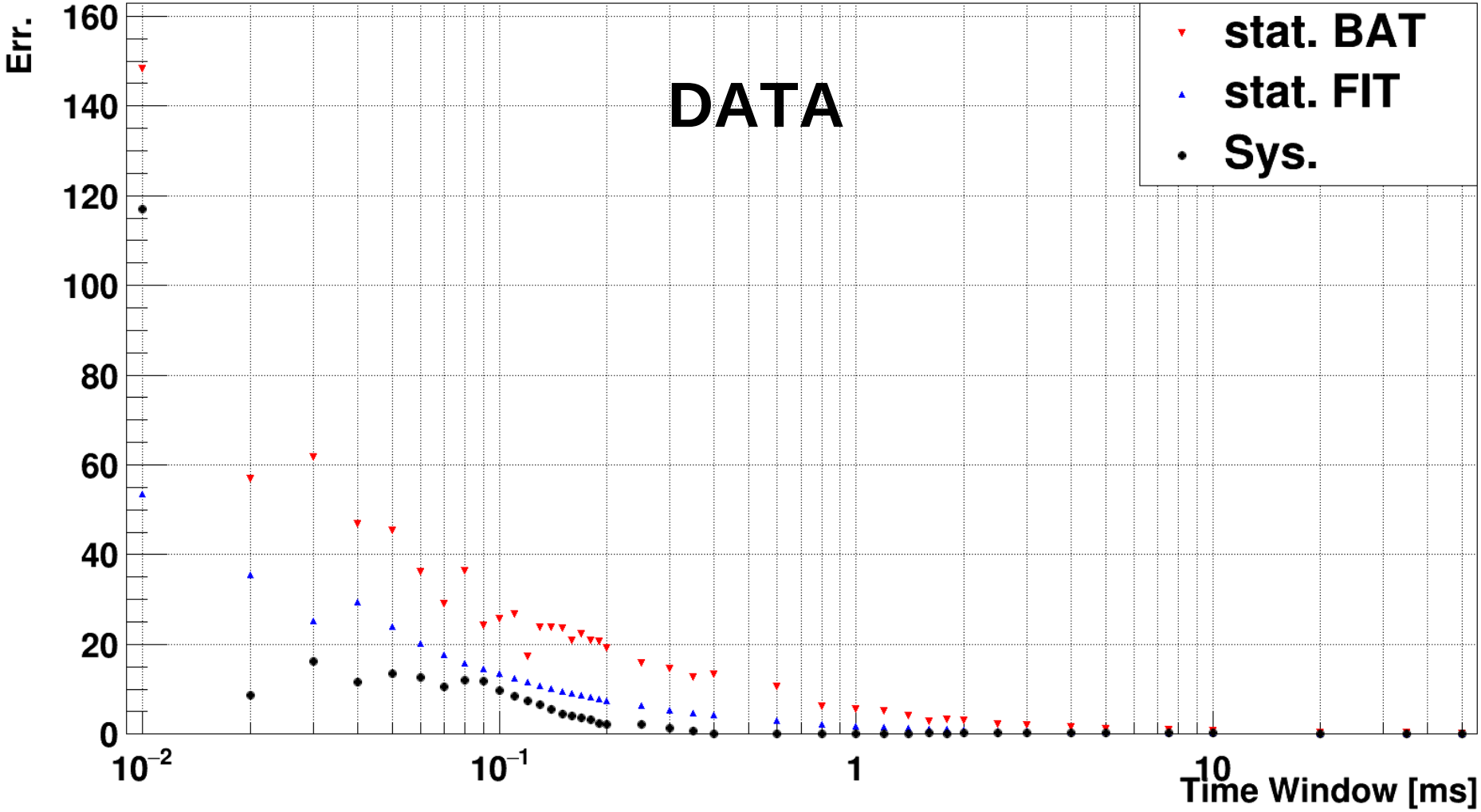
Backup

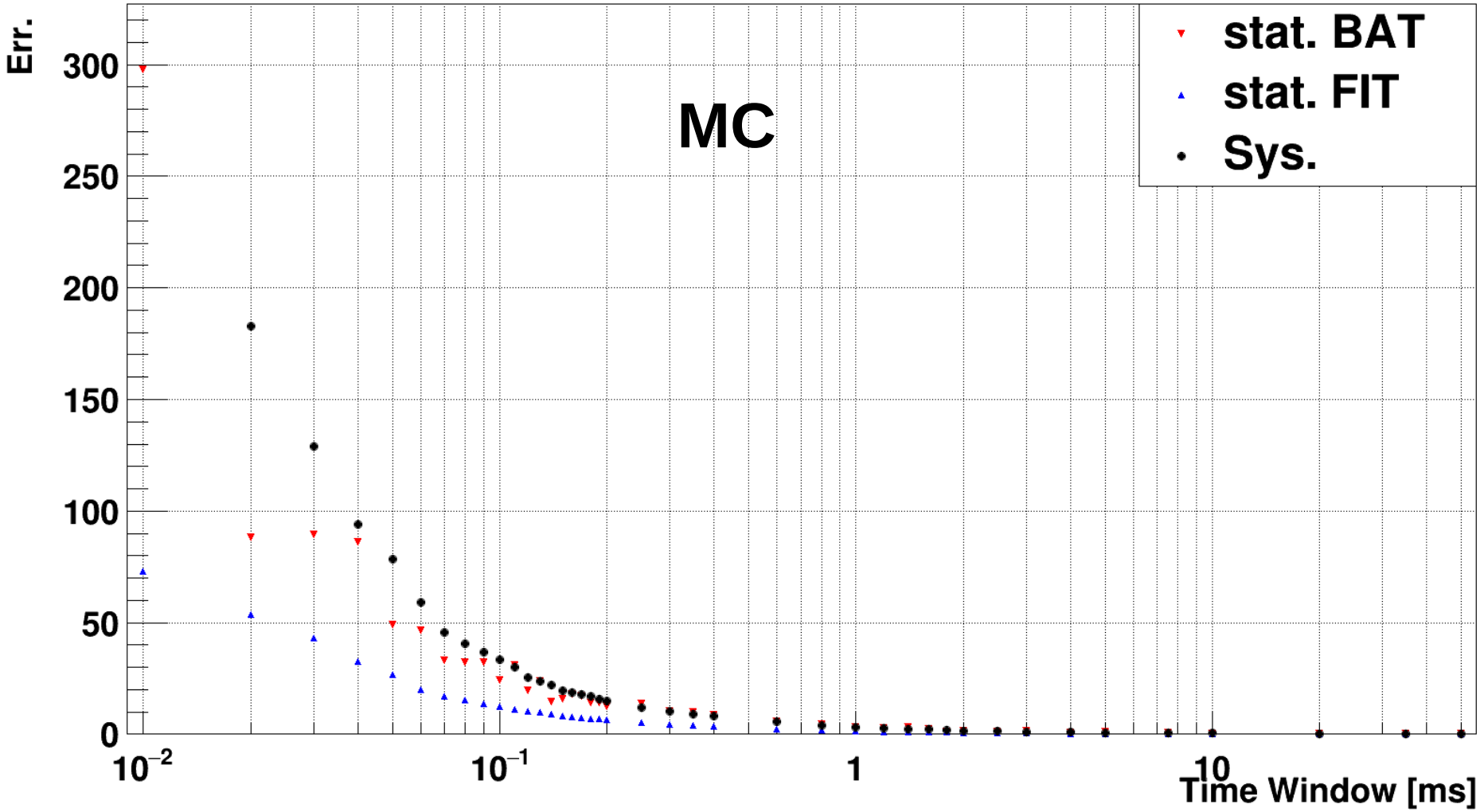

$\rho^{bat}_{S/B}$
450
400
350
300
250
200
150
100
50
10^{-2}
10^{-1}
1
10
Time Window [ms]
DATA
MC

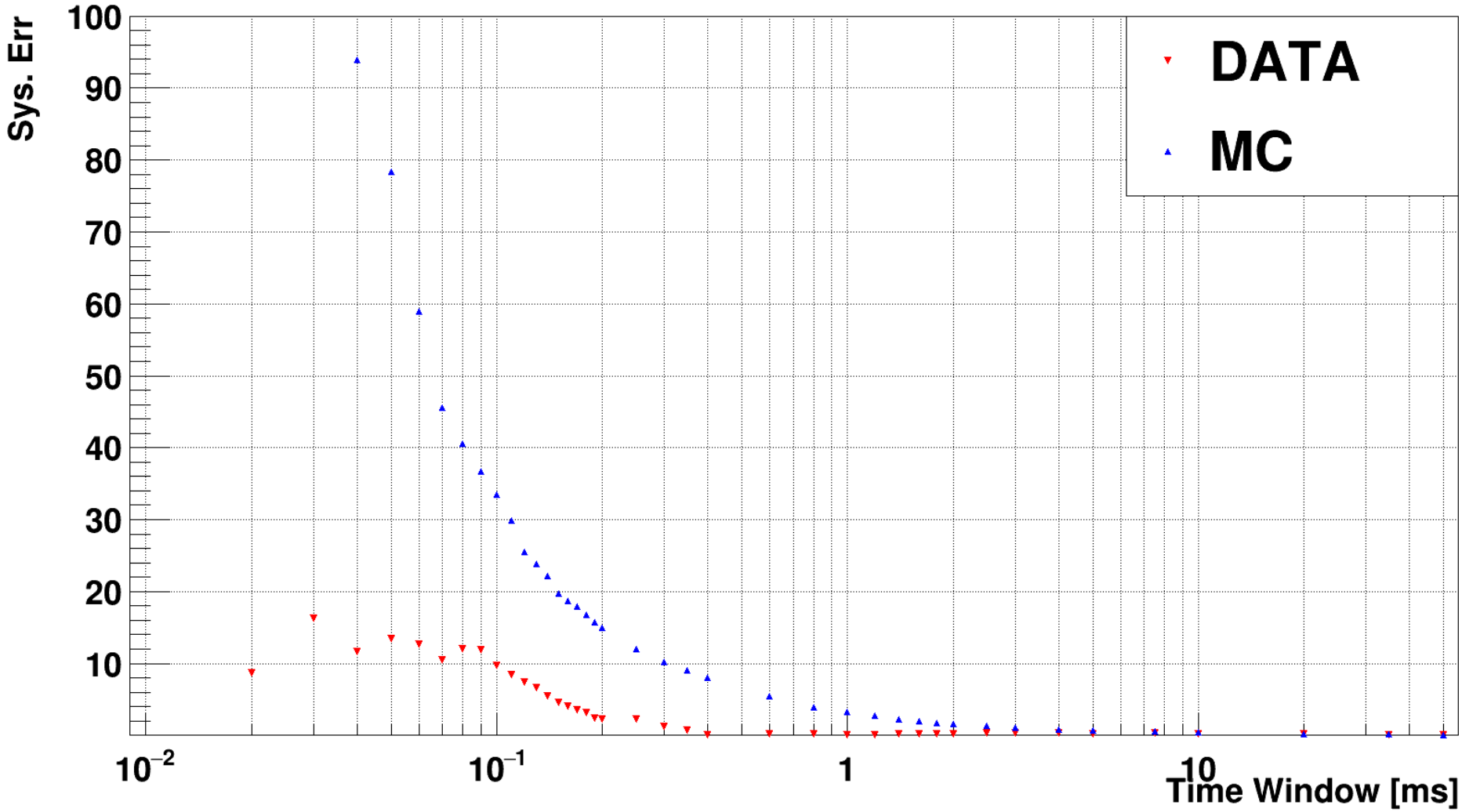

$\rho^{fit}_{S/B}$
100
90
80
70
60
50
40
30
20
10
10^{-2}
10^{-1}
1
10
Time Window [ms]
DATA
MC


$\rho^{fit}_{S/B}$
180
160
140
120
100
80
60
40
20
MC
10^{-2}
10^{-1}
1
10
Time Window [ms]


$\rho^{mc}_{S/B}$
500
400
300
200
100
0
10^{-2}
10^{-1}
1
10
Time Window [ms]
BAT
FIT


DATA
stat. BAT
stat. FIT
Sys.
Err.
160
140
120
100
80
60
40
20
0
10^{-2}
10^{-1}
1
10
Time Window [ms]


Err.
300
250
200
150
100
50
0
10^{-2}
10^{-1}
1
10
Time Window [ms]
MC
stat. BAT
stat. FIT
Sys.


Sys. Err
100
90
80
70
60
50
40
30
20
10
10^{-2}
10^{-1}
1
10
Time Window [ms]
DATA
MC

BAT Method

$$P(R_B, R_S|N_B, N_T) = \frac{P(N_T|R_B, R_S)P(R_S)P(R_B|N_B)}{\int P(N_T|R_B, R_S)P(R_S)P(R_B|N_B)dR_B dR_S} ,$$

with

$$P(R_B|N_B) = \frac{P(N_B|R_B)P(R_B)}{\int P(N_B|R_B)P(R_B)dR_B} .$$

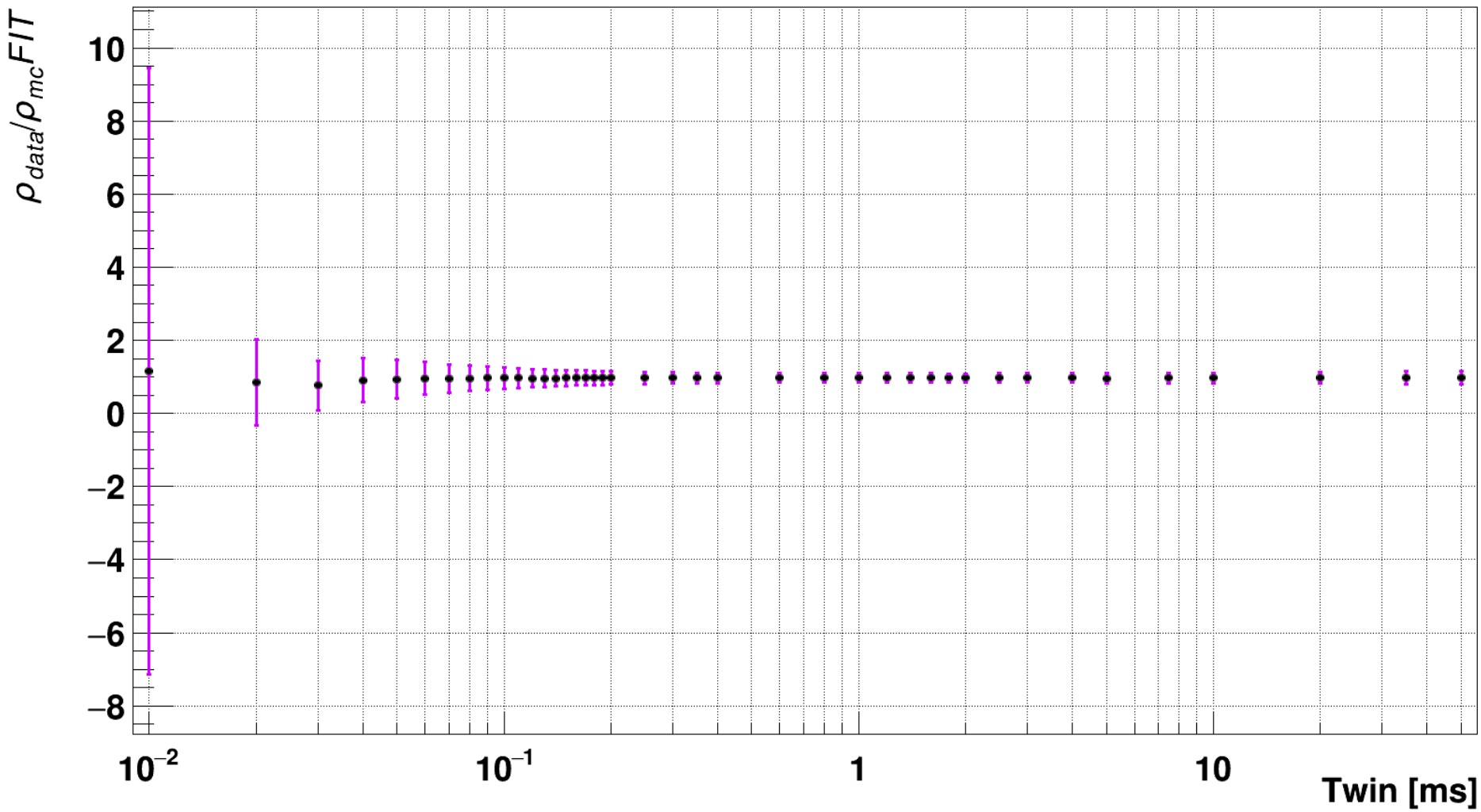
Combining

$$P(R_B, R_S|N_B, N_T) = \frac{P(N_T|R_B, R_S)P(N_B|R_B)P(R_S)P(R_B)}{\int P(N_T|R_B, R_S)P(N_B|R_B)P(R_S)P(R_B)dR_B dR_S} .$$

$$P(N_B|R_B) = \frac{e^{-\lambda_B} \cdot \lambda_B^{N_B}}{N_B!} , \qquad P(N_T|R_B, R_S) = \frac{e^{-\lambda_T} \cdot \lambda_T^{N_T}}{N_T!} .$$

$$P(R_S|N_B, N_T) = \int P(R_B, R_S|N_B, N_T)dR_B ,$$

DATA-MC comparison



References

[1] I. Abt, A.Caldwell. K. Kroeninger, J. Liu, X. Liu and B. Majorovits.
“Neutron interactions as seen by a segmented germanium detector”.
Eur. Phys. J. A 36, 139-149 (2008).

[2] T. Siiskonen, H. Toivonen.
“A model for fitting peaks induced by fast neutrons in an HPGe detector”.
Nucl. Instrum. Meth. A 540 (2005) 403-411.

[3] N. Jovancevic, M. Krmar, D. Mrda, J. Slivka and I. Bikit.
“Neutron induced background gamma activity in low level GE-spectroscopy systems”. Nucl. Instrum. Meth. A 612 (2010) 303-308.

[4] K. W. Geiger, L. Van Der Zwan,
“Radioactive neutron source spectra from Be(α,n)”
Nucl. Inst. and Meth. 131 (1975) 315.

[5] J. Ljungvall, J. Nyberg,
“A study of fast neutron interactions in high-purity germanium detectors”
Nucl. Inst. and Meth. in Phy. Res. A 546 (2005) 553–573

Slow Control

- Germanium detectors temperature
- Ambient temperature
- Ambient umidity
- Level and temperature of the water
- High voltages values
- Anything else??

https://github.com/mppmu/minidex/wiki

Simulation Info

- Gean4 9.6 (neutrons database has been presumably improved wrt 9.4)
- MaGe
- Particle injected: mu+
- Muon spectrum: @ Sea level starting from 1.897 GeV (AMS-02 during commisioning)
- Shooting direction distribution: NO angular distribution included
- Bertini Cascade ON

MINIDEX: Why Lead?

- High Z material → good neutron production
- Often used in Low Background Experiments

In the future, different materials can be used:

- Soil
- Stainless Steel
- Concrete
- Anything else??????

Efficiencies Results

	Efficiency (tot ev.: 1.59998e07 μ)
n OUT from Lead	2.8×10^{-2}
n OUT from Water	4.0×10^{-3}
n IN @GeDet	8.9×10^{-4}
2.2 γ OUT from Water	6.8×10^{-4}
2.2 γ IN @GeDet	1.4×10^{-4}
2.2 γ IN @GeDet after 1 ms	1.1×10^{-6}
2.2 γ Detected by GeDet	7.7×10^{-6}

~ 14%

Water OK:

- γ energy
- thickness

Efficiencies Results

	Efficiency (tot ev.: 1.59998e07 μ)
n OUT from Lead	2.8×10^{-2}
n OUT from Water	4.0×10^{-3}
n IN @GeDet	8.9×10^{-4}
2.2 γ OUT from Water	6.8×10^{-4}
2.2 γ IN @GeDet	1.4×10^{-4}
2.2 γ IN @GeDet after 1 ms	1.1×10^{-6}
2.2 γ Detected by GeDet	7.7×10^{-6}

~ 22%
hitting the detector

Efficiencies Results

	Efficiency (tot ev.: 1.59998e07 μ)
n OUT from Lead	2.8×10^{-2}
n OUT from Water	4.0×10^{-3}
n IN @GeDet	8.9×10^{-4}
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~ 0.8%
=> most γs arrive before 1 ms

Efficiencies Results

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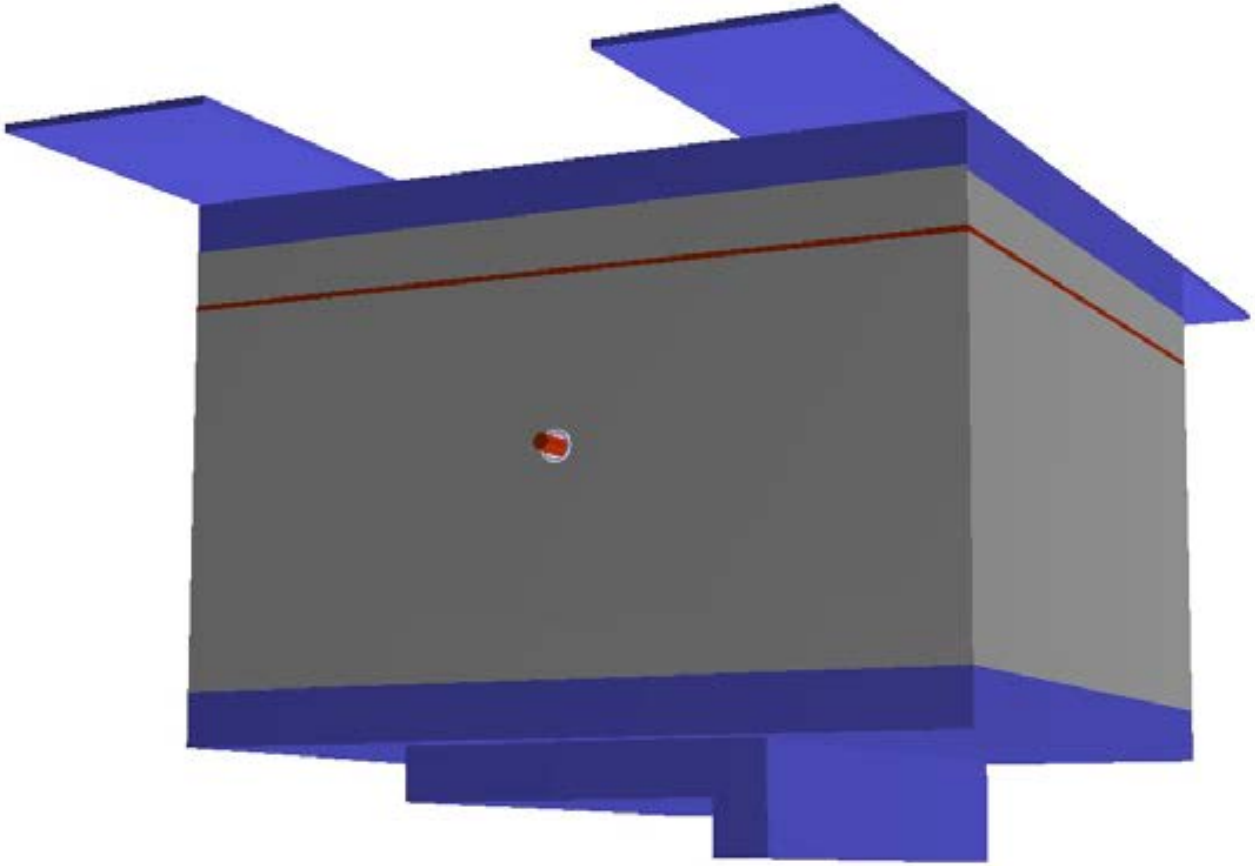
2.2 γ Detected by GeDet	7.7×10^{-6}

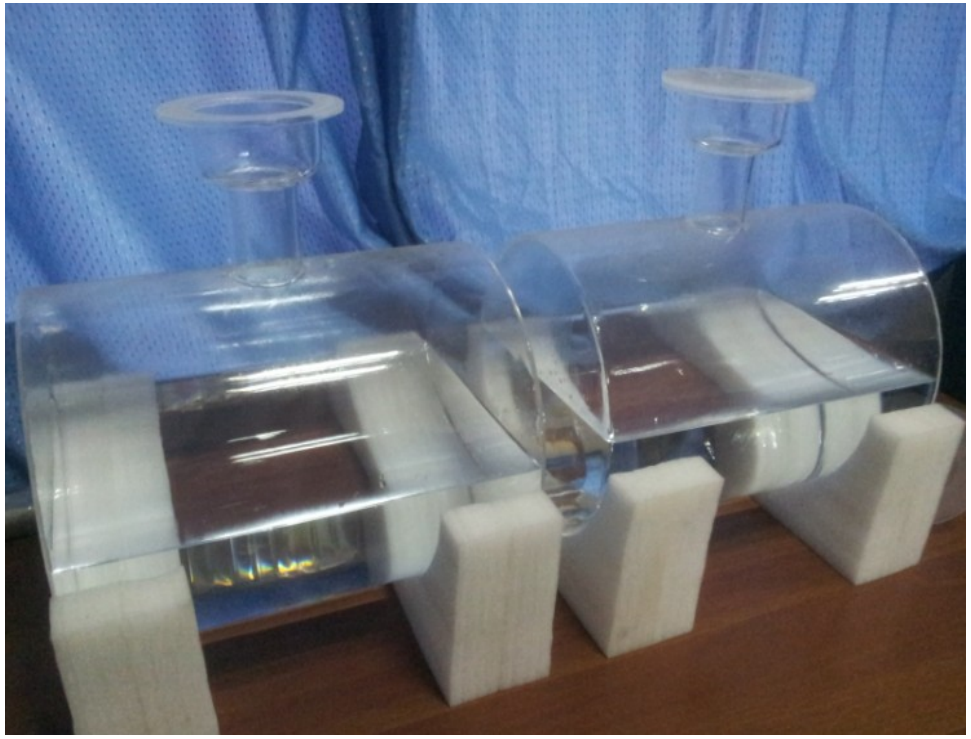
~ 0.8%
=> most γs arrive before 1 ms

MINIDEX: Geometry

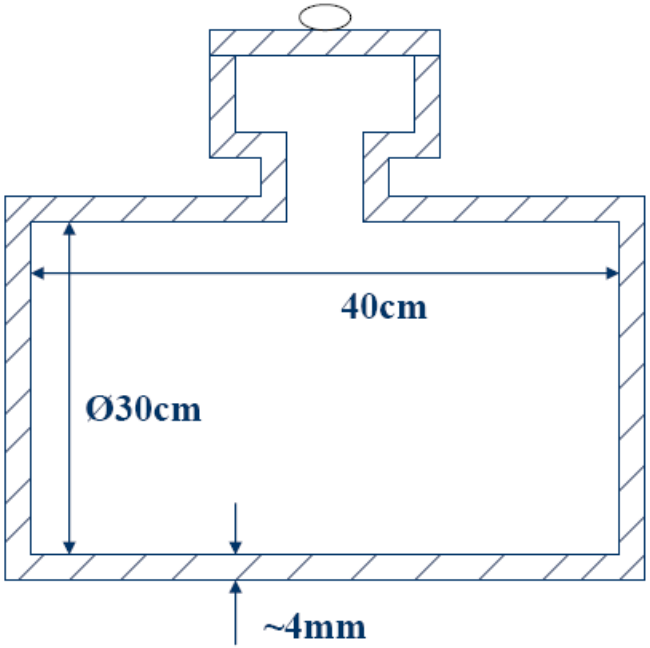


- Summary:
  - Simple and relatively cheap setup
  - **Integrated 2.2 MeV gamma yield per muon DEPOSITING FULL energy into Ge-det ~ 7.66×10^{-6}**
  - Pre-test above ground (insufficient S/B)
- Outlook:
  - Pending issues and details to be discussed
  - Improve the analysis technique
  - Test the whole apparatus at MPI
  - Install MINIDEX at Tuebingen
    - Fast Neutron flux bkg measurement ??
    - Bkg in ROI in Ge measurement ??

Fast Neutron Detector

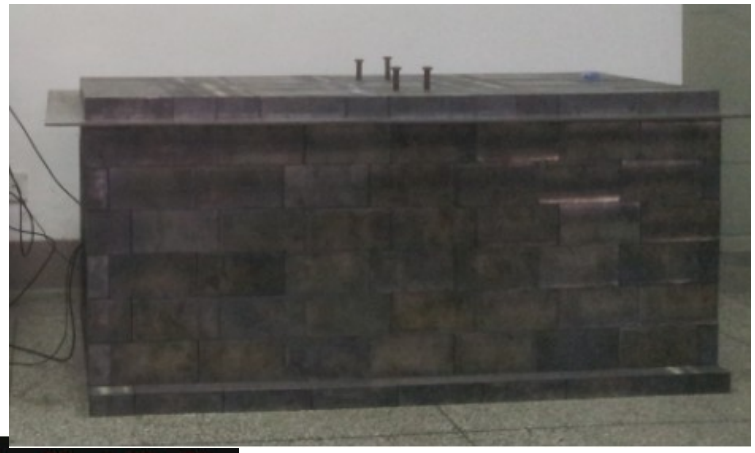


- Shipping issue at the moment
- Quartz glass container
- EJ335 liquid scintillator (organic)
- 2 PMTs



Fast Neutron Detector

- Shipping issue at the moment
- 2 Quartz glass container
- EJ335 liquid scintillator (organic)
- 2 PMTs
- Aluminum or Copper flange
- It will be placed inside a steel container 1295x570x935 mm3, 2 mm thick

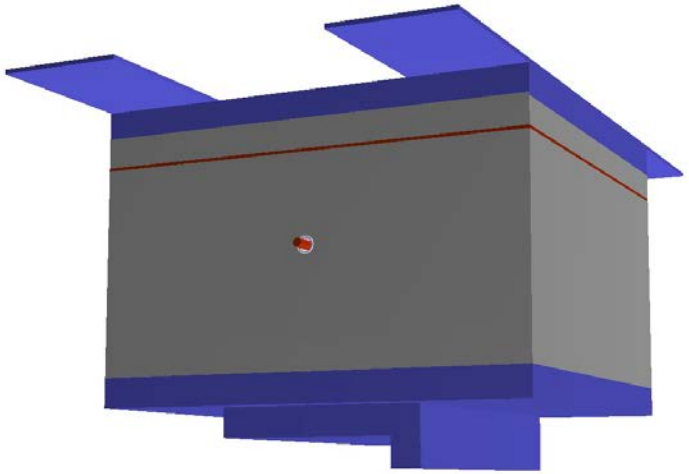


Fast Neutron Detector

Where do we want to place it?

- **Right next to MINIDEX (neutrons production ~6e-3)**

- **Inside the Lead**
  withOUT the water and withOUT its steel container



Signal Rate Estimates

- Measured Muon Flux @SUL $\Phi_\mu(SUL) \approx 80\ m^{-2}\ s^{-1}$
- Estimated muon flux geometrical reduction ~ 1/27.3
- Estimated muon trigger-flux $\Phi_\mu^{trigger}(SUL) \approx 1.05 \frac{\mu}{h \cdot cm^2}$
- Trigger Area = 65x75 cm2
- Estimated 2.2 MeV detection efficiency ~ 7.66×10^{-6}
- Estimated Signal Rate ~ 28 events/month

Background Rate Estimates

- How much underground? ==> ~ 8 m (13.2 m w.e.)
  - μ flux ~ 6×10^{-3} cm^{-2} s^{-1} ~ ½ μ flux @ sea level
  - n_tot flux ~ $3 \div 2 \times 10^{-5}$ cm^{-2} s^{-1}
    ~ 10^{-2} n flux @ sea level

    ==> S/B ~ 50 times better

- Do we need a bkg measurement (without the Lead)?

We might estimate it from the non-trigger events

The Experimental Setup: the idea

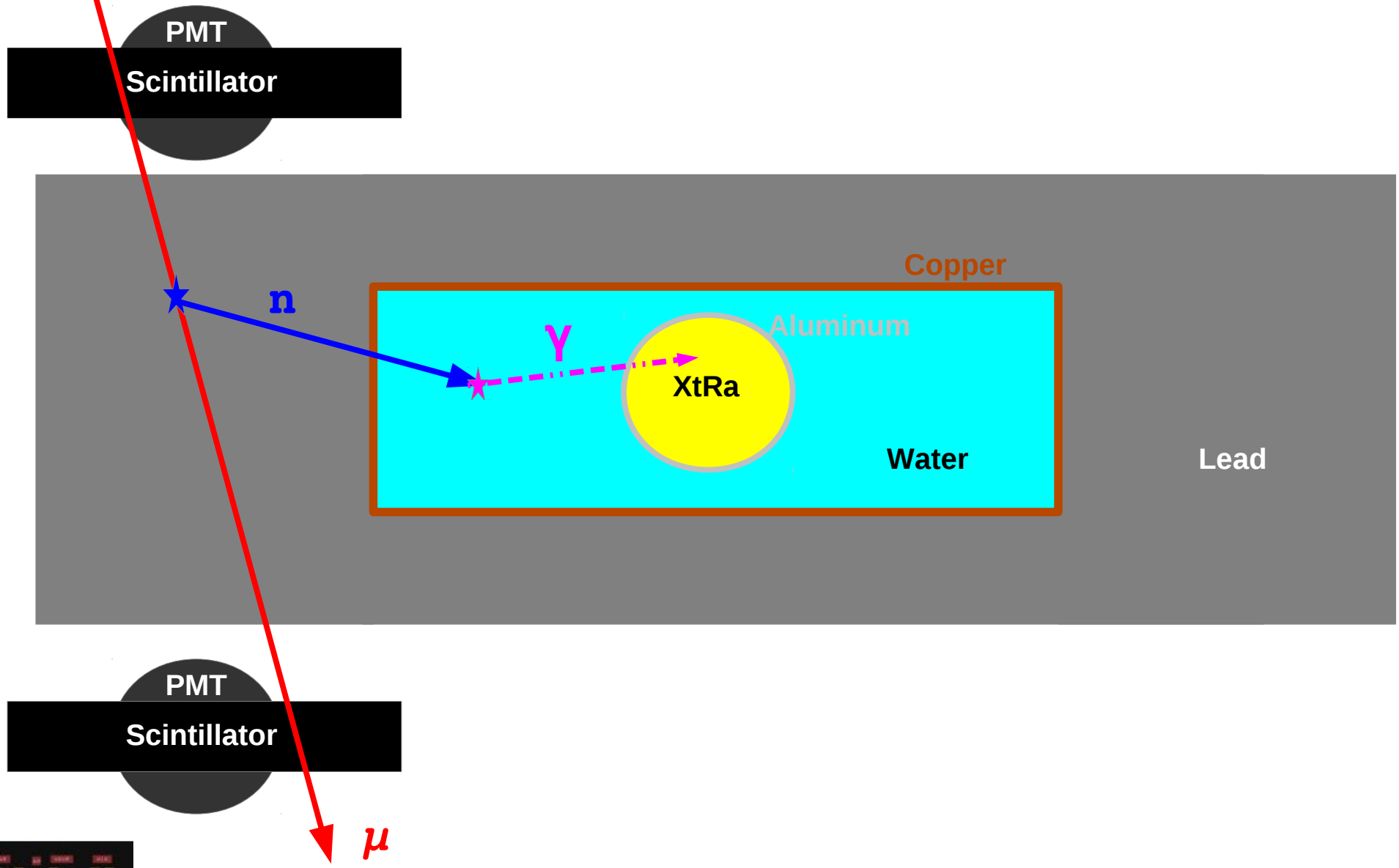


Table 1
Neutron spectrometer characteristics

Spectrometer				Typical characteristics for		
No.	Type	Ref.	Energy range (MeV)	Energy (MeV)	Resolution (FWHM)	Detection efficiency
1	Recoil proportional counter	[27]	0.05–5	1	10%[a]	3%
2	Organic scintillator	[31]	2–150	8	4%[a]	20%
3	Recoil proton telescope	[45]	1–250	60	4%[a]	<0.05%
4	Capture-gated	[49]	1–20	5	50%[a]	1%
5	^{3}He gridded ionization chamber	[61]	0.05–10	1	2%[a]	0.3%
6	^{3}He-semiconductor sandwich	[64]	0.1–20	1	50 keV[a]	0.1%
7	Diamond semiconductor	[68]	8–20	14	1%[b]	1%
8	Time-of-flight	[74]	1–15	2.5	5%[c]	0.05 cm^{-2}
9	Foil radioactivation	[79]	0.2–20	—	—	—
10	Superheated drop (bubble)	[82]	0.1–20	—	—	—
11	Multisphere	[91]	10^{-8}–200	—	—	—

[a] Pulse height resolution.
[b] Energy resolution.
[c] Time-of-flight resolution.

Back Of The Envelope Calculations

- Estimated Trigger Rate ~ 0.2 Hz
- Run Time ~ 15 days
  ==> Estimated # of Trigges ~ $3x10^5$
- Full energy deposition detection eff. @2.2MeV ~ 10^{-6}
- Estimated signal events ~ 0.3 ev/15 days
- Estimated # of BKG events (1 ms win) ~ 10 ev/15 days

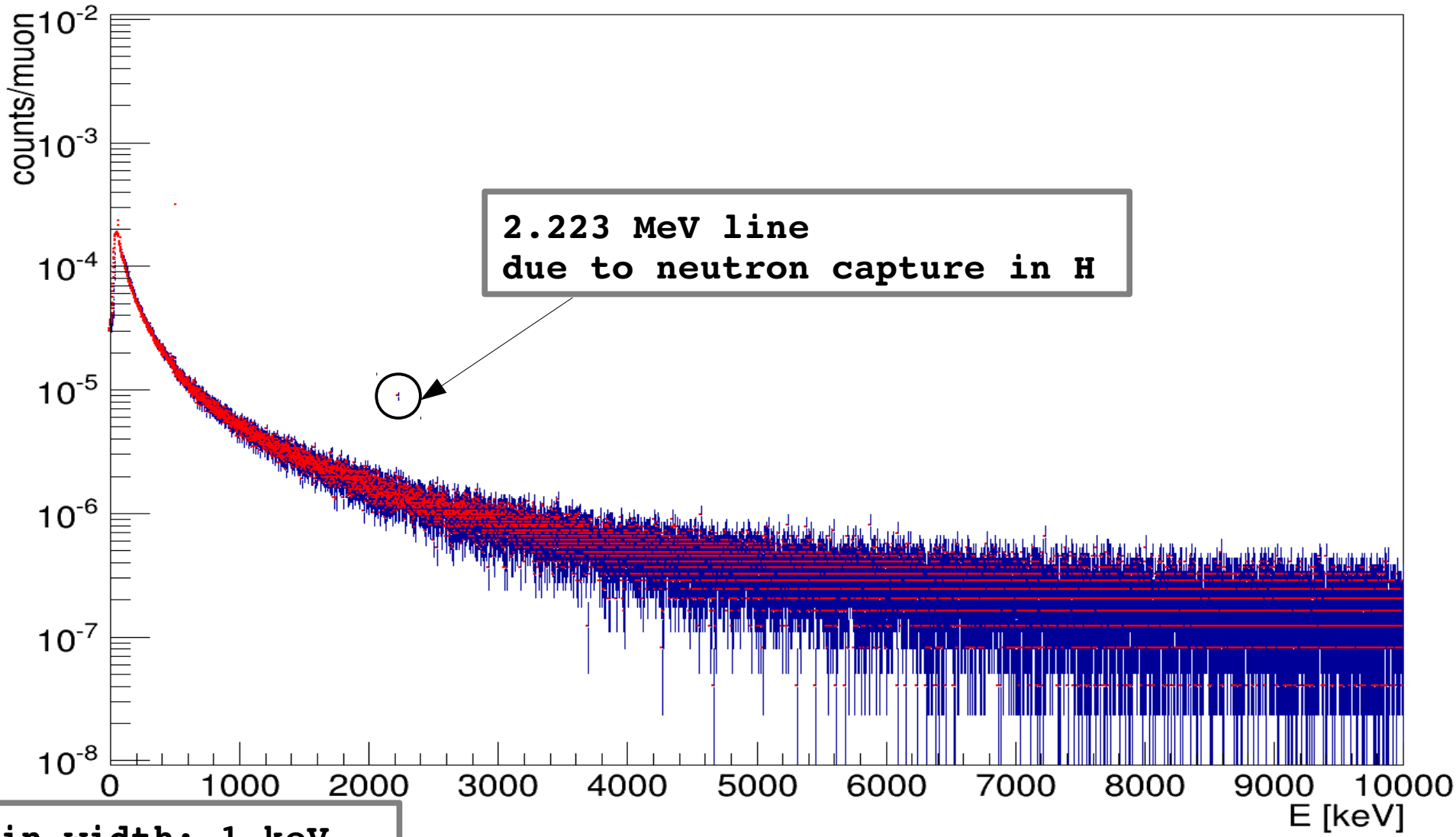
==> increase trigger rate
==> bigger trigger area

==> reduce the BKG
==> go shallow underground

Simulation Info

- Gean4 9.6 (neutrons database has been presumably improved wrt 9.4)
- MaGe
- Particle injected: mu+
- Muon spectrum: @ Sea level starting from 1.897 GeV (AMS-02 during commisioning)
- Physics list used: qgsp_hadron_list
- Muons generation plane == uppuermost scintilator surface
- Shooting direction: vertical

Particle Energy Deposition in Ge



bin width: 1 keV

Efficiency Results

- integrated 2.2MeV gamma yield per muon DEPOSITING FULL energy into Ge-det ~ 2.5×10^{-5}

- Estimated muon flux @ SUL(CJPL) ~ 7×10^{-5} cm^{-2} s^{-1}
  - For 100x50 cm^2 scintillator area ==> 0.35 Hz
  - Assuming that are all energetic enough
    ==> 1 mu every ~3 s
    ==> 2 events every 3 days

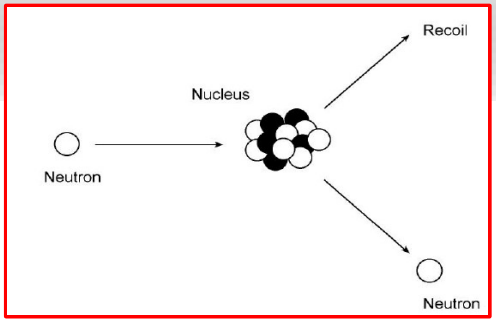
  ==> Not doable!!!

  ==> Need ~ two order of magnitude higher flux

Neutrons Interactions

- **Elastic Scattering:**

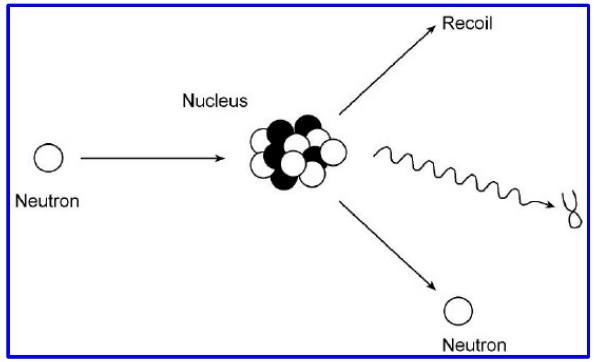
$$n + {}^{A}_{Z}N \rightarrow n' + {}^{A}_{Z}N$$



- **Inelastic Scattering:**

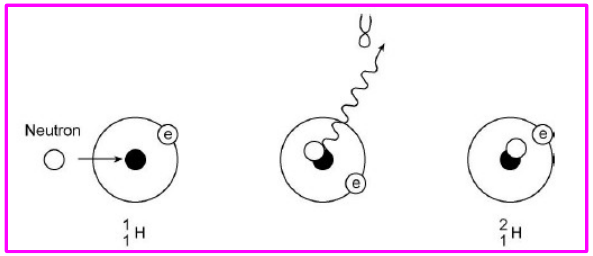
$$n + {}^{A}_{Z}N \rightarrow ({}^{A+1}_{Z}N)^* \rightarrow n' + {}^{A}_{Z}N + \gamma$$

$$n + {}^{A}_{Z}N \rightarrow ({}^{A+1}_{Z}N)^* \rightarrow n' + {}^{A}_{Z+1}N^+ + e^-$$



- **Thermal Capture:**

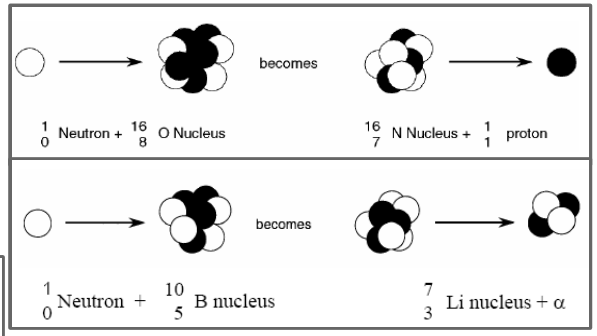
$$n + {}^{A}_{Z}N \rightarrow {}^{A+1}_{Z}N + \gamma$$



- **Transmutation:**

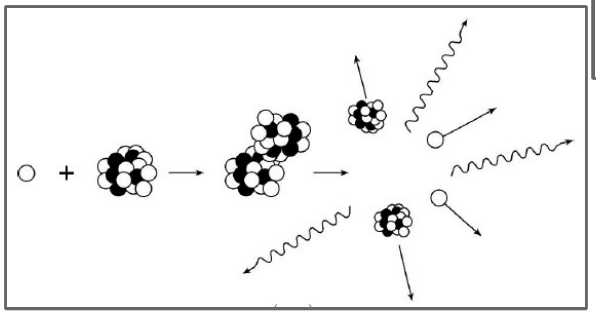
$$n + {}^{A}_{Z}N \rightarrow {}^{A}_{Z-1}N + p$$

$$n + {}^{A}_{Z}N \rightarrow {}^{A-3}_{Z-2}N + {}^{4}_{2}\alpha$$

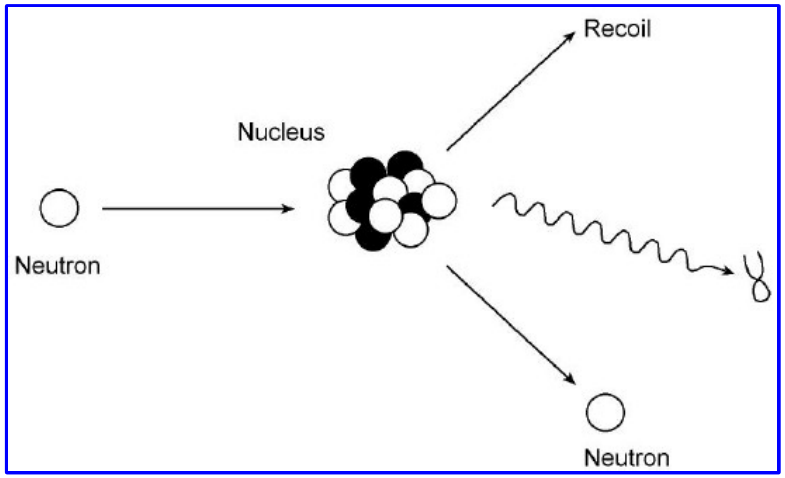


- **Fission:**

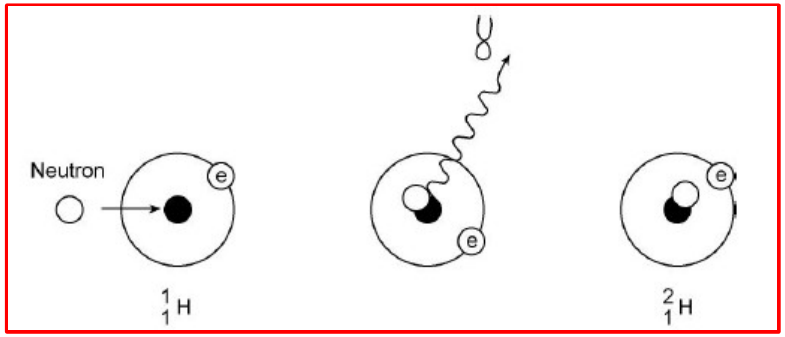
$$n + {}^{A}_{Z}N \rightarrow {}^{A_1}_{Z_1}X + {}^{A_2}_{Z_2}Y + n$$



- **Inelastic Scattering:**



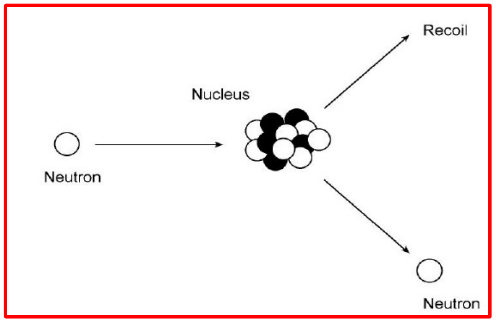
- **Thermal Capture:**

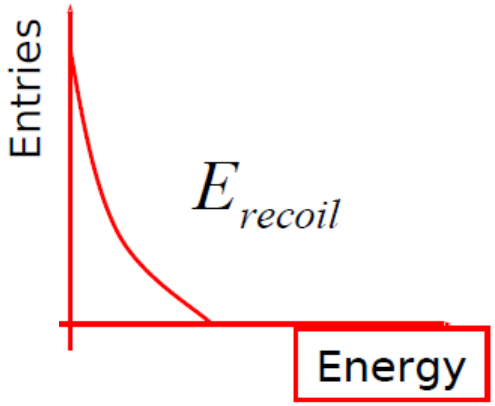


Peaks due to neutron interactions		
Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
139.6	0.6 ± 0.1	$^{74}Ge(n,\gamma^m)$
174.8	0.5 ± 0.2	$^{70}Ge(n,n'\gamma)$
198.3	0.6 ± 0.0	$^{70}Ge(n,\gamma^m)$
326.0	0.7 ± 0.1	$^{70}Ge(n,\gamma)$
500.0	0.7 ± 0.1	$^{70}Ge(n,\gamma)$
574.8	0.7 ± 0.4	$^{74}Ge(n,\gamma)$
596.0	0.6 ± 0.1	$^{74}Ge(n,n'\gamma)$
609.2	1.0 ± 0.3	$^{74}Ge(n,n'\gamma)$
662.4	0.7 ± 0.1	$^{140}Ce(n,\gamma)$
691.8	-	$^{72}Ge(n,n'e)$
708.3	0.7 ± 0.1	$^{35}Cl(n,\gamma)$
831.5	0.7 ± 0.5	$^{70}Ge(n,\gamma)$
834.1	-	$^{72}Ge(n,n'\gamma)$
843.9	0.7 ± 0.3	$^{27}Al(n,n'\gamma)$
846.9	0.8 ± 0.1	$^{56}Fe(n,n'\gamma)$
868.2	0.8 ± 0.2	$^{73}Ge(n,\gamma)$
962.0	0.7 ± 0.2	$^{63}Cu(n,n'\gamma)$
1014.6	0.9 ± 0.3	$^{27}Al(n,n'\gamma)$
1096.8	1.4 ± 0.4	$^{70}Ge(n,\gamma)$
1139.7	0.9 ± 0.3	$^{70}Ge(n,\gamma)$
1165.0	1.0 ± 0.4	$^{35}Cl(n,\gamma)$
1201.6	0.8 ± 0.1	DEP of 2223.2
1204.4	0.9 ± 0.4	$^{73}Ge(n,\gamma)$
1298.7	0.8 ± 0.4	$^{70}Ge(n,\gamma)$
1327.2	0.9 ± 0.4	$^{63}Cu(n,n'\gamma)$
1712.3*	1.4 ± 0.1	SEP of 2223.2
1778.8*	1.0 ± 0.3	$^{27}Al(n,\gamma)$
2223.0*	1.2 ± 0.0	$^{1}H(n,\gamma)$
*These peaks where fitted on the gain 3 spectra.		

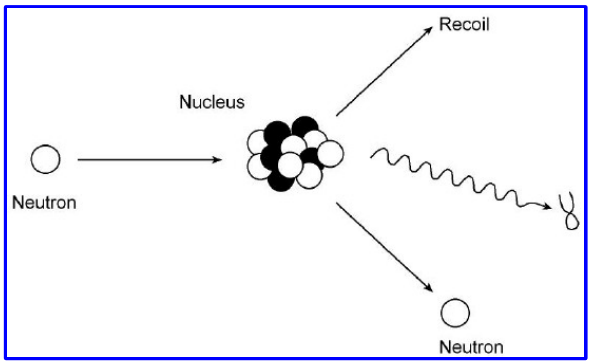
Neutrons Interactions

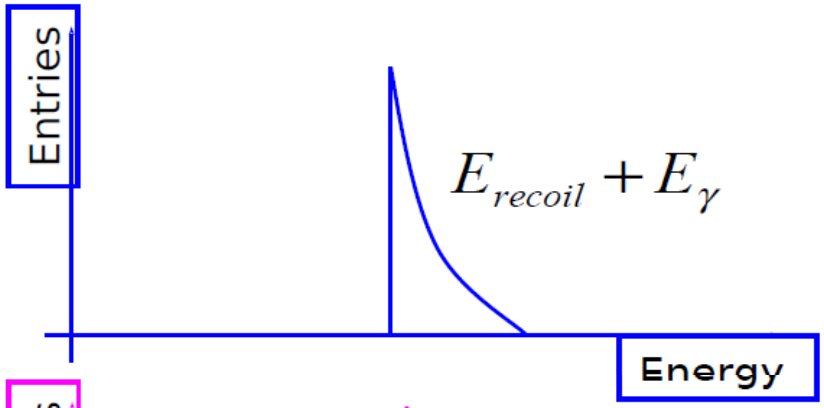
- **Elastic Scattering:**



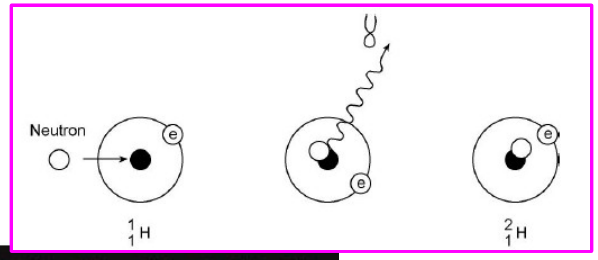


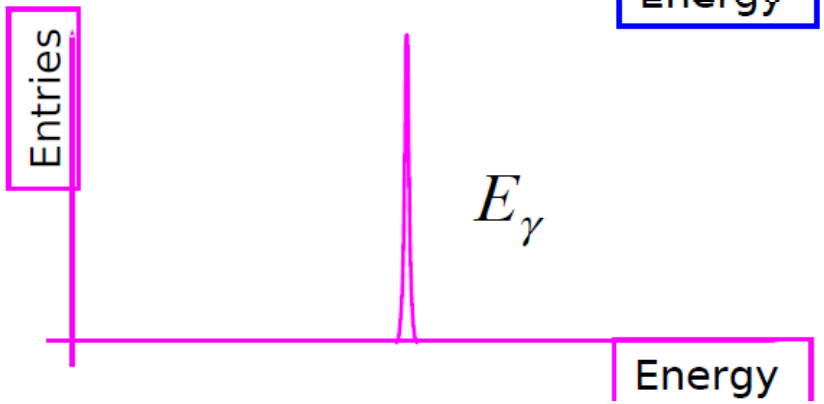
- **Inelastic Scattering:**





- **Thermal Capture:**

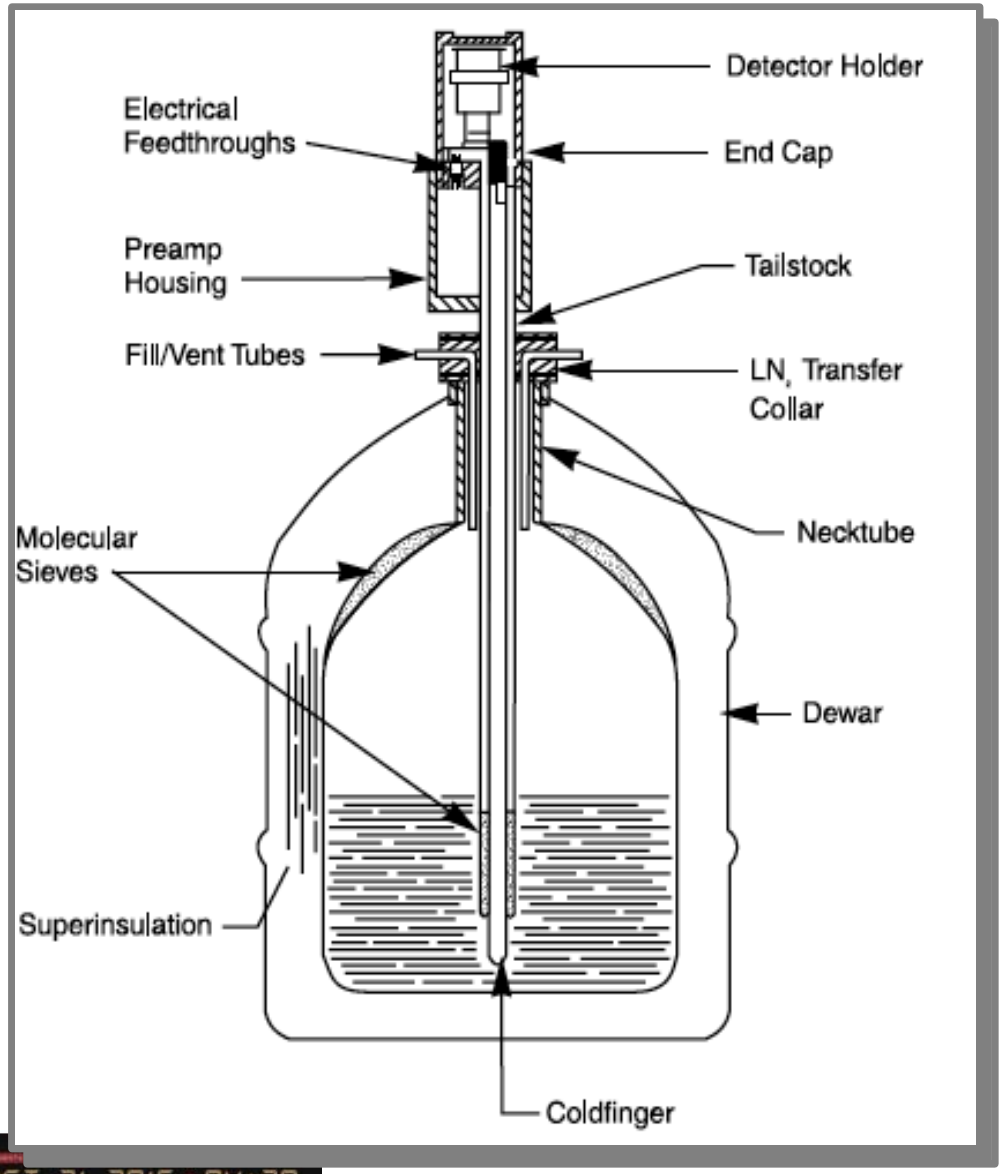




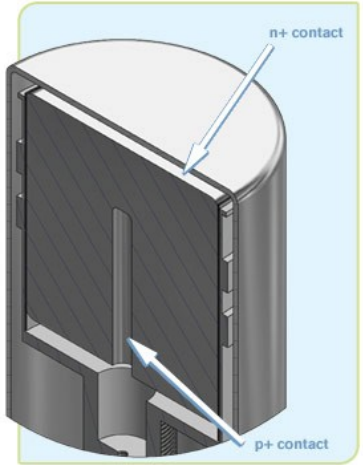
Efficiency Results

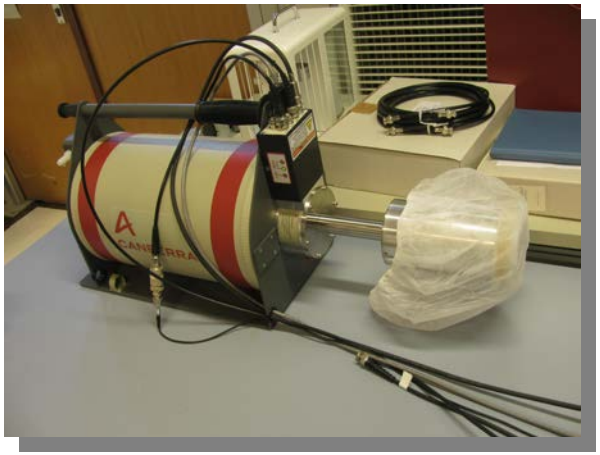
- Integrated neutron yield per muon ~ 0.7×10^{-1}
  - but on average ~ 3.4 neutrons/interaction
    ==> not every 10th muon produces neutrons

The Experimental Setup: eXtended Range GeDet

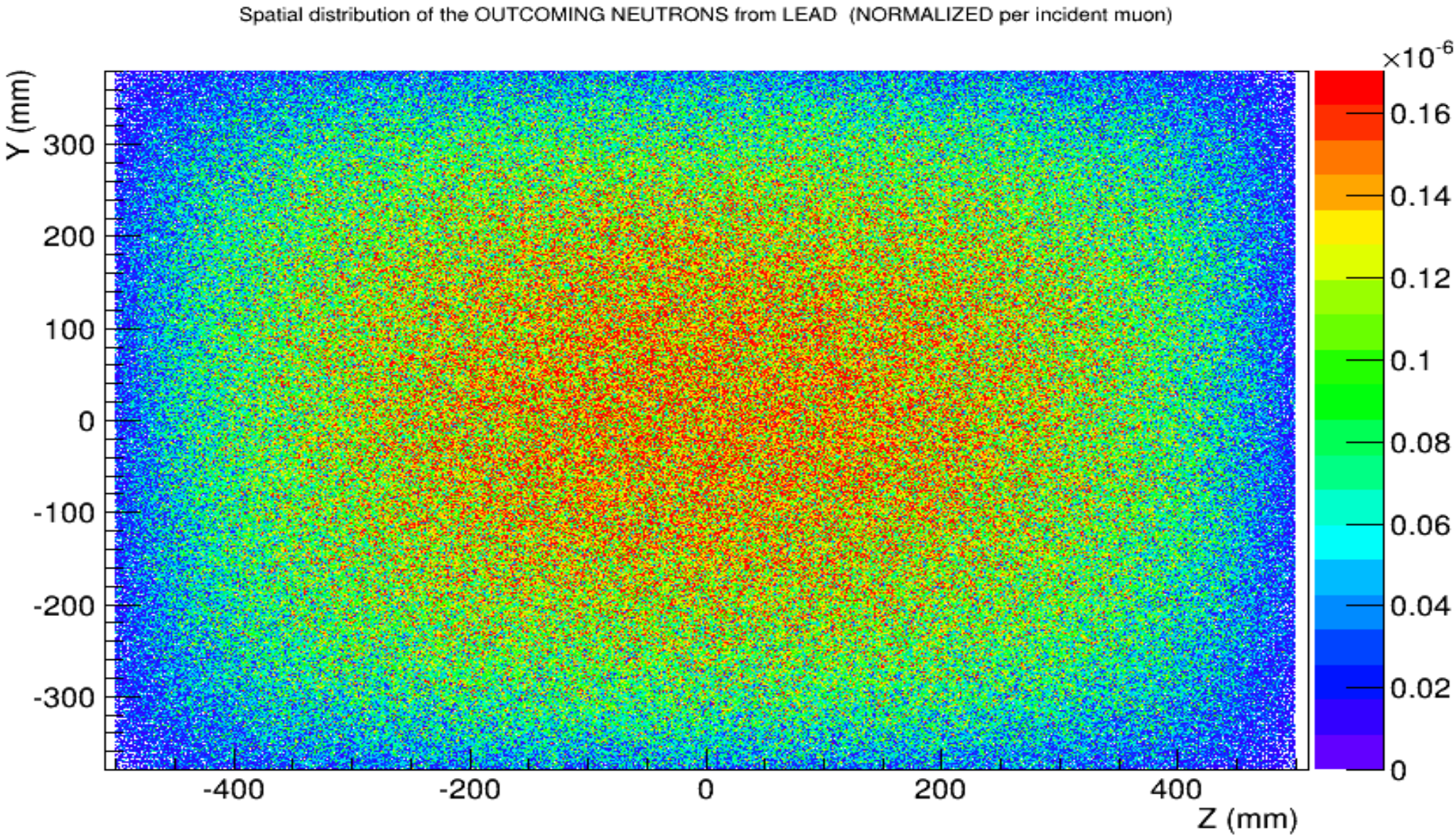


- Resolution: 2 keV @ 1.33 MeV
- p-type
- Peak/Compton 67:1
- Aluminum End Cup
- Copper Holder
- HV = +3000 V
- Charge sensitive pre-amp
- Diameter 6.9 cm
- Lenght 7.2 cm
- Outer electrode (n+) 0.6 mm
- Inner electrode (p+) 0.3 μm

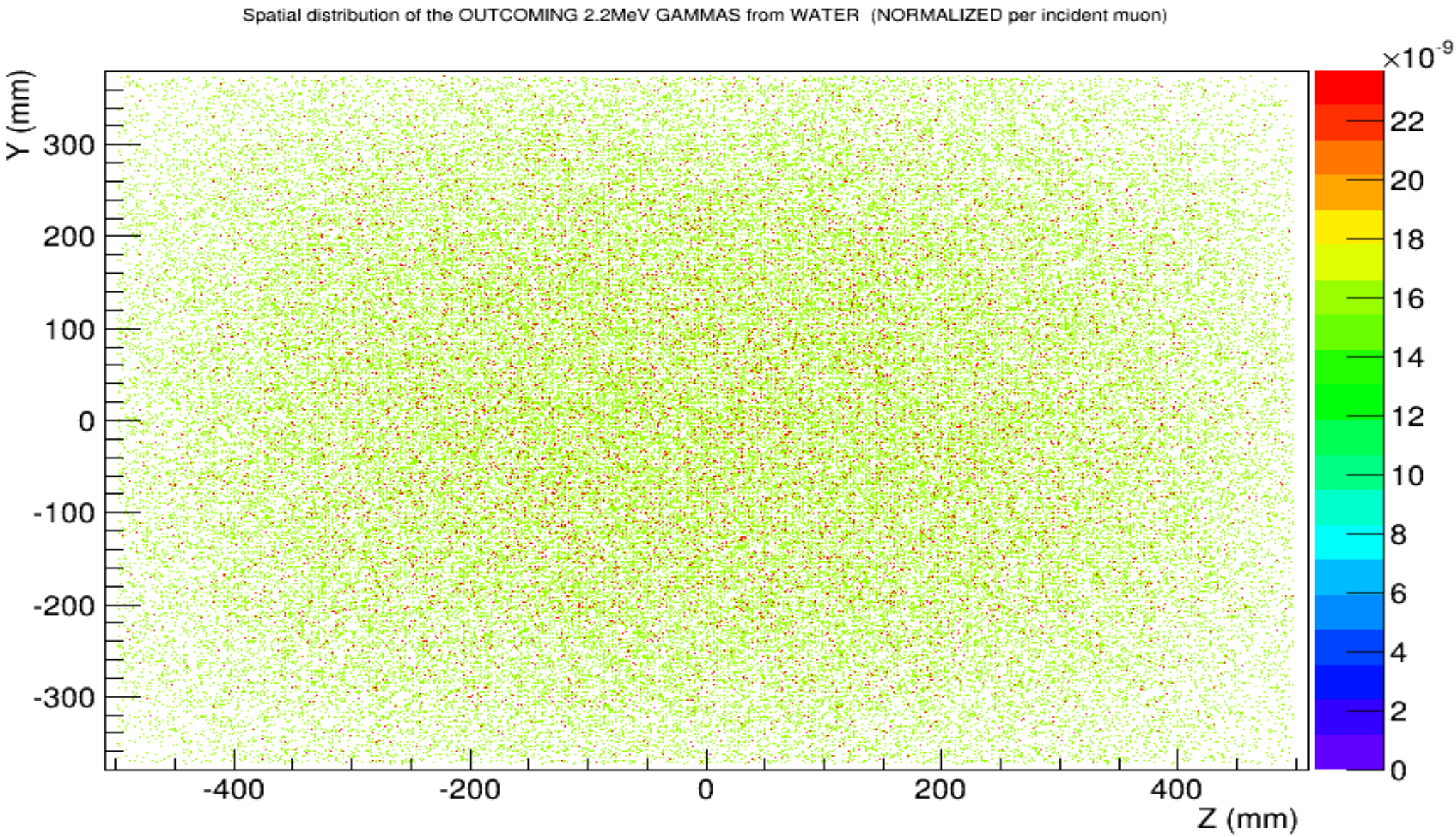




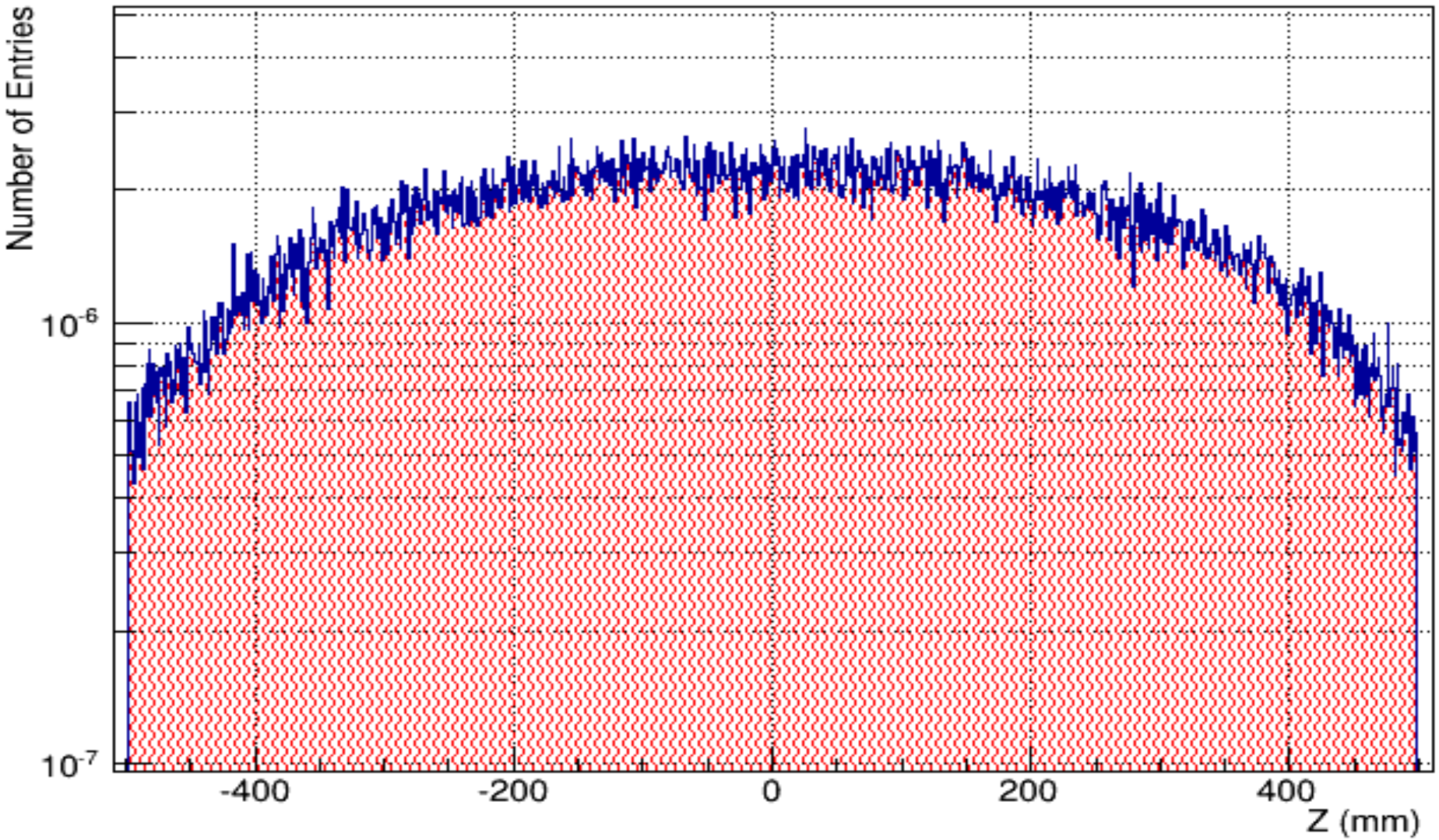
OUTGOING Neutrons @ LEAD wall



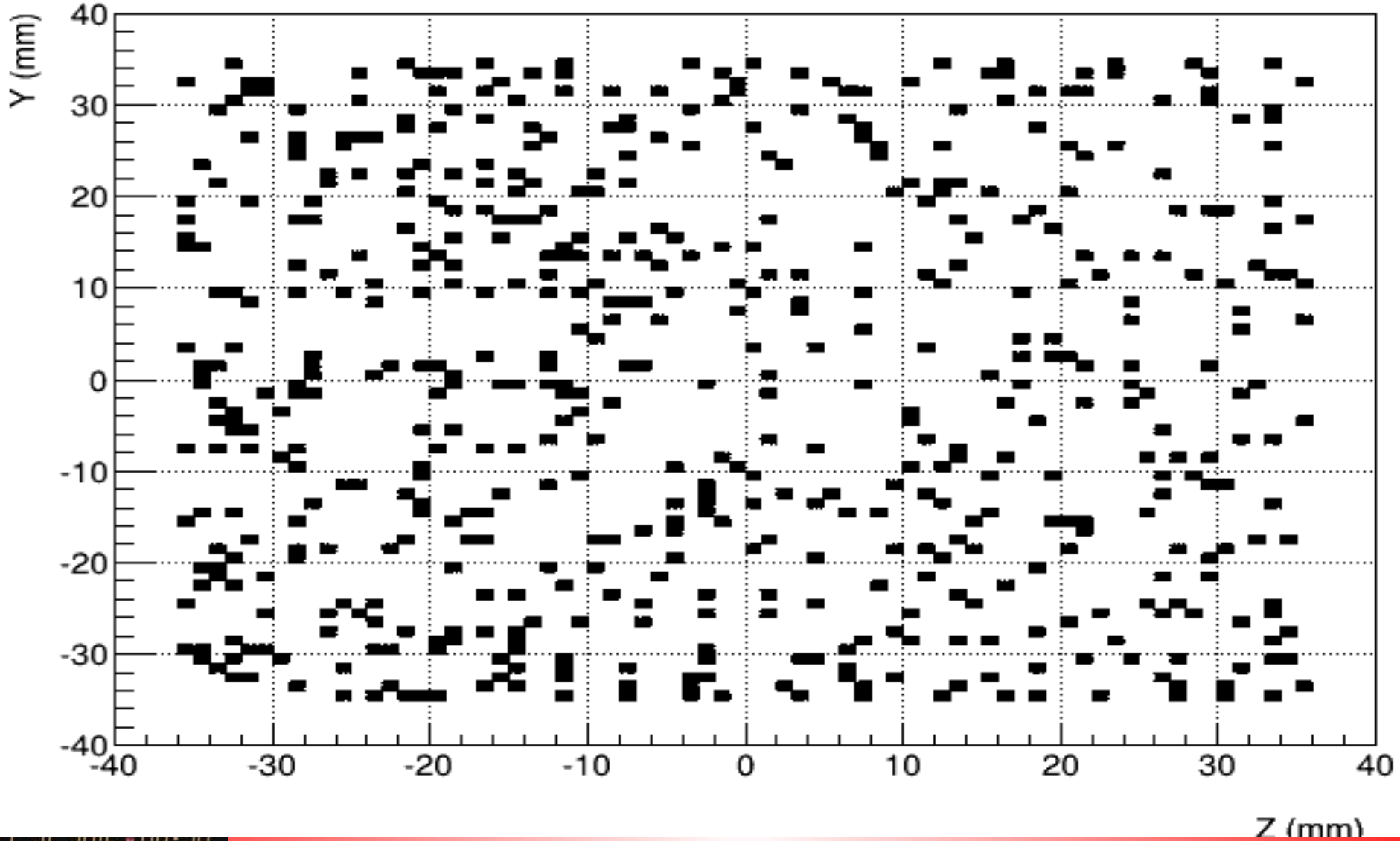
OUTGOING 2.2 MeV Gammas @ Water wall



OUTGOING 2.2 MeV Gammas @ Water wall

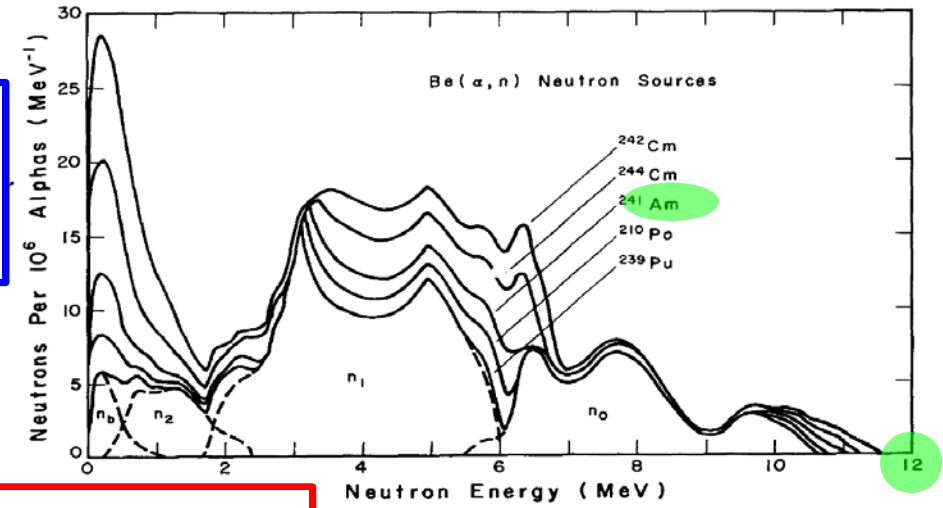


INCOMING 2.2 MeV Gammas into GeDet



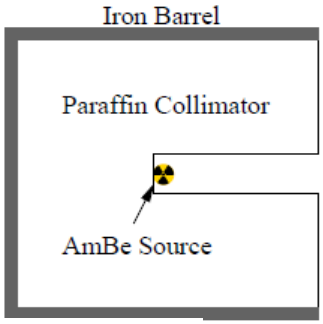
AmBe neutron source

$$^{241}_{95}Am \rightarrow ^{4}_{2}\alpha + ^{237}_{93}Np$$



$$^{4}_{2}\alpha + ^{9}_{4}Be \rightarrow (^{12}_{6}C)^{*} + n$$

de-excitation gammas

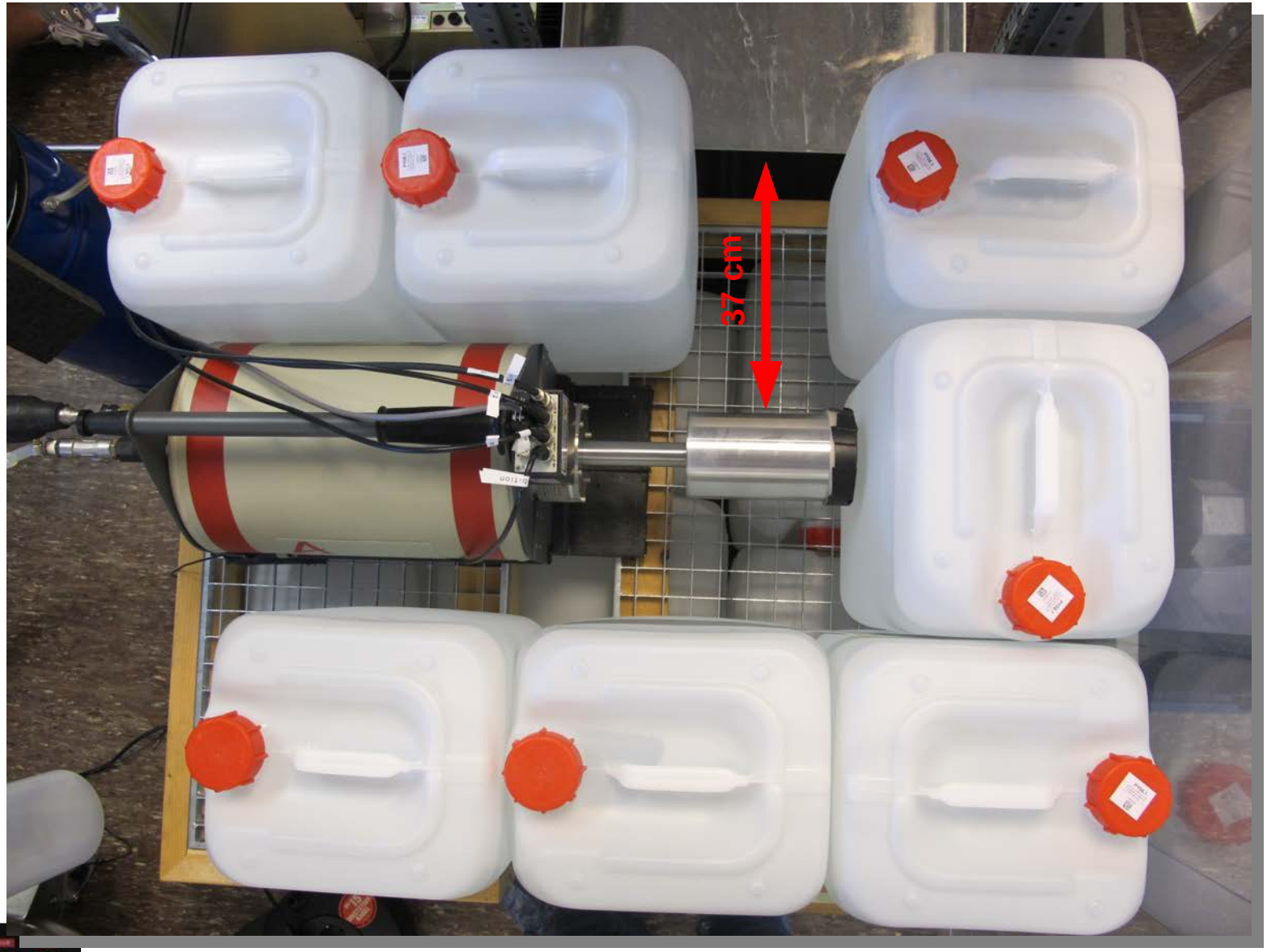


- **1.1 GBq**
- **Am-241 → 432.2 y half life**

Characteristics of Be(α,n) sources.

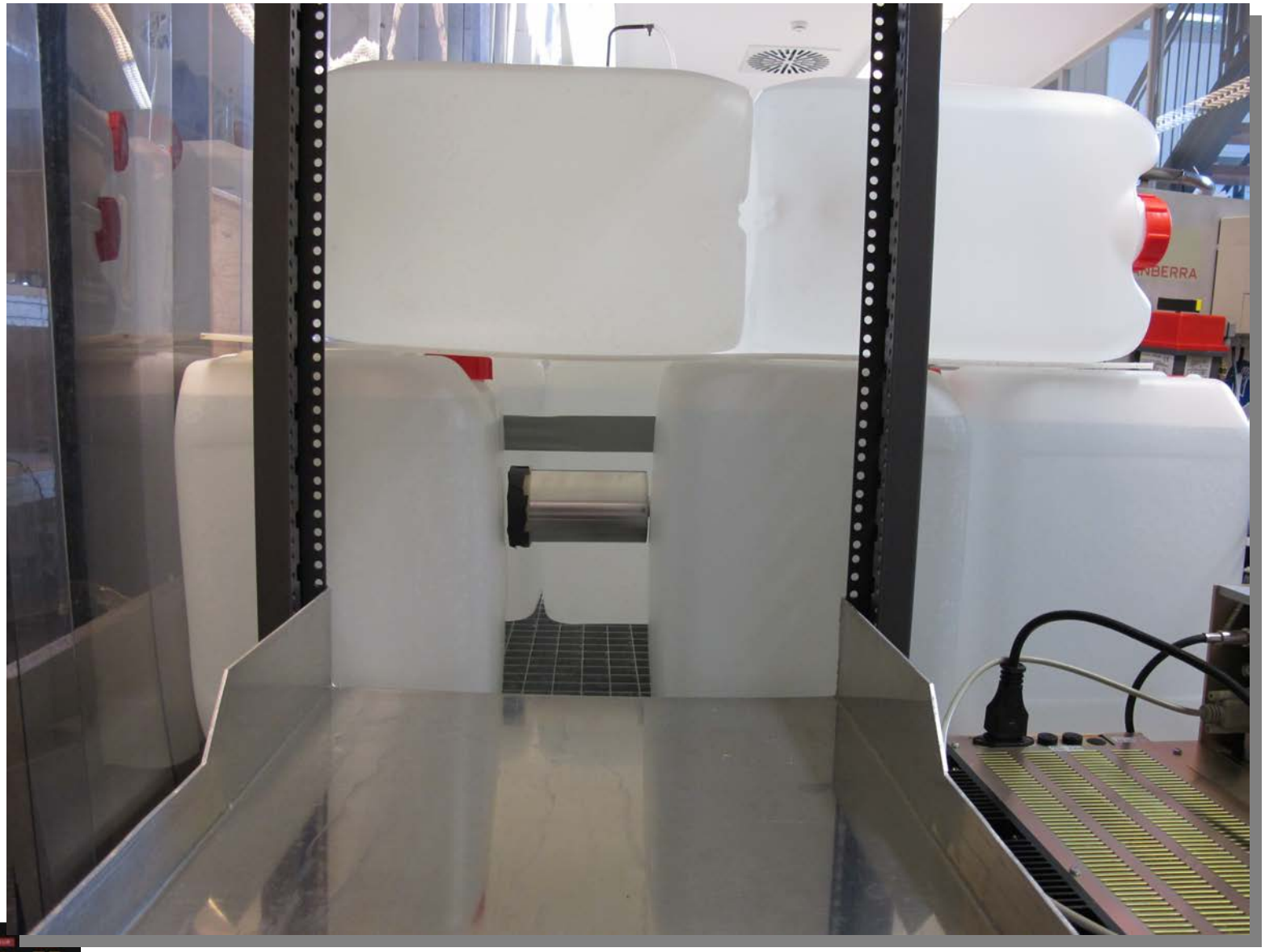
Source	E_α (MeV)	Yield per 10^6 alphas			Fraction with E_n<1.5 MeV		E_n	
		This work	Maximum experimental	Y from eq. (7)	This work (%)	Literature (%)	This work (MeV)	Literature (MeV)
1	2	3	4	5	6	7	8	9
^{241}Am–Be	5.48	82 ± 8	70 ± 3[18]	72	14 ± 2	15[25] 23[21]	4.46	3.9[27] 4.3[26]

Reference measurement: AmBe



Reference measurement: AmBe

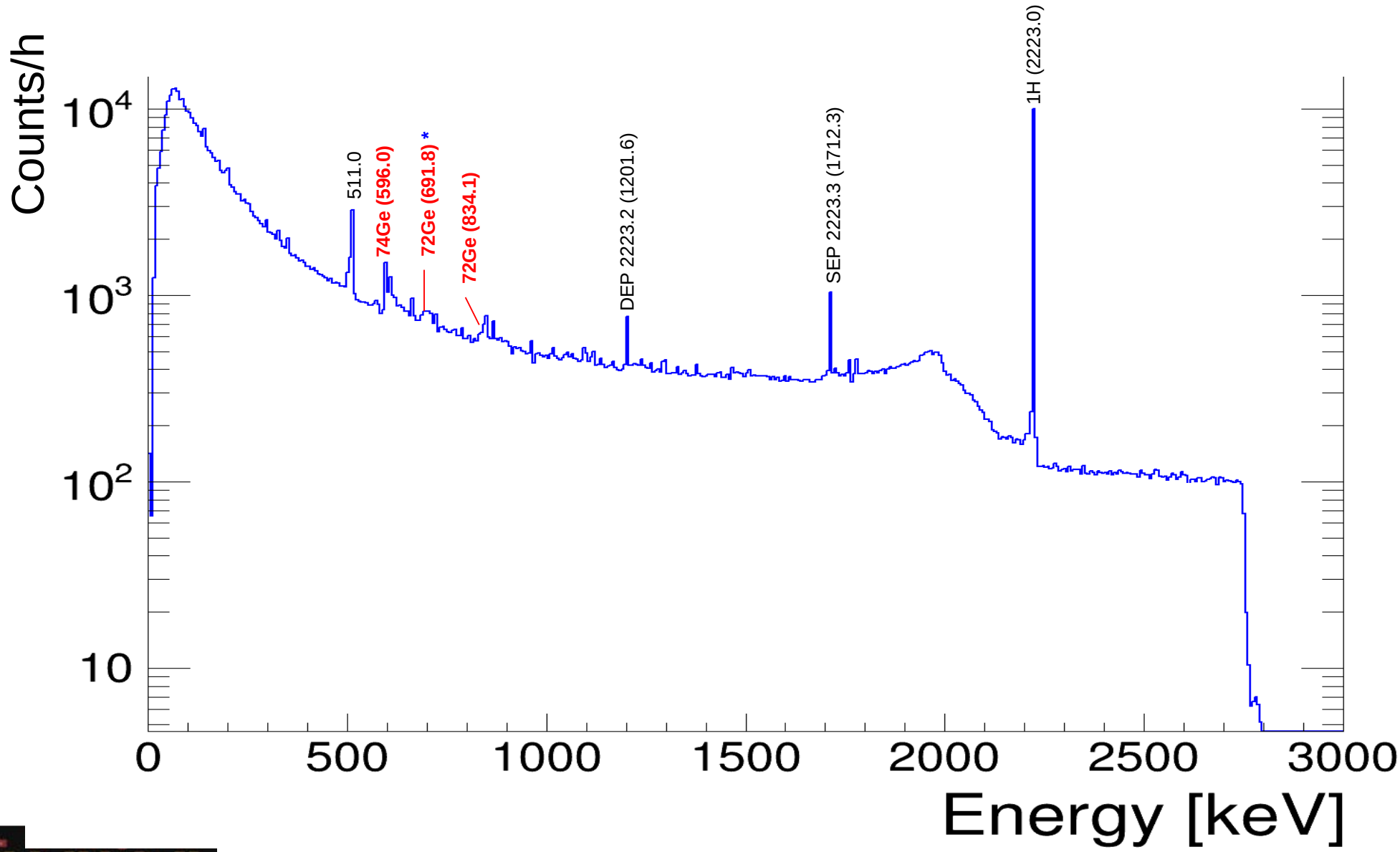
Reference measurement: AmBe



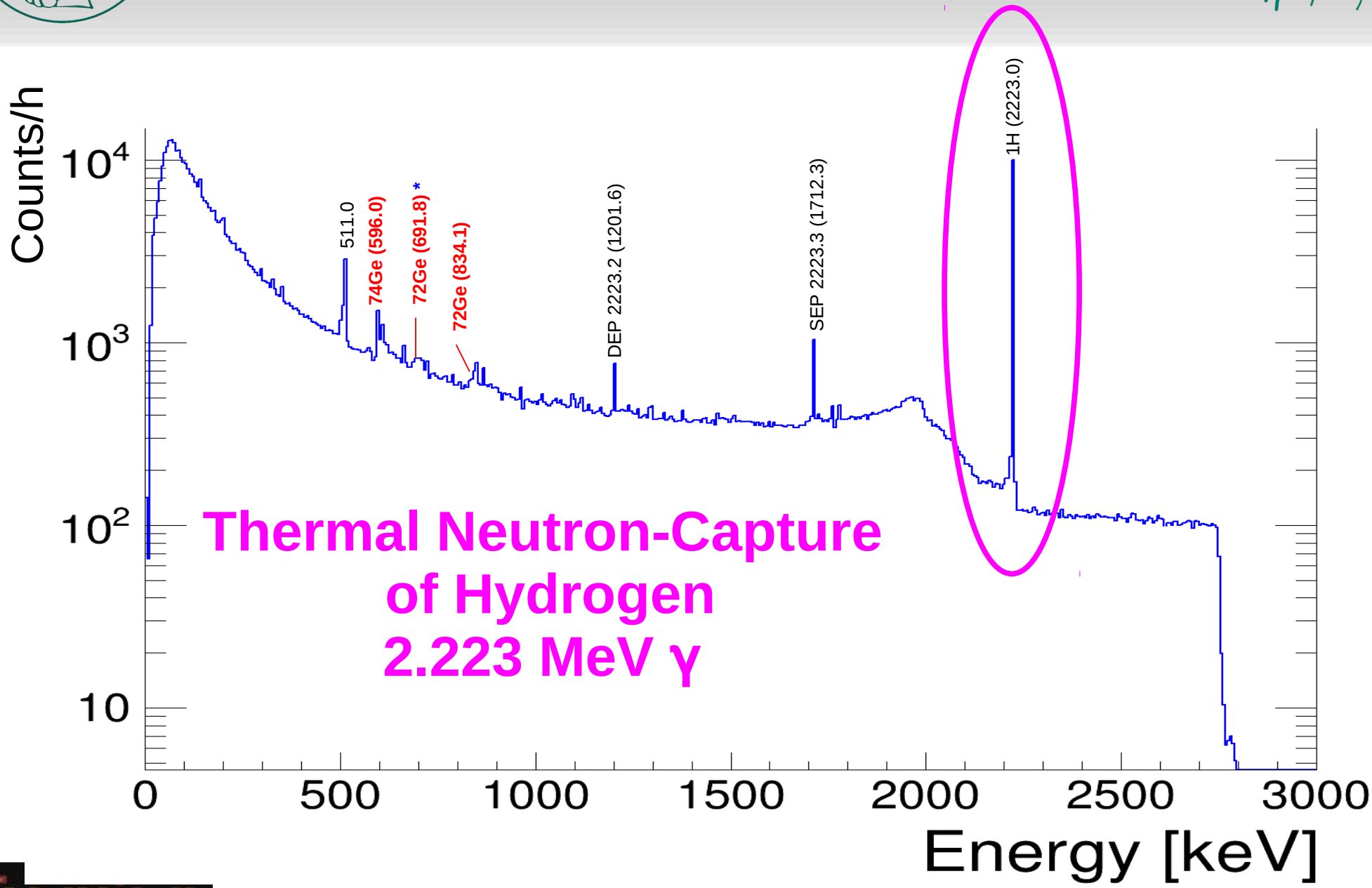
Reference measurement: AmBe

Reference measurement: AmBe

Measured Energy Spectrum



Measured Energy Spectrum



Germanium Detectors

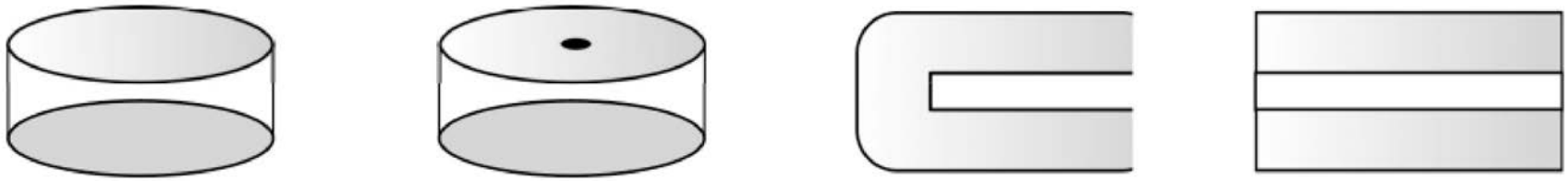
Widely used in nuclear physics experiments and DM searches

- **Concept:**
  - **Secmiconductor diodes with p- or n- structure**
  - **Reverse biasing**
  - **Sensitive to ionizing radiation**
  - **Depleted,sensitive thickness of several cm (for Si only mm)**
  - **Cryogenic Temperatures**

- **Advantages:**
  - **Measurement of low levels of radioactivity**
  - **High gamma-ray detection efficiency**
  - **Excellent energy resolution (~keV)**

Germanium Detectors

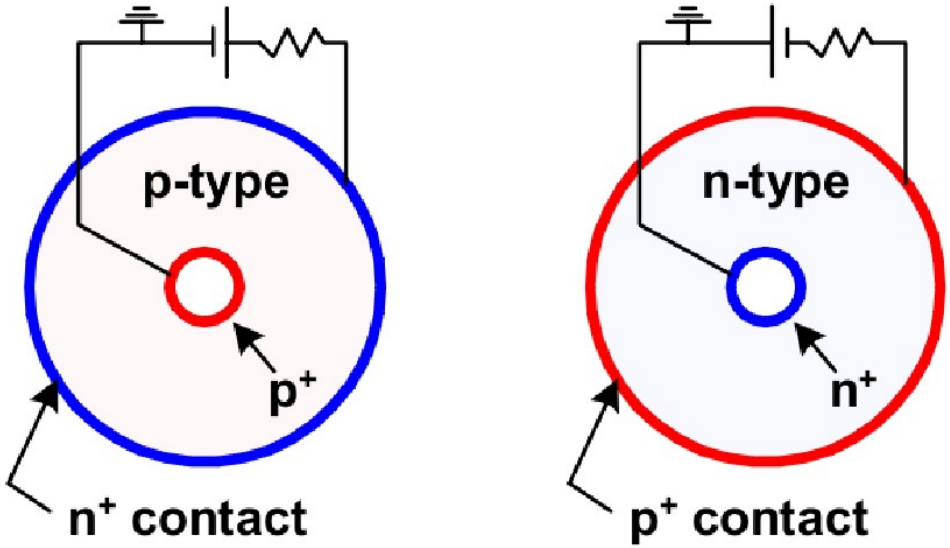
- **Detector configurations:**



Planar | Point-contact | Closed-ended coaxial | True-coaxial

- **Electrode configurations for coaxial detectors:**

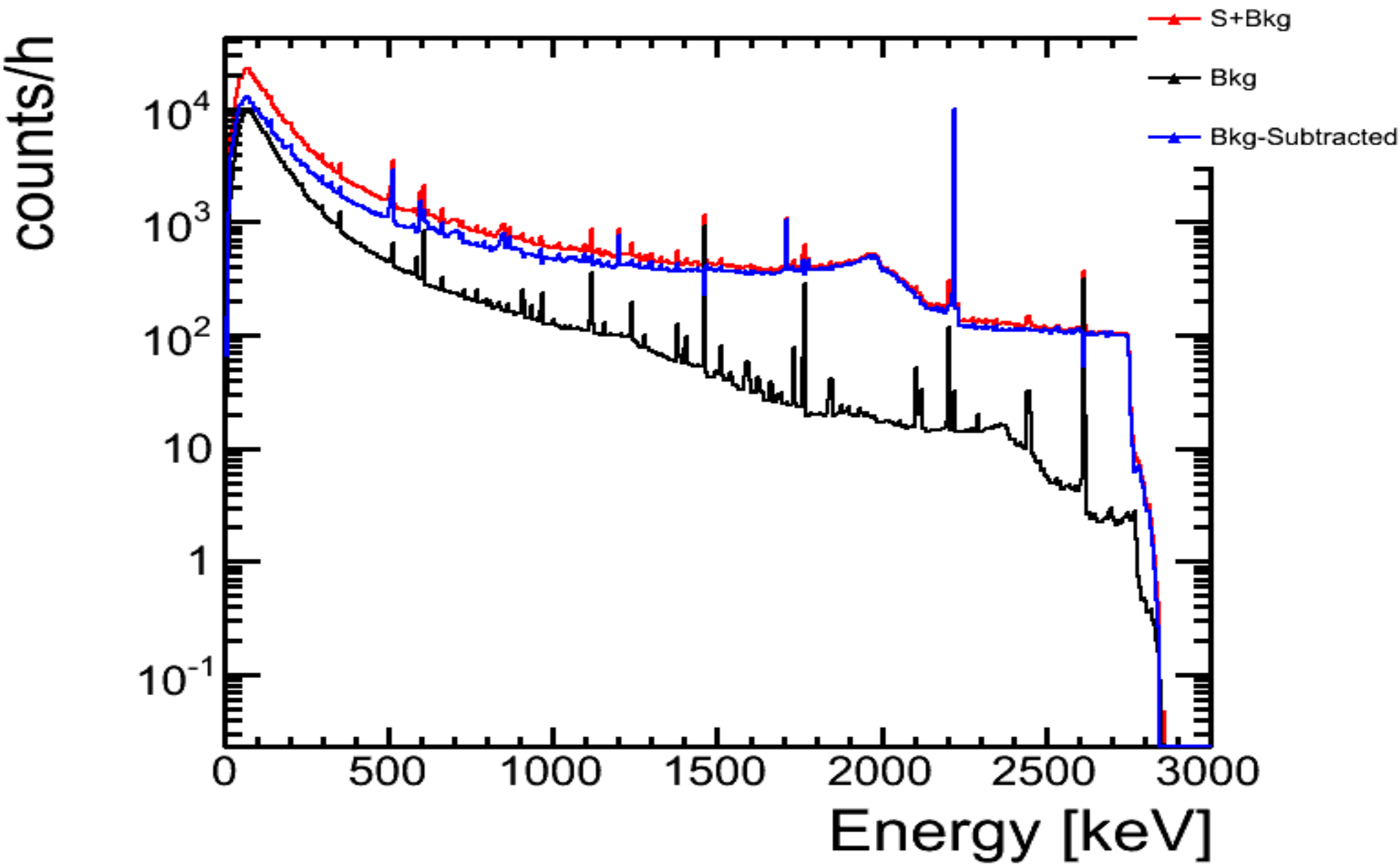
Lithium Diffusion Layer (~mm)



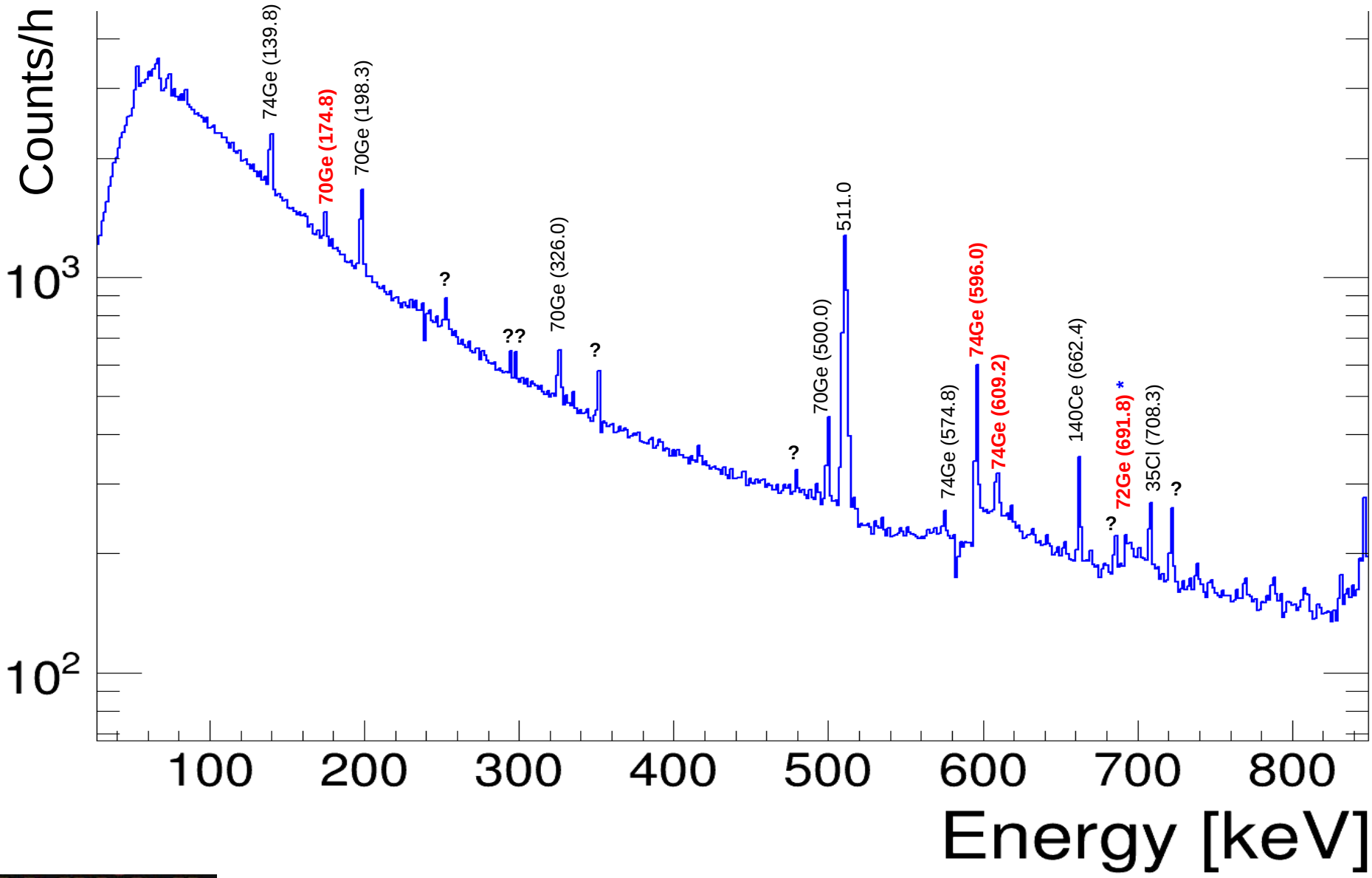
Boron Implantation (~μm)

Source: Med Phys 4R06/6R03 Radioisotopes and Radiation Methodology
Chapter 8: "Hyper-Pure Germanium Detector"

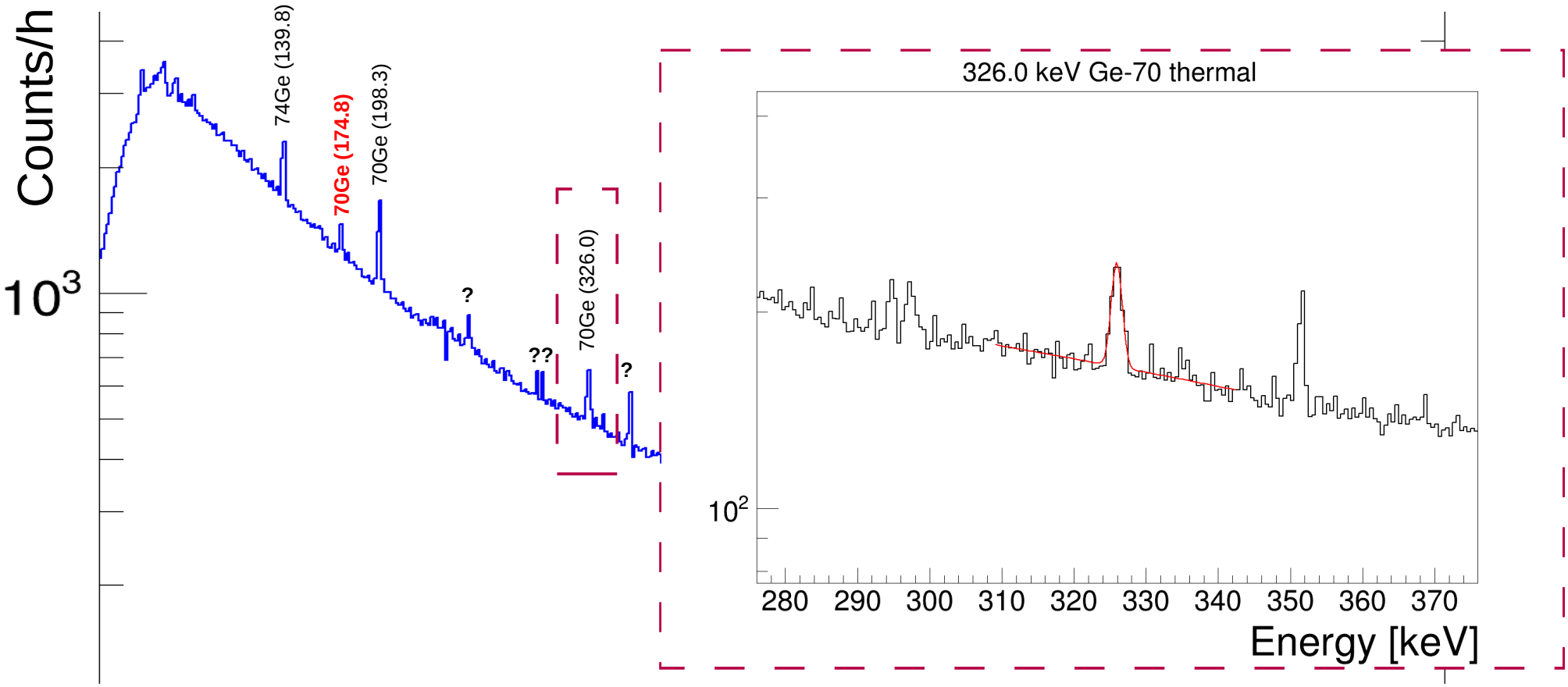
AmBe neutron source: results



Background Subtracted: 0-0.8 MeV

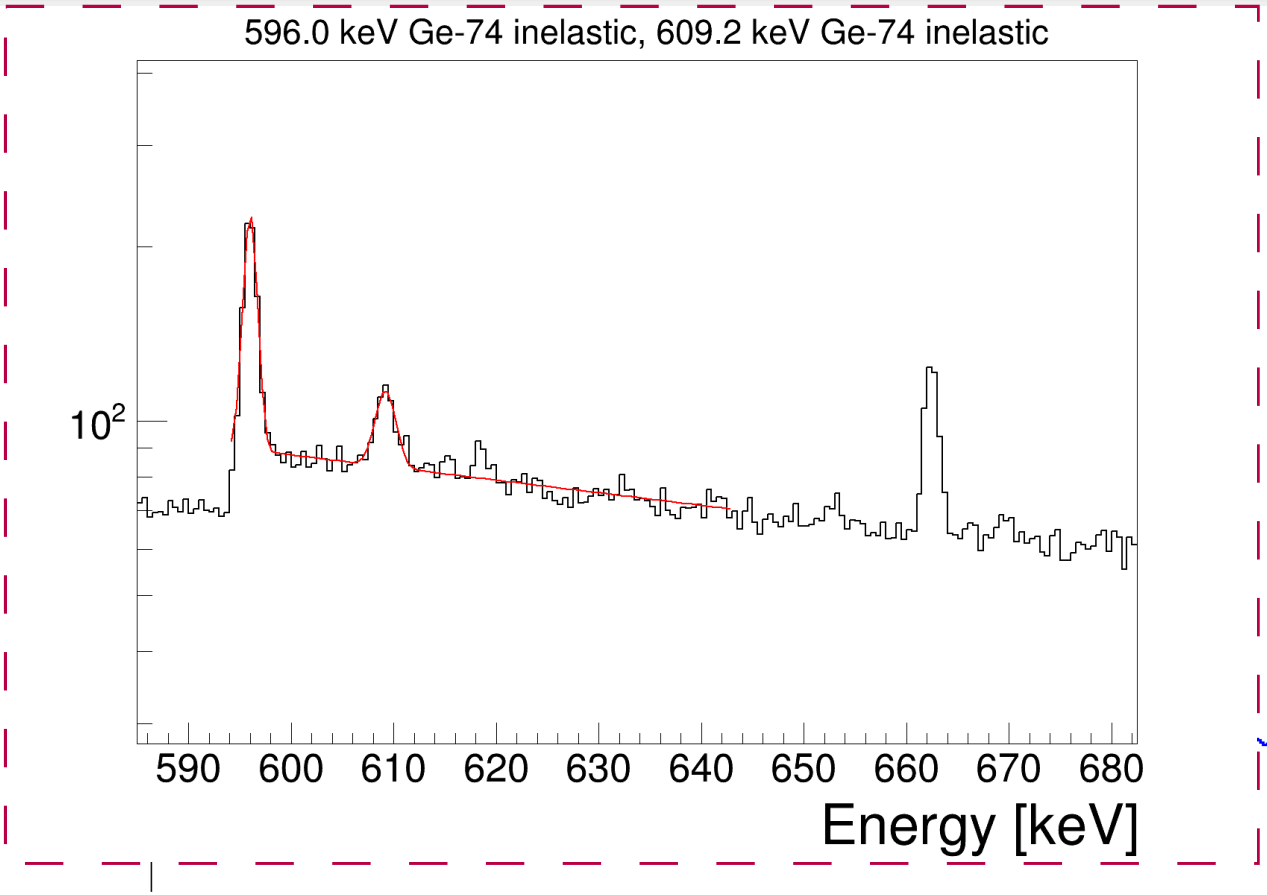


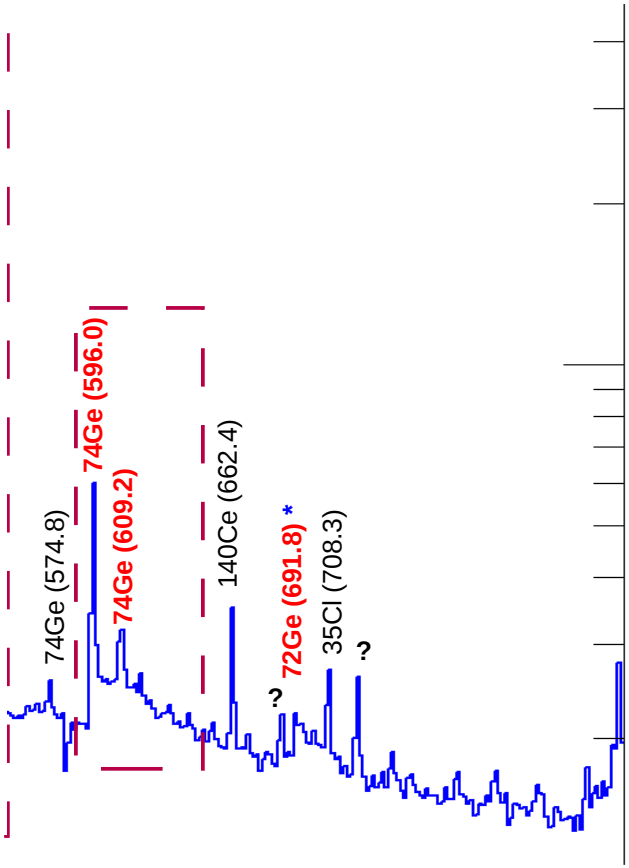
Background Subtracted: 0-0.8 MeV



Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
326.0 ± 0.1	0.7 ± 0.1	$^{70}Ge(n,\gamma)$

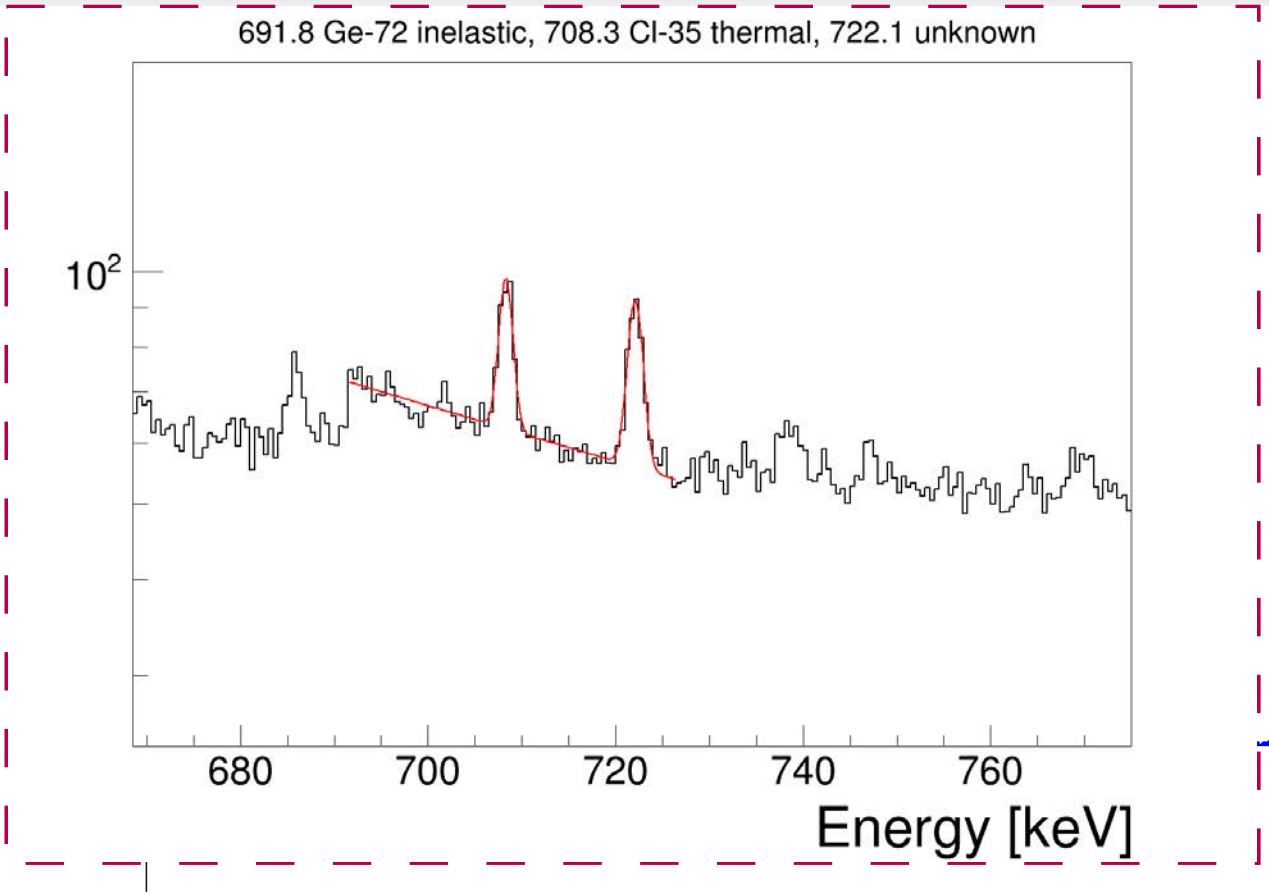
Background Subtracted: 0-0.8 MeV

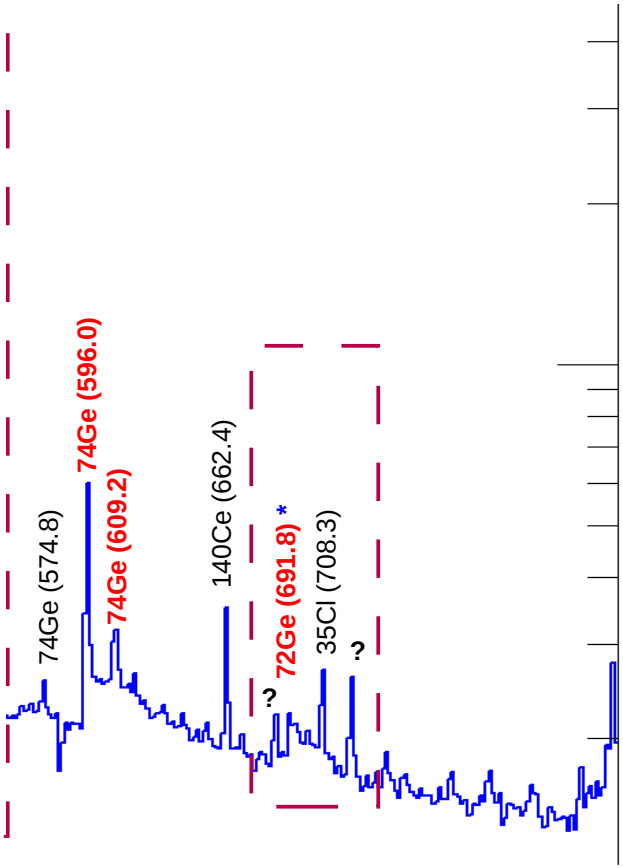




Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
596.0 ± 0.1	0.6 ± 0.1	$^{74}Ge(n,n'\gamma)$
609.2 ± 0.2	1.0 ± 0.3	$^{74}Ge(n,n'\gamma)$

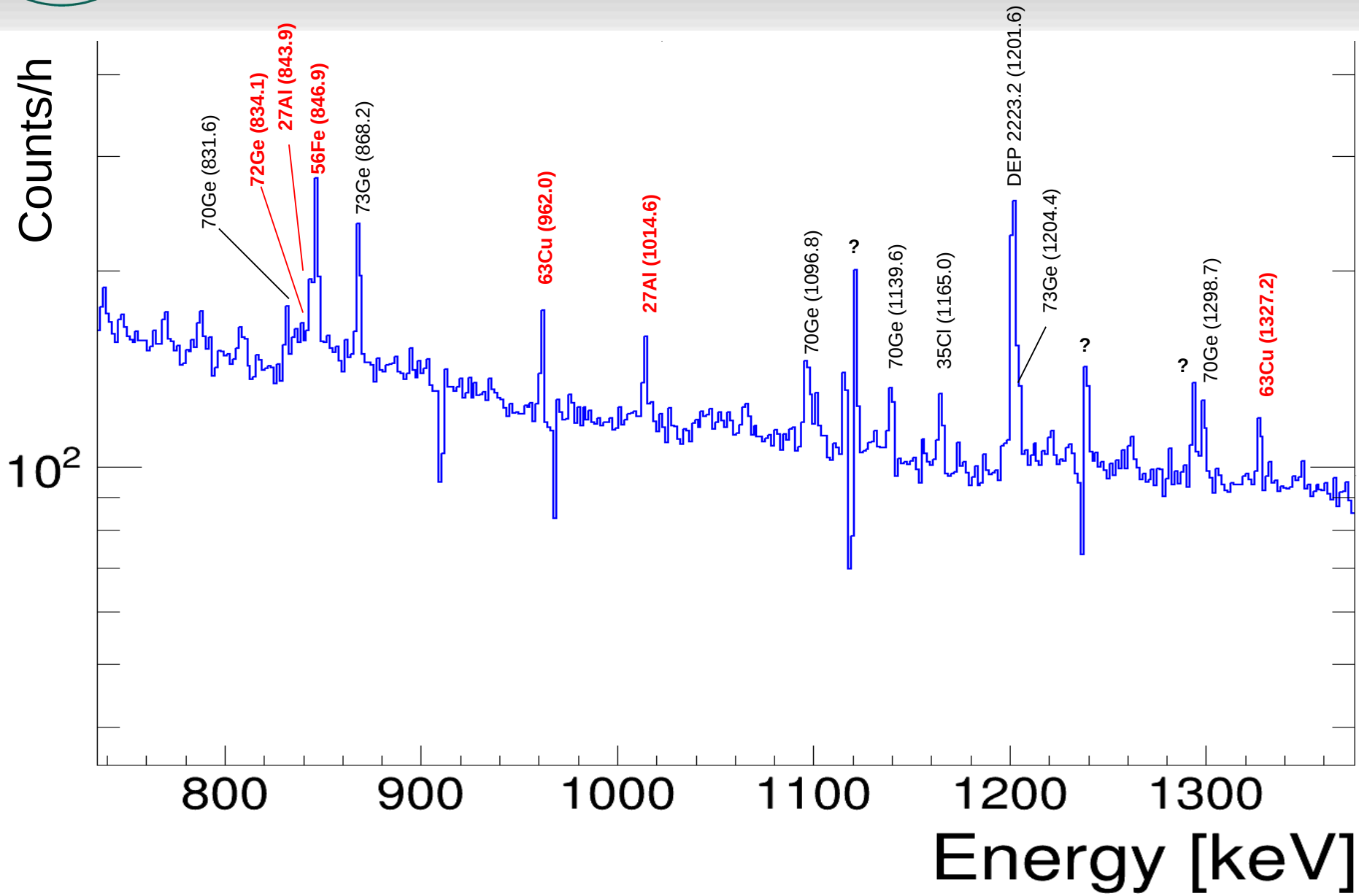
Background Subtracted: 0-0.8 MeV



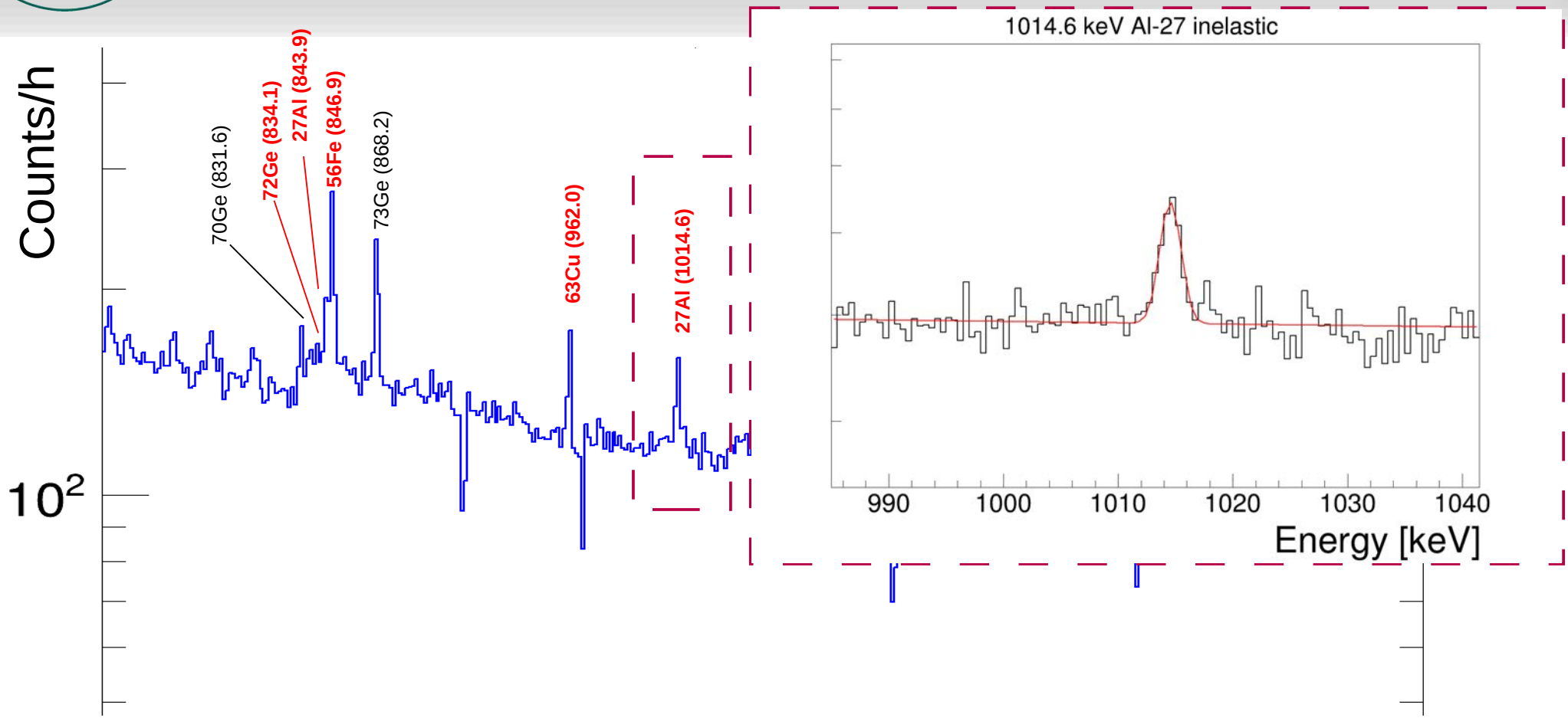


Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
691.8 ± -	-	$^{72}Ge(n,n'e)$
708.3 ± 0.2	0.7 ± 0.1	$^{35}Cl(n,\gamma)$

Background Subtracted: 0.8-1.4 MeV

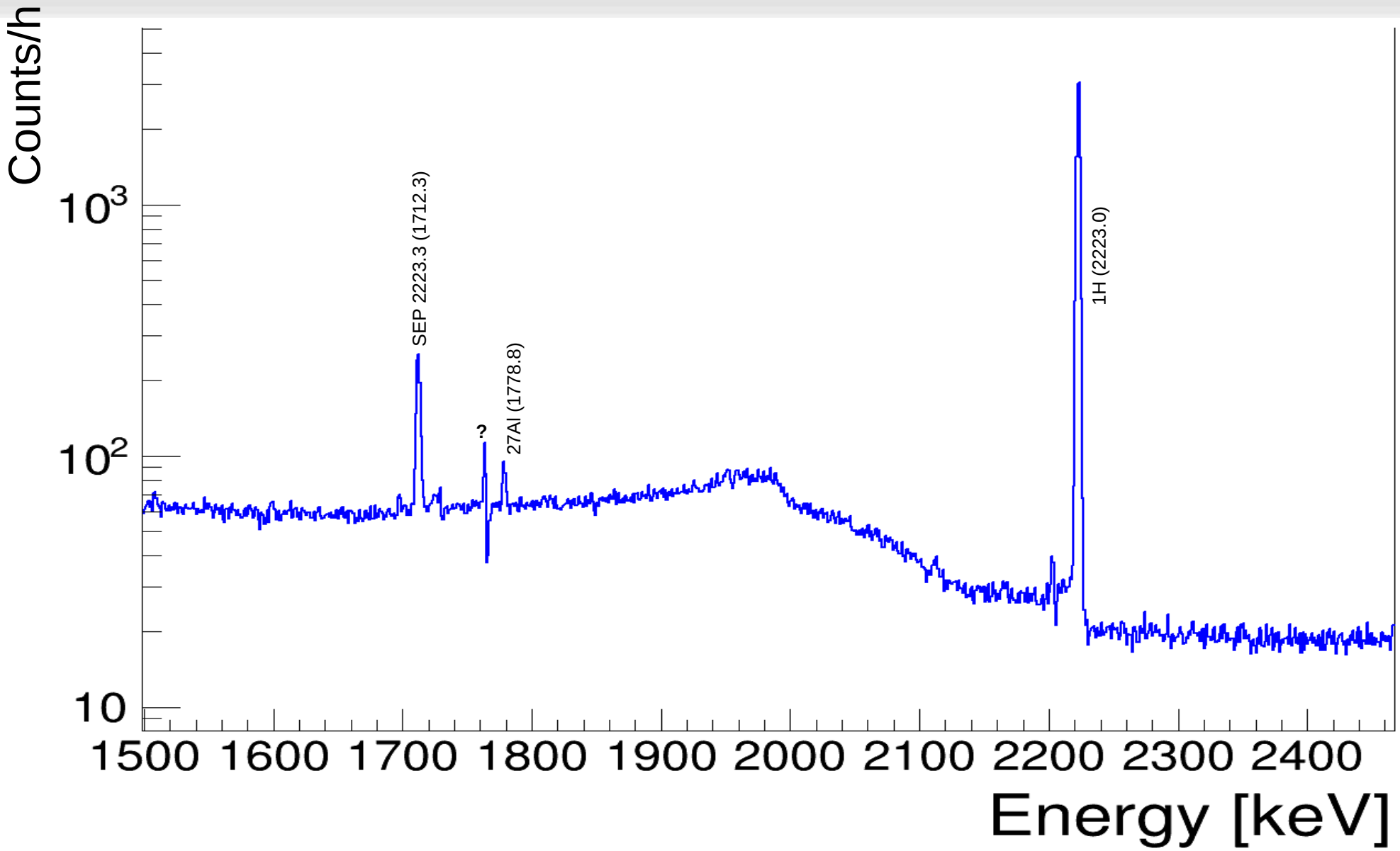


Background Subtracted: 0.8-1.4 MeV

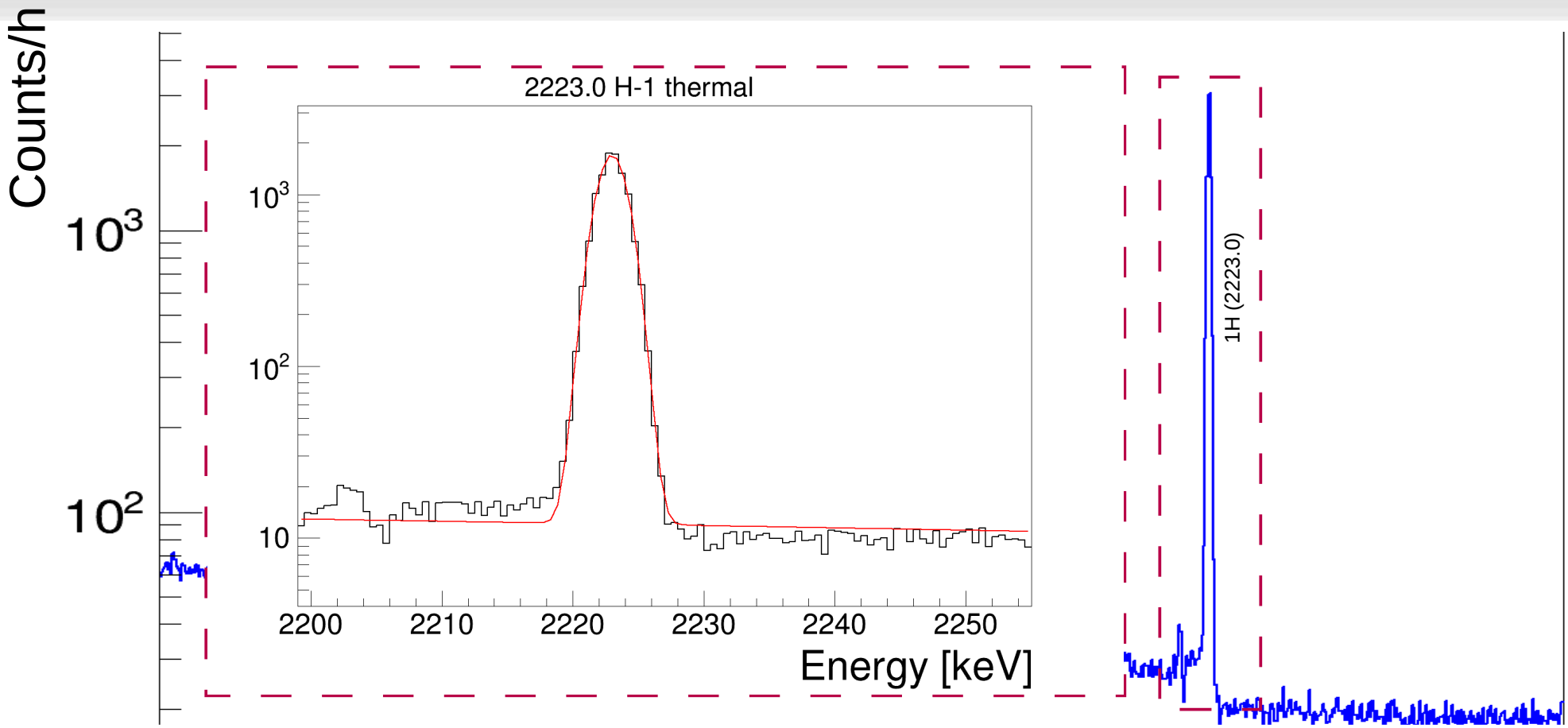


Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
1014.6 ± 0.3	0.9 ± 0.3	$^{27}Al(n, n'\gamma)$

Background Subtracted: 1.5-2.5 MeV

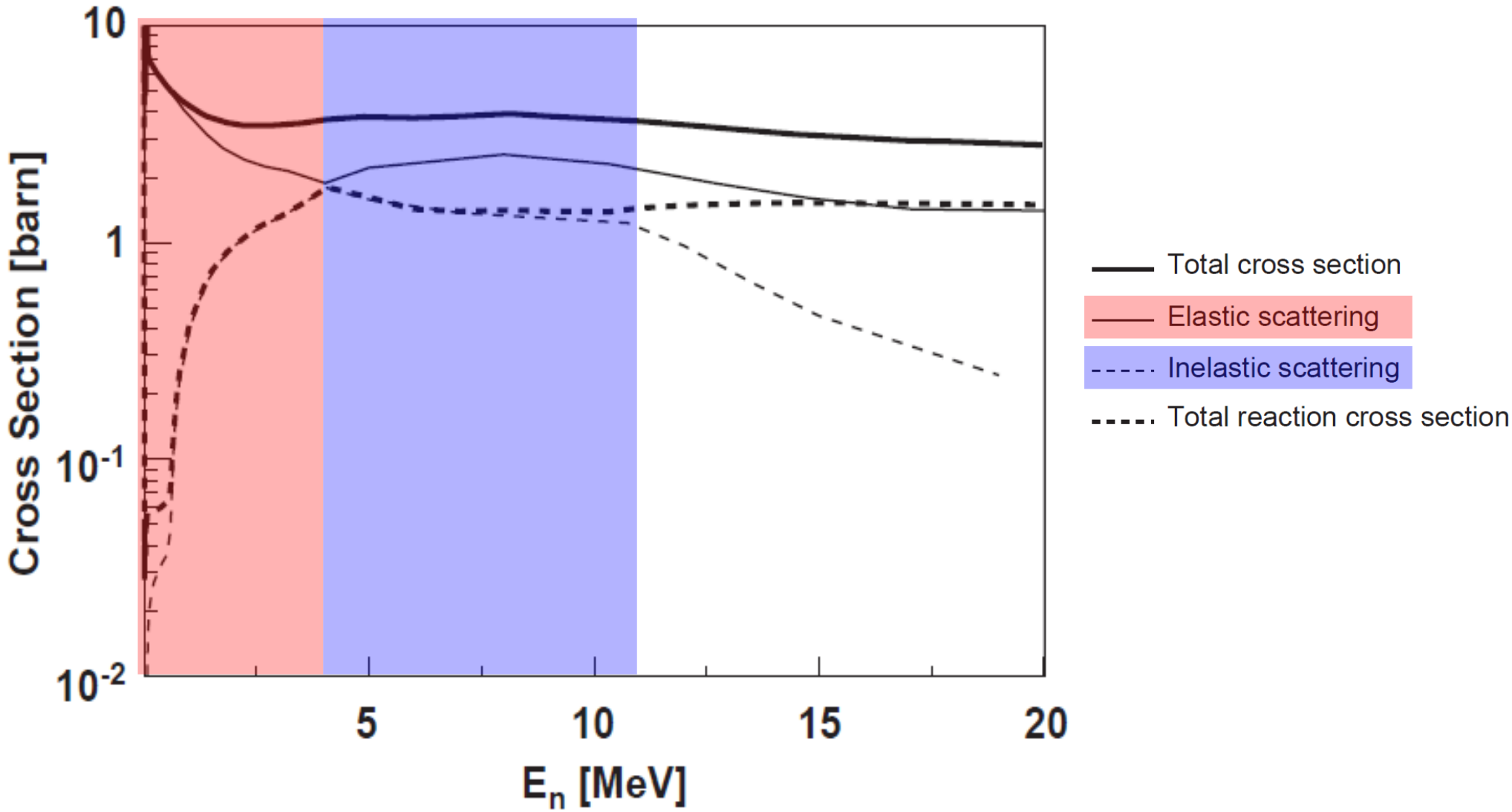


Background Subtracted: 1.5-2.5 MeV



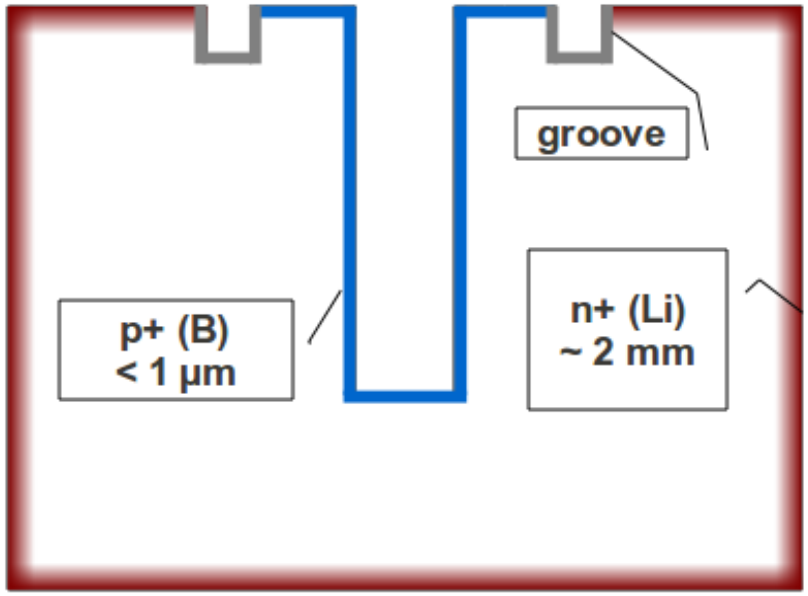
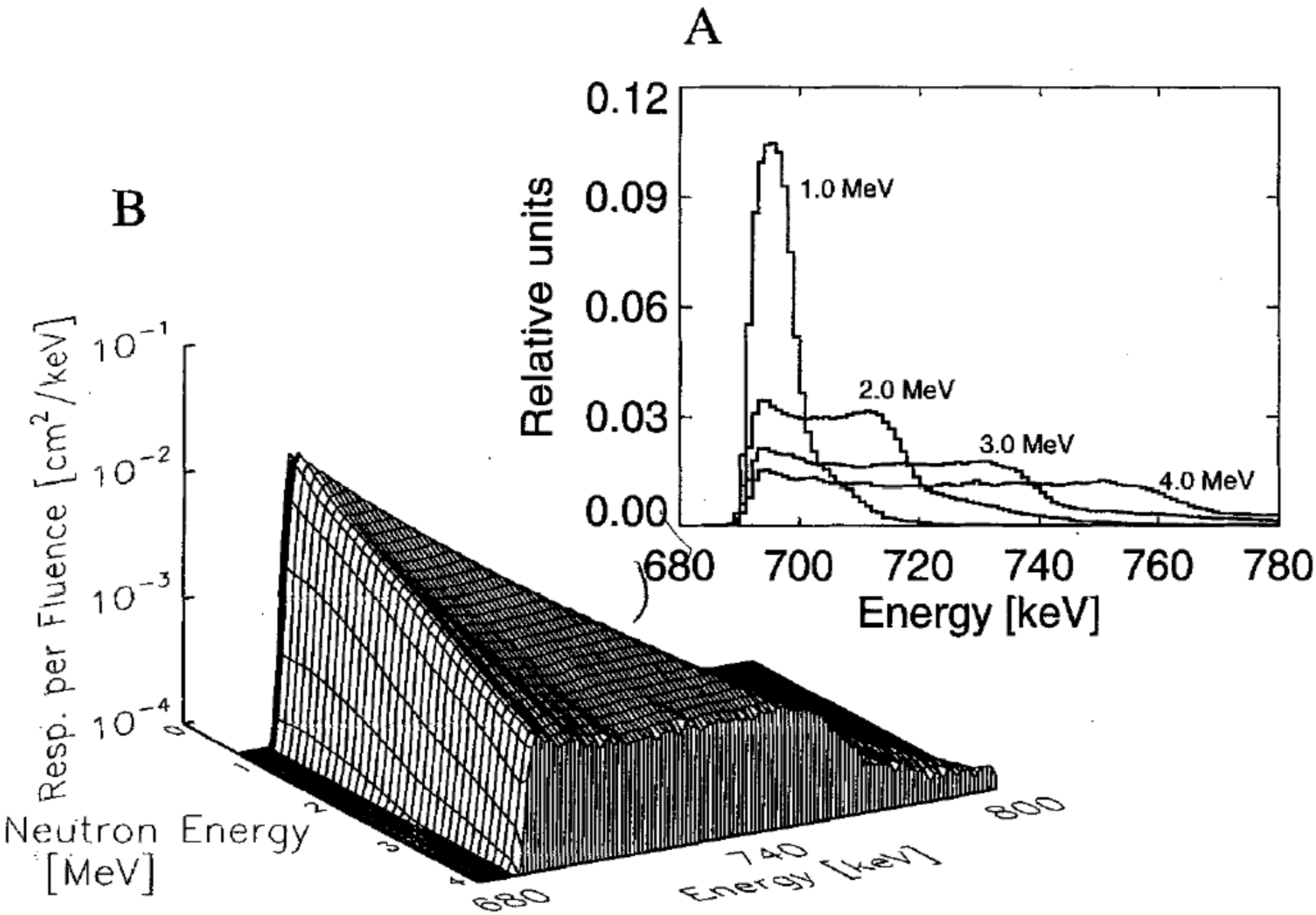
Fitted Energy [keV]	Fitted FWHM [keV]	Interaction type
2223.0*± 0.0	1.2 ± 0.0	$^1H(n,\gamma)$

Neutrons Cros Section



Natural Germanium

Isotope	Atomic mass (m_a/u)	Natural abundance (atom %)
^{70}Ge	69.9242497 (16)	20.84 (87)
^{72}Ge	71.9220789 (16)	27.54 (34)
^{73}Ge	72.9234626 (16)	7.73 (5)
^{74}Ge	73.9211774 (15)	36.28 (73)
^{76}Ge	75.9214016 (17)	7.61 (38)


groove
p+ (B)
< 1 µm
n+ (Li)
~ 2 mm

Inelastic Scattering Distribution