

New Evidence for DM-like Anomalies in Neutron Multiplicity Spectra

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*on behalf of the **NEMESIS** collaboration*

NEMESIS

NEutron
MEasurementS
In Sub-terrestrial
locations



Our research goals

Search for anomalies in high-multiplicity neutron spectra emitted from massive, metallic targets placed deep underground

- Even if no anomalies were found, we'd gain a better understanding of the muon-induced background, which is relevant for underground experiments
- If there are anomalies, what are their properties and origin
 - Unknown intricacies of muon-induced spallation
 - WIMP annihilation-like interaction with heavy nuclei (see poster #221: Dark Matter interpretation of neutron multiplicity anomalies)
 - Something else



<https://youtu.be/0Opxhr5JinI>



Why WIMPs, why NEMESIS?

- The proposed masses of the hypothetical Dark Matter particle span over 65 orders of magnitude (from fuzzy DM objects to the Plank mass)
 - WIMPs are a small but important part of the considered mass spectrum
 - If WIMPs exist, they must **scatter and decay/annihilate**
- **Direct Detection:** practically all terrestrial WIMP searches look for **scattering recoils**
 - A relatively straightforward interaction
 - Very faint signals, high-tech experiments, challenging measurements
- **Indirect Detection:** NEMESIS collaboration looks for signs of **WIMP annihilation** in massive metallic targets in underground locations
 - Poorly understood but highly exothermic event, associated with large neutron emissions
 - The experiment must cope with a significant neutron BGD



<https://youtu.be/0Opxhr5JinI>

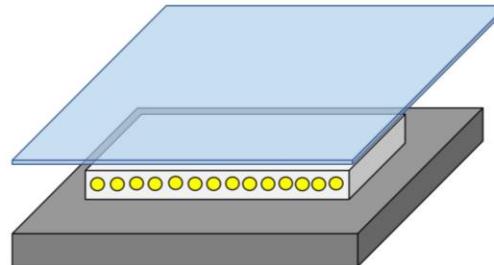


We present data from 6 measurements
collected in 4 locations using 3 experimental setups

- **NEMESIS 0.1**

- 565 kg Pb, 344 d
- 445 kg Cu, 259 d
- BGD (no target), 144 d

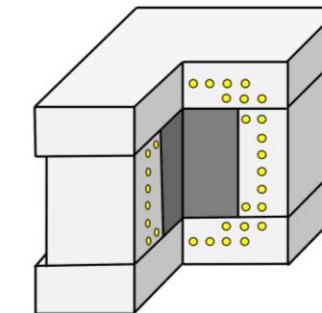
NEMESIS 0.1
@ 210 m.w.e.



- **NMDS, 300 kg Pb**

- 583 m.w.e., 271 d
- 1166 m.w.e., 60 d

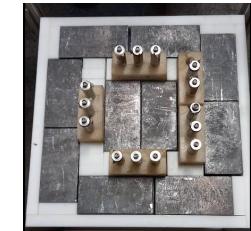
NMDS
@ 583 m.w.e.
@ 1166 m.w.e.



- **NEMESIS 1.4**

- 4000 m.w.e., 1,130 kg Pb
 - Taking data since 11/2022

NEMESIS 1.4
@ 4000 m.w.e.



2019 - 2022

2001 - 2003

Since 2022

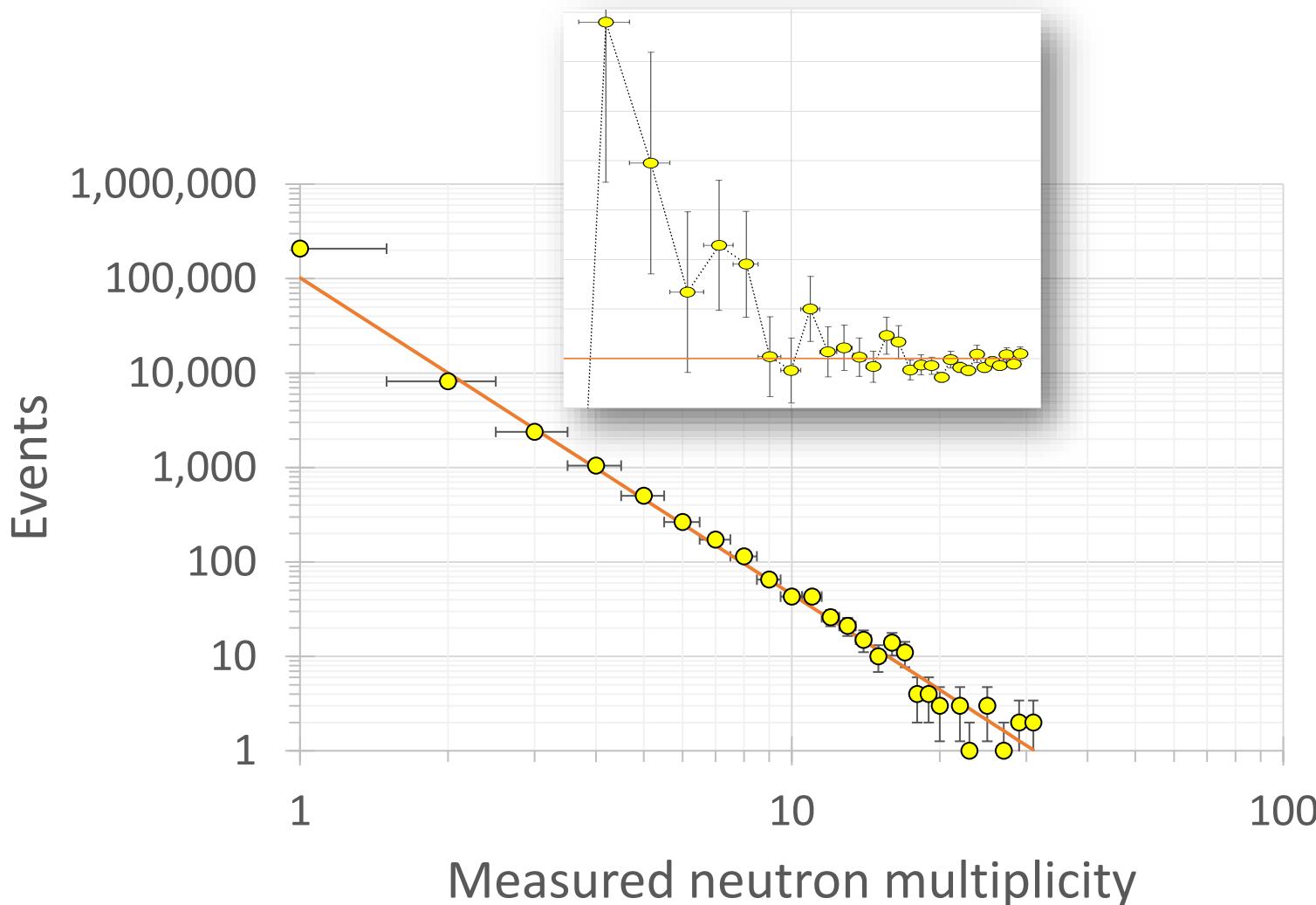
Monte Carlo simulations of the muon-induced background

- Very thorough and independent simulations of the NMDS setup performed by the Purdue group of David Koltick
 - Haichuan Cao (April 2023) [Thesis_HC_04242023.pdf](#)
 - Excellent agreement with measurements using a calibrated ^{252}Cf source
 - Muon-induced multiplicity spectra are well-described by a power-law function (straight line in log-log scale)
$$y = k \cdot m^{-p}$$
 - Geant4 simulations over-estimate the yield of muon-induced neutrons in Pb
 - the p-coefficient is correct, but the k-parameter requires adjustments
- Preliminary simulations for the NEMESIS 0.1 and 1.4 setups



A typical neutron multiplicity spectrum

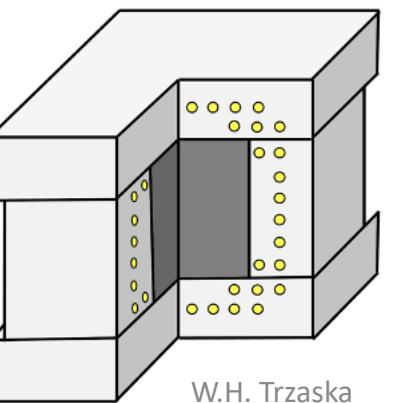
measured with a 565 kg Pb target at 210 m.w.e.



1. The spectra are **dominated by ambient and muon-induced neutron background**
2. To search for possible anomalies, such a **background must be well-understood and subtracted from the spectra**
3. Low count rates require **long measurements** and **careful statistical analysis** of the data



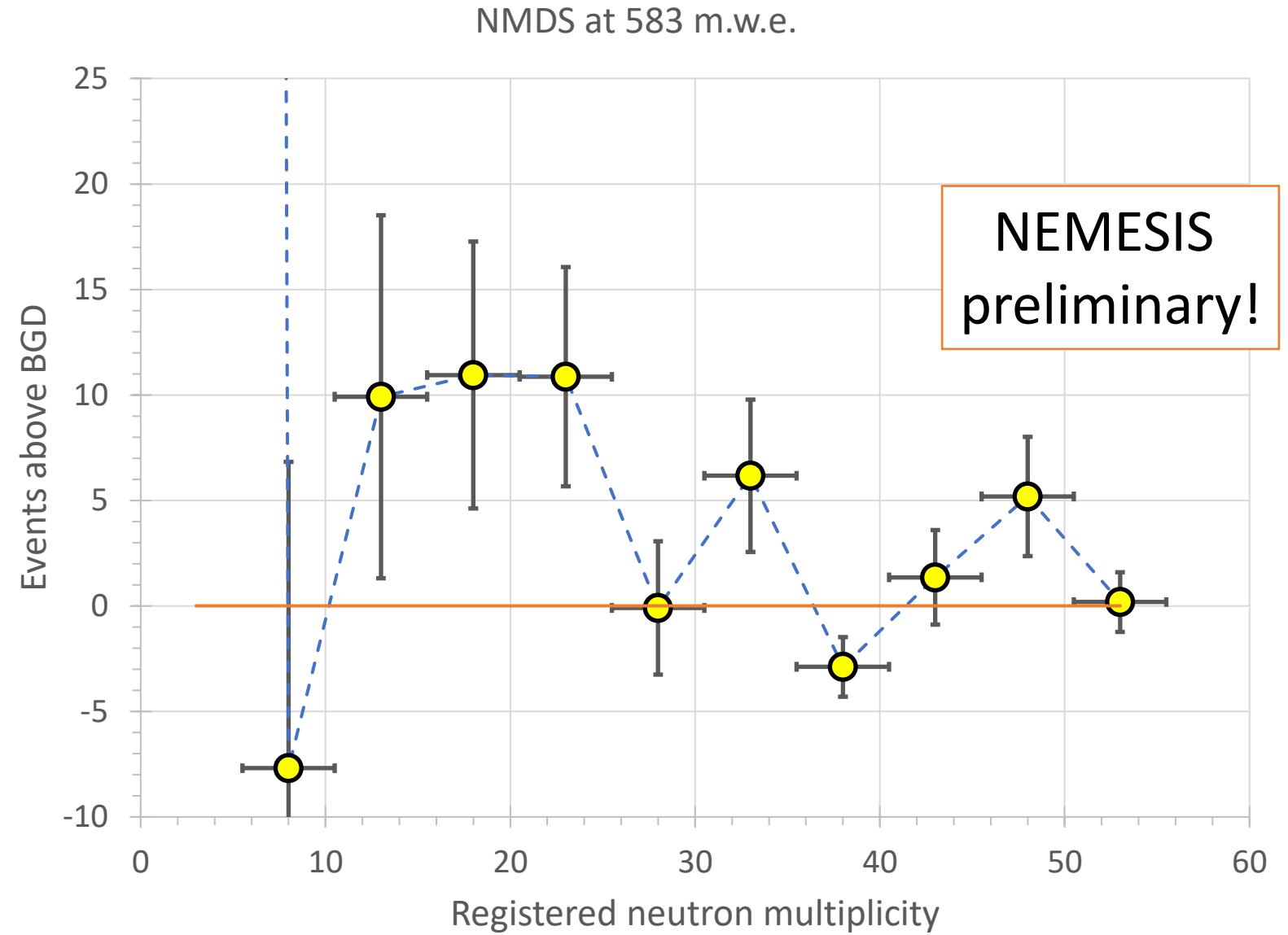
NMDS 2001 - 2003



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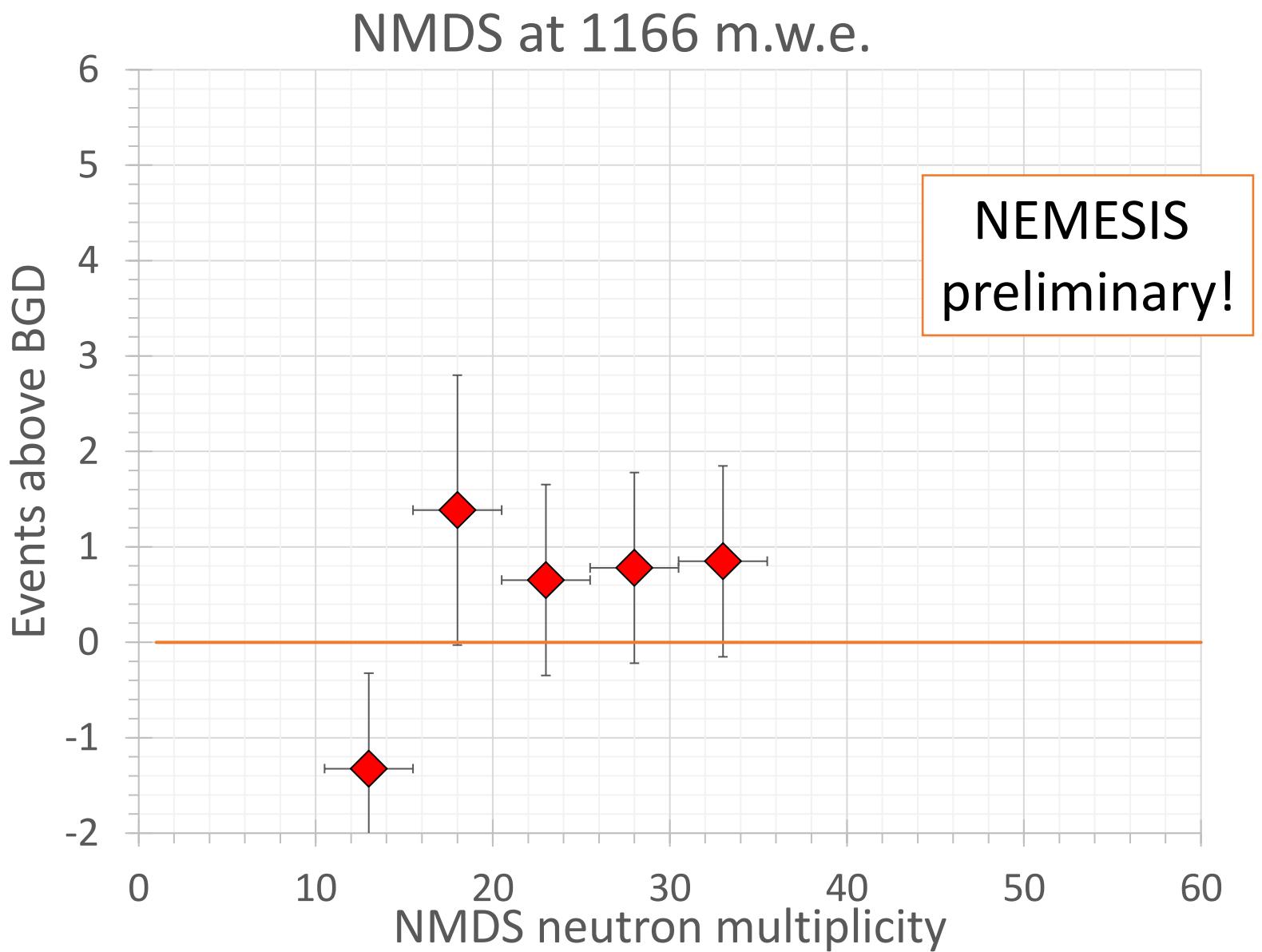
NMDS 583 m.w.e. Events over BGD

9 months; 300 kg Pb; 583 m.w.e.
 $42 \pm 13_{\text{stat}}$ anomalous events at $m > 10$
 $16 \pm 5_{\text{stat}}$ per ton-month



NMDS 1166 m.w.e. Events over BGD

2 months; 300 kg Pb; 1166 m.w.e.
 $3.6 \pm 2.2_{\text{stat}}$ anomalous events at $m > 13$
 $6 \pm 4_{\text{stat}}$ per ton-month

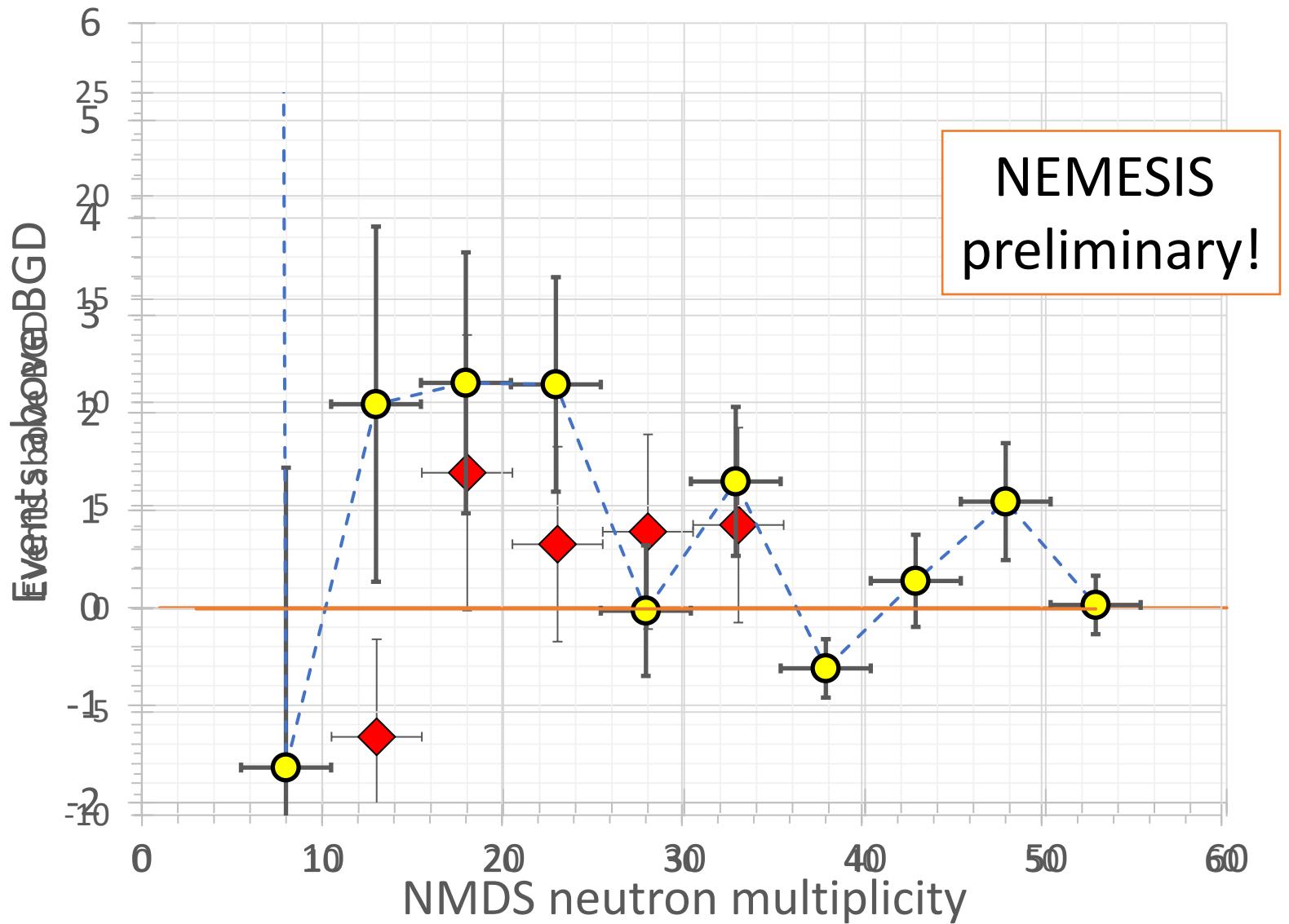


NMDS events
over BGD

1166 m.w.e.

vs.

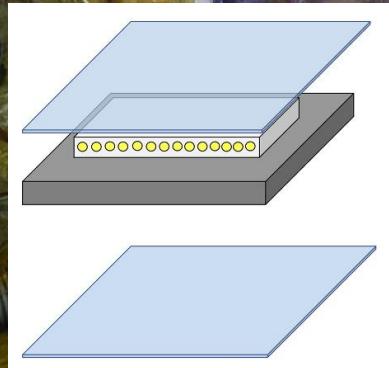
583 m.w.e.



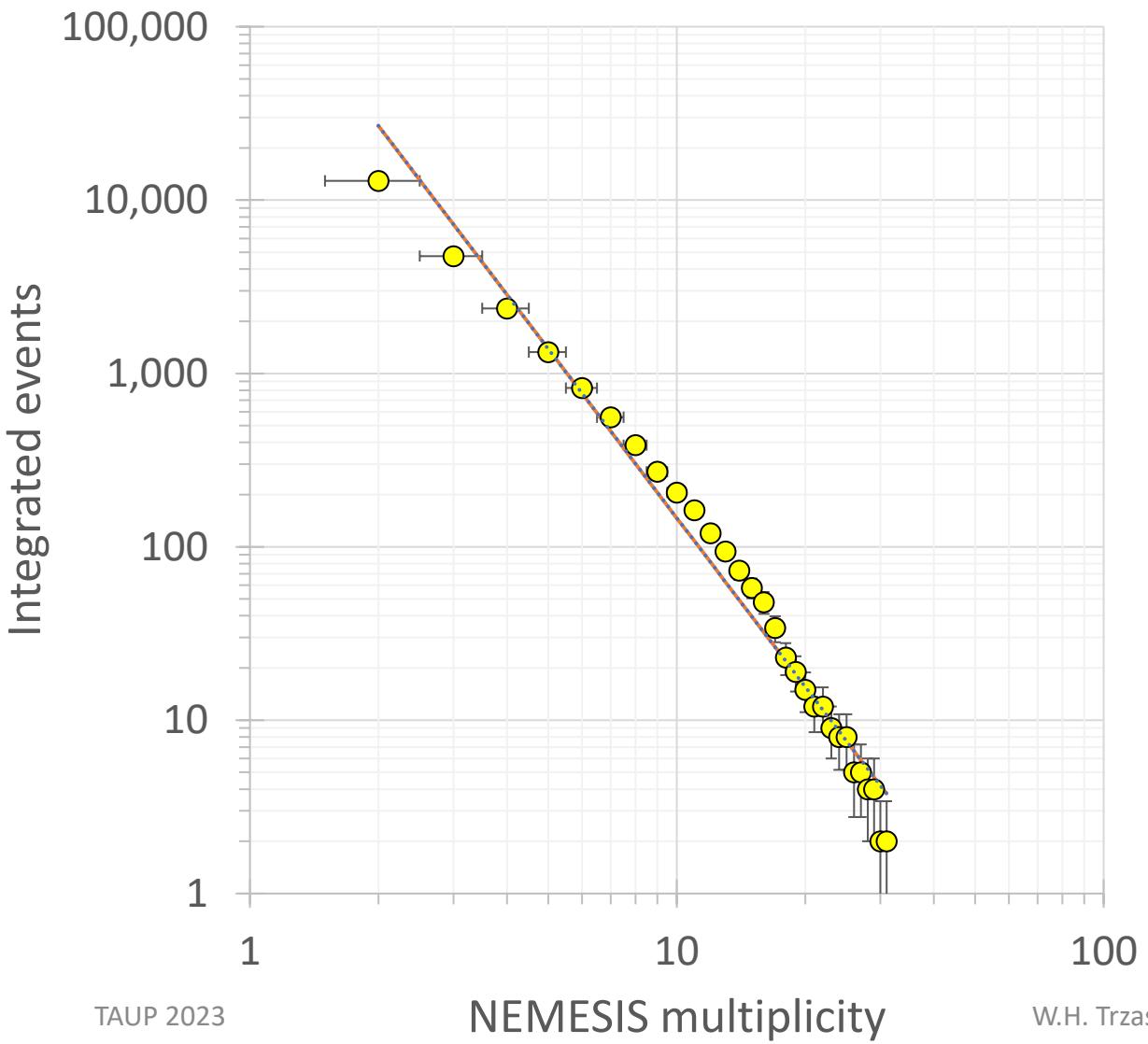
NEMESIS 0.1

2019 – 2022

<https://youtu.be/XibQj4udohA>



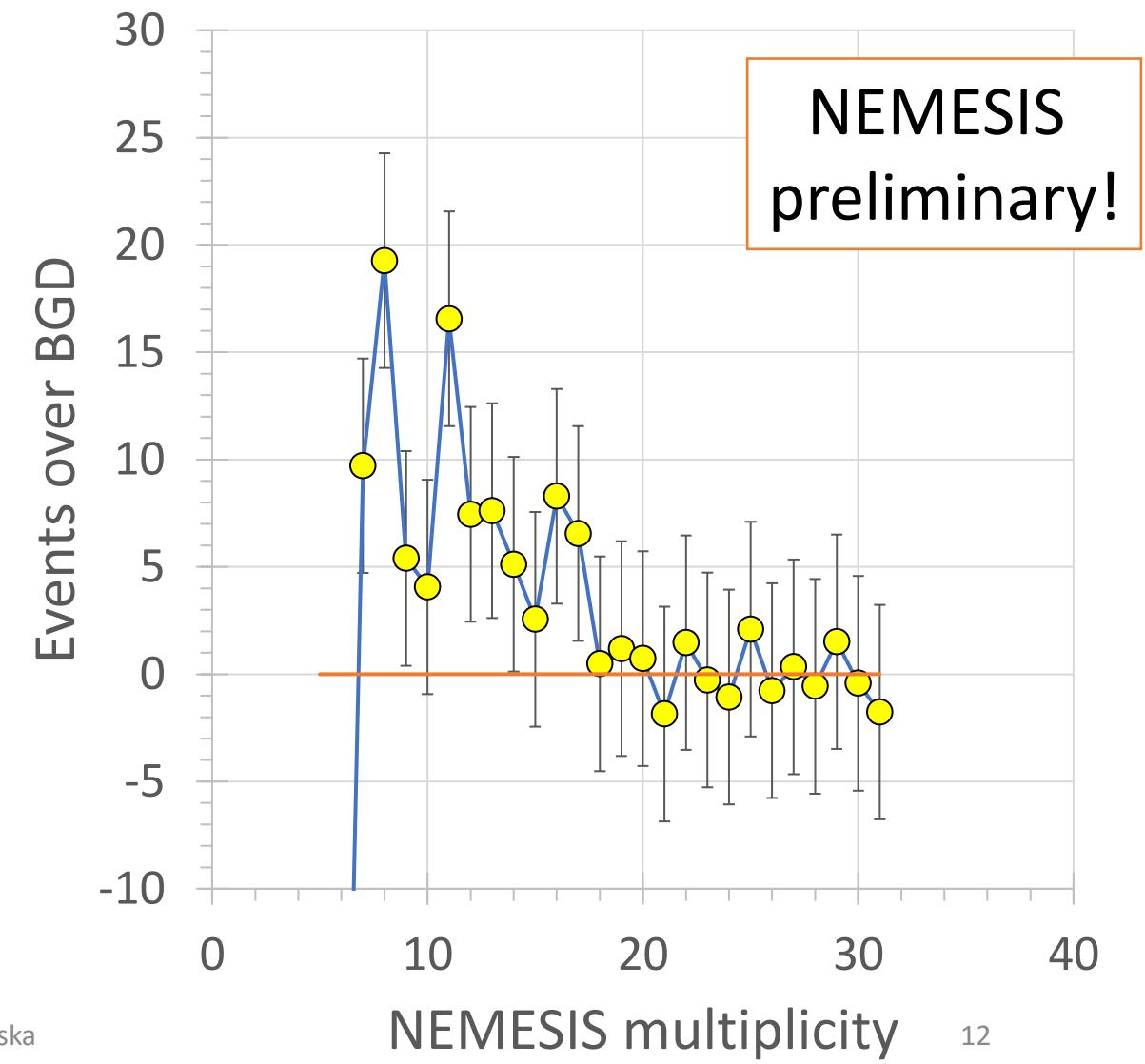
NEMESIS 0.1



TAUP 2023

NEMESIS multiplicity

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NEMESIS multiplicity

NMDS, 583 m.w.e.

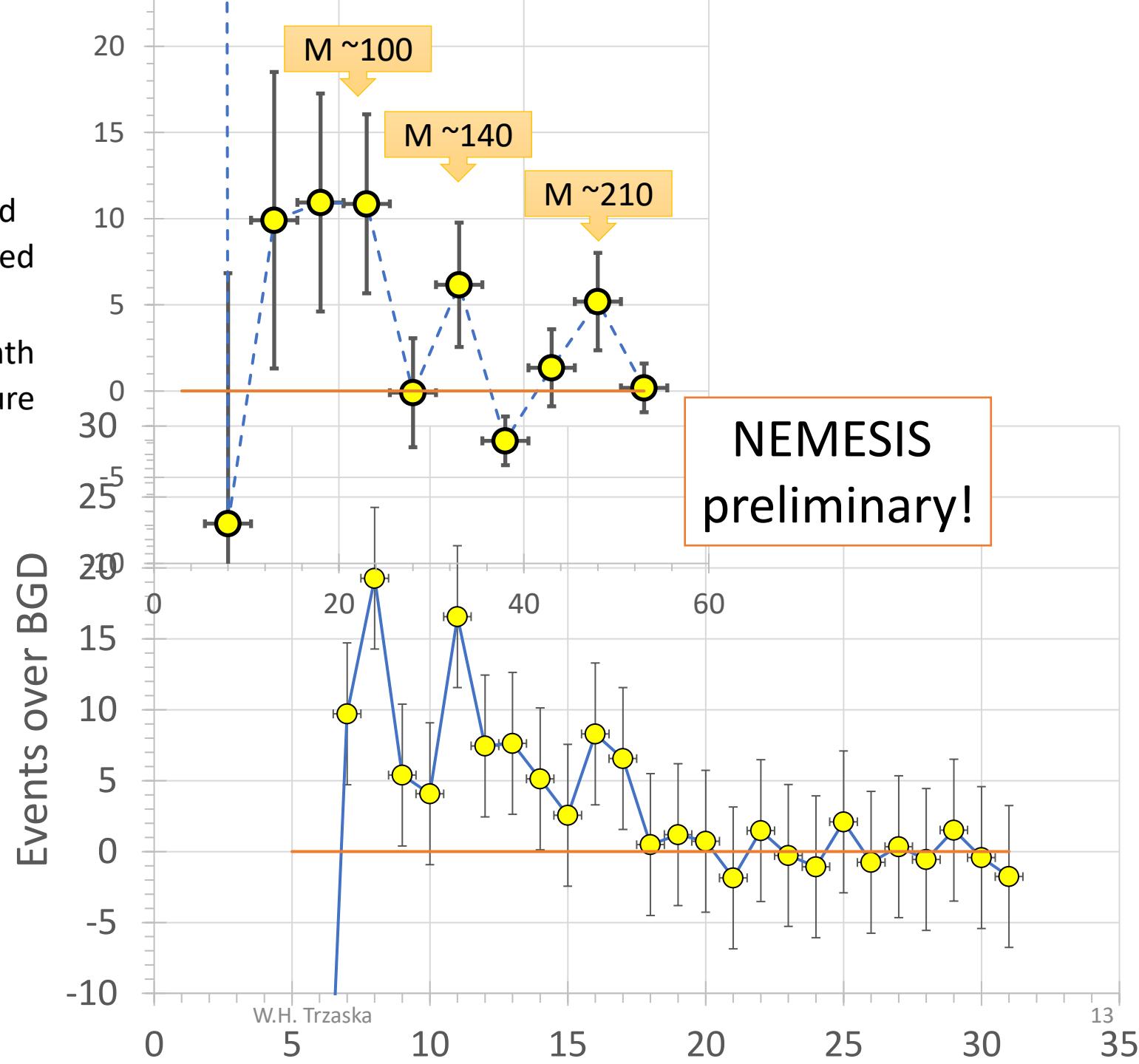
Efficiency $23.2 \pm 1.2\%$ measured
23 % Geant 4 simulated

2.7 ton-month
exposure

NEMESIS, 210 m.w.e.

Efficiency $8 \pm 2\%$

6.4 ton-month
exposure





TAUP 2023

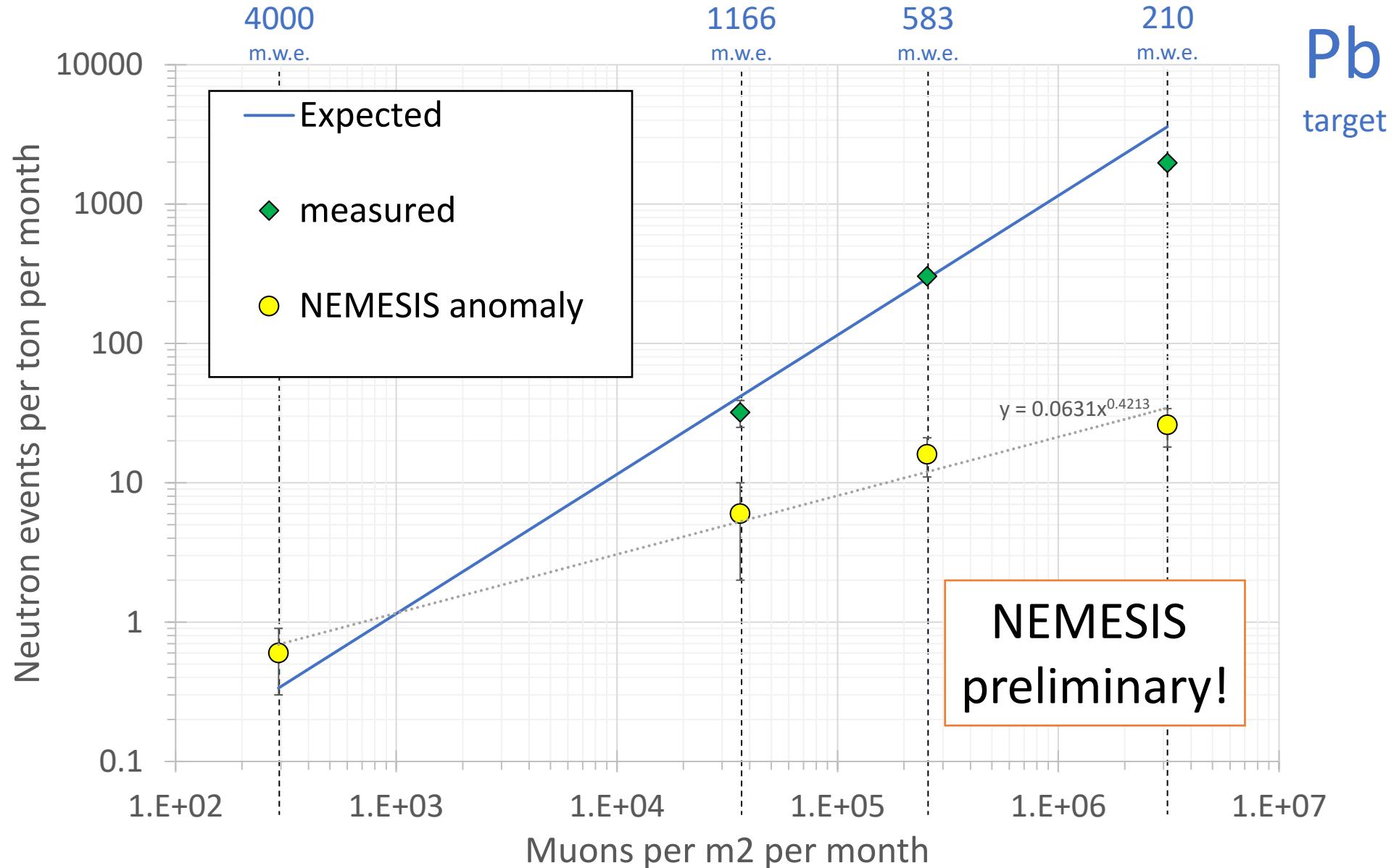
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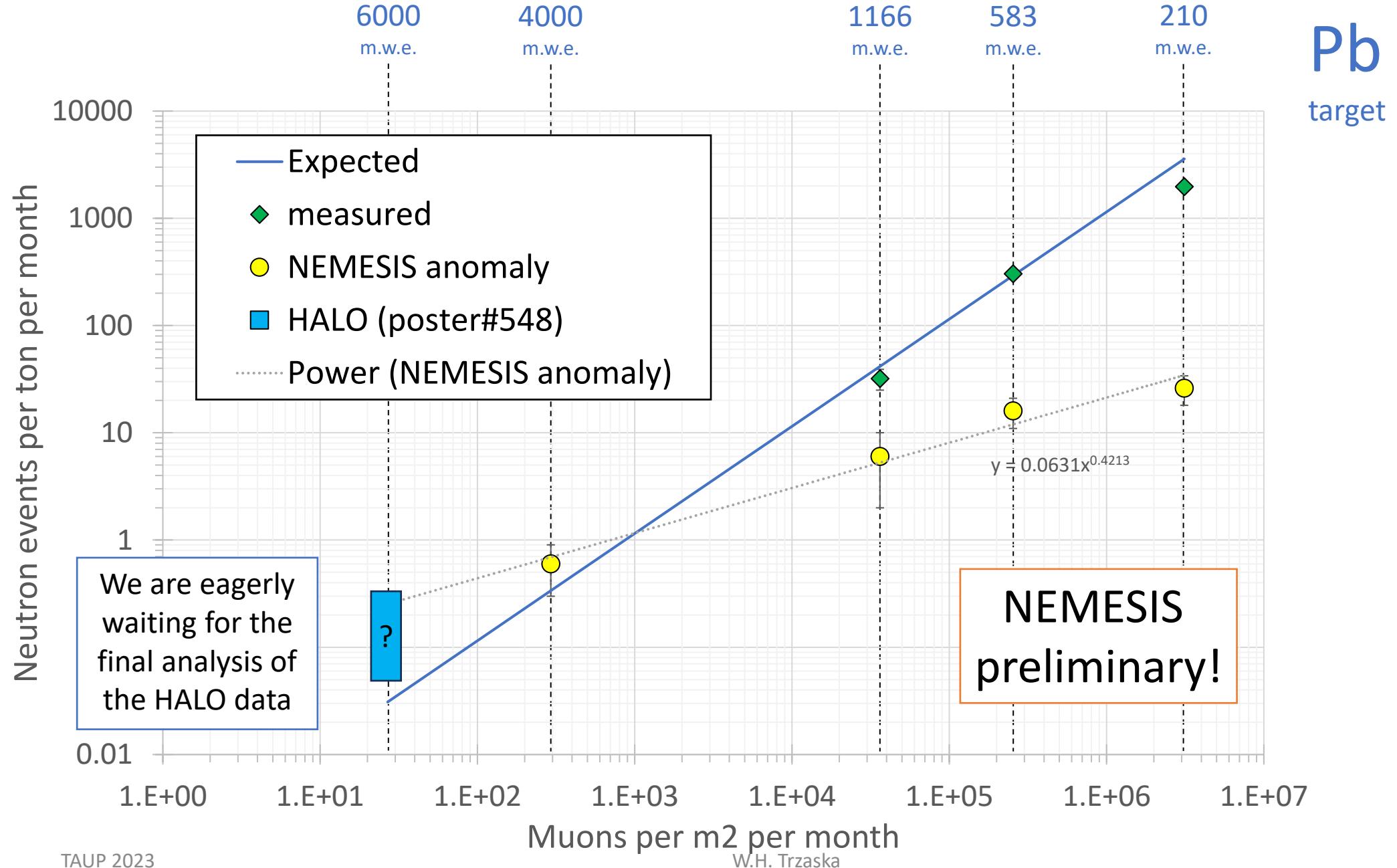


<https://youtu.be/0Opxhr5JinI>



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Evidence for the anomalies

Preliminary!

- Our analysis detects **excess events** in neutron multiplicity spectra obtained from Pb targets measured at 0.1, 0.2, 0.4, and 1.4 km underground
- These excess events appear to have a **peak-like structure**, visible in the long-exposure spectra, available from 583 and 210 m.w.e.
- Such structures **cannot originate** from muon-induced spallation
- There is a depth dependence, but the excess events **do not scale with the muon flux**
- The **A-dependence is unclear**; the Cu run did not yield detectable anomalies
- The muon coincidence requirement **does not enhance** the anomalies; it diminishes them, while the anticoincidence requirement **does the opposite**
- MC simulations **do not account** for the anomalous excesses of events at high multiplicities from **Pb targets**

Thank you for your attention!

- Data taking and analysis are in progress
- We are seeking funding for a larger/decisive experiment
- We welcome new collaborators



<https://youtu.be/0Opxhr5JinI>

NEMESIS collaboration

Poster #221:

Dark Matter Interpretation of
Neutron Multiplicity Anomalies

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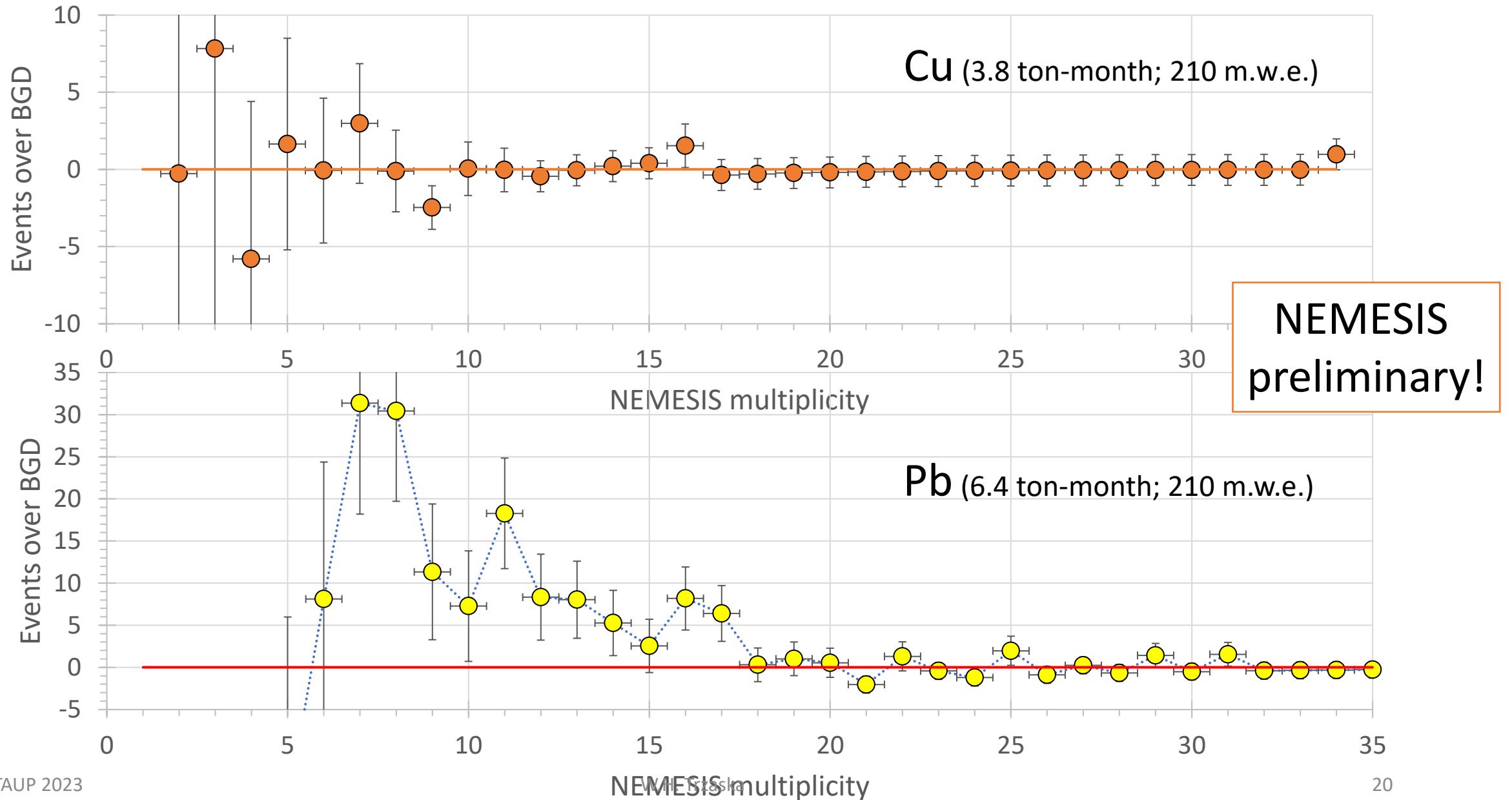
^h*W.H. Trzaska*

^h*TechSource, Santa Fe, NM, USA*

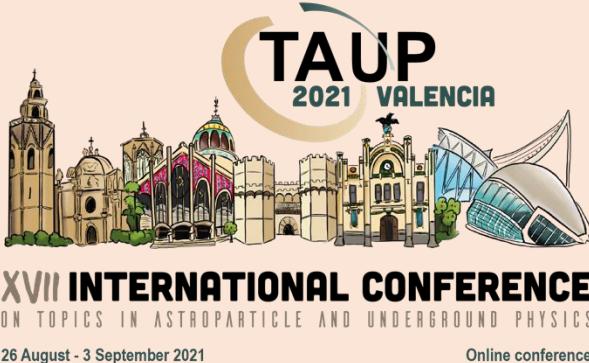


Backup slides

No evidence for anomalies in Cu after 3.8 ton-month exposure



NEMESIS at conferences and meetings



- **ICRC 2021** 12-23 July 2021
 - New NEMESIS results <https://doi.org/10.22323/1.395.0514>
 - High-multiplicity neutron events registered by NEMESIS experiment <https://doi.org/10.22323/1.395.0497>
- **TAUP 2021** 26 Aug – 3 Sep 2021
 - DM-like anomaly in neutron multiplicity spectra
 - Proceedings: <http://doi.org/10.1088/1742-6596/2156/1/012029>
 - YouTube video (<https://youtu.be/0UcEdJje4ms>)
- **JUNO Europe meeting** 13 – 14 Sep 2021
- **VCI 2022** 21 – 25 Feb 2022
 - <https://indico.cern.ch/event/1044975/contributions/4663815/>
- **NDM 2022** 15 – 21 May 2022
 - <https://indico.phy.ornl.gov/event/142/contributions/740/>
 - <https://indico.phy.ornl.gov/event/142/contributions/828/>
- **NeIC 2022** 30 May – 1 June 2022
 - <https://indico.neic.no/event/204/>
- **TAUP 2023** 26 Aug – 3 Sep 2021
 - New evidence for DM-like Anomalies in Neutron Multiplicity Spectra
 - Dark Matter Interpretation of Anomalies in Neutron Multiplicity Spectra
 - YouTube video and relevant links: <https://youtu.be/0Opxhr5JinI>



Main neutron background sources underground 1/2

Nuclear fission in the surrounding rock and shotcrete aggregate

- Constant and uniform BGD
- Less than 6 neutrons per fission
- Far from the detection setup

Our team members have a considerable experience in measurements and analysis of such a background



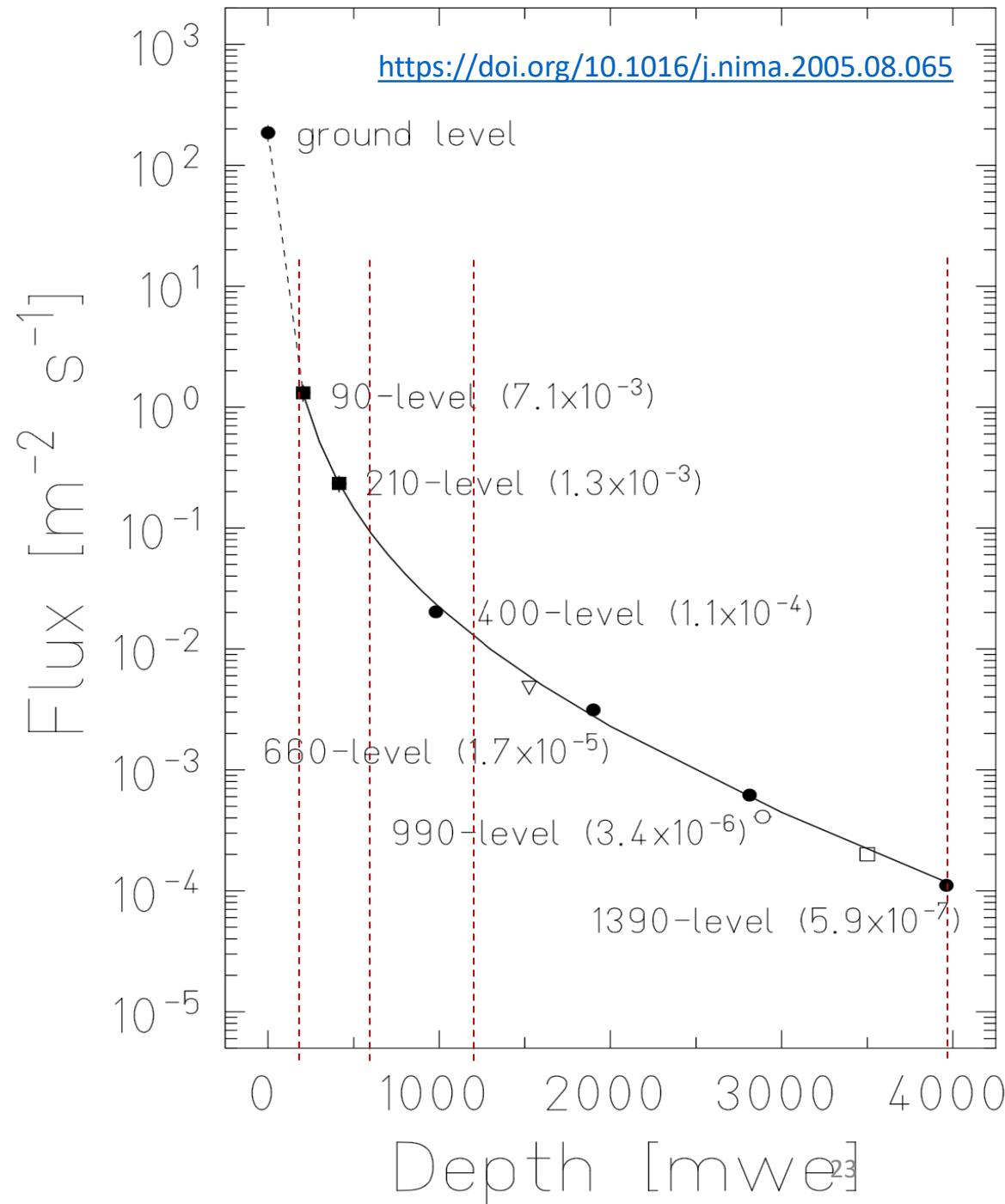
W.H. Trzaska

Main neutron background sources underground 2/2

- CR muon-induced neutrons
 - In the cavern walls & target

Depth [m]	m.w.e.	Muon flux $\text{m}^{-2}\text{s}^{-1}$	Estimated muon-induced events in Pb per ton-month
80	210	1.2×10^0	~3600
220	583	9.7×10^{-2}	~290
440	1166	1.4×10^{-2}	~442
1400	4000	1.1×10^{-4}	~0.3

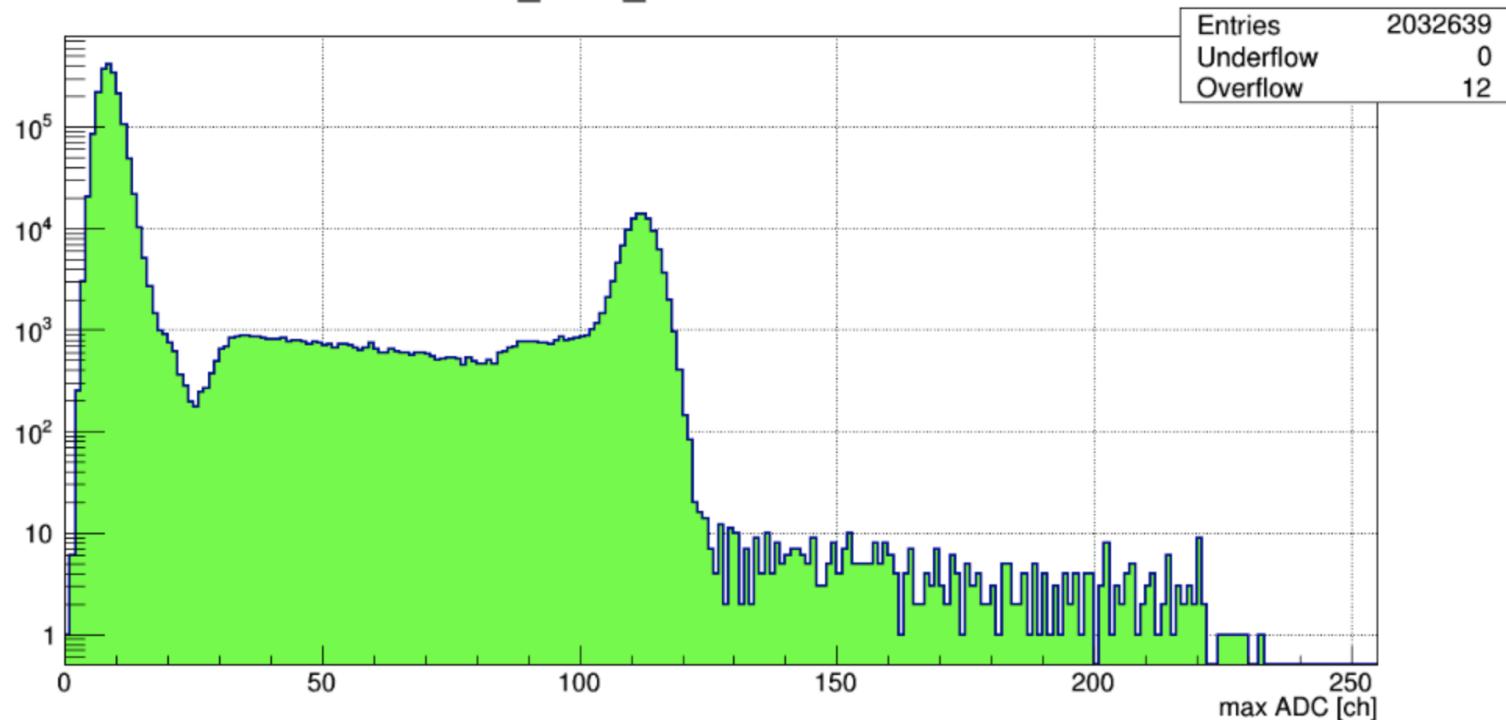
<https://doi.org/10.1016/j.nima.2005.08.065>



Typical ${}^3\text{He}$ -counter spectrum

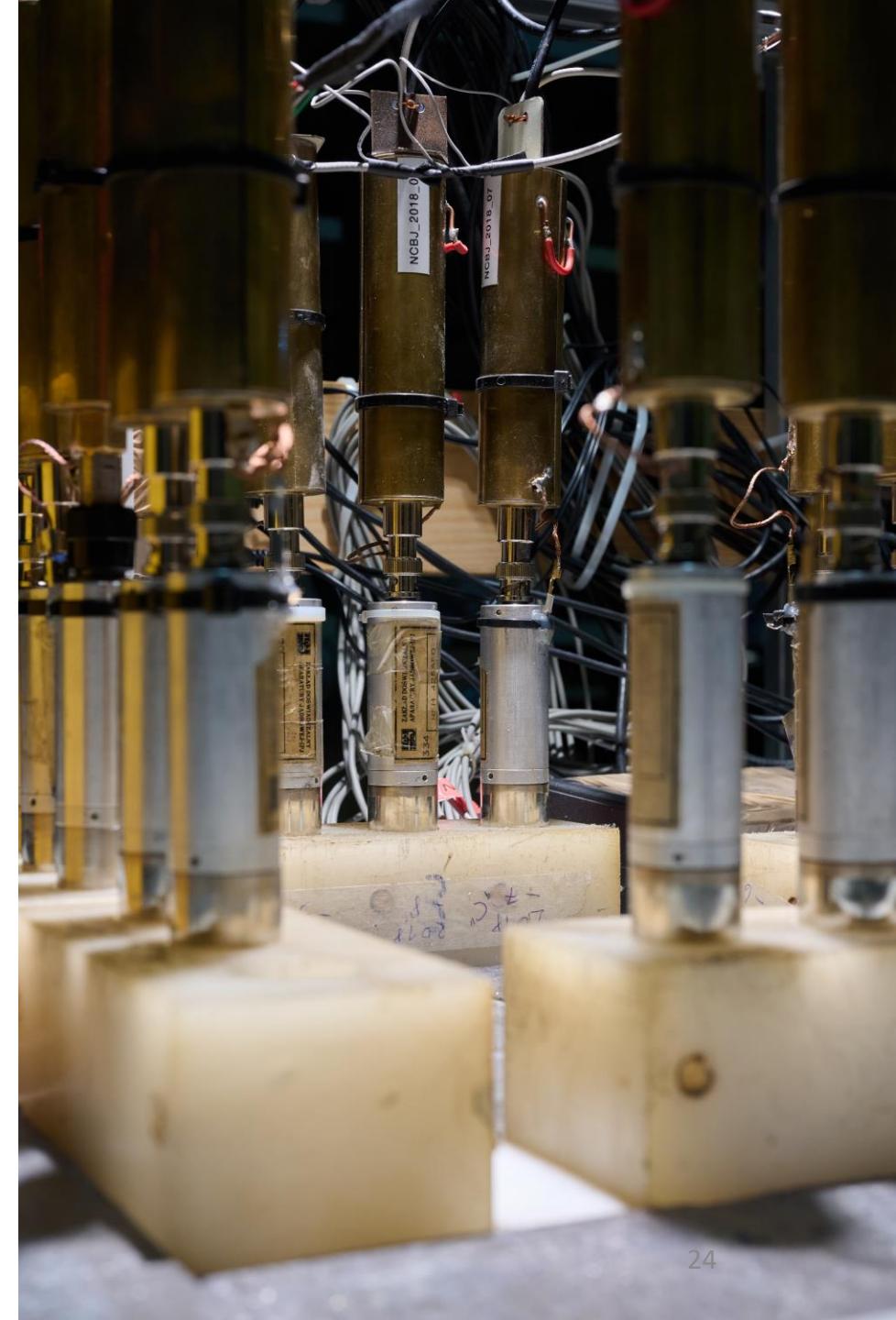
obtained with a Cf source

NCBJ_2018_05h



14 He^3 counters @ 4 atm; 50 cm long, 2.5 cm diameter

<http://www.astrophys-space-sci-trans.net/7/511/2011/astra-7-511-2011.pdf>



Proceedings of Science (ICRC2021) 497

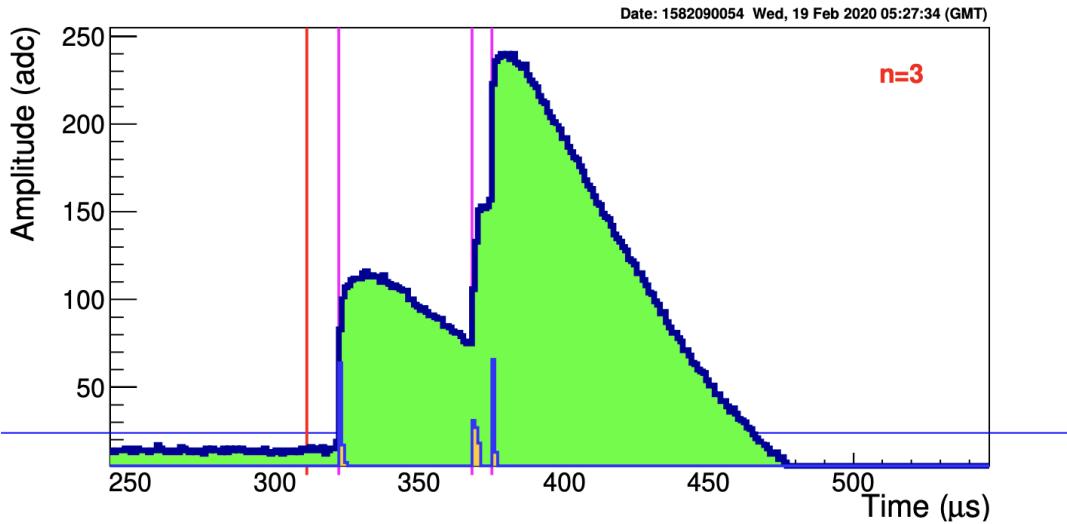


Figure 3: Example of multiple neutron signal registered in single ${}^3\text{He}$ counter with identified 3 neutrons. Only fraction of whole registered wave-form is shown to visualize the structure of neutron signals.

<https://doi.org/10.22323/1.395.0497>

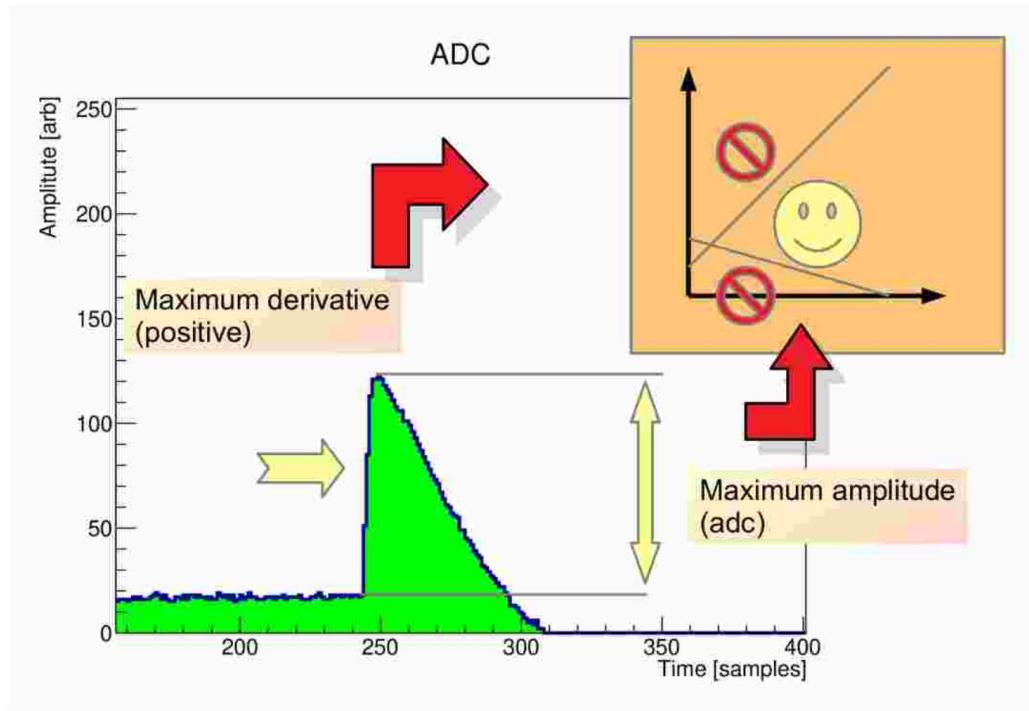


Figure 4: The idea of creating parameters on the basis of which cuts will be made to select signals from neutrons. Amplitude value signal and the maximum difference between successive samples for each pulse is marked in Fig.5

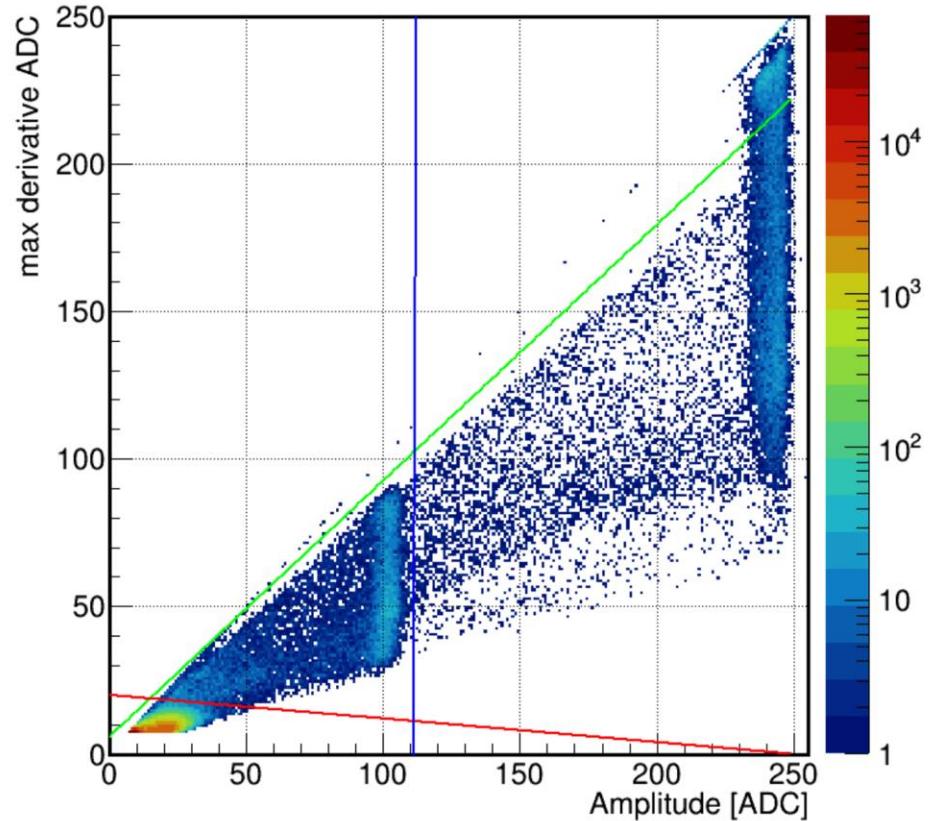


Figure 5: Practical applications of selection cuts on single counter data. Signal corresponding to neutrons are located in triangle between cuts lines. Amplitude distribution corresponding to selected signals is presented on Fig.6.