Muon-induced neutrons at the Boulby Underground Laboratory

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Outline

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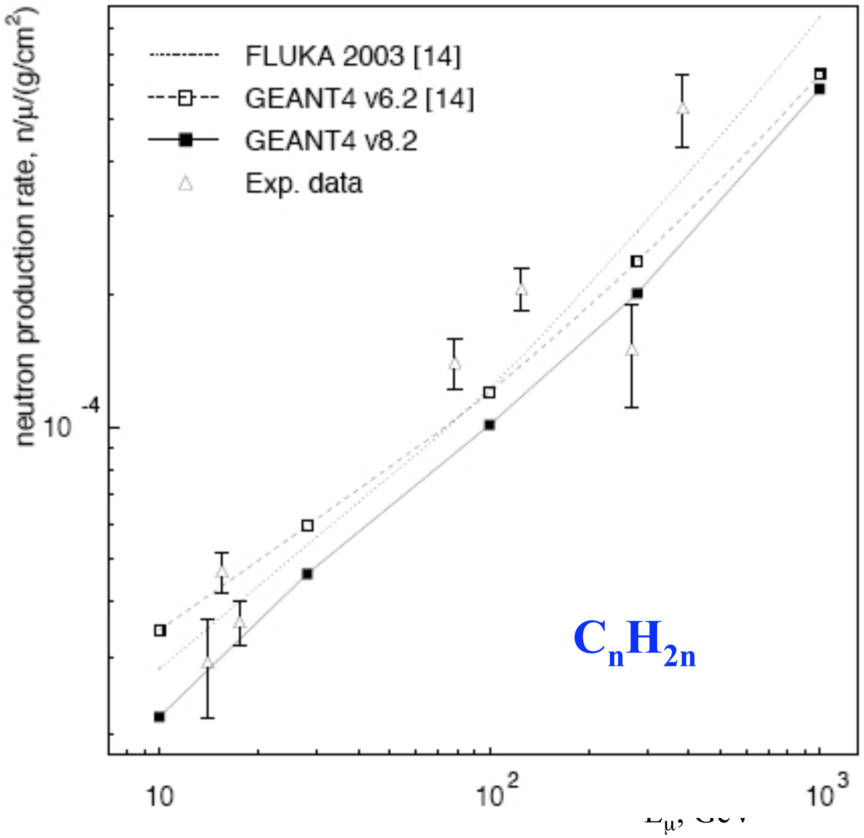
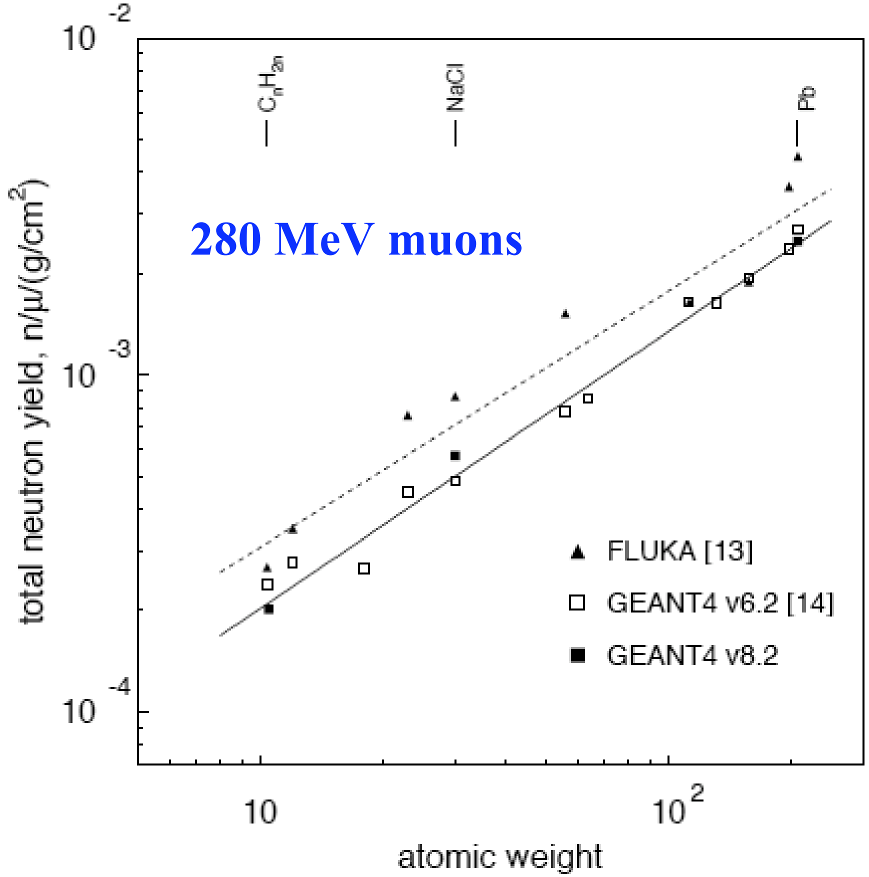
Muon-induced neutrons

FLUKA: Kudryavtsev et al. NIMA, 505 (2003) 688.

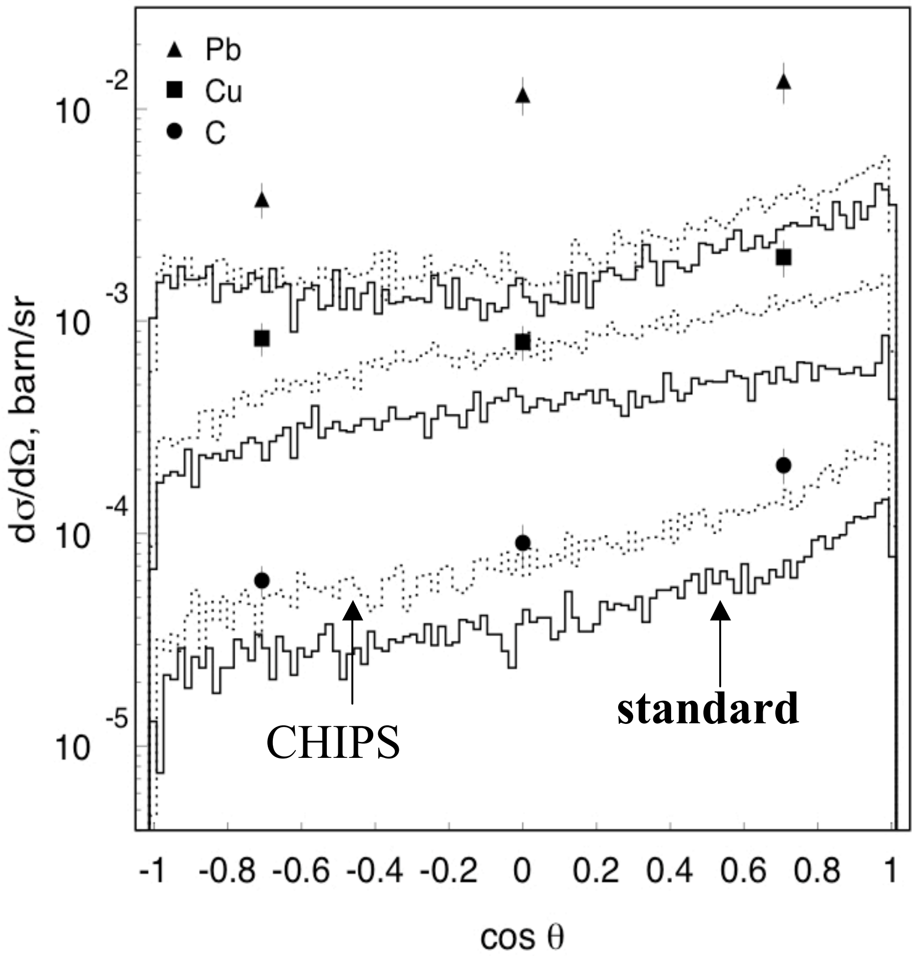


GEANT4 v6.2: Araujo et al. NIMA 545 (2005), 398.
GEANT4 v8.2: Lindote et al., in preparation.



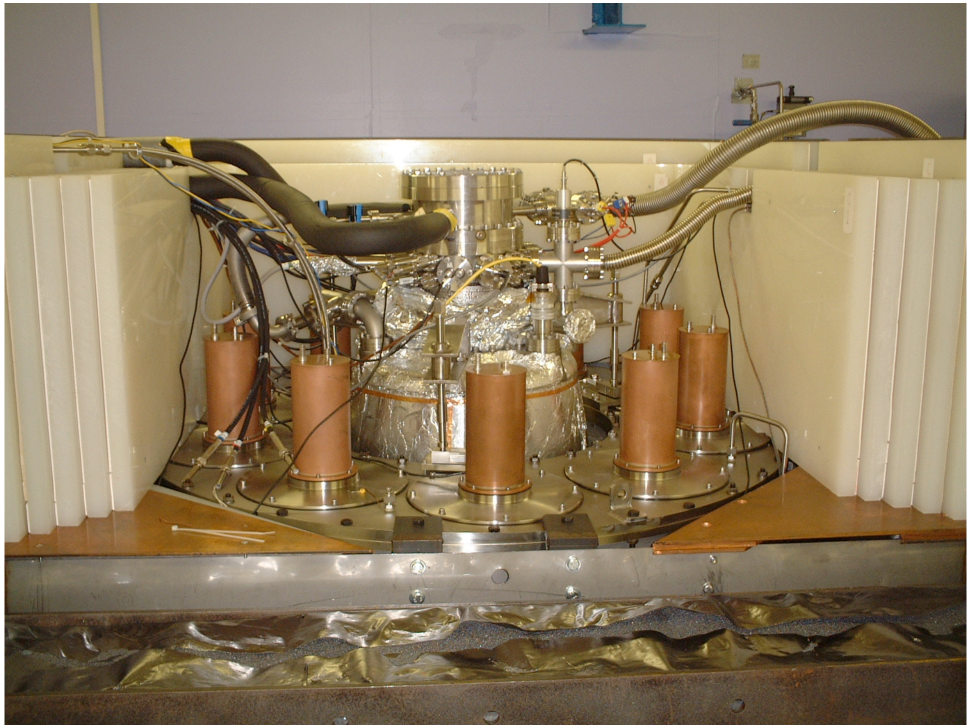
- Most data are for light targets.
- Data are controversial - no full MC for any data point at high energies.
- Models may not be very accurate - tests are needed.

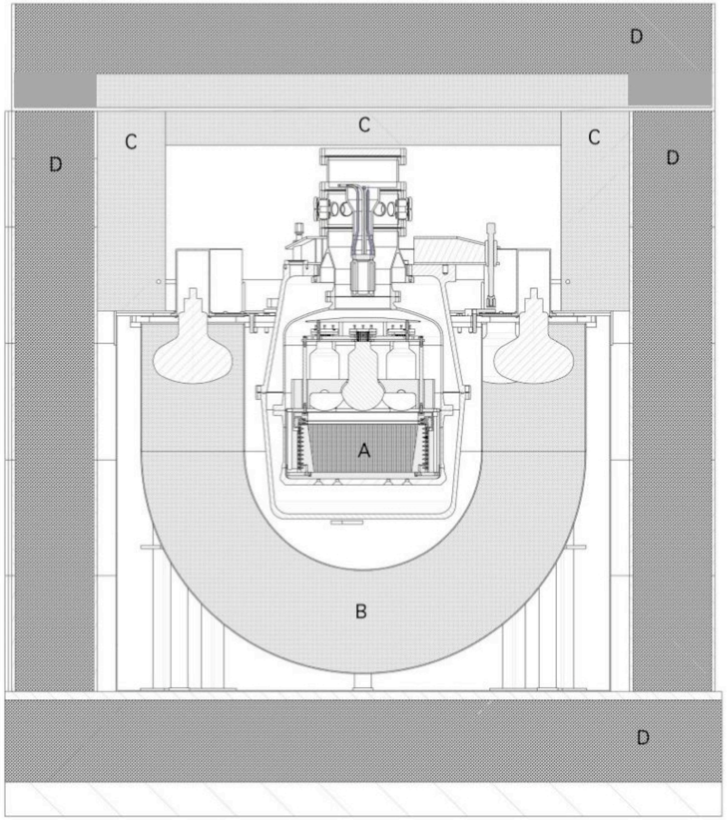
Muon-induced neutrons



- **Differential cross-section of neutron production in thin targets for 190 GeV muons (E_n>10 MeV). Solid histogram - GEANT4 v8.2, standard; dotted histogram - GEANT4 v8.2, CHIPS; data - NA55 (Chazal et al. NIMA, 490 (2002) 334).**
- **Other data for lead (Bergamasco et al. Nuovo Cim. A, 13 (1973) 403; Gorshkov et al. Sov. J. Nucl. Phys., 18 (1974) 57) are old and controversial but also show significantly higher neutron production compared with simulations.**
- **Lead is important since it is used as a shield in underground experiments.**

Measurements with ZEPLIN II veto



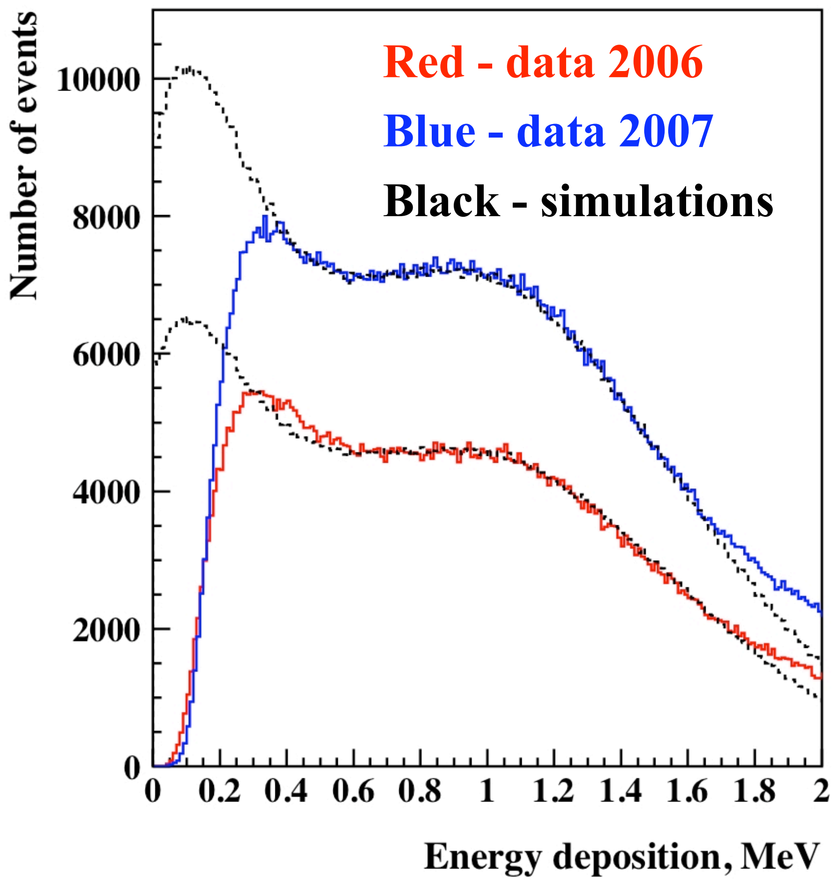


- 0.73 tonne of liquid scintillator + paraffin shielding interleaved with Gd impregnated resin + Gd painted on the inner surface of the veto vessel.
- Lead castle - about 50 tonnes - main target for neutron production.
- Detailed MC was carried out to take into account geometry and physics.

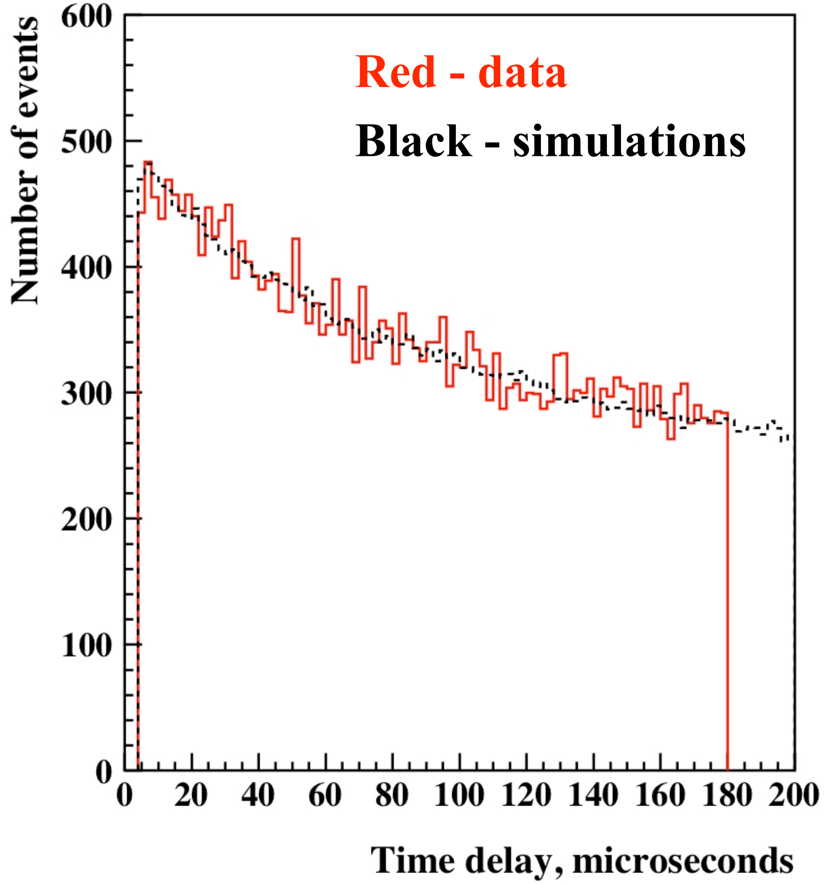
Detection principle

- **Neutron detection principle: delay coincidences between muon signal and neutron capture:**
  - **Muon (or cascade) signal - large energy deposition (PMTs and DAQ are saturated);**
  - **Neutron capture signal - delayed by a few tens of microseconds, capture mainly on H.**
- **The detector is triggered by high-energy pulses: either high-energy gammas depositing energy close to PMTs (non-uniform light collection shifts the measured energy to higher values), or muons (cascades).**
- **Energy threshold: hardware - about 7 MeV, software - 20 MeV. Average energy deposition of muons - more than 50 MeV.**
- **Energy threshold for secondary (neutron) pulse analysis: about 0.15 MeV; increased to 0.55 MeV at the 2nd stage of analysis to avoid background etc.**
- **3-fold coincidences between PMTs are required for trigger and secondary pulses.**
- **Total live time: 204.8 days (August 2006 - April 2007).**

Gamma-ray and neutron calibrations



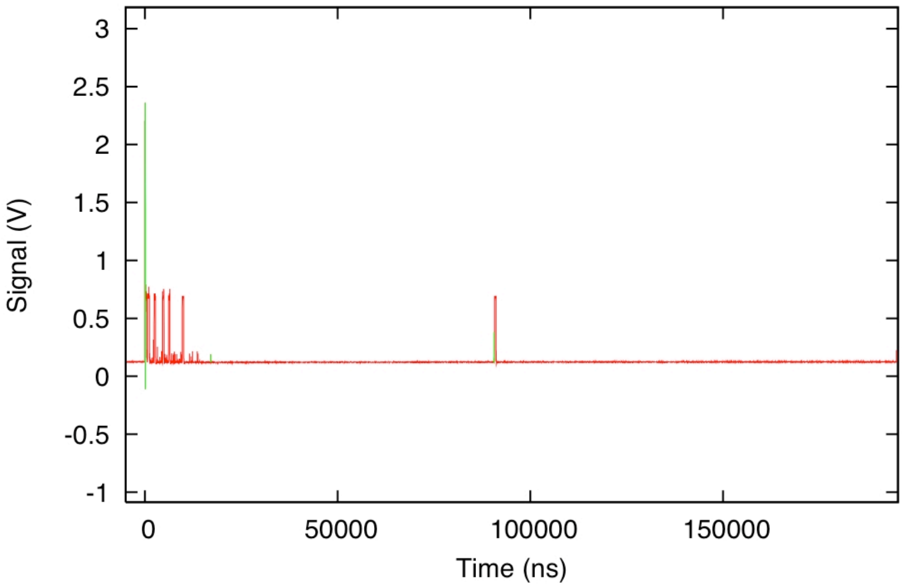
^{60}Co spectra collected in August 2006 and March 2007 (before and after the data run). Difference in pulse area-to-energy conversion factors is 6%.

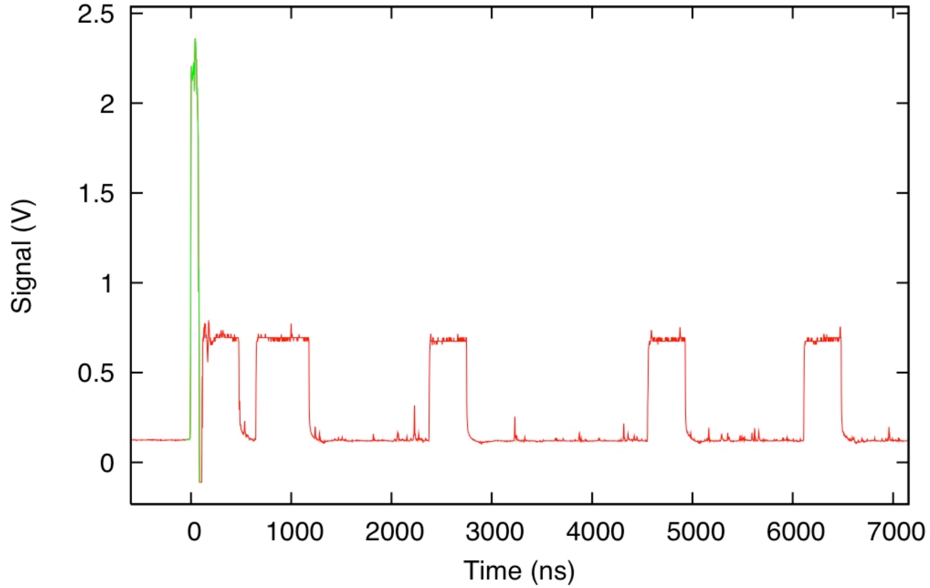


Neutron calibration with Am-Be source; simulations using GEANT4.

Exponential - neutrons, flat background - random coincidences.

Event display, muon selection



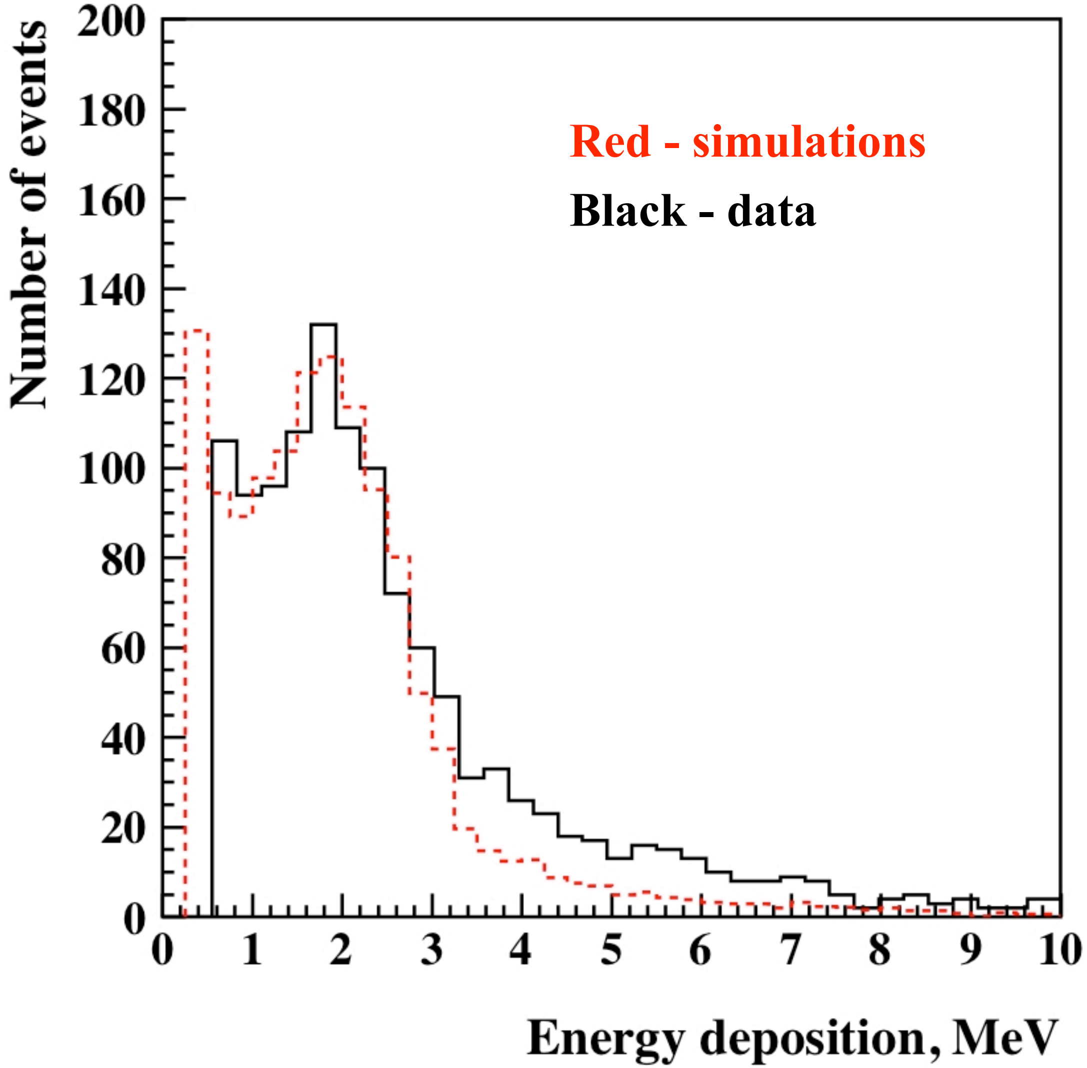


- **Pulses with amplitude of about 0.6 V - logic pulses generated by 3-fold coincidences.**
- **Pulse at about 90 μs is the neutron-like pulse (delayed photon from neutron capture).**
- **Muon events: large amplitude, large area, saturation, large width.**

Muon rate and flux

- 10832 muons during 204.8 days; rate 52.9±0.5 muons/day.
- Comparing with Monte Carlo simulations gives the muon flux as (3.79 ± 0.04 (stat.) ± 0.11 (syst.))×10^{-8} cm^{-2} s^{-1}.
- Systematic uncertainty is due to the uncertainty in the energy scale.
- The muon flux is defined as a flux through a spherical detector with unit cross-sectional area.
- The flux corresponds to the depth of 2850 ± 20 m w. e. in Boulby rock.
- The measured flux is slightly lower (by 8%) and the evaluated depth is slightly higher than previously reported (M. Robinson et al., NIMA 511 (2003) 347) mainly due to:
  - Different location of the new lab;
  - More accurate (3D instead of 1D) simulation of muon passing through and around the detector.

Energy spectrum of the secondary pulses

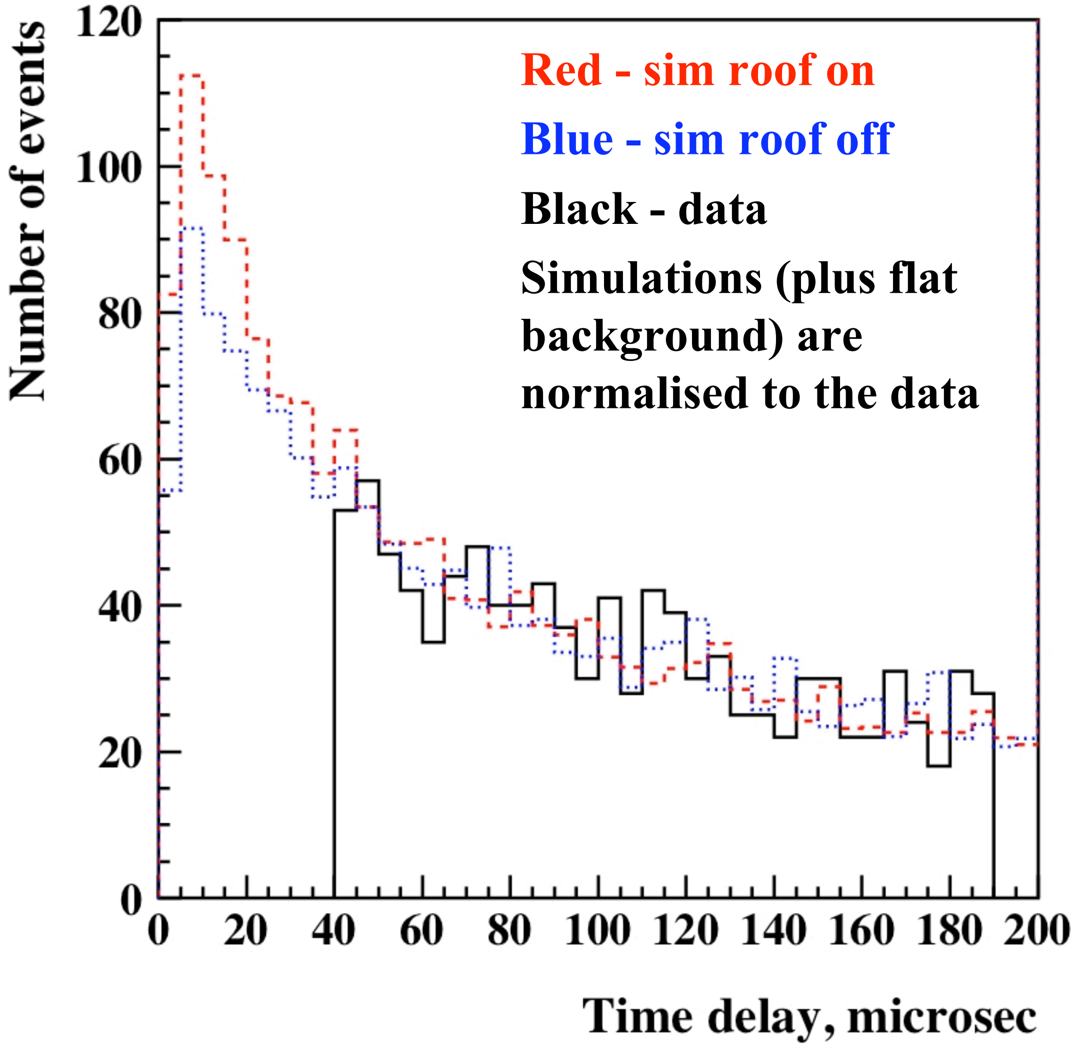


Spectrum of secondary pulses after muon trigger; an independent calibration using 2.22 MeV peak (plus Compton edge) - capture on H.

Simulated spectrum (GEANT4) was folded with the energy resolution function.

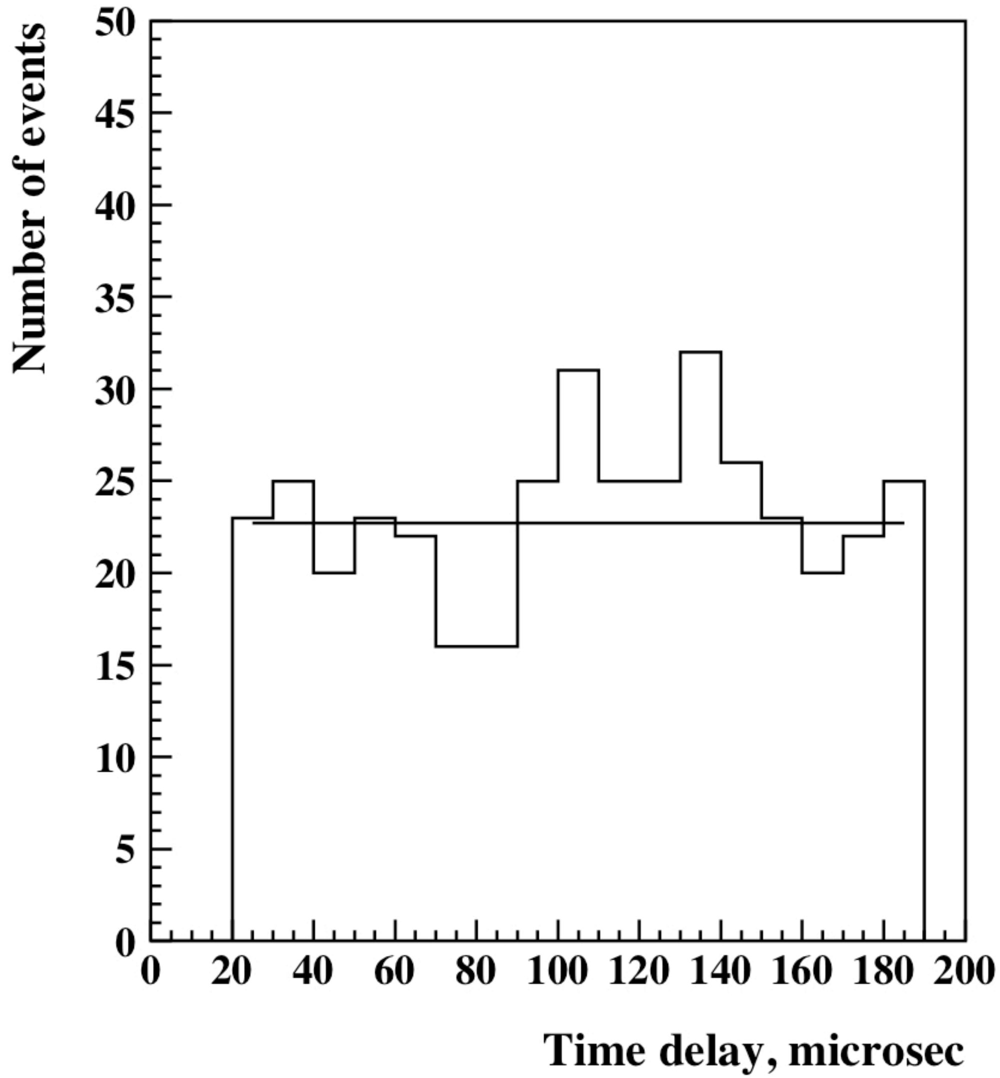
Uncertainty in the energy scale - 20%.

Time delay distributions



- 204.8 days of run time.
- Data run, muon trigger (E>20 MeV). The rate of secondary pulses: 0.096 ± 0.003 (stat) per muon above 0.55 MeV at 40-190 μs.
- Subtracting background rate 0.0164 ± 0.0009 (next slide) gives the neutron rate: 0.079 ± 0.003 (stat) per muon above 0.55 MeV at 40-190 μs.
- Simulations (same conditions): 0.143 ± 0.002 (stat.) ± 0.009 (syst.) n/μ.
- Systematic uncertainty is due to the uncertainty in the energy scale.

Time delay distribution

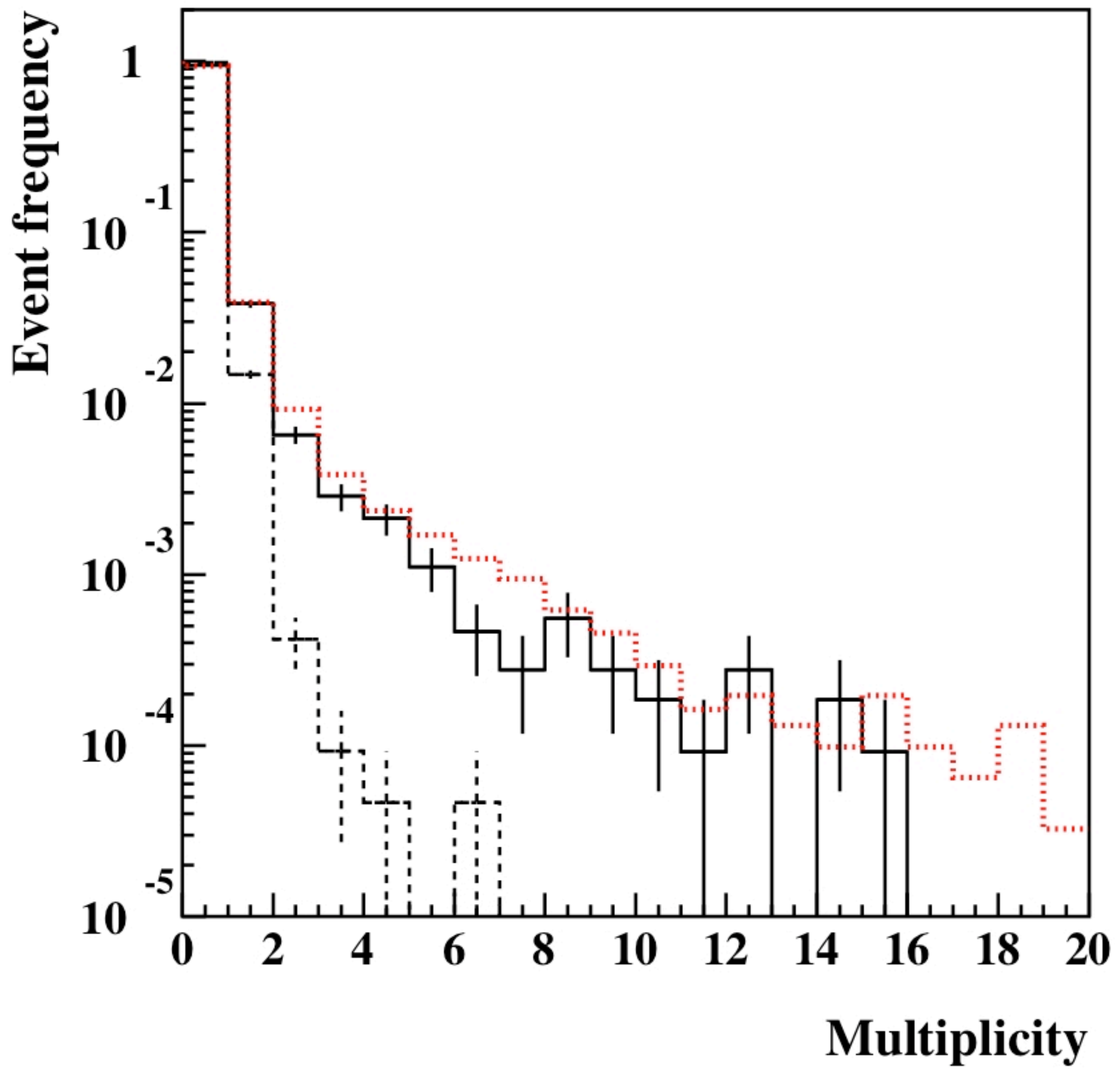


Data run, gamma-ray trigger (7<E<15 MeV, high-energy detected due to non-uniform light collection).

Background rate:

0.0164 ± 0.0009 (stat) secondary pulses per event above 0.55 MeV at 40-190 μs.

Multiplicity distribution



Black solid histogram - neutrons, muon trigger (E>20 MeV);

Black dashed histogram - background, gamma-ray trigger (7<E<15 MeV).

Red dotted histogram - simulations for neutrons.

Conclusions

- Muon flux has been measured using ZEPLIN II liquid scintillator veto (0.73 tonnes) in the new lab (JIF area - Palmer Laboratory) at Boulby: $(3.79 \pm 0.04 \text{ (stat.)} \pm 0.11 \text{ (syst.)}) \times 10^{-8}$ cm^{-2} s^{-1} (through a spherical detector with unit cross-sectional area). The flux corresponds to the depth of 2850 ± 20 m w. e.
- Muon-induced neutron rate has been measured as 0.079 ± 0.003 (stat.) n/μ above 0.55 MeV at 40-190 μs. Simulations give the rate of 0.143 ± 0.002 (stat.) ± 0.009 (syst.) n/μ (with the same selection criteria), a factor of 1.8 higher than the measured value.
- As the vast majority of detected neutrons (90%) are produced in lead we evaluated from our measurements the total neutron yield in lead as $(1.31 \pm 0.06)\ 10^{-3}$ n/μ/(g/cm^2) for mean muon energy of 260 GeV.
- Also: Neutron background from radioactivity in rock has been measured using small liquid scintillator cell: $(1.72 \pm 0.61 \text{ (stat.)} \pm 0.38 \text{ (syst.)}) \times 10^{-6}$ n/cm^2/s (E>0.5 MeV) and found to be consistent with simulations based on the evaluated U/Th concentrations - 1.20×10^{-6} n/cm^2/s (E. Tziaferi et al. Astroparticle Phys. 27 (2007) 326).