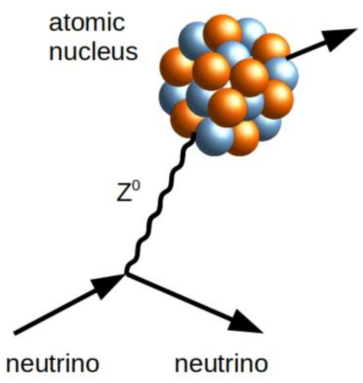
CONUS experiment: new results and the upgrade campaign to CONUS+

Workshop on Weak Interactions and Neutrinos(WIN) 2023

Kaixiang Ni – On behalf of the CONUS collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Coherent elastic neutrino nucleus scattering (CEνNS)



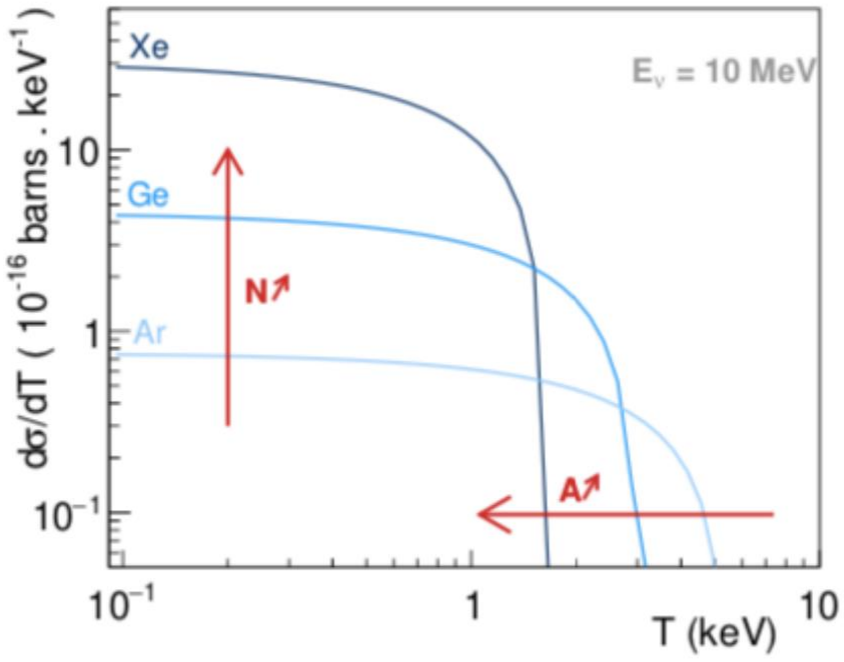
- "Coherent": neutrino interacts with the nucleus as a whole
  → Scale up with nucleon number
- Relatively large cross section: ~10^{-16} barn
- Low energy scale: several keV of recoil energy

$$\frac{d\sigma}{dT} = \frac{G_f^2}{4\pi}\left(N - \left(1 - 4\sin^2\theta_w\right)Z\right)^2 F^2(q^2) M\left(1 - \frac{MT}{2E_v^2}\right)$$

~N^2

Form factor. ~1 in coherent regime

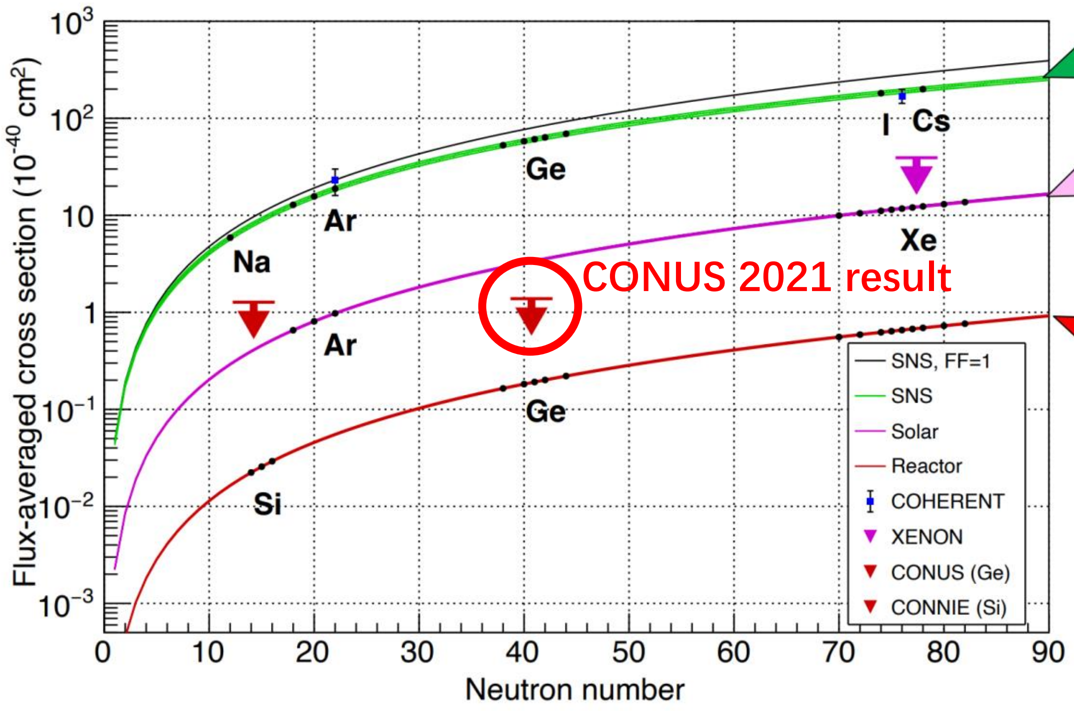
Kinematics



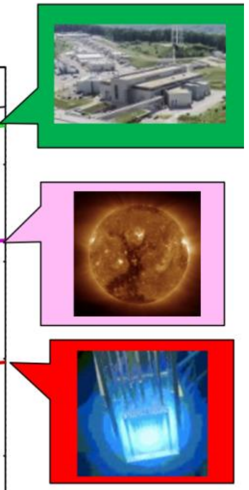
- ✓ *Verification of Standard model (e.g. Weinberg angle) at low energy*
- ✓ *BSM searches for new neutrino interactions*
- ✓ *"Neutrino Floor" study for dark matter detectors*
- ✓ *Insight of nuclear structure (nuclear matrix, etc.)*

Neutrino sources & detection

Source: higher ν energy → larger signal & cross section, but less coherence
Target: heavier nuclide → larger cross section, but lower threshold



Kate Scholberg, PANIC 2021



- Accelerator ν:
  - Detected by COHERENT, Ar/CsI: PRL 126 012002 (2021), PRL 129 081801 (2022)
- Solar ν (^{8}B ν):
  (Liquid xenon dark matter experiments)
  - Xenon-1T: PRL 126 091301 (2021)
  - PandaX-4T: arXiv 2207.04883
- Reactor ν:
  - **CONUS:** PRL 126 041804 (2021)
  - NuGen: PRD 106 L051101 (2022)
  - NCC-1701: PRL 129 211802 (2022)
  - RECODE: in later talk

  More detection technologies showing in today's session!

*Reactor neutrino experiment: **within fully coherent regime!***

The CONUS collaboration

Collaboration:

Max-Planck-Institut für Kernphysik (MPIK), Heidelberg: N. Ackermann, S. Armbruster, H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez-Garcia, J. Stauber, H. Strecker

Former collaborators: T. Schierhuber, E. Van der Meeren, J. Henrichs, T. Hugle

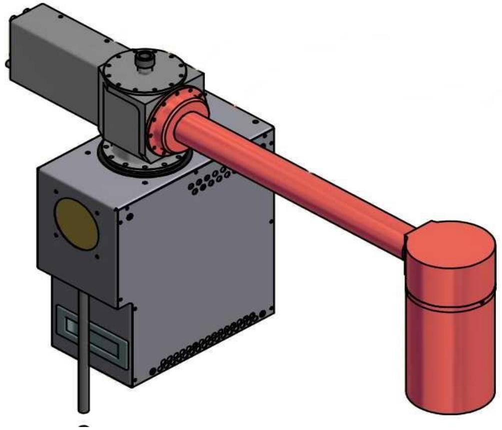
Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf: K. Fülber, R. Wink

Scientific cooperation:

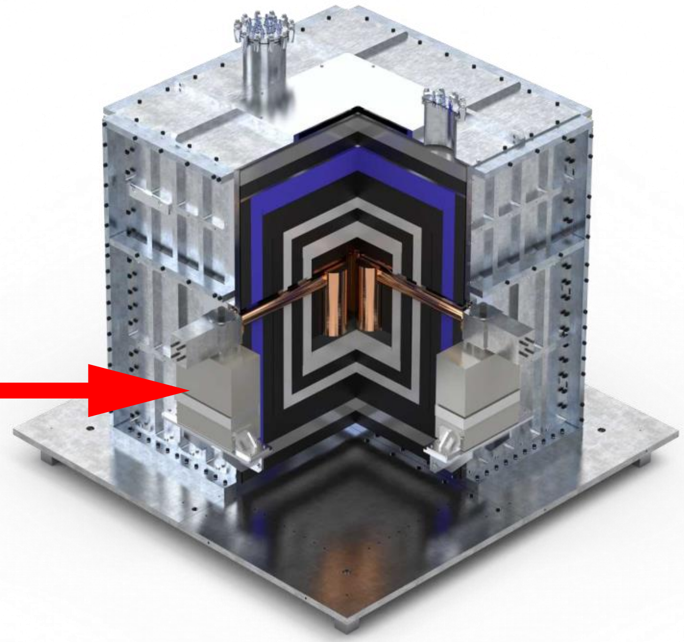
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig: R. Nolte, E. Pirovano, M. Reginatto, M. Zboril, A. Zimbal

Experiment setup

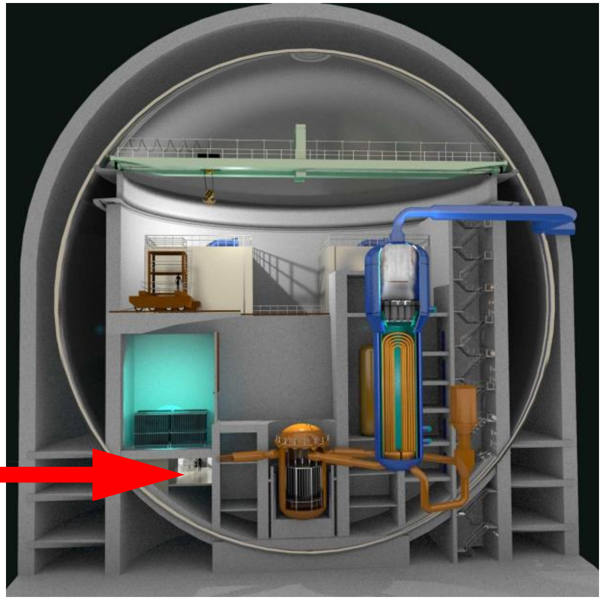
Detector:
- Point-contact high purity Ge detectors
- Electrical cryo-cooled for long-time stable run
- Energy threshold: 200-300eV
- Four 1-kg modules, in array. Additional one for R&D



Shield:
- Lead + Polyethylene + muon veto scintillators
- Volume: 1.65m^3, mass: 11 tons

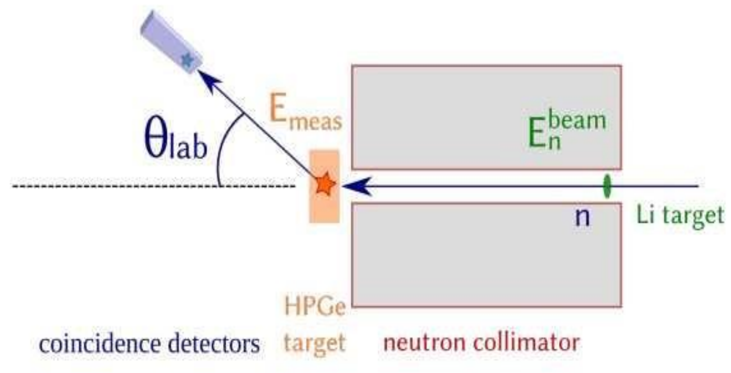


Experiment site: Kernkraftwerk Brokdorf (KBR):
- 3.9GW thermal power
- 17m distance to the reactor core, 2.3 x 10^{13} ν/s/cm^2
- 24m w.e. overburden

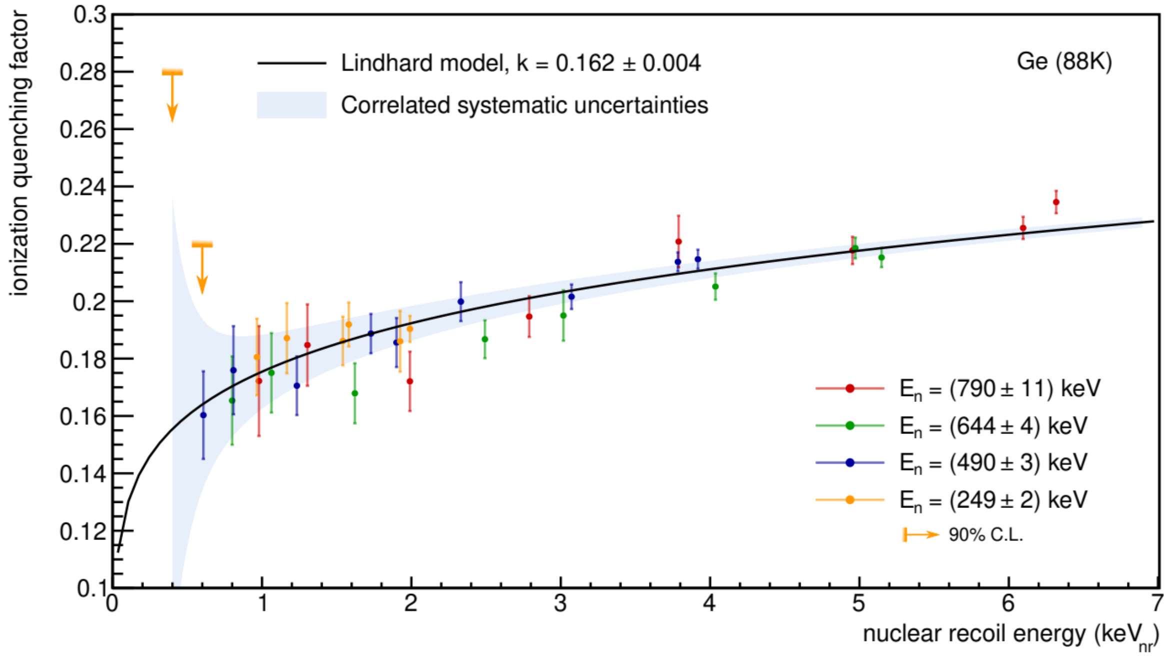


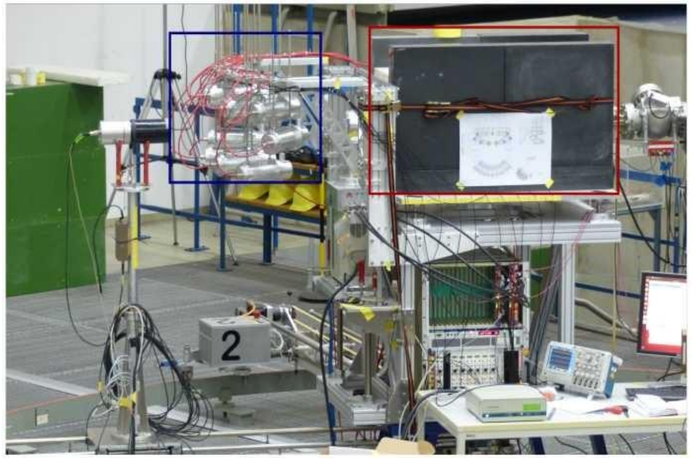
kg-scaled detector is enough to make discovery!

Quenching measurement



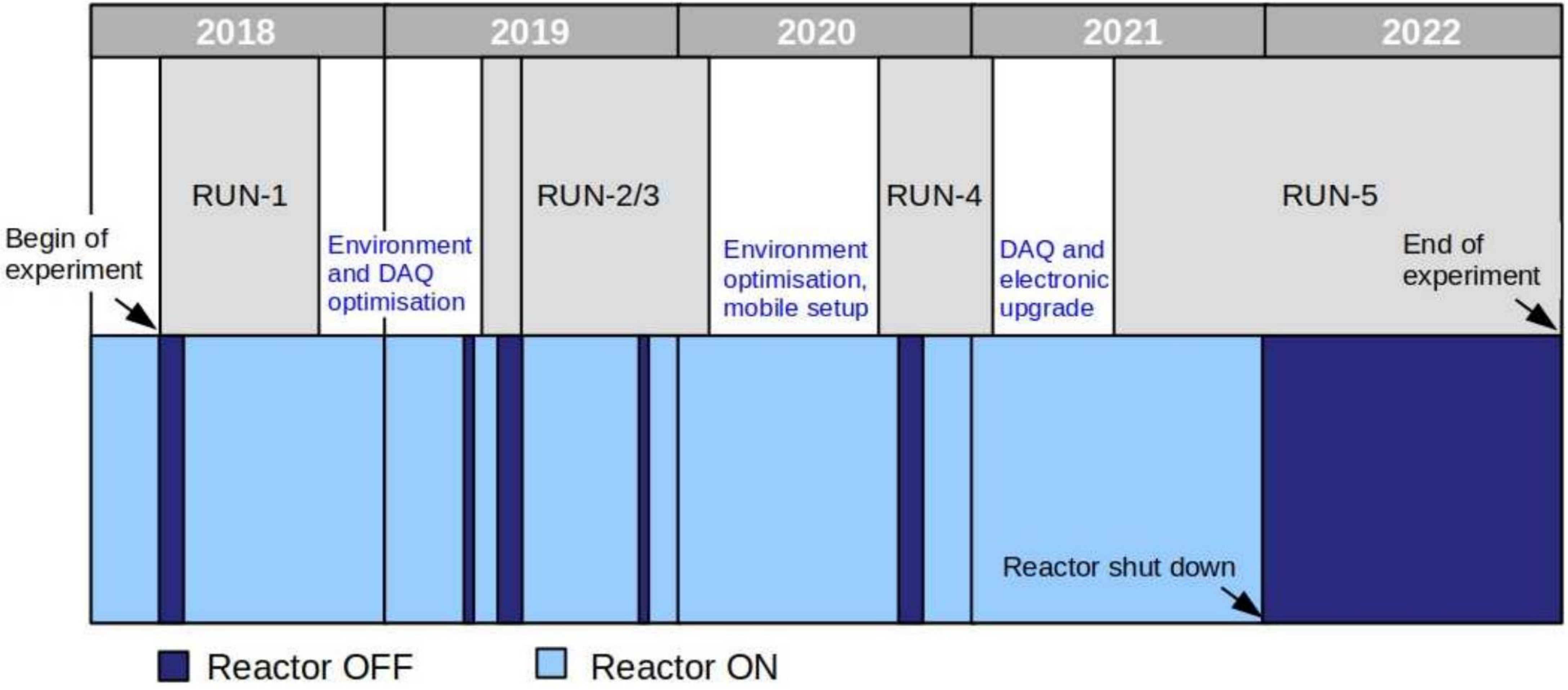
- Only part of the nuclear recoil energy could turn into detectable signal
  → **quenching**
- Most commonly used model: Lindhard model, with unknown parameter k
- Auxiliary measurement done with neutron beams at PTB, Germany
- k=0.162+-0.004 (stat.+syst.)





Eur. Phys. J. C ***82****, 815 (2022)*

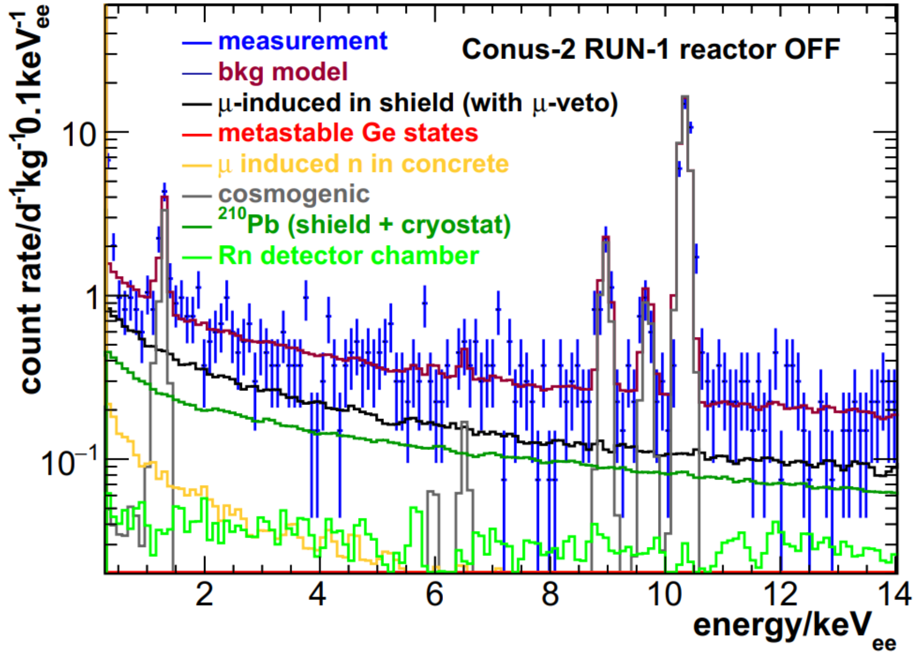
Runs

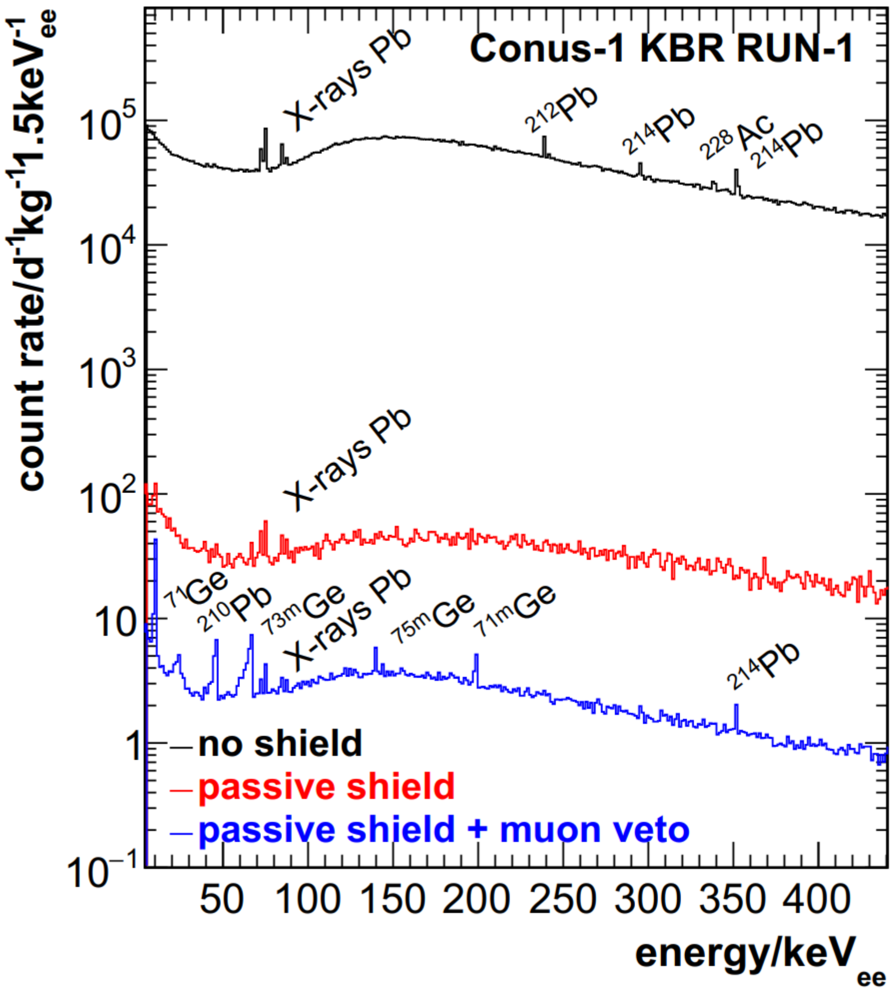


2018
2019
2020
2021
2022
RUN-1
RUN-2/3
RUN-4
RUN-5
Begin of experiment
Environment and DAQ optimisation
Environment optimisation, mobile setup
DAQ and electronic upgrade
End of experiment
Reactor shut down
Reactor OFF
Reactor ON

Background estimation

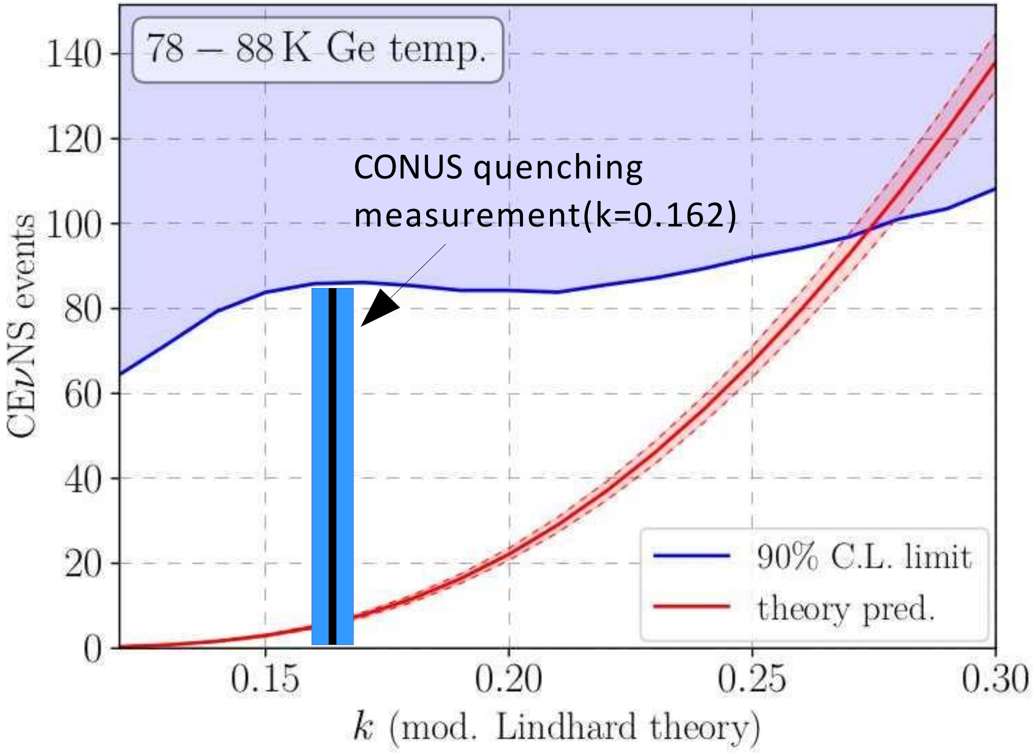
- Suppression factor by shield: >10^4
- Remaining bkg rate in ROI: O(10) cts/d/kg
- Bkg is dominated by muon-induced events and ^{210}Pb events
  - Reactor neutron/activation negligible

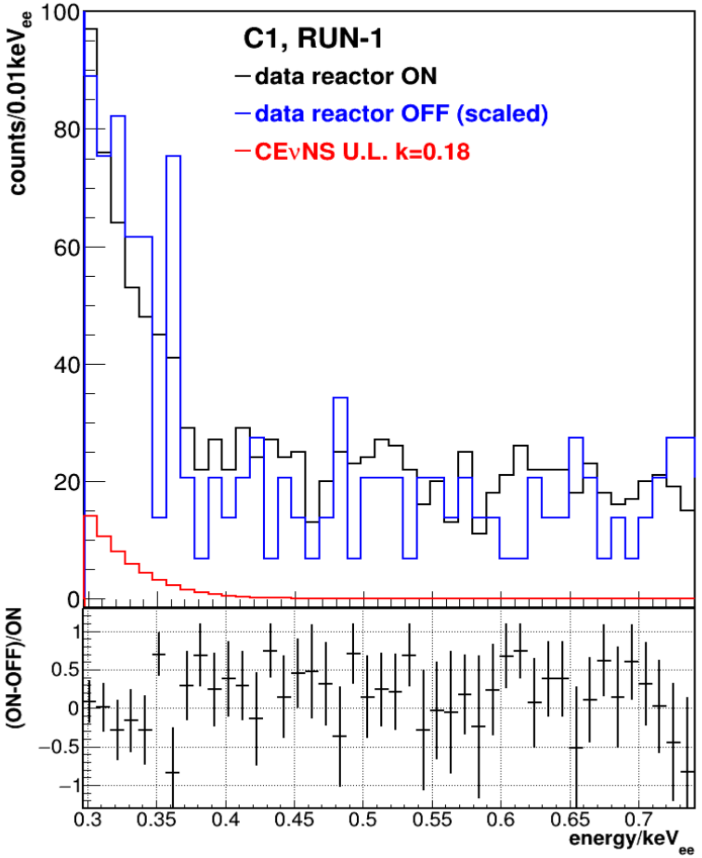




Eur. Phys. J. C ***83***, *195 (2023)*

Results (Run1/Run2)





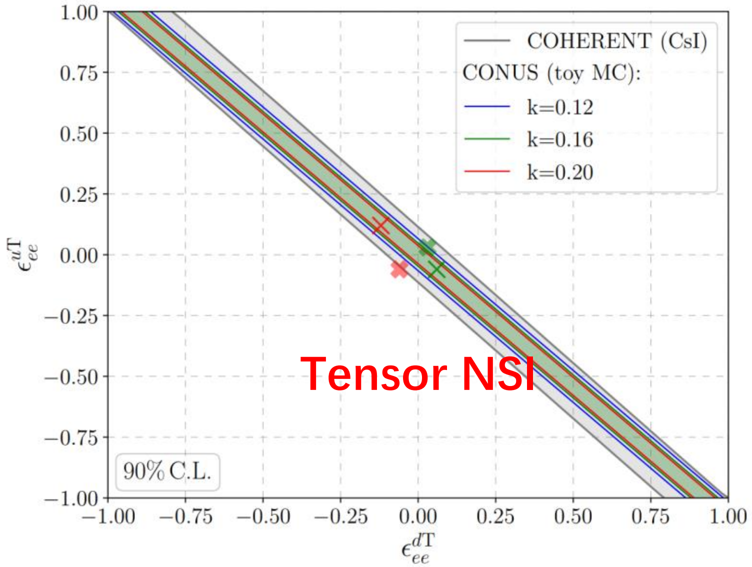
<85 events are detected
Lower limit is still factor 17 higher than SM!

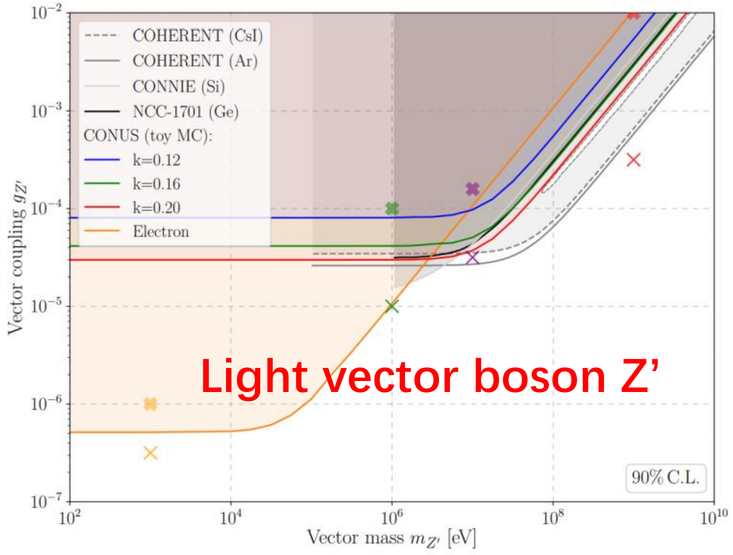
- Data: 248.7kg-d ON, 58.8kg-d OFF
- Threshold: ~300eV
- Binned Likelihood:
  - Simultaneously fit ON/OFF data
  - Poisson distribution in each bin

Phys.Rev.Lett. 126 (2021) 4, 041804

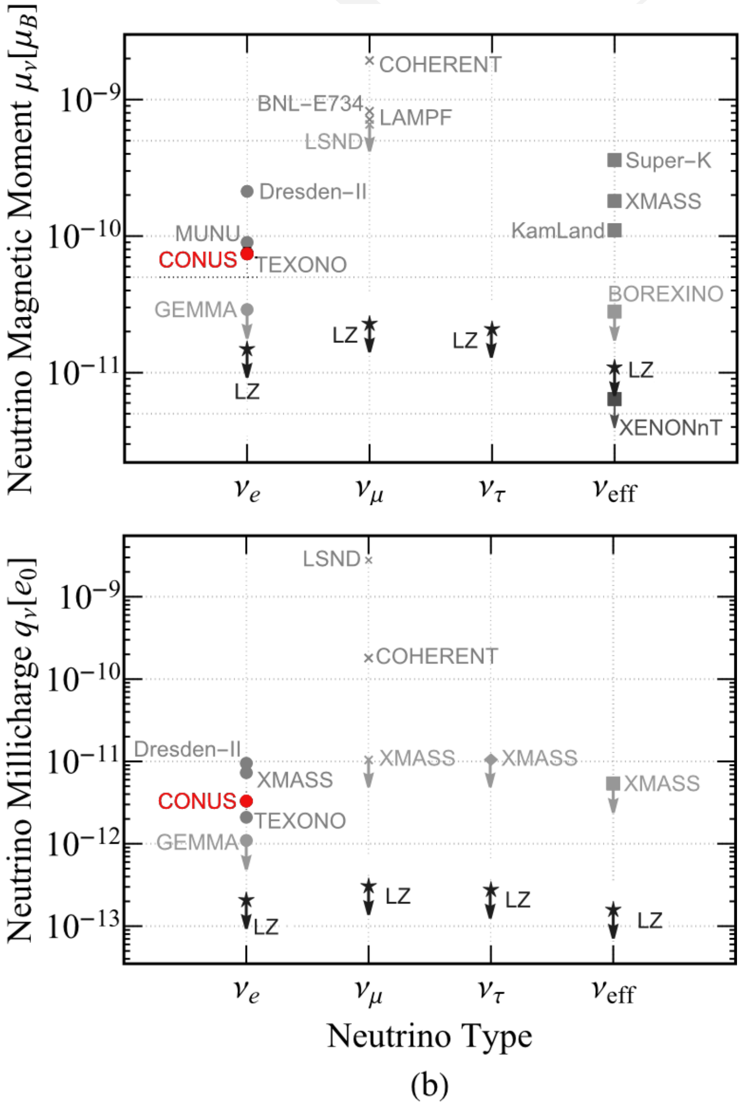
BSM results

Tensor/Vector NSI (non-standard interactions): limits the coupling parameter space
Light vector boson: limits the mass-coupling parameter space
Neutrino millicharged: $|q_\nu| < 3.3 \times 10^{-12}\ e_0$
Neutrino magnetic moment: $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$





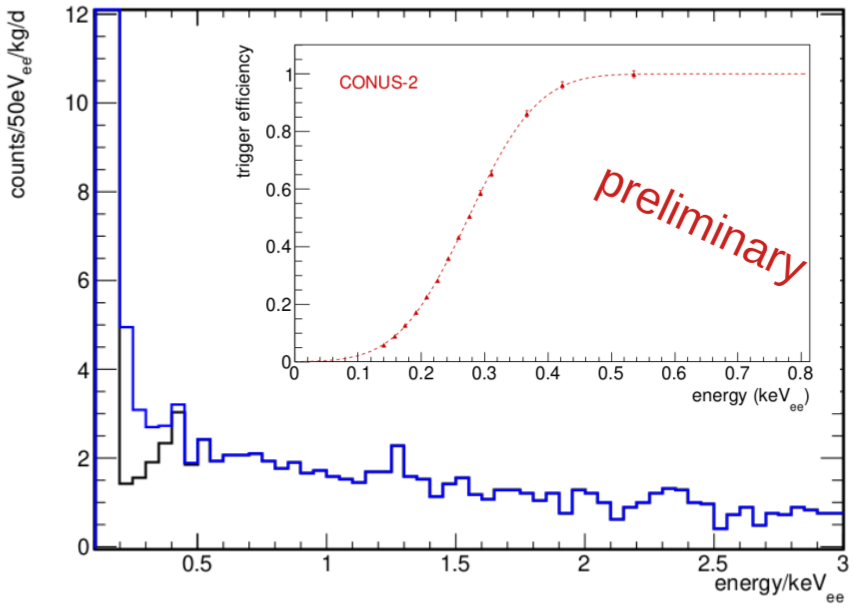
JHEP 05 (2022) 085



Phys. Rev. D 107, 053001 (2023)

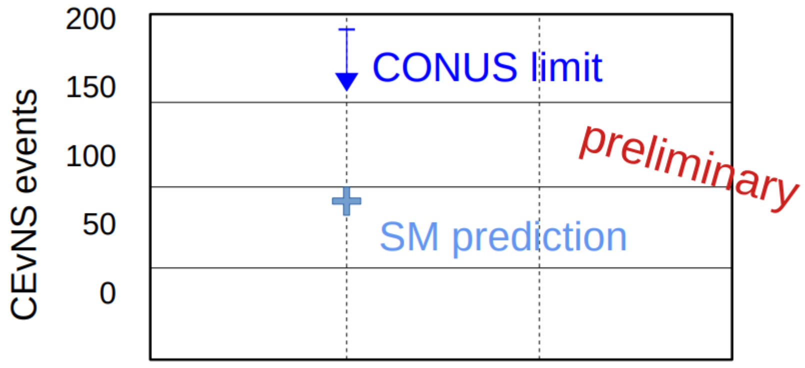
Run5 update

- More statistics: in total 458kg-d ON, 293kg-d OFF
- New DAQ:
  - Waveform readout, PSD available
  - Lower noise level, optimized trigger eff. → Threshold: ~210 eV
- Stabled run condition
- **Lower limit: factor 2 above SM prediction**
- **Strongest limit on reactor CEνNS count rate! (Assuming Lindhard quenching)**



Detector	Exposure (ON/OFF, kg-d)	Threshold (eV)	Anticipated Signals (k=0.16)	Likelihood fit
C1	142/40	220	38 +- 6	<73
C2	146/131	210	28 +- 4	<73
C4	139/102	210	24 +- 4	<111
Total	427/273		90	<182

preliminary



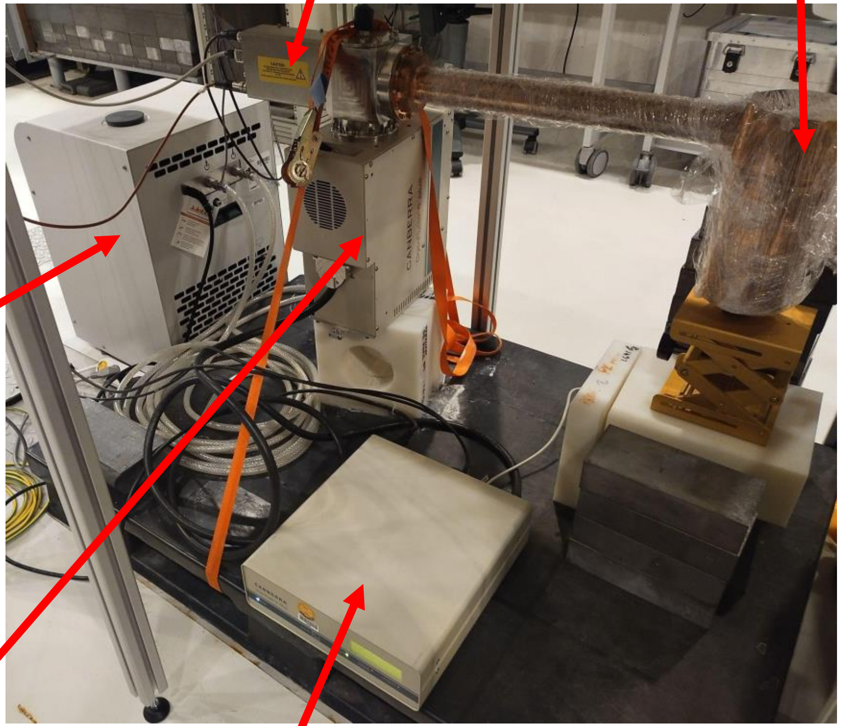
From CONUS to CONUS+

- Nuclear power plants in Germany are being shut-down…
- Our new home: Kernkraftwerk Leibstadt (KKL), Switzerland
- Experiment hall: ~21m from 3.6 GW reactor core, 1.45 x 10^{13} ν/s/cm^2

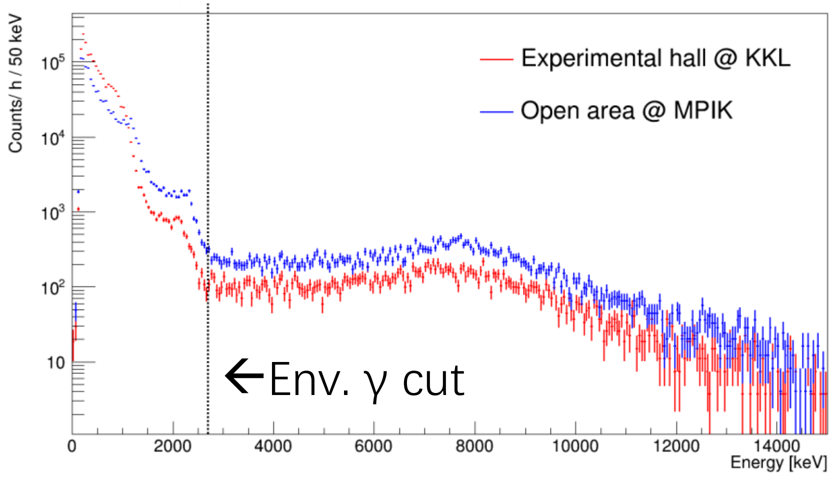
Upgraded Ge detectors

- **Ge refurbishment:** reduced point-contact size
- **ASIC upgrade:** higher trigger efficiency at low energy.
- **Cryostat upgrade:** water-cooled to reduce vibration and microphonic noise
- Under test in MPIK!
- Target:
  - Resolution: <55eV
  - Threshold: <200eV

Cooperate with Mirion Technology

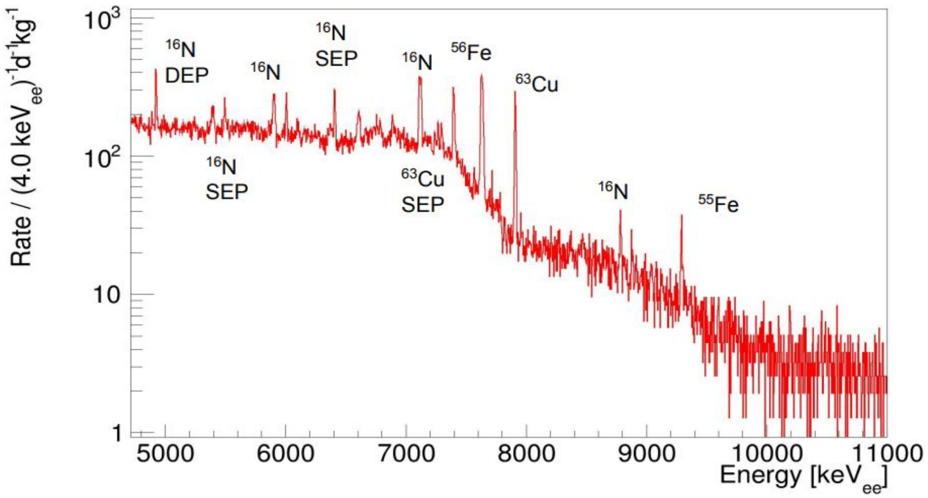


Environmental study



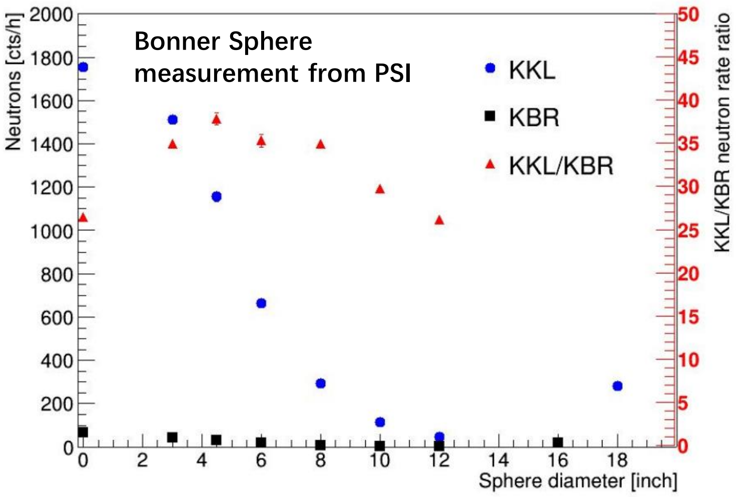
Muon: ~7-8 m w.e., 2.2 times larger

- New muon-veto system mandatory

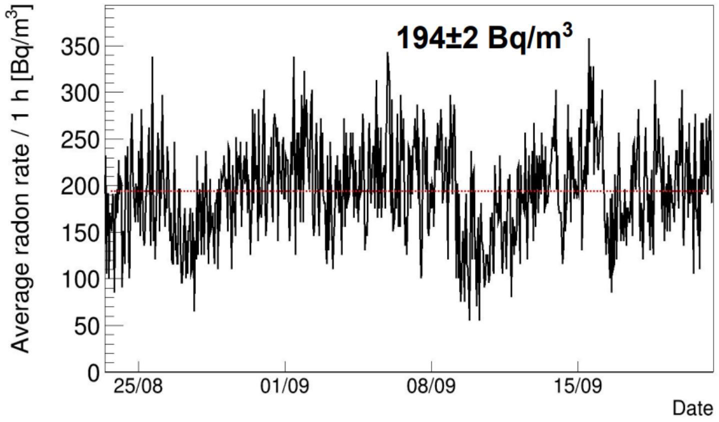


High energy gamma: factor 25 smaller than KBR

- Benefits the muon veto efficiency



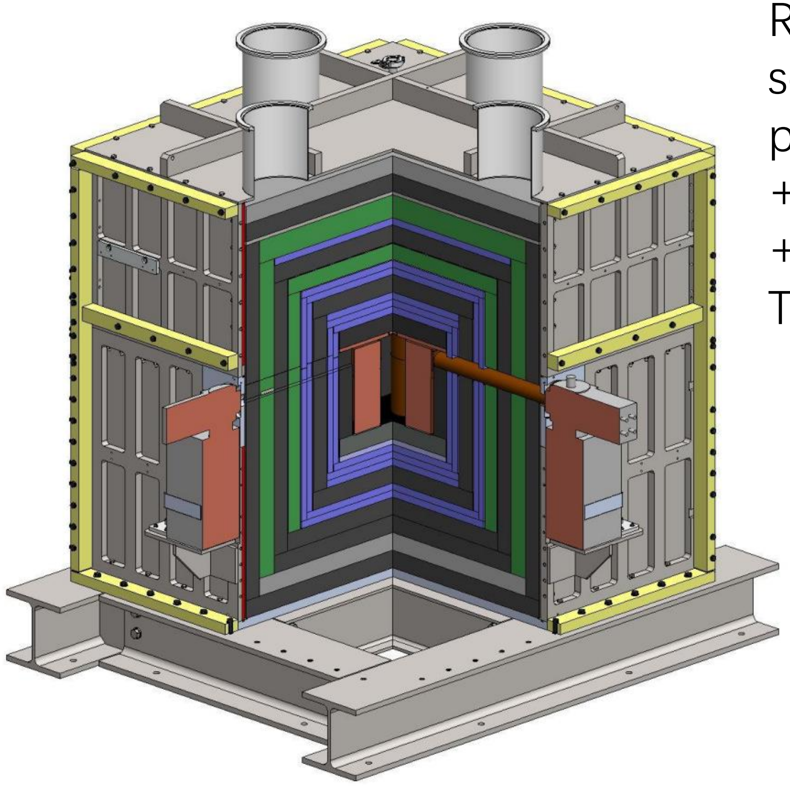
Neutron: 30 times larger (sub-dominant in ROI)



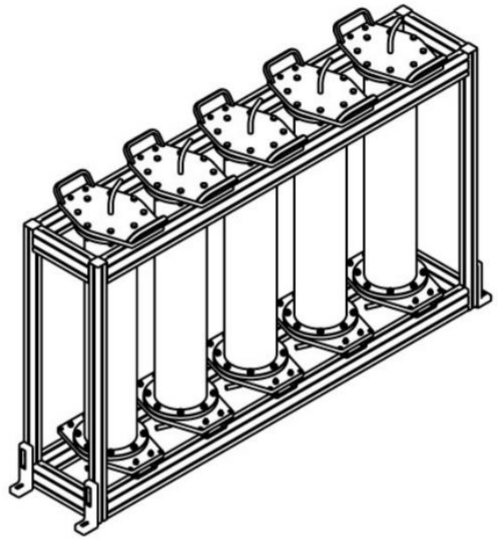
Radon: similar with KBR.

✓ Flush radon free air to the chamber

Environmental control

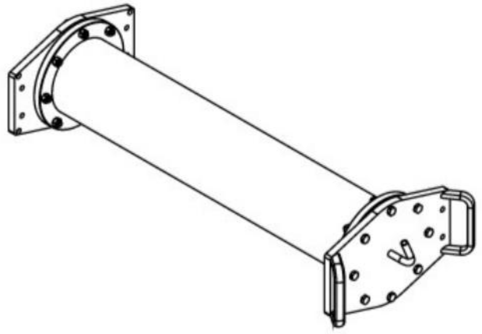


Replace one lead layer with plastic scintillator as **2nd muon veto** (green part)
+ Higher coverage
+ Coincidence available
Target efficiency: >99%



5 charcoal columns to filter external fresh air to make **Rn-free air**

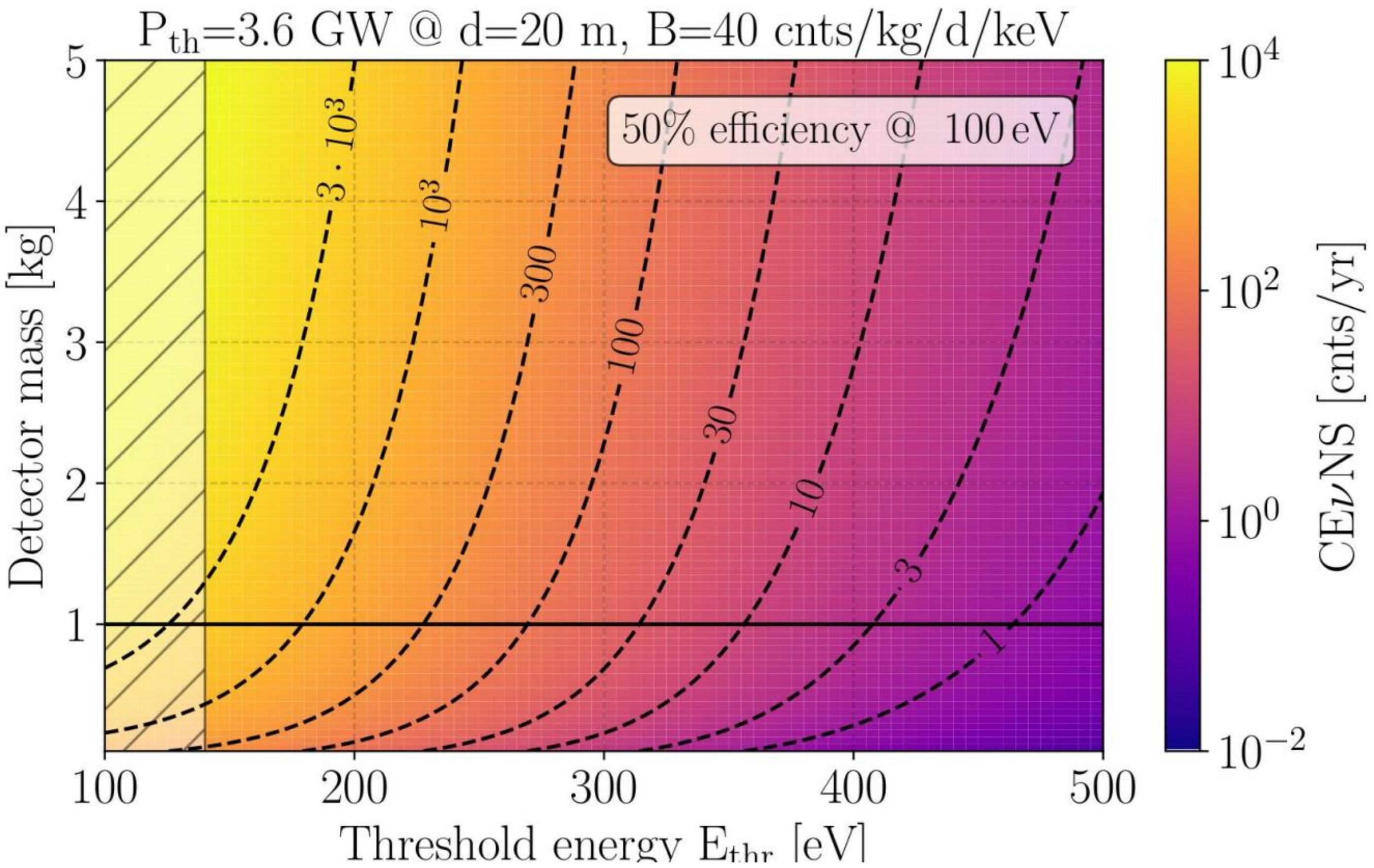
- Static setup for long-term operation
- <50 mBq/m^3 output



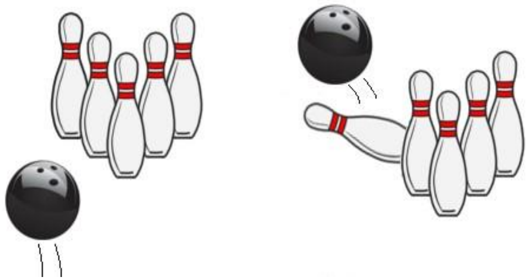
Also new: Slow control system, neutron flux monitoring, earthquake monitoring, temperature control, etc.

Physics potential

Threshold down to 200eV will hopefully provide ~10^3 CEνNS events per year!

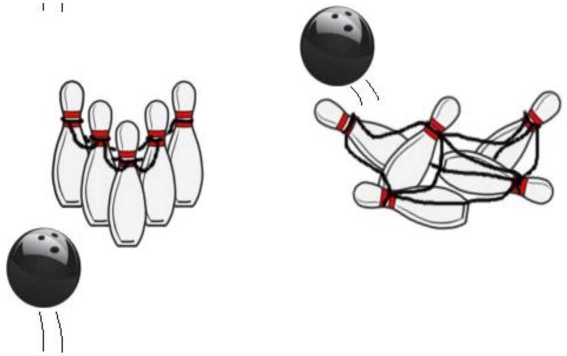


Summary



- CEvNS is the last piece of neutrino interaction within SM which is not fully observed.
- CONUS has been operating in KBR to detect CEvNS, and has successfully finished data taking at 2022.
- Analysis of the full data set is ongoing and the preliminary result shows that *we are at the edge of discovery.*

- The new experiment CONUS+ is moving to KKL with improved Ge detectors.
- Environmental property of the new reactor site is characterized. Adaptions to the new background composition are made.



THANKS

Backup

Comparison with other experiments

Current results from reactor CEvNS experiments:

- constraints from νGen, CONNIE,…
- strong signal preference with NCC-1701 at Dresden-II reactor US:

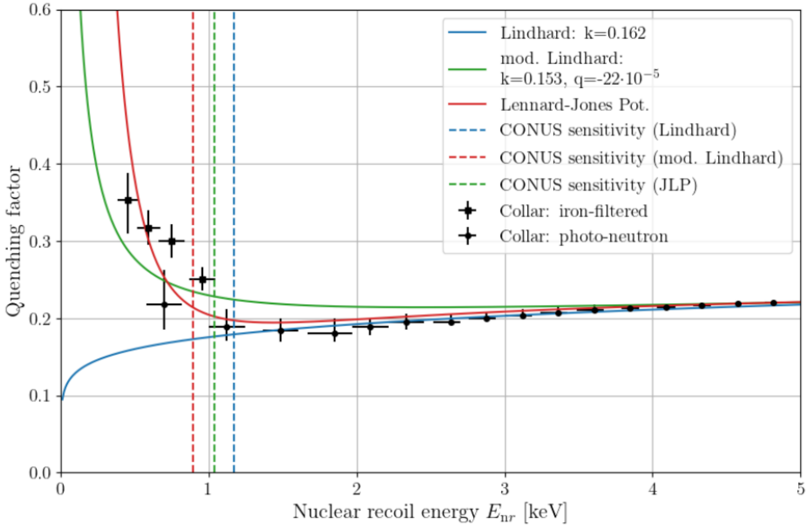
Abstract of Phys. Rev. Lett. 129, 211802 (2022)

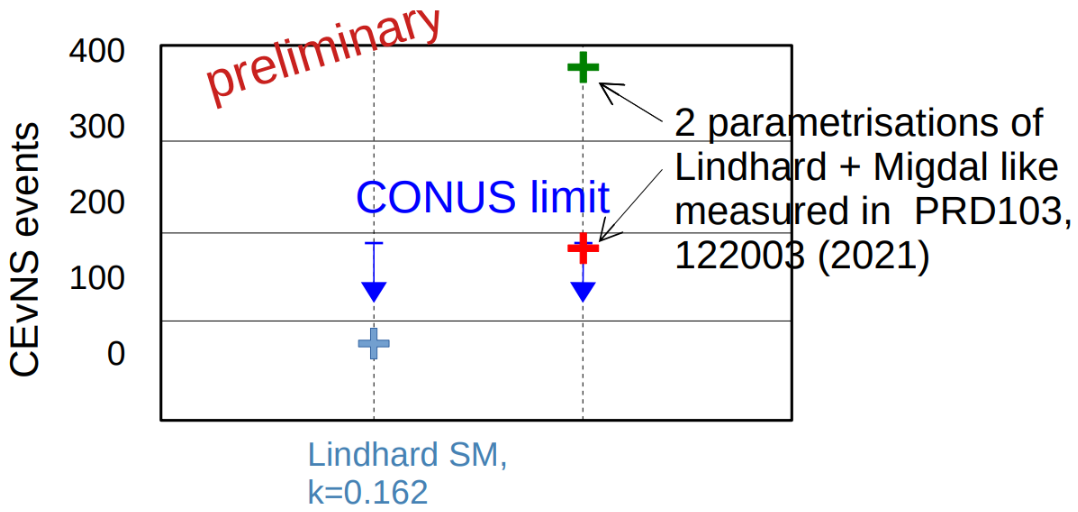
The 96.4 day exposure of a 3 kg ultralow noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference ($p < 1.2 \times 10^{-3}$) for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, when compared to a background-only model. No such effect is visible in 25 days of operation during reactor outages. The best-fit CEνNS signal is in good agreement with expectations based on a recent characterization of germanium response to sub-keV nuclear recoils. Deviations of order 60% from the standard model CEνNS prediction can be excluded using present data. Standing uncertainties in models of germanium quenching factor, neutrino energy spectrum, and background are examined.

Abstract of Phys. Rev. D 103, 122003 (2021)

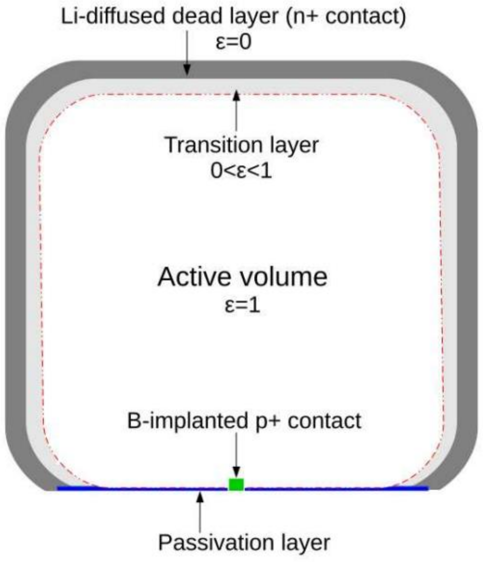
Germanium is the detector material of choice in many rare-event searches looking for low-energy nuclear recoils induced by dark matter particles or neutrinos. We perform a systematic exploration of its quenching factor for sub-keV nuclear recoils, using multiple techniques: photoneutron sources, recoils from gamma-emission following thermal neutron capture, and a monochromatic filtered neutron beam. Our results point to a marked deviation from the predictions of the Lindhard model in this mostly unexplored energy range. We comment on the compatibility of our data with low-energy processes such as the Migdal effect, and on the impact of our measurements on upcoming searches.

Test NCC-1701 signal with CONUS data:

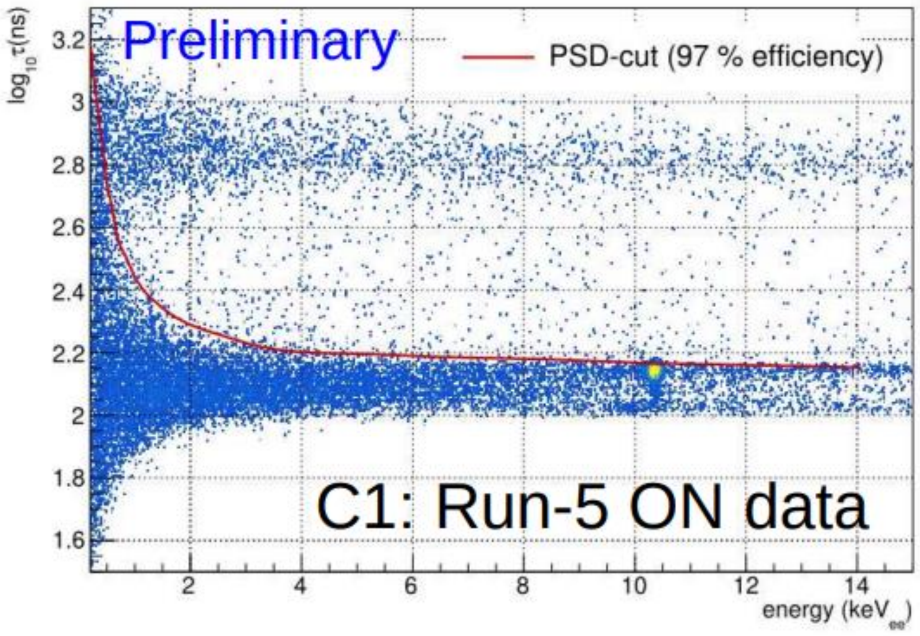




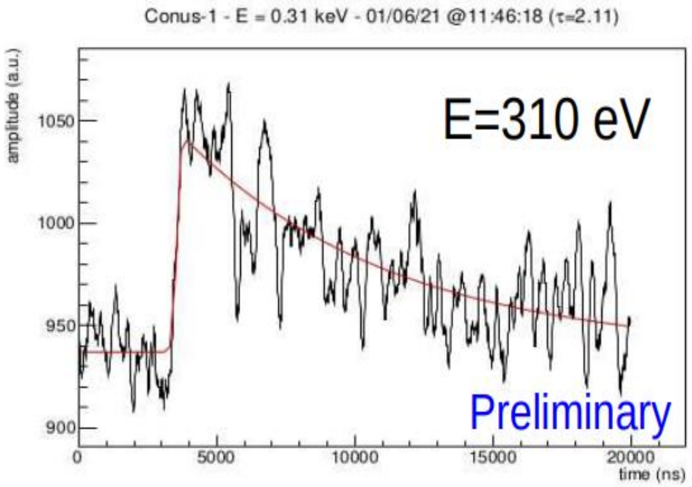
Pulse Shape Discrimination(PSD)



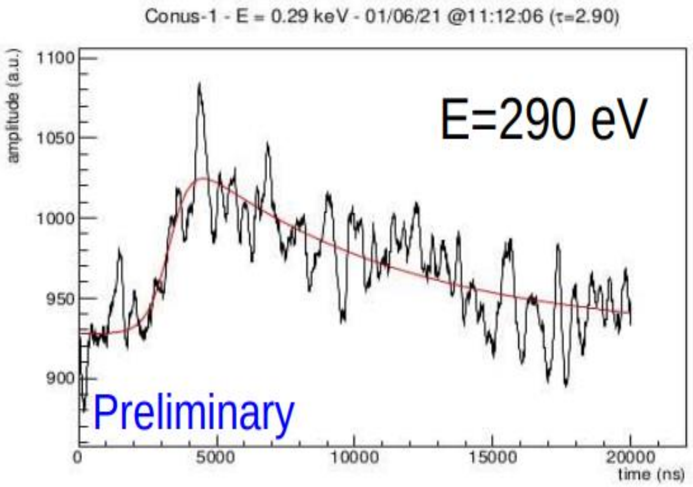
- Energy deposition near the transition layer contributes to a slow signal
- Removing slow pulses could reduce surface background, while losing a little effective mass



Preliminary: remove ~50% of the surface events at ~300eV with >90% bulk event acceptance



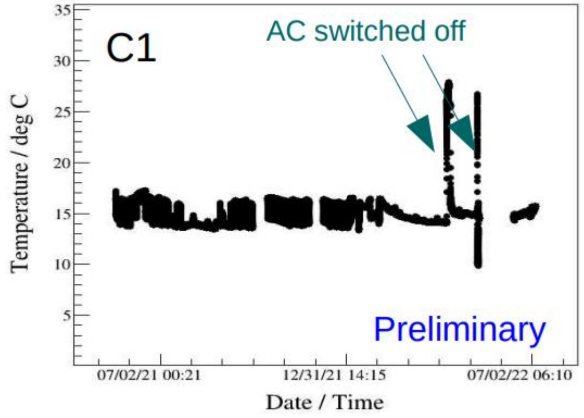
Normal (fast) pulse



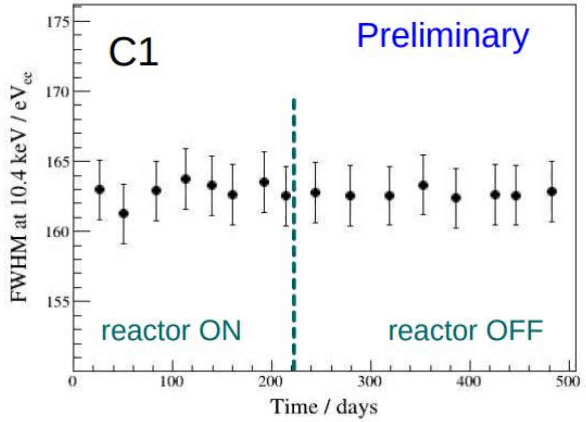
Slow pulse (transition edge)

Run stability (Run5)

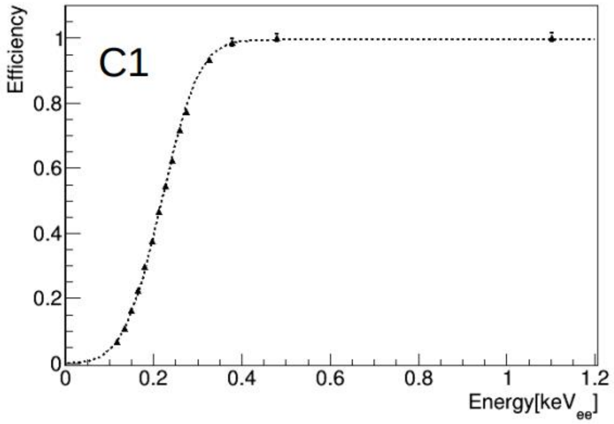
Room temperature



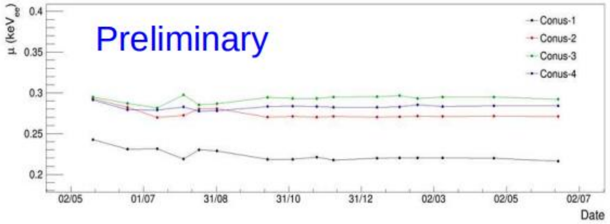
Peak pos. of 10.4 keV line

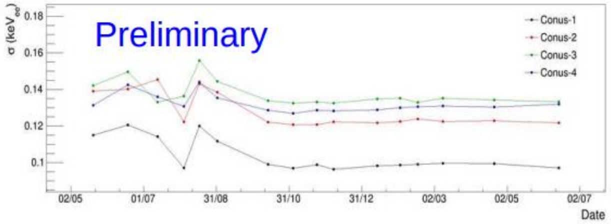


Trigger efficiency curve

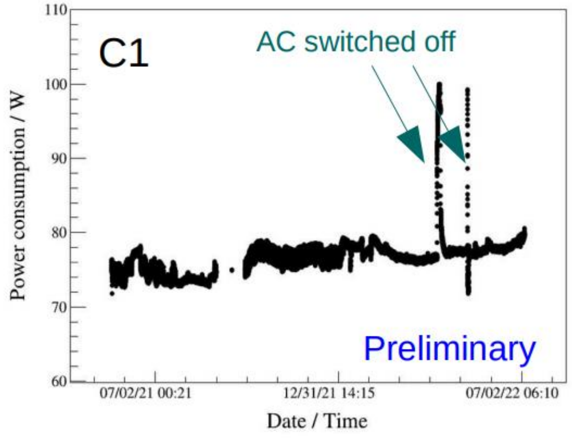


Analytical description: 0.5*[1+erf((x-μ)/σ))]





Power consumption



FWHM of 10.4 keV line