Status of the CONUS experiment

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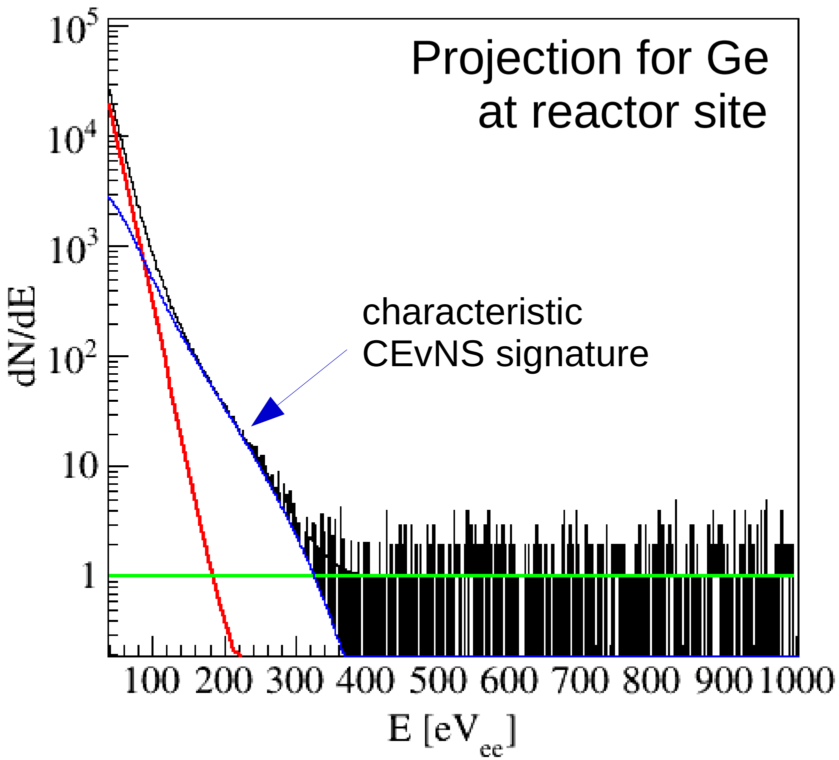
- on behalf of the CONUS collaboration -

NEUTRINO 2018 Heidelberg 4–9 June

Challenges for coherent elastic neutrino nucleus scattering



It's all about...

noise threshold
background
} **minimize**

signal strength:

$$\sigma_{\nu A}^{tot} \approx \frac{G_F^2}{4\pi^2} \cdot N^2 \cdot E_\nu^2$$

maximize E$_\nu$, but coherency condition:

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}} \text{ [MeV]}$$

maximize N, but maximum recoil energy:

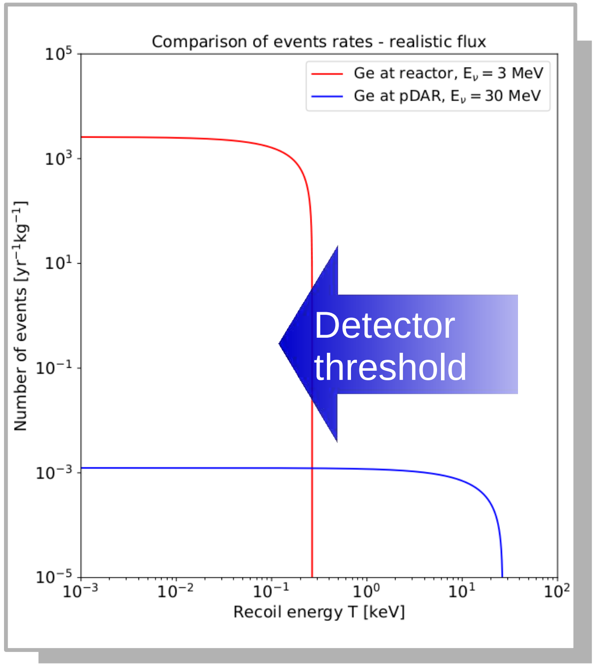
$$E_{rec}^{max} = \frac{2 \cdot E_\nu^2}{m_n \cdot A + 2 \cdot E_\nu} \approx \frac{2 \cdot E_\nu^2}{m_n \cdot A}$$

CEνNS detection: From π-DAR to reactor neutrinos

Main artificial neutrino sources for CEνNS detection:

ν **source**	π-**DAR** ν**'s**	**reactor** ν**'s**
Experiments & Projects	COHERENT	CONNIE, CONUS, MINER, ν-cleus, νGEN, RED-100, RICOCHET, TEXONO,...
ν flux, Φ_ν	$4\times10^{15}/\mathrm{s} \rightarrow$ $4\times10^{7}/(\mathrm{s{\cdot}cm^2})$ in 20m dist. @ SNS	$\mathbf{2\times10^{20}/(s{\cdot}GW)} \rightarrow$ $2\times10^{13}/(\mathrm{s{\cdot}cm^2})$ in 15m dist. @ 3 GW core
ν flux: on/off	**pulsed-beam (60 Hz)**	rare shut down periods
ν flavor	$\nu_\mu,\nu_e,\bar{\nu}_\mu$	$\bar{\nu}_e$
ν ener., E_ν	<50 MeV $\rightarrow$ coh.-decoh. reg.	<8 MeV $\rightarrow$ coh. reg.
overburden	shallow depth	shallow depth
troublesome bg	neutrons	neutrons

Expected number of CEνNS events:



- several experiments/techniques, lead to **complementarities**
- **rich physics program**: SM/BSM, nuclear/solar physics, SN, DM

See talks by H. Wong and O. Miranda

The CONUS experiment

CONUS: Coherent Neutrino nUcleus Scattering

Initiated in 2016

Collaboration:

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T. Rink, T. Schierhuber, H. Strecker

- Max Planck Institut für Kernphysik (MPIK), Heidelberg -

K. Fülber, R. Wink

- Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf -

Scientific cooperation:

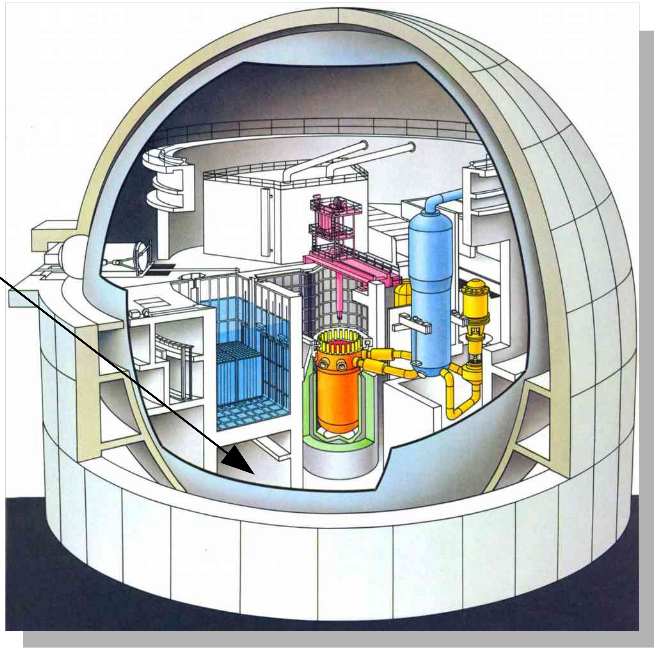
M. Reginato, M. Zboril, A. Zimbal

- Physikalisch-Technische Bundesanstalt (PTB), Braunschweig -

Reactor site for CONUS

Reactor:
- nuclear power plant at Brokdorf (GER)
- pressurized light water reactor
- thermal power: 3.9 GW
- high duty cycle (1 month/yr OFF)
- decommissioning plan: Dec 2021
  → long reactor ON/OFF measurements

Experimental site for CONUS:
- beneath fuel cooling installation: 10-45 m w.e.
- distance from reactor core: 17 m
  → **Φ=2.4 x 10^13 $\bar{\nu}$/s/cm^2**

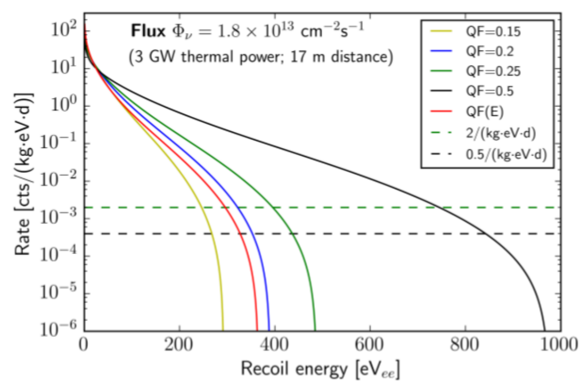


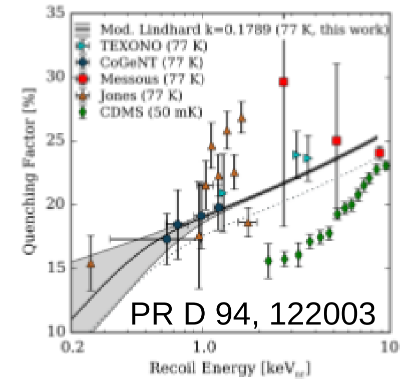
Access permission:
- demanding; full access since **Sep 2017**
- safety requirements inside containment:
  → Impact on detector technology/shield design
- reactor data are available for CONUS

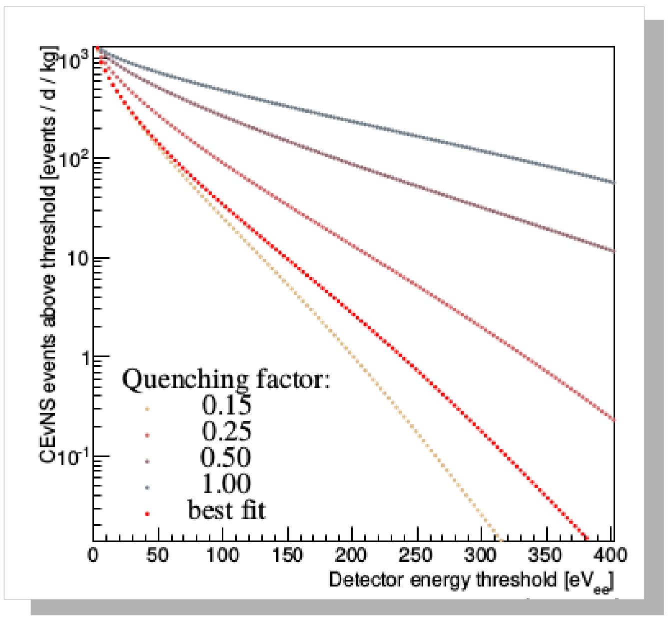
Expected CEνNS signal in CONUS

Main challenges for the calculation:

- reactor neutrino spectrum and flux:
  Parametrisation by P. Huber (Pu239, Pu241,U235)
  Data (U238) from N. Haag
- quenching factor in Ge:
  D.Barker, D.-M. Mei, Astrop. P. 38 (2012): **k=0.159**
  B.J.Scholz et al., PR D 94, 122003 (2016): **k=0.179**







Expected signal rates:

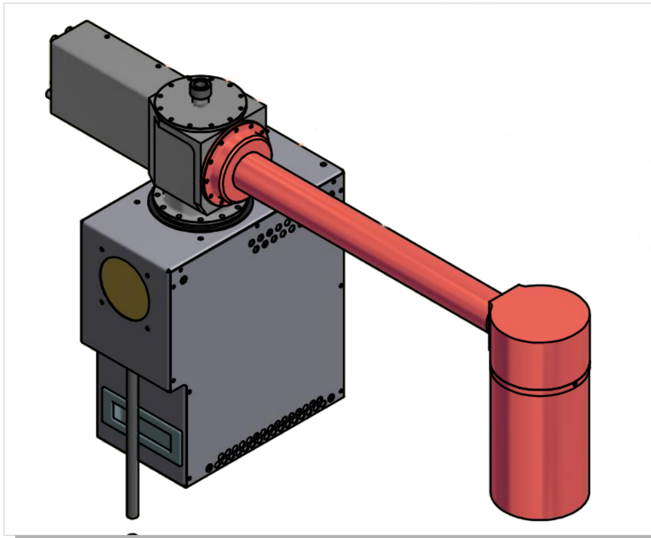
Case study for 3.9 GW thermal power, 17 m distance:
→ Flux: $\Phi_{\bar{\nu}} = 2.4 \times 10^{13}$ s^{-1}cm^{-2}

E_{ion}^{th} [eV$_{ee}$]	k=0.15	k=best fit	k=0.20
300	9±2	64±8	154±12
270	29±5	152±12	339±18
240	90±10	348±19	724±27
210	265±16	769±28	1501±39

Unit of rates: [cts/(kg·yr)]

→ results consistent with TEXONO calculations [1]

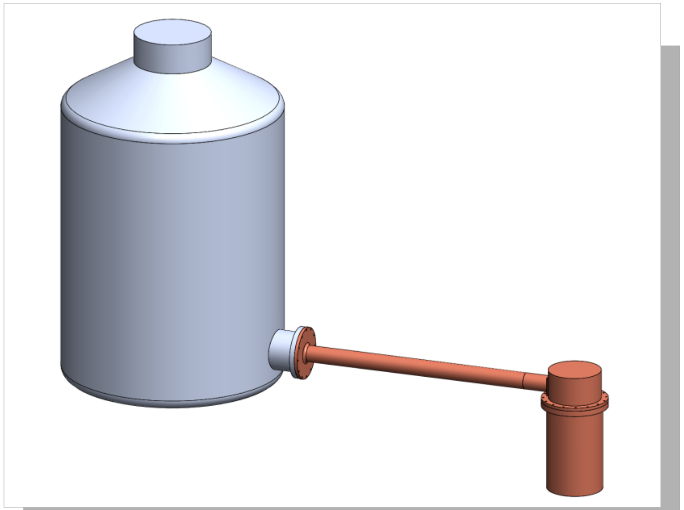
CONUS detectors



CONUS 1-4:

- p-type point contact HPGe
- crystal / active mass: **4.0 kg / 3.85 kg**
- spec for pulser res. (FWHM): ≤85 eV
  → Detector noise threshold of ≤300 eV
- electrical PT cryocoolers
- very low bg components
- design compatible with shield dim.
- prod. in close coop. with Canberra France

} novel development

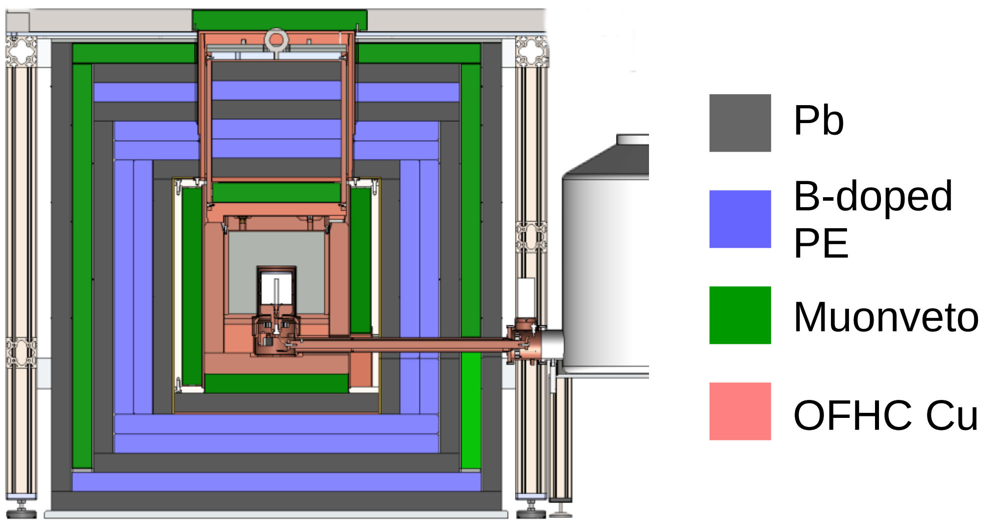


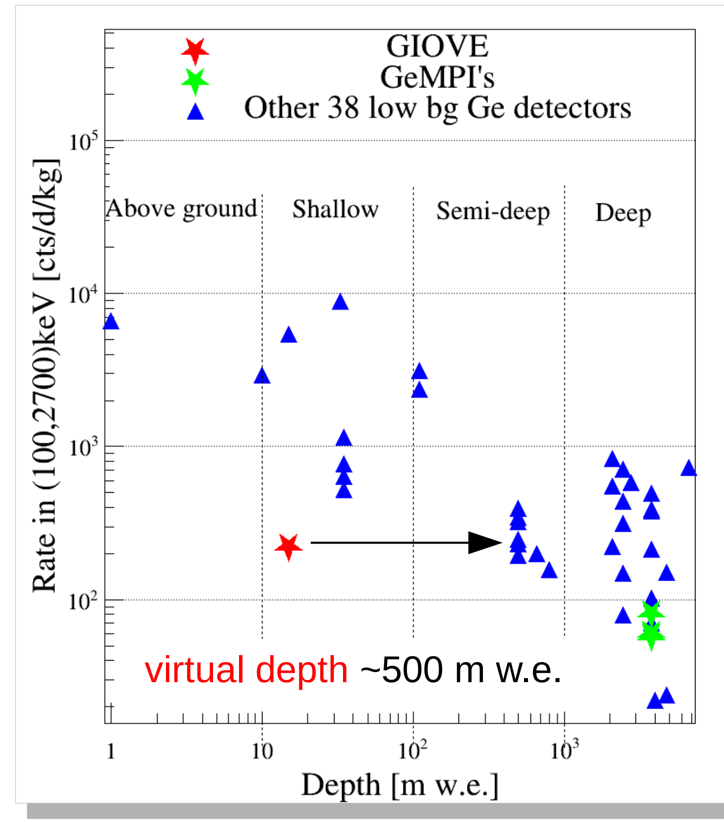
CONRAD: CONus RADiation

- p-type semi-coaxial HPGe
- crystal / active mass: 2.47 kg / 2.2 kg
- standard N2 cooling
- extremely low bg components:
  → refurbished Genius-TF diode [2]
  → refurbished HdM copper cryostat [3]

Basis for CONUS shield design

GIOVE: Germanium Inner Outer Veto [4]

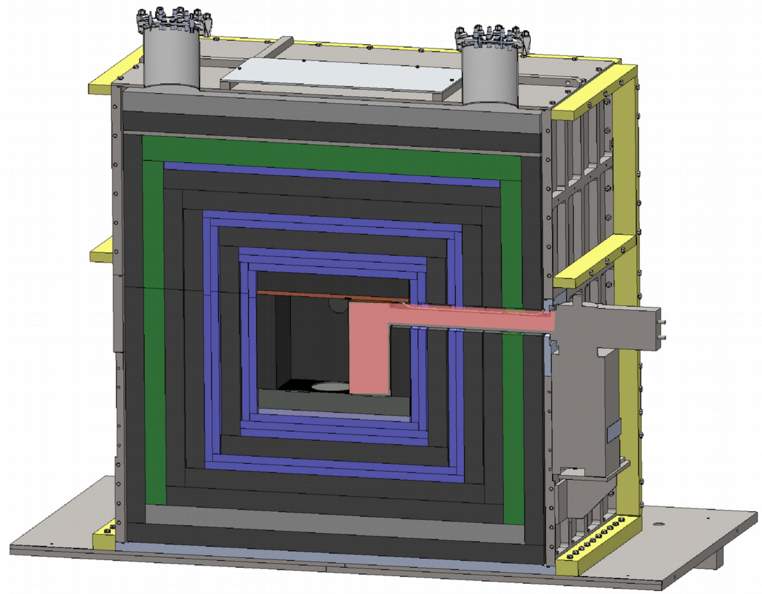




Main purpose: **'Material screening'**

- R&D by **MPIK** in *2007-2013*
- operated at shallow depth laboratory: 15 m w.e.
- optimized to reject muons and muon-induced signals
- background of (290+-4) cts/d/kg in **ROI=(100,2700) keV**
- **test bench** for Ge detector R&D, **MC validation** of bg [5], CONUS **material selection**

The CONUS shield

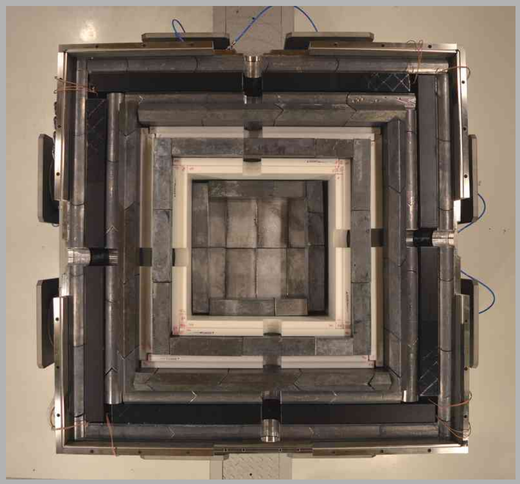


Pb

B-doped PE

Muonveto

120 cm



Volume: 1.65 m³
Mass: 11 tons
→ **Very compact neutrino detector !**

Main goal: **bg supression at low energies:**

ROI-1: (11,500) keV: O(Bg)=1 cts/ (d*kg*keV)
ROI-2: (0.2,11) keV: O(Bg)=10 cts/ (d*kg*keV)

- **better γ-ray suppression:** Pb instead of Cu as innermost layer
  → Pb more bremsstrahlung than Cu (~Z^2), but better self-shielding (~Z^5)
- **radon mitigation:** no N2 flushing on site:
  → hermetical sealing of setup or other solution
- **reactor site conformity:** anti-seismic, reduce fire load & total mass

CONUS: construction and commissioning

2016 | **2017** | **2018**

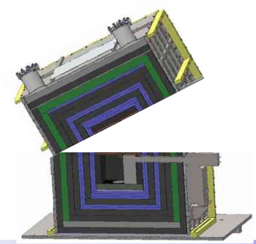
Detector design

Detector construction,
Material screening

Characterisation,
optimisation

Full assembly,
commissioning
at reactor site

...

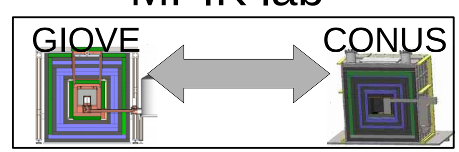


Shield design

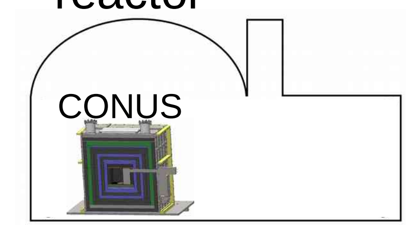
Shield construction,
Material screening

Commissioning at
MPIK-based lab

MPIK lab



reactor

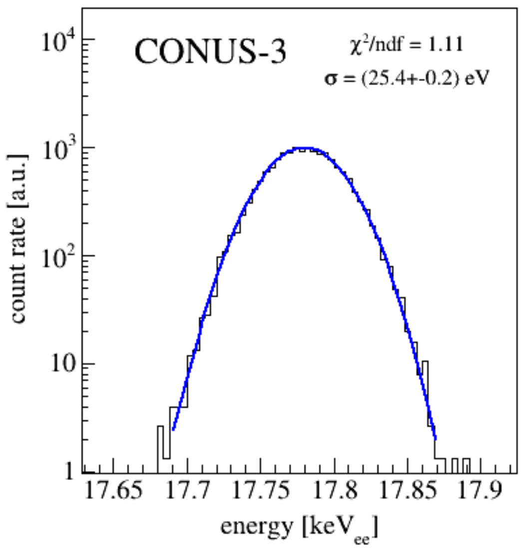


MC for material
screening

MC: intrinsic detector/shield bg,
MC/meas: μ-induced/neutron bg

Detector energy resolution

Pulser resolution:

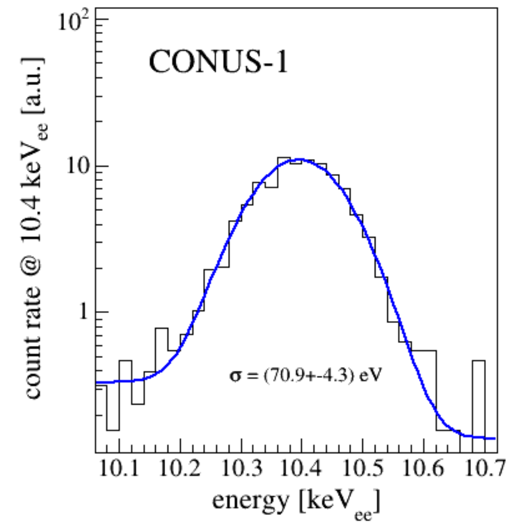


Commissioning at MPIK-based lab:

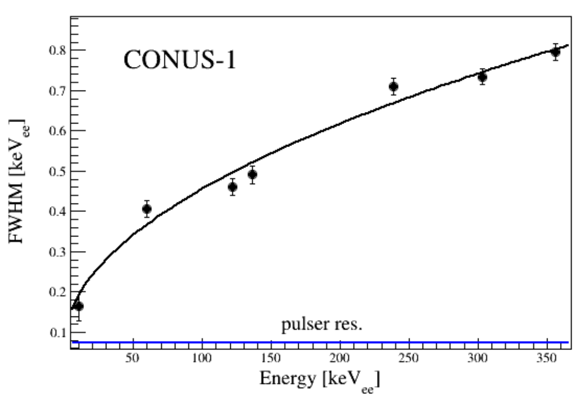
Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	74±1
CONUS-2	75±1
CONUS-3	59±1
CONUS-4	74±1

- pulser res.: all det's within spec's
- exp. elec. noise edge: ≈3xFWHM$_P$
- peak shape: highly Gaussian

X-ray peak resolution:

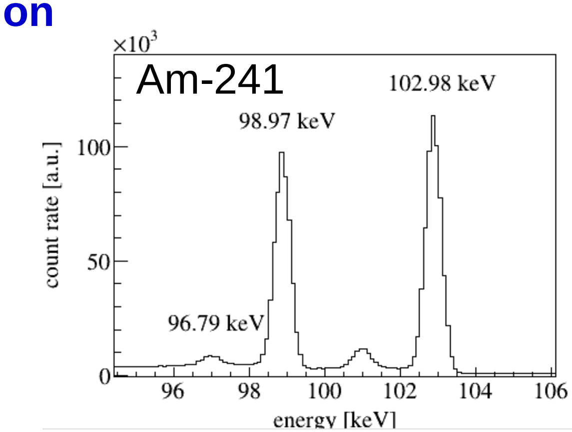


Ene. res. VS energy:



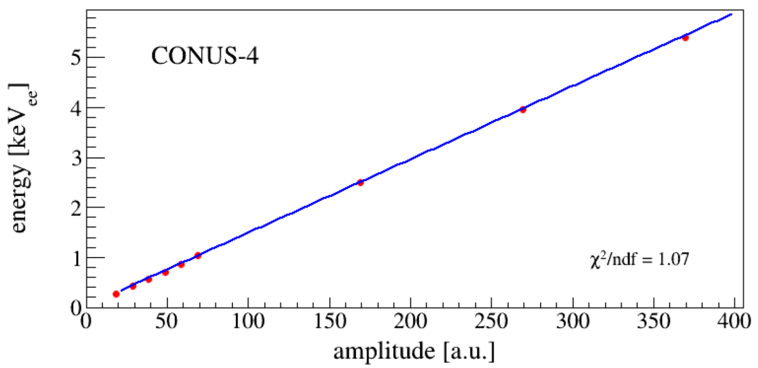
Enhanced gamma-line separation

→ background analysis
→ detector characterisation
(e.g. active volume via
Am-241 source)
...
→ energy scale calibration



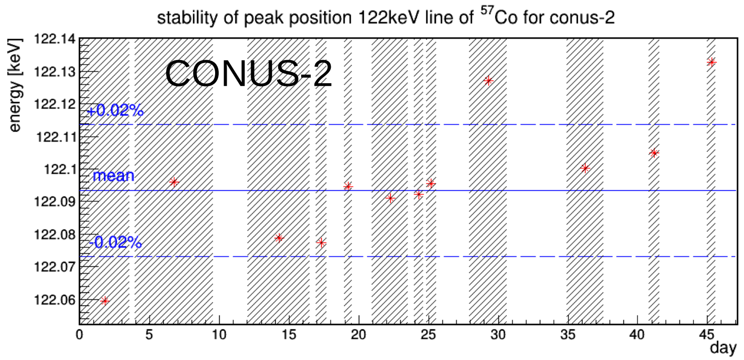
Energy scale: linearity, stability, calibration

1. Linearity of energy scale:



- precision pulse generator: scale highly linear

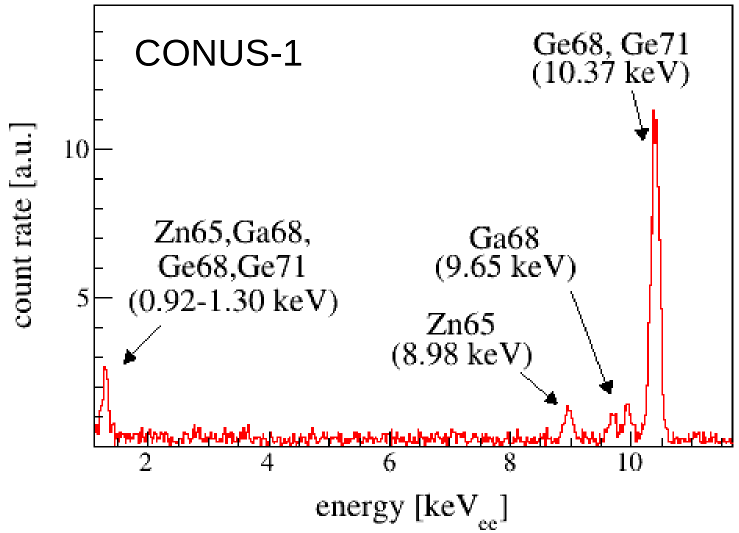
2. Stability of energy scale:



- Co-57 source: monitor 122 keV peak position
- stan. dev. of peak position: +-15eV (+-0.02%)

→ Low repetition rate of calibrations

3. Calibration of energy scale:



- at low energies < 15 keV: **rely** on Ge-related isotopic X-rays:

Main isotope	$T_{1/2}$ [d]	E_n [MeV]
Ge-71	11.4	10^{-6}-1
Ge-68	271.0	>20
Ga-68	0.046	←Ge-68
Zn-65	244.0	>60

- if x-ray rates too low: **generate** Ge71 alone via n-capture using n-sources: e.g. Cf-252 (E=2.13MeV)

Assembly at reactor site

Challenges during assembly:

- preservation of cleanliness
  (commissioning at MPIK-lab useful)
- work under ‘unusual’ conditions:
  up to 35°C, transport by handcraft

Challenges for operation:

- no intranet (due to safety regulations):
  → no remote control
  → data export only via shifter
- radon in air
- potential neutron background
- ...

Commissioning at reactor site

January - February 2018

Radon mitigation at reactor site

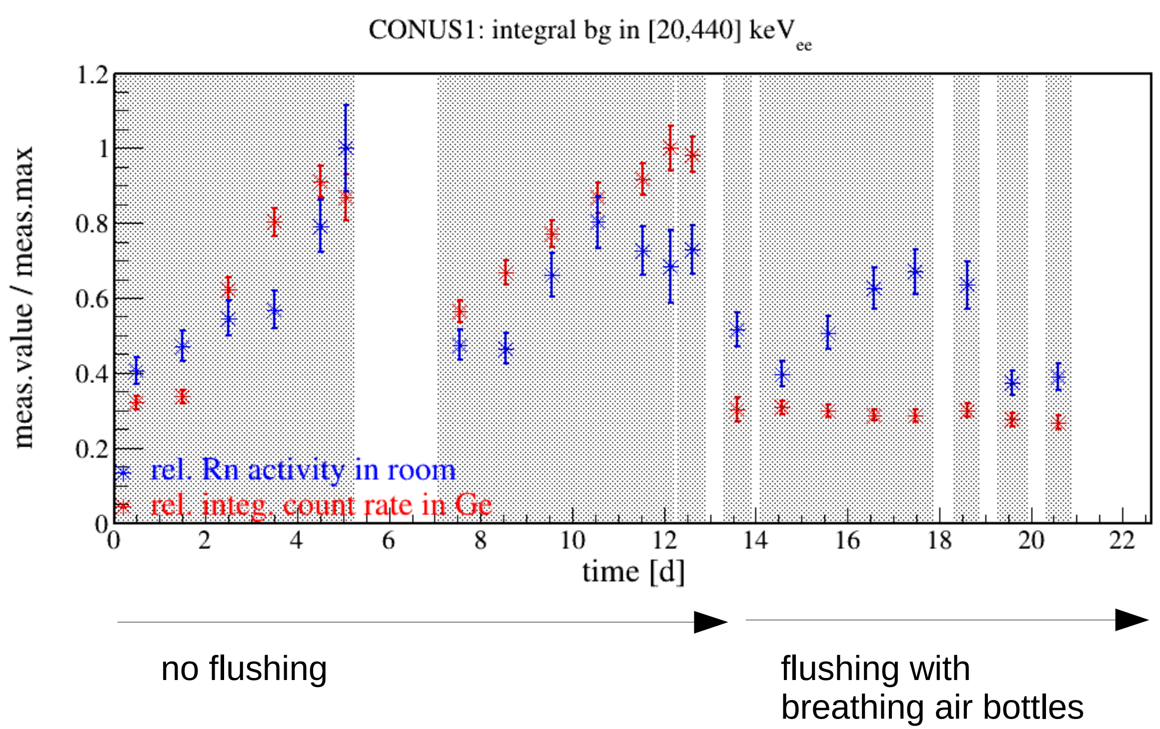
Commissioning at reactor site

Radon in air at experimental site:
- closed environment, no fresh air, thick concrete walls:
  → Rn concentrations: ~100 Bq/m³ (max. 300 Bq/m³)

Counter measures:

Option	Consideration
hermetical sealing	not sufficient
boil-off N_2 dewar	not allowed
pressurized air	to be filtered, still Rn cont.
synthetic air bottle	import/export
breathing air bottle	refill in-house, cheap

→ for CONUS:
cartridge 4 x 6.8 l bottles (300bar)
flux: ~1 l/min



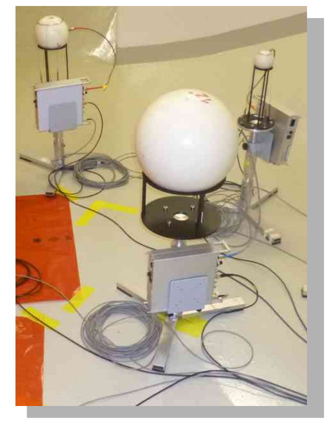
Neutron spectrometry at reactor site

Potential neutron background: Ge recoils from fast neutrons mimic CEνNS signals

Fast neutron classes	Corr. with therm. power
μ-ind. in Pb inside shield	No
μ-ind. above ceiling	No
(α,n)-reactions from walls	No
fission n from spent fuel rods	No
fission n from reactor core	Yes

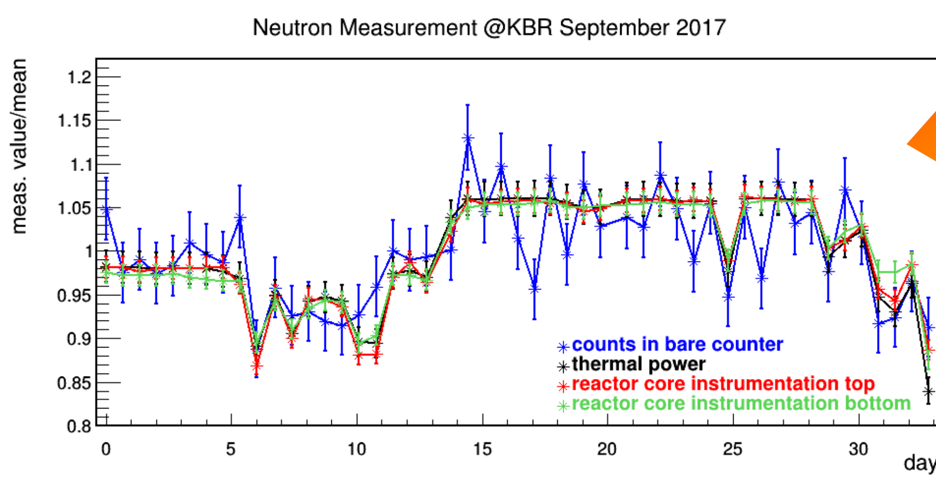
troublesome

} Outside CONUS shield →



Neutron spectrometry on-site with **NEMUS** by PTB [6]

Results from n measurements at experimental site:



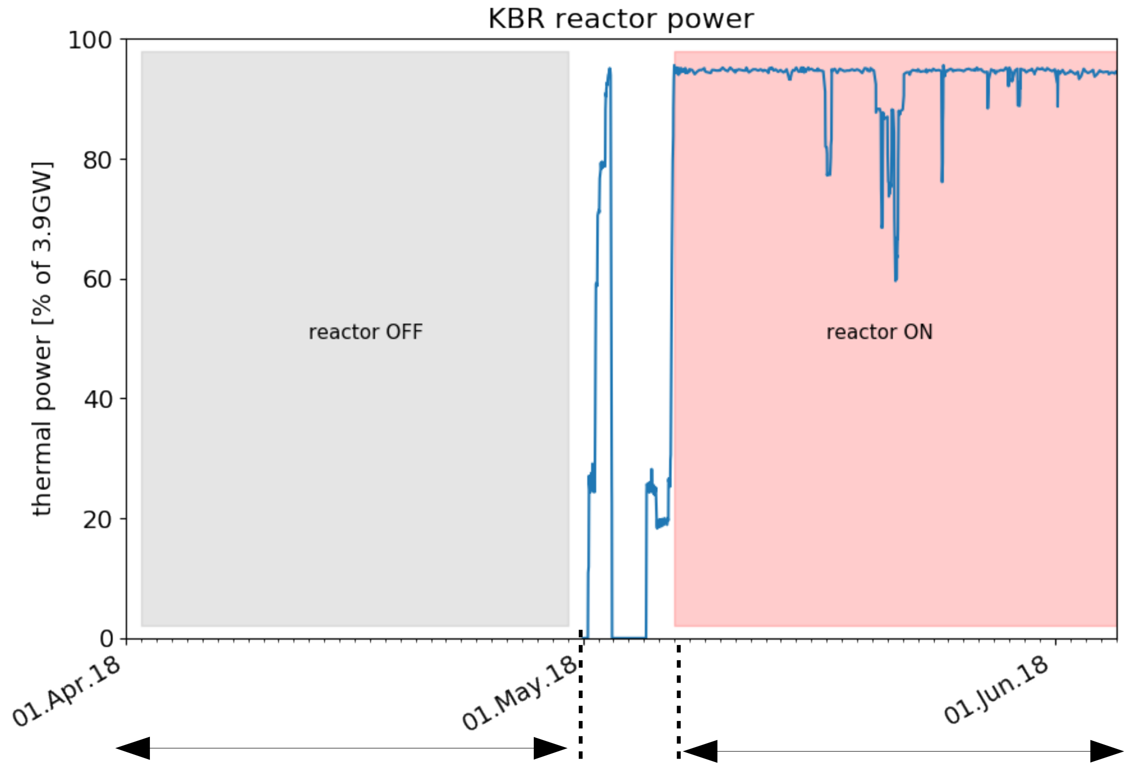
1. **Neutron field** highly thermalized (>80%), correlated with thermal power
   → fully absorbed by B-PE layers (MC)
2. Residual fluence:
   - if at all – epithermal from reactor
   - cosmic 100 MeV n: negligible

   → **reactor-correlated fast n** inside shield **negligible**

Physics data collection: Phase I

Begin of data collection: April 1, 2018

Reactor thermal power:



Datasets and exposure:

DS-1

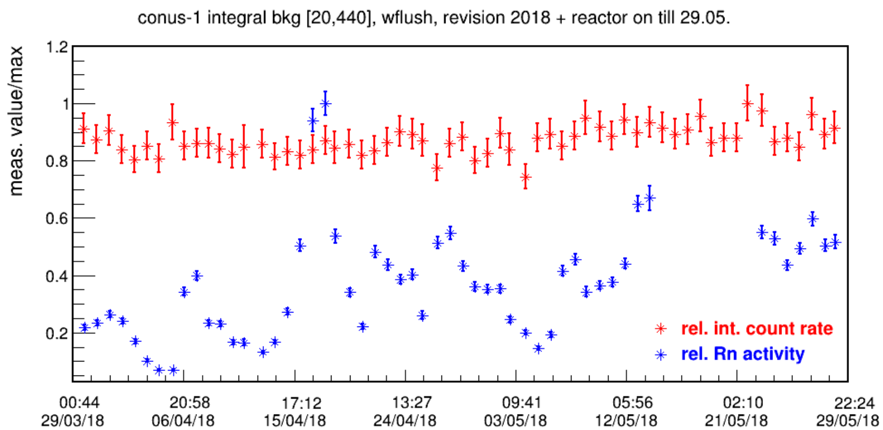
114.4 kg*d

DS-2

~112.3 kg*d
(until yesterday morning)

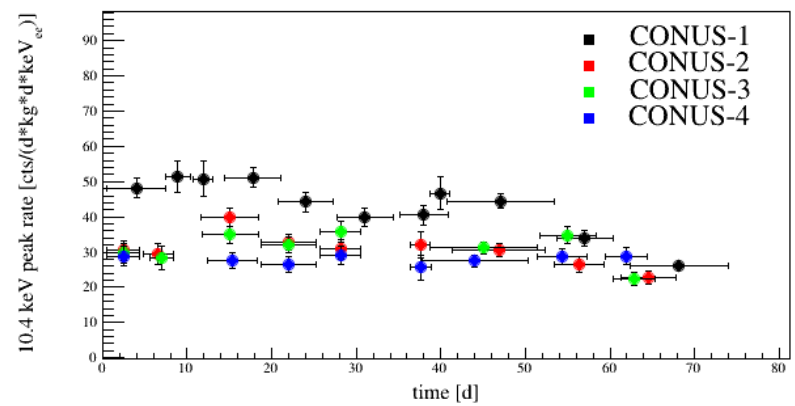
Background stability in DS-1 & DS-2

1. Bg rate stability in [20,440] keV



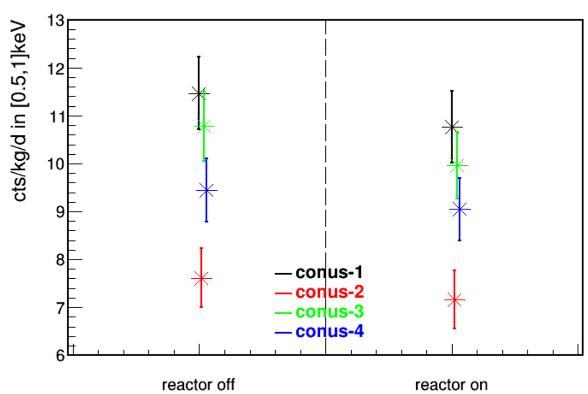
→ **Rn influence** at low energies: negligible

2. Rate stability of Ge line at 10.4 keV

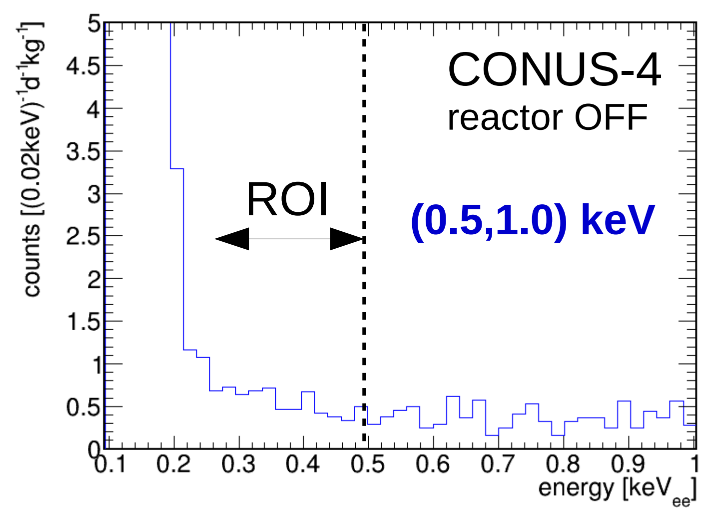


→ **Rate:** C2-C4 ~const, C1 small decrease

3. Bg stability in interval (0.5,1.0) keV



Due to slow pulses, Compton, ..



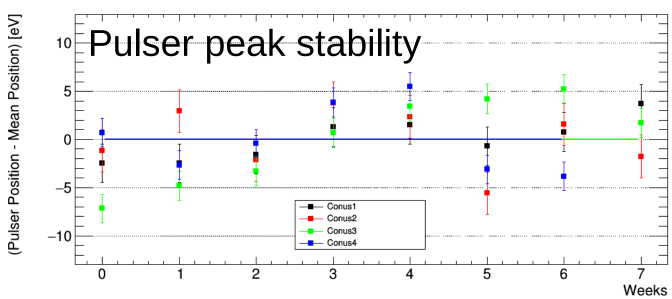
→ **Rate:** C2-C4 ~const, C1 small decrease

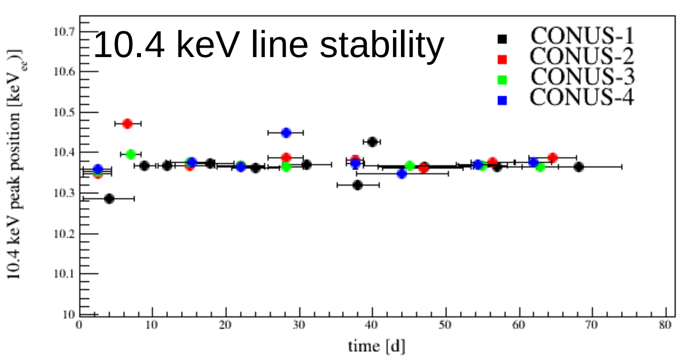
Detector performance in DS-1 & DS-2

1. Pulser resolution

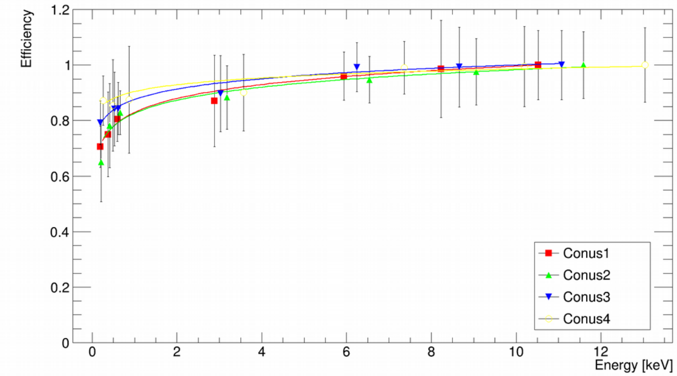
Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

2. Energy scale stability

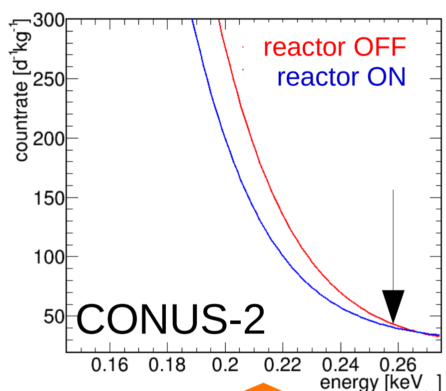


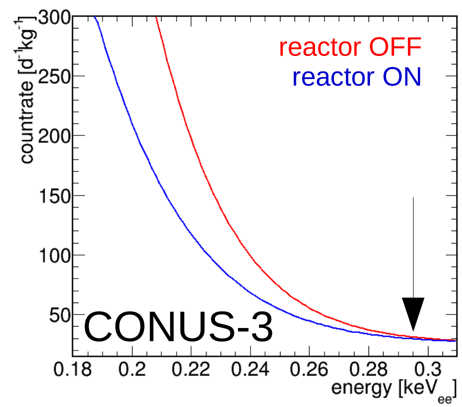


3. Trigger efficiency close to threshold



4. Noise threshold stability





CONUS-1/-4: similar shift for reactor ON/OFF

First rate analysis

Definition of cuts from reactor OFF time:
- energy scale calibration
- quality cuts (noise/spurious event red.)
- conservative ROI for CEνNS window
  (individual for every detector)

Definition of efficiencies:
- active volume: (96+-2)%
- muon AC ind. trg. Efficiency: (98+-1)%
- threshold trg. Efficiency
  (individual for every detector)

Rate comparison (all detectors):

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	**2.4 σ**	2.3 σ

(*) Including stat. uncertainty and above efficiencies

Some systematics still under study

→ **Observed excess of events is consistent with expected CEνNS signal range**

Conclusions

- Since its discovery by the COHERENT collaboration (π-DAR source) in 2017, CEνNS is still an elusive channel, but **not** invisible anymore.
- To cover the fully coherent regime, however, the lower energy **reactor neutrinos are ideal probes**.
- CONUS, a 4 kg based Ge-detector approach, is operational since April 1, 2018, at the nuclear power plant in Brokdorf (3.9GW) at 17m distance to the reactor core.
- After the first 2 months, 114 kg*d / 112 kg*d of reactor OFF/ON data were collected.
- We observe an excess of events in the ROI at a statistical significance of **2.4 sigma**.
  → First hint for CEνNS observation at a nuclear reactor.
- Sensitivity improvements with more statistics and including shape information are expected in the near future and will be published.

Thank you for your attention !

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K. Zink, F. Köck; J. Schreiner, R. Lackner; C. Lüders; Canberra: V. Marian, M.O. Lampert, Q. Pascal

References

[1] H. Wong et al., J Phys. Conf. Ser. 39 (2006)
[2] L. Baudis et al., Nucl. Inst. Meth. A 481 (2002) 149-159
[3] M. Guenther et al., Phys. Rev. D 55 (1997) 54-67
[4] G. Heusser et al., Eur. Phys. J. C (2015) 75: 531
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[6] https://www.ptb.de/cms/ptb/fachabteilungen/abt6/fb-64/643-neutronenspektrometrie/nemus.html