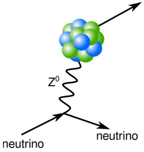
Status and results of CONUS

Aurélie Bonhomme
Max-Planck-Institut für Kernphysik, Heidelberg
on behalf of the CONUS collaboration

GDR Neutrino meeting – 29 Oct. 2019

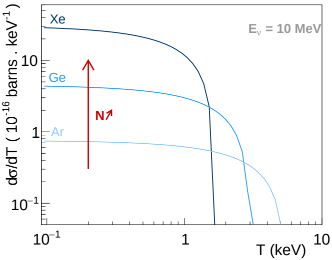


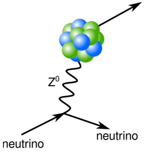
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} \underbrace{\left[N - (1 - 4\sin^2\theta_w)Z\right]^2}_{\sim N^2} \underbrace{F^2(q^2)}_{\to 1} M \left(1 - \frac{MT}{2E_\nu^2}\right)$$

- Predicted in 1974 by Freedmann:
  for low momentum transfer, interaction with the nucleus as a whole $\rightarrow$ **cross-section enhancement**

  full **coherency** feature: $\sigma \ \alpha$ **N**^{2}
  $\sin^2(\theta_w) \sim 0.238$ at low energies and F(q^2)$\sim$ 1
  fully coherent for **E$_\nu \lesssim$ 30 MeV**

- only observable experimentally accessible:
  low energy **recoil of the nucleus**! $T_{max} \ \alpha$ 1/A
  $\Rightarrow$ **very low energy threshold** required!





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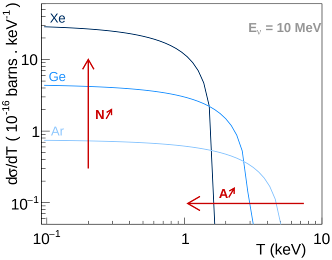
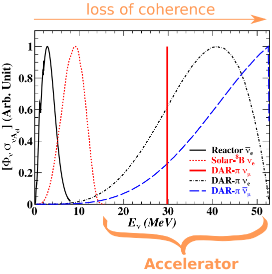


Detecting CEνNS: neutrino sources



2017: first CEνNS observation:
COHERENT experiment
Akimov et al., Science, 357, 6356, (2017)

Reactor neutrinos

$\bar{\nu}_e$ from β-decays of fissile isotopes

- very intense flux
- almost fully coherent

challenges: neutrons, flux prediction, environmental instabilities

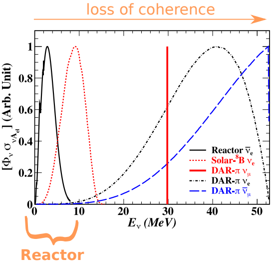
Accelerator neutrinos (π-decay at rest)

pulsed GeV-proton beam, multiple ν flavors

- larger cross-section...
- ...but loss of coherency

challenges: neutrino-induced neutrons, flux prediction, small overburden

complementary approaches!



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complementary approaches!

CEνNS as **measurement tool**…

- SM precision measurements (Weinberg angle)
- nuclear form factor

CEνNS in the search for **New Physics**…

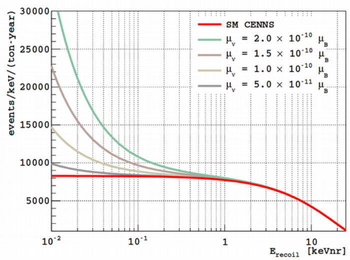
- Neutrino Magnetic Moment
- Non Standard Interactions (NSI)

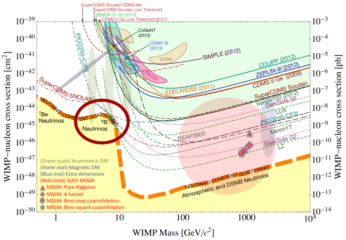
CEνNS at the **crossroad of physics**…

- Supernova evolution
- Dark Matter searches

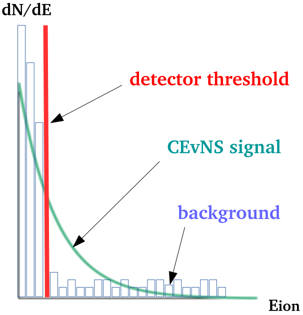
CEνNS for **reactor-$\bar{\nu}_e$ investigations**…

- reactor-$\bar{\nu}_e$ spectrum prediction
- nuclear monitoring





- **Very low energy thresholds**:
  ~keV recoil + **quenching**!
- Signal **statistics**
  → commercial reactors and/or large active masses
- Very **low background**
  → ultra-pure materials
  → passive and active shield
  → efficient background rejection
- Deep **background understanding**
  → on and off site characterization, off-time periods measurements, background modeling...



CONUS experiment:
low threshold **HPGe detectors**
measuring reactor-$\bar{\nu}_e$ from the **nuclear power plant** in Brokdorf (Germany)
within an **elaborated shield**

Detecting reactor $\bar{\nu}_e$: experimental requirements

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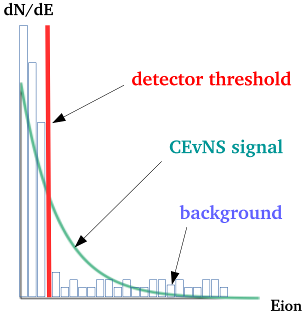

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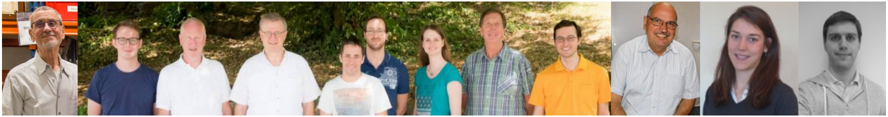
The CONUS collaboration



Collaboration:

A. Bonhomme, C. Buck, J. Hakenmüller, G. Heusser, T. Hugle, M. Lindner, W. Maneschg, T. Rink, T. Schierhuber, H. Strecker - **Max Planck Institut für Kernphysik (MPIK), Heidelberg**

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

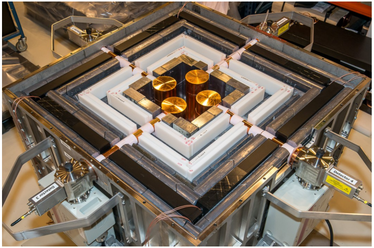
Scientific cooperation:

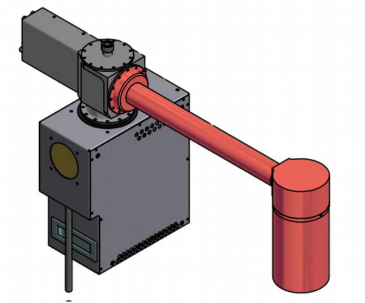
M. Reginatto, M. Zboril, A. Zimbal - **Physikalisch-Technische Bundesanstalt (PTB), Braunschweig**

The CONUS low threshold HPGe detectors

Novel development, cooperation with Mirion:

- **p-type point contact HPGe**
  electrical PT cryocoolers,
  $\sim [-180^\circ\text{C}, -200^\circ\text{C}]$
- 4×1 kg crystals, **3.74 kg total active mass**
- very low background components
- pulser resolution (FWHM) < 85 eV
  $\rightarrow$ **low noise threshold $\lesssim$ 300 eV**



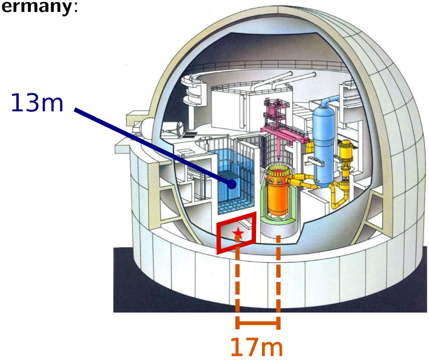


	pulser FWHM [eV]
C1	74 ± 1
C2	75 ± 1
C3	59 ± 1
C4	74 ± 1

The CONUS experimental site

The Brokdorf nuclear power plant (KBR) in Germany:

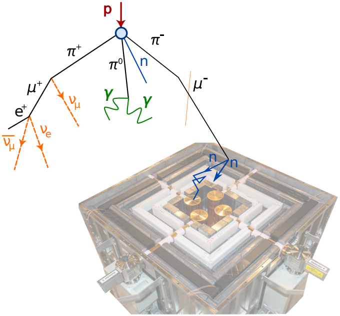
- site @17m from the **3.9 GW$_{th}$ reactor core**
  ✓ **high $\bar{\nu}_e$ flux**: 10^{13} $\bar{\nu}_e$ $s^{-1}cm^{-2}$
- high duty-cycle
  ✓ 1 month/year of **reactor-off**
- shallow-depth site (24 m w.e.)
  x sensitive to **cosmic-induced background**
- reactor environment
  x **potential reactor-induced** background



Reactor site: $\neq$ laboratory conditions!
no fresh air supply, changes in environmental conditions, no remote control, no cryogenic liquids allowed, earth quake safety requirements, restricted access...

neutrons: most dangerous as they can mimic $\bar{\nu}_e$ signal (nuclear recoil)
... but also all other radiations populating the ROI!

- **Cosmic-induced background**
  μ-induced neutrons in surroundings
- **Ambient radioactivity**
  from concrete, radon...
- **Neutron activation in Germanium**
  background γ lines from cosmic activation
- **Reactor-correlated background**
  neutrons, γ correlated with thermal power!



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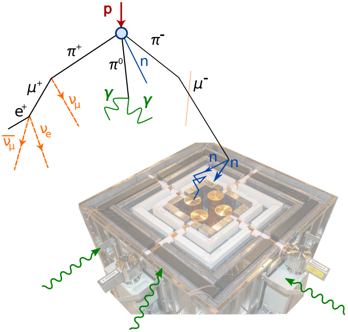

Potential backgrounds at reactor site

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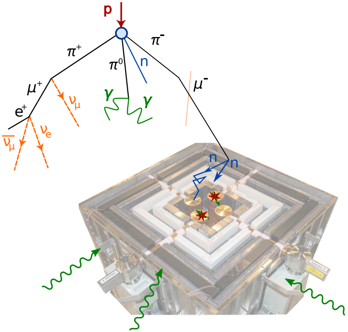

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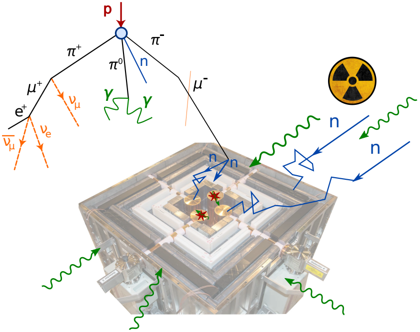
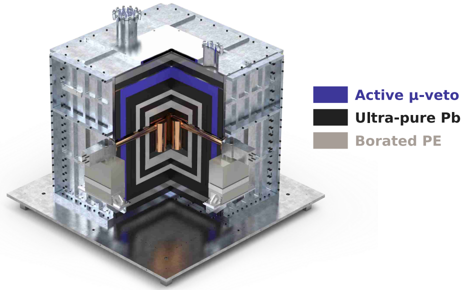
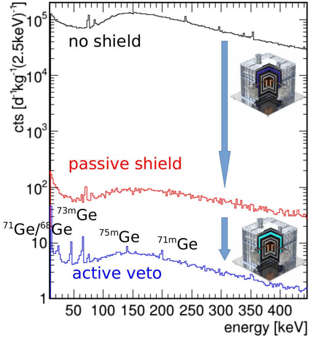
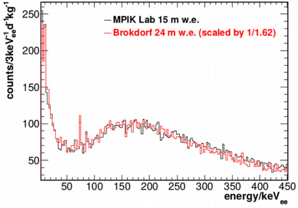


benefits from long studies at MPIK (see e.g. G. Heusser et al., Eur. Phys. J. C (2015) 75: 531)







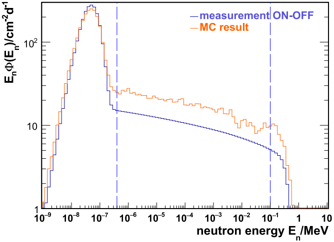
Inside passive shield:
cosmic-induced remaining background compatible in shape with MPIK lab (15 m w.e.) with similar shield

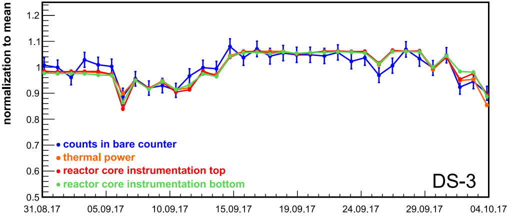
J. Hakenmüller et al., Eur. Phys. J. C. (2019) 79:699

- **Direct neutron measurement**

10 PE (moderator) spheres with 3–12" diameters with ^{3}He counter (n_{th}) at the detector place, for **reactor-on/off periods**
⇒ ambient neutron energy distribution

- thermalized neutron field (∼80 % of the total fluence)
- spatial inhomogeneities up to ∼20 %
- correlated with thermal power





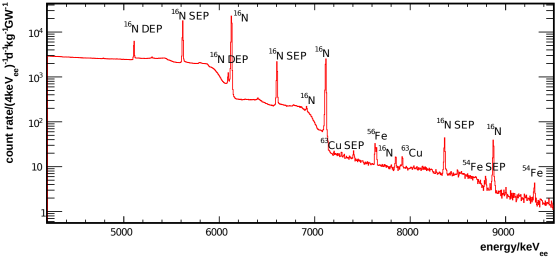
Reactor-correlated background

J. Hakenmüller et al., Eur. Phys. J. C. (2019) 79:699

- **Indirect measurements (γ)** with non shielded HPGe detector

4x more background than in low level labor MPIK (15 m w.e.):

- natural radioactivity (concrete walls, closed atmosphere)
- strong contribution from **nitrogen production $^{16}O(n,p)^{16}N$ in cooling cycle**
- additional lines from thermal **neutron capture on ^{53}Fe, ^{56}Fe and ^{63}Cu**



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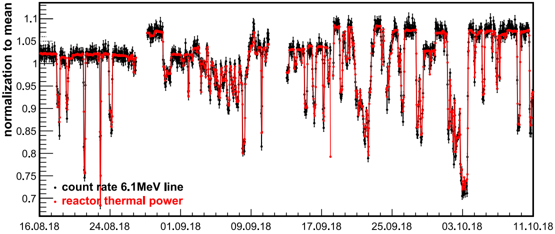
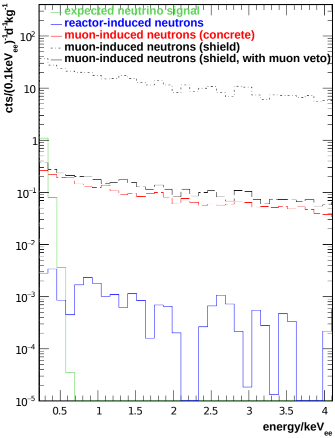


⇒ **correlated with thermal power!**

Reactor-correlated background suppression

Propagation of **measured neutron and γ spectrum** through shield in MC
$\Rightarrow$ estimation of the reactor-correlated background for CONUS



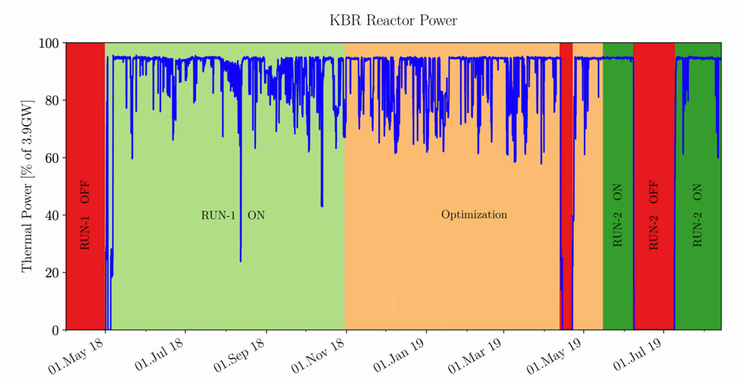
- **Neutrons**
  realistic quenching (k=0.2)
  one order of magnitude below the signal in the ROI

Energy range [keV$_{ee}$]	**Total** (Data) [/kg/d]	**Reactor-correlated contribution** (MC) [/kg/d]
0.3 – 0.6	12 ± 1	0.013 ± 0.004
0.6 – 11	148 ± 2	0.035 ± 0.006
11 – 400	716 ± 16	0.13 ± 0.02

- **High energy γ**
  negligible contribution across 25 cm of Pb:
  $(11\pm2)\times10^{-5}$ /kg/d in [0, 450] keV$_{ee}$

$\Rightarrow$ **Negligible reactor-correlated contributions inside CONUS shield**

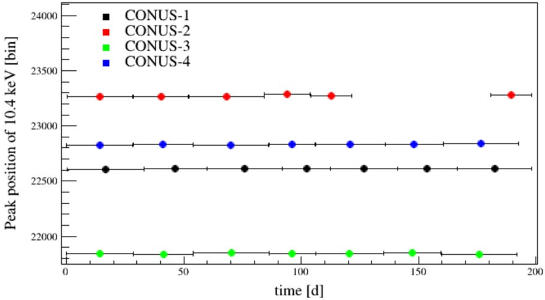
Timeline of CONUS



- Beginning 2018: **Installation at KBR**
- Apr. 2018 – Nov. 2018: **Run-1**
  1 month reactor-off, 6 months reactor-on
- Since May. 2019: **Run-2**
  1 month reactor-off, 4 months reactor-on up to now

Detector response and stability

- **Linearity**
  ✓ linearity of the electronic chain with pulser measurements
- **Energy scale**
  low energy: use **lines produced by Ge isotope decays inside the crystals**
  high energy: regular calibration with ^{228}Th source
- **Stability**
  ✓ achieve $\pm$ 5 eV stability of 10.4 keV mean peak position

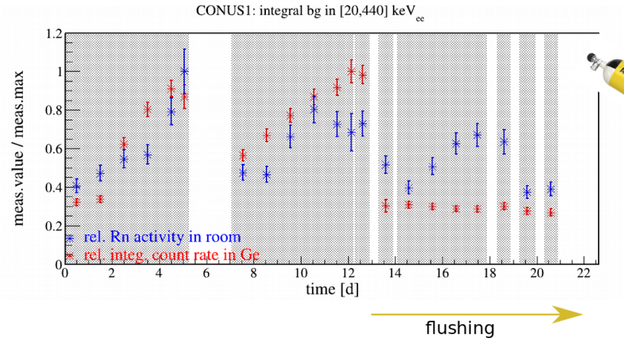


- **radon suppression:** confined environment → ~ **100 Bq/m^3**

Reactor site: no N_2 allowed! ⇒ **flush with breathing air cylinders**

- **temperature dependence of peak position** of the ^{228}Th peak (excellent energy resolution!)

- **mechanical vibrations:** detectors highly sensitive

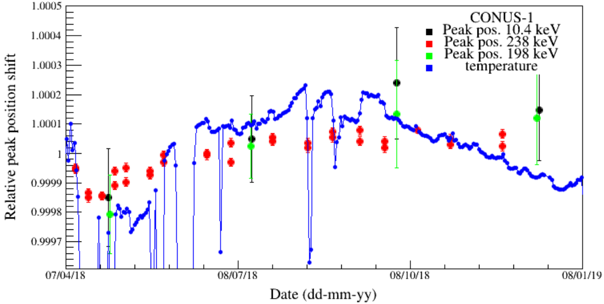


Sensitivity to environment

- **radon suppression:** confined environment $\rightarrow \sim$ **100 Bq/m^3**
- **temperature dependence of peak position** of the ^{228}Th peak (excellent energy resolution!)

Reactor site: room temperature changes! $\Rightarrow$ **enhanced monitoring, stabilization work**

- **mechanical vibrations:** detectors highly sensitive



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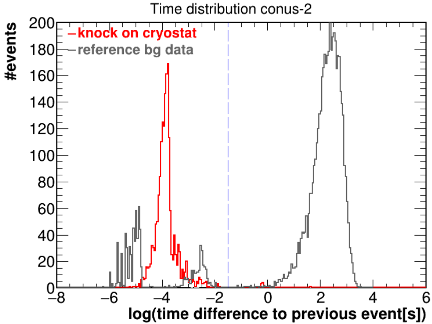
Reactor site: pumps, maintenance... ⇒ **efficient discrimination with time distribution**

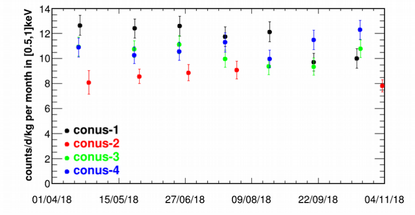


- Only 4 visible activation lines $< 12\,\text{keV}_{ee}$ decaying contrib. from MC:

$$\lesssim 0.2\,/\text{kg/d in } [0.5,\,1]\text{keV}_{ee}$$

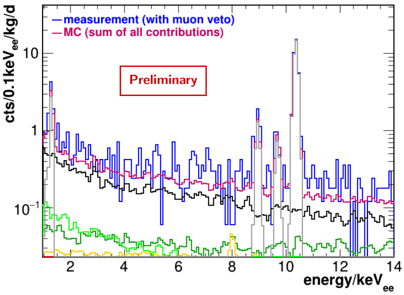
$\Rightarrow$ **very small + ability to correct**

- no correlation observed w.r.t. atm. cond.



$\Rightarrow$ **stable background in the ROI**

background level in $[0.5 - 1]\ \text{keV}_{ee}$:
10 counts/kg/d/keV
(comparable to detectors at ~ 100 m w.e.)



MC contributions:
- μ-induced neutrons in shield
- ^{210}Pb from shield contribution
- μ-induced neutrons in concrete
- contaminations (soldering wires, Rn)
- cosmogenic activation
  ^{71}Ge, ^{68}Ge, ^{65}Zn, ^{68}Ga

Signal prediction

- **Reactor $\bar{\nu}_e$ spectrum prediction:**

$\bar{\nu}_e$ from β-decays of fission fragments: mainly ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu

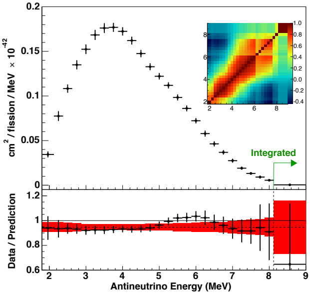
$\bar{\nu}_e$ up to $\sim$10 MeV

	$<\alpha_i>$	E_i (MeV)
^{235}U	0.57	202.36 $\pm$ 0.26
^{239}Pu	0.30	211.12 $\pm$ 0.34
^{238}U	0.08	205.99 $\pm$ 0.52
^{241}Pu	0.05	214.26 $\pm$ 0.33

$$S(E_\nu) = \frac{1}{4\pi L^2} \frac{<W_{th}>}{\sum_i \alpha_i E_i} \sum_i \alpha_i \, . \, S_i(E_\nu)$$

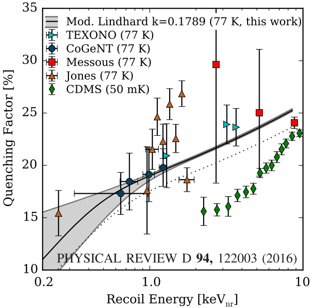
– W_{th}: thermal power known at $\pm$ 2.3 %
– α_i: isotopic fission fractions
– E_i: energy per fission
– $\alpha_i \, . \, S_i(E_\nu)$: energy spectrum per fission for isotope i

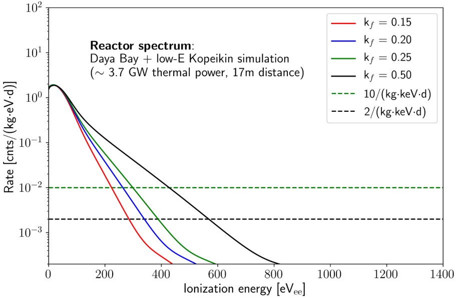
→ use measured $\bar{\nu}_e$-reactor spectrum (Daya Bay)
F. P. An et al., Phys. Rev. Lett. 116, 061801 (2016)



Signal prediction

- **detector response**
  ionization (measured) → **quenching factor** → nuclear recoil energy **T**
  quenching factor in Ge is the dominant uncertainty





Rate only analysis for Run-1 dataset

3 detectors, statistics only in [0.30, 0.55]keV_{ee}

reactor-off	65 kg.day	354 ± 19
reactor-on	417 kg.day	2405 ± 49
on-off		**133 ± 130**

Prediction

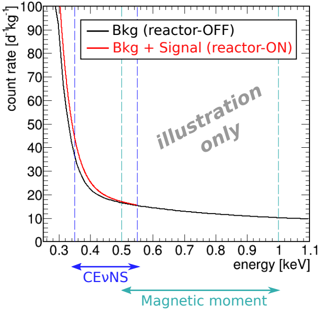
for six months of data, expected CEνNS events for several Lindhard k param.

k	0.15	0.2	0.250
counts	7	41	117

✓ order of magnitude of prediction with realistic quenching

Analysis on-going:

- **Extension of current dataset**
  careful data selection
- **Spectral shape analysis**
- **Systematics uncertainties**
  energy scale, detection efficiency, stability...
- **Upgrades:** pulse shape information



Conclusions and perspectives

- Promising **CEνNS neutrino detection channel** now experimentally accessible: high flux, very low detection thresholds, efficient background suppression
  $\Rightarrow$ **beam–/reactor–based experiments are complementary**

- **CONUS experiment**, running since April 2018:
  – low threshold point contact HPGe detectors in sophisticated shield
  – measuring reactor-$\bar{\nu}_e$ from the 3.9 GW_{th} NPP in Brokdorf (Germany)
  – operation in difficult environment
- **Extensive characterization of backgrounds:**
  J. Hakenmüller et al., Eur. Phys. J. C. (2019) 79:699
  $\Rightarrow$ **reactor-correlated backgrounds are negligible**
- Latest rate analysis (Run-1): **1σ excess in the ROI**

- **Much more to come:**
  – analysis extended with new data set
  – spectral shape analysis
  – systematics
  – PSD
- **A lot of physics potential!**

Thank you for your attention!