Detecting CEνNS and beyond with CONUS

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05.09.2021, 22nd PANIC 2021 conference, Lissabon, virtual

CEνNS at reactor site

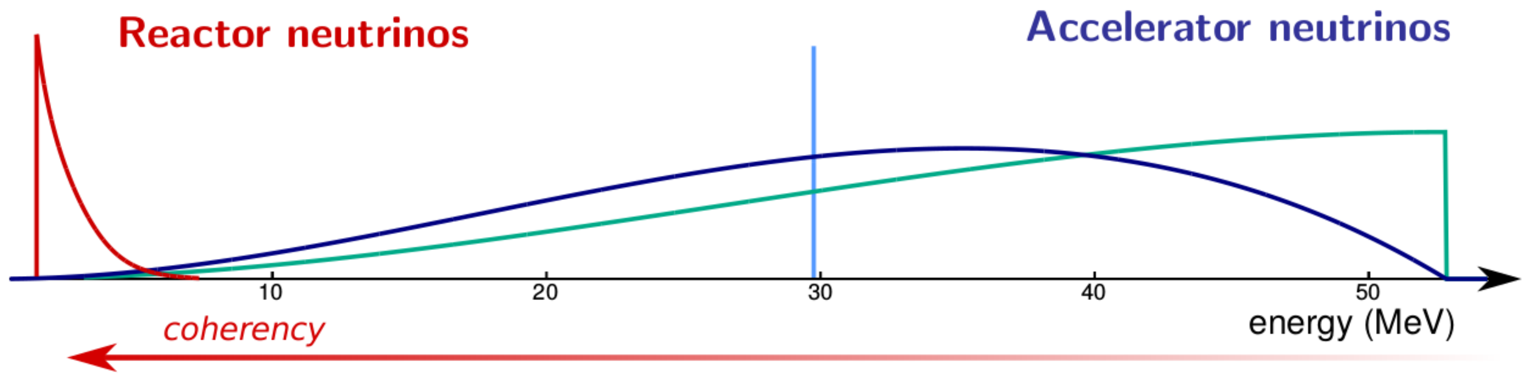


Figure by A. Bonhomme

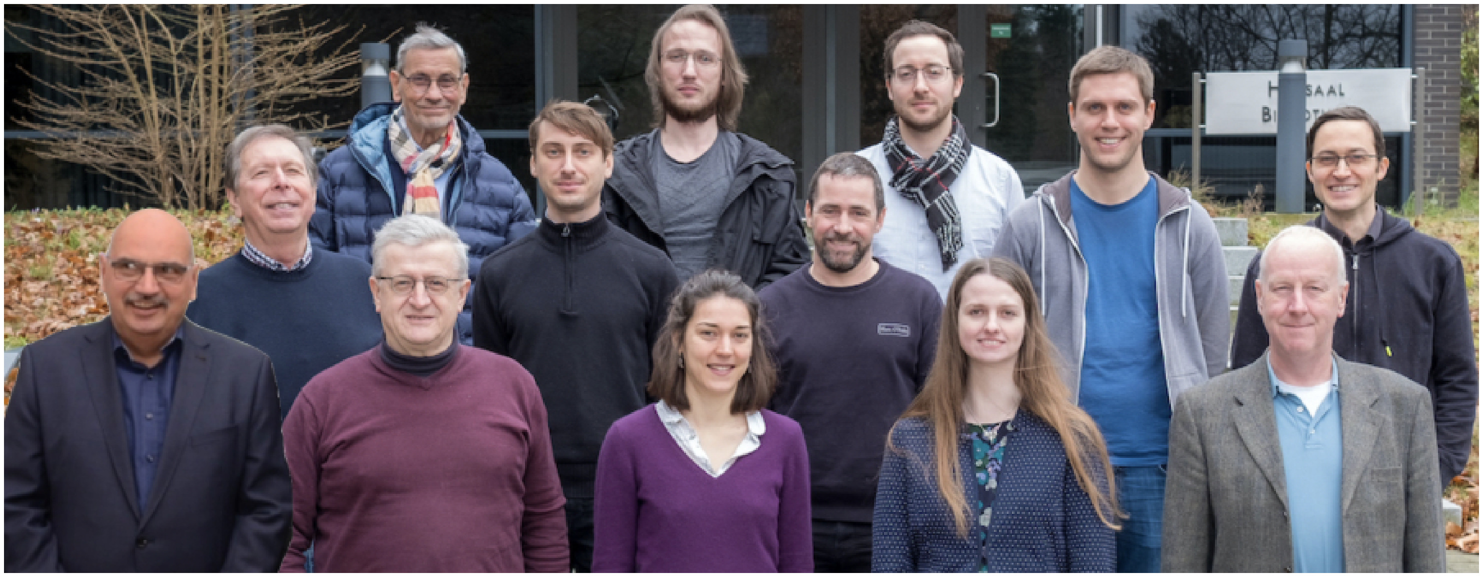
$\bar{\nu}_e$ from β-decays of fissile isotopes

- higher flux (close to core)
- bkg suppression more challenging
- energy <10MeV
  - tiny recoil
  - nuclear form factor ~1
- several experiments running
  → **CONUS**

ν_μ, $\bar{\nu}_\mu$ and ν_e from π-decay at rest

- lower flux
- bkg suppression by beam ON/OFF
- energy 20-50MeV
  - recoil at higher energies
  - nuclear form factor <1
- **COHERENT** at SNS:
  first observation of CEνNS

complementary approaches: neutron form factor, limits on BSM models,...



Collaboration:

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

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

Scientific cooperation:

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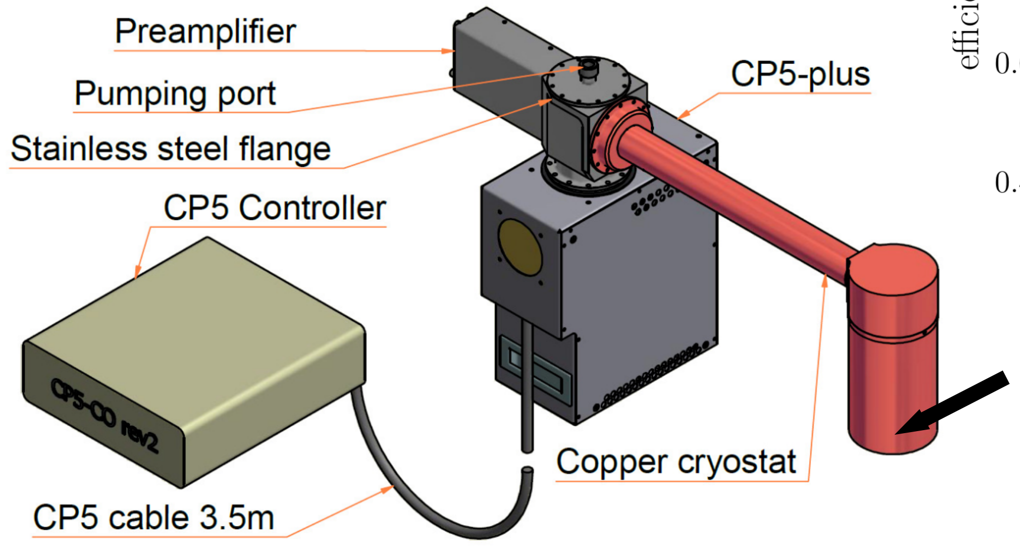
- *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig*

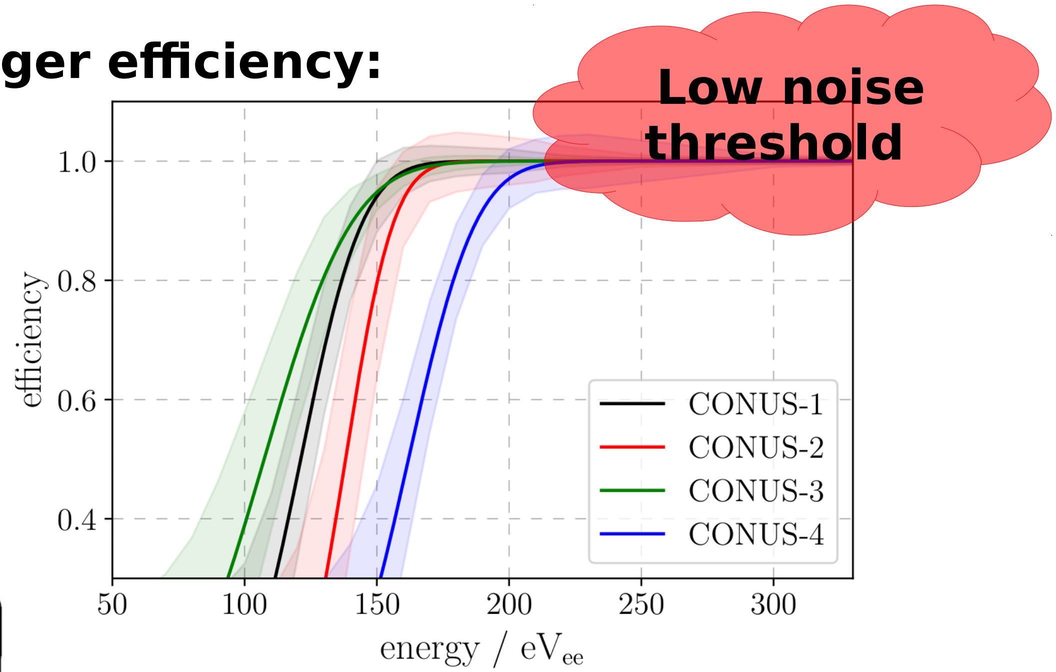
CONUS low energy threshold detectors

Cooling:
electrical instead of N_2

- reactor safety
- low maintenace
- adjustable temperature



Trigger efficiency:



4 p-type point contact HPGe:

- crystal / active mass:
  total: 4.0kg / 3.74kg
- pulser resolution <80eV_{ee}
  energy threshold ≤300eV_{ee}
- screening for radiopurity

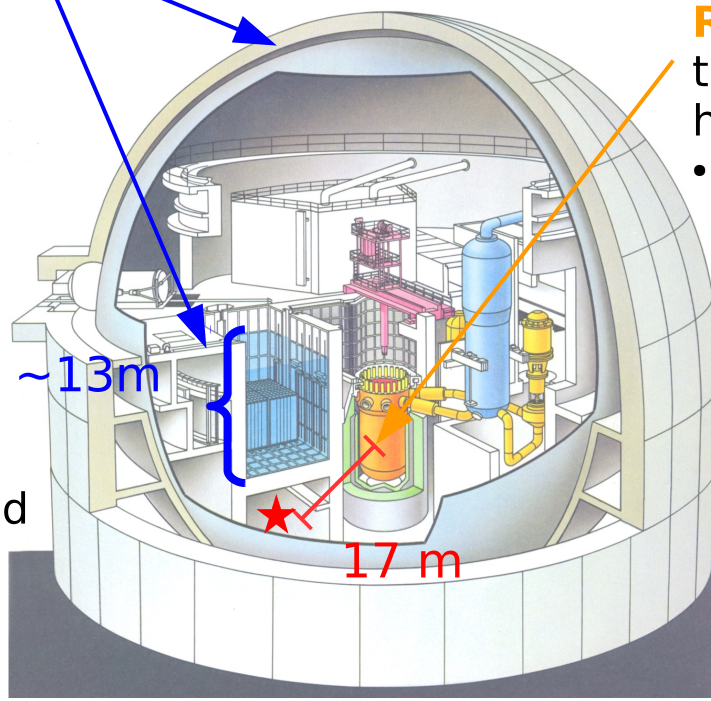
Complete overview:
Eur. Phys. J. C 81, 267 (2021)

Antineutrino source:

Nuclear power plant at Brokdorf (GER)

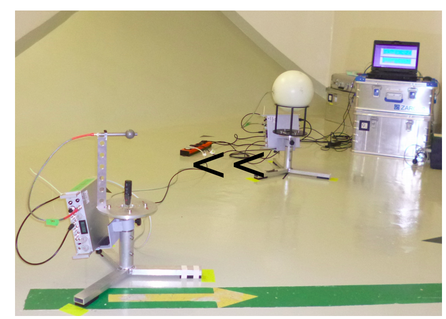
Strong neutrino source

Overburden at <u>shallow</u> depth:
10-45 m w.e. (angular dep.)
=> muon-induced background



Reactor core:
thermal power 3.9 GW
high duty cycle (1 month/yr off)

- **Signal:** antineutrinos @17m
  $\sim 2.3\times10^{13}/(\mathrm{cm}^2\ \mathrm{s})$

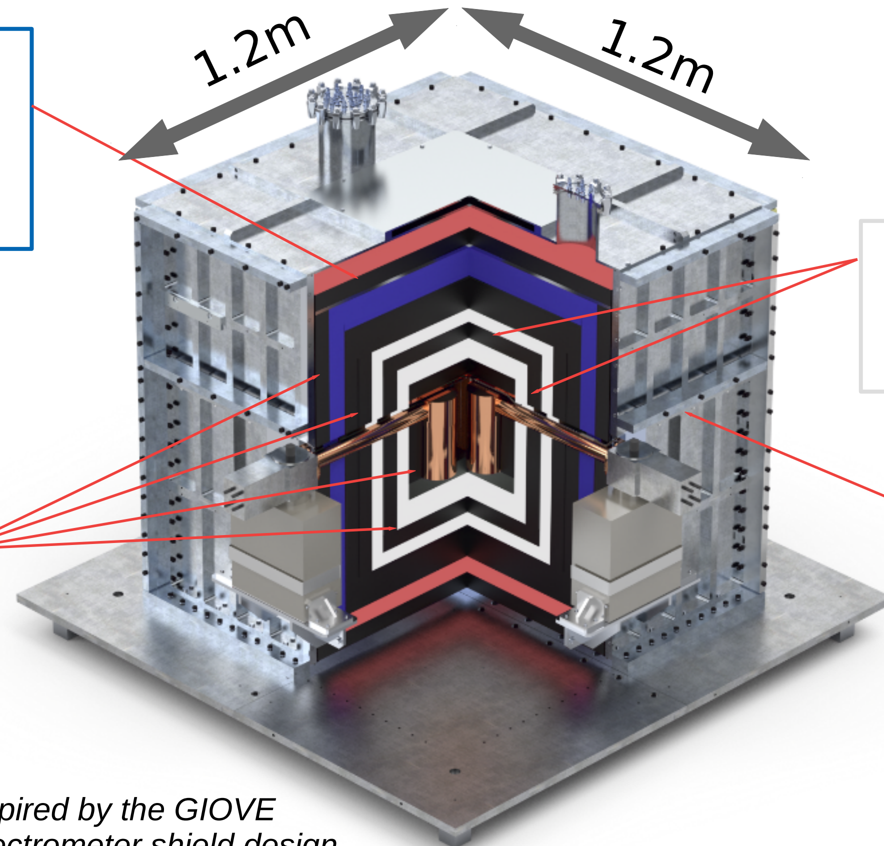


CONUS experiment:
4kg low noise threshold HPGe detectors

potential **reactor correlated background excluded** by measurements and MC!
Eur. Phys. J. C (2019) 79:699

CONUS shield design

Active muon veto:
suppress cosmic ray muon-induced background

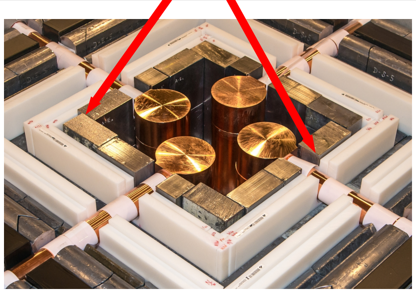


Low background

Borated PE:
moderate and capture neutrons

Steel cage:
confinement of shield flushed with breathing air from bottles against Radon; safety requirements

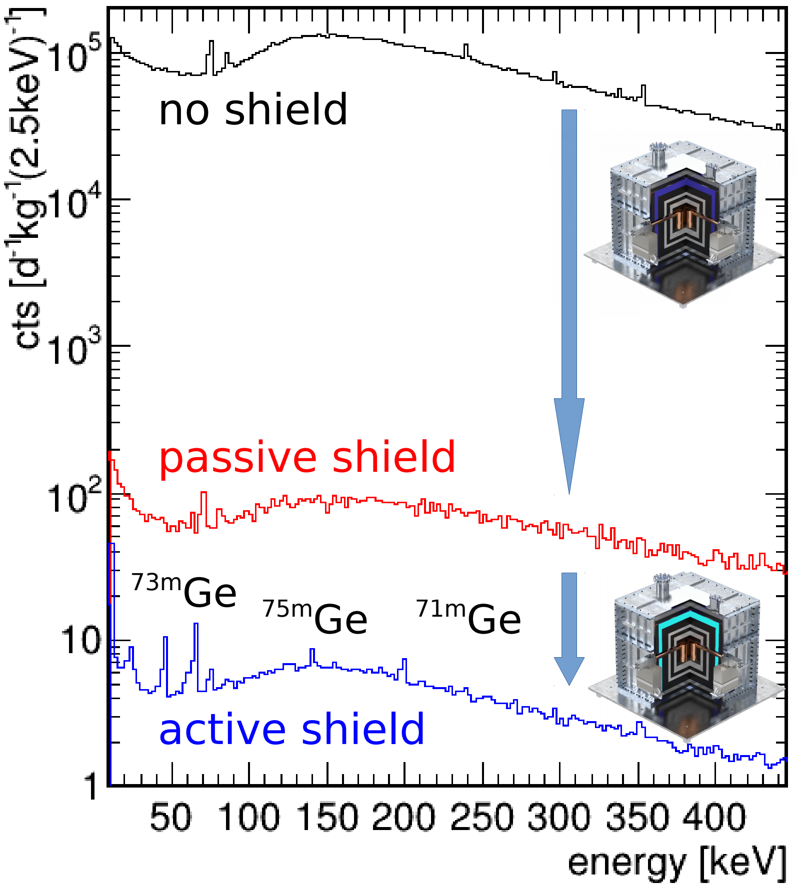
25cm Pb:
Shield radioactivity from environment low in ^{210}Pb



Inspired by the GIOVE spectrometer shield design (MPIK, Eur. Phys. J. C (2015) 75: 531)

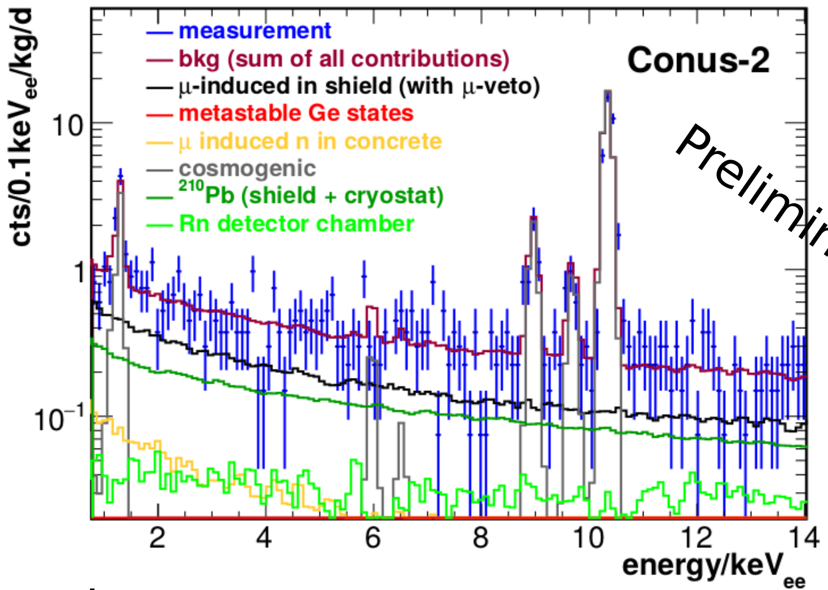
Pb bricks
from Freiburger Minster

Background suppression



Total background suppression factor of active and passive shield: **10^4**

Full background decomposition in MC:



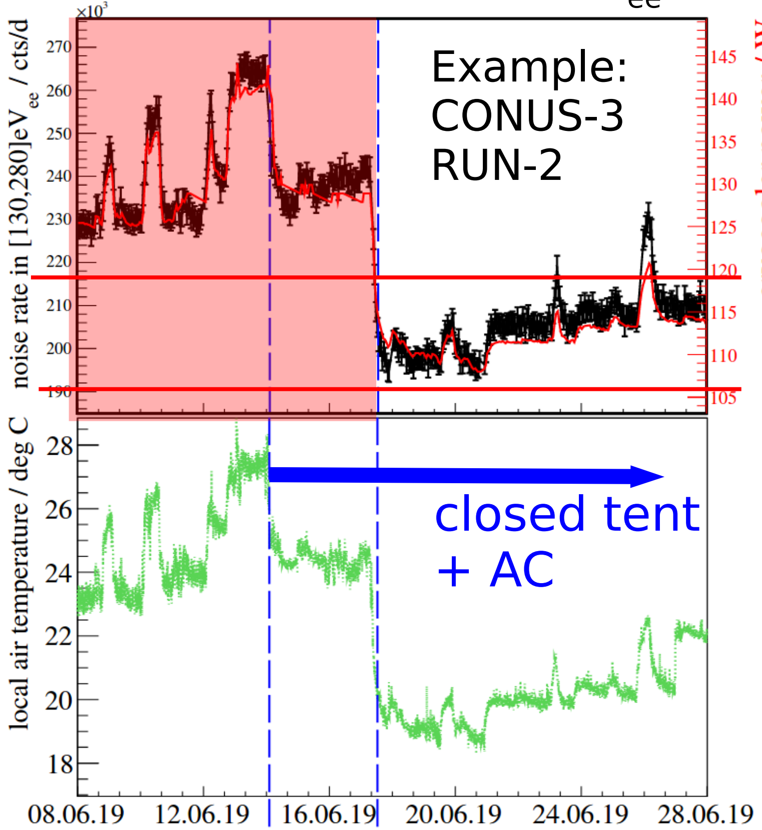
Most relevant:

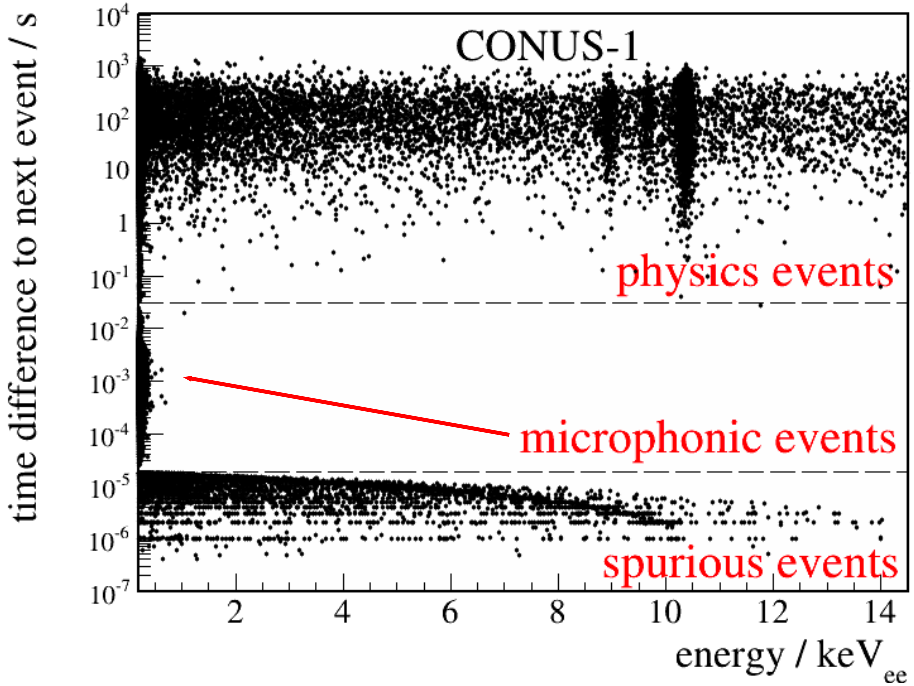
- prompt muon-induced
- (muon veto efficiency ~97%)
- ^{210}Pb in shield
- ^{210}Pb inside detector
- cosmogenic lines
- airborne radon

all contributions understood

Noise examination and cuts

Integral range [130,280]eV_{ee} below ROI:





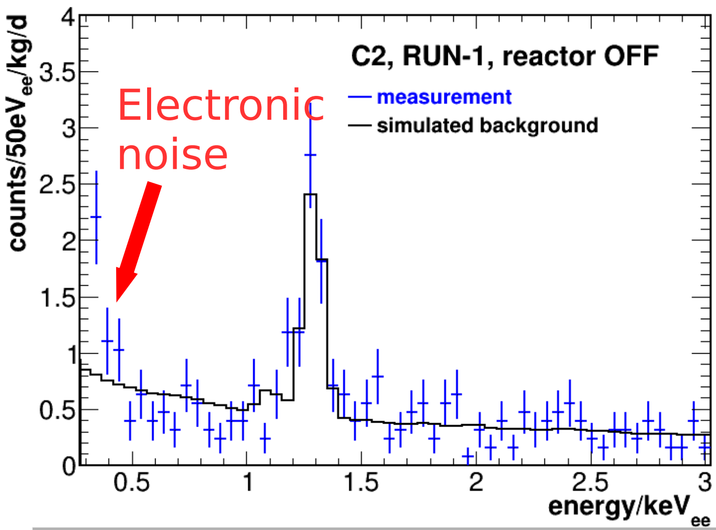
Time difference distribution cut
→ remove microphony

→ Room temperature
→ Cryocooler power
→ noise in Ge detectors

Noise-temperature correlation cut
+ stabilization in RUN-2 by closed tent and Air Cond. Syst.

Total exposure: RUN-1 & RUN-2
ON 248.7 kg*d
OFF 58.8 kg*d

Likelihood fit for CEνNS analysis



Criteria for definition of ROI:

- trigger efficiency close to 100%
- electronic noise/simulated bkg <4 → conservatively suppress potential remaining temperature-induced instabilities

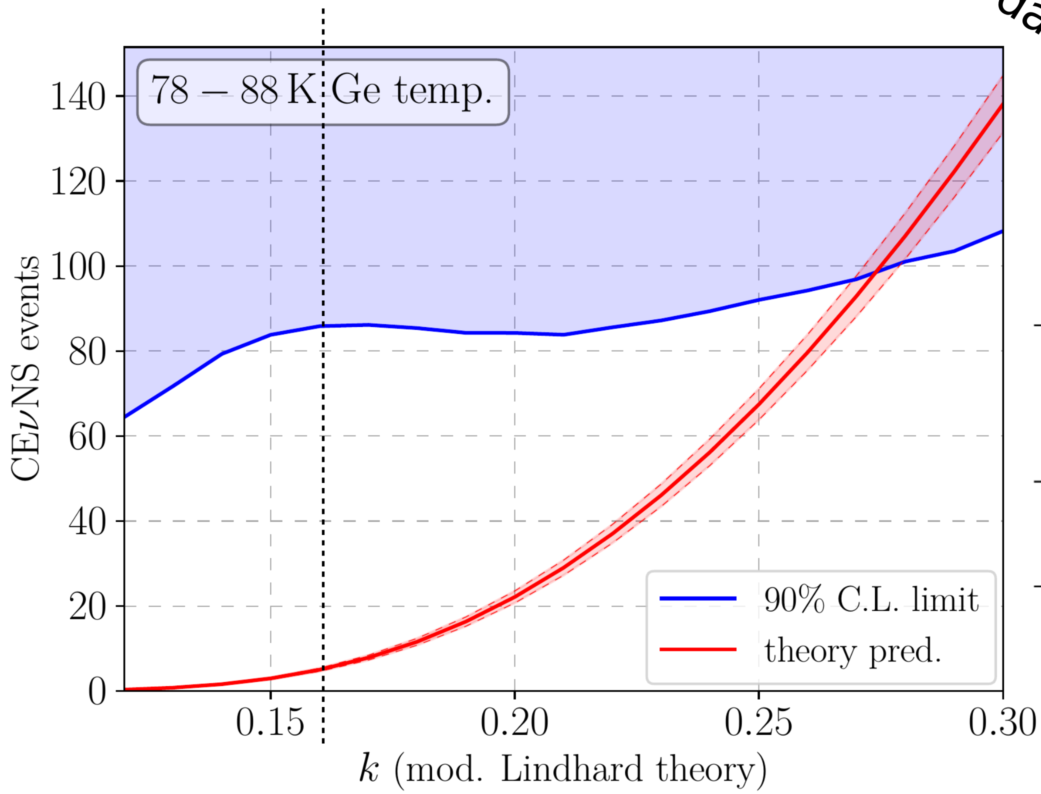
Binned likelihood fit:

- all detectors and runs combined
- Simulataneous fit of ON and OFF data
- Include systematics by pull terms

Parameter	**Uncertainty**
s signal	scanned over
b MC background normalization	free parameter
θ_{thr1} ,θ_{thr2} electronic noise	free parameters, exponential
θ_{rea} reactor neutrino spectrum	~3% (thermal power, fission fractions)
θ_{det} detector and DAQ	1-5% (indep. measurements)
ΔE energy scale calibration	10-20eV, highly stable

Best limit on CEνNS by reactor $\bar{\nu}$ in the fully coherent regime

Upper limit from likelihood ratio test:



RUN-1 and RUN-2 data sets

Complete overview:
Phys. Rev. Lett. 126, 041804

Data set:

Det.	RUN	ON [d]	OFF [d]	ROI [keV_{ee}]
C1	1	96.7	13.8	0.296 - 0.75
C2	1	14.6	13.4	0.311 - 1.00
C3	1	97.5	10.4	0.333 - 1.00
C1	2	19.6	12.1	0.348 - 0.75
C3	2	20.2	9.1	0.343 - 1.00

increase exposure ↗ lower threshold ↙

- Ionization queching: $Q = E_{ion}(meas)/E_{nuclear\ recoil}$
- k = 0.16: <0.4 cts/d/kg (90% C.L.)
- k > 0.27 and above disfavored

=> RUN-3 and beyond!

+ improved quenching factor measurement

BSM constraints from CONUS data

- **Modification of CEνNS cross section** for one type of BSM physics
- **Adaption of region of interest** to respective energy ranges
  - more refined description of noise threshold
  - extention of data sets possible
  - systematics on background description more relevant
- **Likelihood analysis** => limits on BSM models for reactor ν energies (<10MeV)

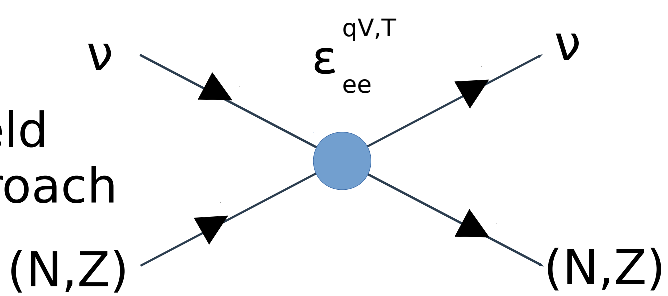
<u>Non-standard interactions (NSIs):</u>

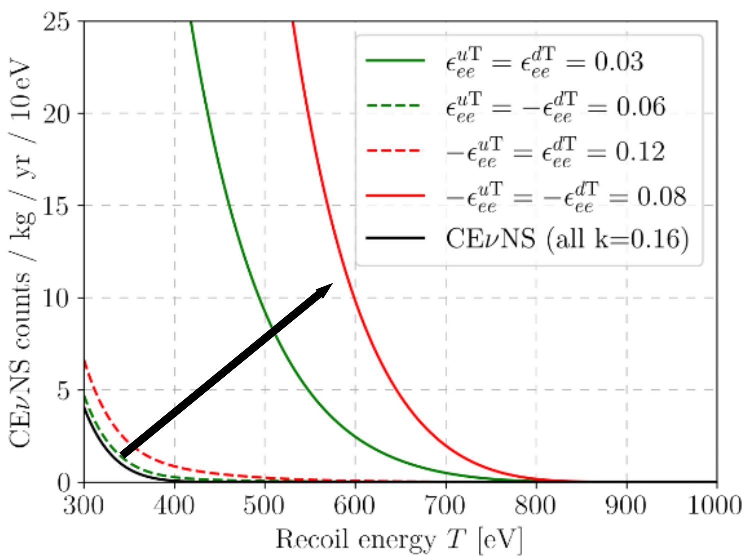
new effective vector/tensor operators => modified/addional weak charge $Q_W \rightarrow Q_{NSI}$

$$\frac{d\sigma}{dT} \mapsto \frac{d\sigma}{dT}_{SM} + \frac{d\sigma}{dT}_{T}$$

$$= \frac{G_F^2 M}{\pi} [Q_W^2 \left(1 - \frac{MT}{2E_\nu^2}\right) + 4\, {Q_{NSI}^{T}}^2 \left(1 - \frac{MT}{4E_\nu^2}\right)]$$

effective field theory approach





BSM constraints from CONUS data: NSIs

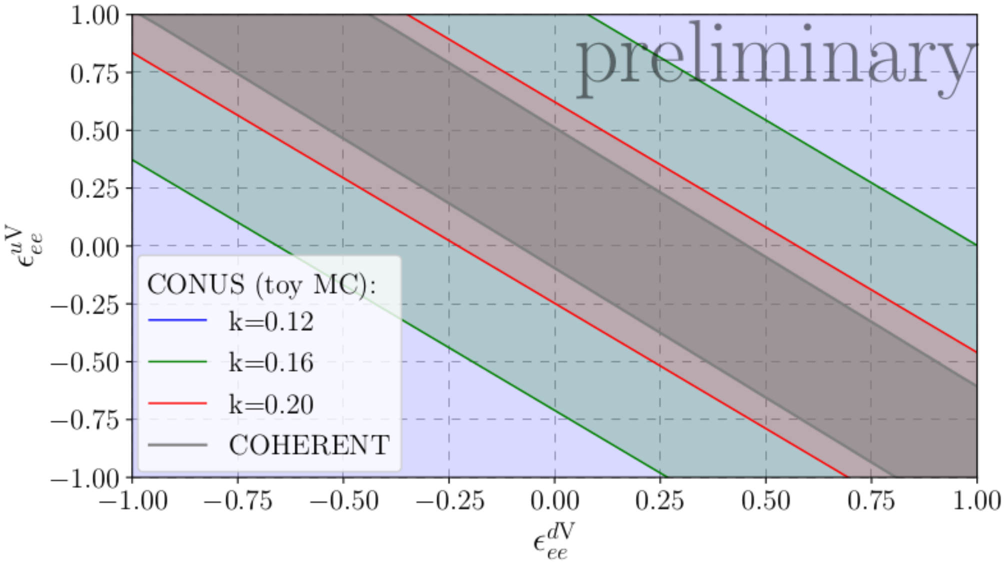
Vector operator

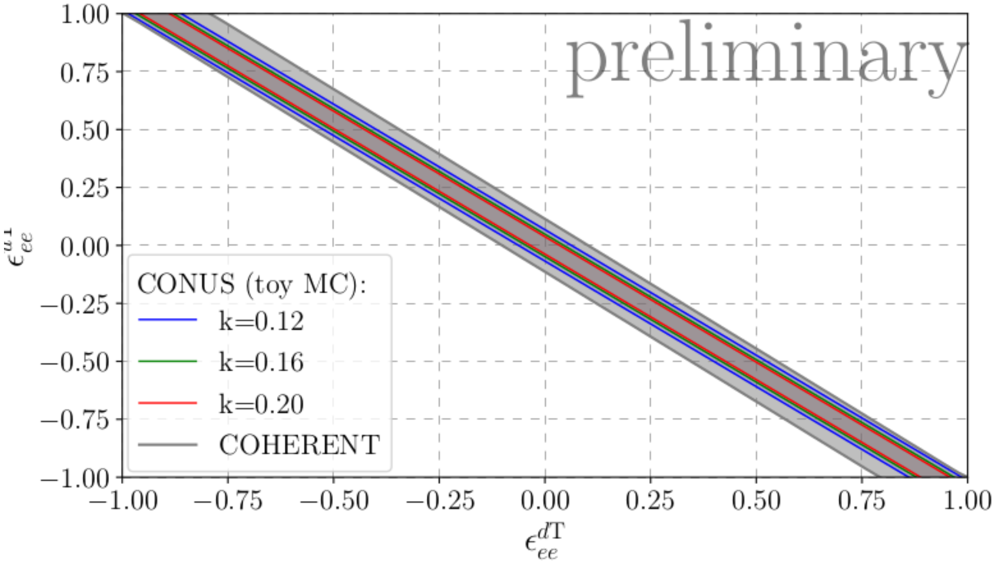
$$\frac{d\sigma}{dT} \mapsto \frac{d\sigma}{dT}_{NSI}^{V} = \frac{G_F^2\, M}{\pi} Q_{NSI}^{V\,2} \left(1 - \frac{MT}{2E_\nu^2}\right)$$

Tensor operator

$$\frac{d\sigma}{dT} \mapsto \frac{d\sigma}{dT}_{SM} + \frac{d\sigma}{dT}_{T}$$
$$= \frac{G_F^2\, M}{\pi} [Q_W^2 \left(1 - \frac{MT}{2E_\nu^2}\right) + 4\, Q_{NSI}^{T\,2} \left(1 - \frac{MT}{4E_\nu^2}\right)]$$

Limits on coupling strength:





Publication in preparation!

BSM constraints from CONUS data: Simplified mediator models

- simplified light scalar m_ϕ/vector m_z mediators, assume universal couplings

vector (nucleus channel)

$$\frac{d\sigma}{dT} \mapsto \mathcal{G}_{Z'}^2(T) \cdot \frac{d\sigma}{dT}_{SM}$$

$$= \left(1 - \frac{g_{Z'}}{\sqrt{2}G_F}\frac{Q_{Z'}}{Q_W}\frac{1}{2MT + m_{Z'}^2}\right)^2 \cdot \frac{d\sigma}{dT}_{SM}$$

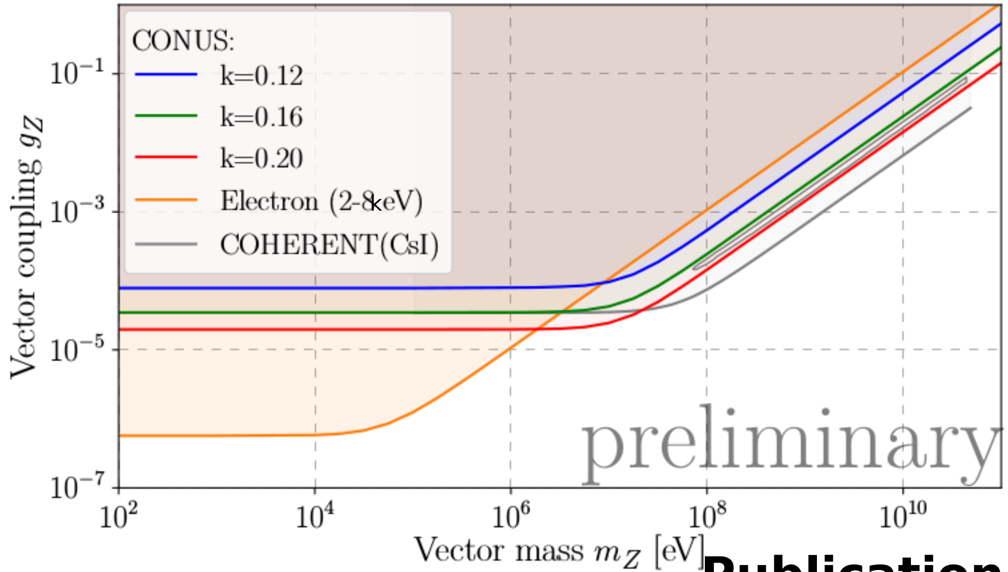
scaler (nucleus channel)

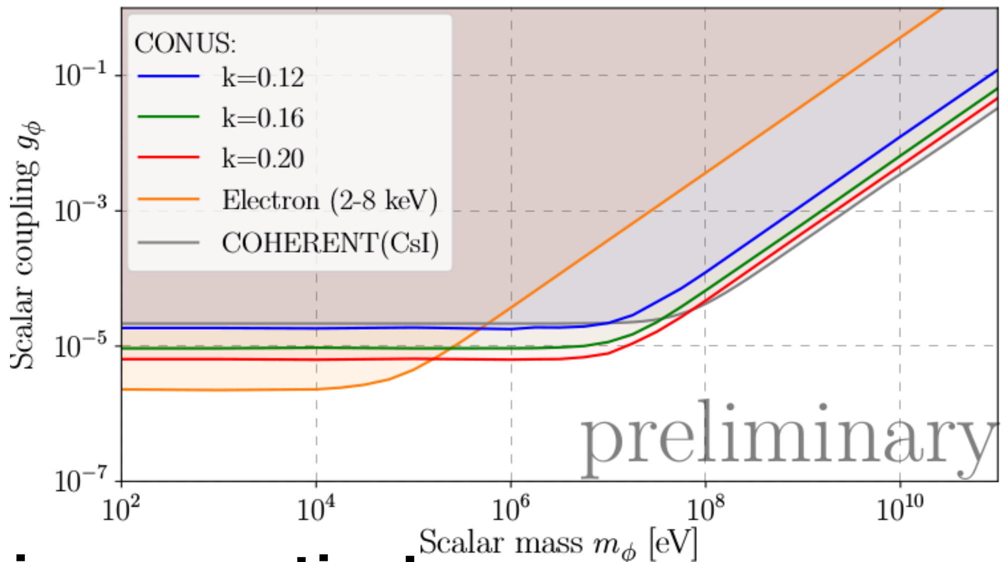
$$\frac{d\sigma}{dT} \mapsto \frac{d\sigma}{dT}_{SM} + \frac{d\sigma}{dT}_{\phi}$$

$$= \frac{d\sigma}{dT}_{SM} + \frac{g_\phi^4 (14N + 15.1Z)^2 M^2 T}{4\pi E_\nu^2 (2MT + m_\phi^2)^2}$$

- nucleus and electron channel examined
  => **stringent limits** due to low energetic high neutrino flux at **reactor site**!

Limits on mass/coupling:

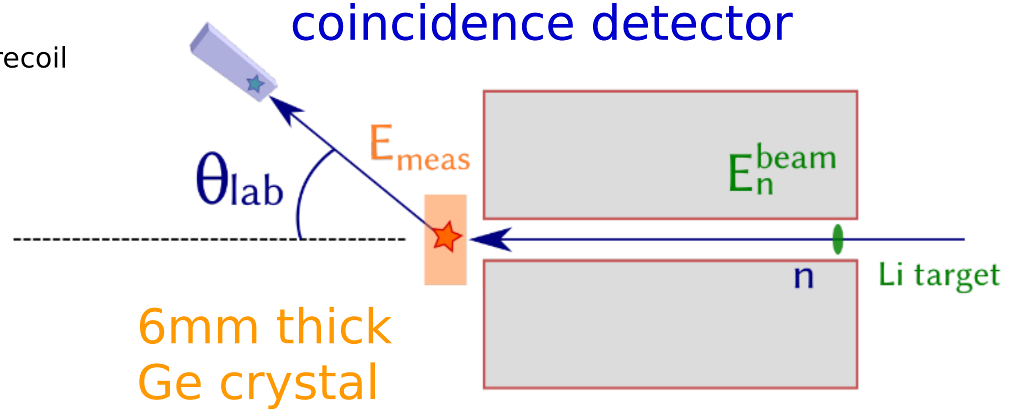


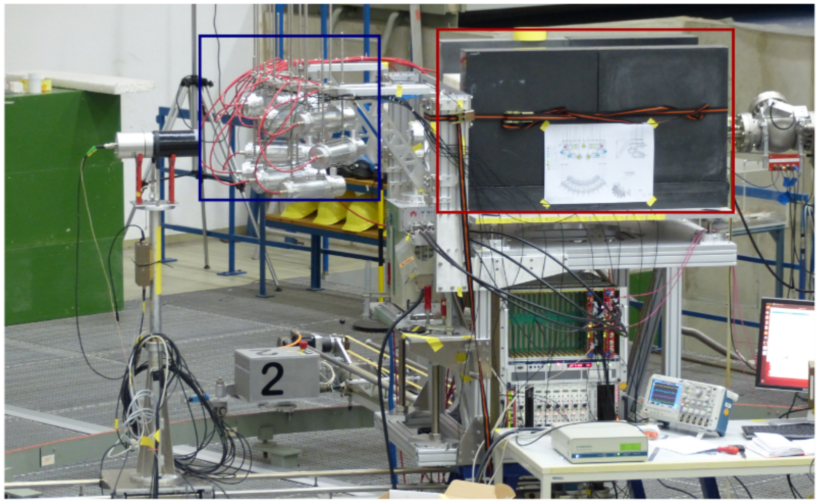


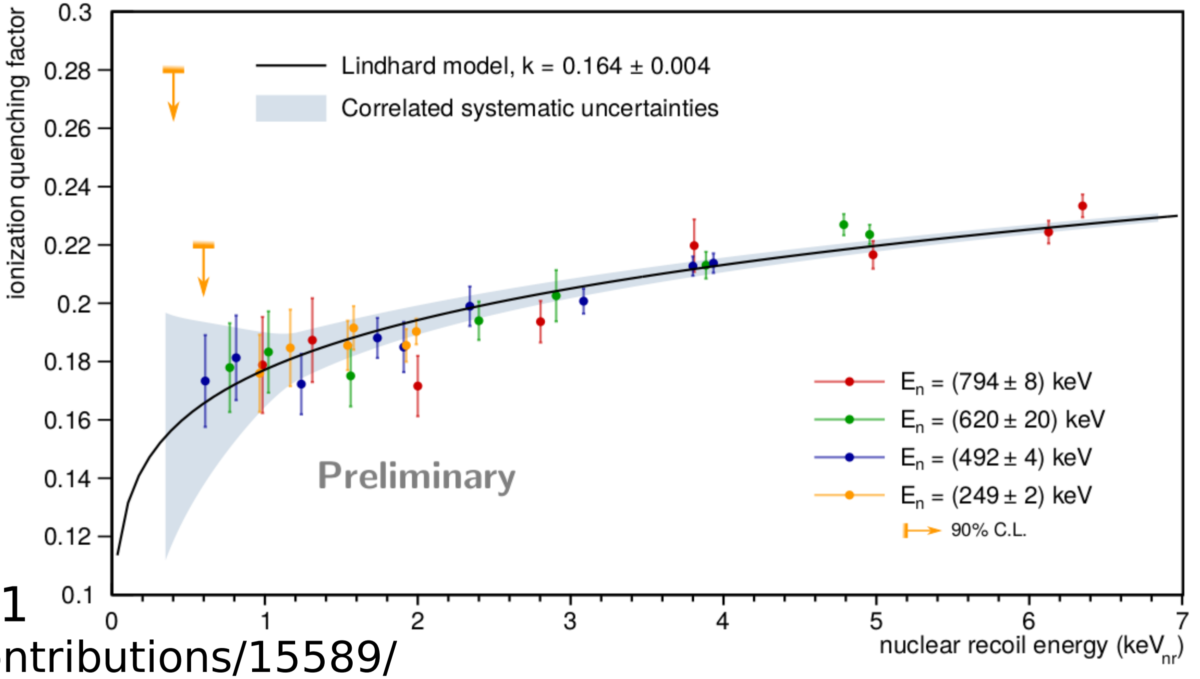
Publication in preparation!

Ge quenching factor measurement for CONUS at PTB

- Ionization queching: $Q = E_{ion}(meas)/E_{nuclear\ recoil}$
- direct measurement at collimated neutron beam at PTB Braunschweig
- scan over recoil energies [0.4,7]keV_{nr}
- data compatible with Lindhard model for: **k = 0.164±0.004 (stat+syst)**







Details: A. Bonhomme, TAUP 2021
https://indico.ific.uv.es/event/6178/contributions/15589/

Summary and Outlook

- **CONUS experiment at KBR Brokdorf,** operational since April 2018

- **Full CEνNS spectral shape analysis** of RUN-1 and RUN-2: Phys. Rev. Lett. 126, 041804
  - includes detailed study of systematics, see Eur. Phys. J. C 81, 267 (2021)
  - includes full MC description of bkg
    → reactor correlated bkg negligible, see Eur. Phys. J. C (2019) 79:699
    => best limit on CEνNS with reactor antineutrinos
- competitive limits on NSIs and simplified mediator BSM models => publication in preparation!

- direct and precise measurement of **ionization quenching factor in Ge** down to $0.4keV_{nr}$

- **Outlook:**
  - further BSM analyses, magnetic moment $\mu_\nu < 10^{-10}\ \mu_B$
  - extended data set: more OFF data (shut-down of KBR end of 2021)
  - lower energy threshold
    - improved control of environmental parameters
    - upgrade DAQ: pulse shape (noise, background suppression)

Thank you for your attention!