First observation of reactor antineutrinos by coherent scattering with CONUS+

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on behalf of the CONUS collaboration

The XIX International Conference on Topics in Astroparticle and Underground Physics

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TAUP XICHANG

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The CONUS Collaboration

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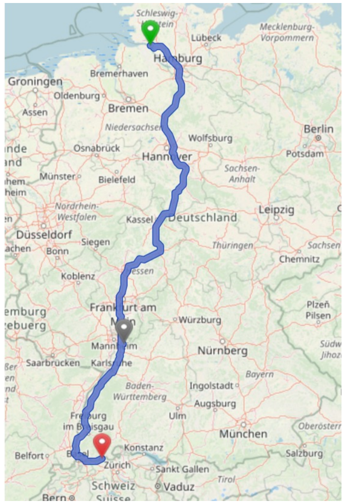
CONUS

CONUS+

1) Very intense anti-neutrino flux at a commercial power reactor:
➔ CONUS experiment @Brokdorf: KBR
➔ CONUS+ @Leibstadt (CH): KKL

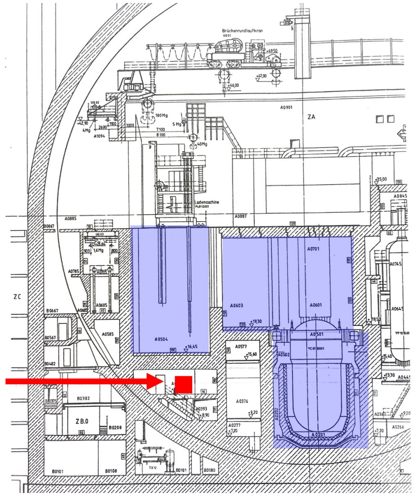
2) Sophisticated shield against all sort of backgrounds at a reactor site

3) Very low threshold Germanium detectors



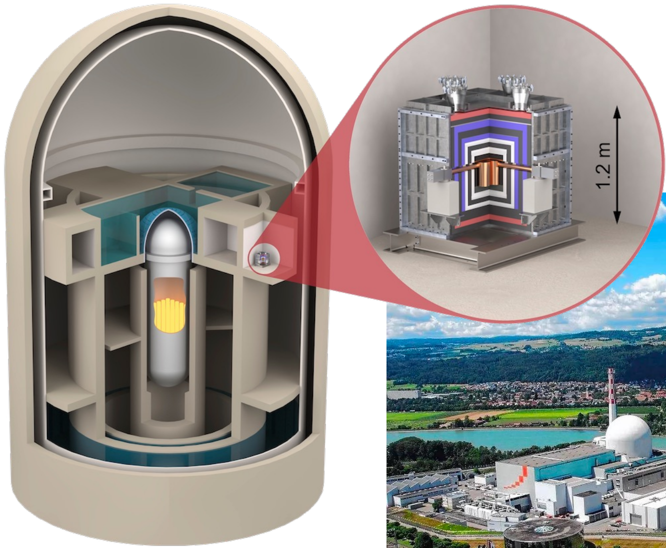
Experimental Sites

CONUS 2018 – 2022 @Brokdorf (KBR)
3.9 GW_{th} reactor
distance: 17m → $2*10^{13}$ ν/cm²/s
→ Eur.Phys.J.C 79 (2019) 8, 699
→ Eur.Phys.J.C 83 (2023) 3



final shutdown in 2021 → more off data
final result: factor 1.6 (90%CL) away from SM
→ Phys.Rev.Lett. 133 (2024) 25, 251802

significant detector improvements
→ CONUS+

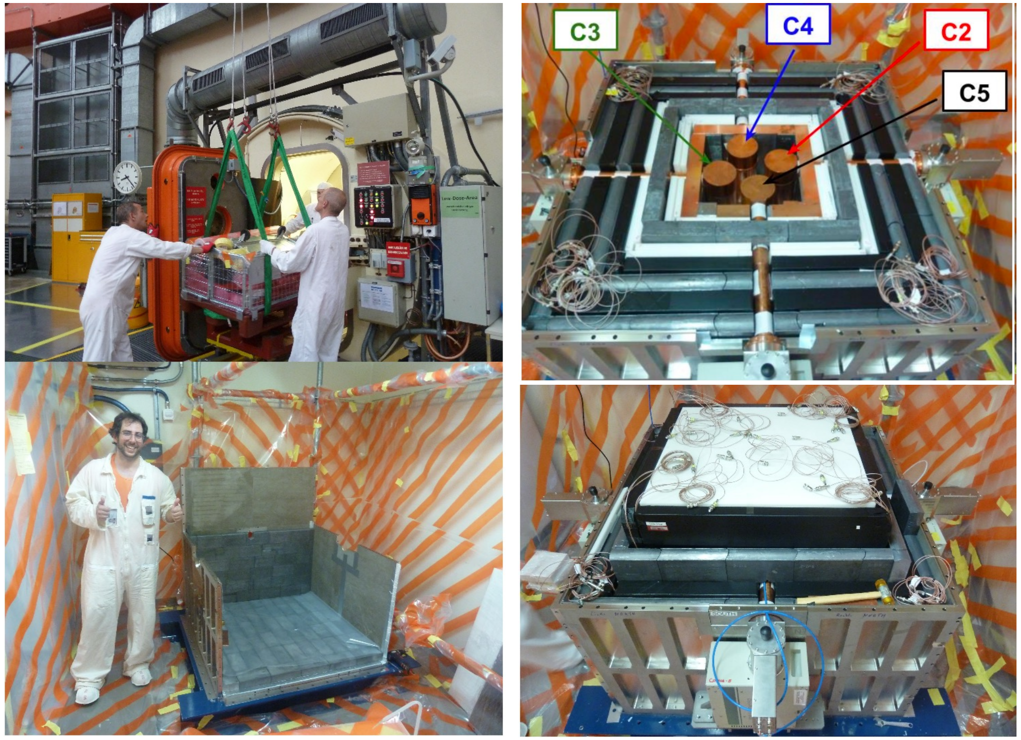


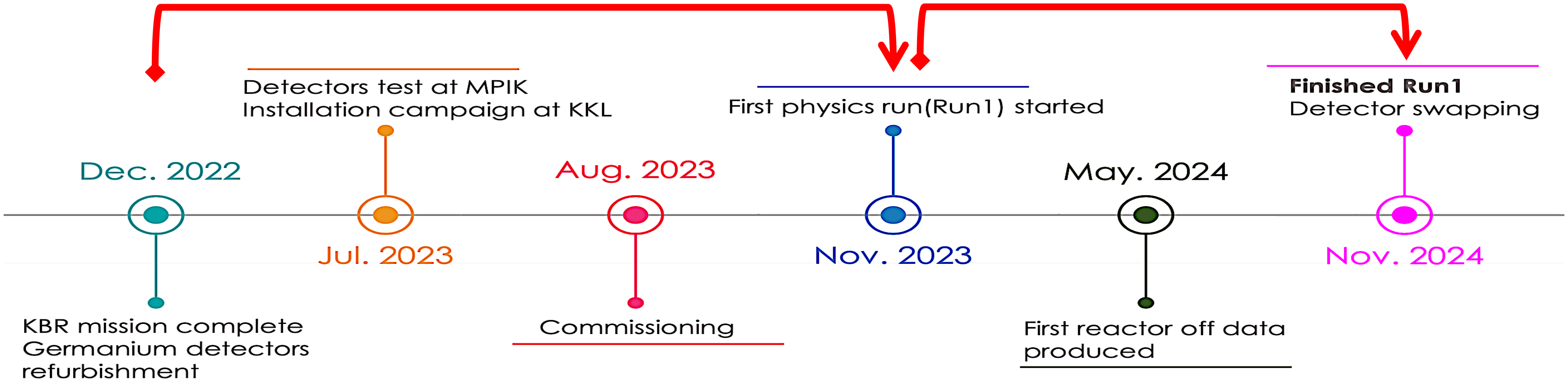
Since 2023 @Leibstadt, CH (KKL)
3.6 GW_{th} reactor
CONUS+ @20.7m → $1.45*10^{13}$ ν/cm²/s
different overburden: 7-8 mwe → better veto
outage: drywell above detector +3.8cm steel

typical reactor operation: 11 months per year ON, 1 month OFF for maintenance

Timeline of CONUS+

- dismantling
- transport
- improvements
- installation ➔
- data taking
- analysis

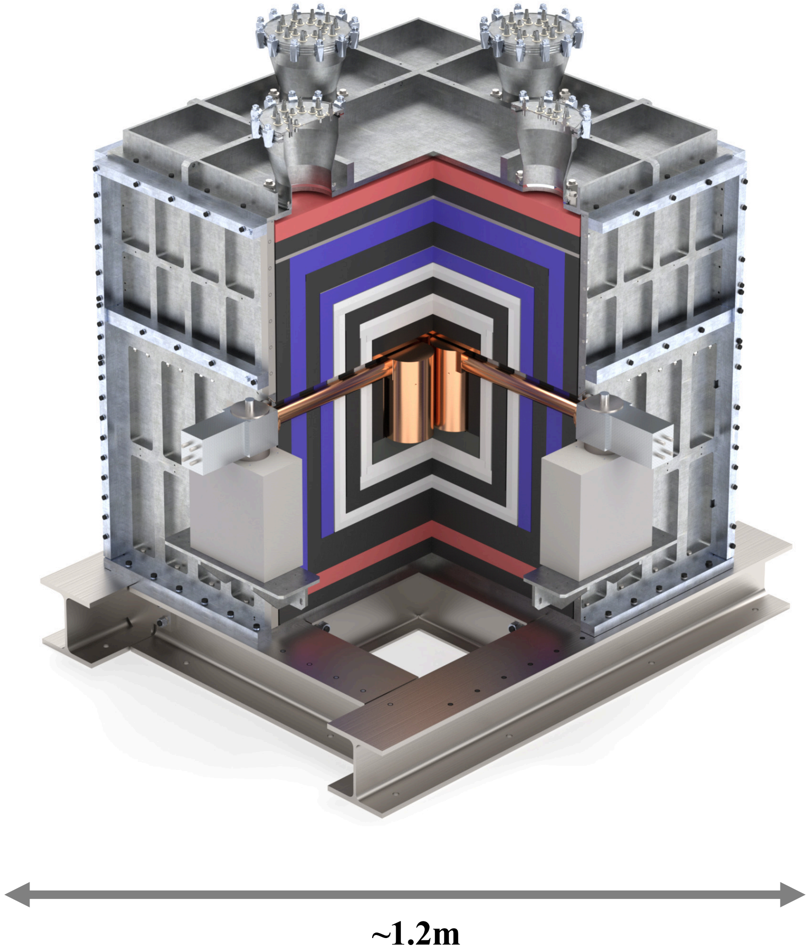




The CONUS+ Setup

Shield for background suppression:

- stainless steel cage → safety (earthquakes)
- optimized shield with active and passive layers:
  - outer and inner μ-veto layers
    ←→ higher muon flux @KKL
  - lead for gamma suppression
  - PE (and borated 10B PE) layers ←→ neutrons
- all materials carefully selected and screened
- flushing with radon-free air → remove ^{222}Rn
  → background reduction by 4 orders of magnitude
- 10 tons total mass



low background conditions like in UG labs

➔ ``virtual depth”

CONUS: Eur.Phys.J. C83 (2023) 3, 195
CONUS+: Eur.Phys.J. C85 (2025) 4, 465

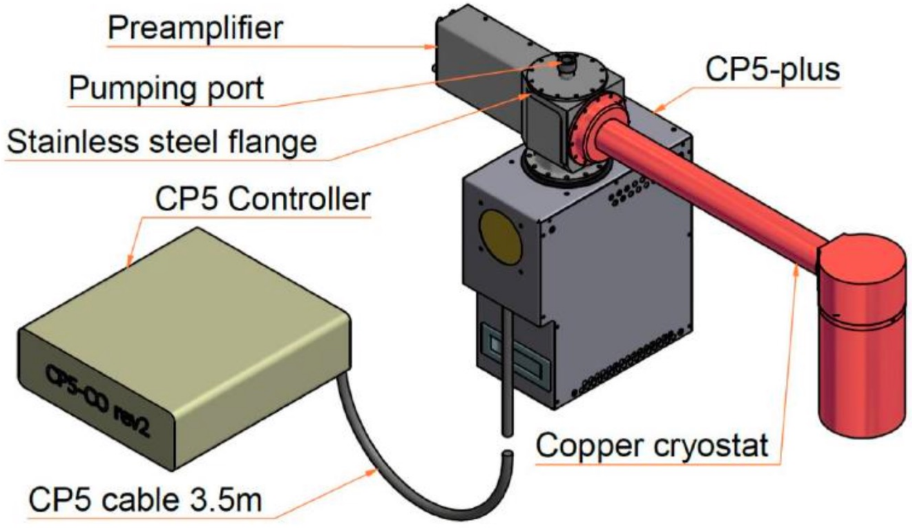
Improved CONUS+ Detectors

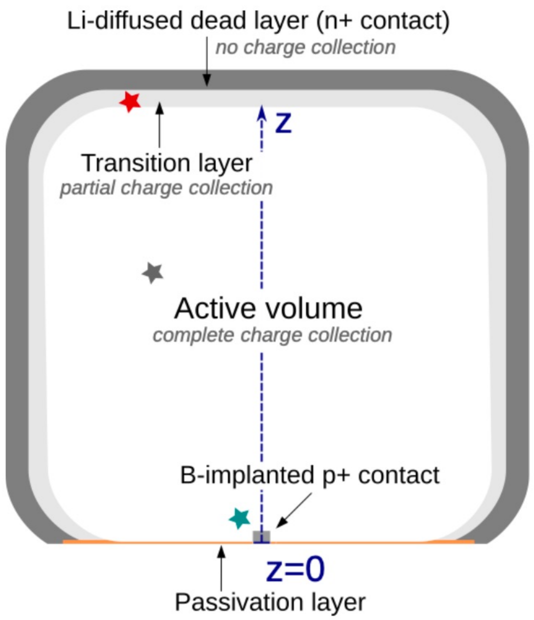
point-contact HPGe detectors

- point-contact HPGe detectors
  → diode in reverse direction, ~kV voltages
- 1kg crystals: C2,C3,C4,C5 plus C1@MPIK
  → active mass in CONUS(+): 3.74 kg
- electrical PT cryocoolers (LN not allowed)
- long cryostat arms
- all components with very low background
- intensive R&D cooperation with producer
- ASIC based electronics
  → improved low E trigger efficiency
- reduced point contact size & bonding technology
  → reduced electronic noise
  → lower threshold: ~250 → 160 eV
  → improved energy resolution
- pulse shape discrimination (PSD ←→ slow pulses)

Eur. Phys J. C81, 267 (2021)

Eur.Phys.J. C84, 1265 (2024)

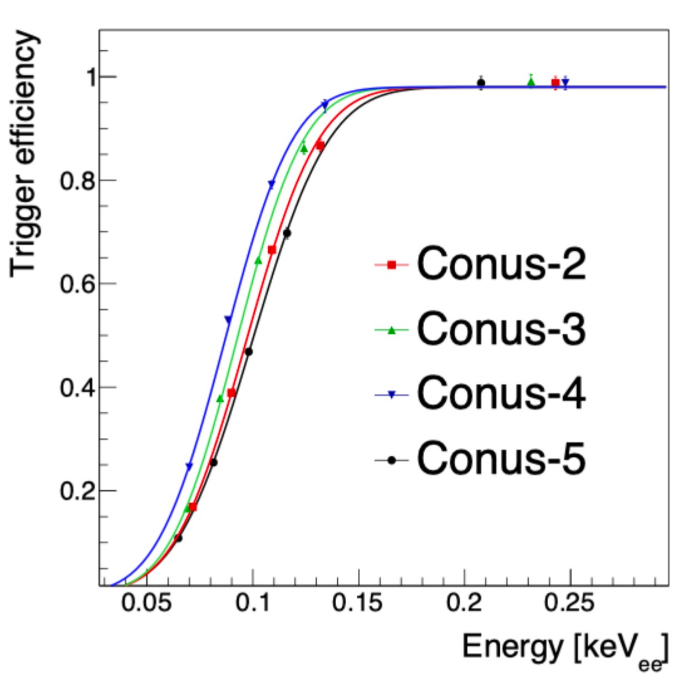


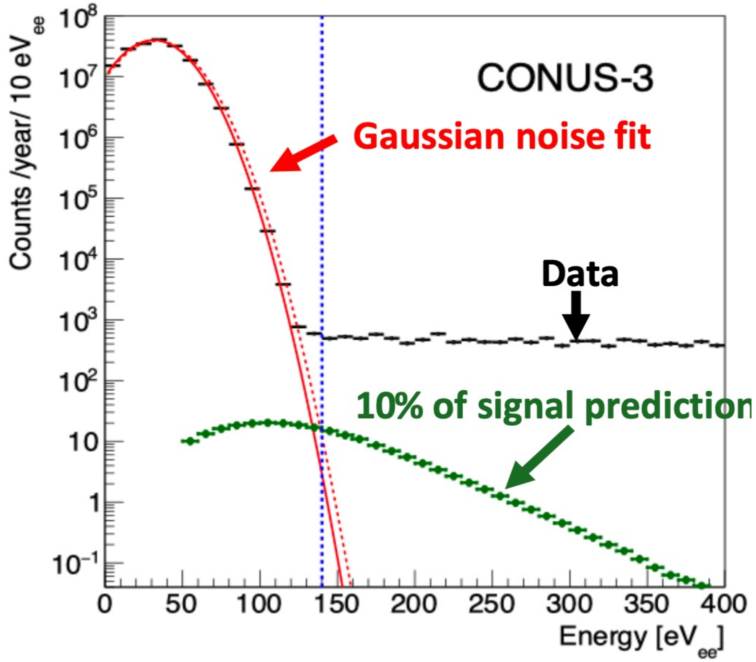


Trigger Efficiency, Resolution, Threshold

trigger efficiency = "probability" of signal detection
→ **improved CAEN DAQ system**

	C4 before refurbishment	C4 after refurbishment
100 % down to	~ 500 eV_{ee}	~ 150 eV_{ee}
50 % at	~ 300 eV_{ee}	~ 85 eV_{ee}
20 % at	~ 200 eV_{ee}	~ 65 eV_{ee}

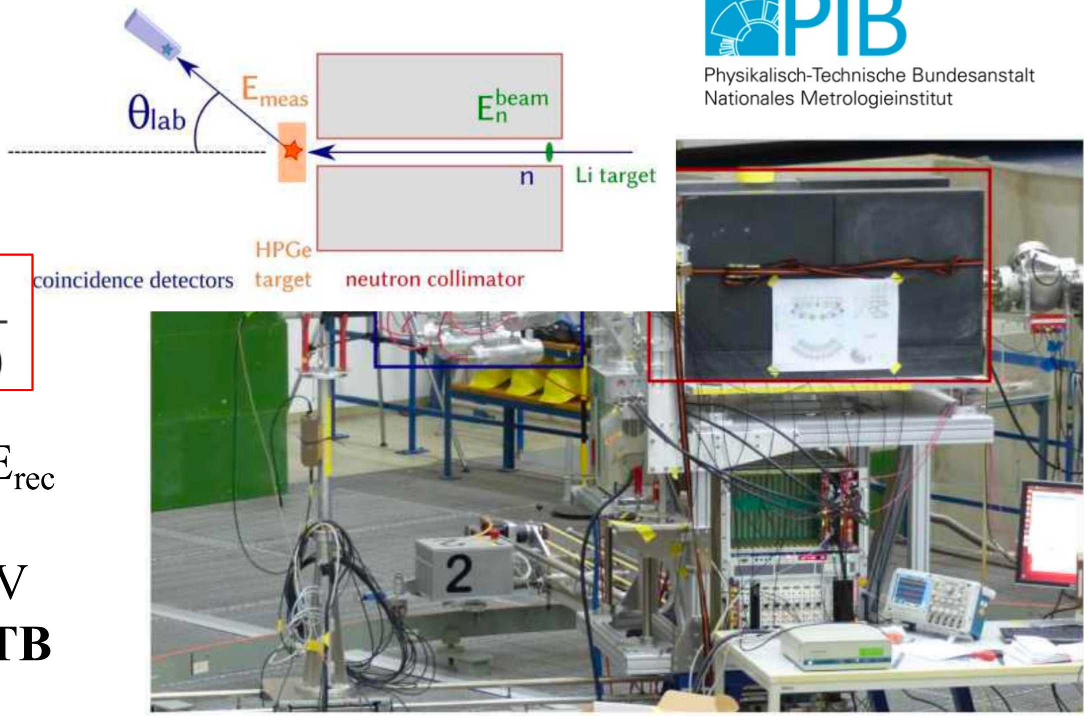




Detector	Pulser resolution after refurbishment (FWHM) [eV_{ee}]	Pulser resolution before refurbishment (FWHM) [eV_{ee}]	Threshold after refurbishment [eV_{ee}]	Threshold before refurbishment [eV_{ee}]
C5	48 +- 1	-	170	-
C2	47 +- 1	73 +- 1	180	210
C3	47 +- 1	74 +- 1	160	230
C4	47 +- 1	77 +- 1	-	210

Quenching

Recoil energy deposition in Ge detector:
- partially converted into ionization
- drift to point contact, amplification, ...



quenching factor:
(energy dependent)

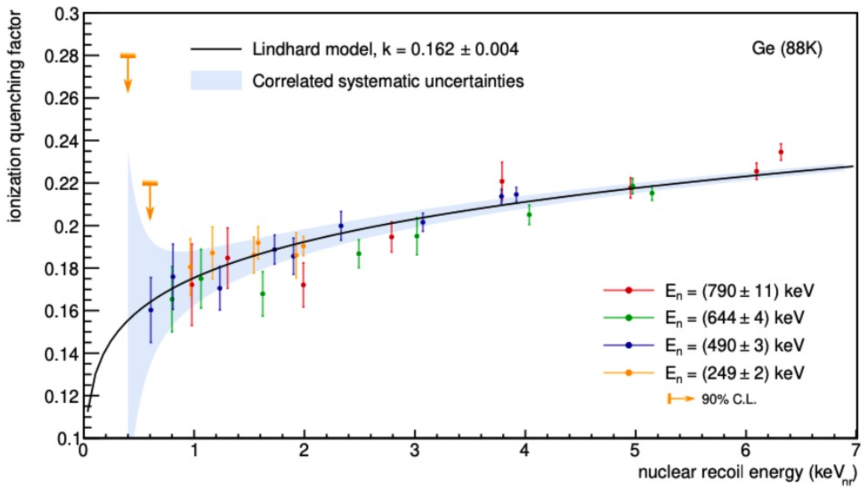
$$q = \frac{E_{ion}}{E_{rec}} = \frac{k\, g(\varepsilon)}{1 + k\, g(\varepsilon)}$$

$g(\varepsilon) = 3*\varepsilon^{0.15} + 0.7*\varepsilon^{0.6} + \varepsilon$; $\varepsilon = 11.5*Z^{-7/3} E_{rec}$

before: large uncertainties for E_{rec} < few keV
→ **dedicated measurement: CONUS + PTB**

monoenergetic neutron beam:
- recoil angle → energy transfer E_{rec}
- signal in Ge detector: E_{ion}

→ significantly improved measurement
→ consistent with Lindard theory (as it should)
→ **k =0.162 ± 0.004**



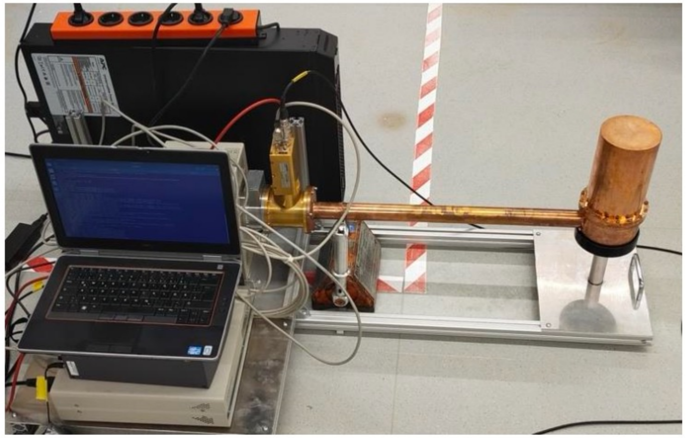
Eur.Phys.J.C 82 (2022) 9, 815

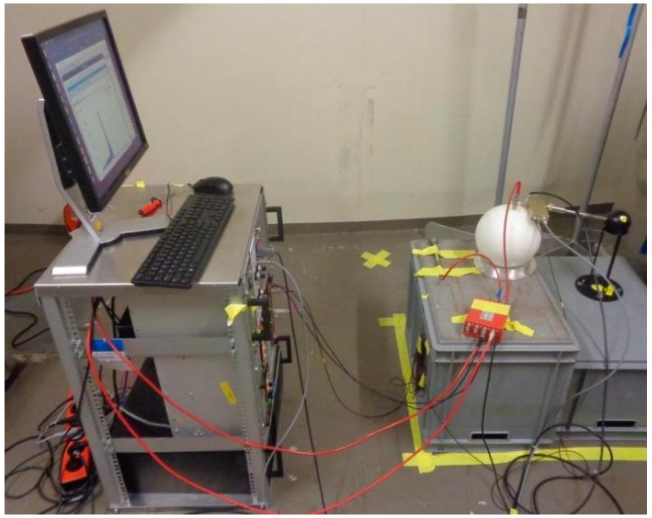
Characterization of Backgrounds

@KKL before the experiment was moved:

- Gamma measurement with HPGe detector (CONRAD)
- Neutron measurement with Bonner sphere array
- Environmental parameters:
  - radon level
  - temperature
  - vibrations with piezoelectric sensors
- Cosmic muons with custom liquid scintillator detector
- Wipe tests to measure surface contamination

Eur.Phys.J. C85 (2025) 4, 465





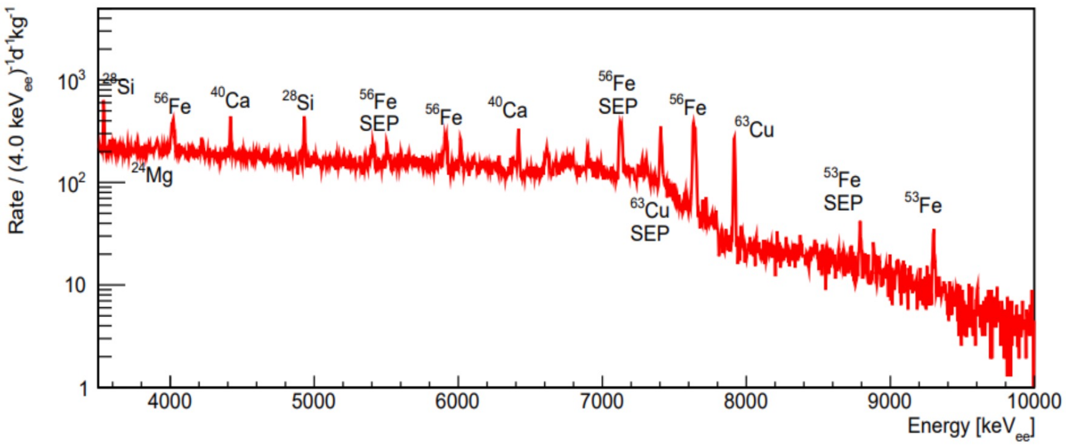
in parallel (at MPIK, at company, transport,...):

mitigate backgrounds in detector

- material screening of all used components
- avoid cosmogenic activation (underground storage)
- minimize transportation times
- ...

Backgrounds: Results @KKL

Gammas (with CONRAD, unshielded in ZA28R027)

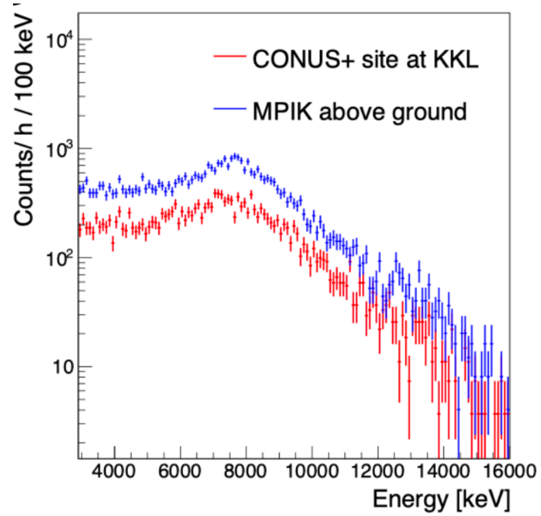


Muons

Muon rate in CONUS+ room:
(107 +- 3) counts/s/m^2

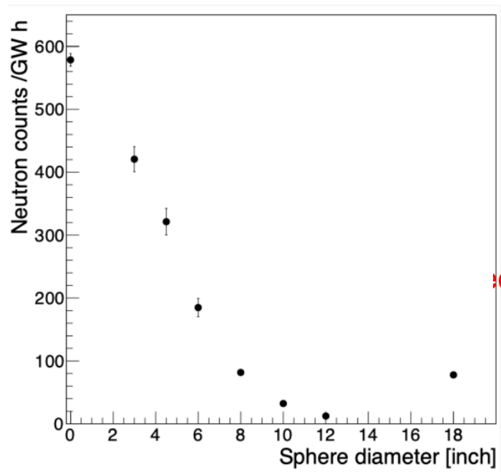
→ factor 1.9 reduction compared to outside

→ 7.4 m w.e. overburden

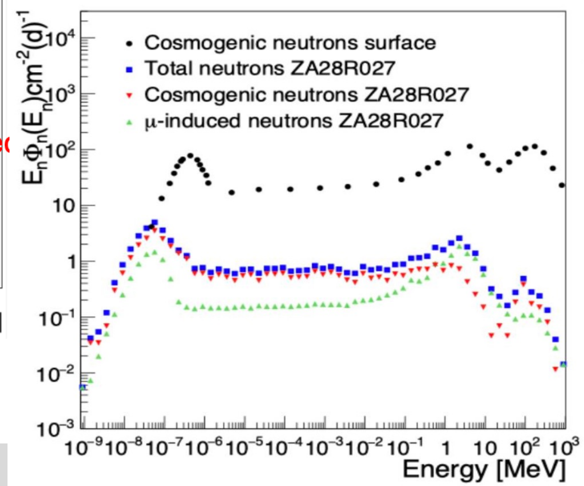


Neutrons

Energy region	$\phi\ (cm^{-2}\ (GW\ h)^{-1})$
Thermal	172.1 +- 16.3
intermediate	91.6 +- 6.3
Fast + cascade	1.0 +- 0.8
Total	264.7 +- 13.2



Cosmic Neutrons



Radon:
commercial device ~150 Bq/m^3

all backgrounds well understood
Eur.Phys.J.C 85 (2025) 4, 465

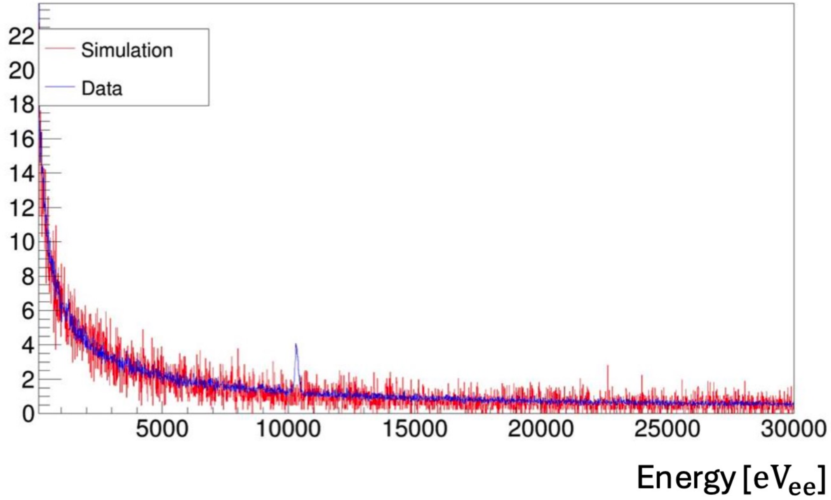
Background Model

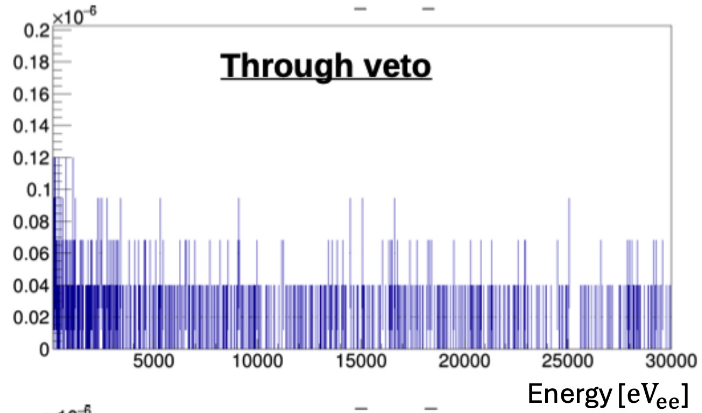
Full decomposition of backgrounds using:

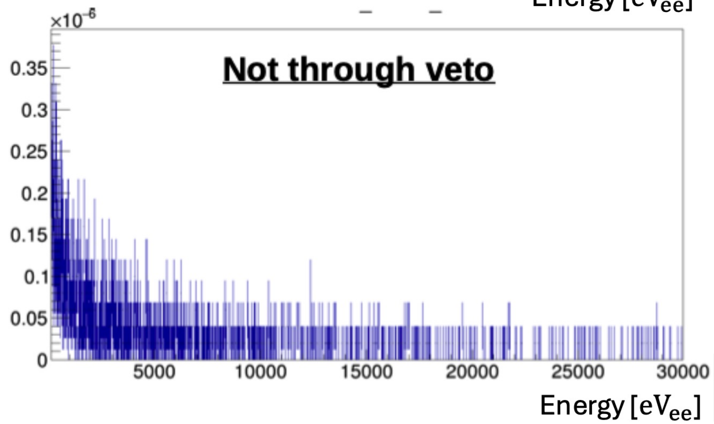
- material screening
- Monte Carlo simulation
- detector data

Relevant components:

- cosmogenic: muons and neutrons (from CR)
- natural radioactivity (external and internal)
- artificial components in reactor environment neutrons, surface contaminations, inert gases (Xe, Kr, H^3)







<u>**Muons:**</u>

flux inside room: $(107 \pm 3)\ s^{-1} m^{-2}$

→ **consistent with expectation from overburden**

muon veto efficiency: 99%

at low E: μ-induced signals from μ's not crossing veto

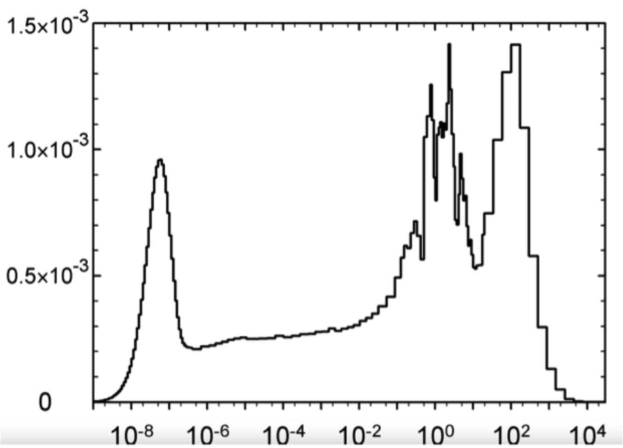
→ **slowly decreasing efficiency: 97% < 400 eV)**

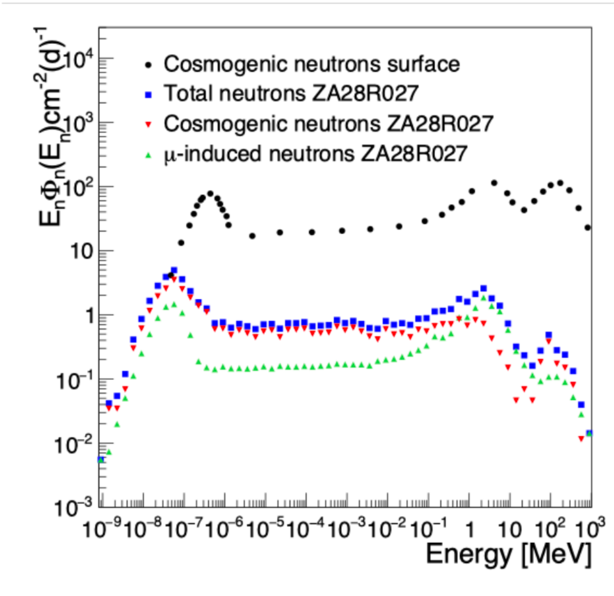
Cosmogenic Neutrons

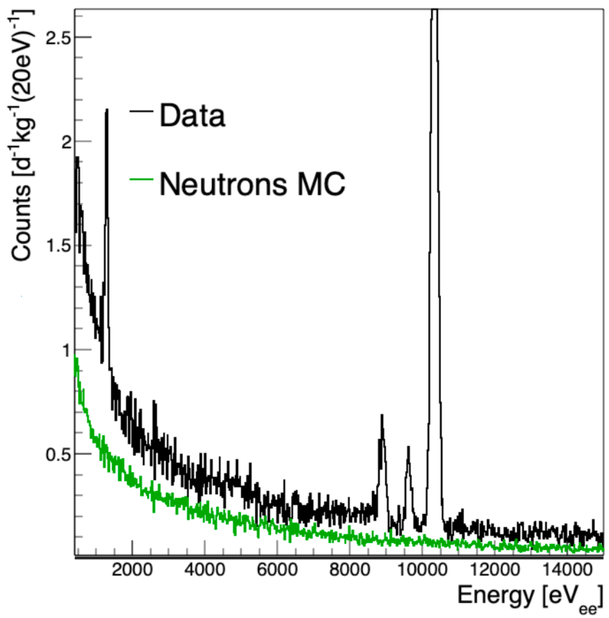
neutrons produced by cosmic-rays:
flux varies with magnetic latitude, elevation, the sun's magnetic activity cycle, nearby materials, humidity/moisture

→ constant conditions during data taking

initial cosmic neutron spectrum: 0.014 neutrons/s/cm^2	cosmic neutrons inside room 0.9±0.2 neutrons/d/cm^2	21.6±3.1 cts/d/kg in [0.4-1 keV$_{ee}$] (50.3±7.2% of C5 background)







Radon inside the Detector

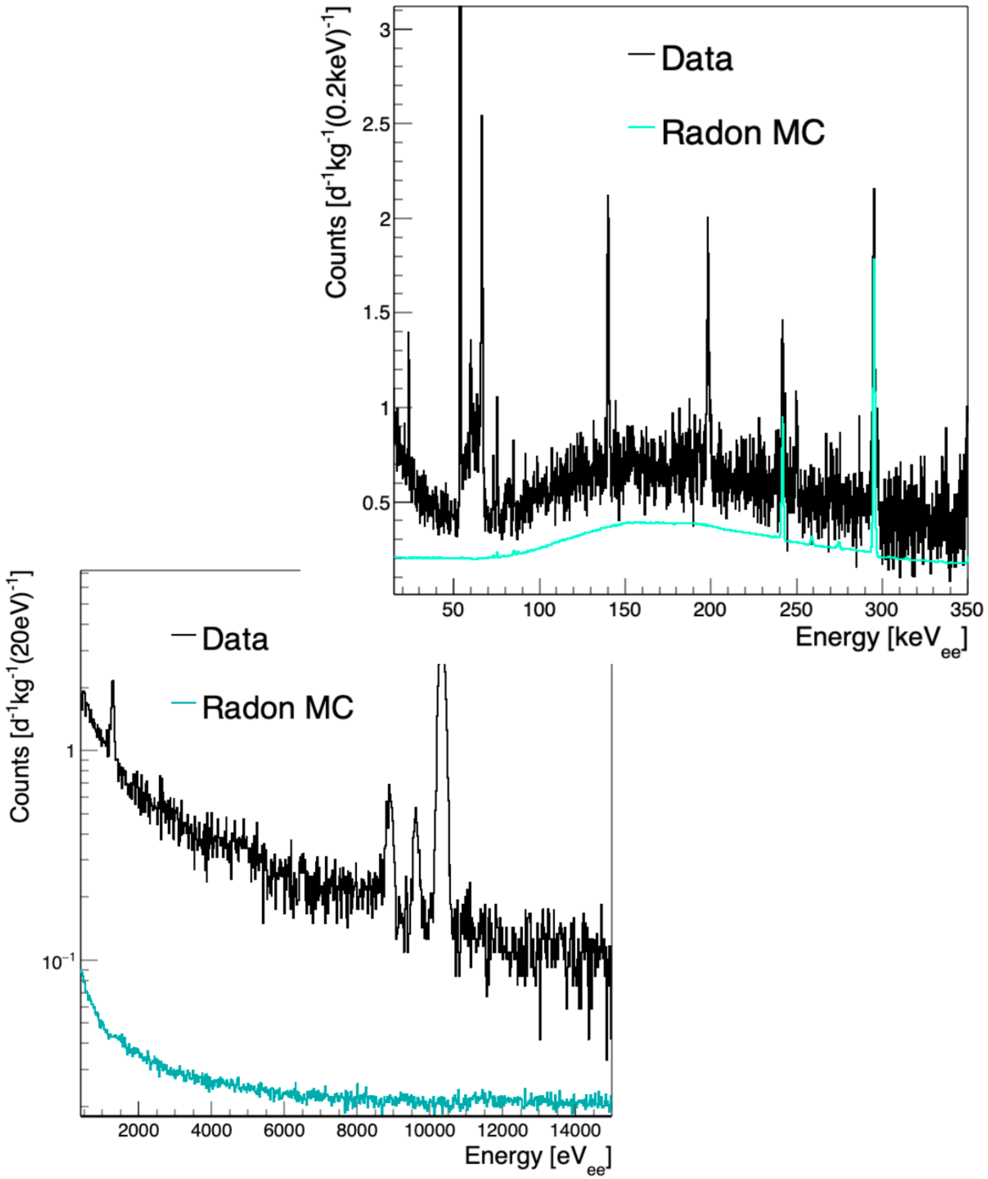
Radon:

- shield flushed with aged air

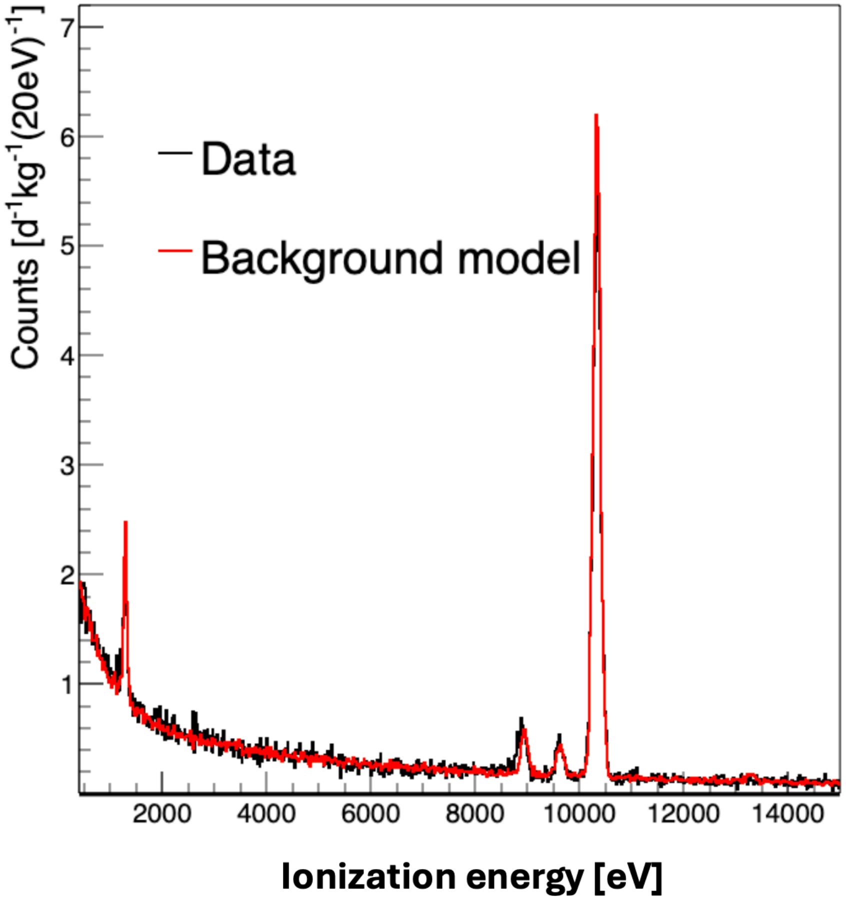
Stability plots show:

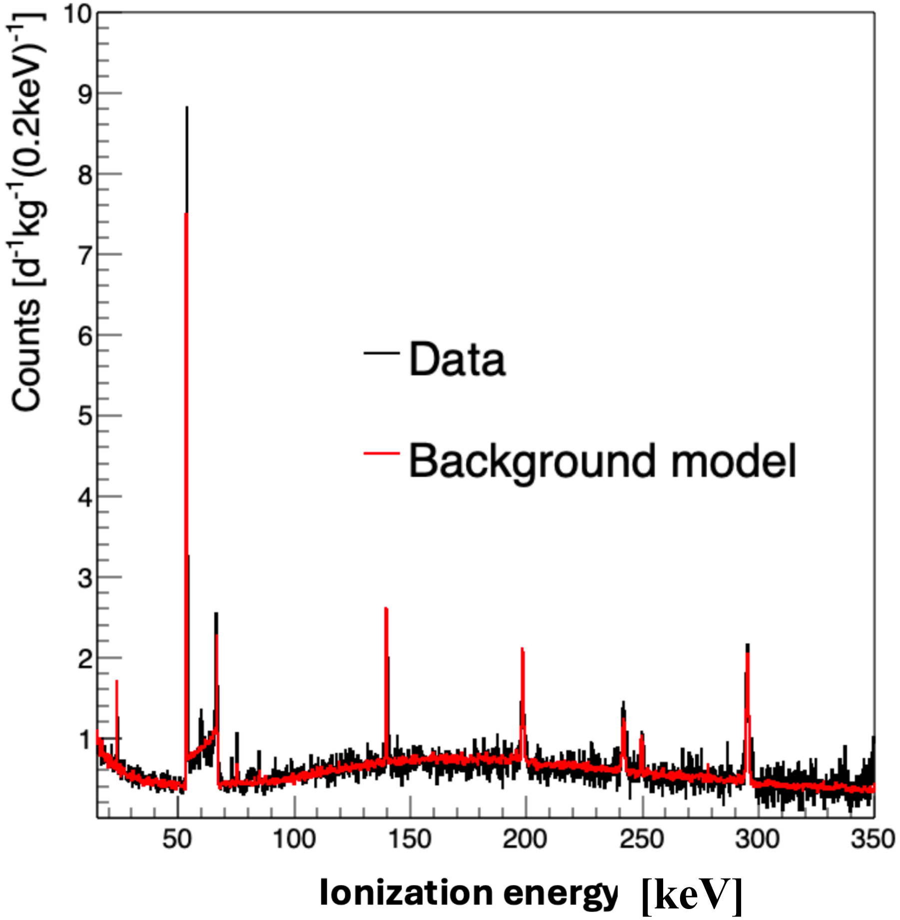
- Radon greatly reduced by
- but lines still visible

→ impact in [100,400] keV
→ small in ROI



Full Background Model versus Data



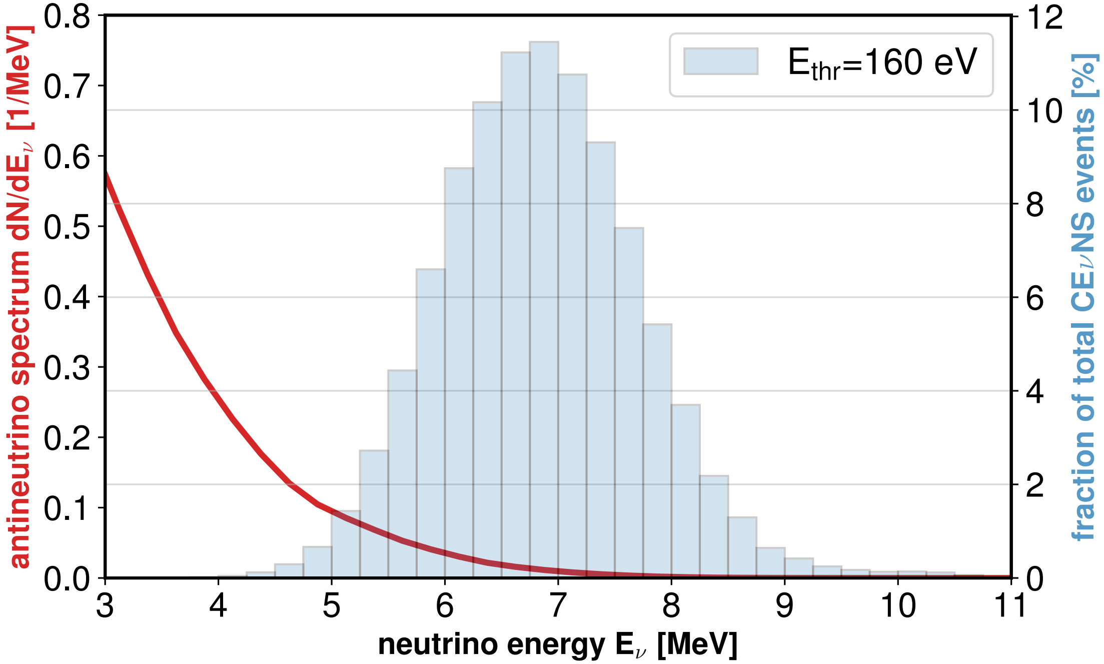


- perfect agreement of data with expectation
- 0 - 400 eV blinded

Full Background model (C5, [400 – 1000] eV_{ee})

Component	Contribution ON [counts/d/kg]	Contribution OFF [counts/d/kg]
Muons	15.2 +- 0.3	15.1 +- 0.3
Neutrons	21.6 +- 3.1	17.7 +- 2.5
Muon-induced neutrons in overburden	2.2 +- 0.1	1.8 +- 0.1
Cu cosmogenics	0.1 +- 0.05	0.1 – 0.05
Pb210 in cryostat	< 0.1	< 0.1
Pb210 in shield	0.1 +- 0.02	0.1 +- 0.02
Ge cosmogenics	0.2 +- 0.02	0.2 +- 0.02
Metastable Ge states	0.1 +- 0.01	0.1 +- 0.01
Radon	1.9 +- 0.1	0.3 +- 0.1
Kr85	< 0.1	< 0.1
H3	1.3 +- 0.2	0.5 +- 0.2
Xe135	0.1 +- 0.01	< 0.1
Total	42.9 +- 3.1 (DATA = 43.5 +- 1.1)	35.8 +- 2.5 (DATA = 33.4 +- 1.8)

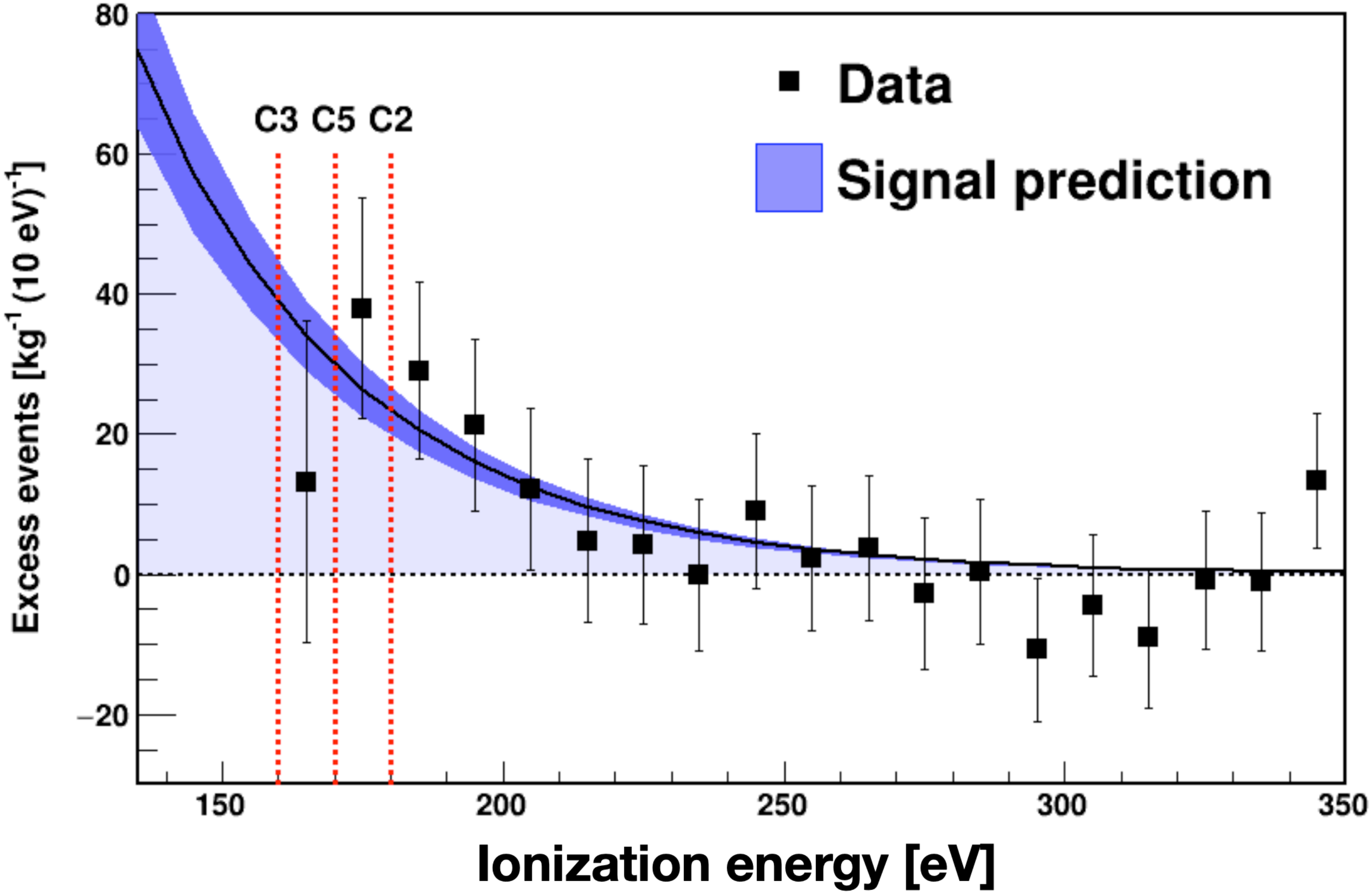
Signal Prediction



Detector	Threshold [eV_{ee}]	Predictetd CEvNS counts
C5	170	116 (+20/-18)
C2	180	96 (+16/-14)
C3	160	135 (+23/-20)
COMBINED	-	345 (+34/-30)

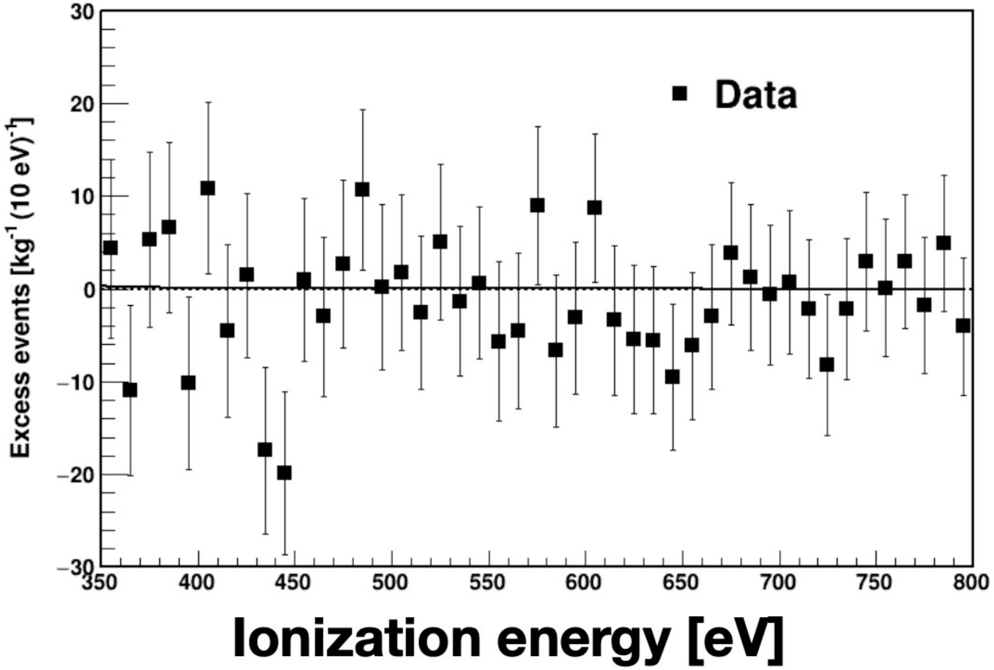
lower detector thresholds
➔ increased impact
of lower energy neutrinos

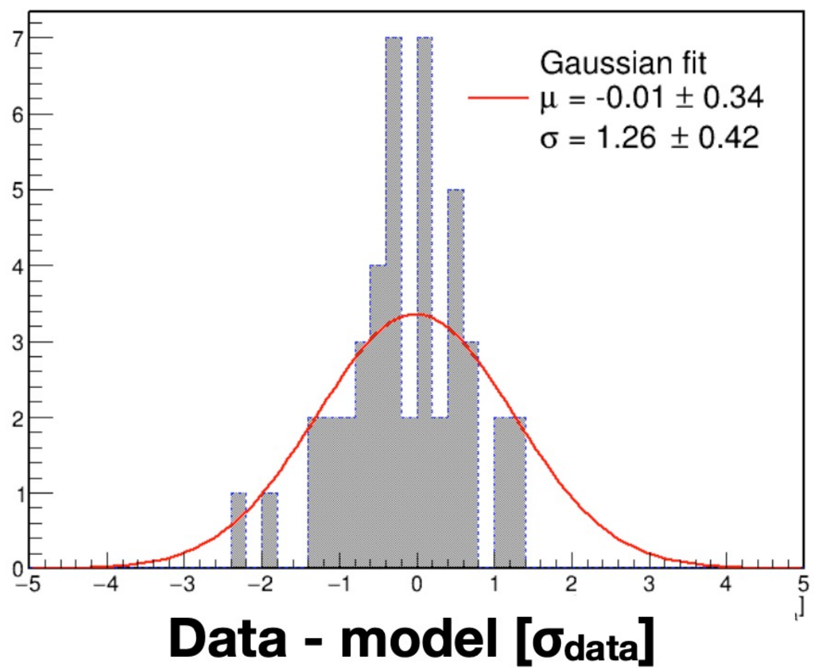
Excess Events (below 350 eV_{ee})



- difference between 119 days of reactor on to the background model scaled to the total detector mass
- vertical lines indicate the energy thresholds of the three detectors used in the analysis

No Excess above 350 eV_{ee}





agreement between data and background model above the signal region from 350−800 eV

spread of the data points around the model

Result: Number of Events

Detector	Threshold [eV_{ee}]	CEνNS counts fit	SM prediction
C5	170	117 +- 57	116 +- 20
C2	180	69 +- 47	96 +- 16
C3	160	186 +- 66	135 +- 23
Combined		395 ± 106	347 ± 34

- CEνNS counts from the combined fit = 395 ± 106 (additional systematics included)
- Rejection of null hypothesis: 3.7σ

first detection of CEνNS with reactor antineutrinos!

➔ **arXiv: 2501.05206**
➔ **Nature 643, 1229 (2025)**

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Direct observation of coherent elastic antineutrino–nucleus scattering

N. Ackermann, H. Bonet, A. Bonhomme, C. Buck, K. Fülber, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, M. Rank, T. Rink, E. Sánchez García, I. Stalder, H. Strecker, R. Wink & J. Woenckhaus

Comparison to Other CEνNS Results

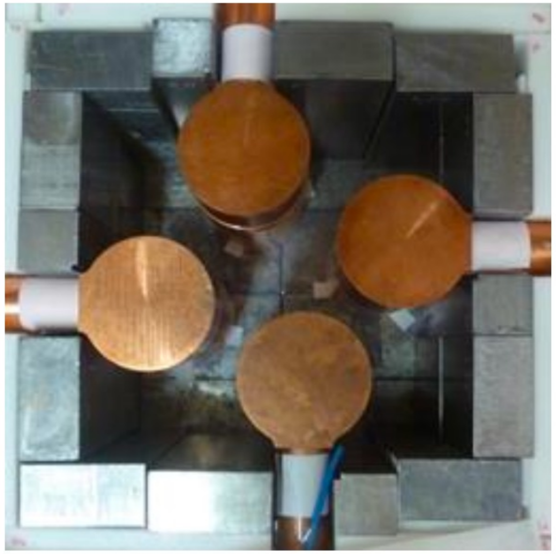
Experiment	Target	Source	Neutrino energy	Flux $[cm^{-2}s^{-1}]$	Data [counts]	Data/ SM prediction	Significance of null hypothesis rejection
COHERENT	Cs	Accelerator	10 – 50 MeV	$5 * 10^7$	306^{+20}_{-20}	$0.90^{+0.14}_{-0.14}$	$11.6\,\sigma$
COHERENT	Ar	Accelerator	10 – 50 MeV	$5 * 10^7$	140^{+40}_{-40}	$1.22^{+0.49}_{-0.49}$	$3.5\,\sigma$
COHERENT	Ge	Accelerator	10 – 50 MeV	$5 * 10^7$	21^{+7}_{-6}	$0.59^{+0.26}_{-0.24}$	$3.9\,\sigma$
XENONnT	Xe	Sun (^{8}B)	< 15 MeV	$5 * 10^6$	11^{+4}_{-2}	$0.90^{+0.65}_{-0.67}$	$2.73\,\sigma$
PandaX-4T	Xe	Sun (^{8}B)	< 15 MeV	$5 * 10^6$	4^{+1}_{-1}	$1.25^{+0.69}_{-0.69}$	$2.64\,\sigma$
CONUS+	Ge	Reactor	< 10 MeV	$1.5 * 10^{13}$	395^{+106}_{-106}	1.14^{+036}_{-036}	$3.7\,\sigma$

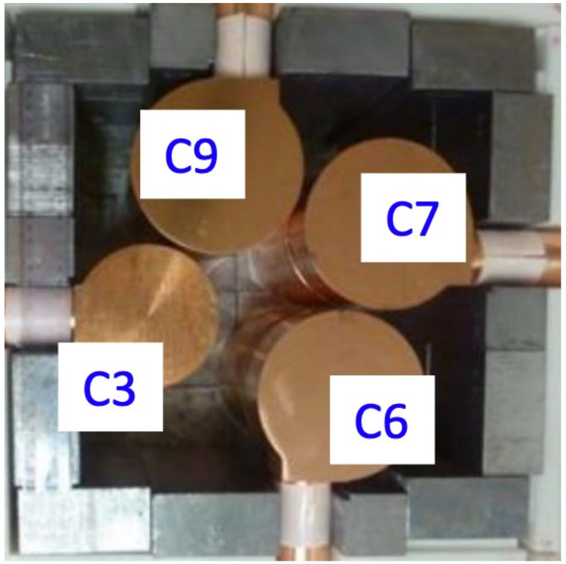
CONUS+

➔ **has detected the lowest energy neutrinos (down to 4 MeV) via the CEνNS channel**

➔ **accumulated the highest number of CEνNS counts in one single isotope (low threshold + high flux)**

Outlook





- 3 new 2.4 kg PPC Ge detectors: C9, C7 and C6

  Crystal mass: **3 kg → 1 + 3*2.4 = 8.2 kg**

- better cryocooler stability with new coolant
- slight background improvement in new detectors
- thresholds at least as low as in previous detectors

  ➔ installed in 11/2024

- commissioning → data taking on-going

➔ expect significantly improved results O(1yr)

Summary

With:
- 119 days of reactor ON and 19 days of reactor OFF data in Run 1
- a sophisticated and well tested background model

- **CONUS+** observes CEνNS events consistent with the standard model prediction
- Lindhard theory (verified also by dedicated quenching measurement)
- detailed knowledge about neutrino flux, fissile fuel burning and thermal power
- not due to a non-considered reactor-correlated background component

➔ **Null hypothesis rejected at 3.7σ**

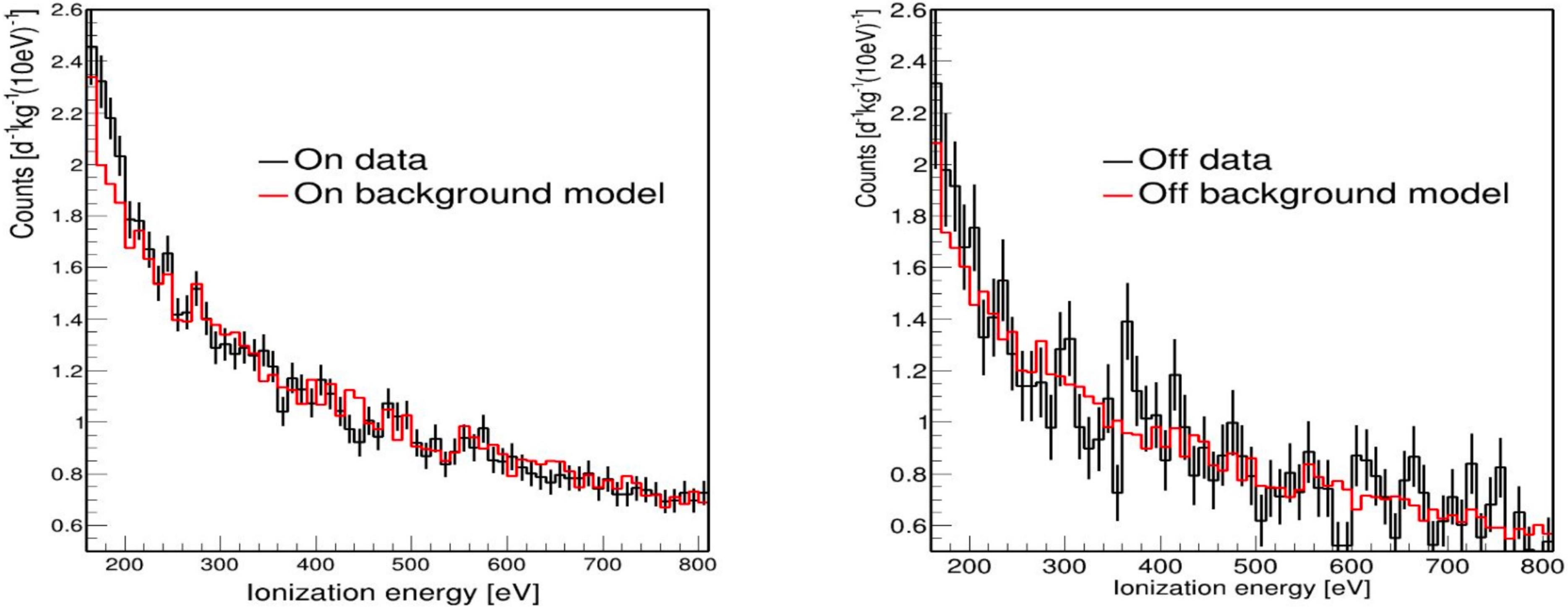
- First observation of CE*ν*NS with reactor anti-neutrinos in the fully coherent regime
- Very interesting implications: BSM physics, sources, nuclear physics, ...

- Run 2 is ongoing since end of 2024, 3→8.2kg, further improvements → stay tuned!
- Motivates upscaling based on CONUS+ technology (+improvements)
- Combined with other experiments ➔ precision CEνNS physics

➔ **Excellent potential (within years – not decades...)**

BACKUP

Background Model versus On and Off-Data

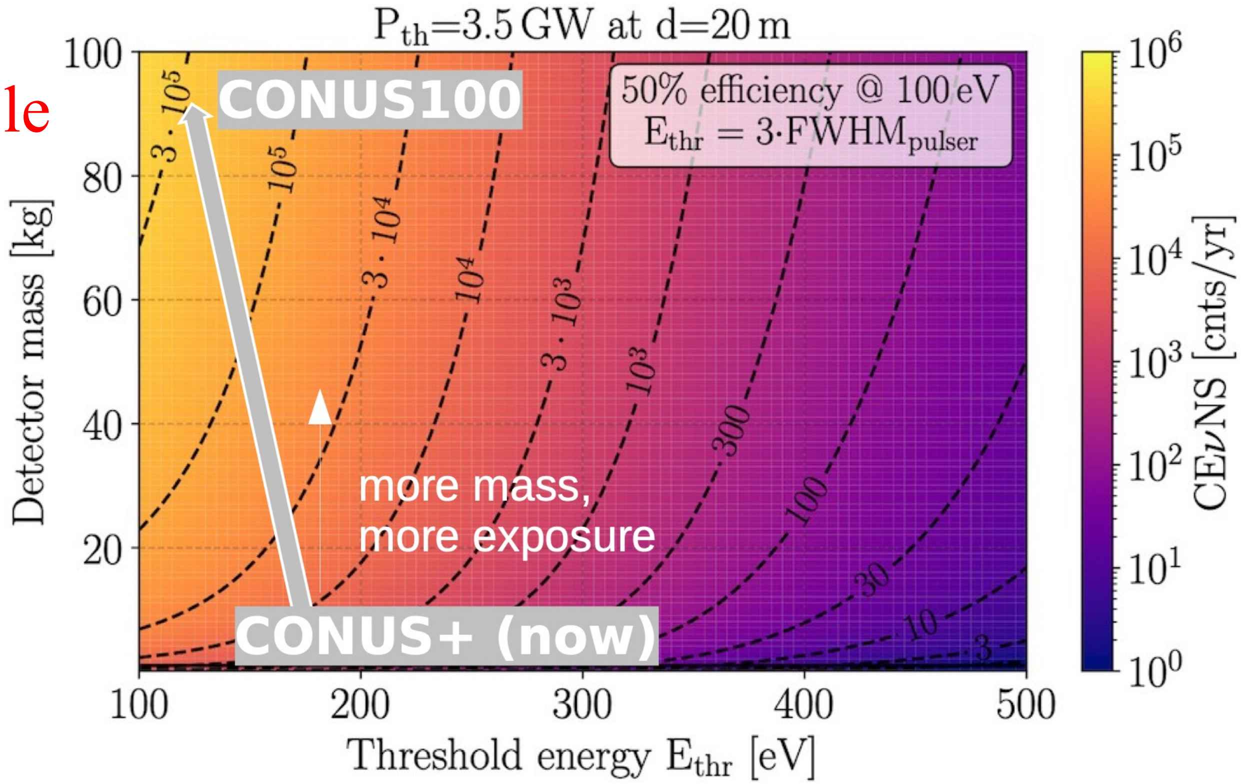


Run 1 result: predominantly from On-data versus very well understood background
Upcoming runs: Combination of On-Off and On-background

Prospects: CONUS100

technology for moderate size high statistics experiments established:

- O(100kg) possible
- ~100 eV threshold feasible



ML, T. Rink, M. Sen,
JHEP 08 (2024) 171

→ 500.000 events in 5y

+ other technologies @reactors

in addition:

- upgrades of COHERENT
- next generation LXe dark matter (XLZD, ...)

→ precision CEνNS physics within a few years...

What can be learned from CEνNS?

aim at the most precise measurement

nuclear uncertainties
➔ lowest q^2 where $F(q^2)=1$ or combinations

$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$

$$Q_w = N - (1 - 4\sin^2\theta_w)Z \quad \sim \mathbf{N}$$

⊗ **modifications relevant with more precision**

More precision requires improved description:

- $F(Q^2) \rightarrow F_N(Q^2)$ and $F_Z(Q^2)$
- more SM corrections and quantum effects e.g. $\sin^2(\theta_W)$
- QFT description: advanced coherence conditions, scattering on N, Z or on quarks, ...
- **effects of BSM physics: NSI (heavy), LET (light), oscillation effects, ...**

Inverted logic: If only SM ➔ CEνNS can be used to:

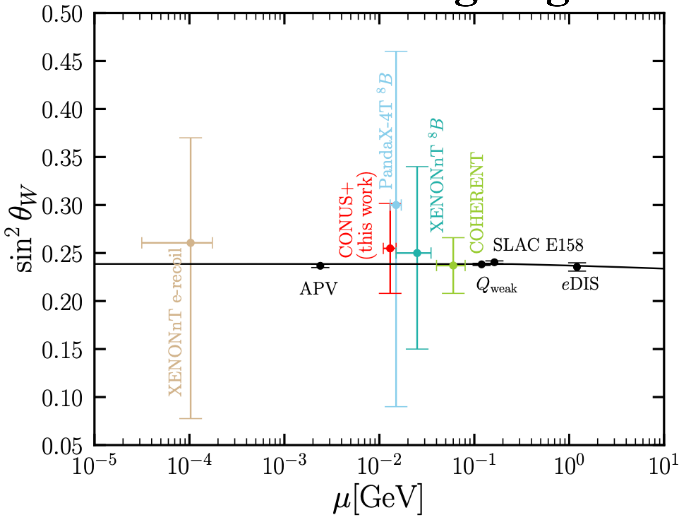
- test sources: the Sun, reactors, π–decay@rest@beams, ...
- unique tests of nuclear physics
- technological applications: reactor monitoring, safe-guarding,...

➔ **extremely rich and promising field within a few years**

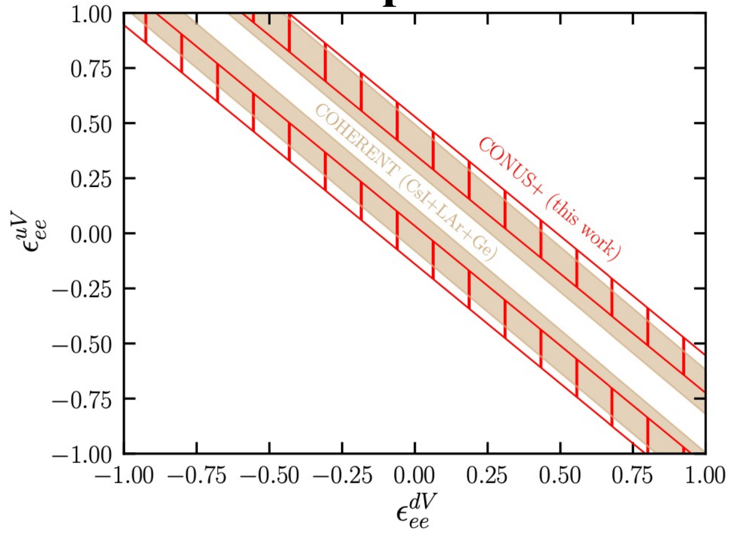
Some Studies based on CONUS+ Result

M. Alpízar-Venegas et al., arXiv:2501.10355

low E Weinberg angle

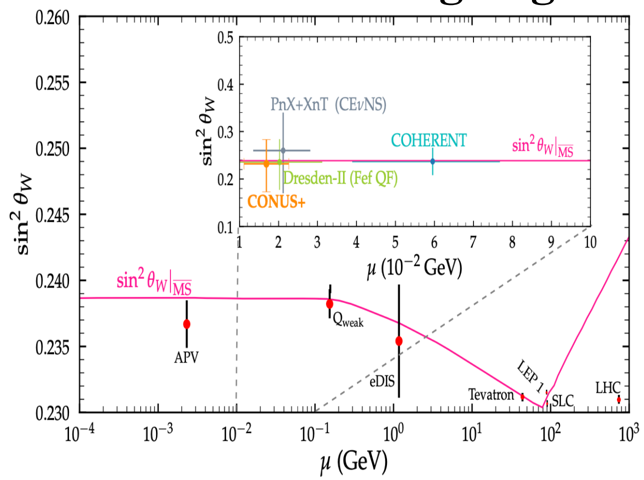


NSI operators



A. Chattaraj, et al., arXiv:2501.12441

low E Weinberg angle



new light scalar or vector B-L mediator