The search for CEvNS with the CONUS experiment

Nicola Ackermann – On behalf of the CONUS collaboration

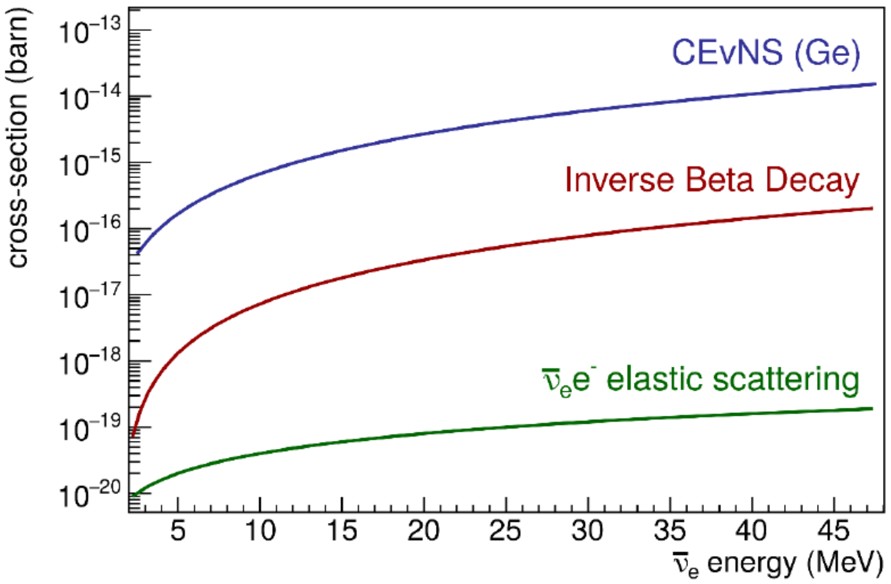
Lake Louise Winter Institute 2023

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

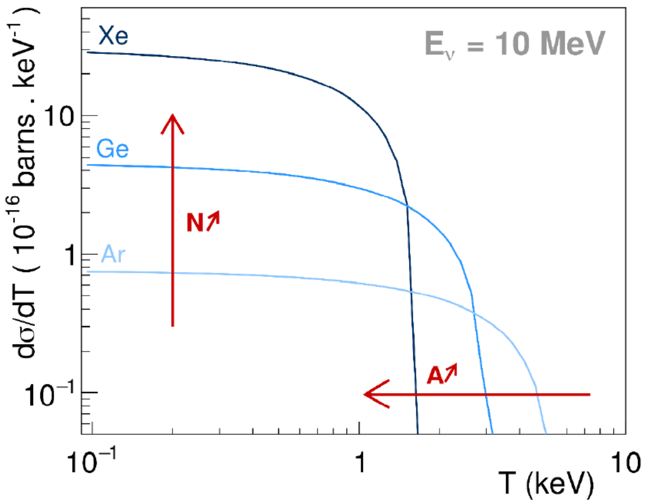
Coherent Elastic Neutrino Nucleus Scattering

- Coherent interaction of neutrinos with nuclei

$$\frac{d\sigma(E_\nu,T)}{dT} \simeq \frac{G_F^2}{4\pi} \underbrace{[N-(1-4\sin^2(\theta_W))Z]^2}_{\approx N^2} \underbrace{F^2(q^2)}_{\to 1} M \underbrace{\left(1-\frac{MT}{2E_\nu^2}\right)}_{kinematics}$$



- Interaction with entire nucleus → cross section enhanced



- First described by D. Freedman in 1974

Detecting CEvNS

- Only low-energy nuclear recoil observable (~ keV)
  → very low energy threshold, low background and high neutrino flux required

- Neutrino sources:

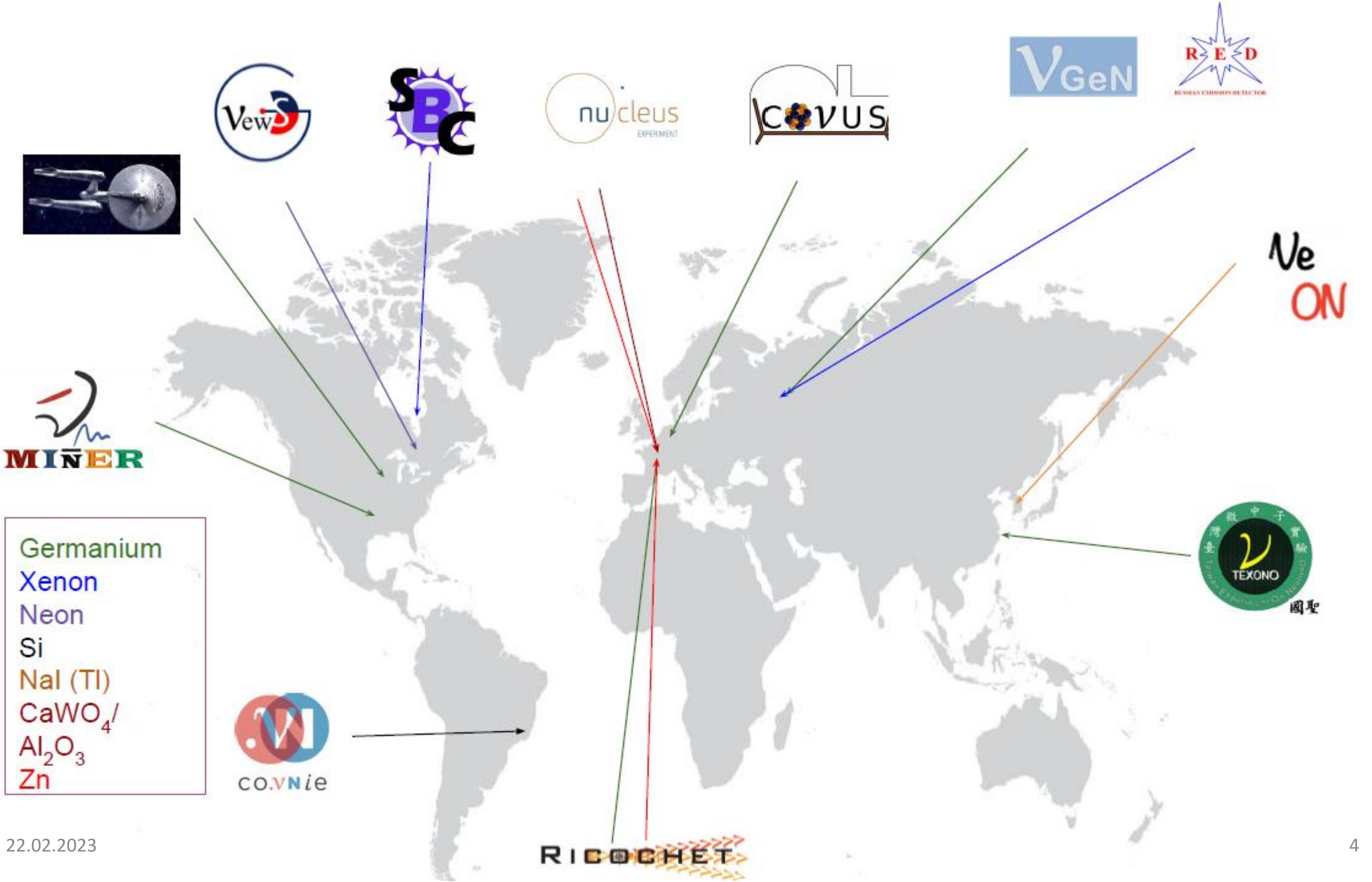
Accelerators

- Neutrinos from π-DAR
- Different flavors: ν_e, ν_μ and $\overline{\nu_\mu}$
- Energies of ~ 20 – 50 MeV
- First CEvNS observation:
  COHERENT in 2017 using CSI[Na]

Reactors

- Neutrinos from fission products
- Only $\overline{\nu_e}$
- Energies of < 10 MeV
  → fully coherent regime

- Physics potential: - SM measurements (eg. Weinberg angle)
  - BSM searches for new neutrino interactions
  - Nuclear structure
  - Reactor investigations (e.g. Reactor monitoring)



Germanium
Xenon
Neon
Si
NaI (Tl)
$CaWO_4$/
Al_2O_3
Zn

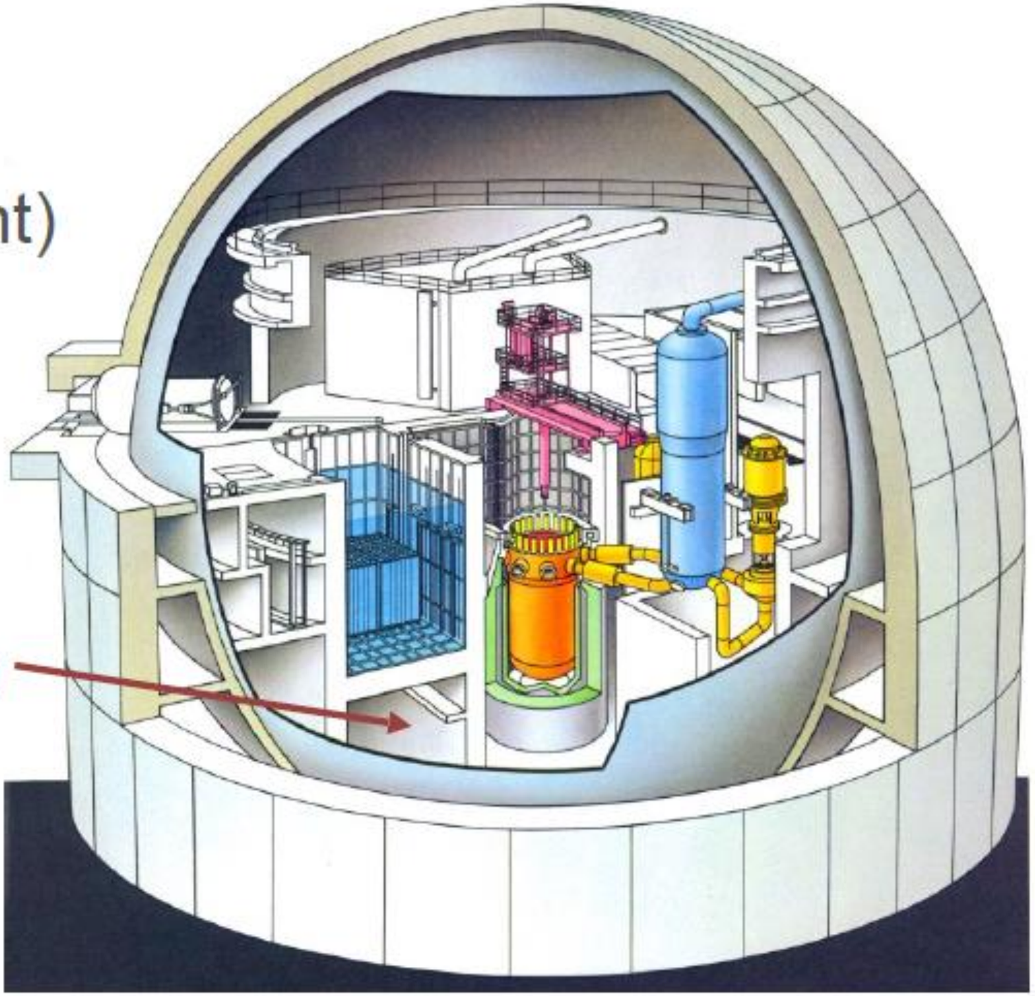
The CONUS collaboration

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

Preussen Elektra:
K. Fülber and R. Wink

Experimental site

Overburden:
10 - 45 m w.e.
(angle-dependent)

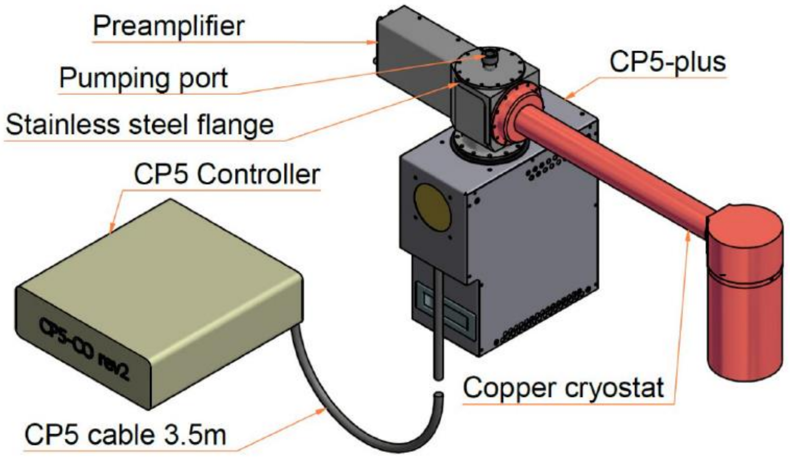

CONUS location

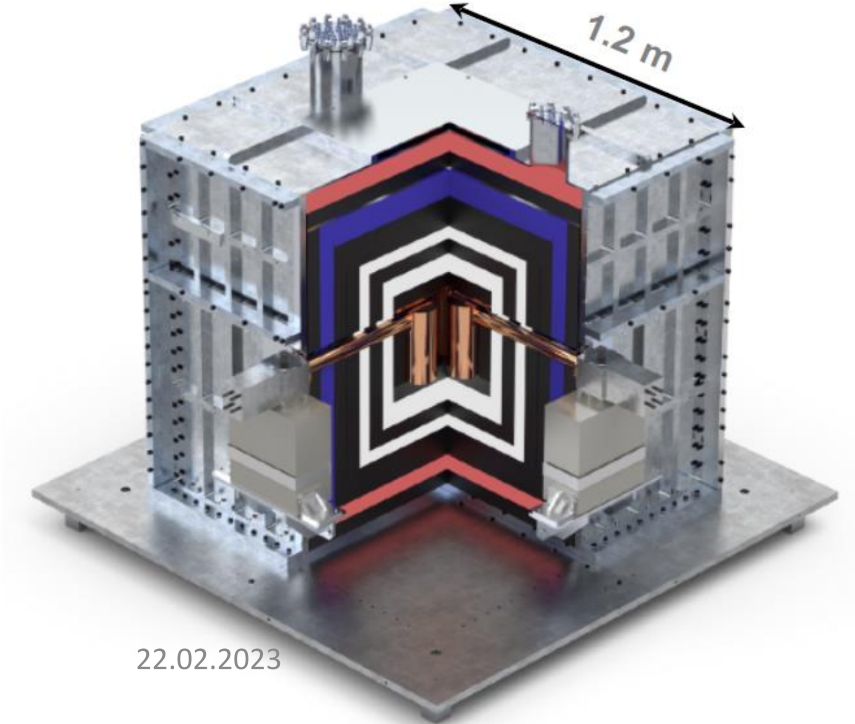
KBR Brokdorf:

- 3.9 GW thermal power
- Distance from core: 17.1 m
- Neutrino flux: $2 * 10^{13}\ s^{-1} cm^{-2}$
- Operational until end of 2021
- Data taking in reactor OFF period in 2022

Experimental setup

4 p-type point contact HPGe detectors
- 1 kg each
- Ultra-low background materials
- Electrical cryocolling
- Energy resolution: 60 – 80 eV (Pulser, FWHM)
- Energy threshold: < 250 eV





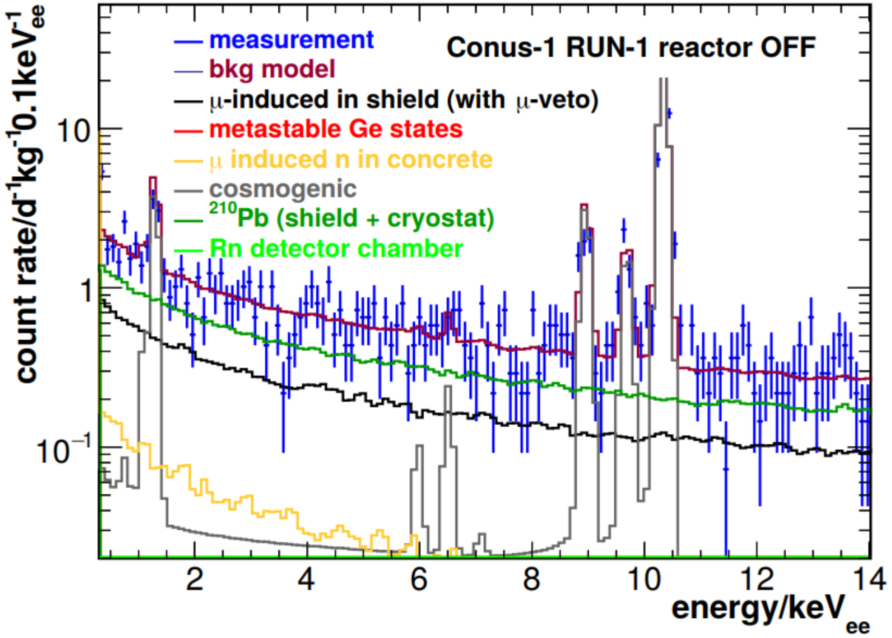
CONUS shielding:
- 11 tons in total
- Active + passive shielding
- Lead for gamma suppression
- (borated) PE for neutron suppression
- Active µ-veto system
- Flushing of detector chamber against radon

Background suppression and Monte Carlo

- Background suppressed by four orders of magnitude

- Stable background level:
~ 10 counts/kg/d/keV in [0.5 - 1] keV

- Residual background fully described by Monte Carlo
→ Biggest contributions: μ-induced in shield,
cosmogenics & Pb210 in shield and cryostat



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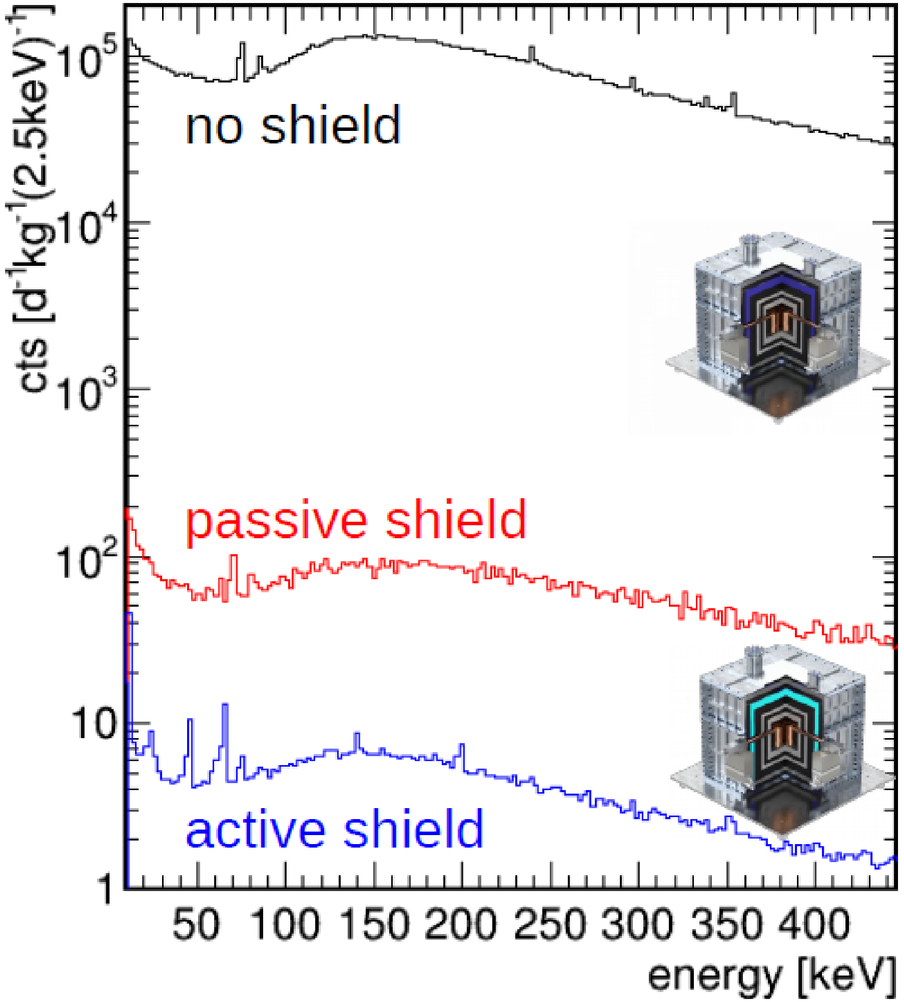
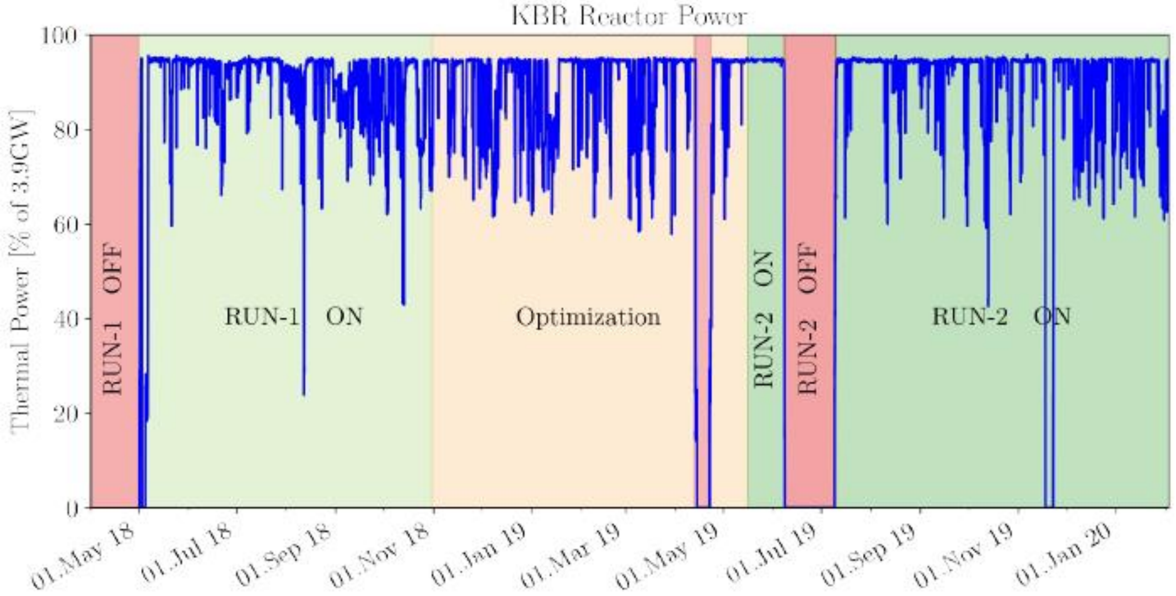


Data selection and analysis

- Exposure in Run I and Run II for CEvNS:
  248.7 kg d (Reactor ON)
  58.8 kg d (Reactor OFF)



- Applied cuts to data:
  - Noise-temperature correlation cut
  - time-difference distribution cut

- Simulataneous Likelihood fit for all detectors & runs taking into account:
  - theoretical CEvNS signal prediction
  - reactor spectrum
  - MC + electronic noise fit for background description
  - systematic uncertainties

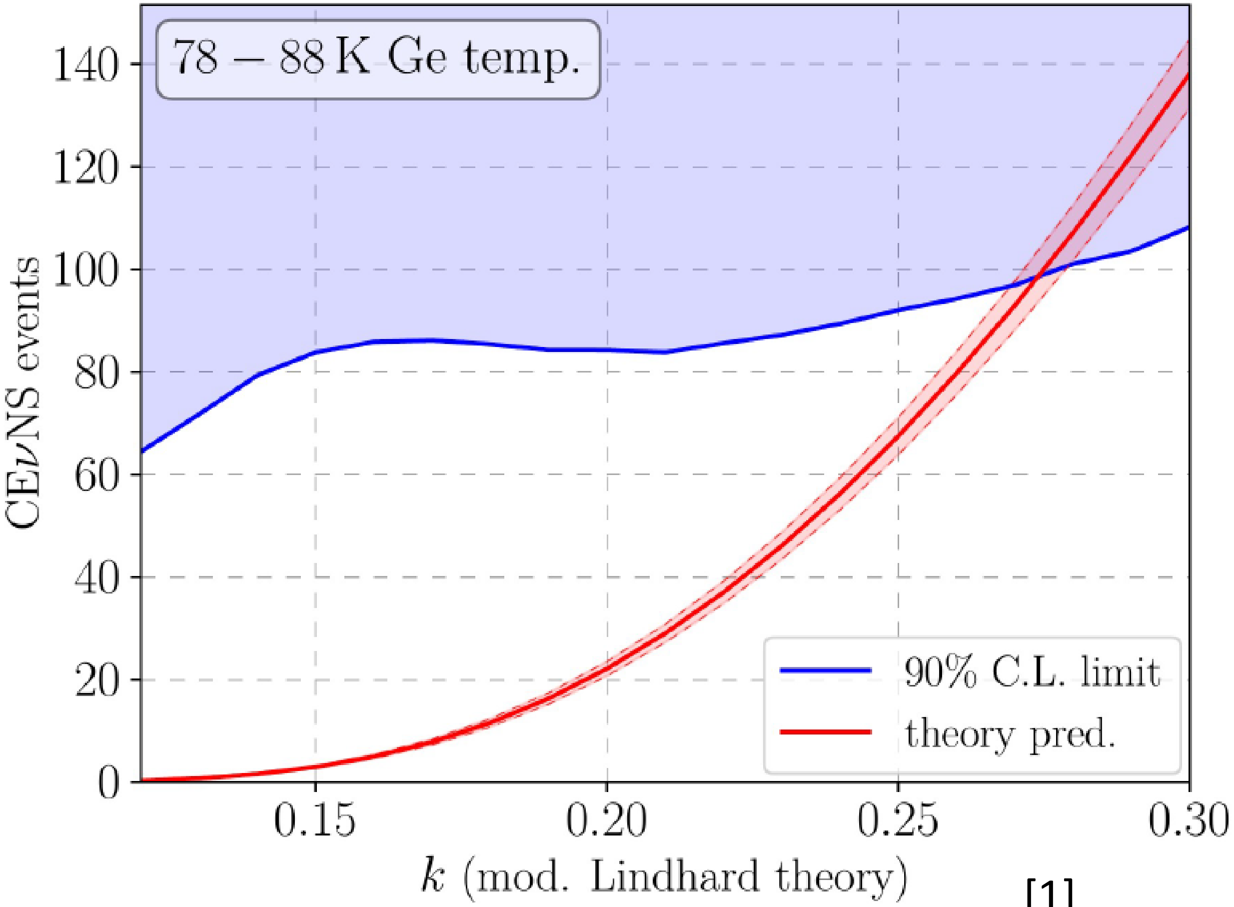
Results of the CONUS experiment

- Best CEvNS limit with Ge at reactor site:

  < 0.4 $d^{-1} kg^{-1}$ (90 % CL)

- Signal expectation depends on quenching factor
- Ionization quenching factor:

  IQF = Ionization energy / Recoil energy

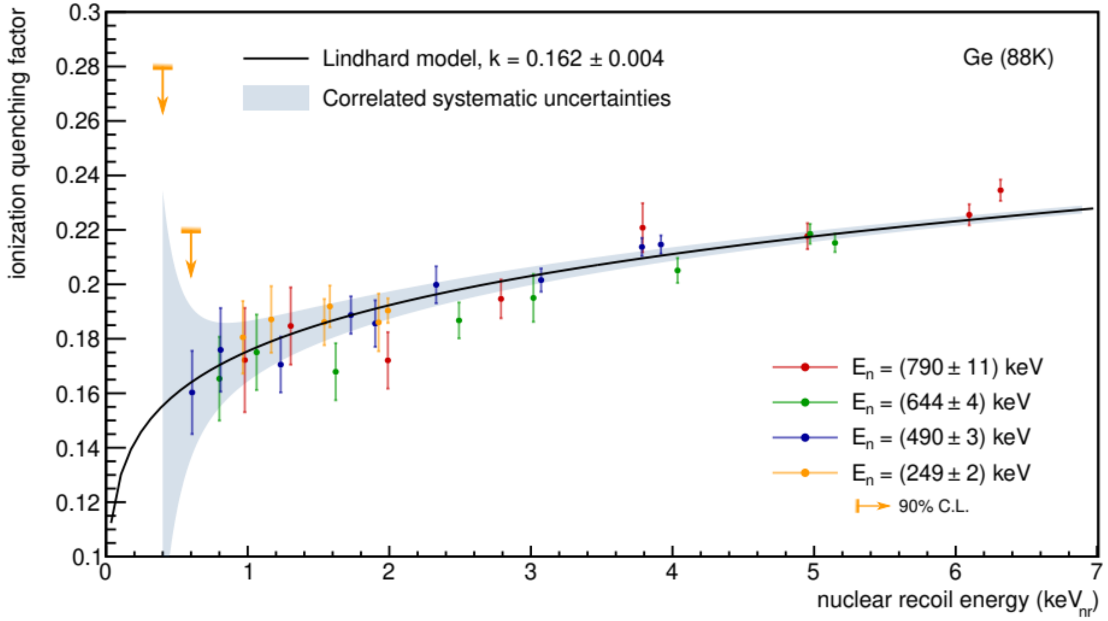


[1]

Results of the CONUS experiment

- Best CEvNS limit with Ge at reactor site: $< 0.4\ d^{-1}kg^{-1}$ (90 % CL)
- Signal expectation depends on quenching factor

→ at k = 0.16: expected signal is 17x below CONUS detection limit



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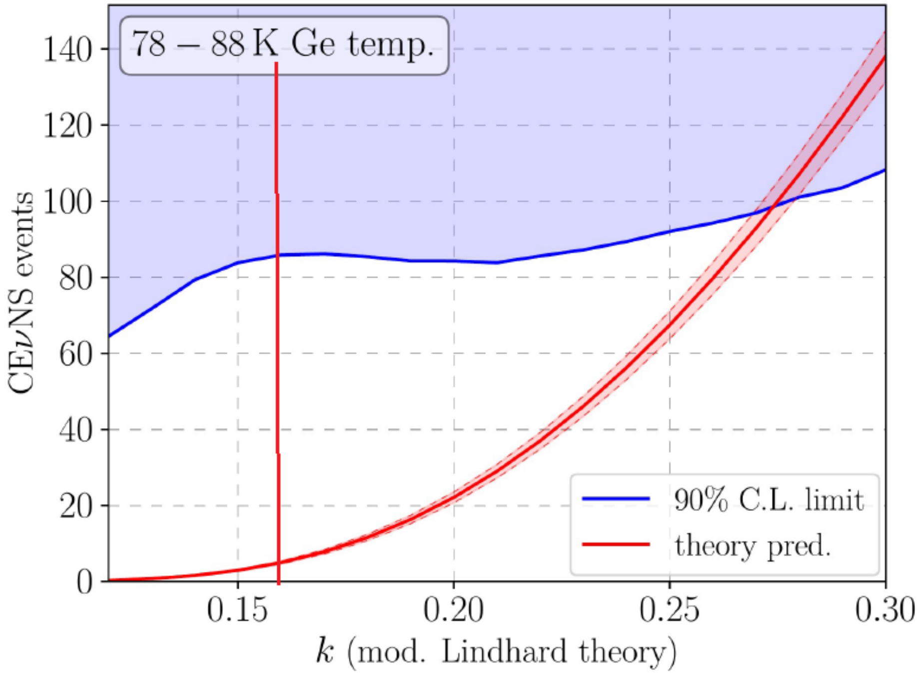
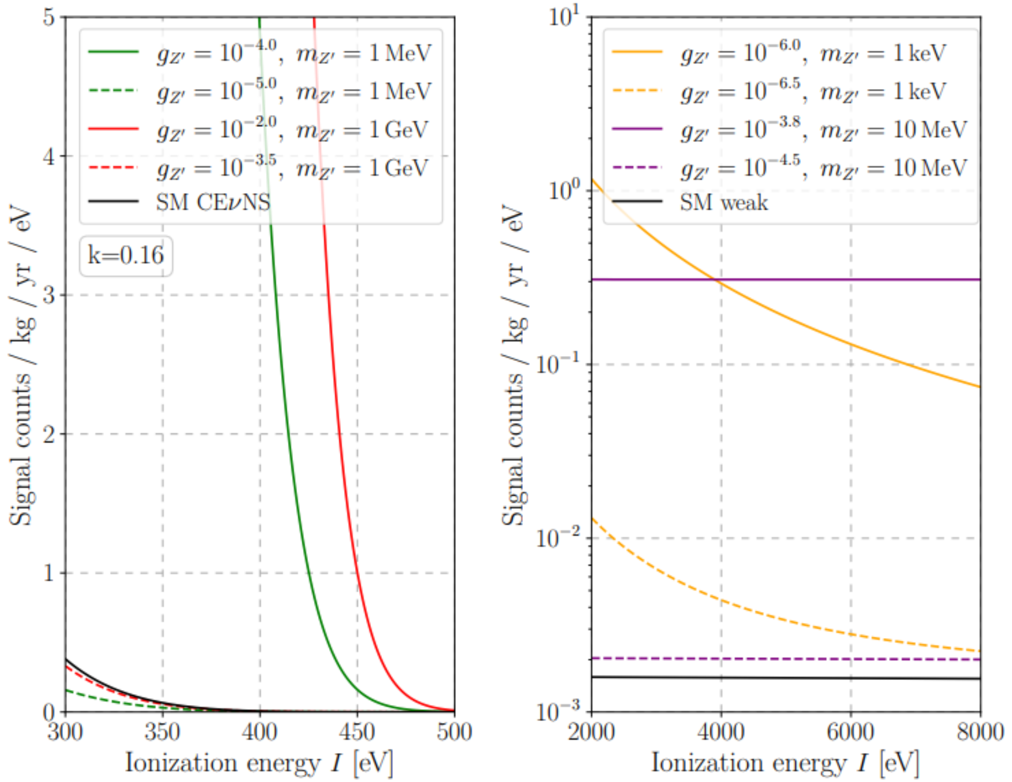
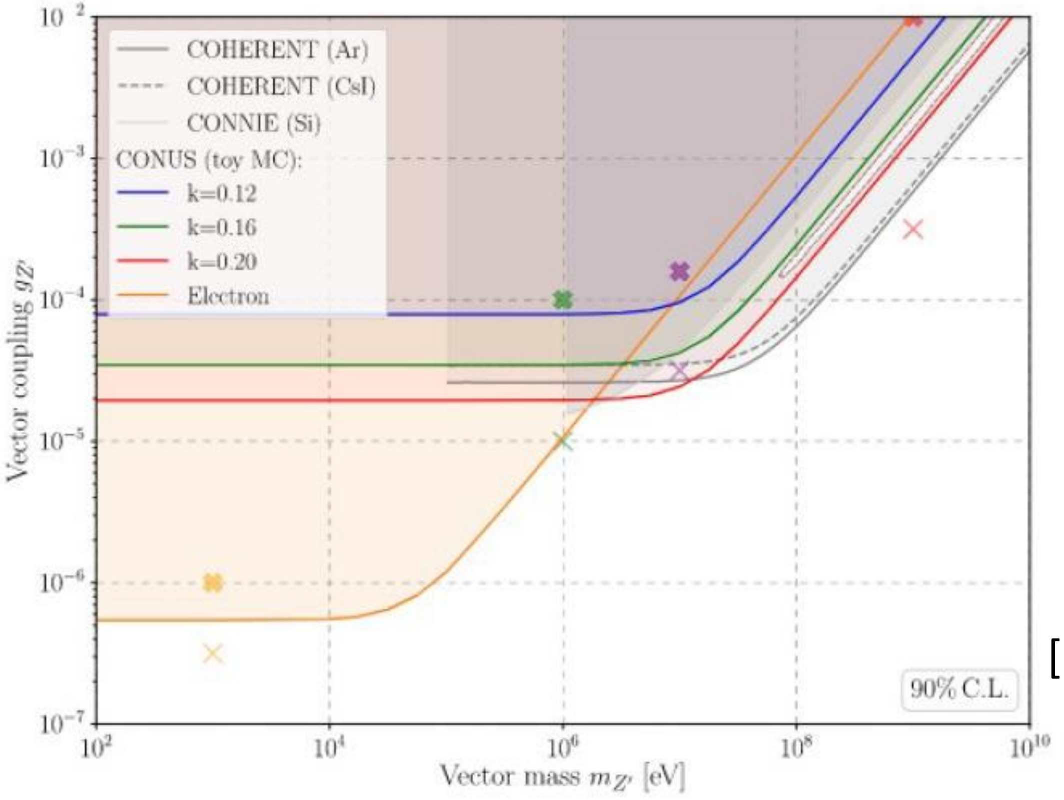


Some BSM results – Z‘, μ_ν and q_ν

Lght vector boson Z‘

$$\mathcal{L}_{Z'} = Z'_\mu \left(g_{Z'}^{\nu V} \bar{\nu}_L \gamma^\mu \nu_L + g_{Z'}^{eV} \bar{e} \gamma^\mu e + g_{Z'}^{qV} \bar{q} \gamma^\mu q \right) + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu ,$$





[3]

Neutrino magnetic moment: $\mu_\nu < 7.5 * 10^{-11}\ \mu_B$ [5]

Neutrino millicharge: $|q_\nu| < 3.3 *\ 10^{-12} e_0$ [5]

Updates for Run 5

- Run 5 data taking: 2021 – 2022
- KBR stopped running at the end of 2021 ⍰ Reactor OFF data taking until November 2022
- Data is currently being analysed
- Change of DAQ system before Run 5

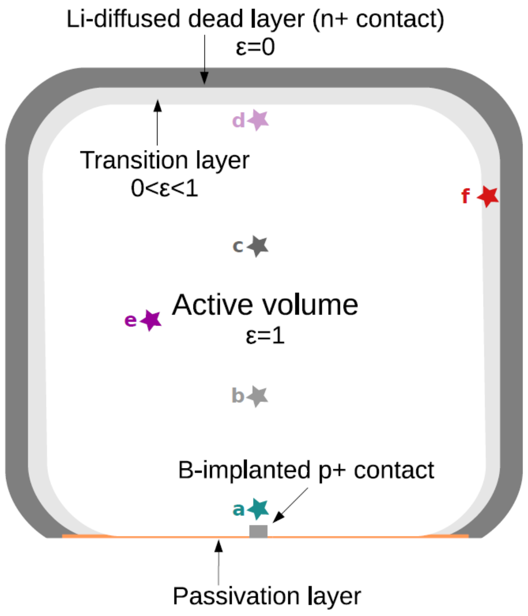
→ improved stability
→ better energy threshold
→ allows for pulse shape discrimination (PSD)

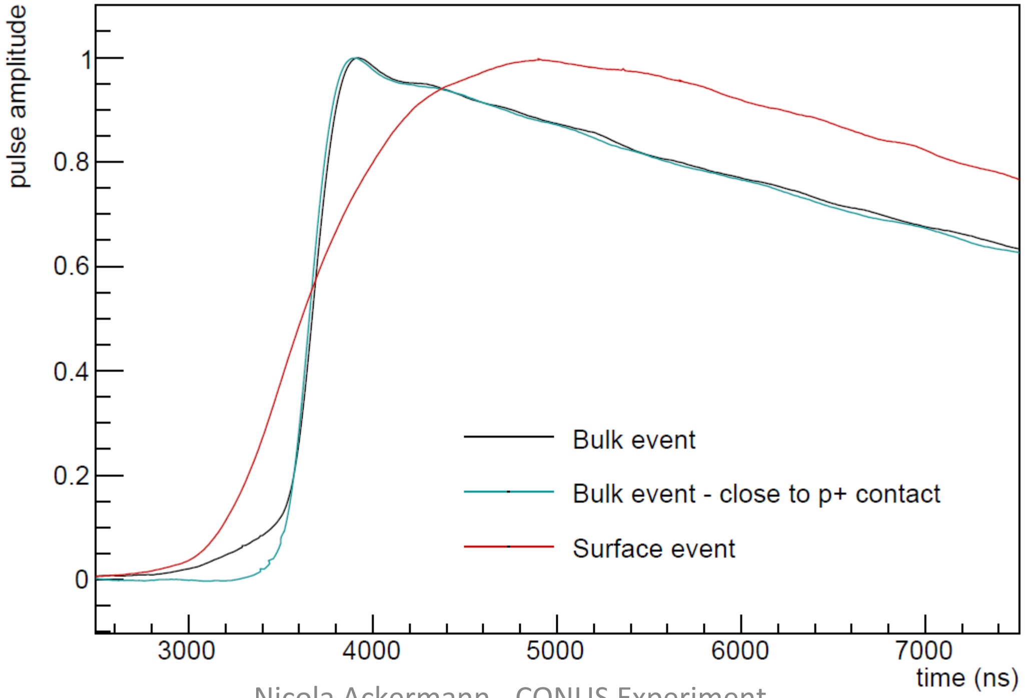
Pulse shape discrimination in Run 5

- Origin of different pulse shapes:
  Events inside the active volume → All charges are collected → „Normal pulses“
  Events inside the transition layer → Created charges need to diffuse out of the transition layer → „Slow pulses“

- Neutrinos interact homogeneously inside the whole diode

- At low energies: Background often originates from events in the transition layer
  → Signal to bkg ratio is much smaller in transition layer → Apply pulse shape cut based on fit



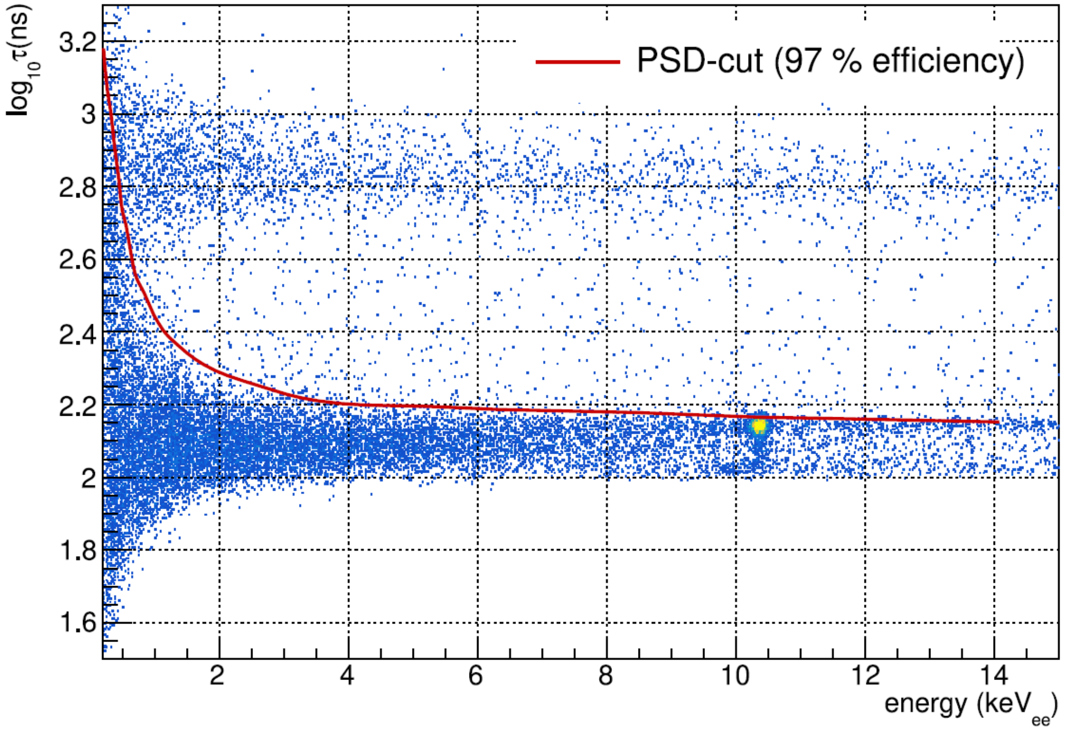


Fit function:

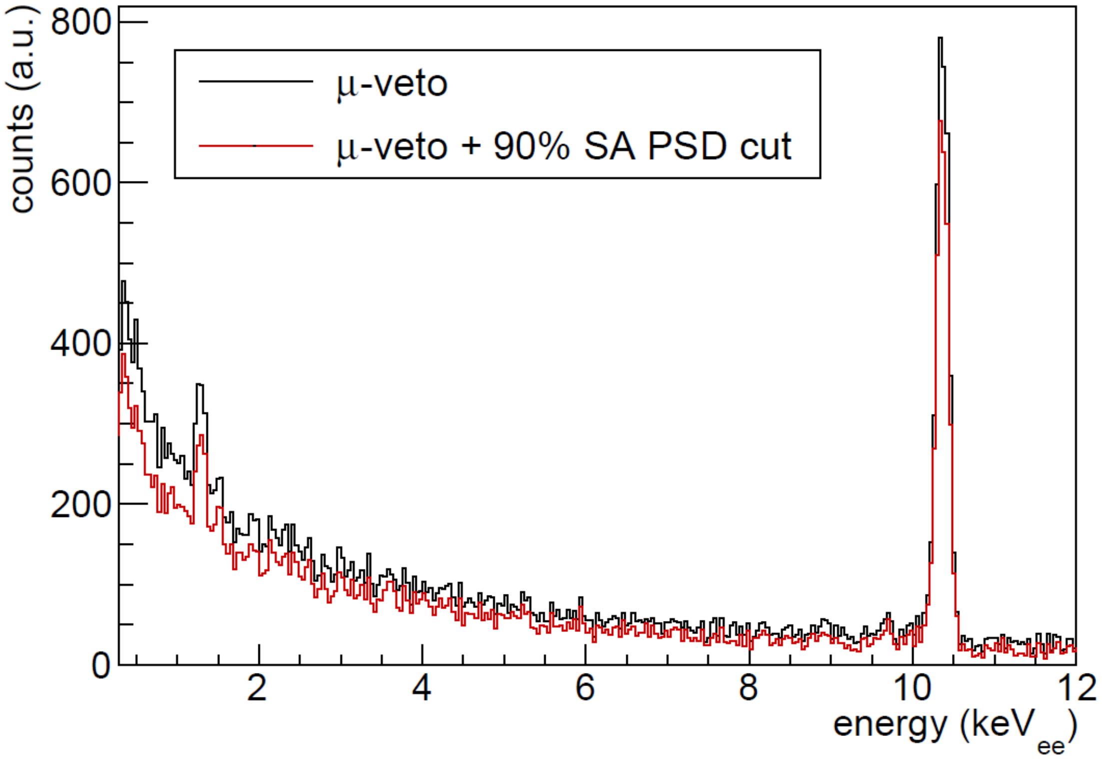
$$f(t) = A_0 \left[\tanh\left(\frac{t - t_0}{\tau}\right) + 1\right] \exp(-\tau_c(t - t_0)) + P_0$$

[7]

The CONUS experiment – PSD in Run 5



Distribution of rise time parameter



PSD cut will lead to a background reduction of up to 20 % !

Summary & Outlook

- CONUS is one of the leading experiments for CEvNS searches at nuclear reactors
- Currently provides the best limits for CEvNS at reactors with Ge at < 0.4 $d^{-1}kg^{-1}$ (90 % CL)
- Competitive limits for BSM physics such as NSIs and light mediators

- Analysis of the Run 5 data is ongoing → Results to be published soon
- What‘s next?

Nuclear power plant in Brokdorf, Germany has shut down at the end of 2021
→ CONUS needs a new home

CONUS+ in Leibstadt, Switzerland

Sources

[1] CONUS collaboration - PHYSICAL REVIEW LETTERS 126, 041804 (2021)

[2] CONUS collaboration - Eur. Phys. J. C (2021) 81:267

[3] CONUS collaboration - JHEP05(2022)085

[4] A. Bonhomme et al - arXiv:2202.03754v1 [physics.ins-det]

[5] CONUS collaboration - arXiv:2201.12257

[6] CONUS collaboration – arXiv:2112.09585

[7] J. Hempfling and J. Stauber - Pulse Shape Discrimination and Simulation for the CONUS Experiment – Poster for Neutrino Conf. 2022

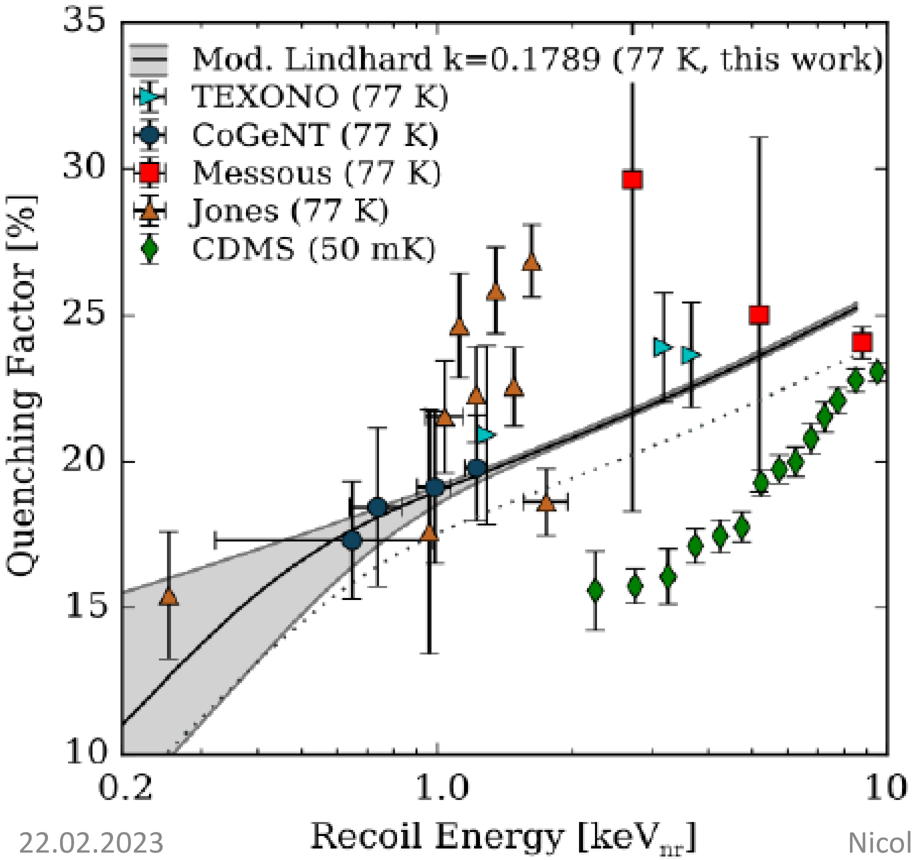
Backup

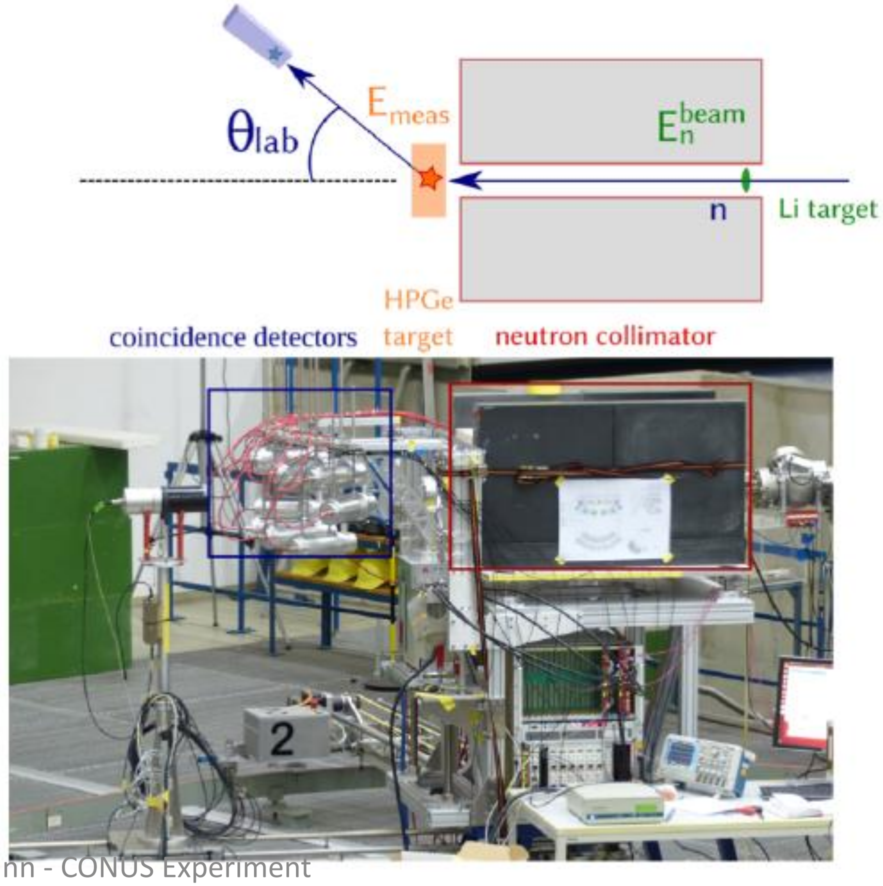
The CONUS experiment – Quenching measurement

- Ionization quenching factor (IQF)

$$IQF = \frac{E_{ionization}}{E_{nuclear\ recoil}}$$

- Before CONUS: Large variation of data points, lack of data in CONUS ROI



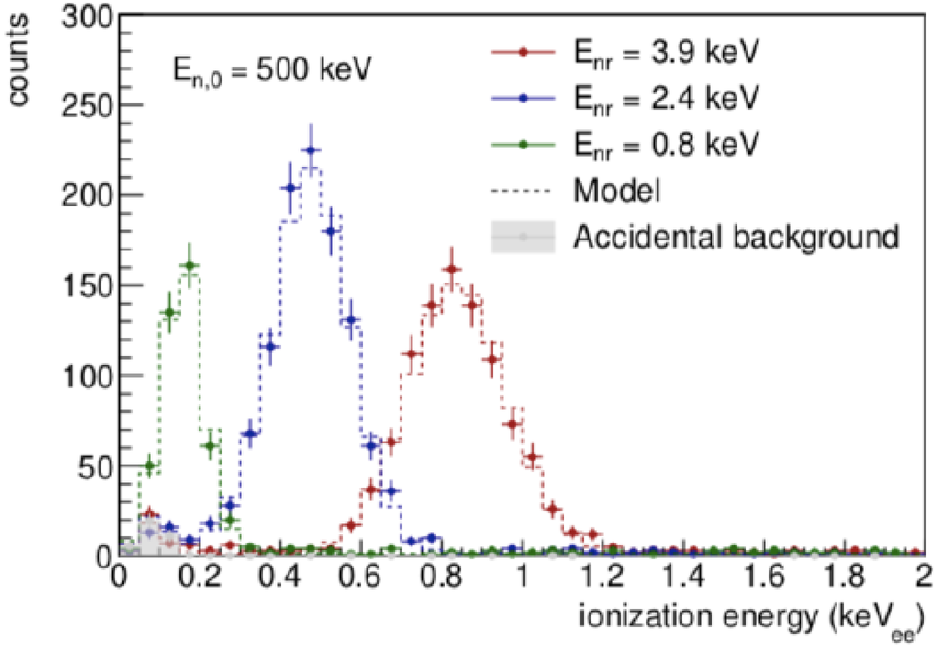


Cooperation with
PTB Braunschweig

PTB Physikalisch Technische Bundesanstalt Braunschweig und Berlin

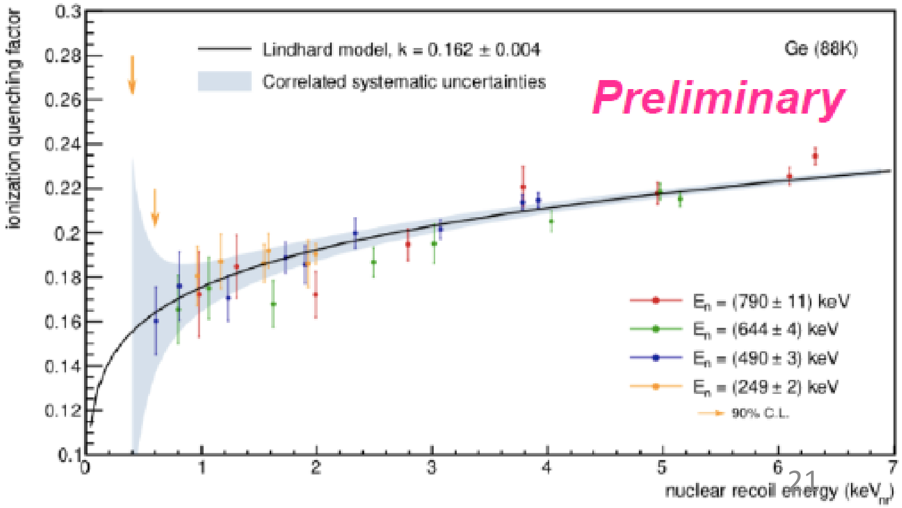
The CONUS experiment – quenching measurement

- Direct model-independent measurement using neutrons
- Beam energy 250 – 800 keV
  ⍰ Nuclear recoils 0.4 – 0.6 keV
- Angles 18 – 45°
- Triple coincidence

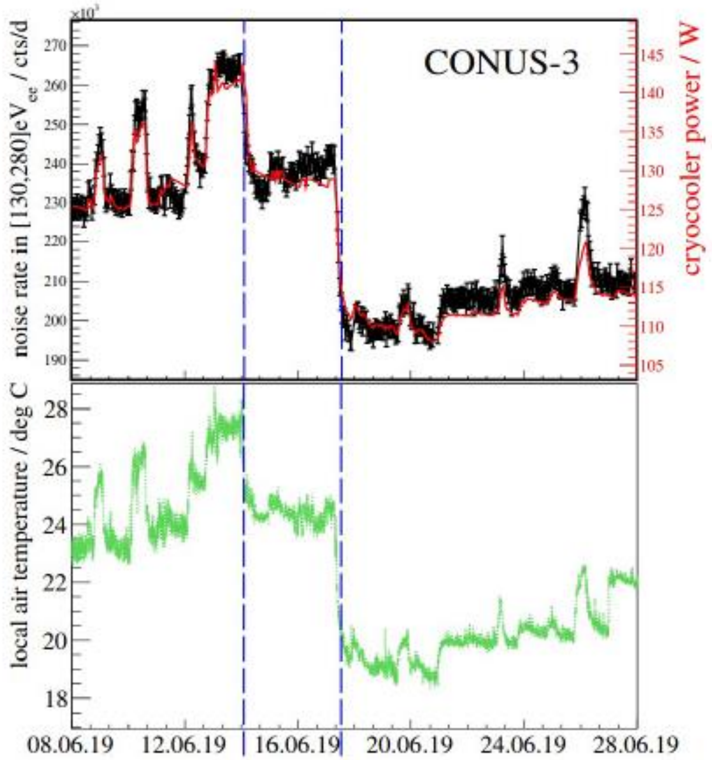


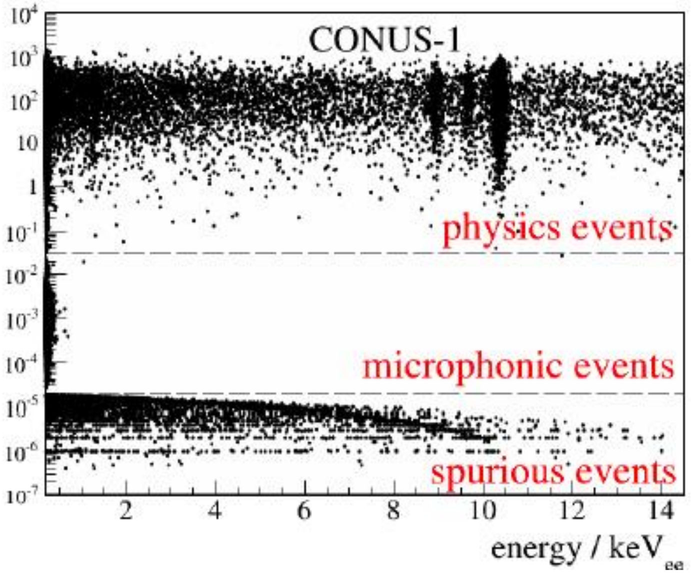
Results:

- Good agreement with Lindhard theory
- k = 0.164 +- 0.004 (syst. + stat.)

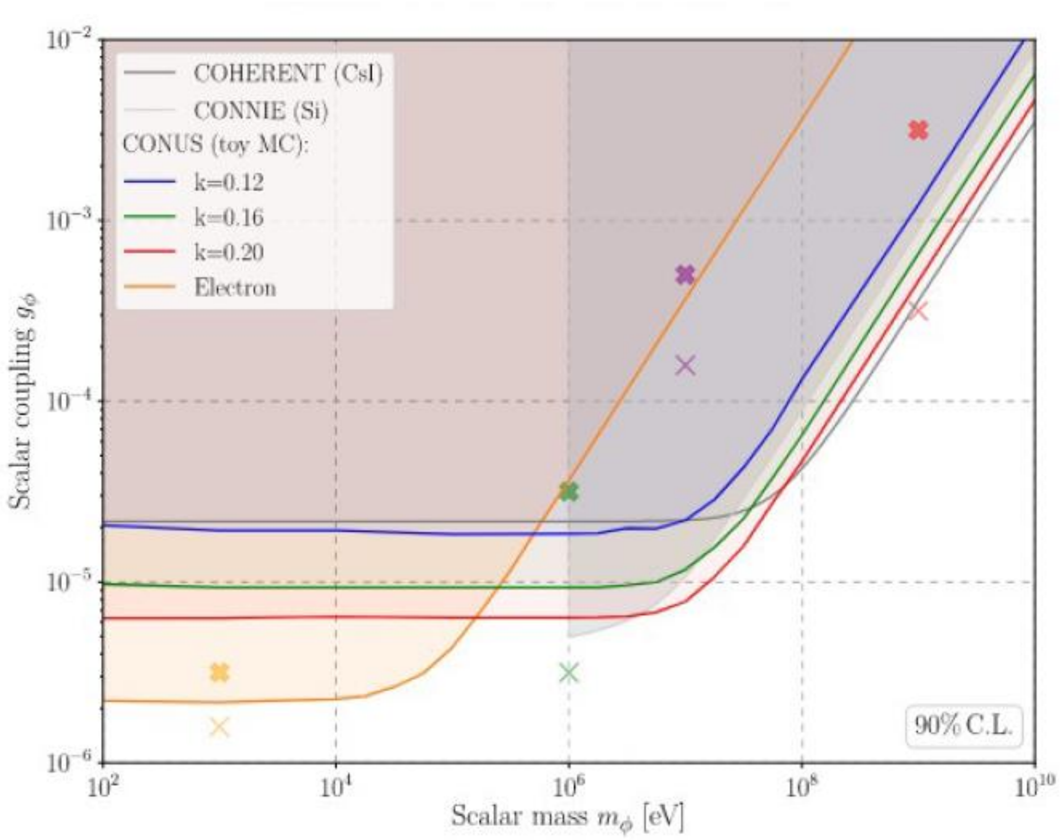


Data selection

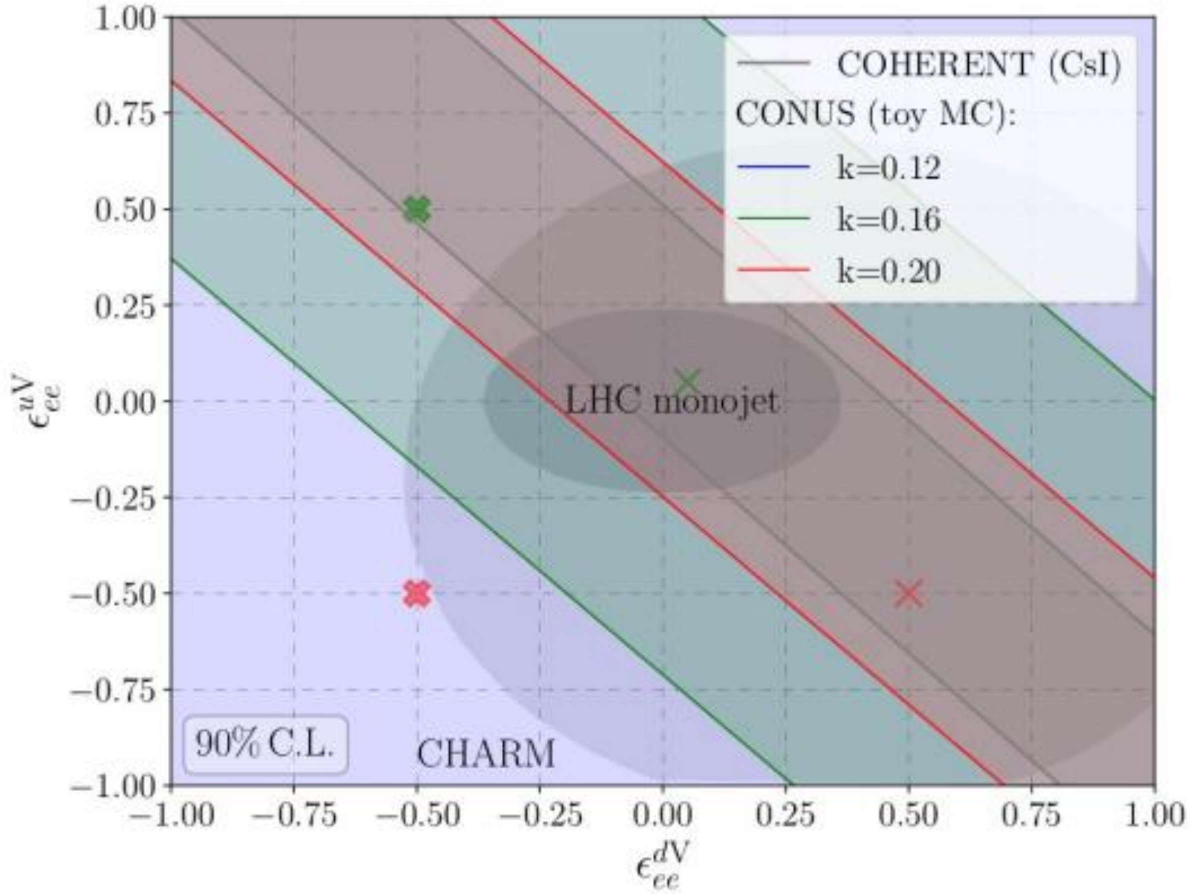




More BSM results



Light scalar boson



Light vector boson