Pulse-Shape Discrimination for the CONUS Experiment

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based on arXiv: 2308.12105 (2023)

CONUS Experiment

- Search for Coherent Elastic Neutrino Nucleus Scattering (CEvNS) with reactor-$\bar{\nu}$
- Located at the nuclear power plant of Brokdorf in Germany
- 4 x 1kg p-type point contact HPGe detectors in elaborate shielding
- 17 m distance to reactor core and shallow depth overburden of 24 m w.e.

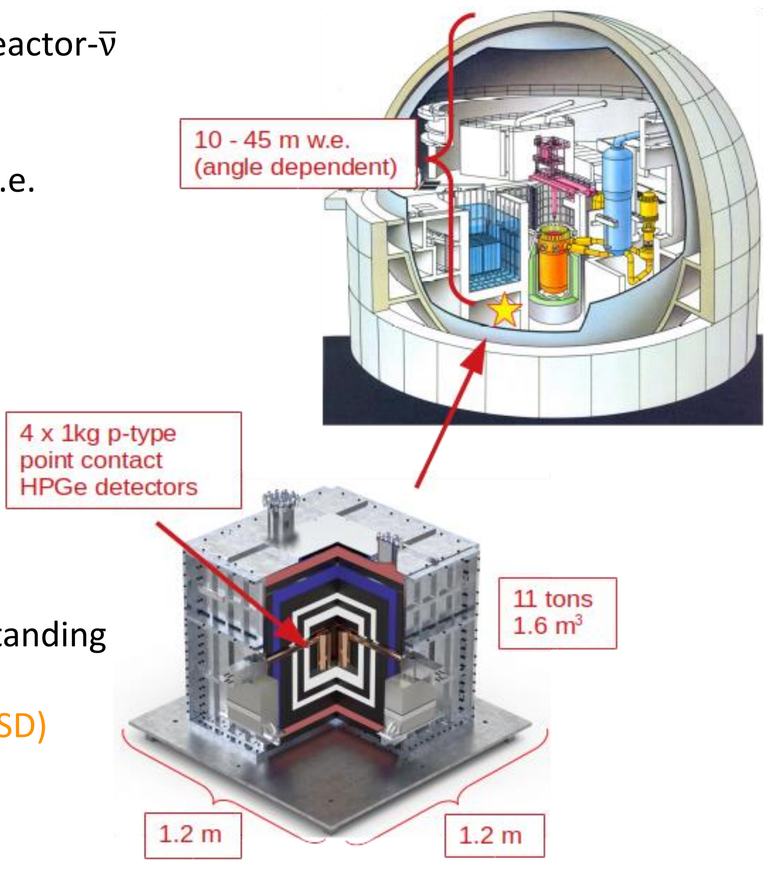
More information on CONUS:

➡ Parallel talk "*New CEvNS limit from the CONUS experiment*" by Edgar Sanchez (29.08.2023 4:45 PM)

- Requirements for CEvNS detection:
  1. Strong neutrino source with energies < 50MeV
  2. Low energy detector threshold << 1keV (sub-keV)
  3. Low background

  ➡ Call for further background reduction efforts & deeper understanding of signals below $500\mathrm{eV}_{ee}$

  Background can be improved by pulse shape discrimination (PSD) (selecting events via shape of readout-pulse)



- Anomalous signals from interactions at the surface of the diode (e.g. ^{210}Pb on the surface of the diode)

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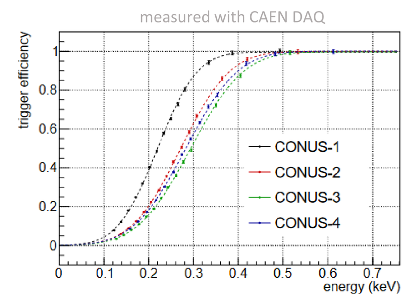
➡ Background rejection by discrimination of surface events from bulk events

Data Aquisition & Processing

- Signals at p+ contact read out by transistor reset preamplifier (TRP)
  ➡ Ultra-low noise and low background
- Data aquisition system (DAQ) based on CAEN digitizers offering pulse processing
- Triggered by a combination of slow and fast triangular discriminator
- Additional simultaneous recording of µ-veto logic rates and TRP reset sign
- Offline application of time cuts



- Trigger efficiency can be described by $\varepsilon_{trig} = 0.5 \cdot \left(1 + \mathrm{erf}\left(\frac{E_{ee} - t_1}{t_2}\right)\right)$

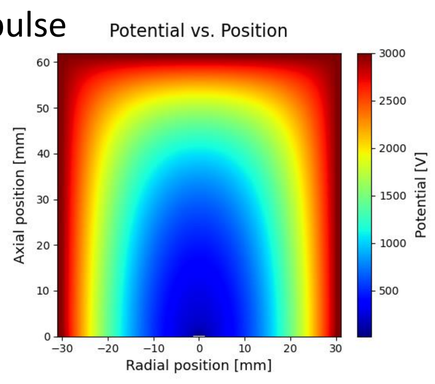
HPGe Detectors & Signal Formation

- Ionizing events in detector volume create electron-hole pairs drifting in opposite directions according to the electric field
- Charges are collected at the contacts forming a characteristic pulse

Fast Pulses (FP):
Interaction inside the active volume (bulk) of the detector crystal.
Rise-time ∼300ns

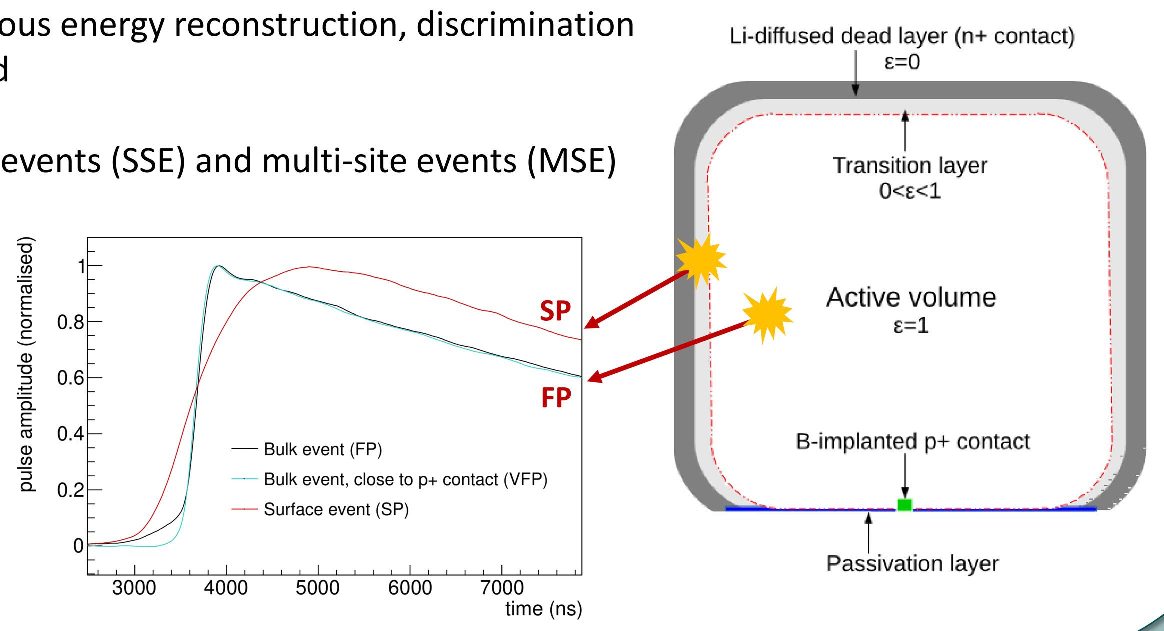
Slow Pulses (SP):
Interaction inside the transition layer of the detector crystal. Created charges diffuse until they recombine or reach the active volume, surface events

➡ Erroneous energy reconstruction, discrimination needed



Simulation of pulses and electrical field with modified version of siggen
(D. Radford, icpc_siggen: https://github.com/radfordd/icpc_siggen)

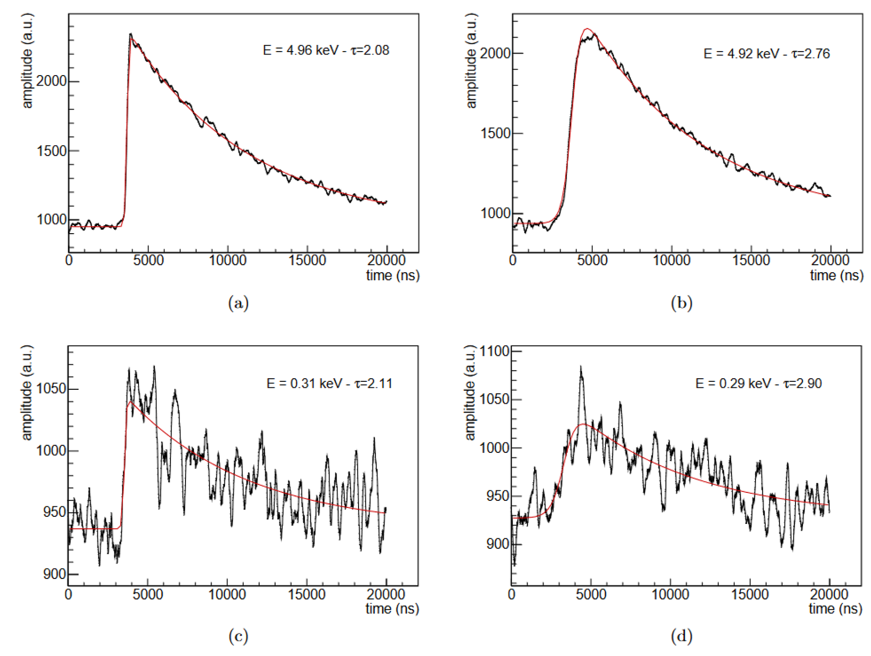
Single-site events (SSE) and multi-site events (MSE) possible



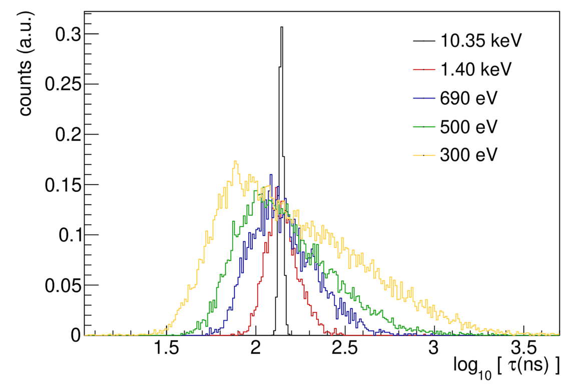
Rise-Time Fit

- Physical information to discriminate bulk from surface events is contained in rise-time of signals
- Rise-time is obtained by fitting each waveform by
  $f(t) = A_0 \left[\tanh\left(\frac{t - t_0}{\tau}\right) + 1\right] \exp(-\tau_c(t - t_0)) + P_0$

  A_0: amplitude of pulse
  t_0: timing offset
  P_0: baseline noise level
  τ_c: AC coupling decay time
  τ: rise-time related parameter
- FP rise-time for CONUS detectors ∼ (120-180)ns (equivalent to $t_{10-90\%}$ of (275-325)ns)
- Complementary methods as A/E method (ratio of current pulse amplitude to total event energy) less efficient below a few keV_{ee}



Artificial generation of bulk signals



- Determine cut acceptance for neutrino events
  ➡ pure homogeneous bulk event sample over whole energy range needed
- Artificial signals generated by electronic pulser mimicking bulk events injected through DAQ chain
- Correct shape determined by data-driven deconvolution of measured bulk signals at higher energies

➡ Measured rise-time distribution of artificially generated bulk events:
- Electronic noise responsible for smearing of the distributions with lower energies
- Below $1\mathrm{keV}_{ee}$ deviation from gaussian shape
- Bulk signal acceptance can be estimated for any rise-time cut value

Physical Event Samples

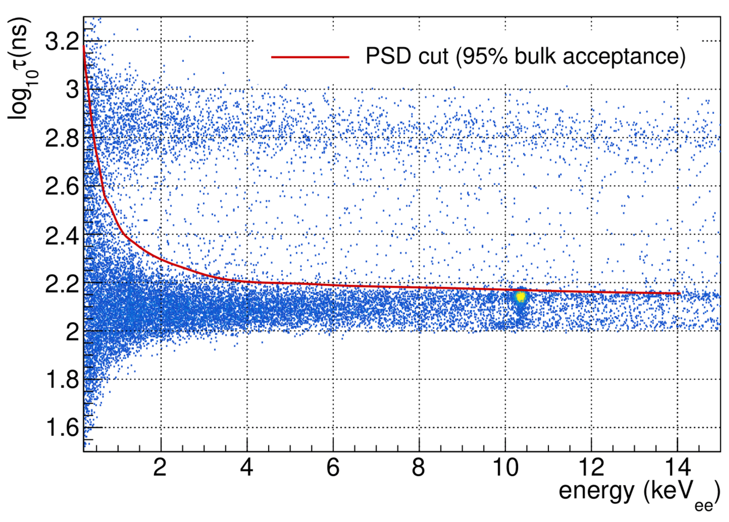
- **Calibration and study of pulse-shapes:**

- ^{228}Th source calibrations ➡ good mixture of SP, FP, pile-up and MSE

- Data recorded in reactor-OFF time before µ-veto cut application
  ➡ µ-induced events with electromagnetic and neutron component
  ➡ Neutron component dominant in ROI, mainly bulk events (FP)
  ➡ Gamma-rays create mainly surface events (SP)

- Neutron activation in germanium (neutron capture on ^{70}Ge)
  ➡ Characteristic lines in spectrum, homogeneously distributed events within the whole Ge volume

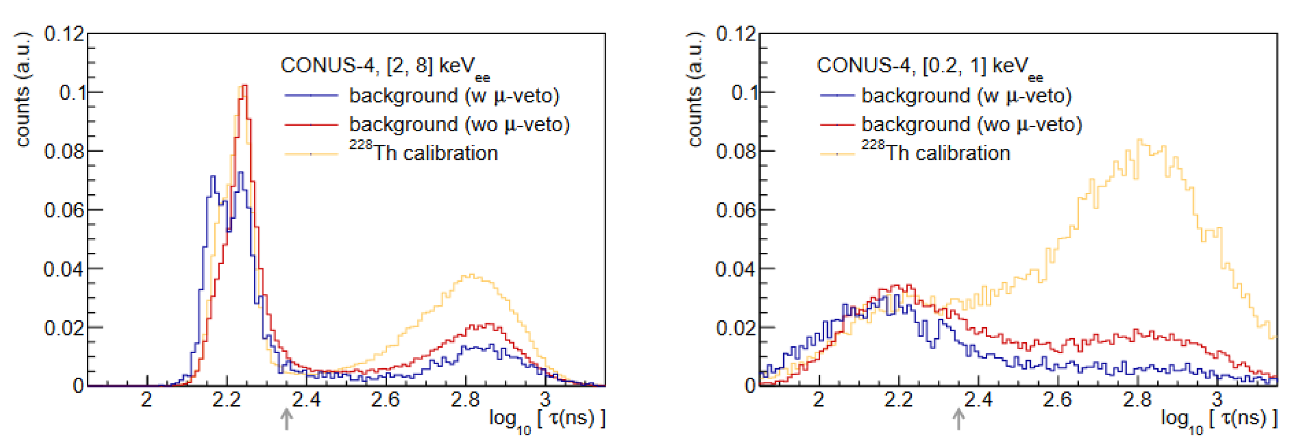
- **Rise-time of background events in reactor-OFF after µ-veto cut application:**



- Two populations: fast ($\log_{10}\tau \sim 2.1$) and slow ($\log_{10}\tau \sim 2.9$) clearly separated at higher energies, start to mix in sub-keV_{ee} regime
  ➡ Influence of electronic noise
- Gap between bands populated by pile-up events and MSE
- Two sub-populations inside the fast band: correspond to different interaction positions inside active volume

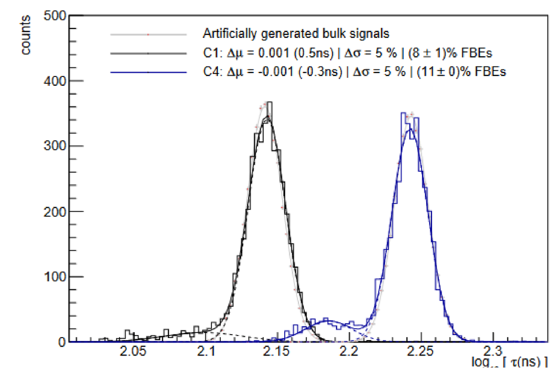
- **Rise-time distribution at mid and low energy:**

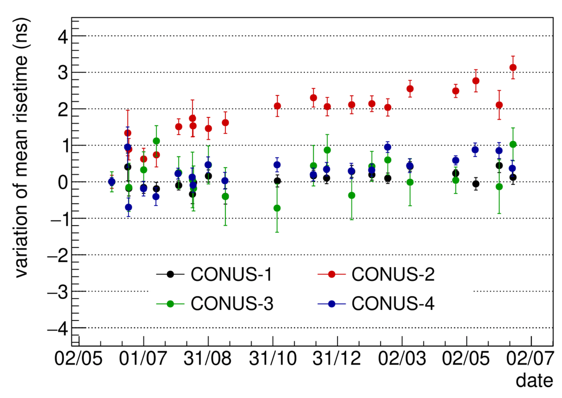
- Discrimination power between FP and SP population visible
- Information on underlying background components

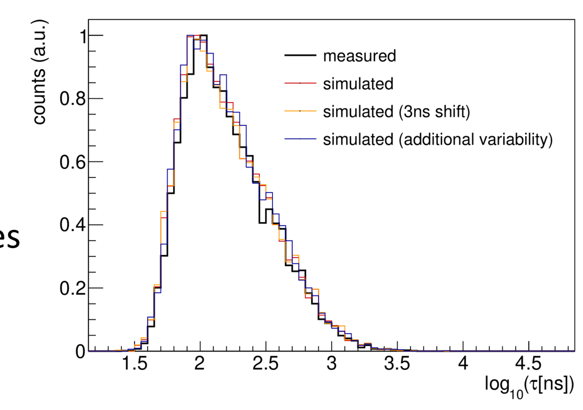


Results

- **Validation:**
  - Ratio of bulk to surface events:
    Comparison of ^{228}Th calibration data rise-time distribution to MC simulation
    ➡ Agreement on 5% level achieved, accurate description of detector transition layer and consistency of surface event identification over energy, no unexpected component
  - Procedure of artificial generated bulk events:
    Measured rise-time distributions from injected signals compared to sample of real physical events from $10.37\mathrm{keV}_{ee}$ line
    ➡ Agreement of mean rise-time at ns level, width of distributions in agreement at (5-10)% level, noise mostly responsible for smearing
  - Stability of rise-time:
    Monitored over time with bulk event distribution of ^{228}Th calibration data
    ➡ Maximum deviation of ∼3ns observed due to other instabilities
  - Qualitative understanding of boradening of rise-time distribution due to electronic noise:
    Elementary simulation of event samples (theoretical input pulses convoluted with response function of the detectors including accurate noise model)
    ➡ Simulated rise-time distributions match well the measured distributions also at lowest energies







- **Impact of systematic uncertainties:**
  Simulation of input pulses with slightly variing rise-times and artificial variability in the signals
  ➡ Small changes do not affect the distributions, dominated by noise, systematic uncertainties can be neglected

➡ **PSD application to CONUS background data:**
- Close to energy threshold ∼half of the SP can be rejected (90% signal acceptance)
- More conservative cut with 97% signal acceptance used for CONUS CEvNS analysis
- Background level reduction of ∼(15-20)% in ROI ((5-10)% with 97% bulk acceptance)
- Refining understanding of background and detector properties