

Enhancing the neutrino detection rate of in-ice radio detectors with neural-network-based triggers

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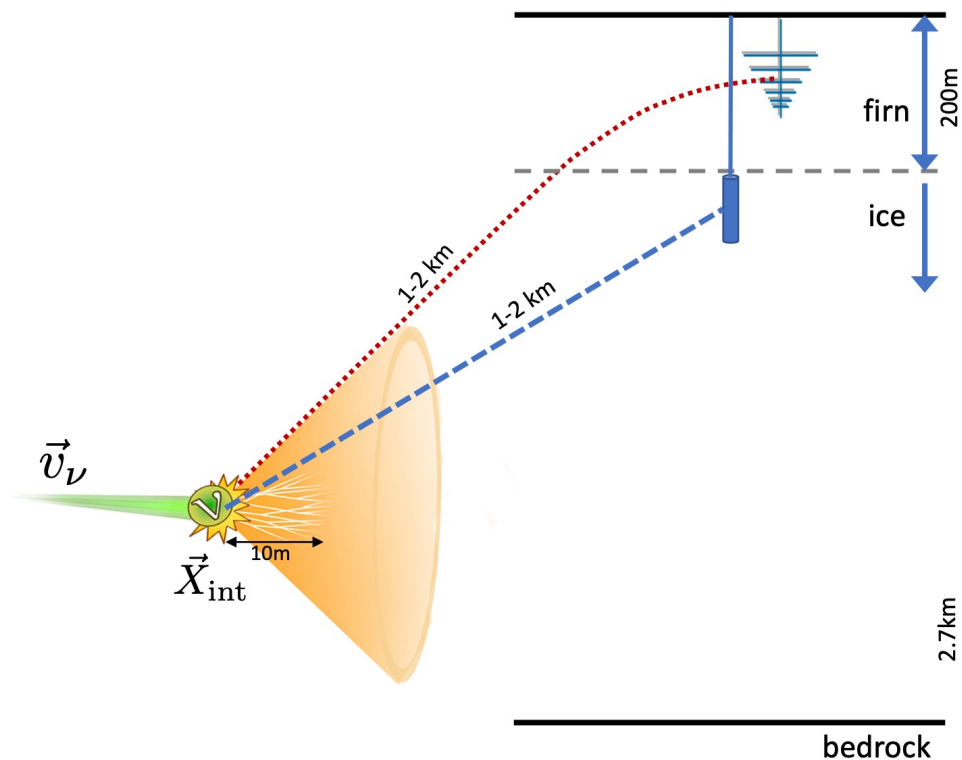
Federal Ministry
of Research, Technology
and Space



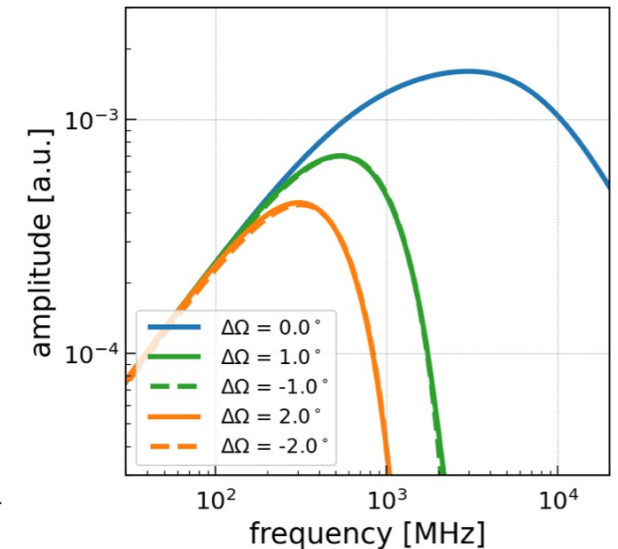
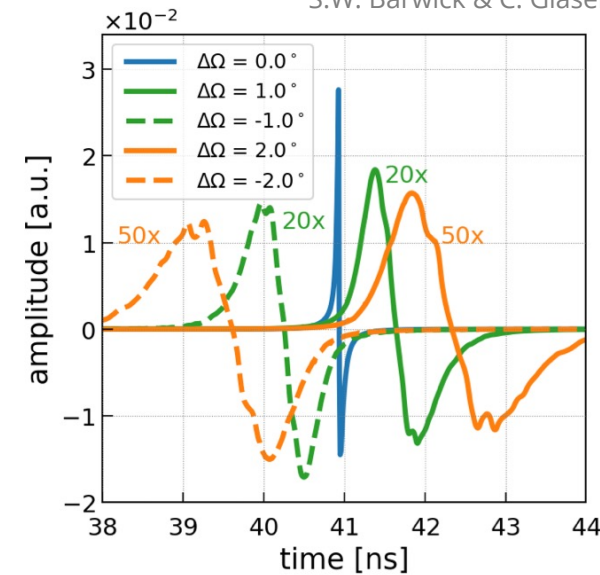
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In-ice Radio Detection

- Cascades produced in neutrino interaction develop a charge excess
- Moving charge excess produces radio signal
- Attenuation length in ice $\sim 1\text{km}$



S.W. Barwick & C. Glaser, The Encyclopedia of Cosmology (2023) 237-302

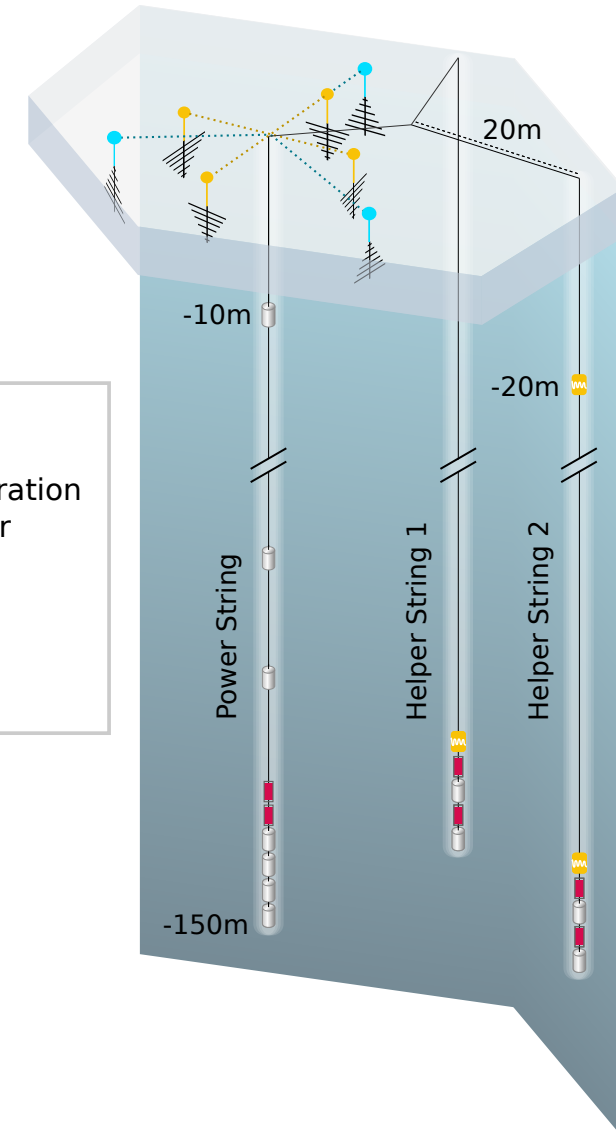
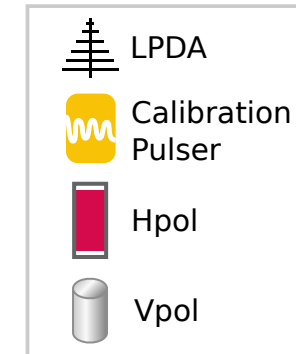
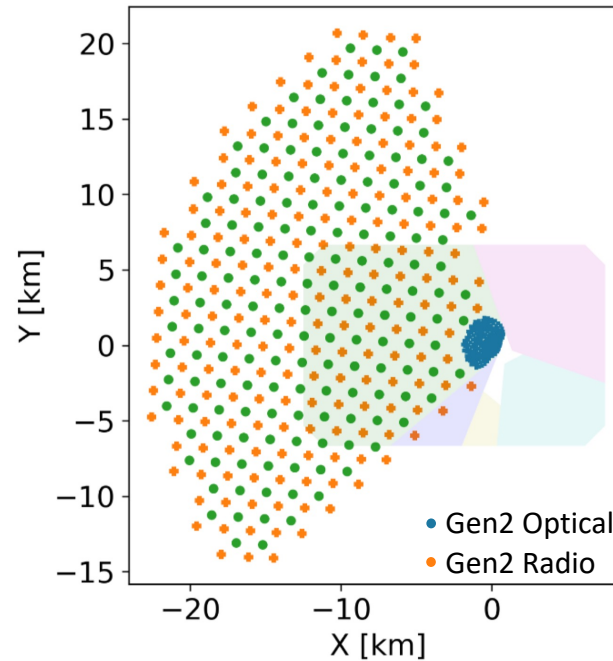


Signal Characteristics

- Bi-polar signal shape
- Frequency spectrum 100 MHz – 1GHz

In-Ice Radio for IceCube-Gen2

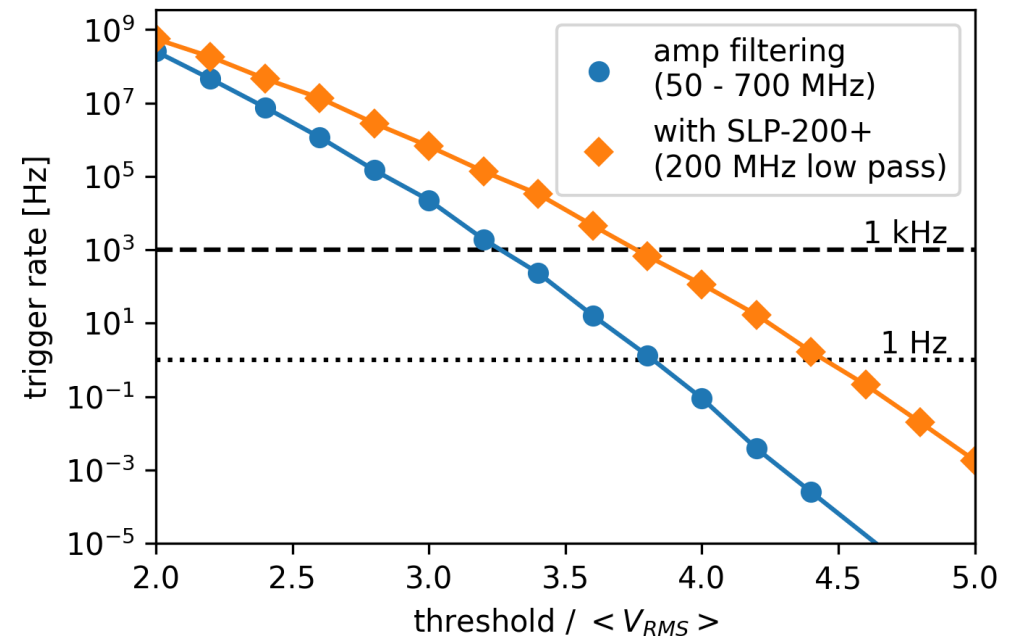
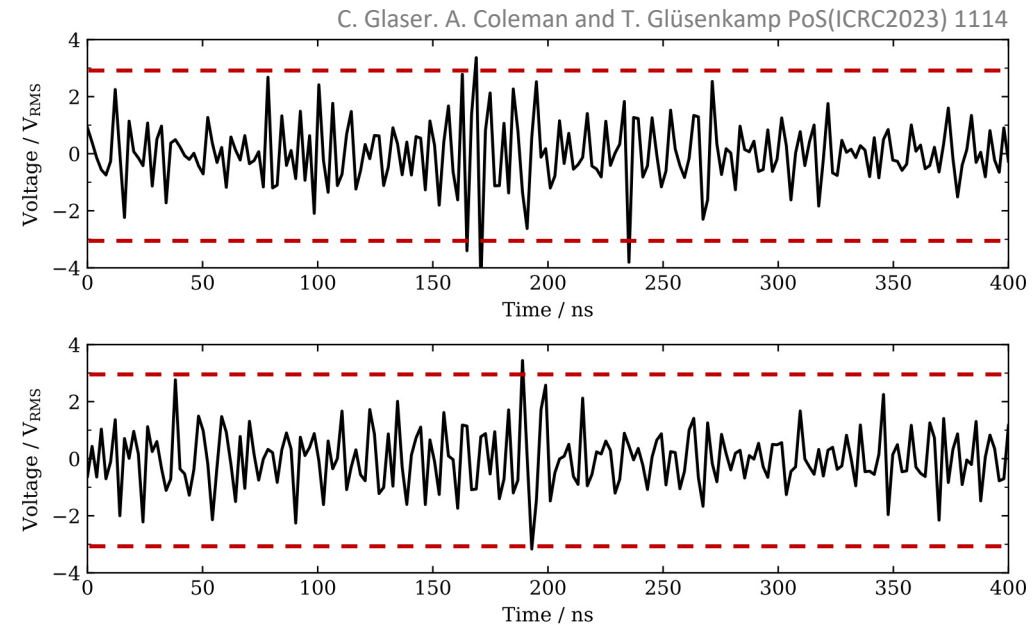
- Two station layouts
 - Shallow
 - Hybrid (Shallow + Deep)
- Stations separated by $\sim 1\text{km}$
 - Attenuation length of $\sim 1\text{km}$
 - Increase effective volume
- Autonomous stations
 - Power budget limited
 - $< 30\text{ W/station}$
 - Data bandwidth limited
 - Trigger rate $\sim 1\text{Hz}$
 - Autonomous trigger decision
- Construction limited by logistics



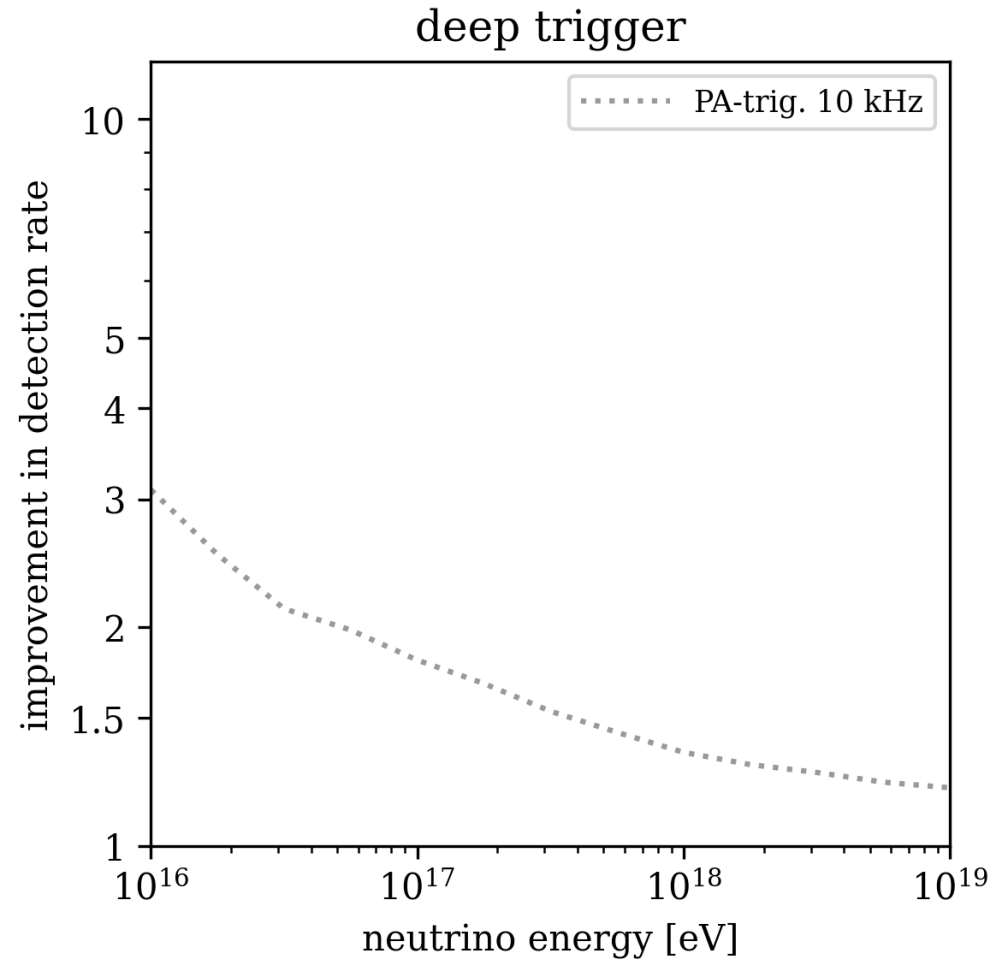
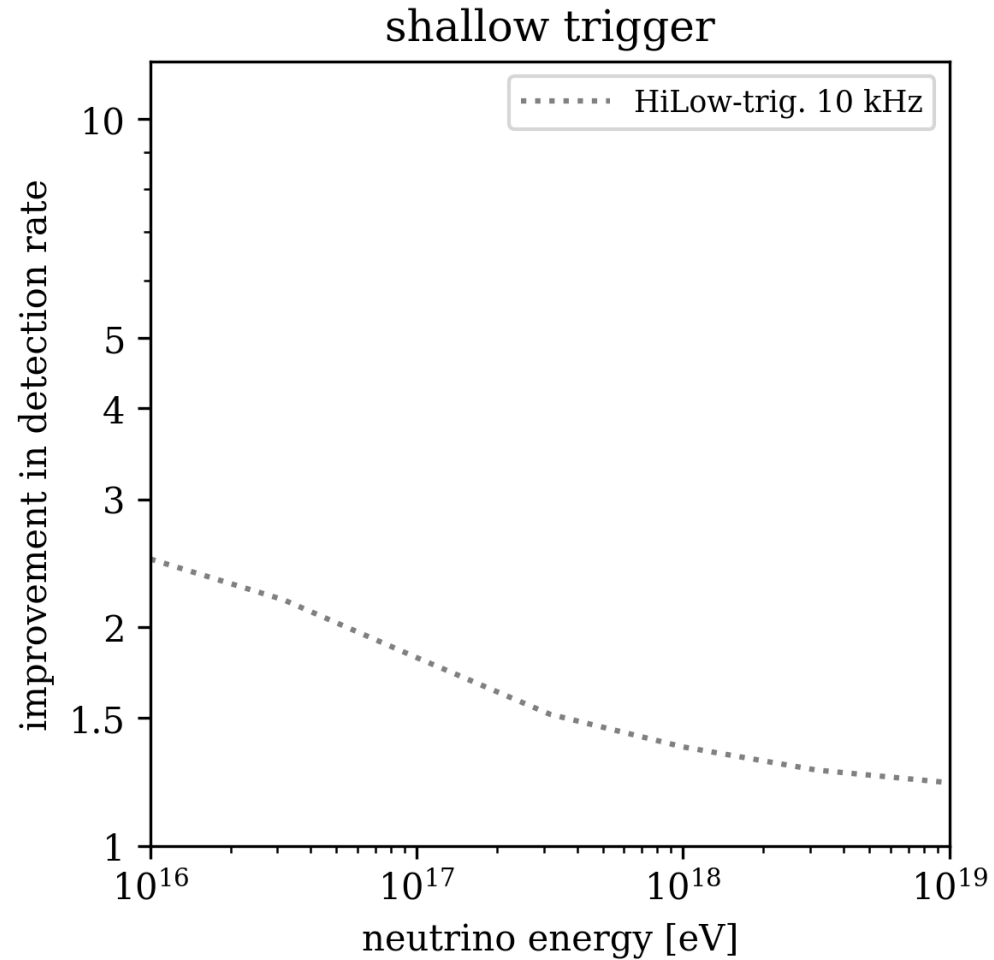
Autonomous, low power & high-efficiency trigger key for effective volume

Trigger Algorithm (Classic)

- Signal with thermal radio noise & antenna response
- Hi-Low-Trigger:
 - In shallow stations
 - Coincidence of positive excess & negative excess within 5ns per channel
 - Coincidence of 2 out of 4 channels within 30ns
- Phased Array Trigger:
 - In deep stations
 - Beam forming signal, highly optimized
 - Reduces noise by $\sqrt{N_{\text{antenna}}}$
- Threshold tuned to result in 1Hz background rate
 - Noise threshold depends on bandwidth
 - Effective volume depends on V_{RMS} and bandwidth

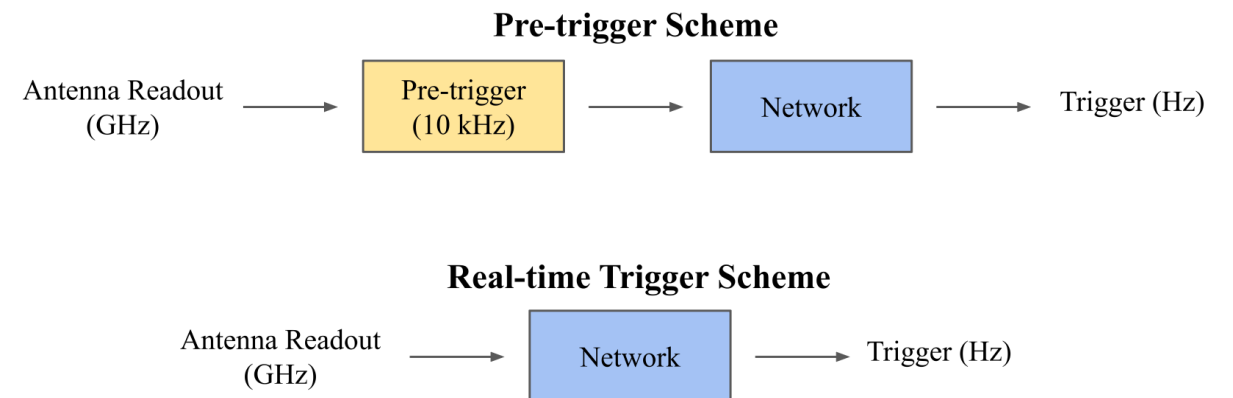


Trigger Improvements



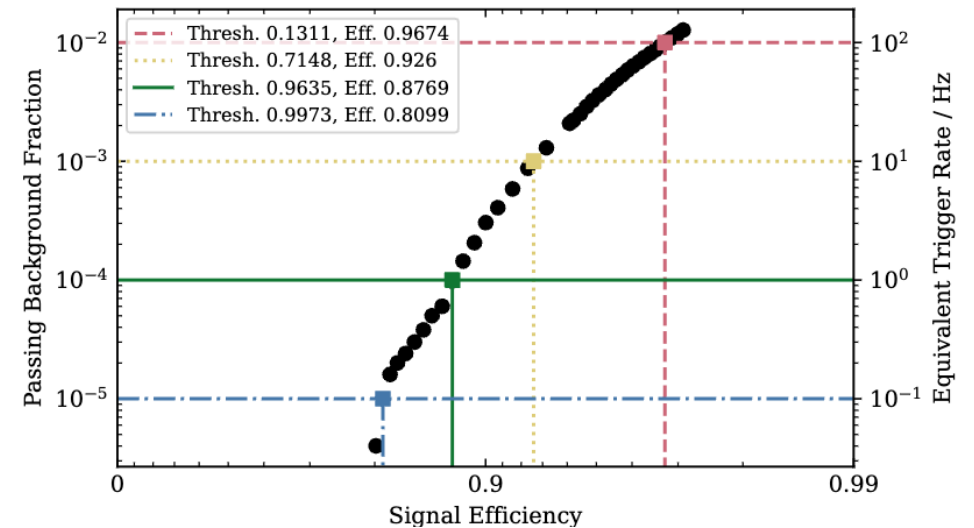
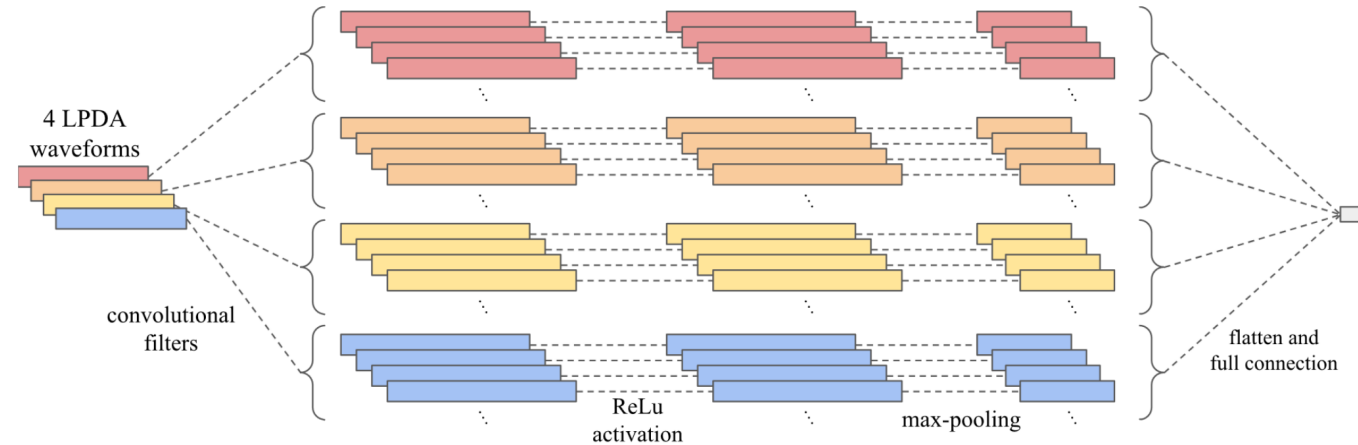
Deep-Learning based Trigger

- offline analysis: thermal noise can be rejected with high efficiency
- Neural networks are very good at classification tasks
 - **Huge potential of improvement**
- Fully digitized DAQ system
- Input: two 4-channel 12-bit ADC @ 1.6 GHz
- Neural network decision has to keep up with data rate → Constraints latency
- Two baseline Schemes
 - Pre-triggered NN
 - Real-time NN



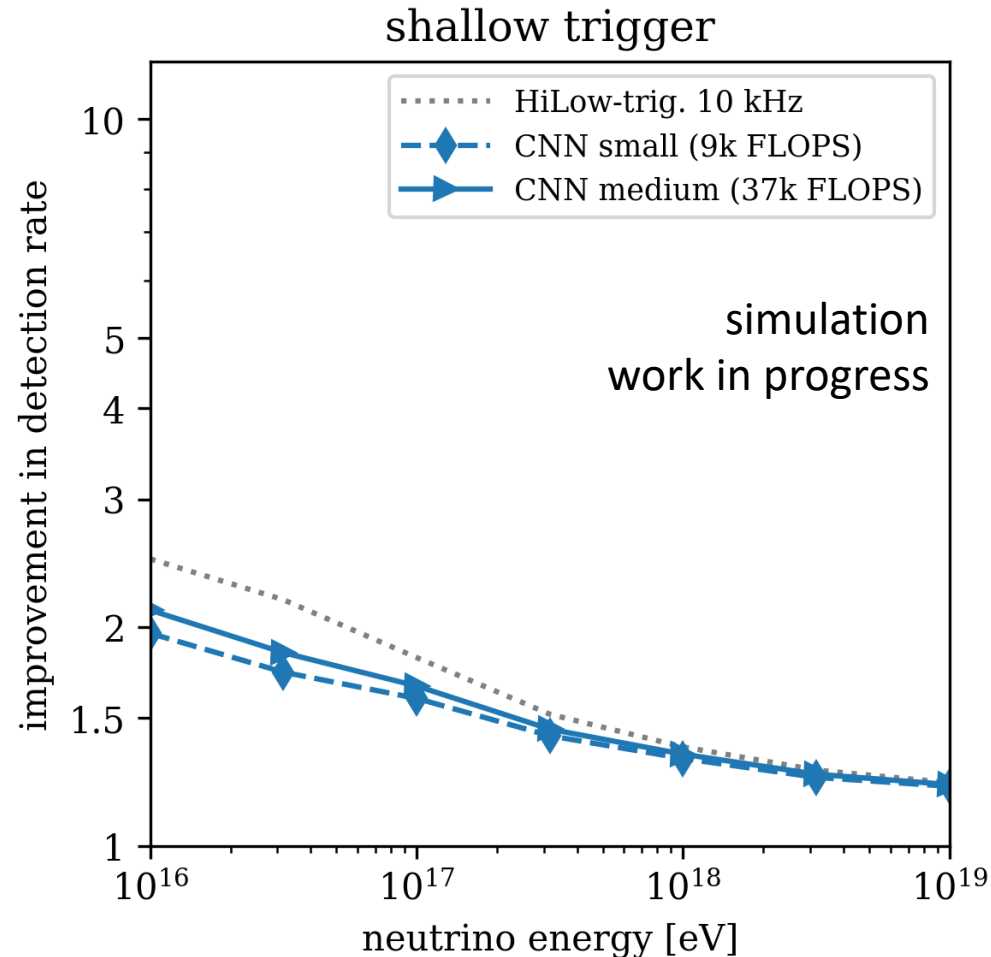
Pre-triggered Neutral Network

- Network type
 - Single layer CNN
- Manual implementation on FPGA by P. Marciniewski @ Uppsala
- Fits easily on an “old” Cyclone V FPGA
- Updated design with two CNN layers ongoing



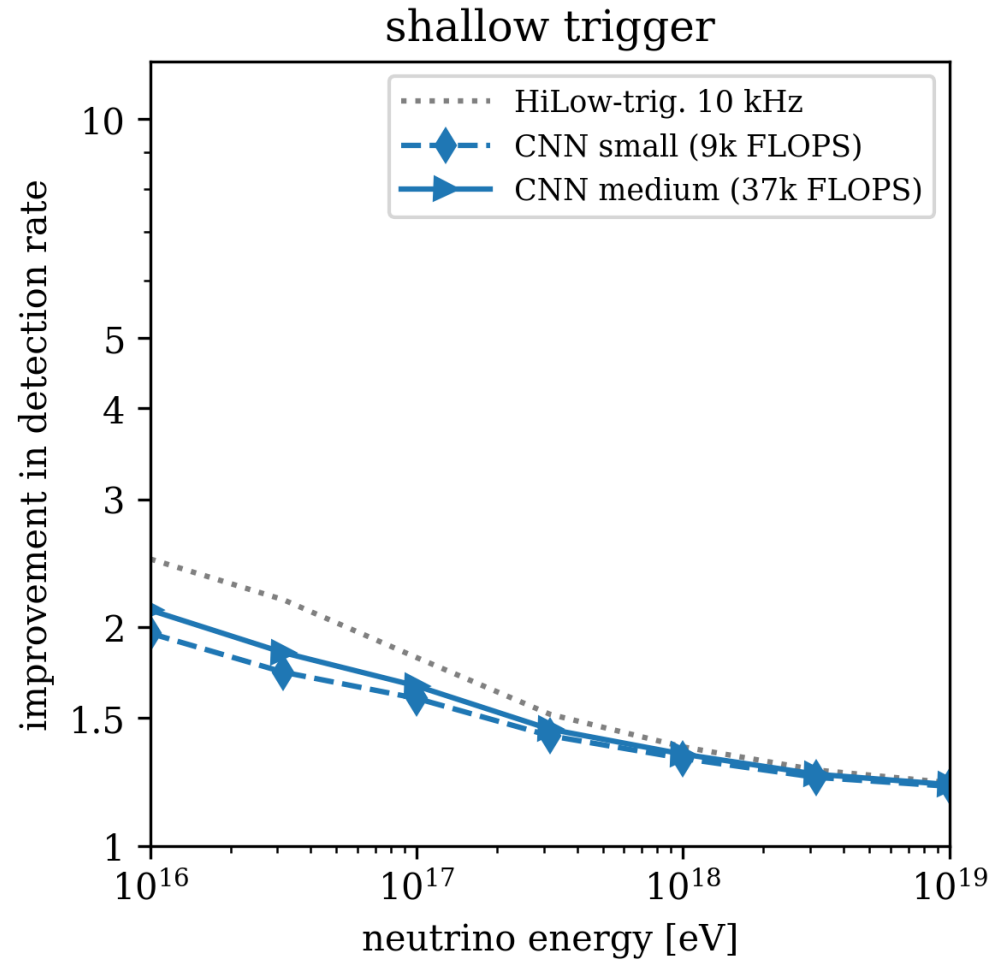
CNN rejects 99.99% of noise at ~90% signal efficiency

Neural Network (Performance)

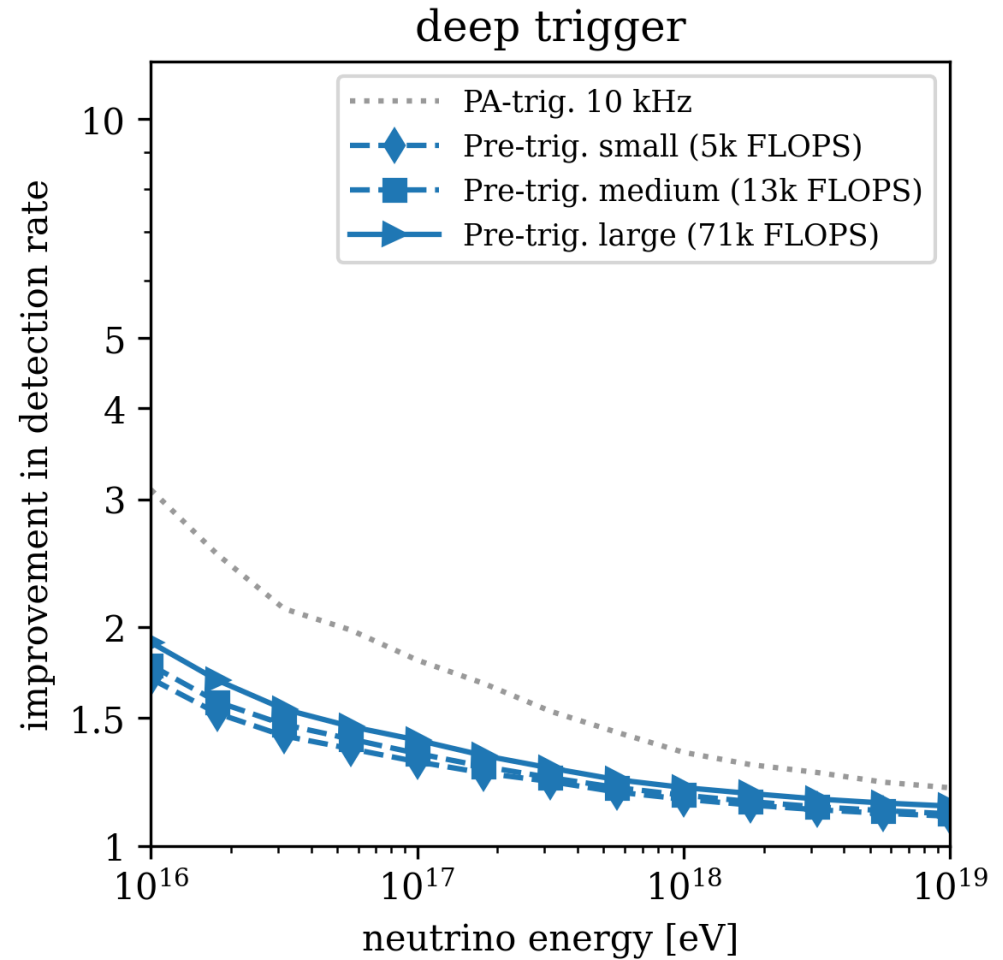


- Improvement w.r.t. classical hi-low trigger
- Improvement scales with model size
 - Larger models have higher resources
 - Larger models have power consumption
 - Larger models have larger latency
- Improvement depends on signal strength (neutrino energy)
- Improvement limited by 10kHz pre-trigger

Trigger Improvements



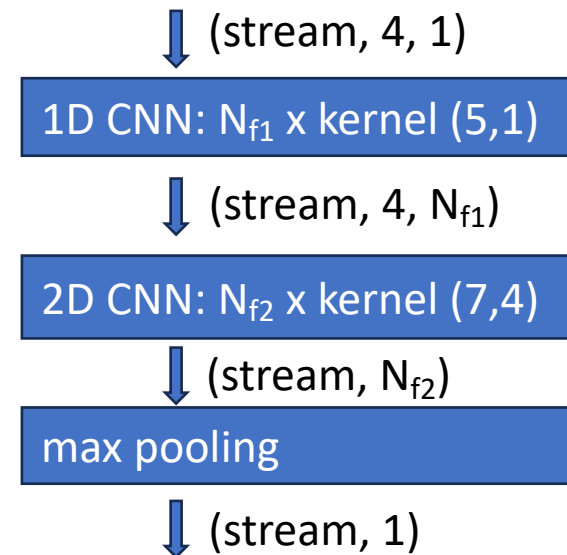
Improvement limited by pre-trigger



PA trigger already well optimized

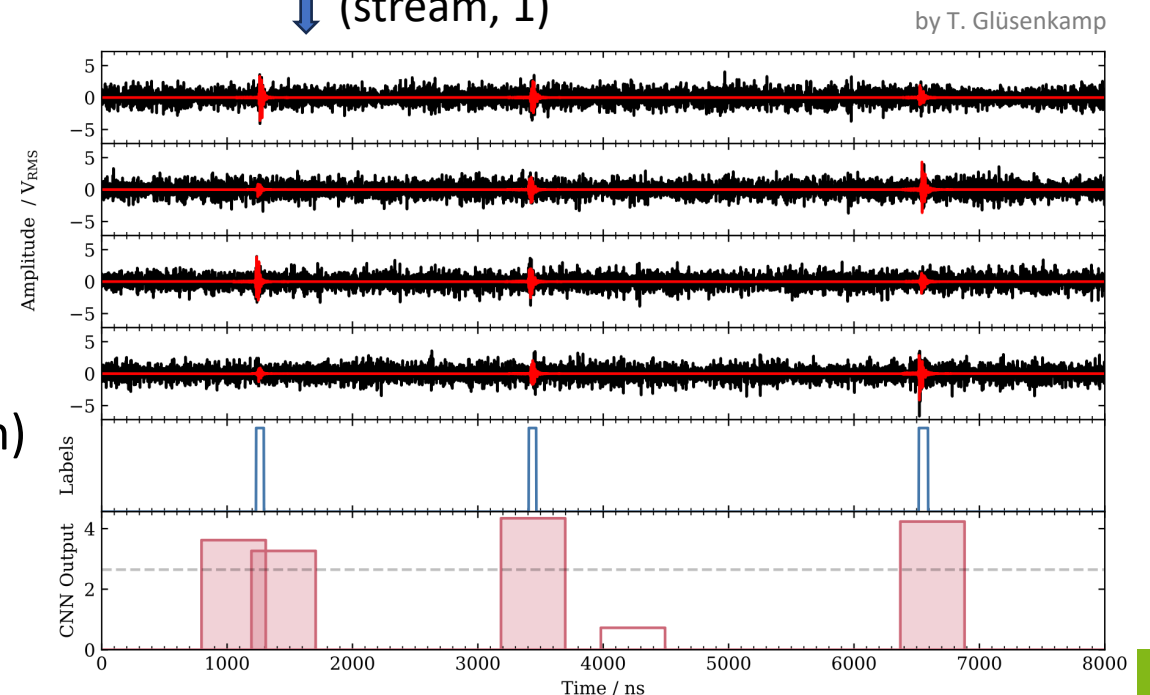
Real-Time Neural Network

- Translational invariant network
- Simplest option:
 - Run CNN on overlapping chunks of data
 - Trigger on CNN output
- Challenge: threshold set to trigger at 1Hz on thermal noise
 - 1 trigger every 10^9 samples
 - 1 trigger every 3.9M data chunks
- Solution:
 - No sigmoid activation (reduces computation)
 - Hinge loss (penalize wrong predictions)

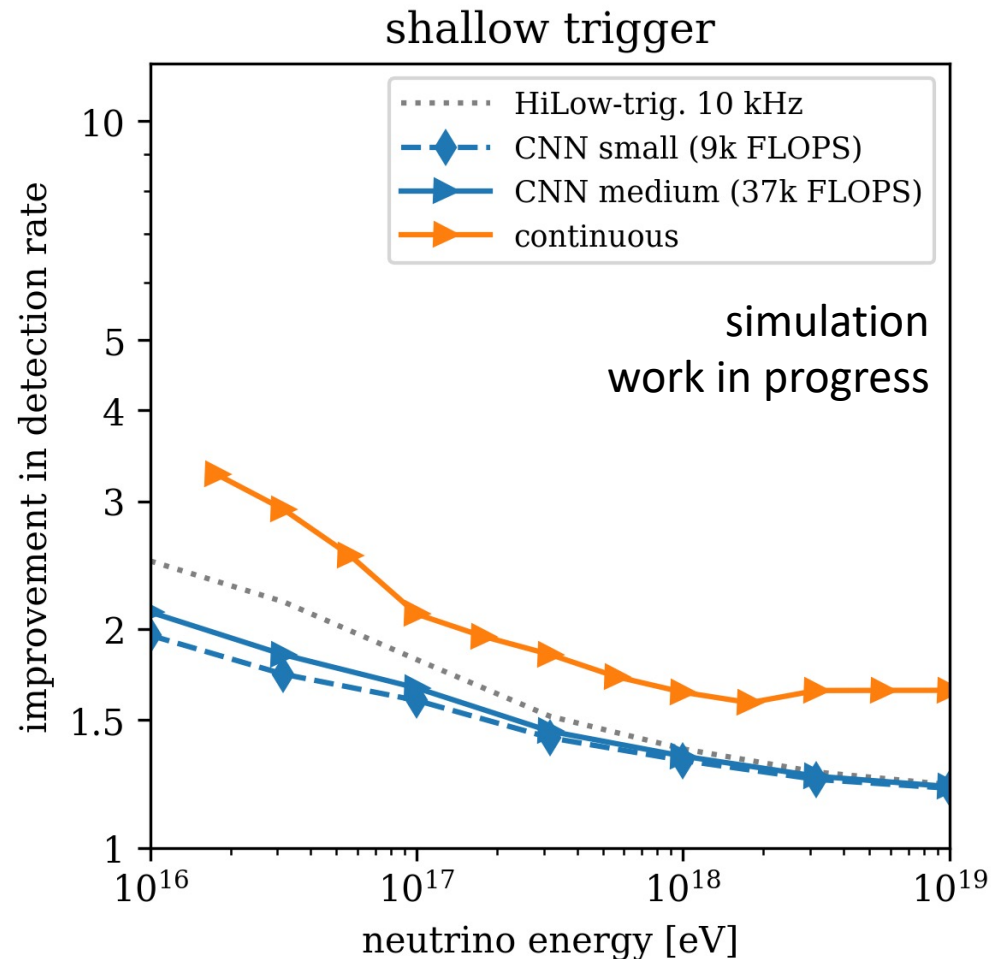


encoding of time series
pattern recognition

time coincidences
between antennas

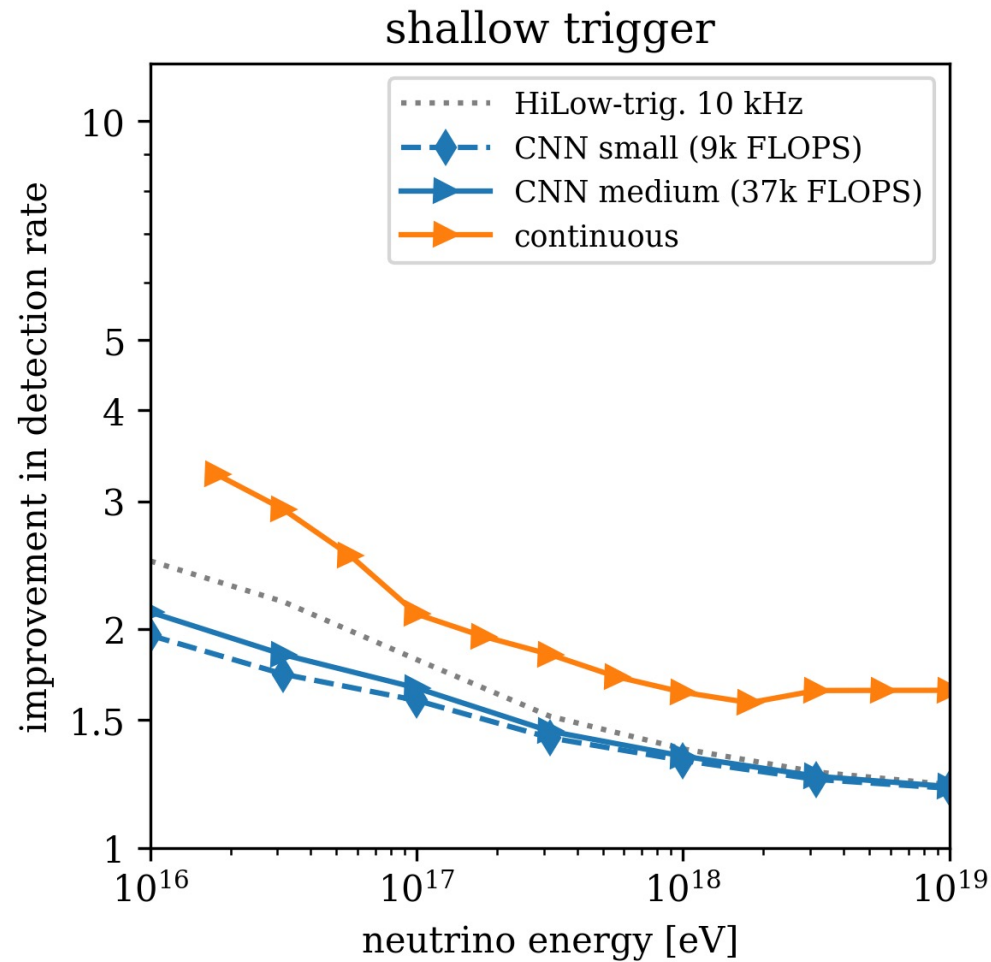


Neural Network (Performance)

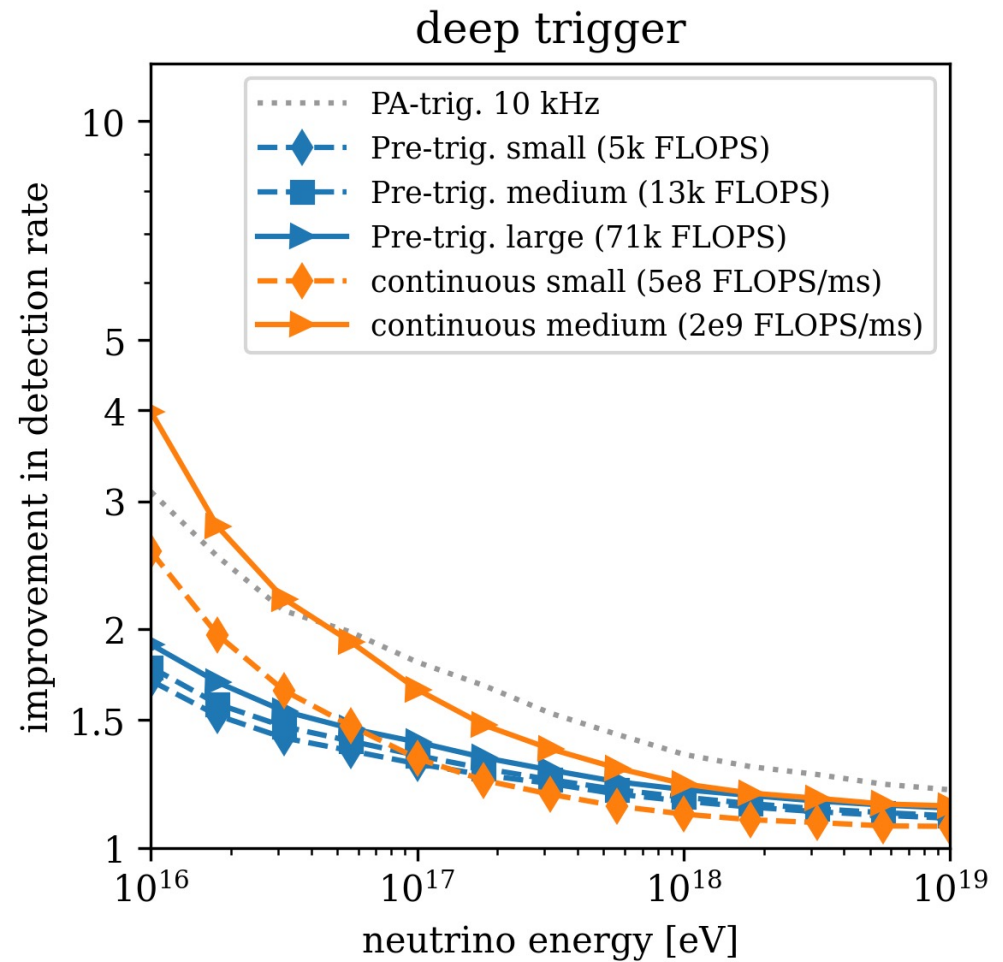


- Improvement w.r.t. classical hi-low trigger
- Improvement scales with model size
 - Larger models have higher resources
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- Improvement depends on signal strength (neutrino energy)
- Continuous trigger outperforms pre-trigger limit

Trigger Improvements

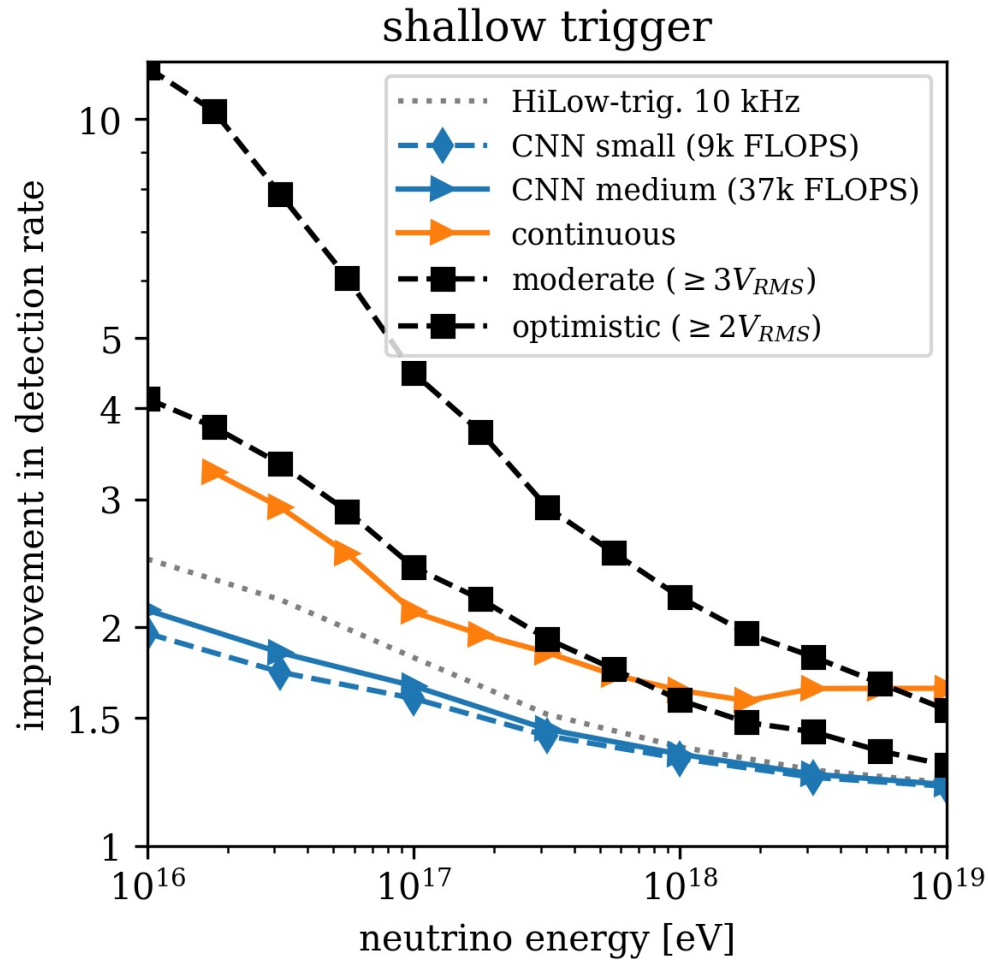


Outperforms pre-trigger

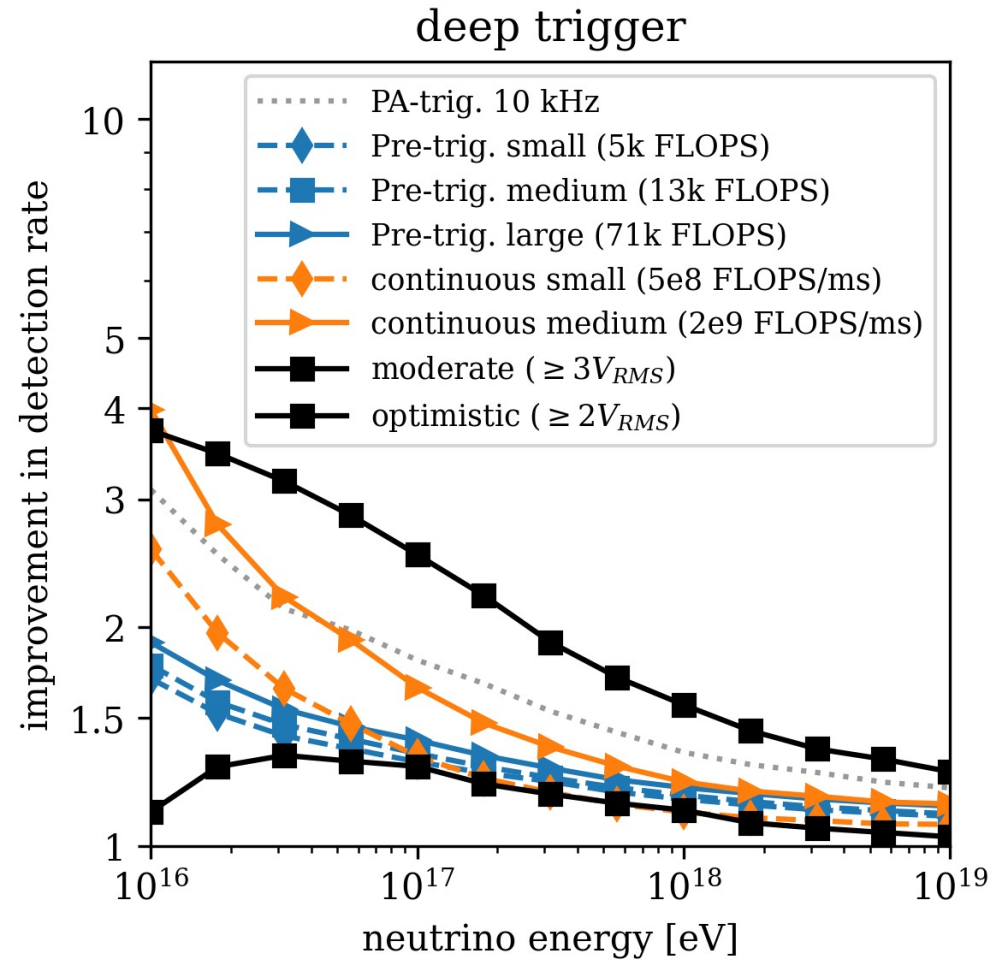


Harder to optimize

Trigger Improvements



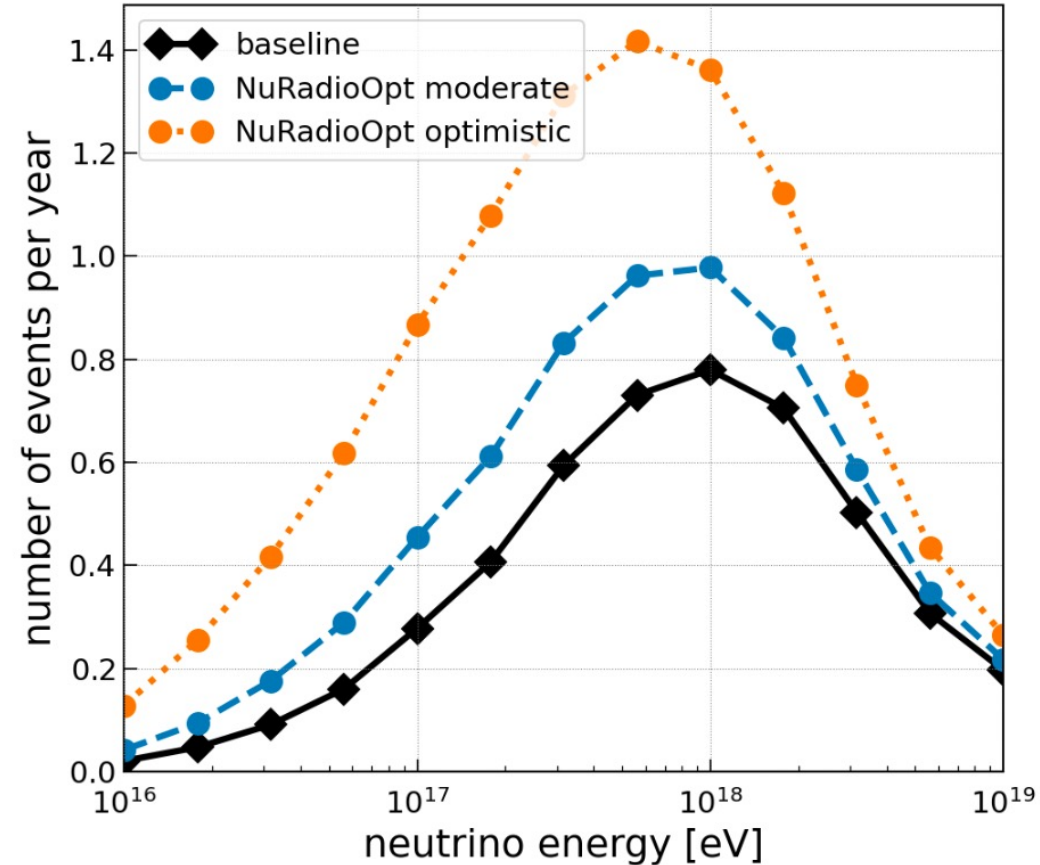
Outperforms pre-trigger



Harder to optimize

Estimate Impact on Effective Volume

- Estimate impact of generic improvements on event rate
- Estimates based on effective thresholds
- Relative improvement of 34% (moderate) and 100% (optimistic)
- Pre-triggered model already achieves moderate improvement in deep stations
- Deep stations dominate effective volume
- Improvement at effectively no additional cost



Detector: IceCube Gen-2

Flux: IceCube astrophysical flux + GZK neutrino flux

Improvement in Physics Analysis

Neutrino-Nucleon Cross Section

→ 3x more precise measurement

V. Valera, M. Bustamante, C. Glaser, JHEP 06 105 (2022)

Diffuse Flux

→ expedite the detection of UHE neutrino fluxes by up to a factor of five

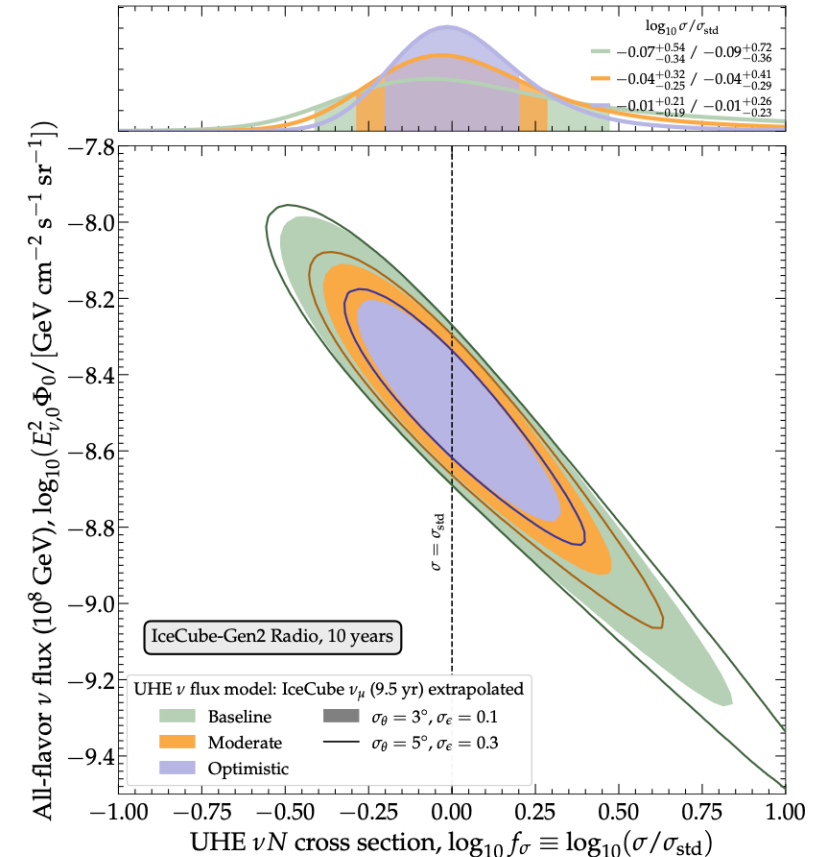
V. Valera, M. Bustamante, C. Glaser, PRD 107, 043019 (2023)

Point Sources

→ Identify sources from deeper in our Universe increasing the observable volume by a factor of three

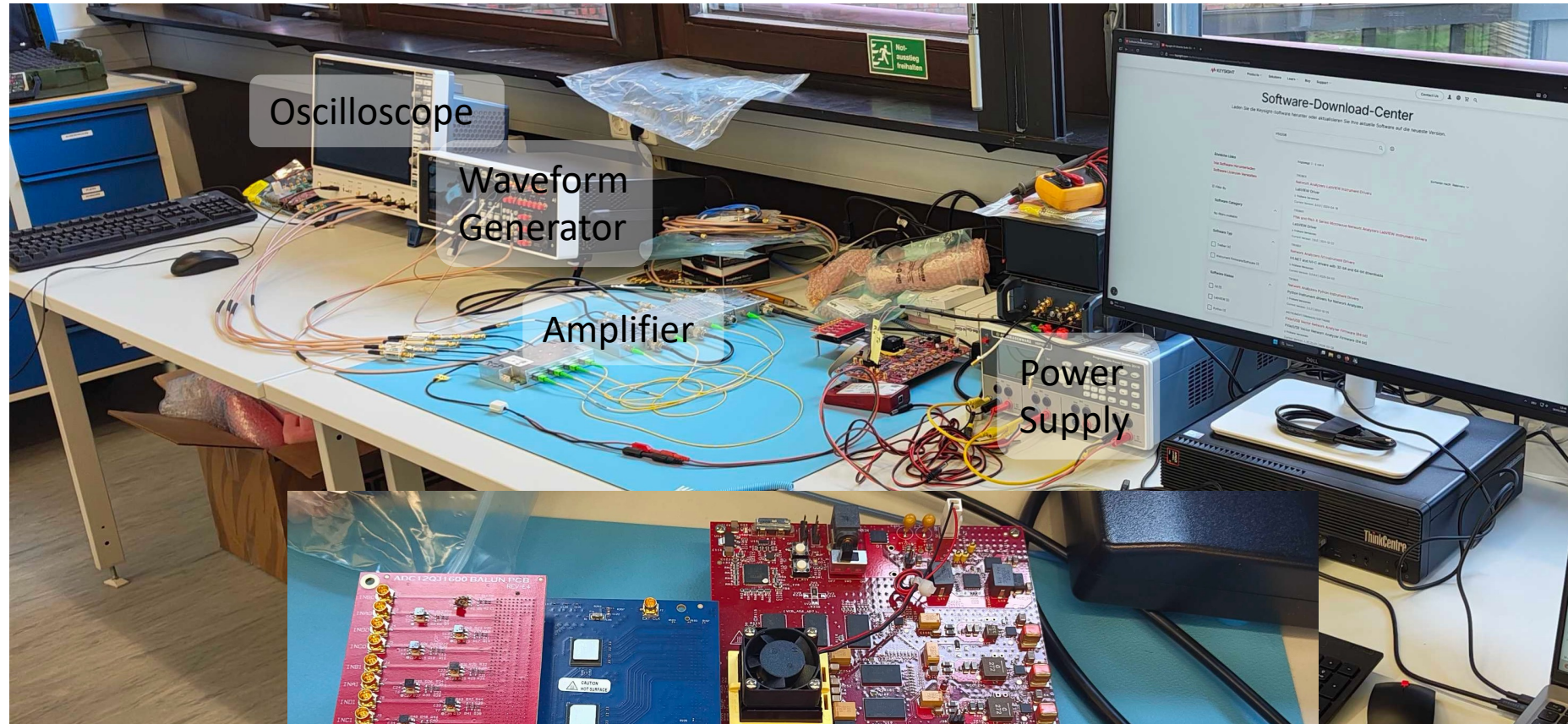
D. F. G. Fiorillo, V. Valera, M. Bustamante, JCAP03 (2023) 026

UHE Neutrino Cross-section



due to improved event rate & reconstruction

Lab Tests in Dortmund



Oscilloscope

Waveform
Generator

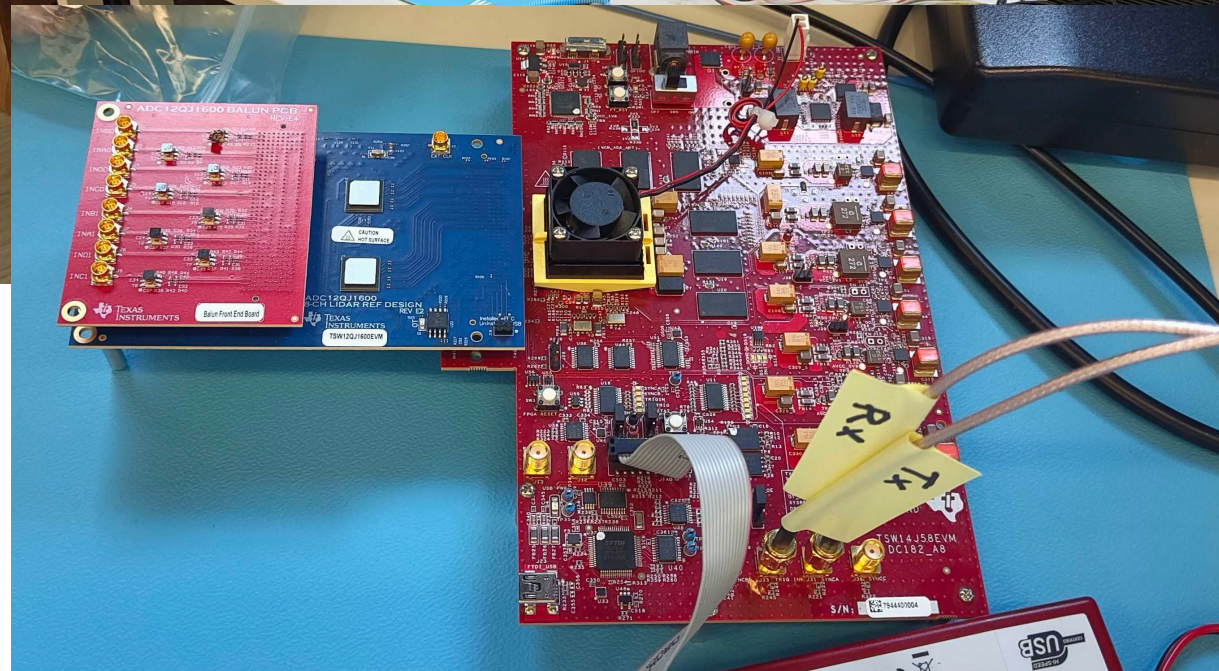
Amplifier

Power
Supply

Software-Download-Center

two ADC's

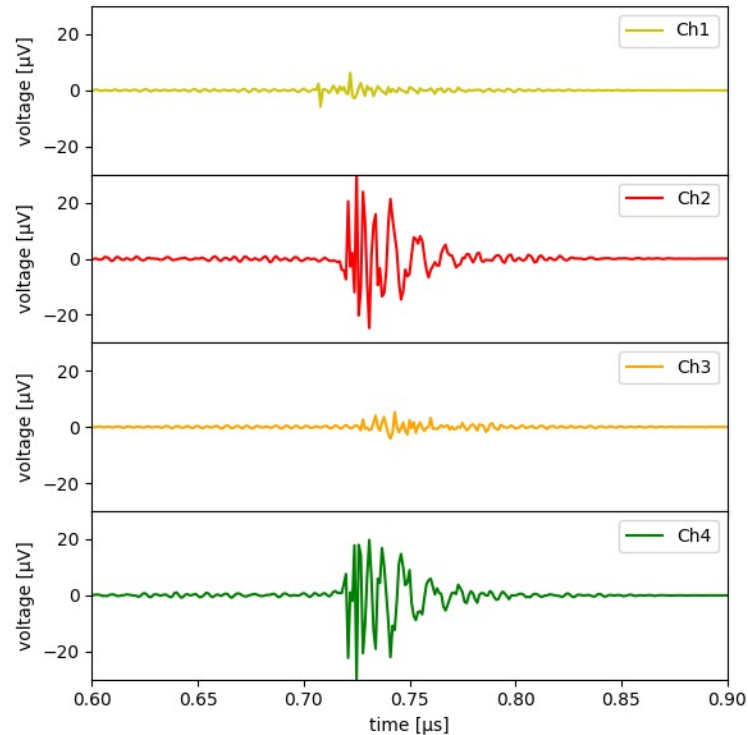
- 4 channels each
- 12bit resolution
- up to 1.6 GHz sampling rate



FPGA evaluation board

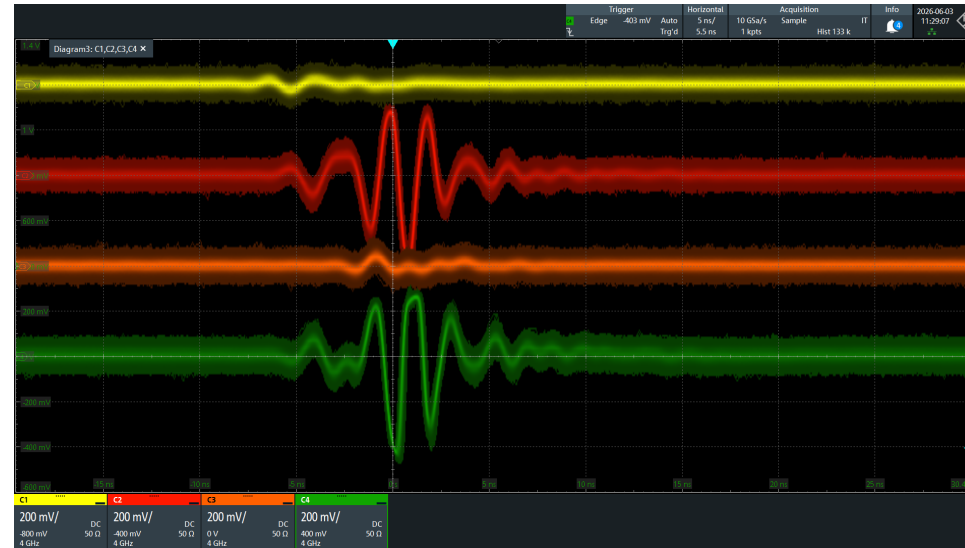
Xilinx® Kintex™
UltraScale+™

Lab Tests in Dortmund



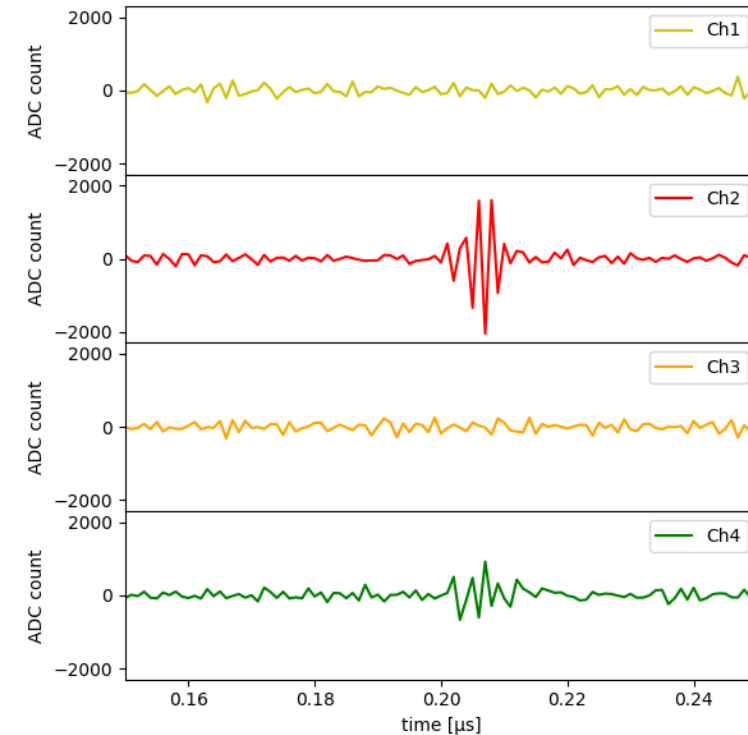
AWG

Programmed with simulated neutrino pulses



Amplifier Chain

Pulses observed with RNO-G 2-staged filter chain



Recording

Recorded waveforms with 12bit resolution @ 1GHz

Station: shallow, IceCube-Gen2
Shower: 89° , 10^{17} eV, had

Low-level firmware ready
Start implementing and test of NN

Outlook

- Simulation results show improvement of 34% (moderate) and 100% (optimistic) in event rate
- Low-level firmware ready
- Implementation & testing of NN in lab started
- Updated pre-triggered NN model in development
- Determination of
 - Background rate
 - Signal efficiency
 - Power consumption

