Signal digitization and time-over-thresholds in KM3NeT

Bouke Jung - **on behalf of the KM3NeT collaboration**

KM3NeT detector

KM3NeT-ORCA: atmospheric neutrino oscillations
KM3NeT-ARCA: cosmic neutrino sources

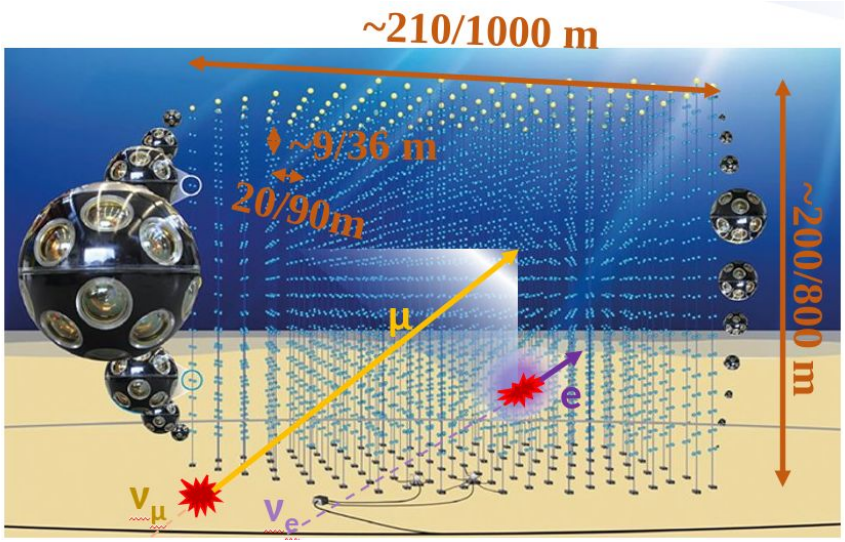
Goal: detection of Cherenkov photons induced by neutrino interactions in the sea

Main infrastructure:

- 115 string
- 18 module / string
- 31 PMTS / module
  - 3" Hamamatsu R12199-02

64.170 PMTs

x2 (x1) for ARCA (ORCA)



Data acquisition in the Mediterranean

- Optical properties:
  - λ_{abs}, λ_{scatt} > 30m

- Challenges:
  - R_{BG} ~ 7kHz per PMT
    - radio-active decays (K40)
    - Bioluminescense
  - Max. 200 Mbps throughput per optical module

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KM3NeT has committed to an **all-data-to-shore** principle

- Sending full PMT-waveforms impossible
- **Rigorous data-reduction essential!**

31 · 7e3 · 160 · 8 / 1e6 ~ **278 Mbps**

Data reduction

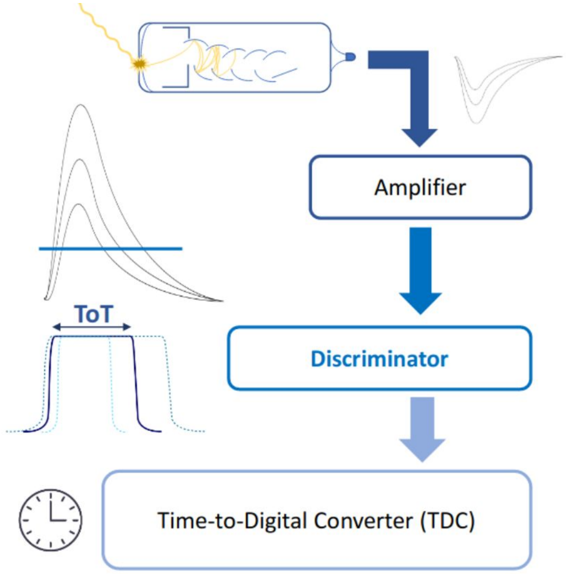
I. Off-shore filtering

A. PMT hardware threshold

B. Reduction of PMT analogue pulse to 6 Bytes (a hit):

1. PMT address i (1B)
2. Hit arrival time t_i (1B)
3. Time-over-threshold ΔT_i (4B)

} 1 ns least significant bit



II. On-shore filtering

A. Data aggregation into 100 ms timeslices

B. Realtime hit filtering based on coincidence levels

1. Level 0: single PMT hits
2. Level 1: >1 PMT hits within set timewindow in same module
3. Level 2: Level 1 criteria + maximal angle between PMTs

Data reduction

III. Online event triggering

- Specific triggers are applied **online** and **in parallel** on stored filtered data

  1. Muon trigger
     → hit coincidences within a cylinder surrounding a track hypothesis

  2. Shower trigger
     → Based on maximal distance between PMTs

  3. …
     → Extendible by any (B)SM physics event trigger
     E.g.: trigger for slow long-lived particles, like magnetic monopoles

No hardware event triggers used!

Calibration

Performance of KM3NeT relies on accurate calibration, i.e. determination of:

- Relative timing offsets between PMTs, modules and strings
- Position and orientation of modules
- PMT efficiencies
- PMT gains ⇦ **This talk!**

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How to calibrate PMTs based on 6B hit information?

Need to relate:

$$\begin{pmatrix} \underline{r}_i \\ t_i \\ \Delta T_i \end{pmatrix} \longrightarrow \begin{pmatrix} \Delta t_i \\ QE_i \\ G_i \\ \Sigma_i \end{pmatrix}$$

Pulse shape model

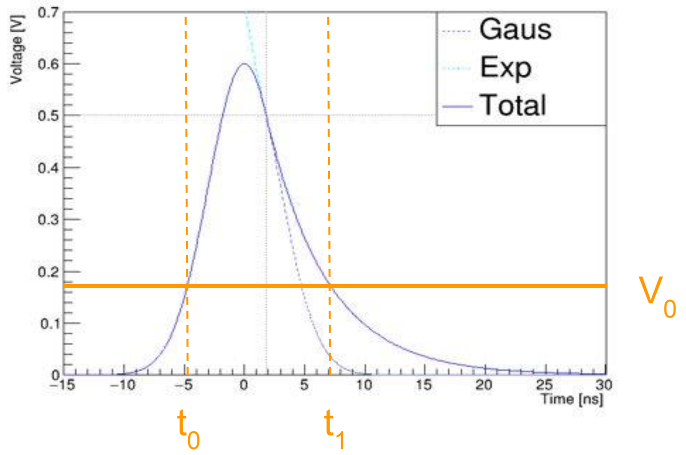
Analogue pulses to good approximation follow shape of **Gaussian + Exp tail** with 2 parms:

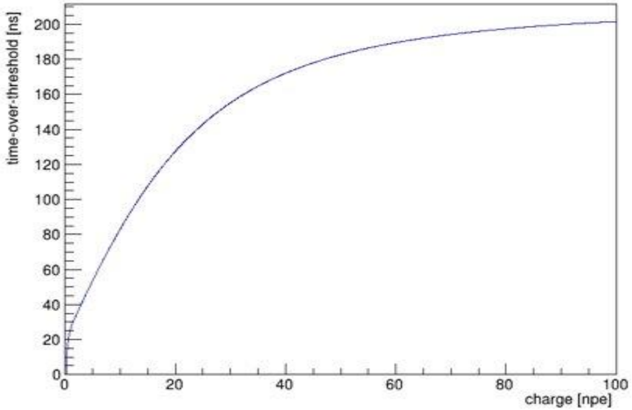
1. Gaussian spread, σ
2. Exponential decay time, τ

Yields ΔT which depends on q logarithmically
→ good sensitivity in 1 p.e. Regime

2 additional effects:

- Pulses exceeding voltage bias are clipped
  → linear regime above 1 p.e.
- Saturation after 30 p.e.





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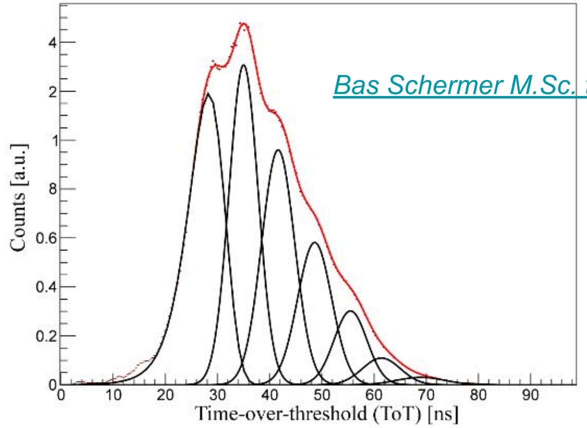
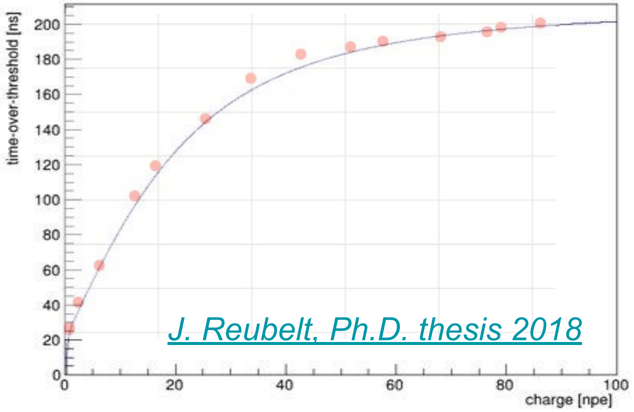


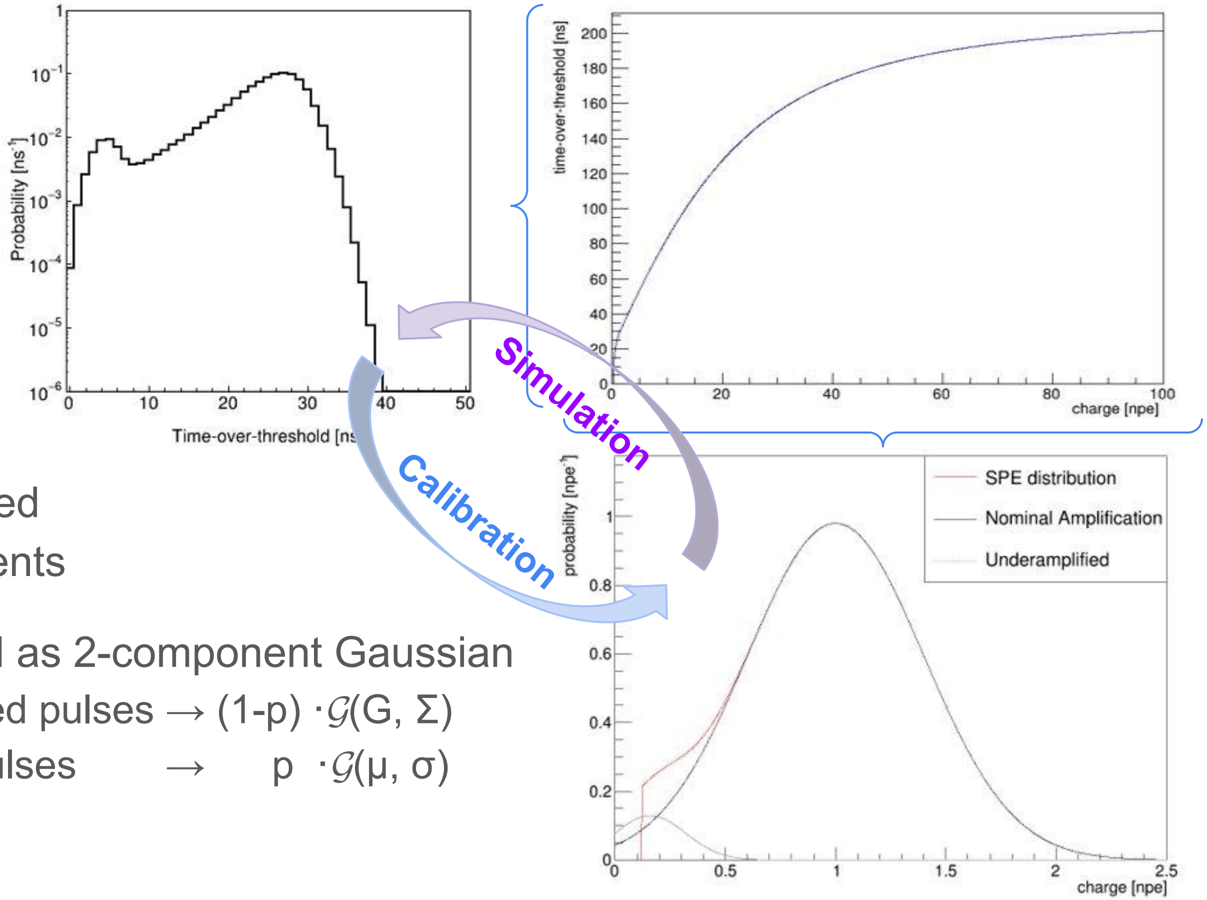


Gain calibration

Analogue pulse model bridges ΔT and q

→ Allows **simulation** of ΔT-distributions based on q-distribution model

→ Allows **calibration** of q-distribution parameters based on ΔT-distribution measurements



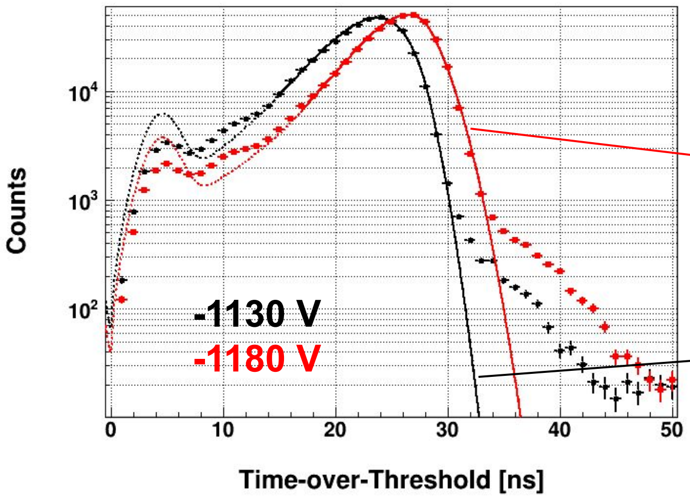
- q-distribution modeled as 2-component Gaussian
  a. Nominally amplified pulses → (1-p) $\cdot\mathcal{G}(G, \Sigma)$
  b. Underamplified pulses → p $\cdot\mathcal{G}(\mu, \sigma)$

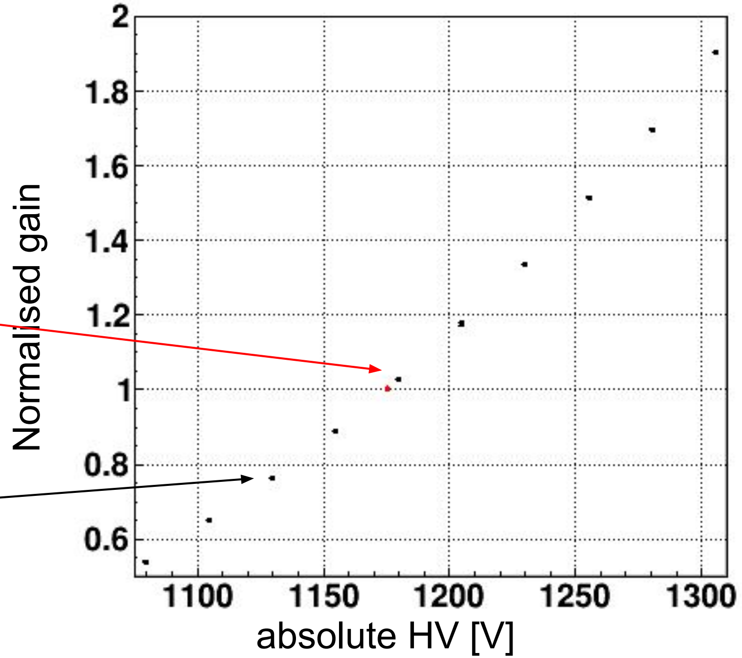
Tuning the gain

Gain and HV are related according to a power-law: $G = A \cdot V^{kn}$

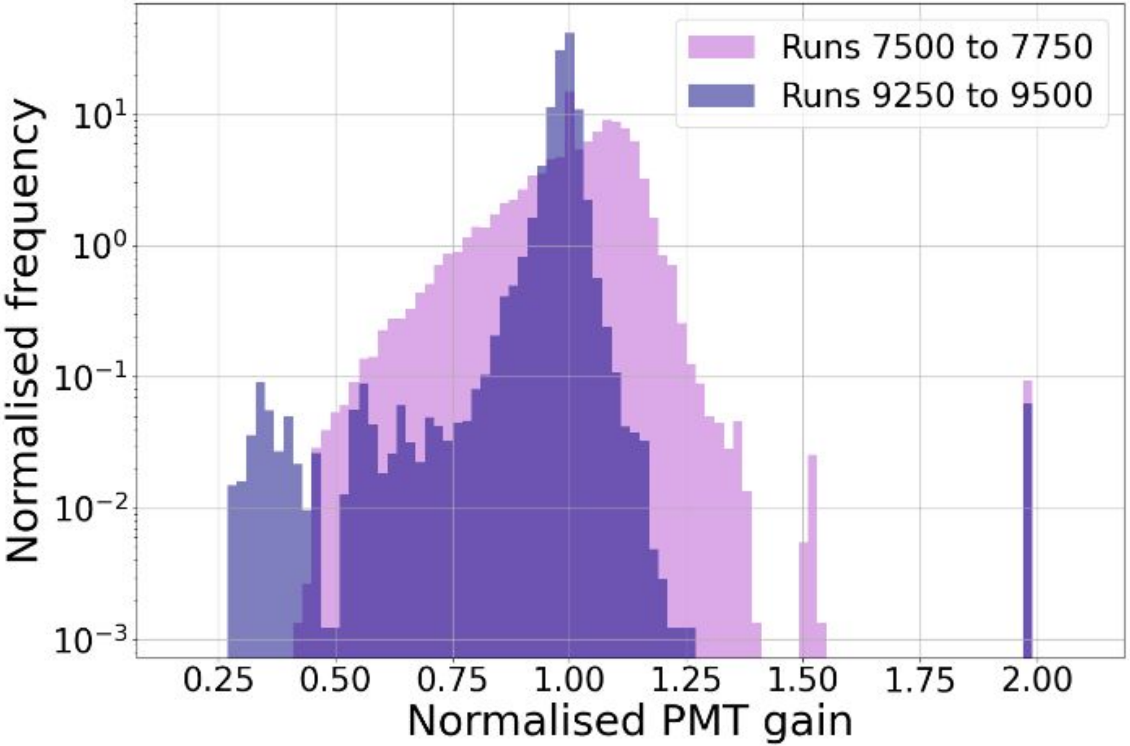
Allows gain-tuning by:

1. Fitting gain @ varying HV
2. Interpolating HV for G = 1.0





Tuning the gain



Method applied in-situ since summer 2020

Significant improvement in gain-values

Summary

KM3NeT tackles a unique challenge

- High data rate, limited bandwidths
- All-data-to-shore-principle

Rigorous data-reduction is applied

- Off- and onshore filtering; online event triggering
- ~~Storing full waveforms~~ →leading edge + time-over-threshold

PMT calibrations based on 6B hit info developed and working

- E.g. PMT gain calibration based on time-over-threshold

Thank you

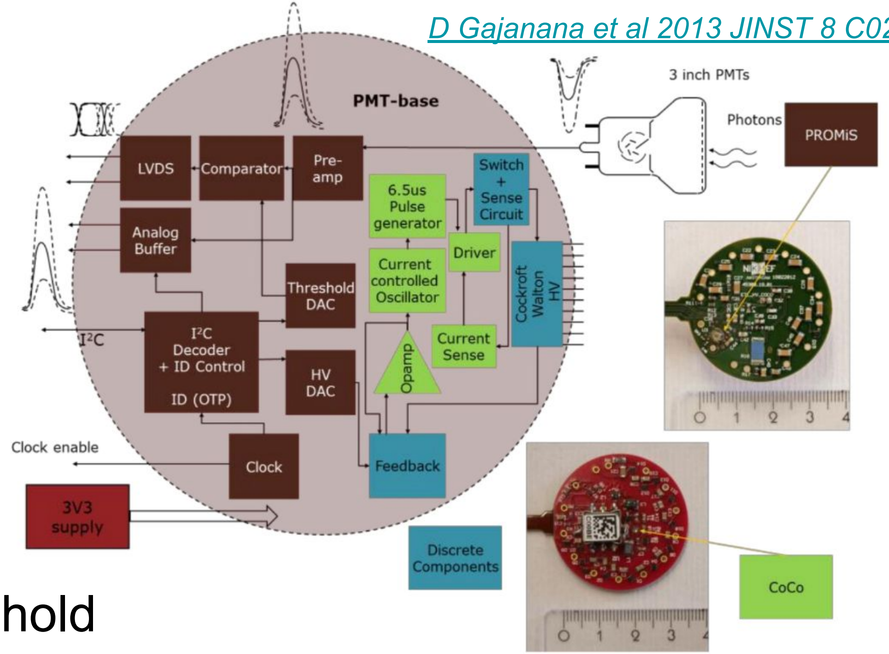
Questions?

Extra

PMT base

[D Gajanana et al 2013 JINST 8 C02030](#)

Each PMT equipped with individual low power HV base



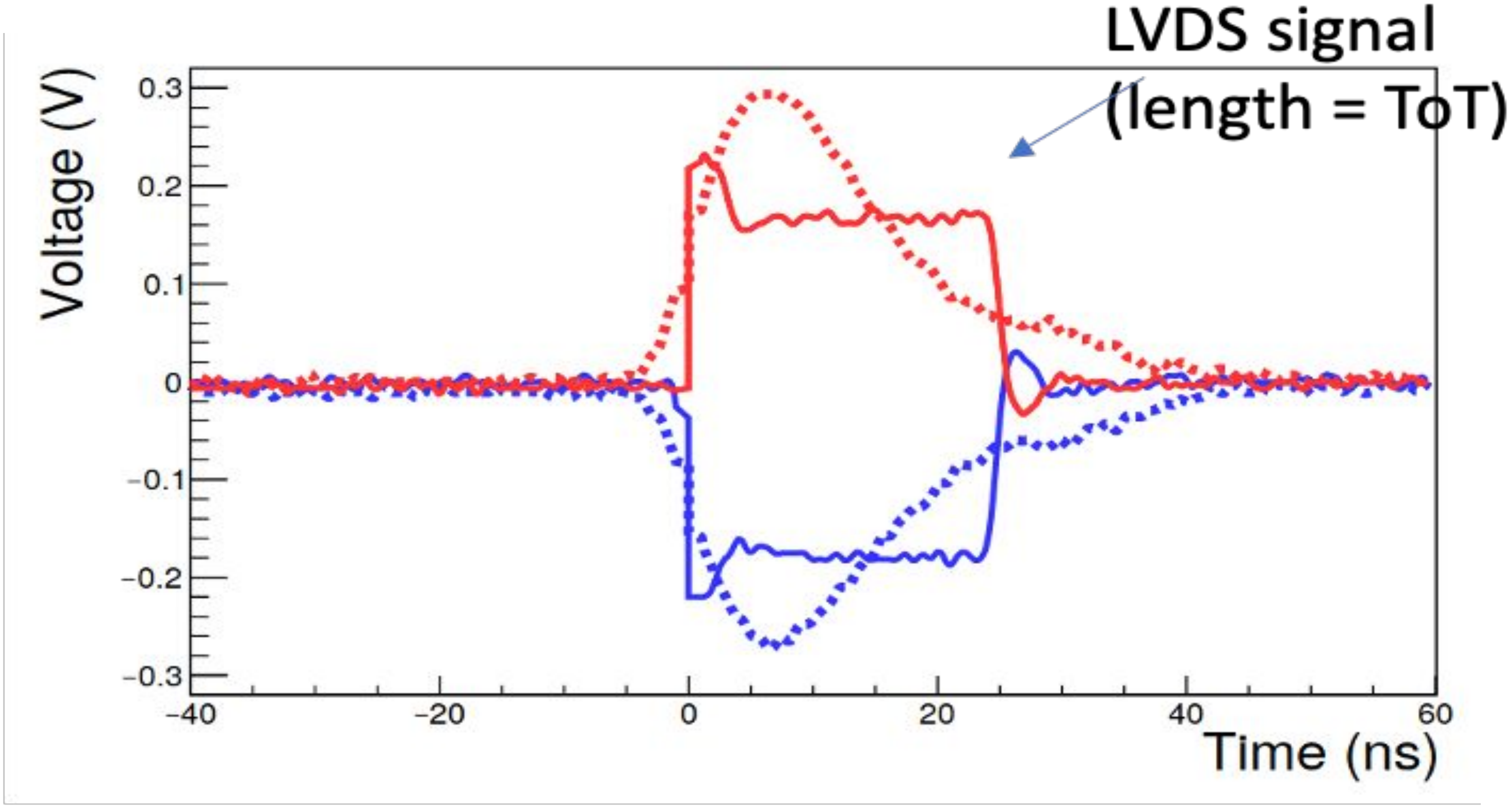
HV generated on base via CW circuit

- Controlled with custom ASIC

PMT signal is:

1. Amplified
2. Discriminated against tunable threshold
3. Transformed into Low-Voltage Differential Signal (LVDS)
4. LVDS duration (leading edge) recorded as time-over-threshold (arrival time)

See also: [arXiv 2203.10048](#)


LVDS signal
(length = ToT)
Voltage (V)
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−40
−20
0
20
40
60
Time (ns)