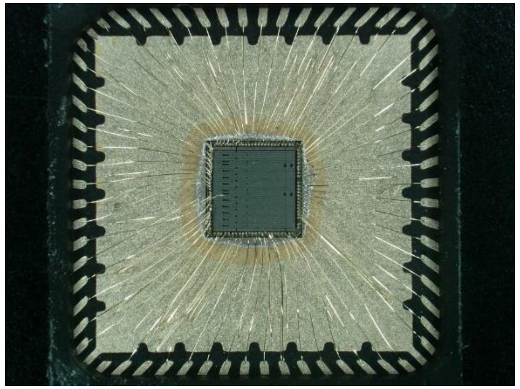

# The FastIC project: From the FastIC ASIC to FastIC+ and FastRICH


R. Ballabriga on behalf of the CERN-ICCUB collaboration

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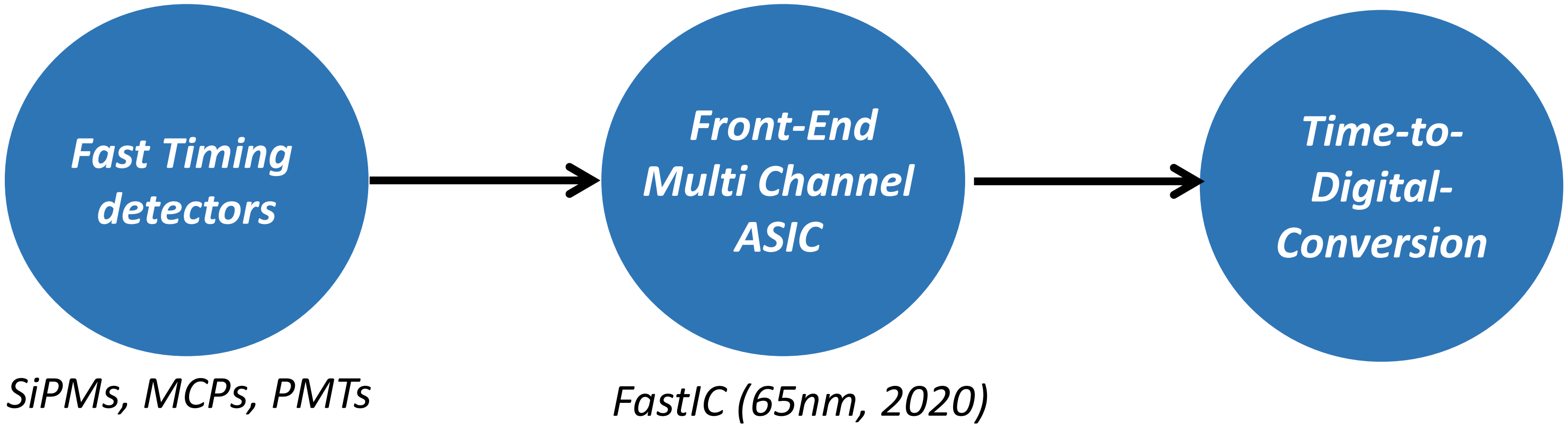
# Outline

- FastIC project context
- Architecture
- Readout
- Measurements (Linearity, Energy resolution, SPTR, CTR)
- Derivatives of FastIC (FastIC+, FastRICH)
- Summary

# The FastIC project: context

# The FastIC project: motivation




FastIC addresses limitations from NINO (2004, 0.25μm): mainly non-linearity of the energy measurement and power consumption

Highly configurable:

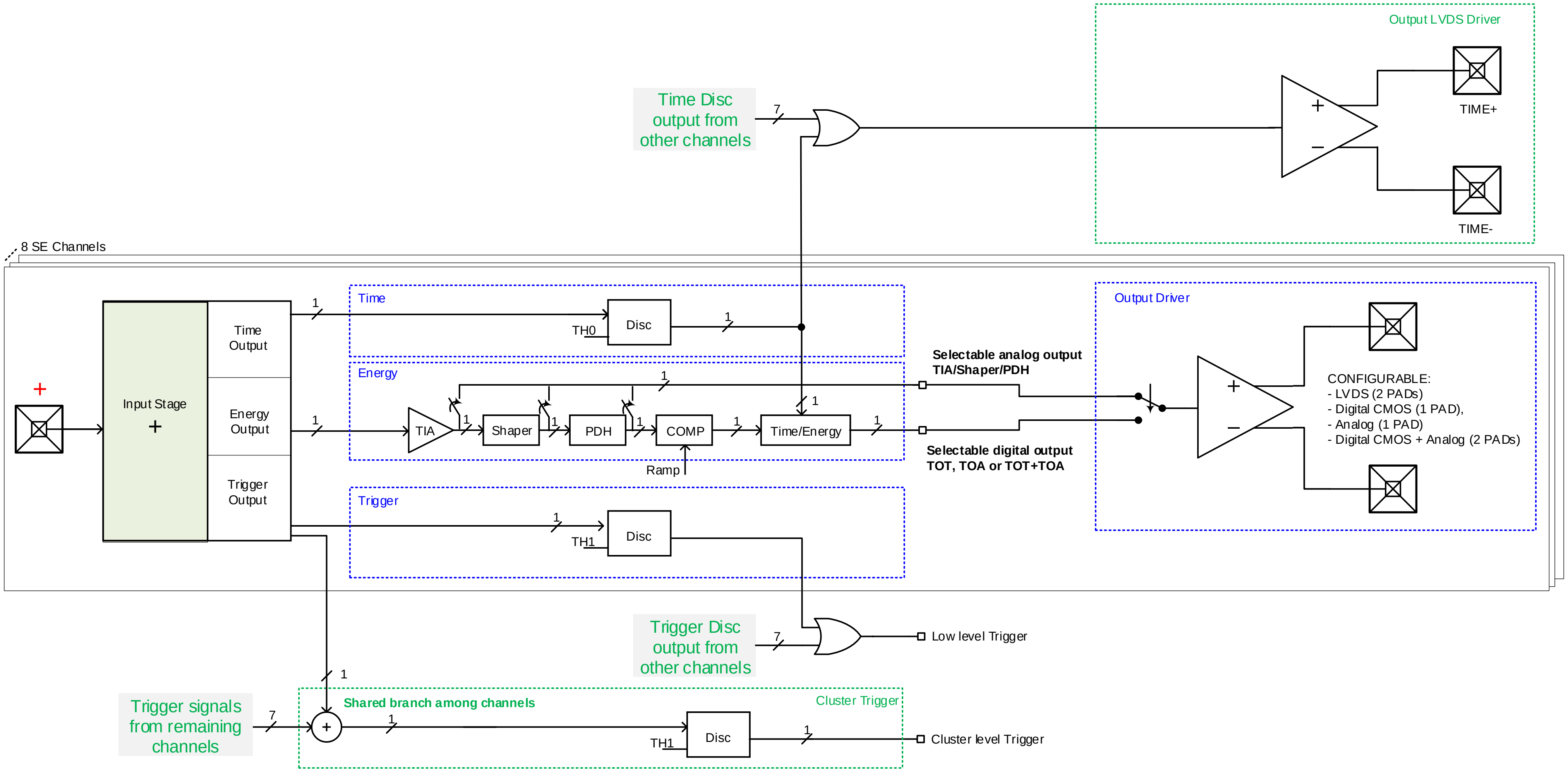
- Singled ended, differential and summation of 4 single-ended channels to explore benefits of segmentation of detector areas
- Positive and negative polarity
- Large range of input capacitances
- Large dynamic range (with positive and negative polarity readout)

~30 ps r.m.s. Jitter (electronics) (Hamamatsu S13360-3050CS, 3600x50μm microcells, 4.5$V_{OV}$, wirebonded) + Linear energy measurement (~2.5 % error) up to 20 mA peak (12mW single ended channel)

Collaboration between CERN (KT funded) and University of Barcelona (ICCUB)

# The FastIC project: Architecture

# Single Ended (Positive Polarity) configuration

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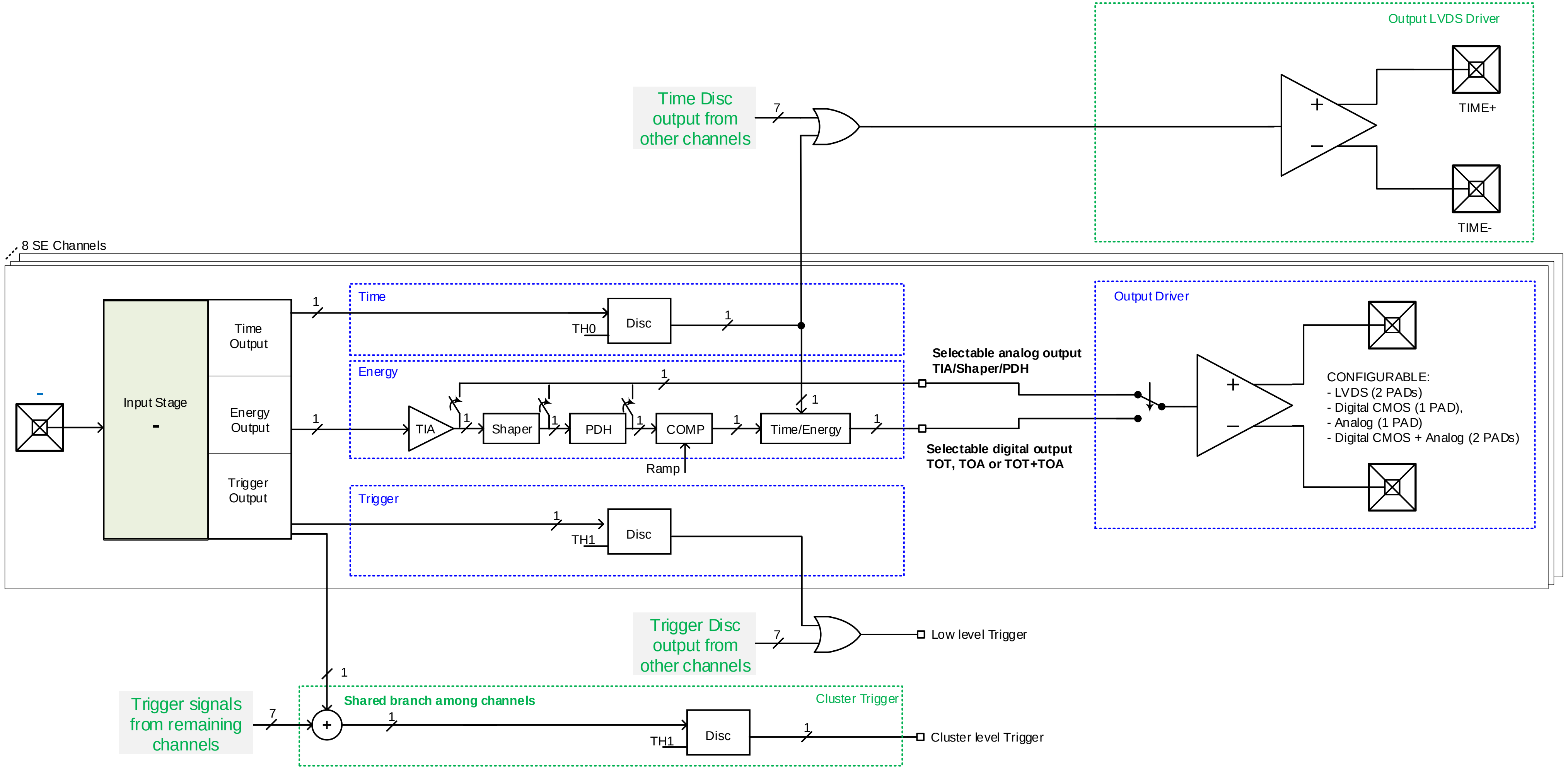
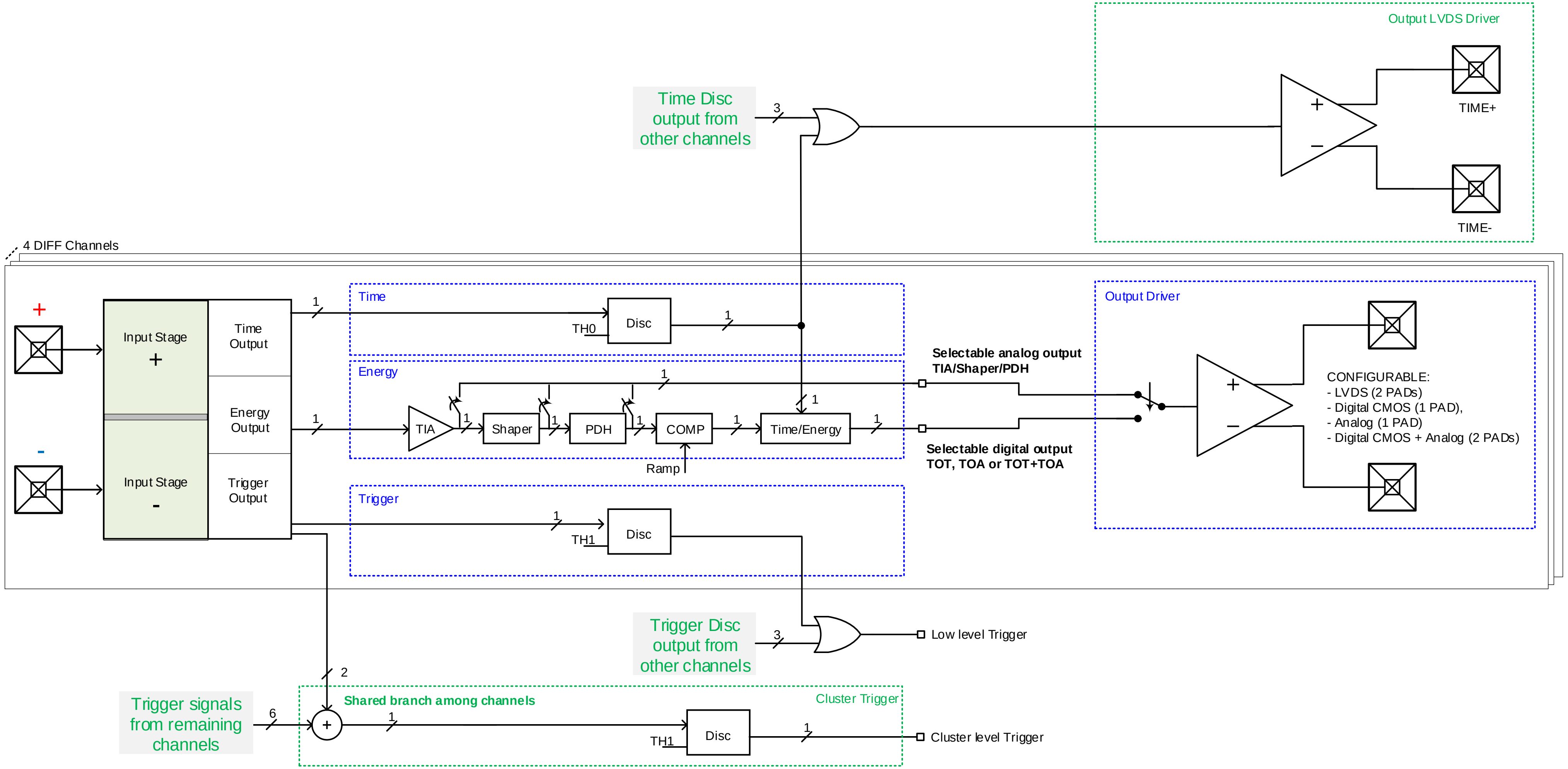
# Single Ended (Negative Polarity) configuration

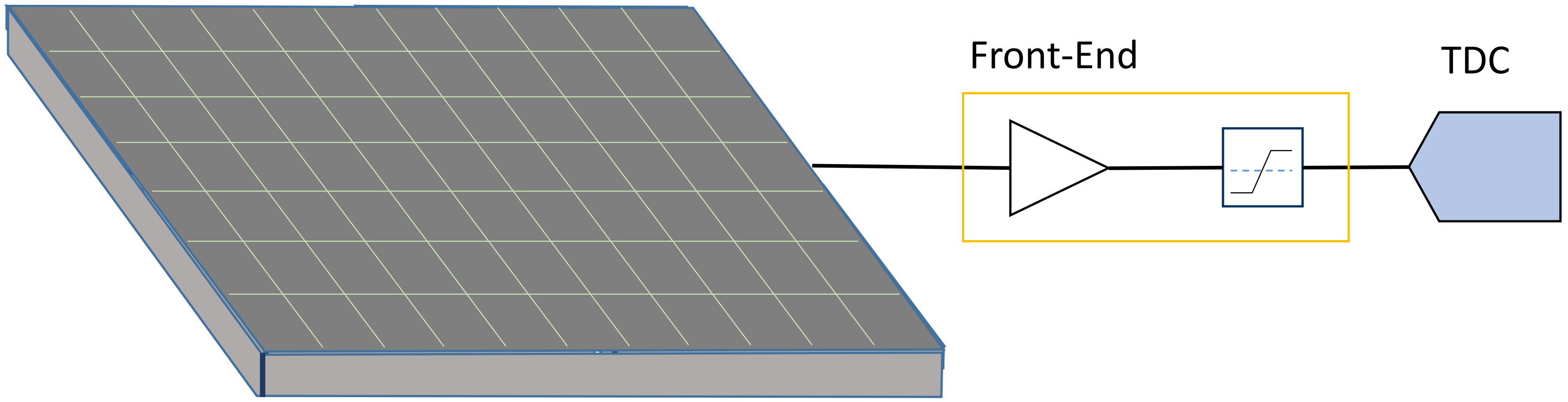


# Differential configuration



# Implementation: combination of signals

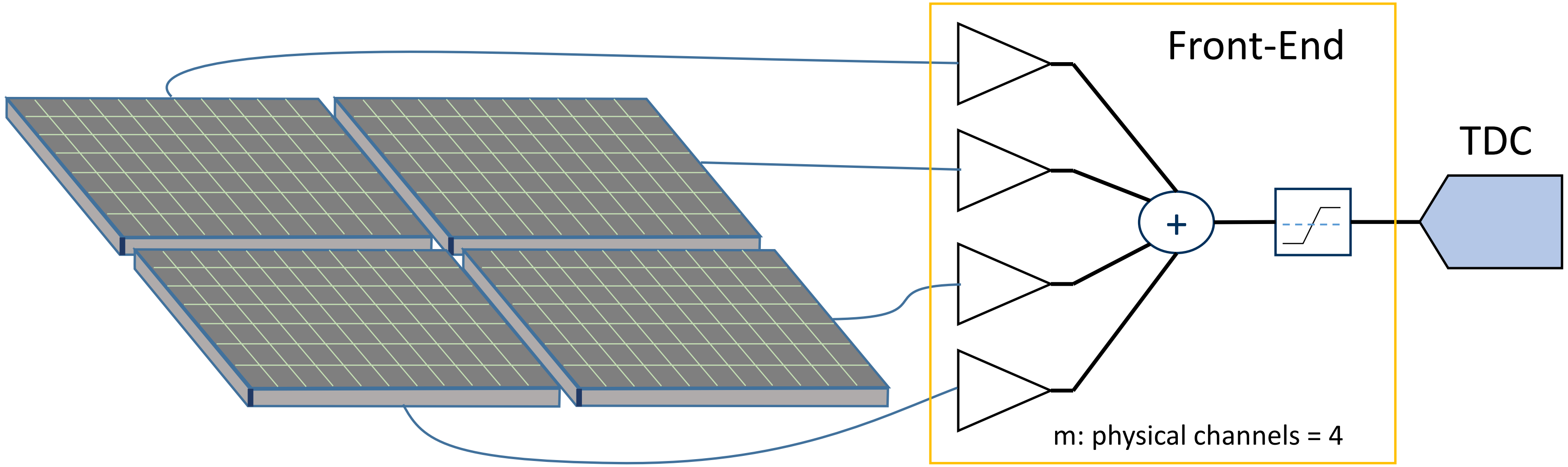
**Large area SiPM → Large Cdet**




- Large area SiPMs can have an equivalent detector capacitance higher than 1 nF
- This high input capacitance degrades the slew-rate $SR \propto \frac{Q_{det}}{C_{det}}$

# Strategy to cope with large detectors

**Segment SiPMs to cover same area → Cdet/4**



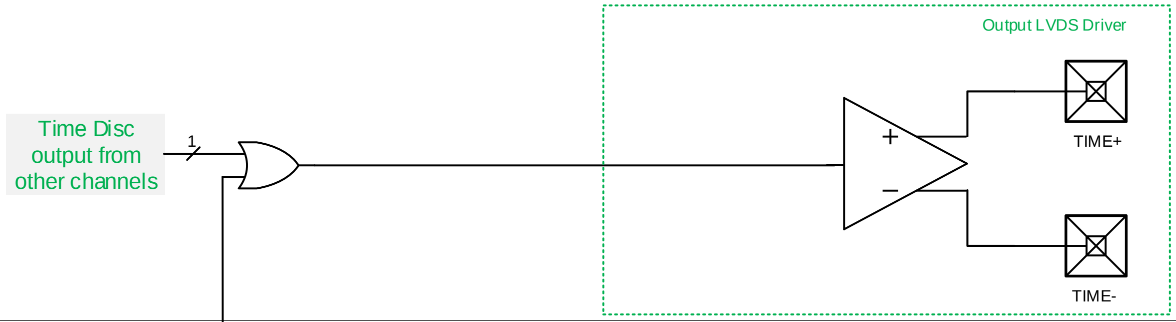

- Segmentation: Cover same area with ***m*** smaller sensors.
  - Potential improvement of the slew-rate by a factor of m (i. e $SR \propto m\frac{Q_{det}}{C_{det}}$)
  - Series noise contribution is approximately constant w.r.t. segmentation
    - (i.e. $\sigma_n \sim \sqrt{m} \cdot \sigma_{n,smallDet} \sim \sqrt{m} \cdot \frac{C_{largeDet}}{\sqrt{m}}$)

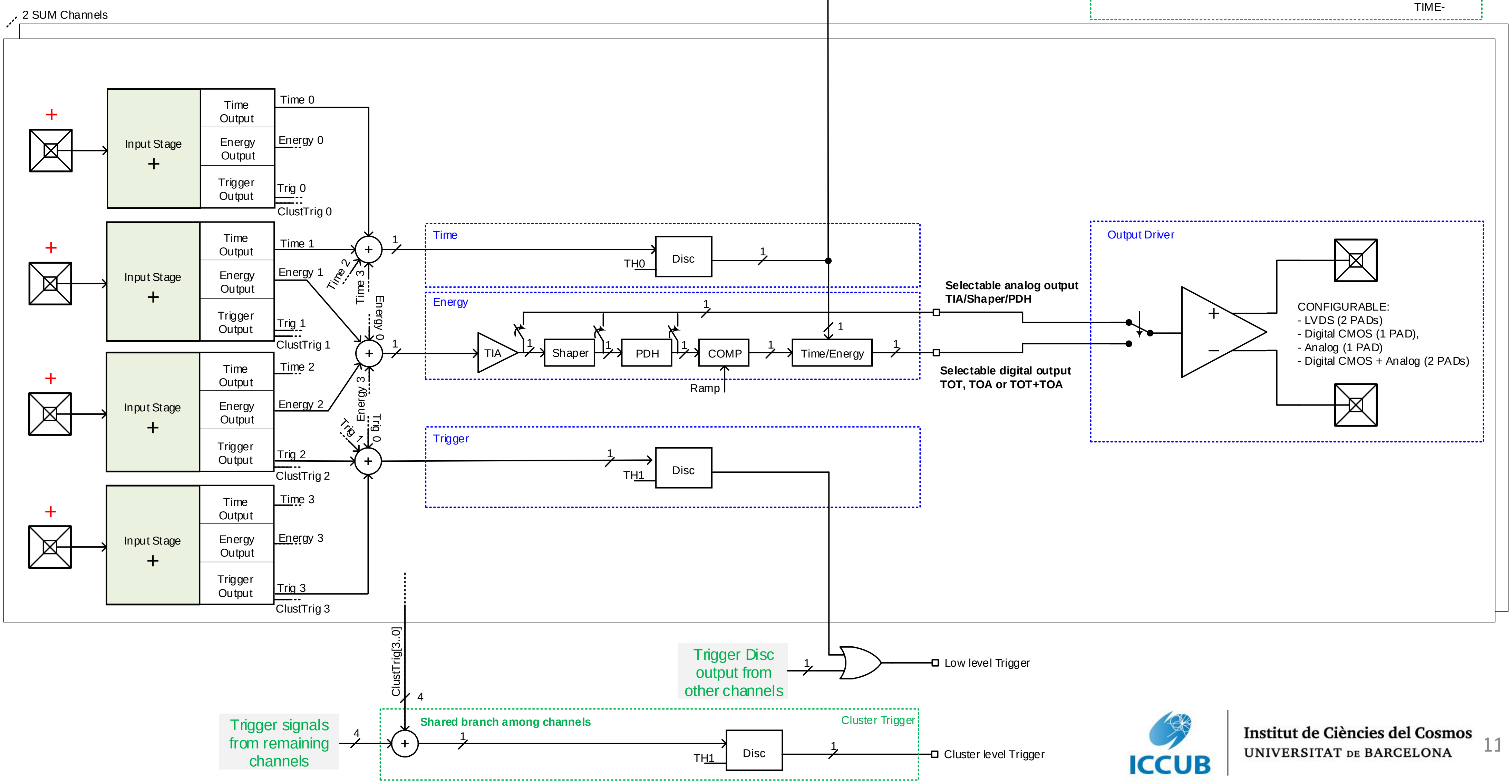
Potential reduction of $\sigma_t$ by a factor $m$

Sum of $m$ uncorrelated contributions

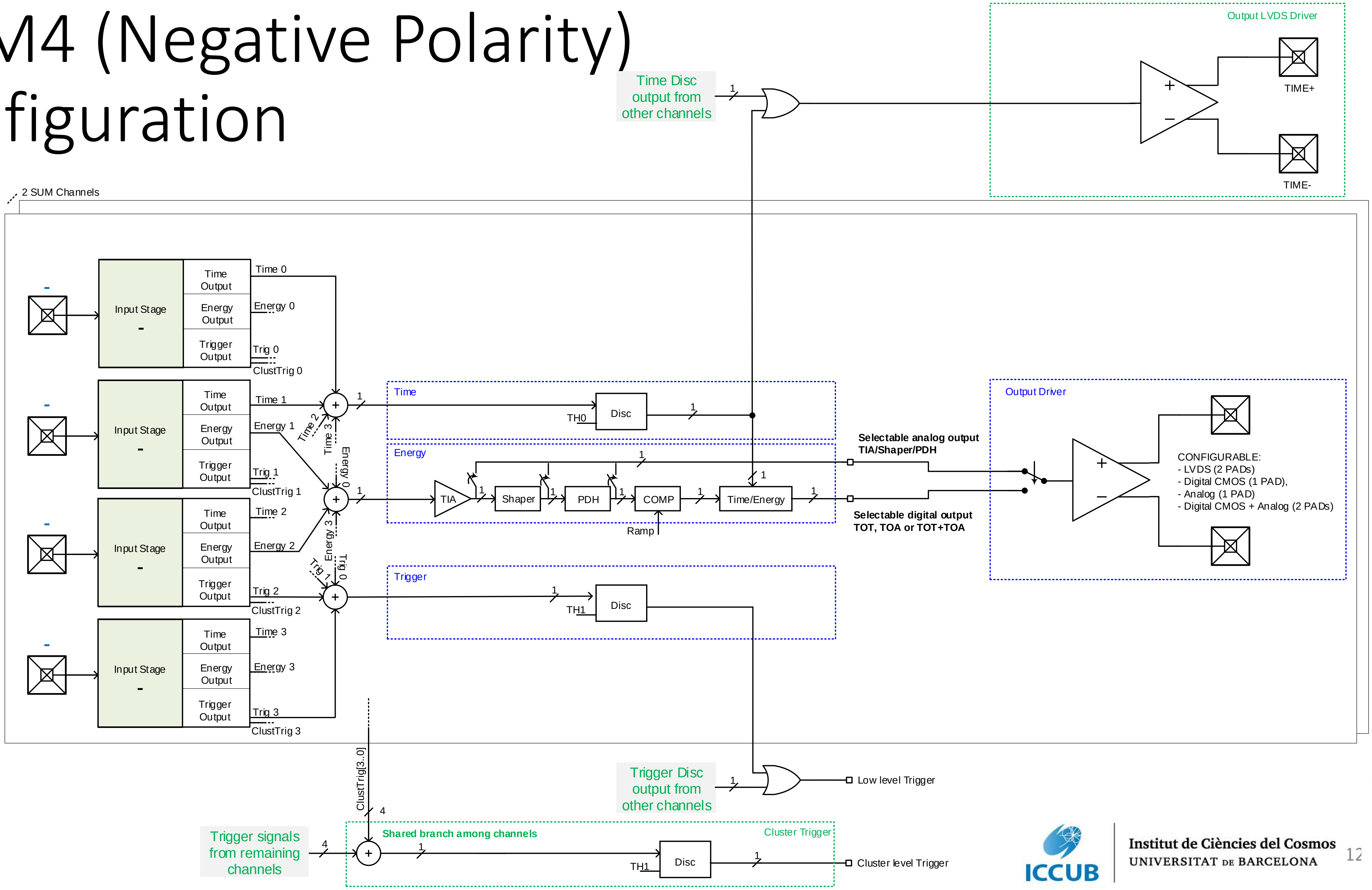
The series noise is proportional to the detector capacitance, which reduces a factor *sqrt(m)*

# SUM4 (Positive Polarity) configuration



# SUM4 (Negative Polarity) configuration

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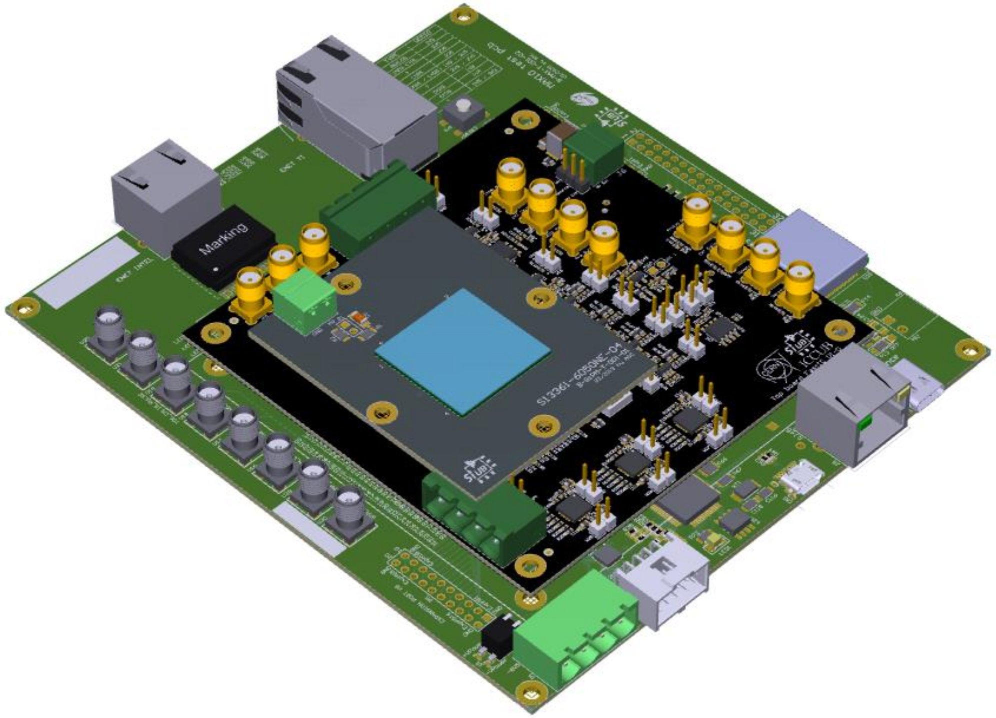
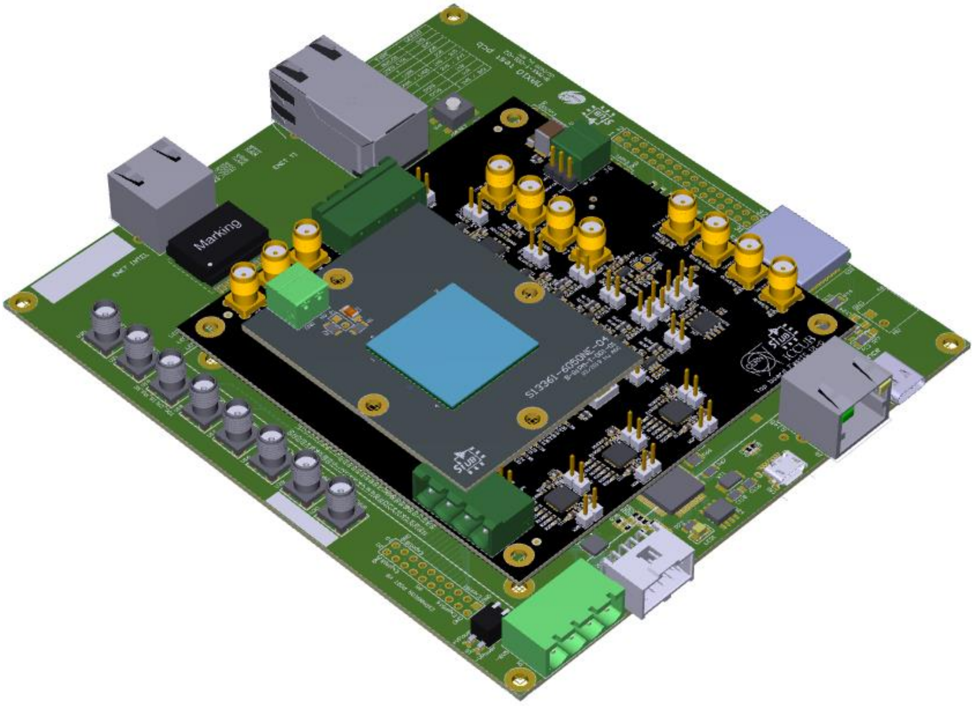
# The FastIC project: readout system

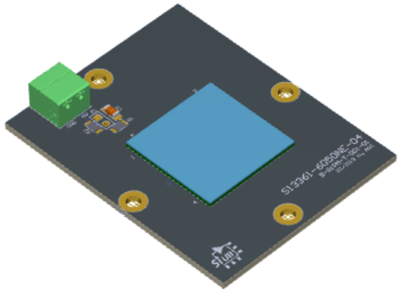
# Evaluation system

- Aims of the evaluation system:
  - Basic operational test & debug ASIC functionalities
  - Initial electrical characterization and linearity analysis.
  - Initial benchmark i.e. evaluate the FastIC chip by comparison
    - With respect previous designs (NINO, HRFlexTOT)
    - Using reference SiPM sensor:
      - Hamamatsu S13360-3050CS
      - FBK NUV-HD
  - Interface with other sensor based on adaptor board
  - Signal acquisition:
    - FPGA-based TDC (45ps time bin)
    - Differential sLVS link to external system

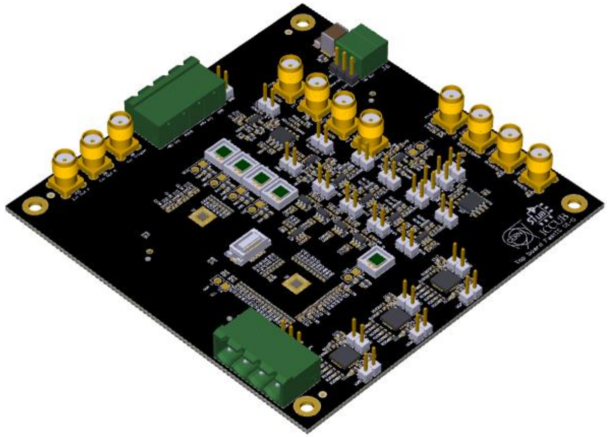


# Evaluation system

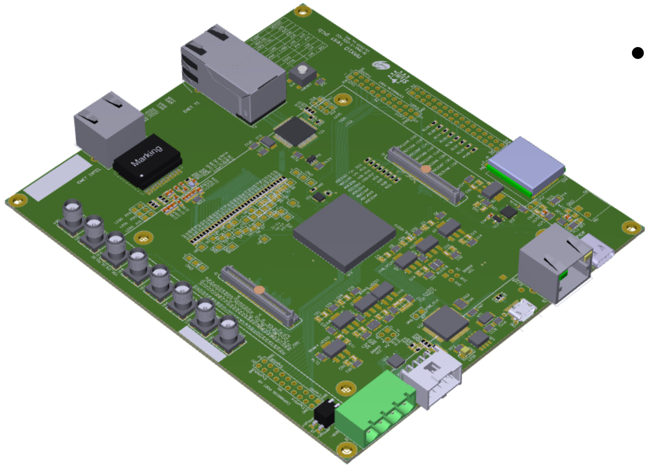




- Custom sensor board



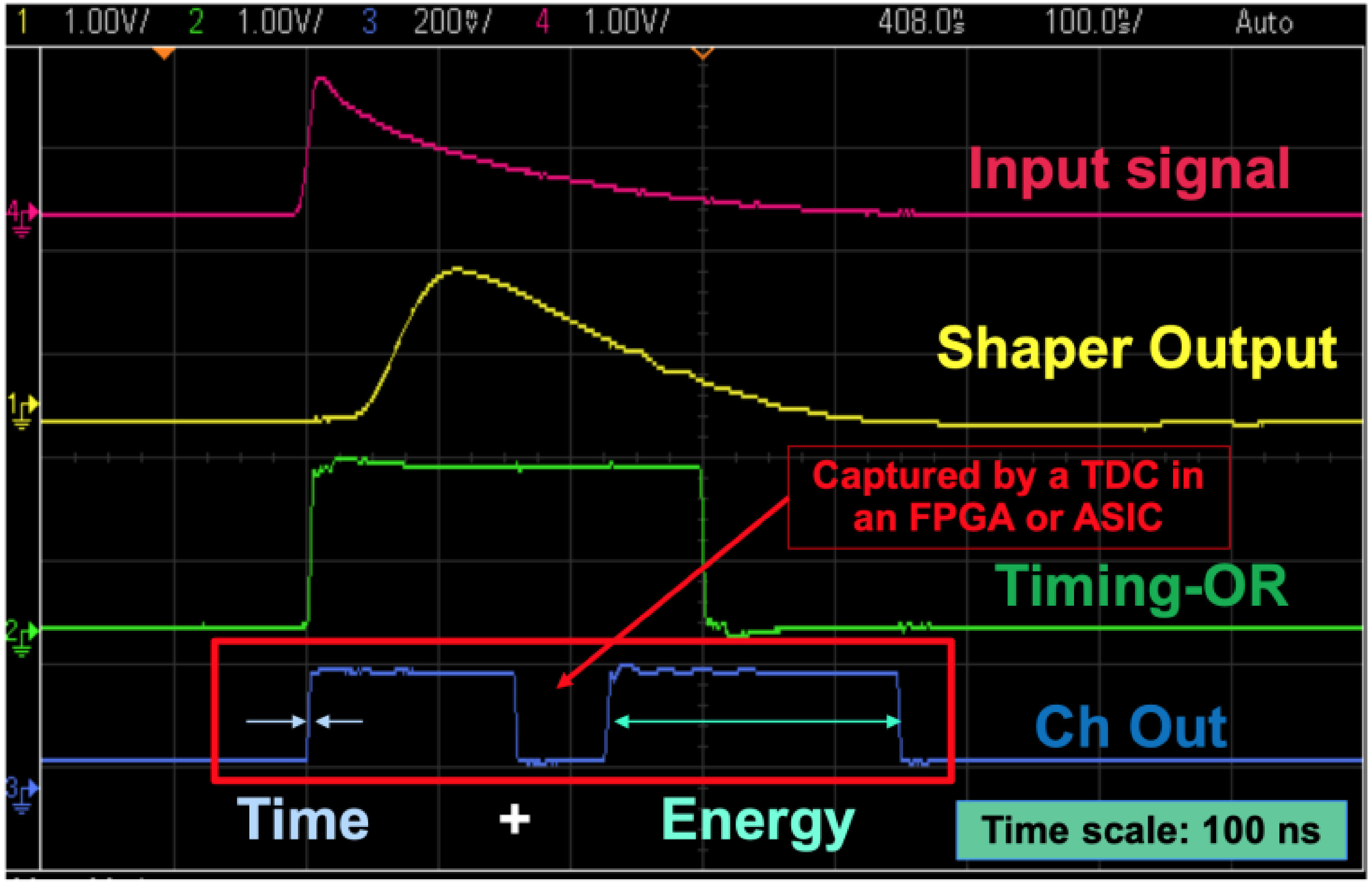
- FastIC generic board
  - 2 FastICs on QFN64 (16 channels)
  - Reference SiPM sensors included
  - The board can be used stand alone



- FPGA board
  - FPGA board for slow control, acquisition and additional biasing.
  - Multichannel TDC is implemented in the FPGA (45ps time bin)

# The FastIC project: measurements

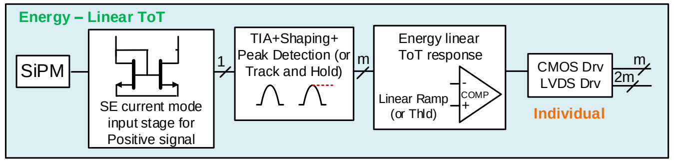
# Time waveforms



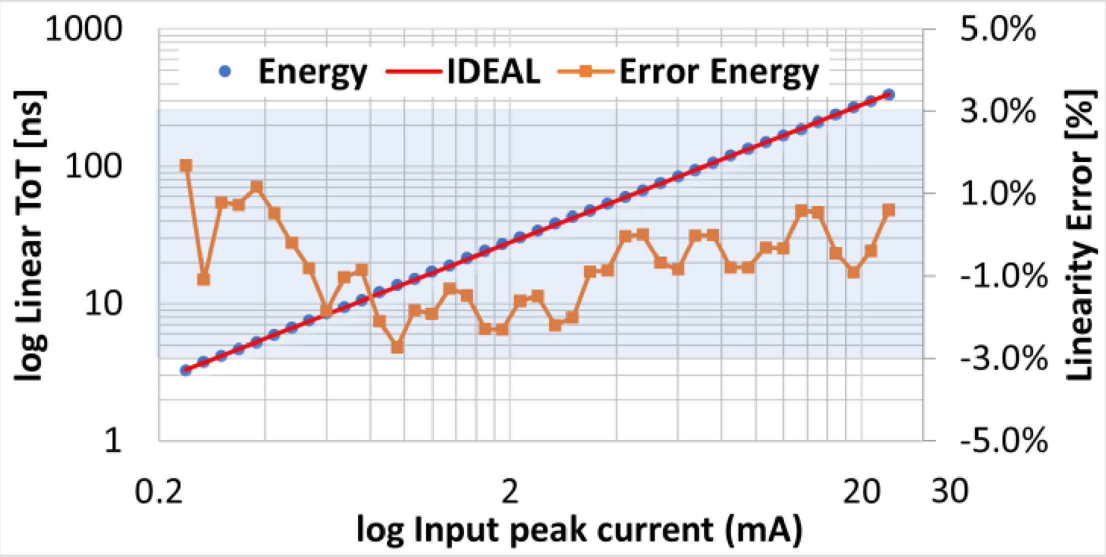

- FastIC provides a measurement of time and energy per channel in two consecutive pulses
- Time is encoded in the rising edge of the first pulse
- Energy is encoded on the width of the second pulse. The readout is based on HRFlexToT architecture*

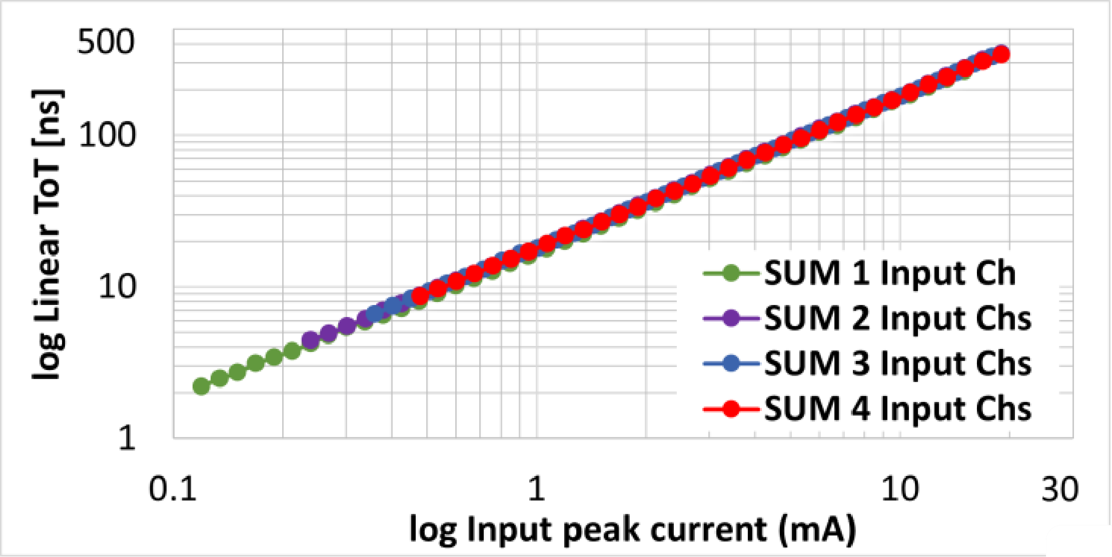
*D. Sanchez, S. Gomez, et. al. "HRFlexToT: A High Dynamic Range ASIC for Time-of-Flight Positron Emission Tomography" 2021, IEEE TRPMS, https://doi.org/10.1109/TRPMS.2021.3066426

# Linearity of the energy measurement




- An electrical SiPM-like signal is injected into the FastIC for energy evaluation using an AWG
- Linearity error is below 3% over the whole dynamic range
- Saturation is reached at 25 mA input current (positive polarity) and 20 mA (negative polarity)
- Summation in the energy is linear, independently of the channels added
- This makes FastIC very versatile and suitable for LYSO/LSO, BGO, Cherenkov, Monolithic, etc.



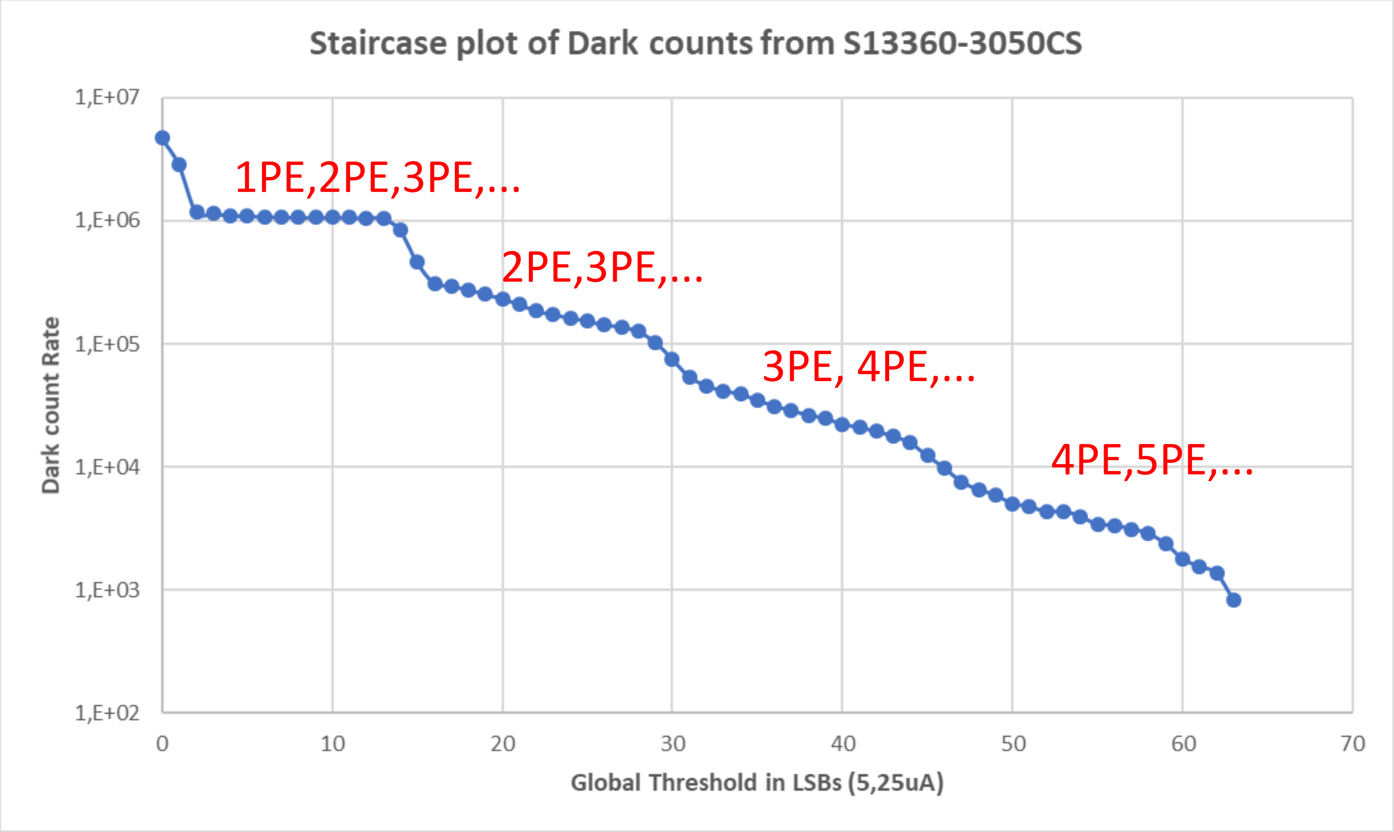



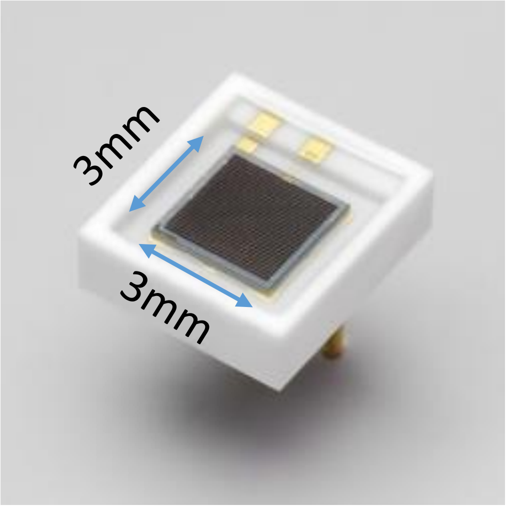

*S. Gomez*

# The FastIC project: measurements with sensors

# SiPM measurements

- Positive Input stage
- SiPM S13360-3050CS operated at 60V of HV (Over-voltage ~7.6V)




SiPM Hamamatsu S13360-3050CS

*S. Gomez, D. Sanchez*

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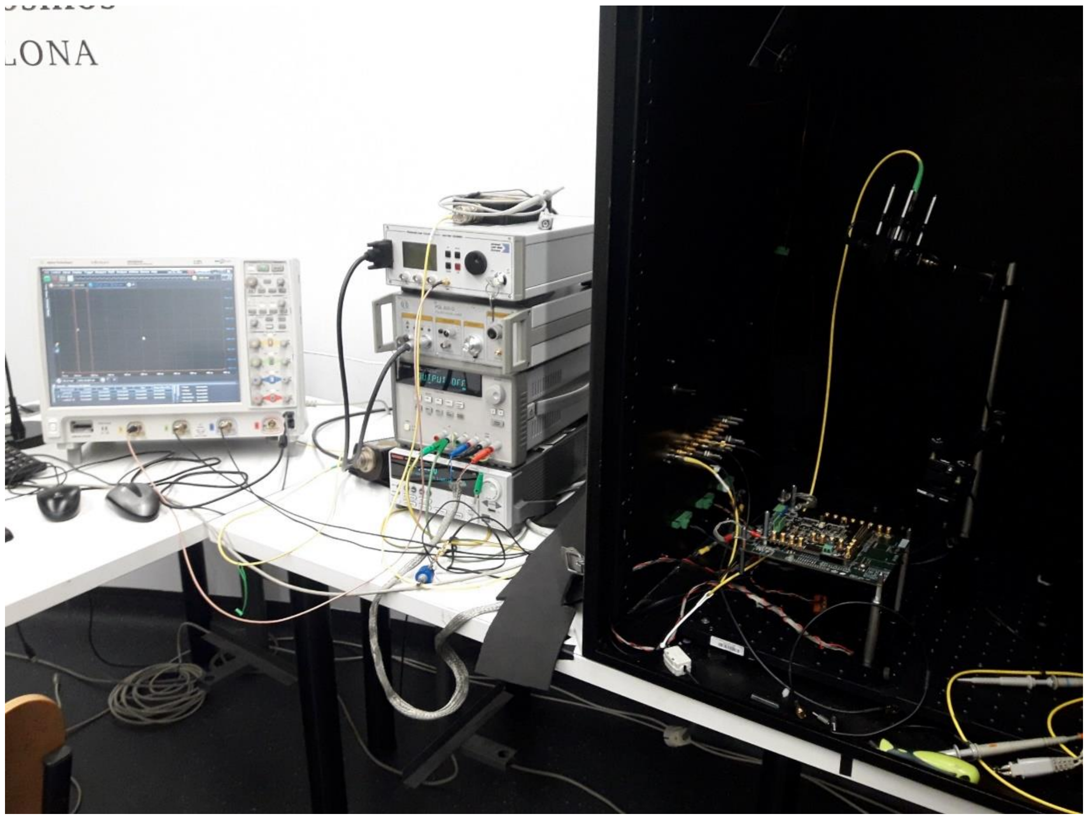
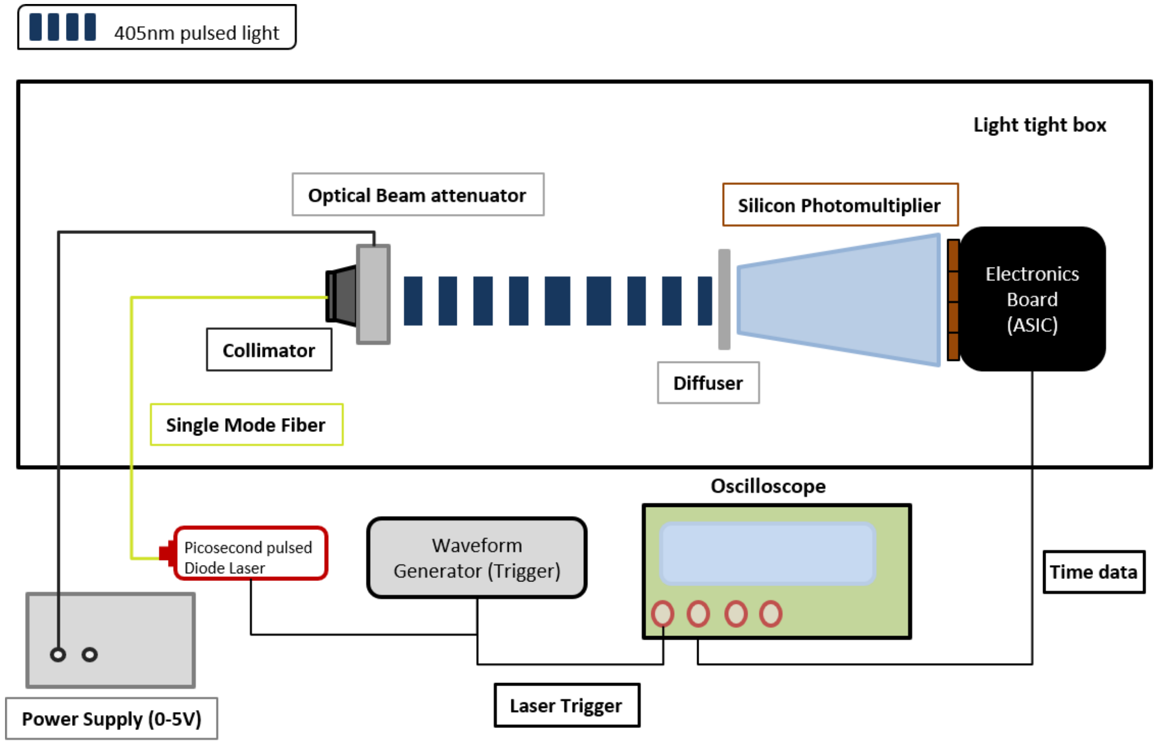
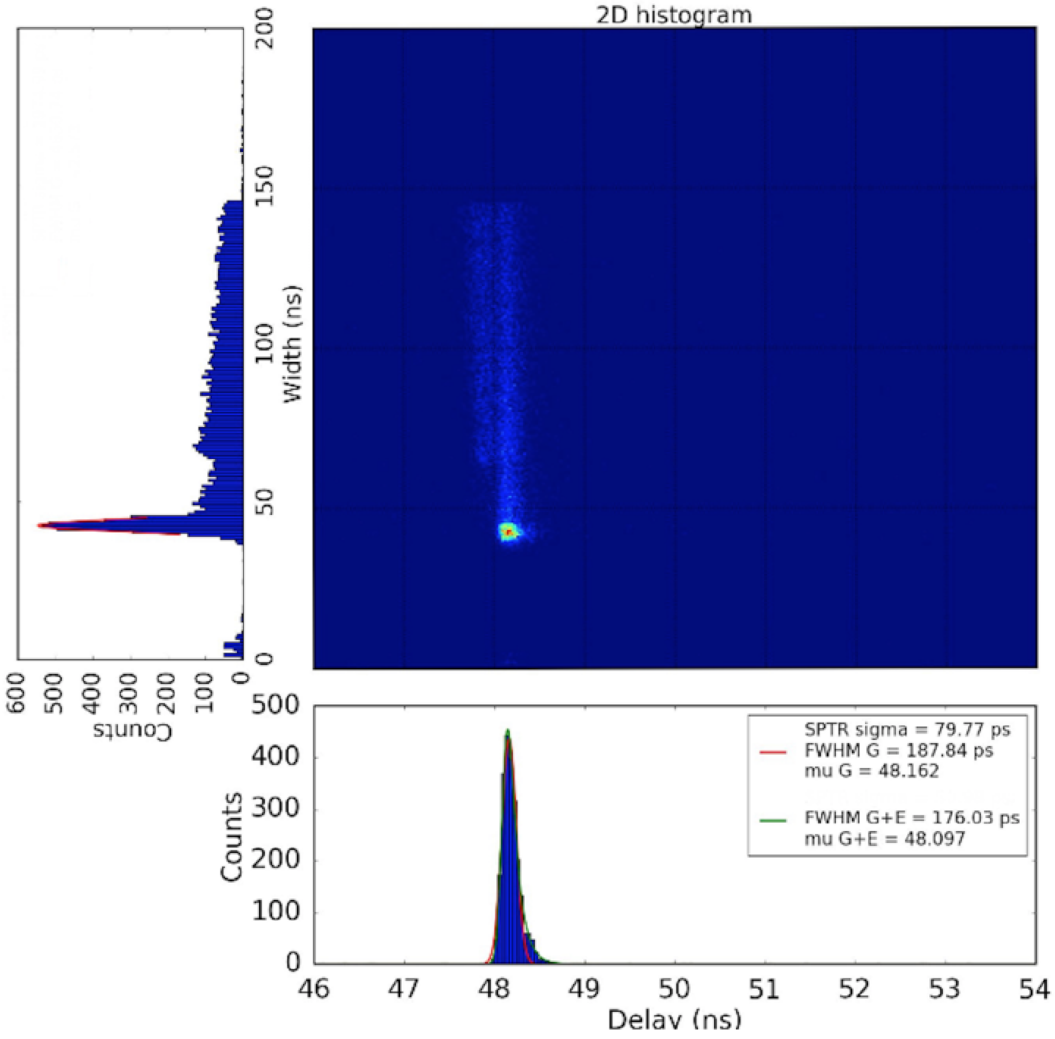
# Setup for SPTR measurement

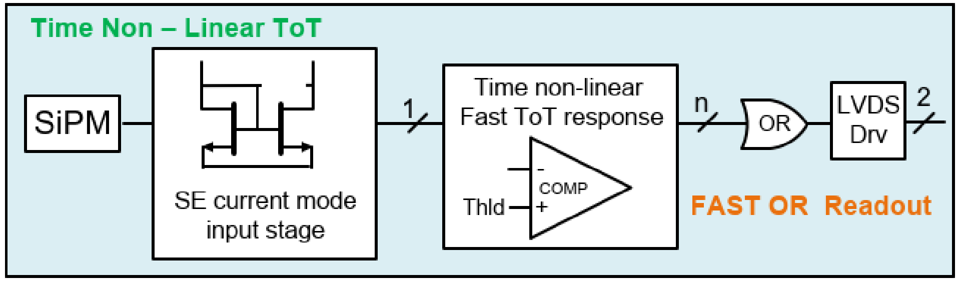
- Laser (405 nm) – 40 ps FWHM pulse width



# SPTR measurement




Hamamatsu S13360-3050CS (3x3 mm$^2$ 50$\mu$m cell pitch, $V_{OV}$=11V)

**SPTR= 176 ± 5 ps FWHM**

FBK NUV-HD Low Field V2 (3.12x3.2 mm$^2$ 40$\mu$m cell pitch, $V_{OV}$=10.5V)

**SPTR= 151 ± 5 ps FWHM**

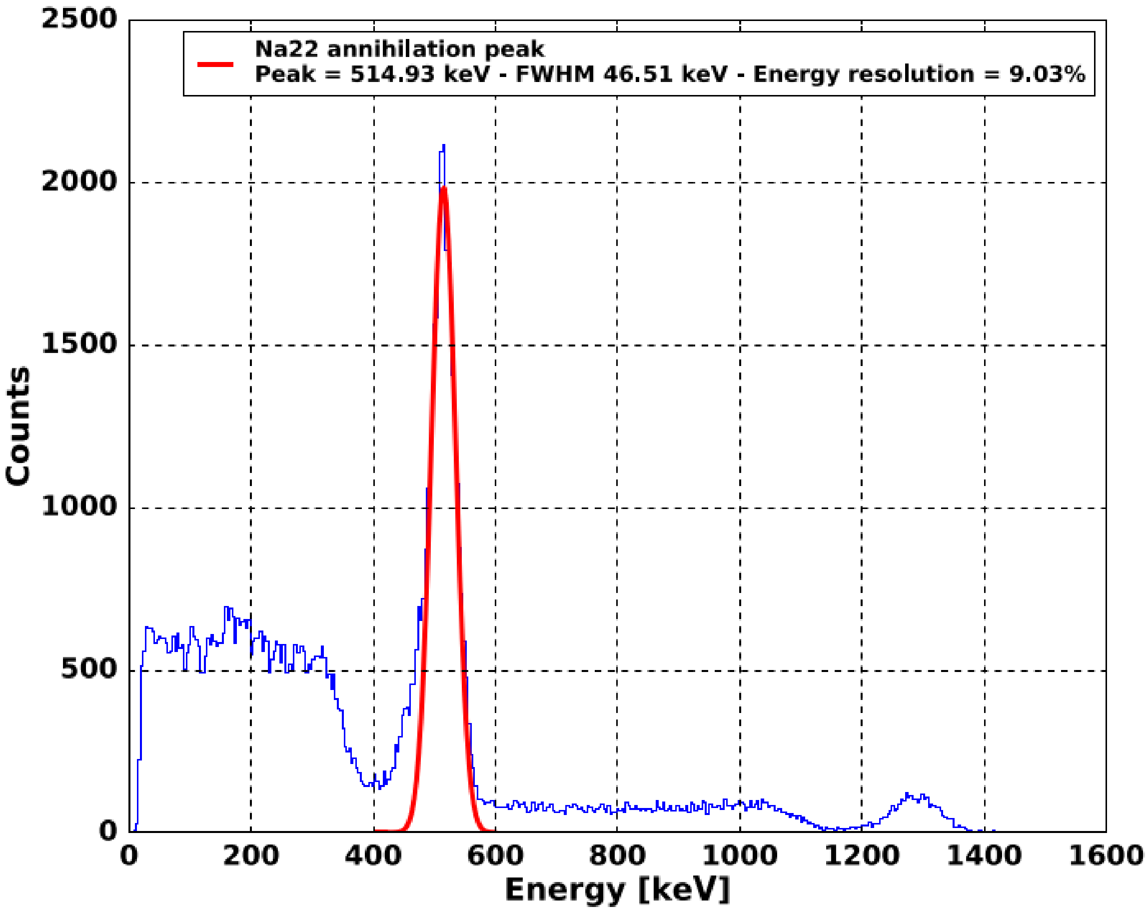


S. Gómez

# Energy resolution measurement

- The Energy Resolution was measured with a $^{22}Na$ source
- The TDC implemented in the FPGA was used to digitize the data
- Crystal: LYSO:Ce:0.2%Ca 3.13x3.13x20mm$^3$
- SiPM: Hamamatsu S13360-3050CS (3x3 mm$^2$ 50$\mu$m cell pitch, $V_{OV}$=3V)
- Compton edges and gamma peaks are used to calibrate the nonlinearities of the SiPM*
- Energy resolution expressed in FWHM/$\mu$ [%].

**Energy resolution of 511 keV $^{22}Na$ ~9%**

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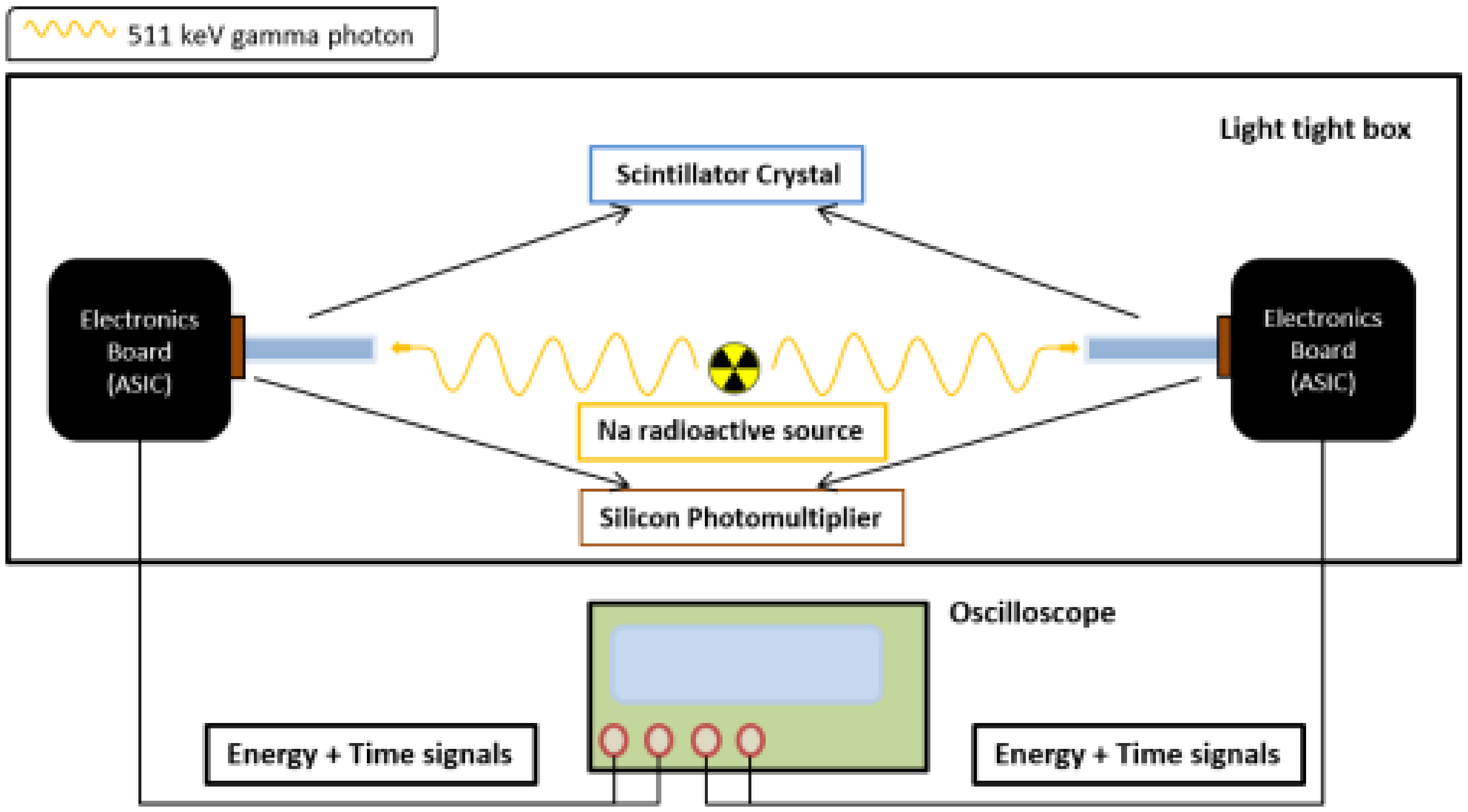
*D. Sanchez, S. Gomez, et. al. "HRFlexToT: A High Dynamic Range ASIC for Time-of-Flight Positron Emission Tomography" 2021, IEEE TRPMS, https://doi.org/10.1109/TRPMS.2021.3066426

# Coincidence Time Resolution

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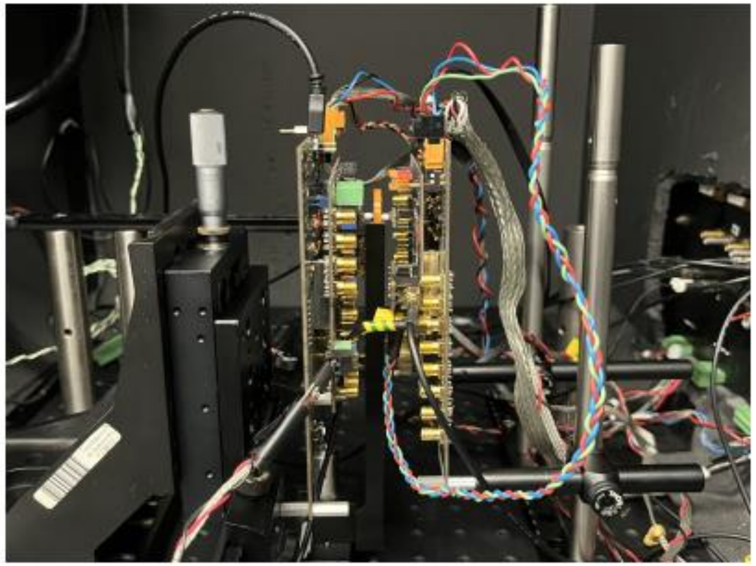
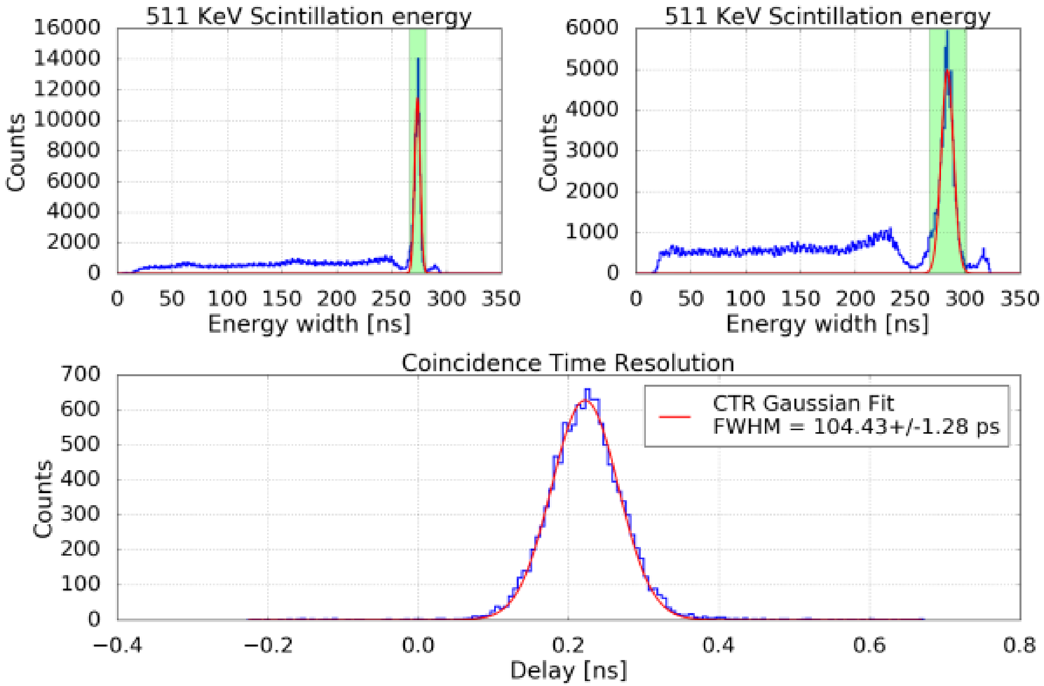
# Coincidence Time Resolution

Crystal: LSO:Ce:0.2%Ca 2x2x5 mm$^2$, LY=39.2 ph/keV, $\tau_d$=~32ns

SiPM: Hamamatsu S13360-3050CS (3x3 mm$^2$ 50$\mu$m cell pitch, $V_{OV}$=8V)

**CTR= 104 ± 3 ps FWHM**



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# Coincidence Time Resolution

Crystal: LSO:Ce:0.2%Ca 2x2x3 mm$^2$, LY=39.2 ph/keV, $\tau_d$=~32ns

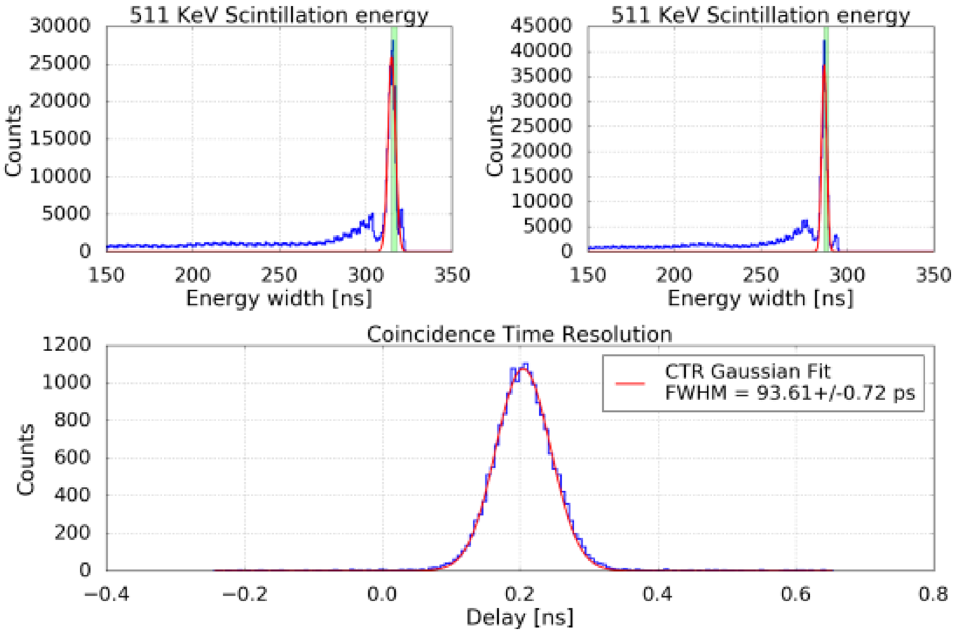
SiPM: Hamamatsu S13360-3050CS (3x3 mm$^2$ 50$\mu$m cell pitch, $V_{OV}$=8V)

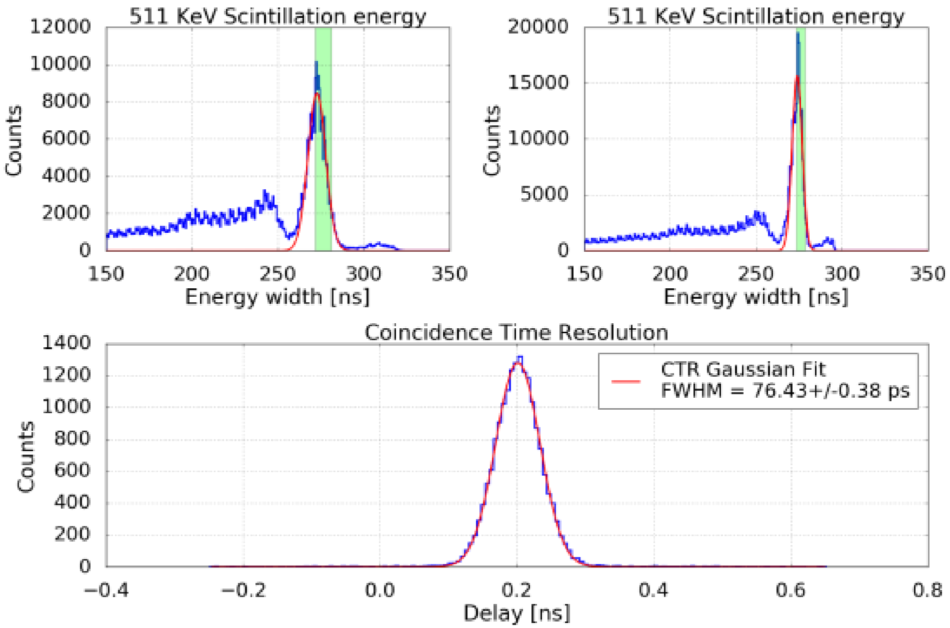
**CTR= 93 ± 3 ps FWHM**

Crystal: LSO:Ce:0.2%Ca 2x2x3 mm$^2$, LY=39.2 ph/keV, $\tau_d$=~32ns

SiPM: NUV-HD LF V2 (3.12x32 mm$^2$, 40$\mu$m cell pitch, $V_{OV}$=6.1V)

**CTR= 76 ± 2 ps FWHM**



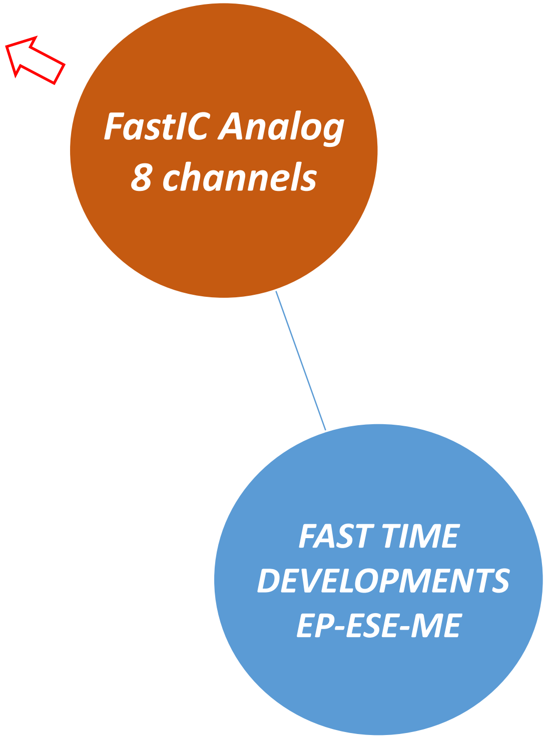




S. Gómez

*Design completed (CERN-UB)*

FastIC Analog:

- Analog chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with external TDC
- Not radiation hard



*Design completed (CERN-UB)*

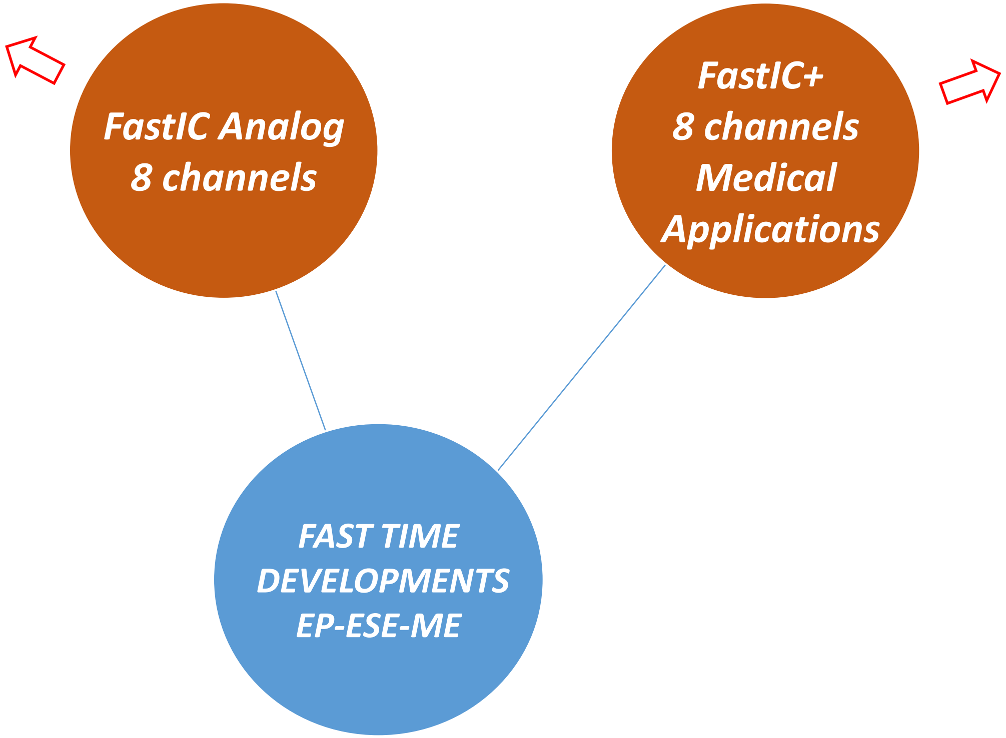
FastIC Analog:

- Analog chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with external TDC
- Not radiation hard

*Design ongoing (CERN-UB)*

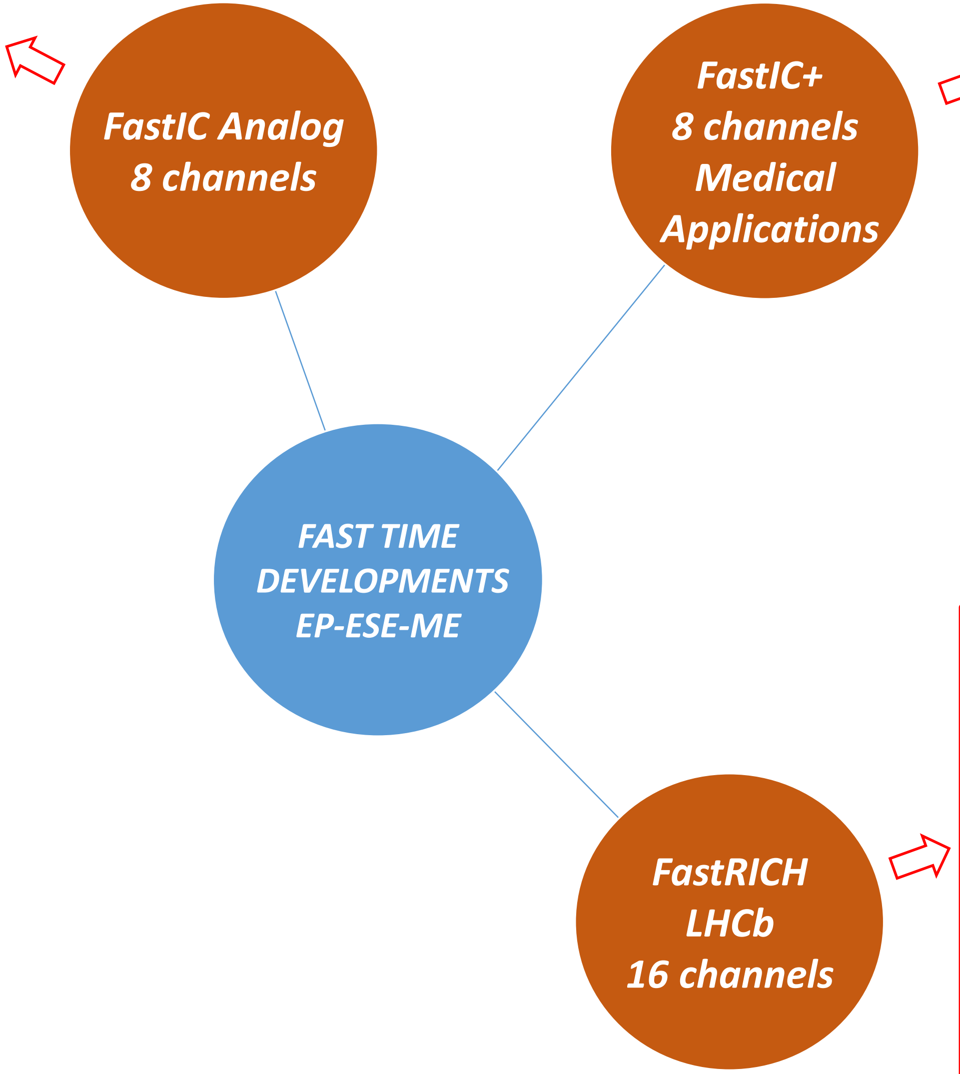
FastIC+:

- Analog and Digital chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with internal ~25ps bin TDC
- Not radiation hard



*Design completed (CERN-UB)*

FastIC Analog:
- Analog chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with external TDC
- Not radiation hard




*Design ongoing (CERN-UB)*

FastIC+:
- Analog and Digital chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with internal ~25ps bin TDC
- Not radiation hard

*Design ongoing (CERN-UB)*

FastRICH:
- Analog And Digital chip
- Application specific
- Smaller range $C_{DET}$ (PMTs/Small SiPMs)
- Small dynamic range (single photon operation)
- No signal summing
- Internal TDC (~25ps bin TDC)
- ~2ns Gate (duration/phase programmable)
- CFD
- Radiation hard

# Towards FastRICH

- FastRICH is based on the experience from the CERN-UB team on the design of FastIC for the readout of fast detectors
- The design involves major changes in the analog part, the implementation of a TDC and a full digital readout
- The chip provides a radiation hard (TID and SEE), low power and compact system for the LHCb RICH detector for interfacing with the detector on one side and on the other with lpGBT/optical links
- The chip aims at reducing the amount of data generated
    - With Zero Suppressed Readout
    - A programmable ~2ns Shutter signal
    - A Constant Fraction Discriminator (CFD)
- And also a configurable number of output links (1/2/4) to adapt to the occupancy of the different regions of the experiment

*Design completed (CERN-UB)*

FastIC Analog:
- Analog chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with external TDC
- Not radiation hard

***FastIC Analog***
***8 channels***

***FastIC+***
***8 channels***
***Medical Applications***

*Design ongoing (CERN-UB)*

FastIC+:
- Analog and Digital chip
- Generic
- Wide range $C_{DET}$
- Large dynamic range
- Signal summing
- Used with internal ~25ps bin TDC
- Not radiation hard

***FAST TIME DEVELOPMENTS***
***EP-ESE-ME***

Future Roadmap
- Emphasis on module
- Analog and Digital chip
- **Pixelized, Sensor co-design, hybrid integration**
- More channels
- Smaller range $C_{DET}$
- Large dynamic range
- No signal summing
- Used with internal TDC

***Future developments***

***FastRICH***
***LHCb***
***16 channels***

*Design ongoing (CERN-UB)*

FastRICH:
- Analog And Digital chip
- Application specific
- Smaller range $C_{DET}$ (PMTs/Small SiPMs)
- Small dynamic range (single photon operation)
- No signal summing
- Internal TDC (~25ps bin TDC)
- ~2ns Gate (duration/phase programmable)
- CFD
- Radiation hard

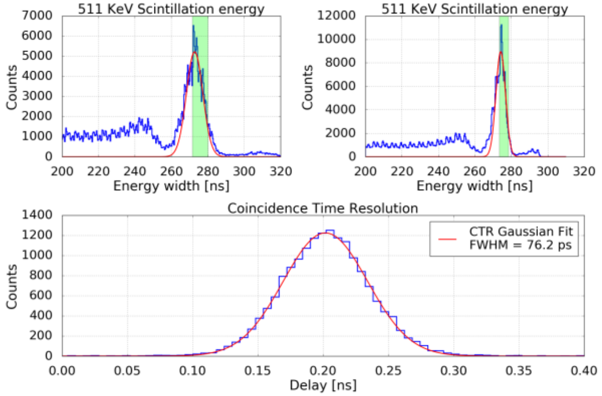
# Summary of results with FastIC

- Single Photon Time Resolution (SPTR) measurements
  - Blue light laser (PiL040X, 405nm, jitter <3ps, pulse width<45ps)
  - Agilent MSO 9404A, 4GHz, 20GS/s
  - $18^{o}$C Temperature
  - 176 ±3ps FWHM (HPK SiPM S13360-3050CS, 3x3mm$^2$ $V_{OV}$=10.6V)
  - 151 ±3ps FWHM (FBK HD-NUV Low Field SiPM, 40μm cell, 3.12x3.12mm$^2$ $V_{OV}$=10.6V)
  - Fits with the initial spec ~30$ps_{rms}$ contribution from electronics with large SiPM
- Coincidence Time Resolution (CTR) measurements
  - LSO:Ce:0.2%Ca 2x2x3mm$^3$
  - 93 ±3ps FWHM (HPK SiPM S13360-3050CS, 3x3mm$^2$ $V_{OV}$=8V)
  - 76 ±2ps FWHM (FBK HD-NUV Low Field SiPM, 40μm cell, 3.12x3.12mm$^2$ $V_{OV}$=6.1V)
- Linearity error <3% up to 25mA (+ polarity stage) or up to 20mA (- stage)
- 9% energy resolution for 511keV (LYSO:Ce:0.2%Ca 3.13x3.13x20mm$^3$)

- R5900 Hamamatsu PMT, 800V.
  - Jitter of ~340 ps FWHM, which corresponds to the intrinsic PMT time uncertainty when detecting tens of photons.

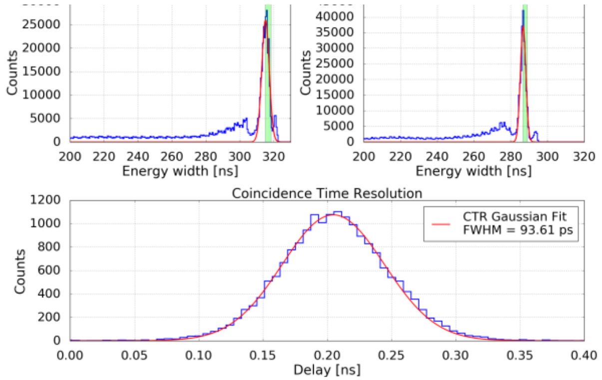
- Two spin-off projects: FastIC+ and FastRICH

CTR measurement with 2 × 2 × 3 mm$^3$ LSO:Ce0.2%Ca crystals coupled to FBK (a) and HPK (b) devices in coincidence (20 K events used).




(a) FBK HD-NUV Low Field SiPM at 7 V of over-voltage.

FBK HD-NUV Low Field SiPM at 6.1 V of over-voltage.




HPK S13360-3050PE SiPM at 8 V of over-voltage.