Jennifer 3 Kickoff meeting
Barcelona, Jan. 27-28, 2025

EU grant n.101183137

Institut "Jožef Stefan", Ljubljana, Slovenija

WP4 -Advanced particle detector technologies Task 4.2 Photodetection devices for particle detectors

Rok Pestotnik
On behalf of the task participants
Jožef Stefan Institute, Ljubljana

Task 4.2 Photodetection devices for particle detectors

WP4 Objectives:

Develop and test new technologies for particle detectors to be installed in future high-intensity facilities
Foster networking among detector experts to address common problems and stimulate collaboration with technology producers to achieve the required performance.

Task 4.2 description

- **T4.2.1** Study of silicon photomultipliers as single photon counters in neutron irradiated areas [JSI, KEK]
- **T4.2.2** Test of SiPM for crystal calorimeter readout in high pile-up conditions [INFN]
- **T4.2.3** Characterisation of ASICs designed for photosensors readout [CEA, JSI, KEK, and CAEN]
- **T4.2.4** Studies of Digital SiPMs and Spad Arrays with Integrated Electronics coupled with Scintillating Fibers and water-based scintillators [INFN and ETHZ]

Key people: R.Pestotnik (JSI), WP4 leader in the ECFA DRD4, C.Cecchi (INFN), S.Bolognesi (CEA)

T4.2.1 SiPM for single photo detection

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We will exploit the basic properties of Silicon Photomultipliers (SiPM) in a single-photon regime in highly irradiated areas of Belle II Particle identification devices (expected fluence of more than 10^{12} n/cm2).

SiPM has a very high photon detector efficiency, reaching 60% at the peak, is very easy to operate as it only requires reverse biasing from 30 to 70V, and has an excellent timing resolution. They are inherently insensitive to magnetic fields.

However, they have serious drawbacks, namely the sizeable dark count rate and their sensitivity to radiation. The radiation damage increases the sensor currents, affects its breakdown voltage, and increases the dark count rate.

Close collaboration with the sensor producers is ongoing to reduce neutron sensitivity and find suitable operational parameters to control the damage. These parameters can be exploited by reducing the sensor's operating temperature, using timing information for background rejection, using a light collection system to reduce the sensor's sensitive surface, and performing high-temperature annealing.

Upgrade of photon detector of Belle II ARICH with SiPMs

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SiPM very attractive sensor :
Extend Belle II ARICH capabilities for low momentum region

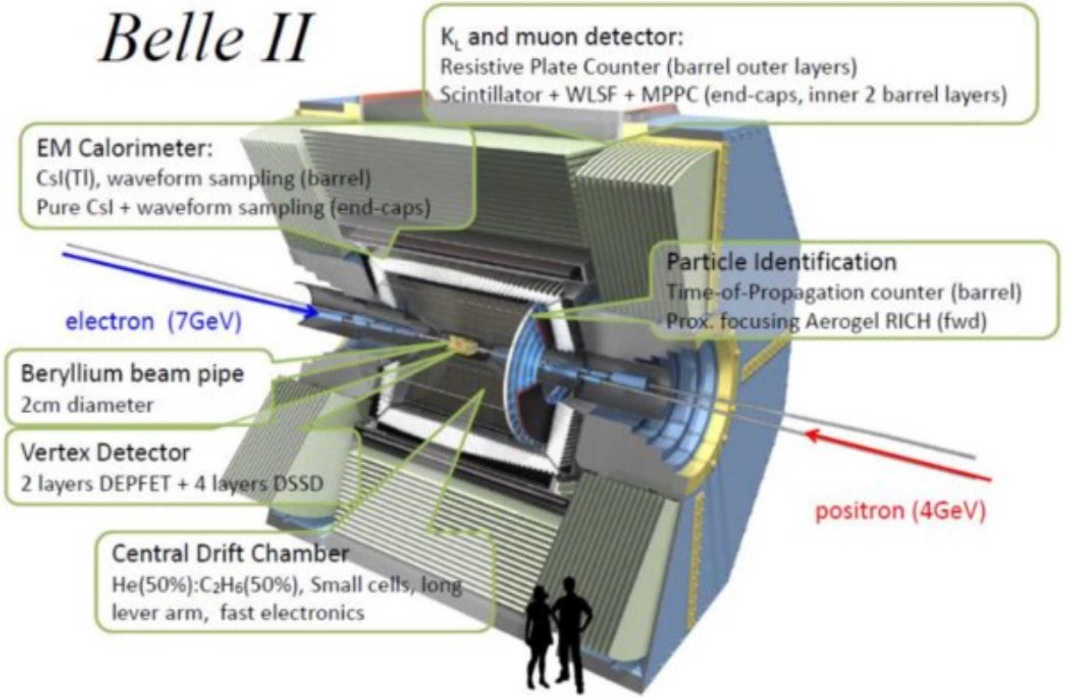
The use of irradiated SiPMs at room temperature is very challenging.
Recover the operation at lower temperatures - annealing.

Several potential improvements to be studied:

- Reduction of cross-talk and after-pulses
- Use of smaller area SiPMs
  - a large number of electronic channels needed
  - Integration of the readout electronics with the sensor:
    - TSV interconnects with the ASIC -> dSIPM
    - Signal Processing in the front end
  - Light collection:
    - Focus light from e.g. 3x3mm2 to 1x1mm2

Can we afford to operate at lower temperatures?

- We will need a cooling system.



R.Pestotnik, ARICH meeting@ 37th B2GM Nov 4 2020

Characterisation of SiPMs at different temperatures

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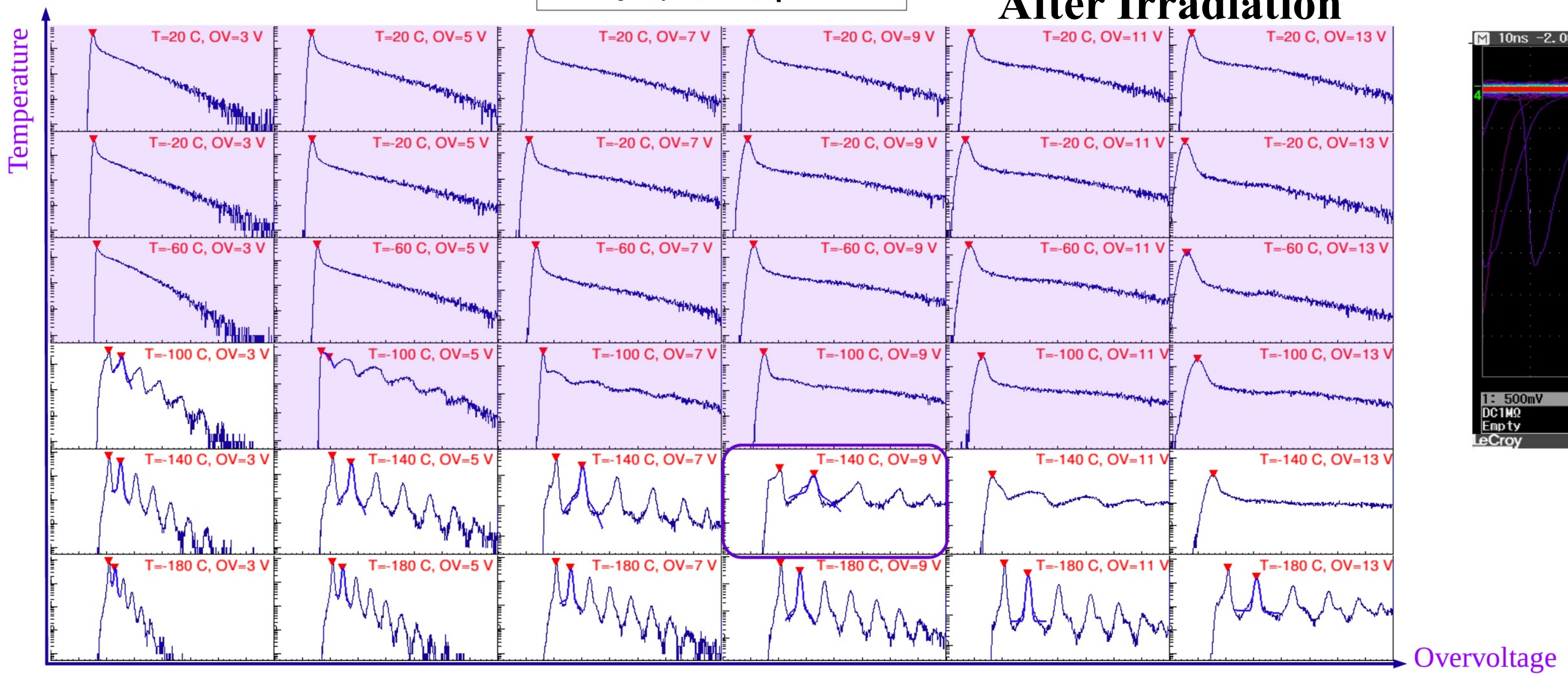
Characterizaton of irradiated SiPMs at different temperatures

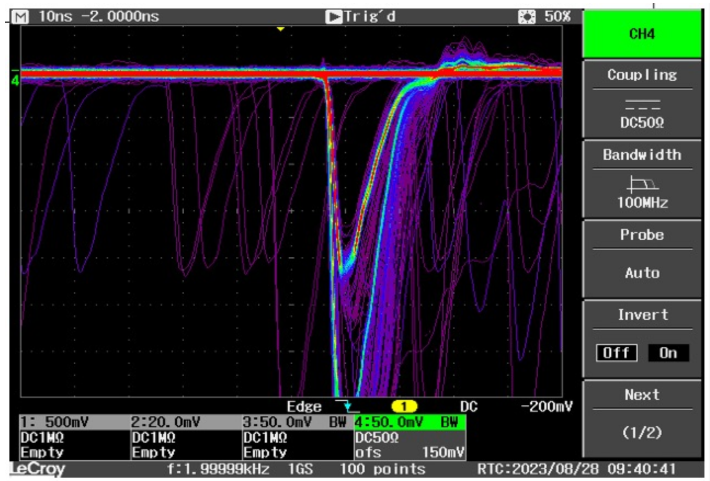
- I-V dependance
- Dark Count Rate (DCR)
- Waveform acquisition:
  - Single Photon Time Resolution (SPTR)
  - Pulse height distributions

Pulse height distributions

QDC, 10^{12} neq/cm²

After Irradiation





Stable operation: **Single photons at 9 V Over Voltage can be resolved after irradiation**

Works at -140 ^{0}C

Characterisation of Neutron irradiated SiPMs @JSI

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AidaInnova has received funding from the EU Horizon 2020 RIA programme under Grant No 101004761

Co-funded by Slovenian Research and Innovation Agency project - J1-4358

EU grant n.822070
Jennifer 2 is an MSCA-RISE project funded by EU under grant n.822070

Evaluation of SiPMs :

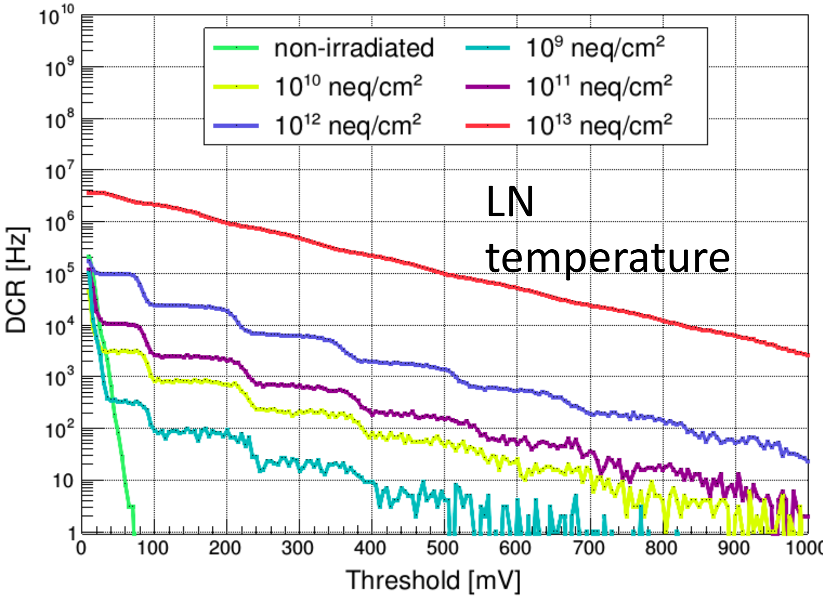
- 1x1 mm2 FBK NUV-HD-RH samples
- **HF high power cryogenic readout**

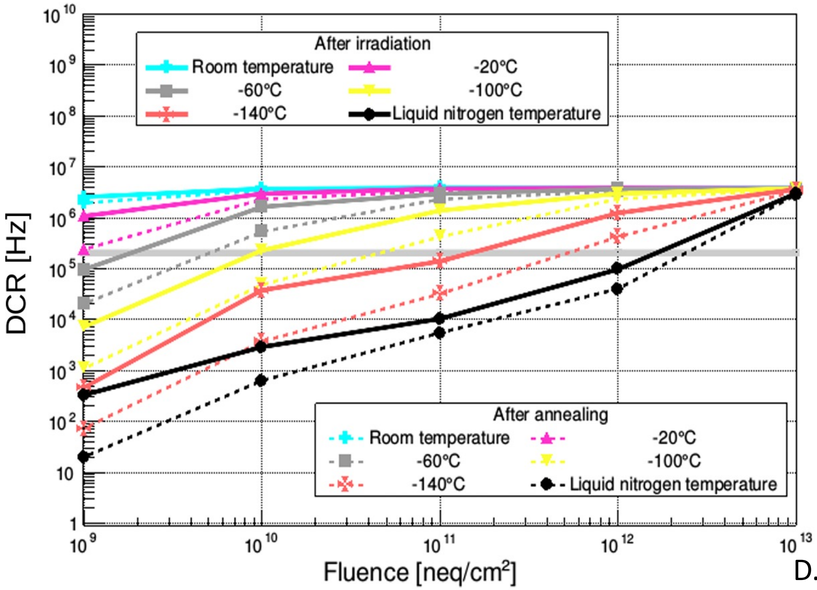
Irradiated with neutrons : $10^9 \dots 10^{13}$ n_{eq}/cm^2 and later annealed at 80 deg. for 24h
Cooled down to -196 deg. in steps of 40 deg.

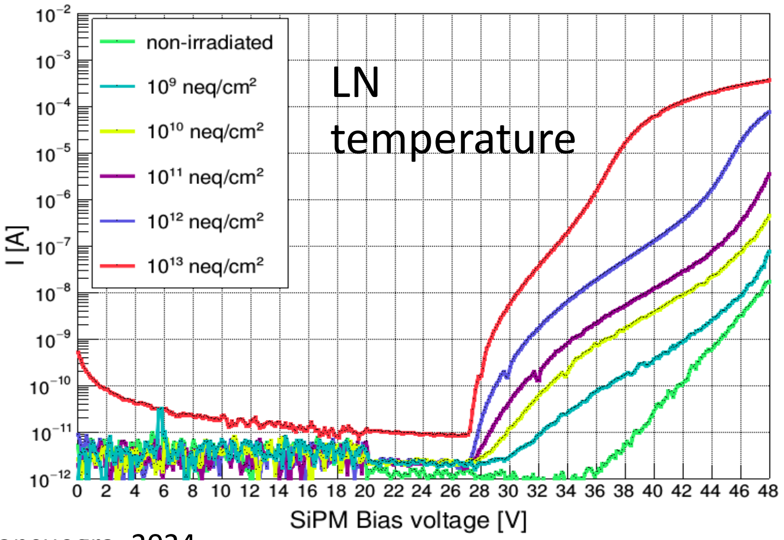
Dark count rate

I-V dependance

Damage visible already at LN







D. Consuegra, 2024
https://doi.org/10.1140/epjc/s10052-024-13302-7

Temperature of operation

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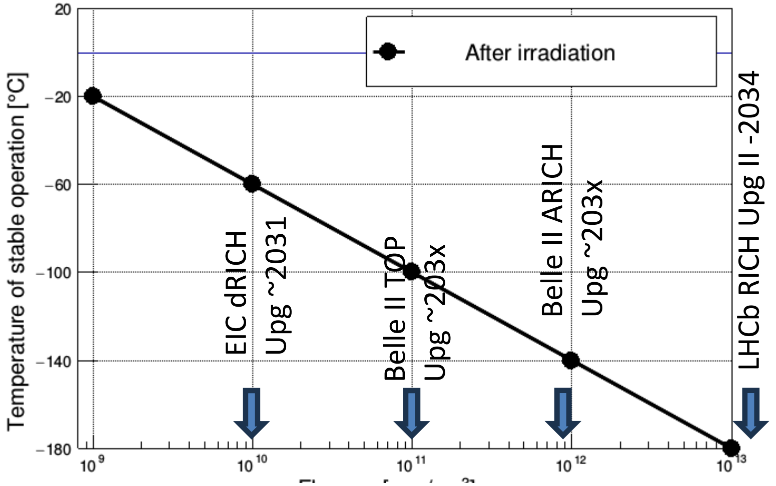
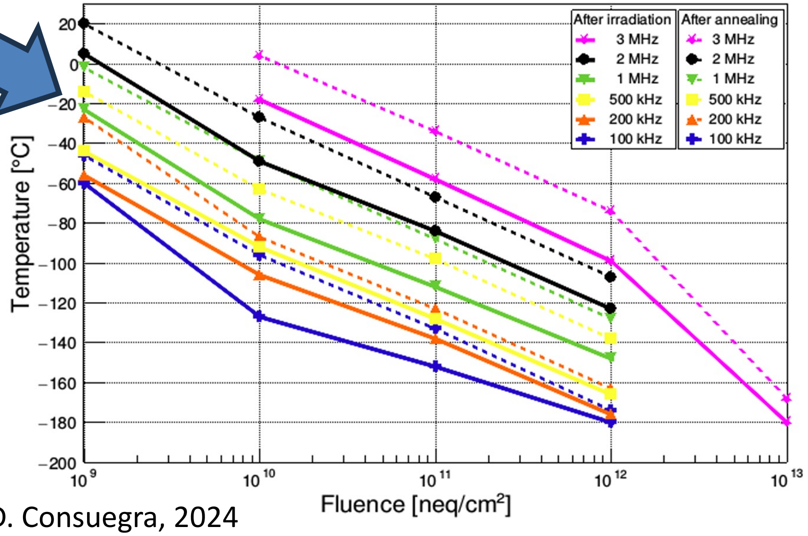
- The temperature at which the SiPM single p.e. peak is separated from the background.
- Temperature below which the Dark Count rate falls below certain value.
- Depends on the readout electronics





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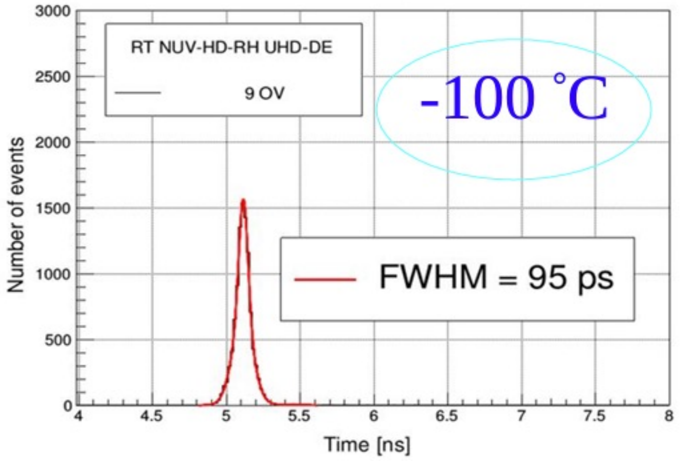

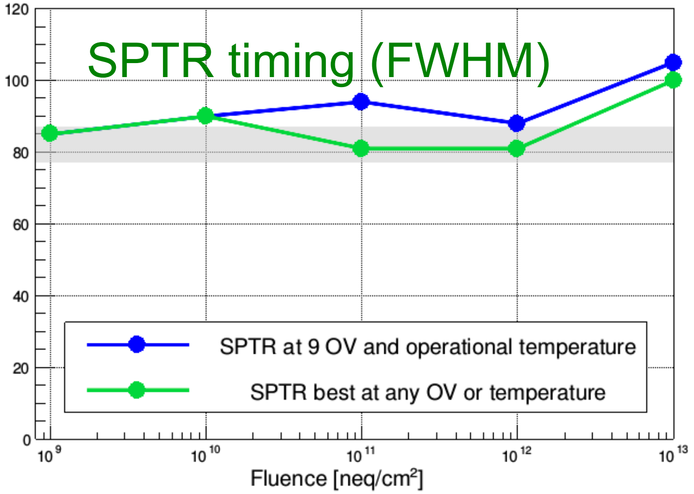

Similar timing dependance for Hamamatsu and Sens

Annealing

Hamamatsu S13360-3050PE @ -50°C

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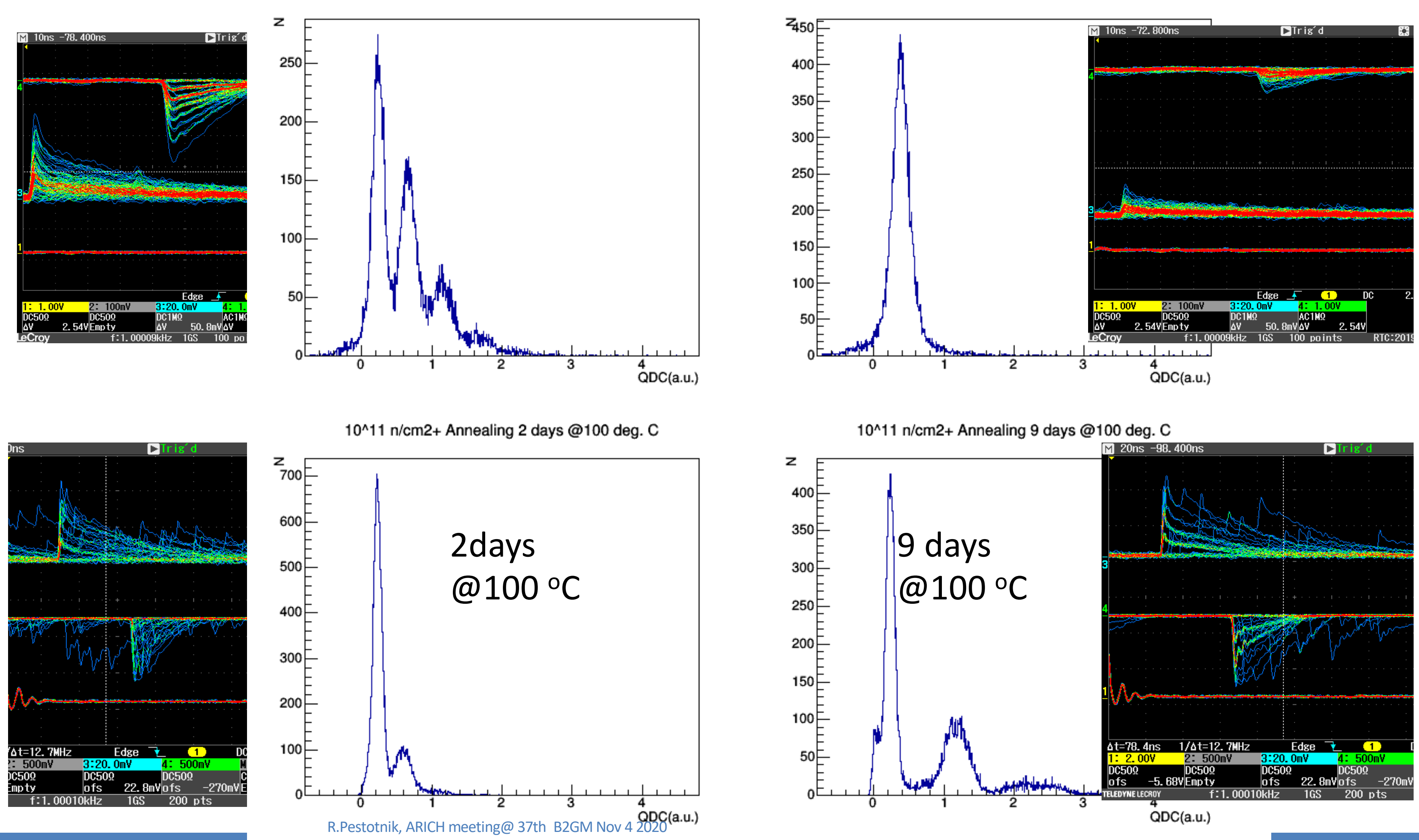
10^{11}n/cm^2



Characterisation of **AIDAinnova FBK Run**

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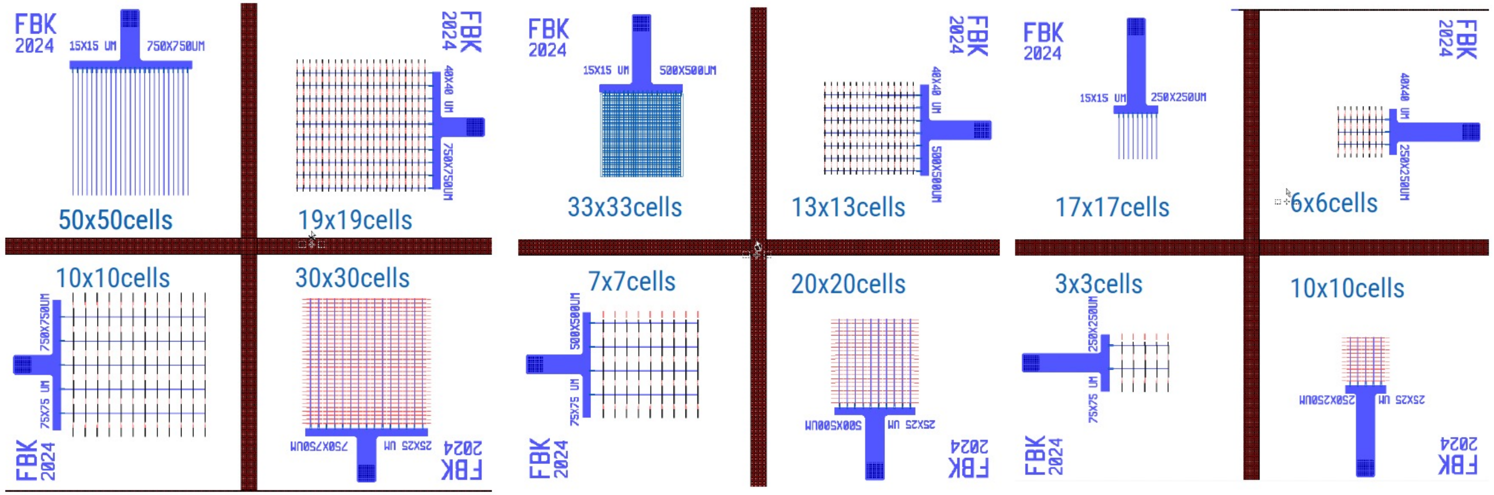
Test structures of Different variants of SiPMs with two splits:

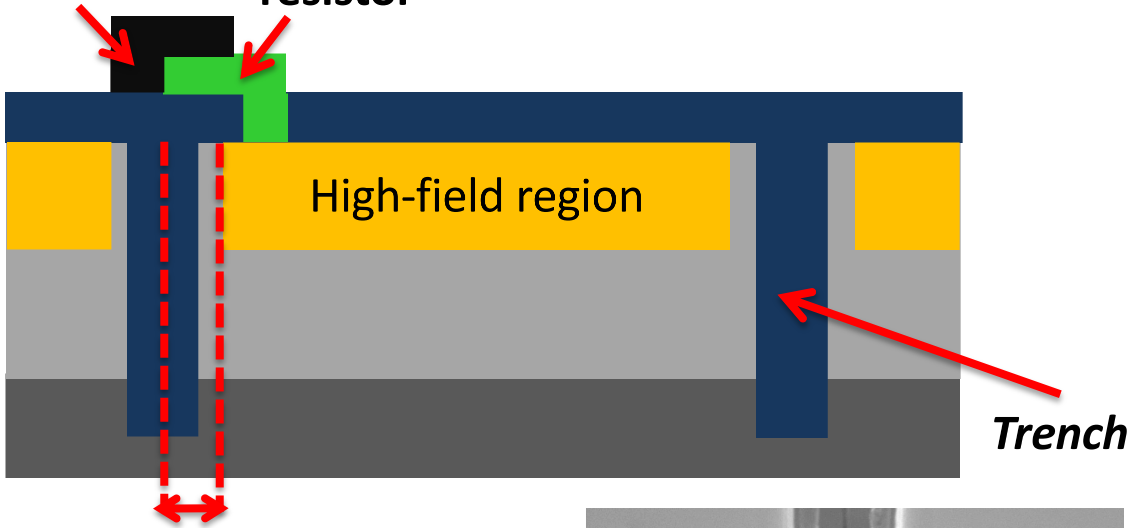
- Low electric field and
- Ultra-low electric field

The production is expected to finish on Feb. 2025

Variants of 2x2 arrays:

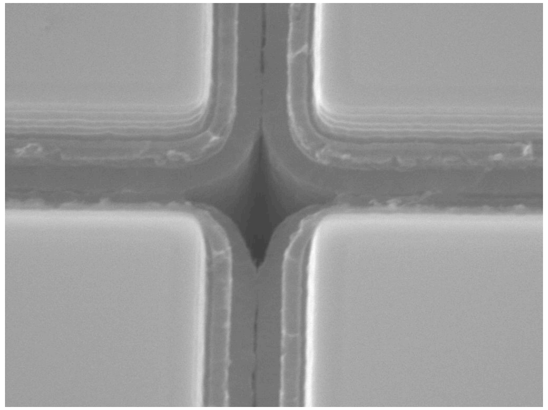
1) 2x2 array of SiPM 1x1mm2 with 15um-25um-40um-75um cell size
2) 2x2 array of SiPM 0.75x0.75mm2 with 15um-25um-40um-75um cell size
3) 2x2 array of SiPM 0.5x0.5mm2 with 15um-25um-40um-75um cell size
4) 2x2 array of SiPM 0.25x0.25mm2 with 15um-25um-40um-75um cell size
5) 2x1 array of SiPM 1.5x1.5mm2 with 15um+25um cell size
6) 2x1 array of SiPM 1.5x1.5mm2 with 40um+75um cell size
7) single SiPM 2x2mm2 with 15um cell size
8) single SiPM 2x2mm2 with 40um cell size





Advantages:

- Lower cross-talk



Trenches between cells filled with highly doped polysilicon as light absorbing material

T4.2.2 SiPM for crystal calor. readout in high pile-up conditions

The use of SiPM in a multiphoton regime for the light readout of crystal electromagnetic calorimeters plays a key role in mitigating pile-up effects in conditions of high background. This is achieved through precise time measurements, which are made feasible by the substantial amount of light emitted by the CsI(Tl) crystals.

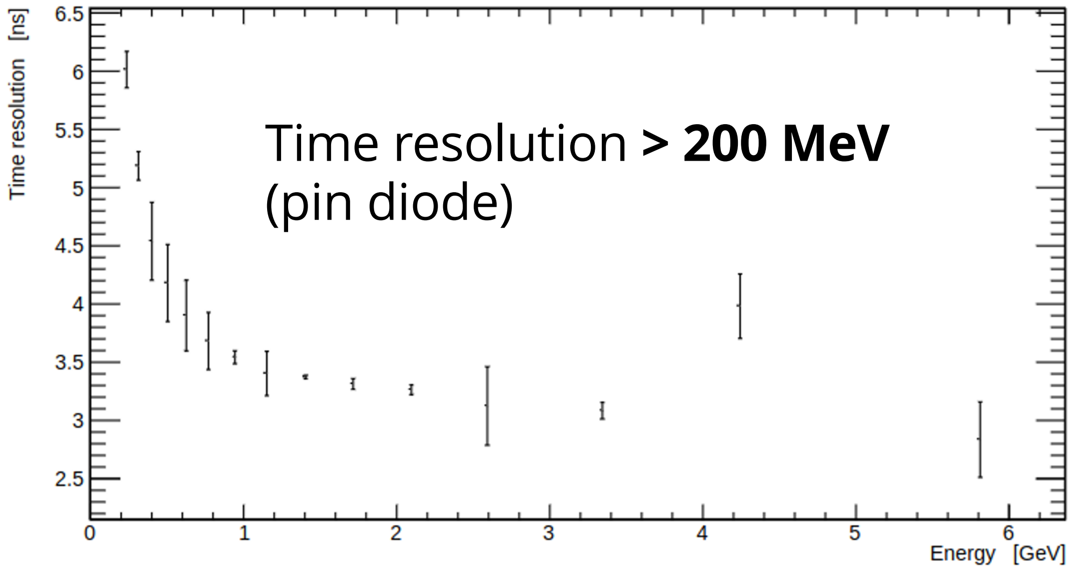
SiPM's emerge as an excellent choice due to their rapid response, high gain and simplicity in use. Preliminary studies have been conducted using prototypes manufactured by Fondazione Bruno Kessler (FBK), with which a synergic collaboration is continuing. Critical challenges have been identified, particularly in achieving a good match between the CsI(Tl) emission spectrum and low-noise front- end electronics design.

Extending beyond the Belle II applications, notably within the DRD6, and in AIDA-Innova, our exploration encompasses other crystals such as Pure CsI, LYSO, LaBr3. Aiming to further optimisation, samples of photosensors from the Japanese manufacturer Hamamatsu have also been investigated. Further evaluation of new samples is planned to find the most effective matching between the crystal and the photosensor. This comprehensive approach not only enhances our contribution to Belle II upgrade but also broadens the scope of crystal measurements, providing advancements in various collaborative projects.

ECL upgrade studies

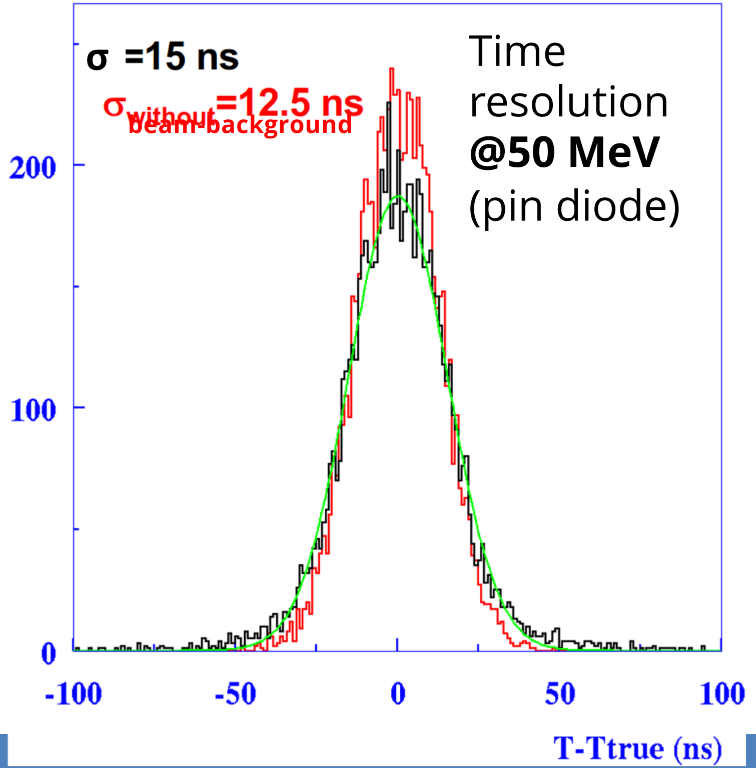
Higher rate and **occupancy** with increasing luminosity

- Low energy spectrum dominated by beam-background
- Performance degradation in the low energy region impact **soft photons** and π^0 reconstruction



Possible solutions:

- **New crystals** with shorter decay time
  - **APD** + pure CsI studied in a past R&D [JINST 12 C07032]
  - high impact and very expensive solution
- Same CsI(Tl) crystals but **new photodetector**
  - fast **timing** for rejecting beam-background → need **internal gain**
  - require high dynamic-range (~10^4), must operate in high magnetic field



→ new R&D with **SiPM**

SiPM readout option

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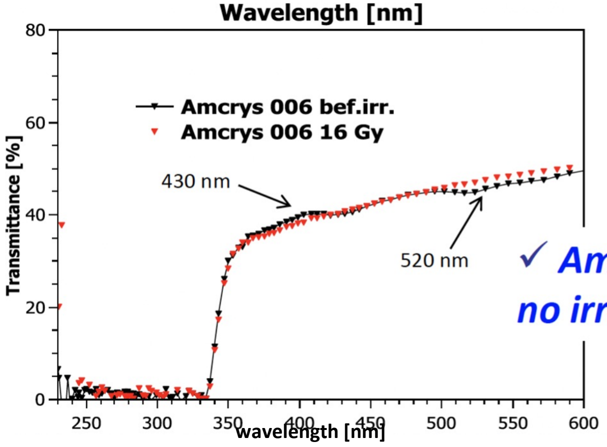
- Simpler and cheaper w.r.t. APD
- Good solution for **timing** at low deposited energy
- Sub-optimal for **amplitude measurement** in the required dynamic range (loss of linearity)
  - however rapid developments for SiPM with high number of pixels
- Beyond CsI(Tl), different crystals investigated:
  - pure CsI, LYSO, $LaBr_3$, BGO
  - synergy with **AIDA Innova** (Task 8.3.1) and **DRD6** (WP3)



✓ *Amcrys 006:*
no irradiation effect (@ 16Gy)

CsI (Tl)	
Density (g/cm^3)	4.51
λ max emission (nm)	550
Light yield (γ/keV)	54
Primary decay time (ns)	1000
Rise time (ns)	35
Refractive index	1.78

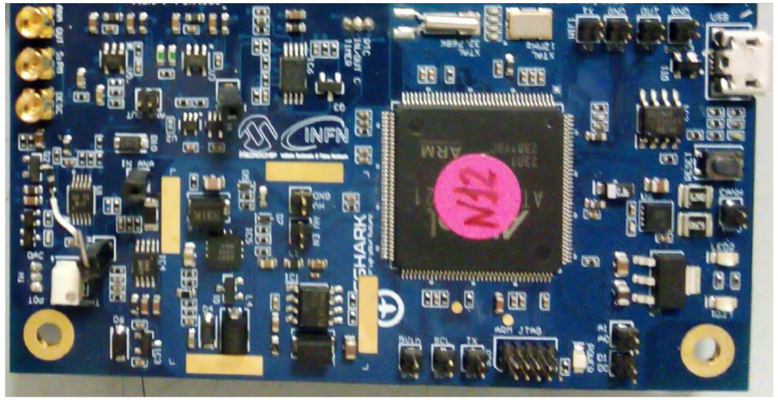
ArduSiPM for readout

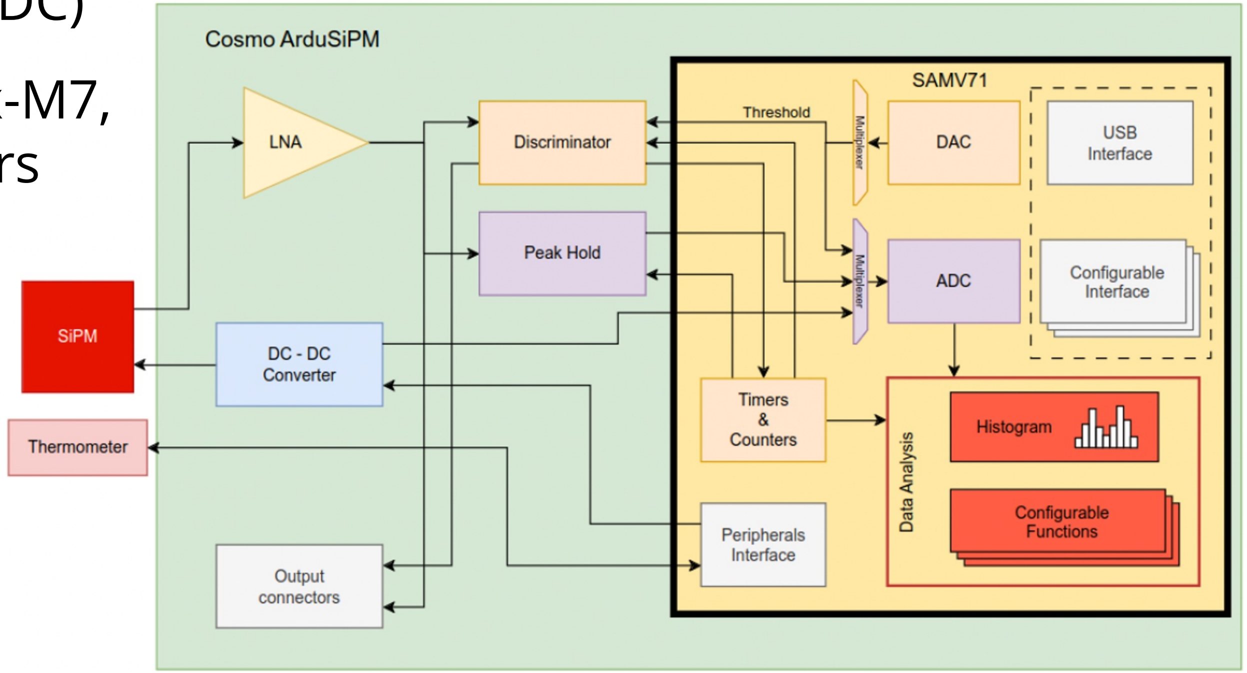
System on Chip (SoC) for easy SiPM measurements

- SiPM **power supply** adjustment circuit
- Low-noise voltage amplifier and fast discriminator
- Peak height measurement (peak hold and ADC)

Atmel SAMV71 microcontroller, with ARM Cortex-M7, provides 10-bit DAC, 12-bit ADC, and time counters

size	$50cm^2 \times 3mm$
weight	21g
CPU speed	300MHz (SAMV71)
power consumption	<1W
rad. tolerant version	yes





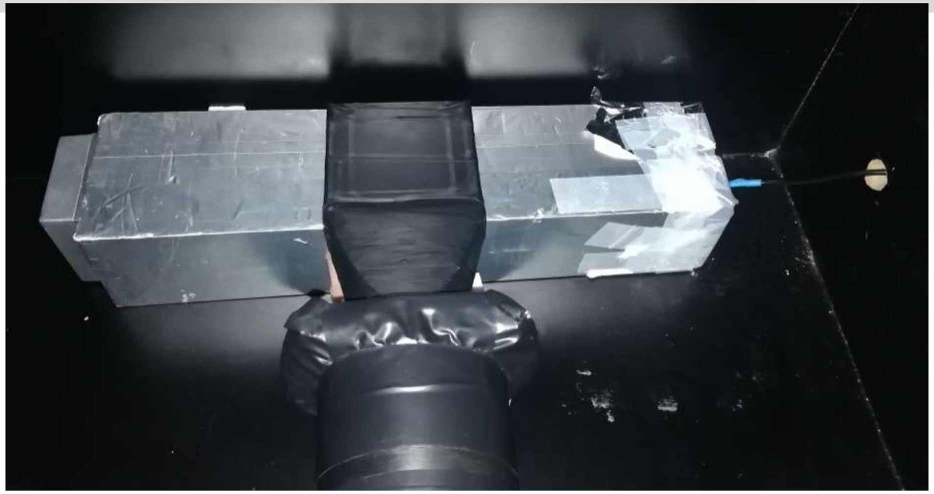
Setup @Perugia

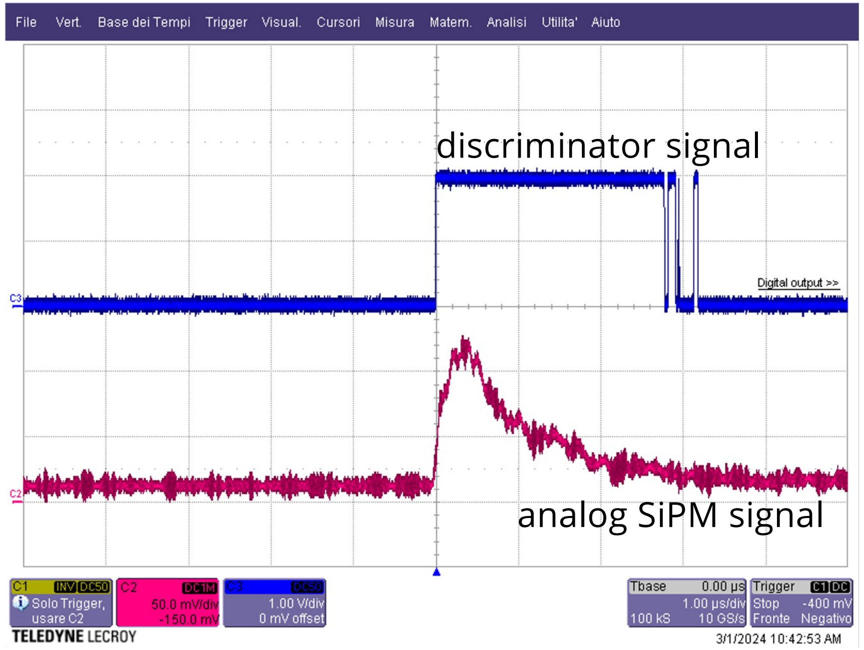
- **CsI(Tl)** crystal
  - Belle spare, 7.5x6.5x30 cm^3
  - wrapped with Tyvek + aluminized Mylar
- SiPM HPK **S13360-6025CS**
  - coupled to CsI(Tl) via EJ-550 grease
- **ArduSiPM** for bias voltage, SiPM readout and ADC spectrum
- Plastic scintillator + PMT as time reference for trigger
- Lecroy oscilloscope to digitize signals (10 Gs/s)
  - offline time measurement t(fast discriminator) – t(trigger)

Noisy signal observed for this measurement. Improve for next iteration:

- Better shielding of apparatus against pick-up noise
  - copper box + RL filter
- Implemented reset latch in ArduSiPM firmware

Next: CAEN DT5550W with PETIROC-2A for readout of multiple SiPM with time and amplitude measurements



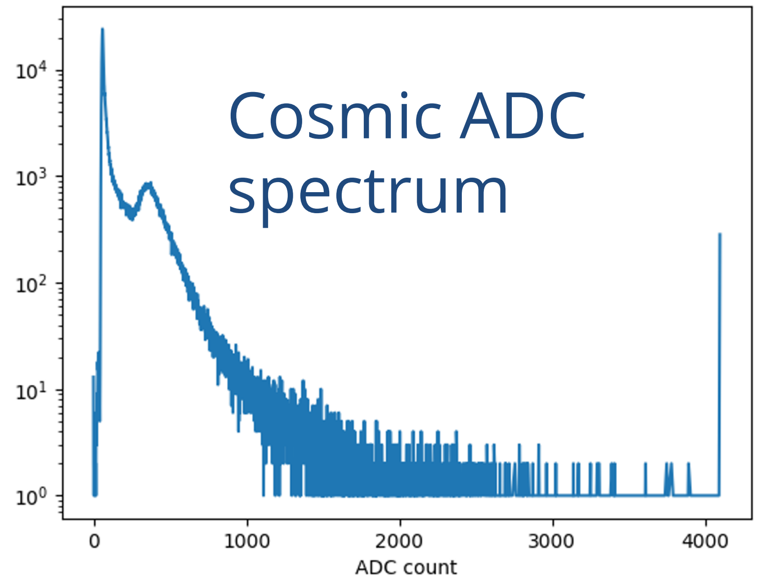


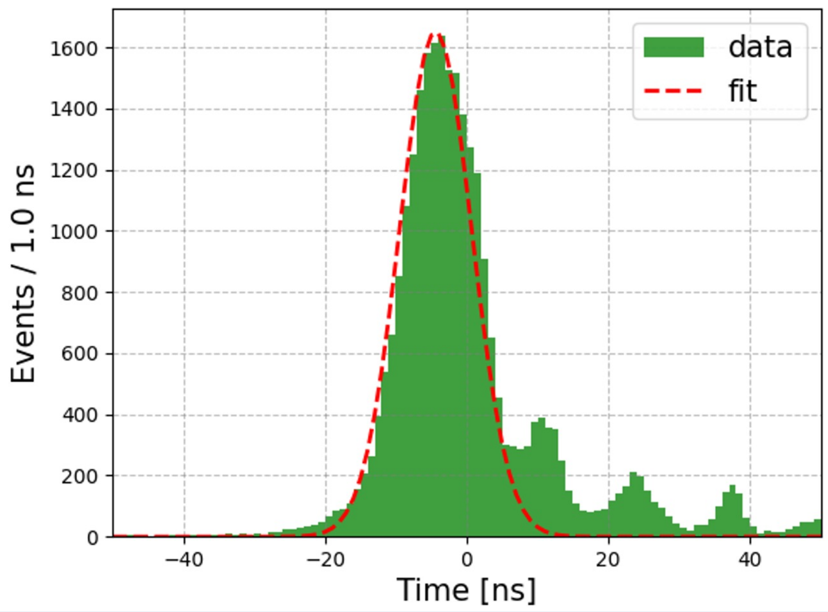
CsI(Tl) + SiPM time resolution

Consider **50% rise time** of discriminator output to evaluate time resolution

Fit the central peak with a Gaussian:

- **5 ns time resolution** for cosmics (~50 MeV deposited in CsI(Tl))
- Sub-peaks from 90 MHz pick-up noise





SiPM time resolution (other crystals)

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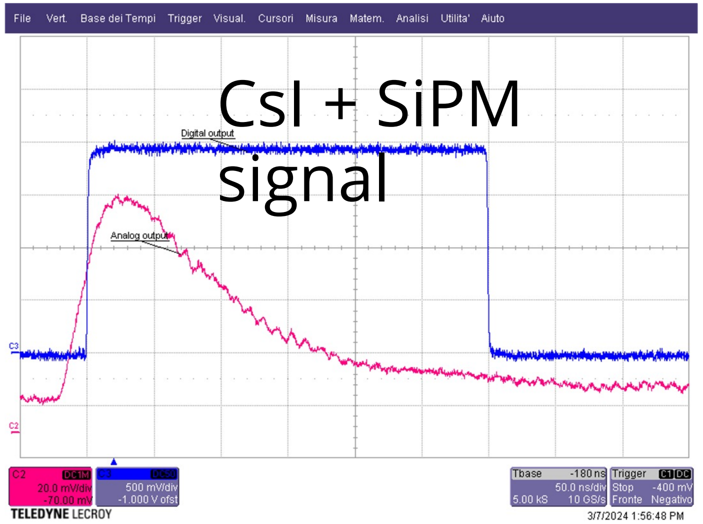
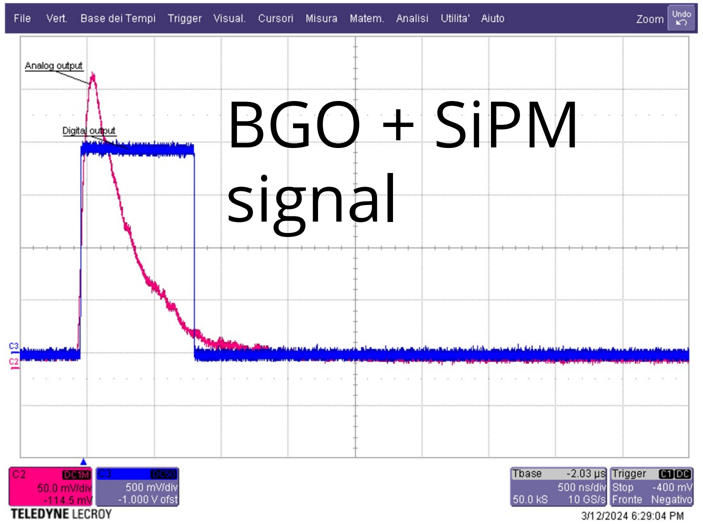
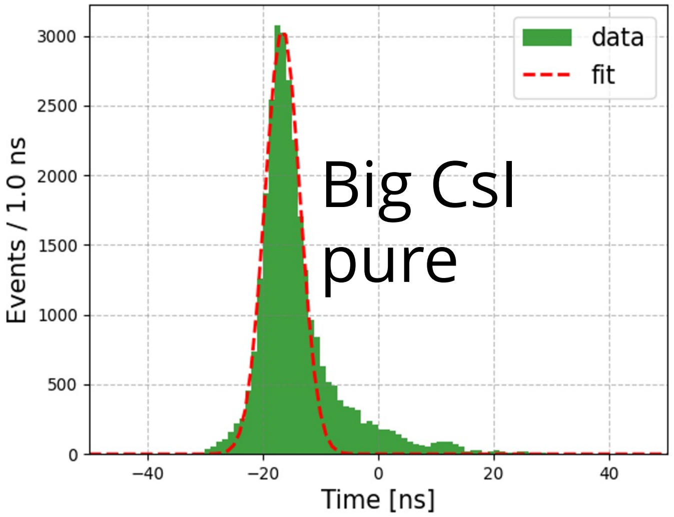
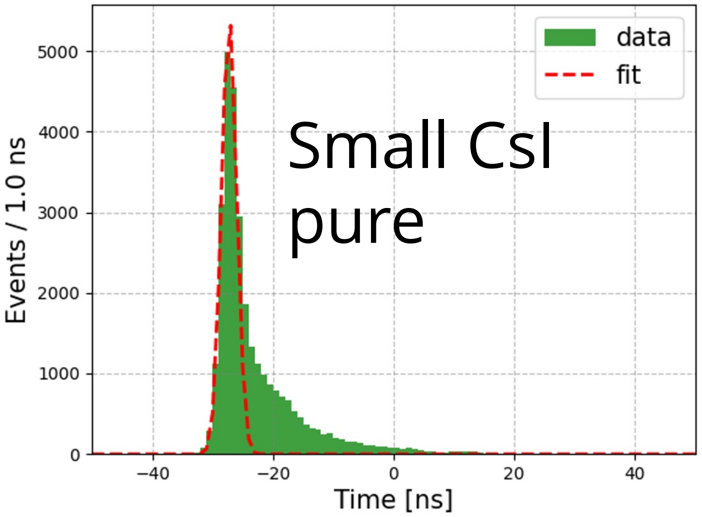
Use same setup, test different crystals

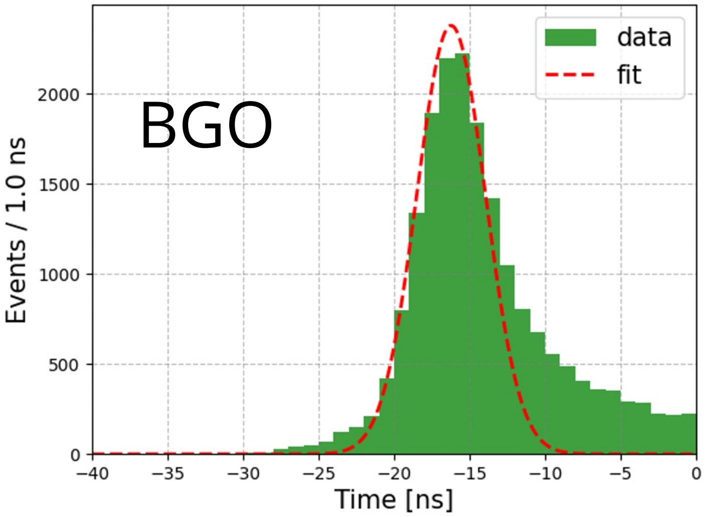
- **Pure CsI** 5x5x30 cm^3 (Amcrys)
  - time resolution **3.0 ns**
- **Pure CsI** 4x4x8 cm^3 (Amcrys)
  - time resolution **1.3 ns**
- **BGO** 24x2x3 cm^3 (L3)
  - time resolution **2.3 ns**











T4.2.2 Summary

The Belle II community must define a scenario for a long-term ECL upgrade.

- The **increase in luminosity** @Belle II could lead to a significative **performance degradation.**
- Complete redesign of the calorimeter may not be feasible → investigate **low-impact solutions.**
- A **SiPM readout** represents an interesting option
  - may allow to keep existing crystals and mechanics
  - recover good **time resolution** at **low energy** deposits → reject overlapping **beam backgrounds**
  - ongoing study: evaluate the **impact on physics** of an improved timing
- Strong synergy with other activities (AIDA Innova) and further development in the DRD6 field

T4.2.3 Characterisation of ASICs designed for photosensors readout

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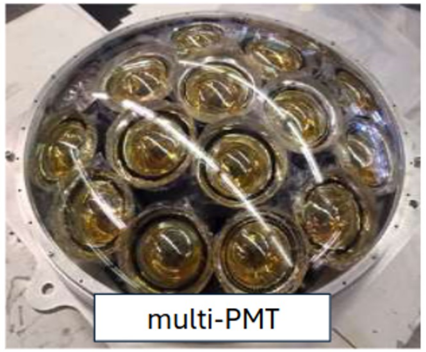
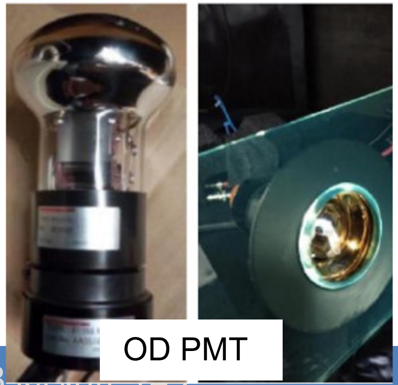
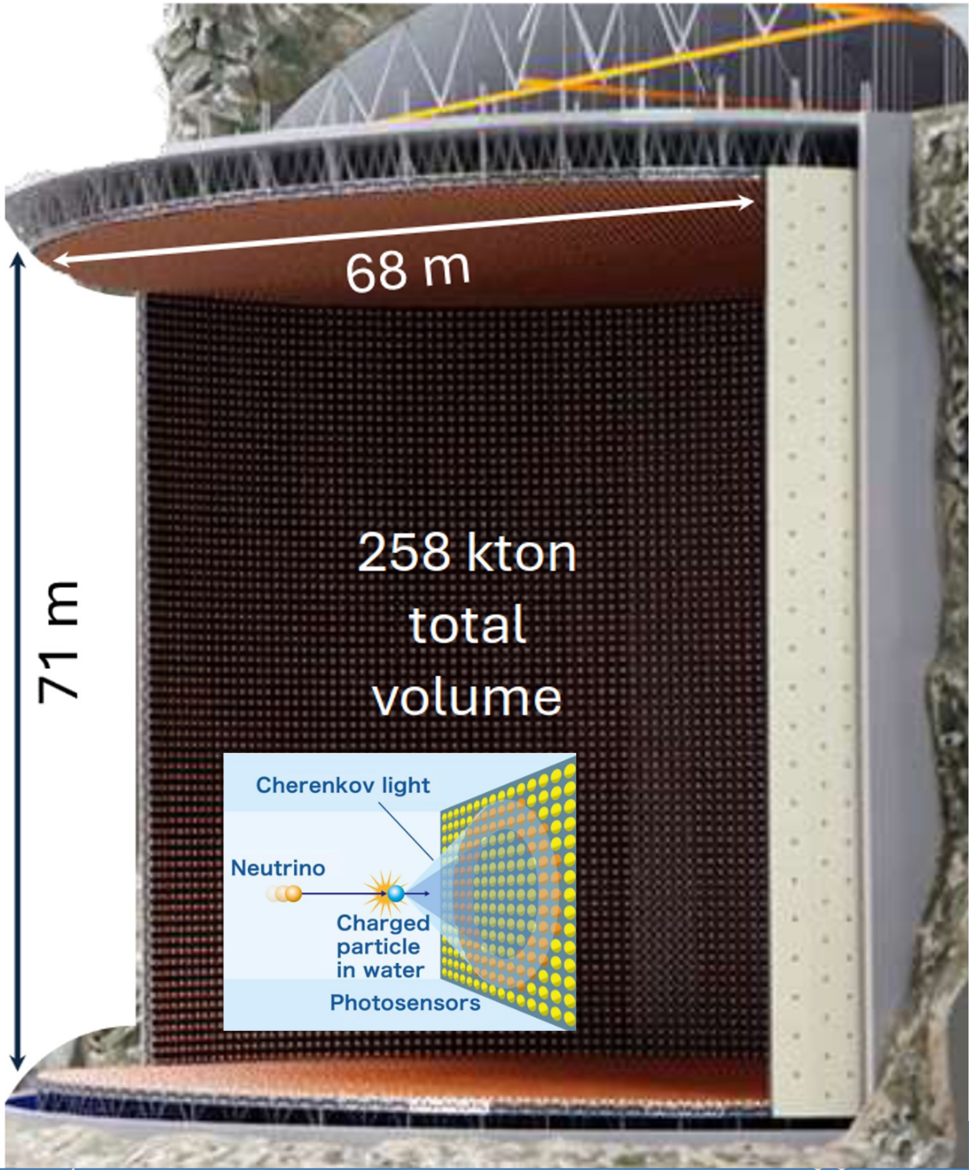
HyperKamiokande photodetection system

New photo-detector technology for increased sensitivity

- 20,000 Box&Light 50-cm PMTs (20% photo-coverage)
  - 1.5 ns timing resolution (half that of SK PMTs)
  - Double quantum efficiency of SK PMTs
- Additional photo-coverage from multi-PMT modules
  - 8 cm PMTs grouped in modules of 19 PMTs
  - Improved position, timing, direction resolution
  - Also used for in-situ calibration of 50cm PMTs
- 8 cm PMTs+WLS for Outer Detector veto







From Super- to Hyper-Kamiokande

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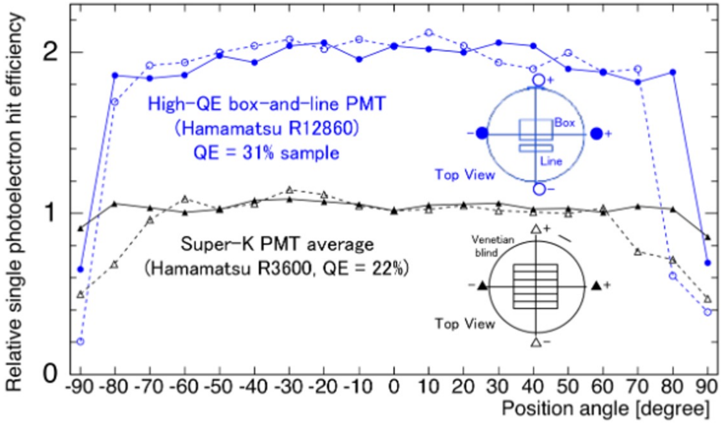
A number of improvement compared to R3600 used in Super-Kamiokande:

➢ Higher QE and electrons less likely to miss first dynode => higher detection efficiency

➢ More uniform electron drift path => better timing and charge resolution



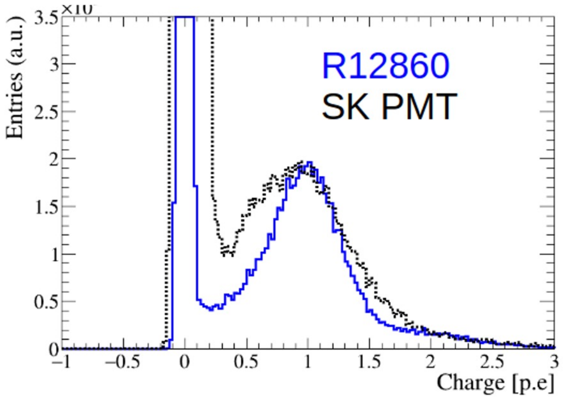
Results of tests :

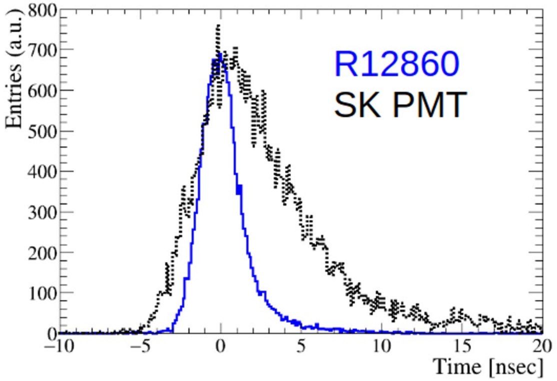
➢ ~2x photo-detection efficiency

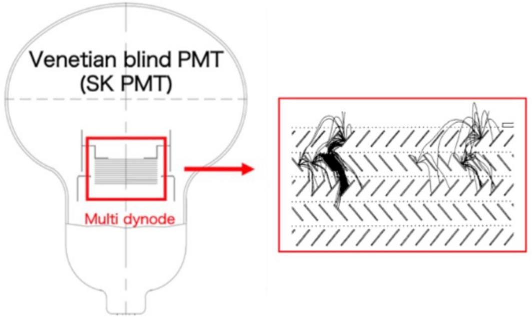
Mass production on-going !

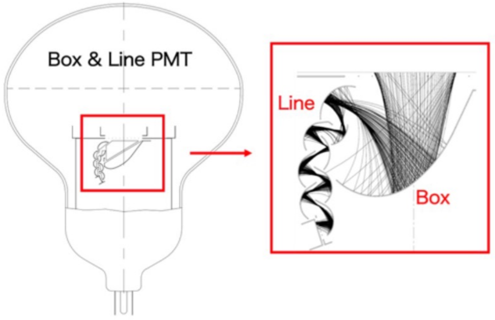
Super-K PMT
Hamamatsu R3600
Venetian blind dynode

Hamamatsu R12860
Box and line dynode
+ high QE









➢ Charge resolution: 60.1% → 30.8%

➢ TTS: 6.73 ns → 2.59 ns (FWHM)

Multi PMTs

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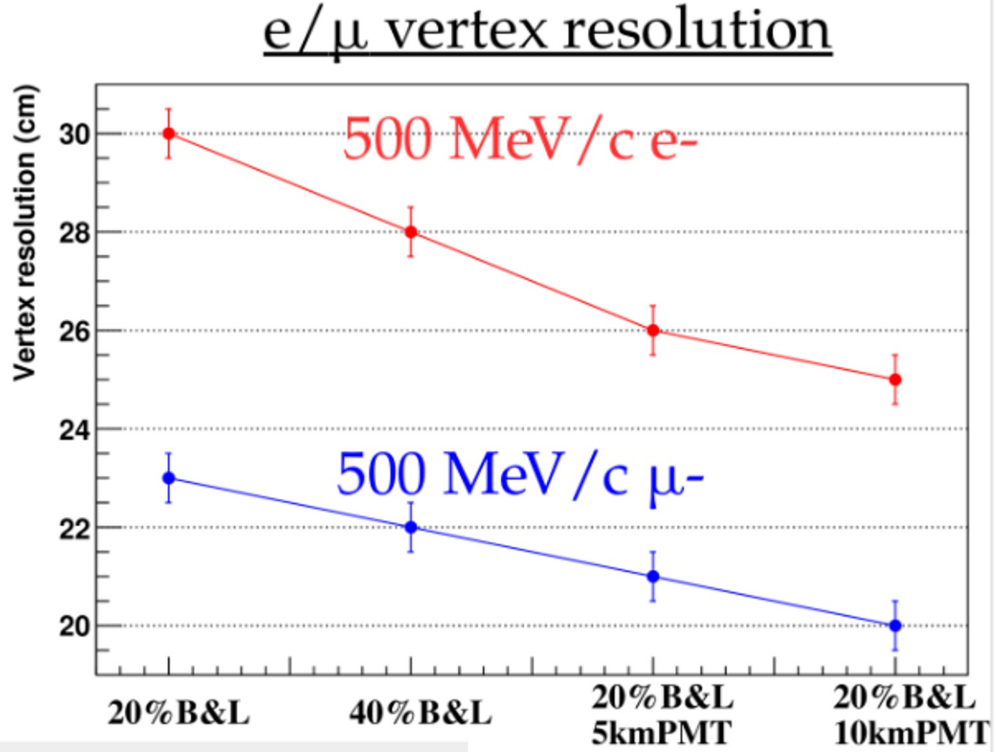
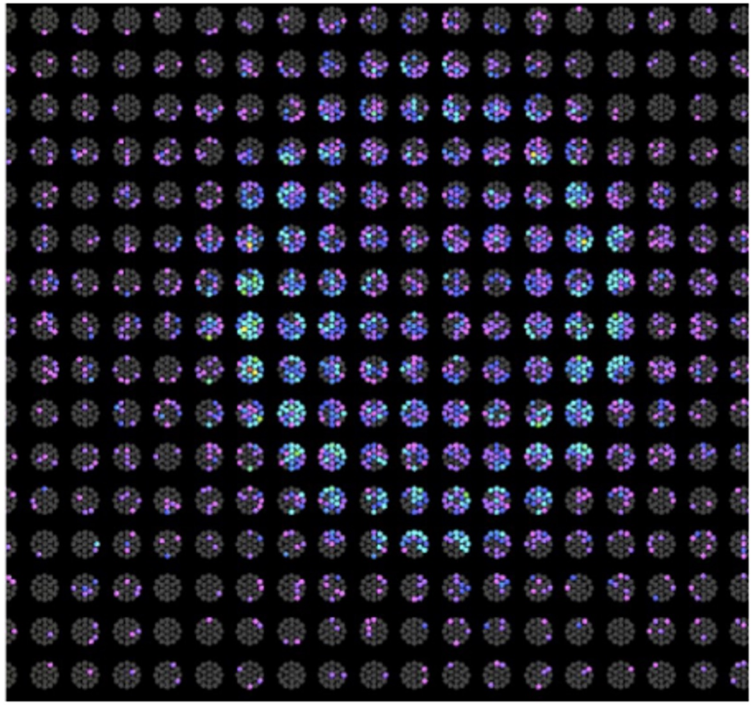
➢ High granularity, directional information improves reconstruction (especially near the walls and for 'busy' events, aka milti-ring)

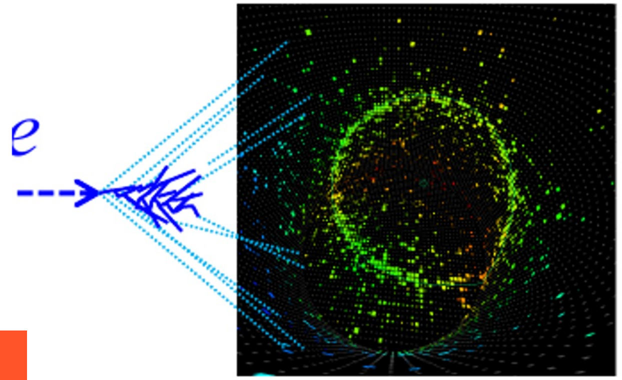
➢ Better timing resolution improves vertex resolution and PID (e/μ)

➢ Improves calibration: reference photo-sensor with good charge/timing characteristics

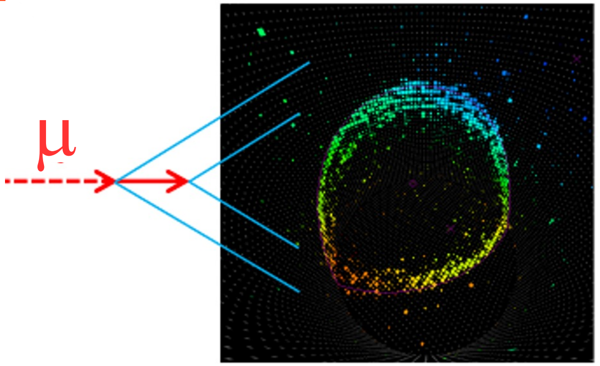
Intense R&D in the Jennifer3 groups aimed at minimal dark-noise, mechanical assembly resistent to pressure, include LED calibration ...







fuzzy ring



clear ring

3’ PMTs for Outer Detector

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Studies, tests and optimization from Jennifer 3 groups

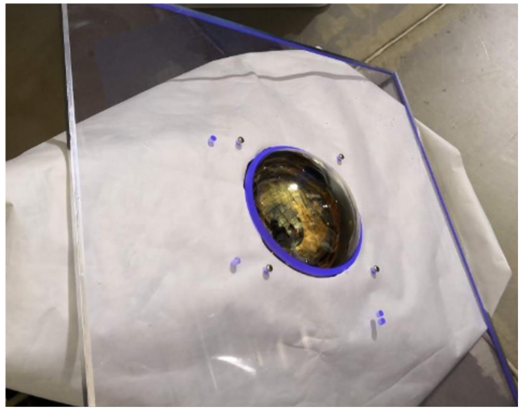
Reject entering background (veto based on cluster of hits above threshold):

➢ Large number of PMTs to increase information entropy of the signal

➢ Good light collection efficiency

➢ Low dark rate to be able to use low threshold

→ **3” PMTs in WLS plates with high reflectivity Tyvek**



➢ Several 3” PMT models considered have been tested

➢ Found to satisfy gain, resolution and dark rate requirements

HZC XP72B2F 3”

ET Enterprises D459/2KFLB 3”

Hamamatsu R14689 3.5”

Hamamatsu R14374 3”

➢ Simulation shows that **higher reflectivity Tyvek is a cost-efficient way** of increasing light collection

➢ Baseline design uses 30 cm plates with >90% reflective Tyvek

T4.2.3 Studies of Digital SiPMs and Spad Arrays with integrated electronics

The development of high-fill factor SPAD arrays (hffSpArr, R&D at ETH) with integrated readout electronics and digital SiPM (DSiPM, R&D in the DRD4 Collaboration) will be highly relevant to possible future upgrades of the ND280 detector.

The combination of ultra-fine pitch sci-fi layers readout by hffSpArr and super fine-grained scintillator targets readout by DSiPM will result in imaging neutrino targets, capable of measuring almost all secondary particles, including low-energy gy protons invisible to state-of-the-art neutrino detectors and fast neutrons. Integrated electronics of such photodetectors with optical link-based readout will allow ultra-high-resolution imaging with a very low passive material budget.

T4.2.4 Integrated Electronics

Closely integrated photo sensors with electronics with low power consumption, excellent timing resolution, and small dead time require optimal pulse shaping to maximise the detector capabilities. Studies will be first done using modular electronics.

In parallel, two ASICs are being developed for deployment in different experimental setups in the next few years and push further the R&D to specific use cases of present and future photodetectors:

- The FastIC+ ASIC is a low-power, low-noise amplifier, shaper, and discriminator with a 25 ps sensitivity TDC. Close collaboration with Japanese groups is essential for this activity.
- The HKROC digitiser (JINST 18 (2023) 01, C01035) is used to measure the charge deposited in the sensors and its Time-of-Arrival (ToA).

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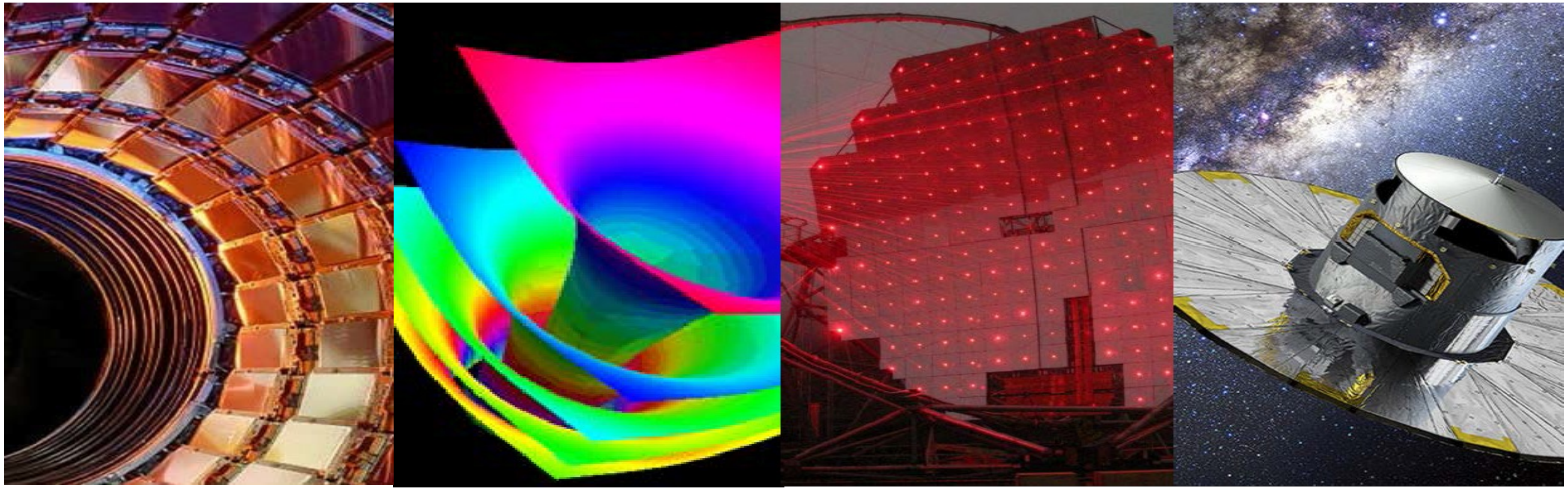


FASTIC+: a general-purpose fast readout including one TDC per channel

J. Alozy, E. Auffray, F. Bandi, R. Ballabriga, M. Campbell, J.M Fernández, D. Gascon, S. Gomez, J. Kaplon, N. Kratochwil, A. Paterno, S.Portillo, J. Mauricio, R. Manera, A. Mariscal, M. Piller, A. Pulli, A. Sanuy, J. Silva

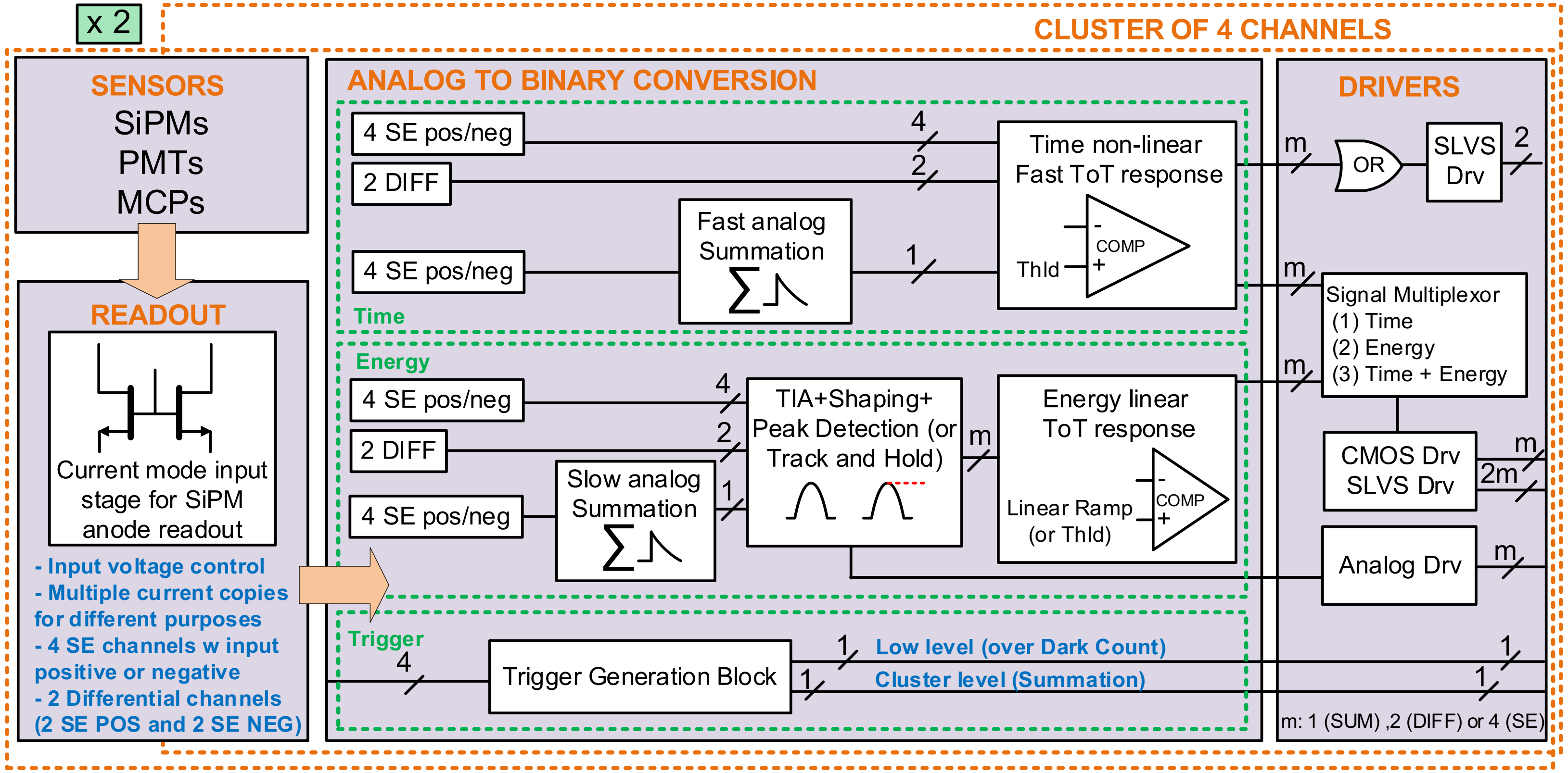
ICCUB – Universitat de Barcelona

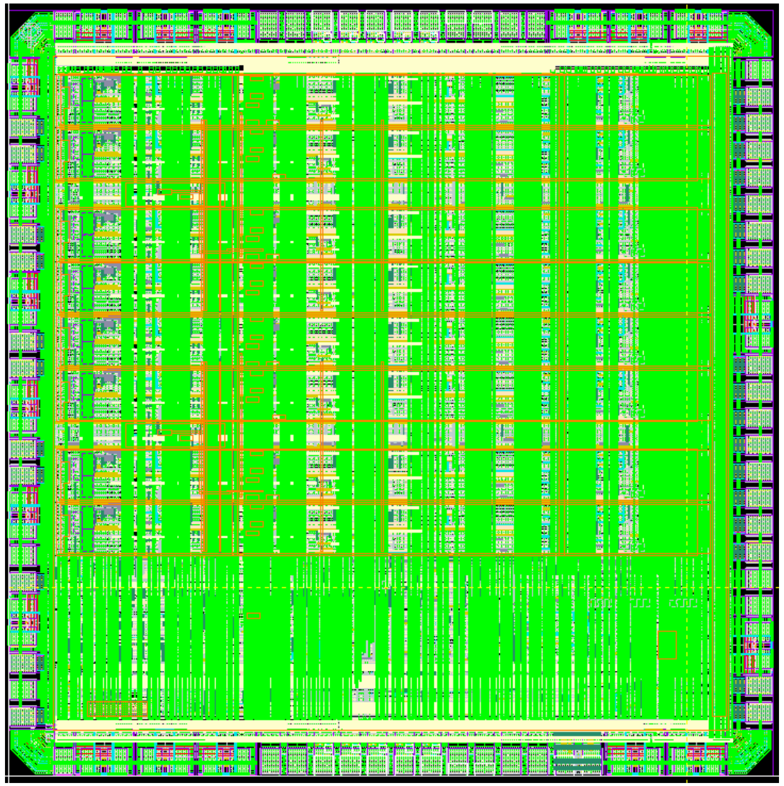
CERN microelectronics section (EP-ESE-ME)

26 January 2025

Based on FastIC architecture

- **FastIC** current mode ASIC.
  - **8 Inputs:** 8 Single Ended (POS/NEG) / 4 differential / 4-ch active summation (POS/NEG).
  - **3 Output modes:** binary (SLVS or CMOS) and Analog.





Tech: 65 nm CMOS
Size: 2x2 mm^2
Power: 12 mW/ch

FastIC: Linearity of the Energy measurement

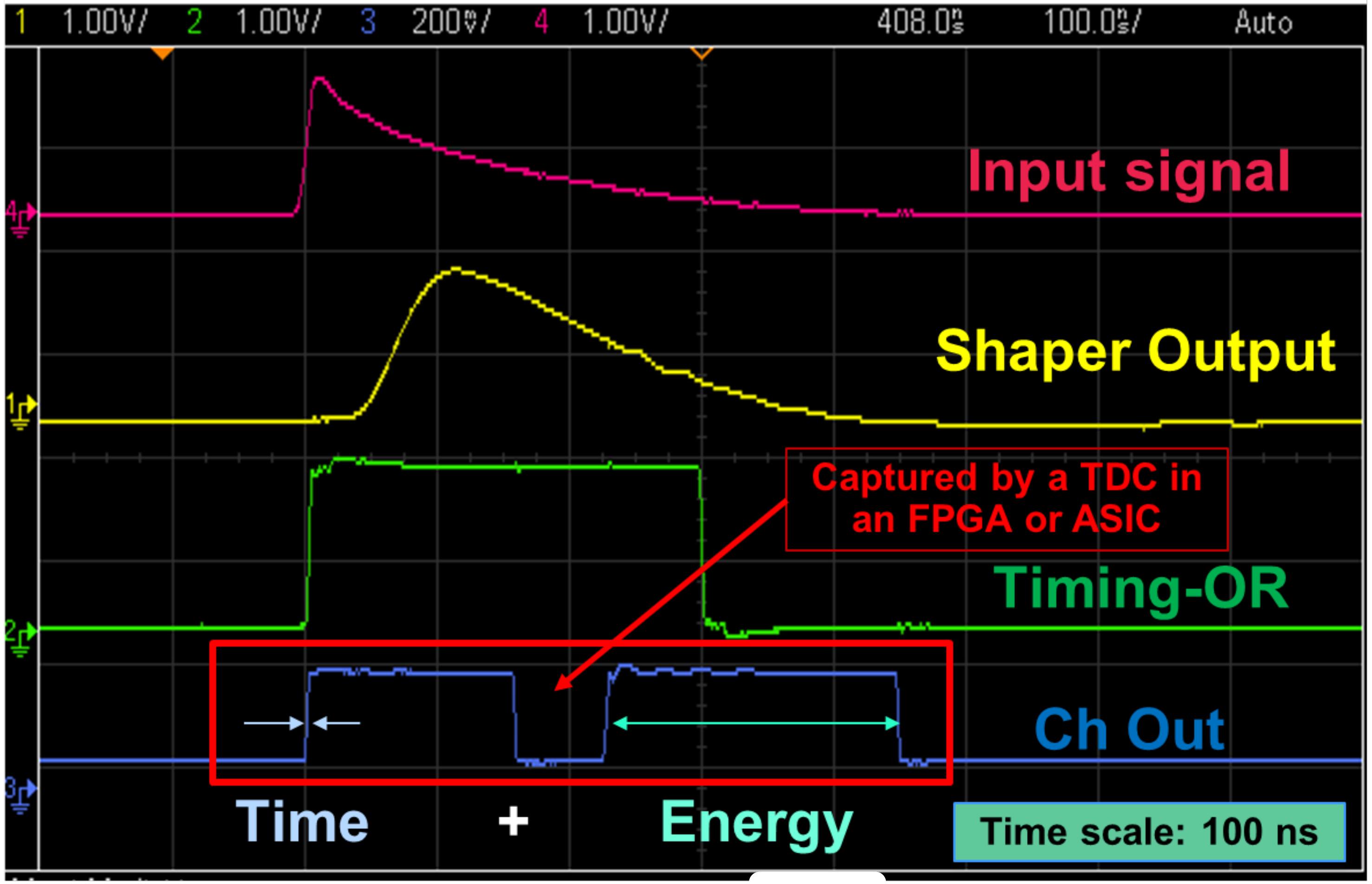
- FastIC provides a measurement of the time and energy per channel in two consecutive pulses:

Linear energy by pulse width encoding

- "Wilkinson ADC-like" conversion
- Controlled by on-chip state machine
- 1st pulse:
  - Time-of-Arrival
  - Non-Linear ToT (optional)
- 2nd pulse: energy response

It can also operate in Non-Linear ToT mode:

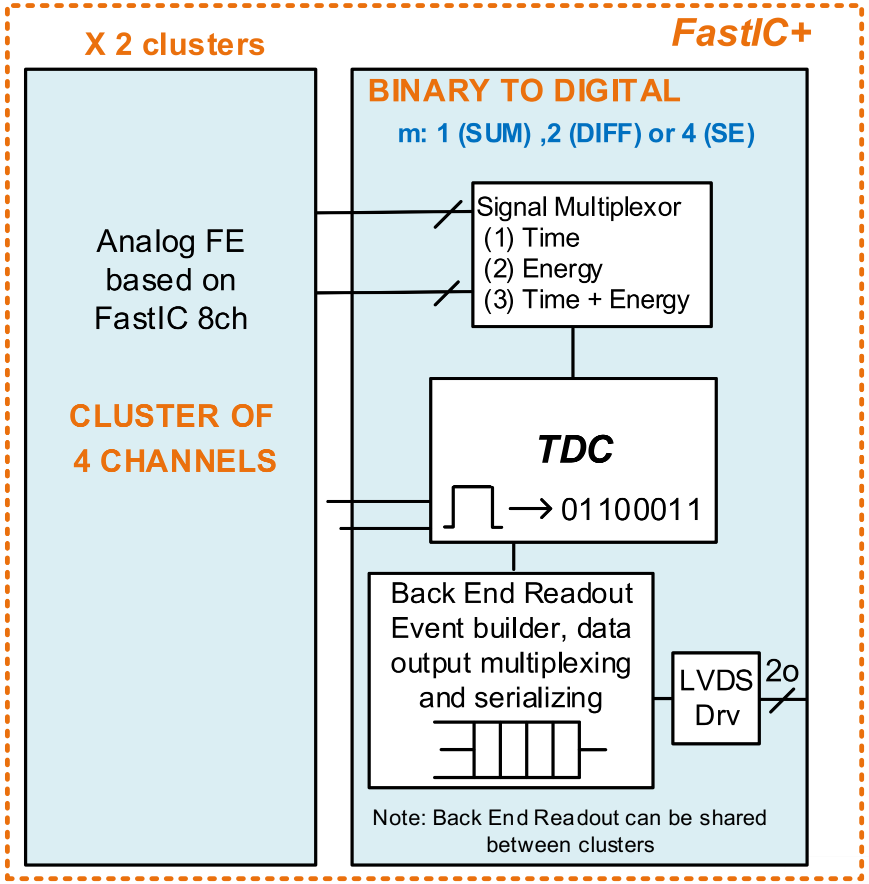
- High rate (>3 MHz) applications.



[1]: Sanchez, D., Gomez, S., 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

FastIC+: integration of 25 ps bin TDC on FastIC

- Specifications:
  - System-on-Chip.
  - Per channel TDC.
  - ToA: 25 ps time bin.
  - ToT: <500 ps time bin.
  - Backwards compatibility with FastIC
  - Low power consumption (<5 mW/ch).
  - Scalable & reusable design for future developments.



Summary

Institut "Jožef Stefan", Ljubljana, Slovenija

- Task 4.2 Photodetection devices for particle detectors include several activities which are at the technological edges or the solutions are not yet available

Tasks include

- the study of the fundamental properties of SiPMs
- Study of SiPM in the calorimeters
- Study of readout electronics for photomultiplier tubes
- Study of multi-channel integrated readout electronics

- Very diverse and demanding