Plastic scintillator detector with the readout based on array of large-area SiPMs for the ND280/T2K upgrade and SHIP experiments

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5-th International Workshop on New Photon-Detectors

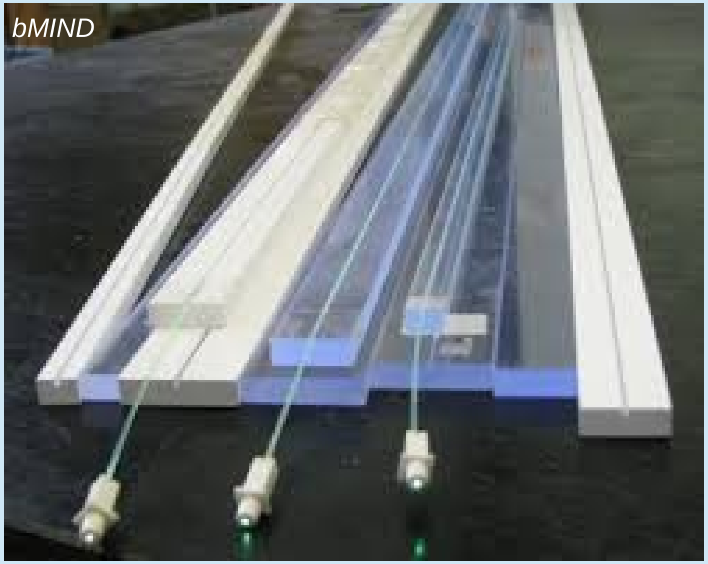
University of Tokyo, Japan

November 27-29, 2018

Outline

- Introduction to the concept
- Timing Detector for the SHIP experiment in CERN SPS
- ToF for the ND280 upgrade project in JPARC
- Testbeam results for the large-scale prototype in CERN

Common approaches for a long-bar readout

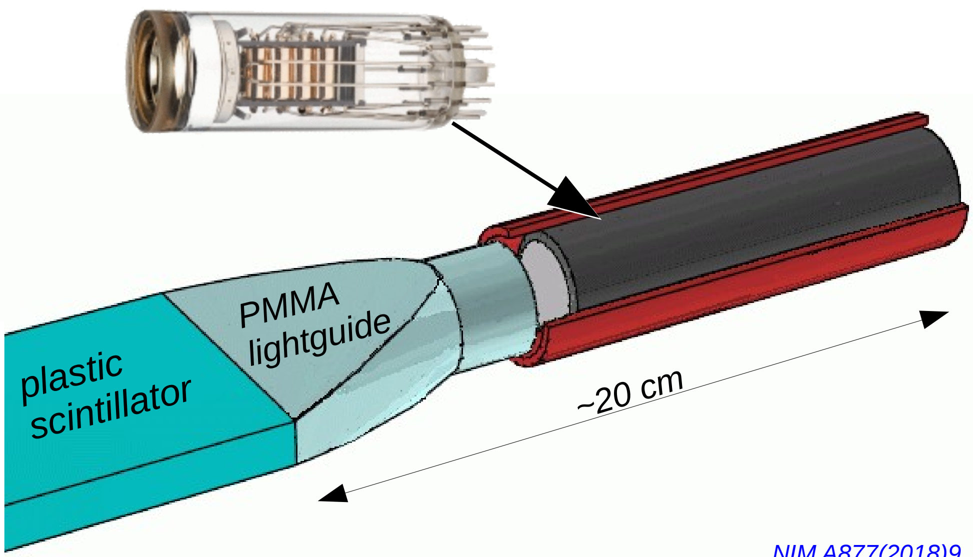


- Extruded plastic polystyrene based
- Reflected coating (chemical etching)
- WLS fiber + SiPM readout
- Typical light yield $\lesssim$100 γ
- Typical time uncertainty $\lesssim$1ns

- Cast plastic scintillator PVT based
- γ transfer by total internal reflection
- PMT readout
- Typical light yield $\lesssim$1000 γ
- Typical time uncertainty $\lesssim$0.1ns

PMT compared to SiPM-array readout

Readout by PMTs which coupled to the bar via lightguide



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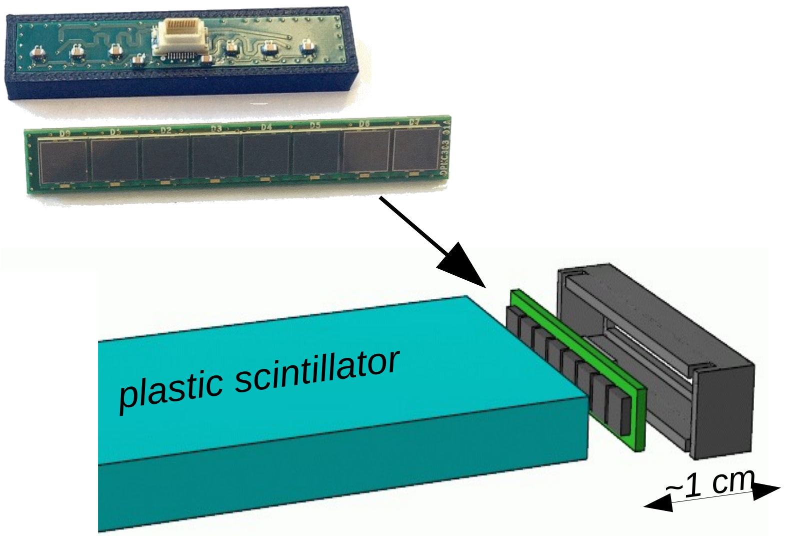
Array of large area SiPMs directly coupled to the bar



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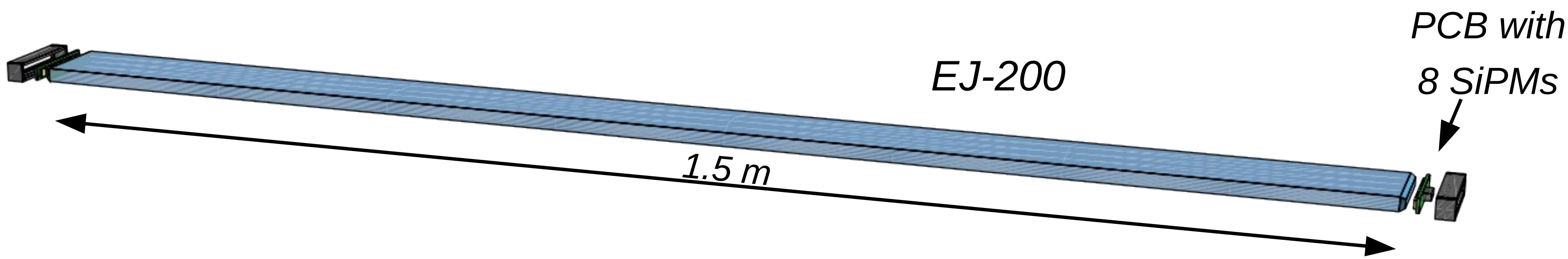
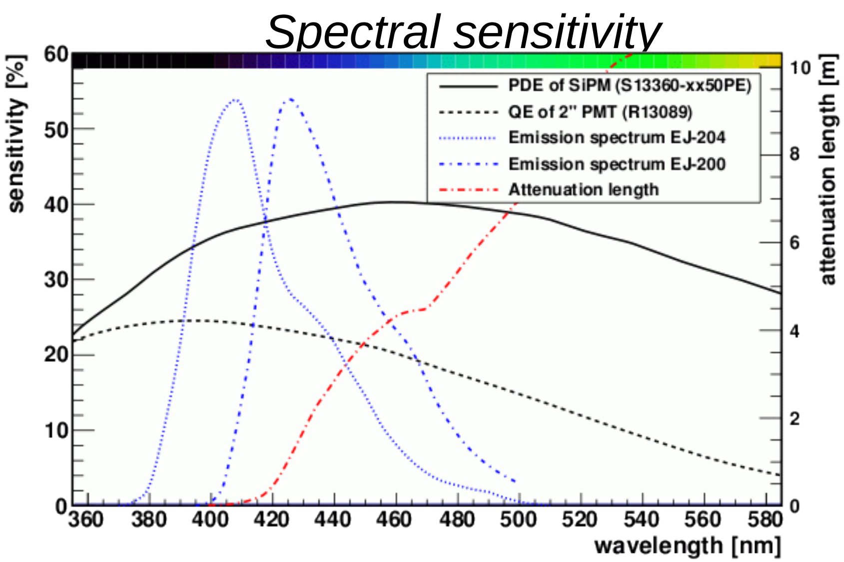
Advantage of SiPM-array *vs* PMT

- Compactness: 1 cm *vs* 20 cm
- Low bias voltage: 50 V *vs* few kV
- High photon detection efficiency: 40% *vs* 25%
- Easily scalable system. In general any SiPM shape can be ordered from a producer company
- Can be directly attached to a scintillator surface. No need in a complex shape light-guide which provides an adiabatic connection
- Can be used in magnetic environment. PMT requires ferromagnetic housing which make the construction bulky
- Lower cost

Choice for the plastic scintillator material





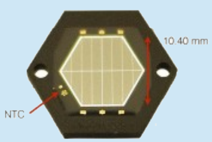
- PVT based plastic scintillators have been considered: EJ-200 and EJ-204 (commonly used for ToF systems)
- Bar dimensions **150 cm x 6 cm x 1 cm**, cast surface, edges diamond milled
- Trade-off between two effects
  - Fast scintillator (shorter rise and decay constants) emits light in the NUV region
  - Shorter wavelength photons are stronger affected by absorption in the material

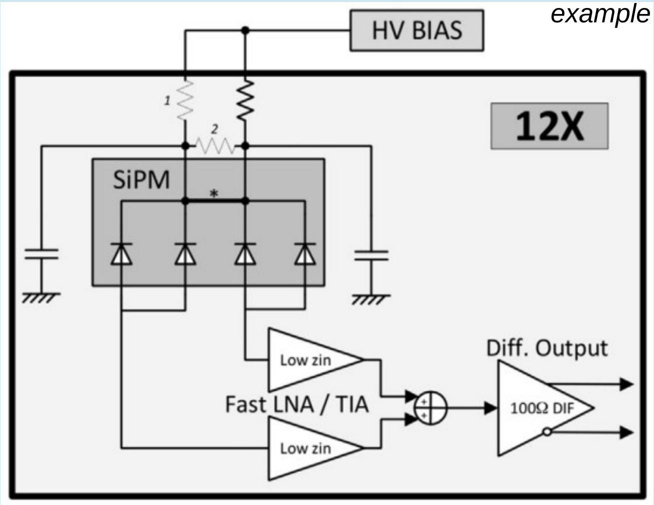
ELJEN Technology	SAINT-GOBAIN CRYSTALS	γ / 1MeV e-	Wavelength	Rise time	Decay const	Att. length
EJ-204	BC-404	10.4k	408 nm	0.7 ns	1.8 ns	1.6 m
EJ-200	BC-408	10k	425 nm	0.9 ns	2.1 ns	~3.8 m

Readout circuit for a SiPM array

A *large SiPM capacitance* increases the rise time and width of the signal and worsens the time resolution. A reduction of the capacitance can be achieved by using an *independent sensor readout and amplification* to isolate the sensor capacitances from each other. Signals are summed up at the end.

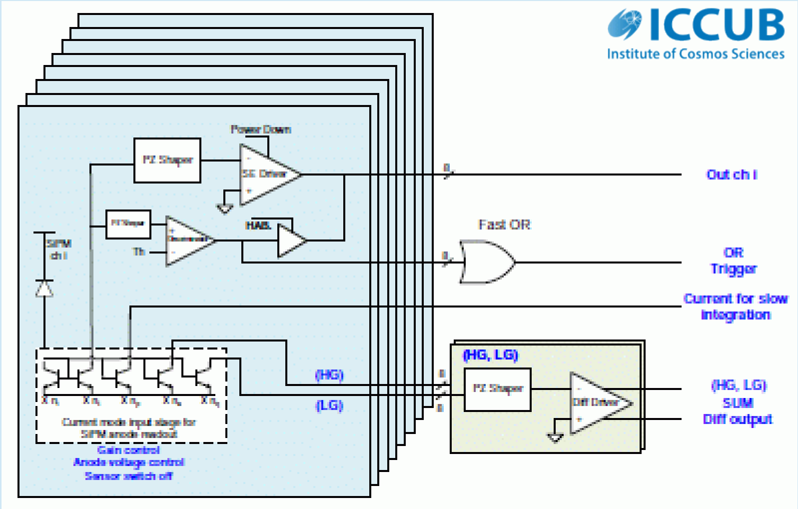
Discrete circuit





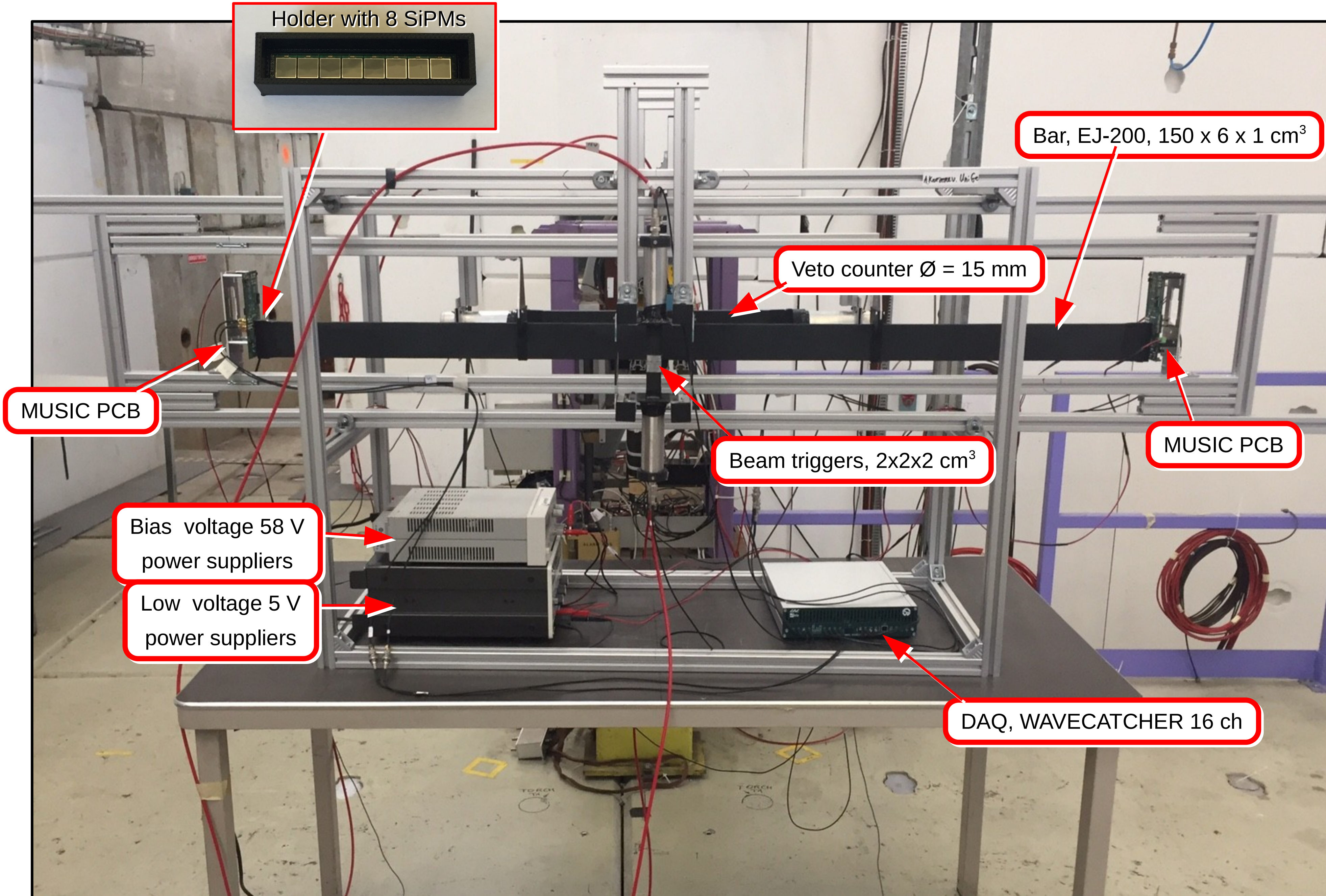
- Example of the circuit: front-end of the CTA SST-1M camera
- One operational amplifier per SiPM plus summation stage make PCB bulky
- One can not change parameters (individual offsets, pole zero)

ASIC / MUSIC R1



- MUSIC: Multiple Use Sipm IC
- Input: up to 8 SiPM of any size
- SPI control: pole zero cancellation, individual offsets, gain control
- PCB of smaller size
- Controller is mandatory

Test-beam at T9 / Est Area CERN PS, June 2017



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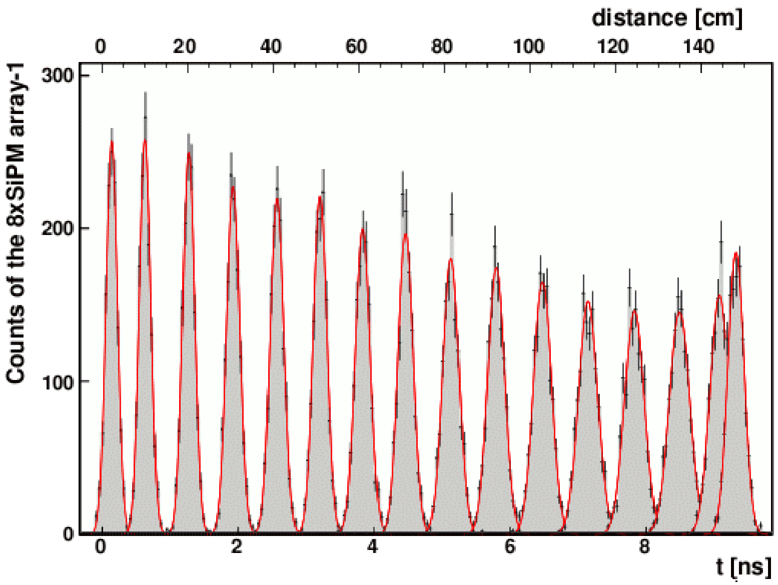
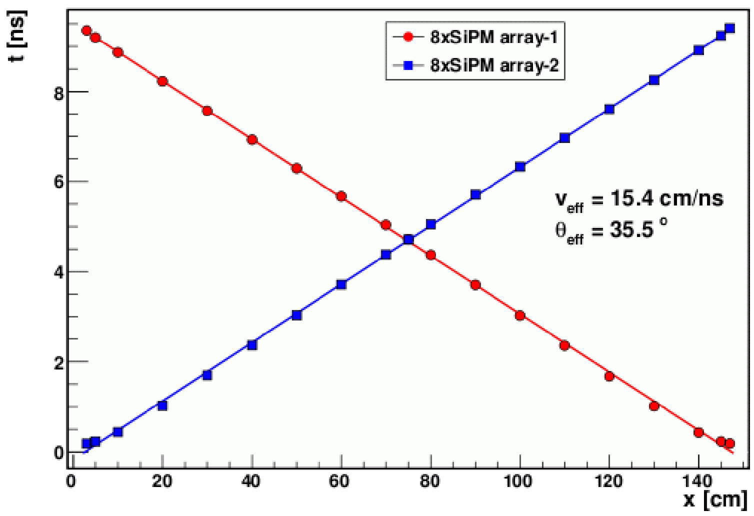
Results of the testbeam measurements





- Scan of the time resolution along the bar
- Digital CFD technique has been applied
- Walk corrections (time vs amplitude) have been applied
- Trigger time resolution 21 ps (not subtracted)
- 80 ps time resolution for the 2-side readout
- The resolution improves with an increase of the bias voltage
  - Time-walk effect (due to MUSIC) limits the voltage

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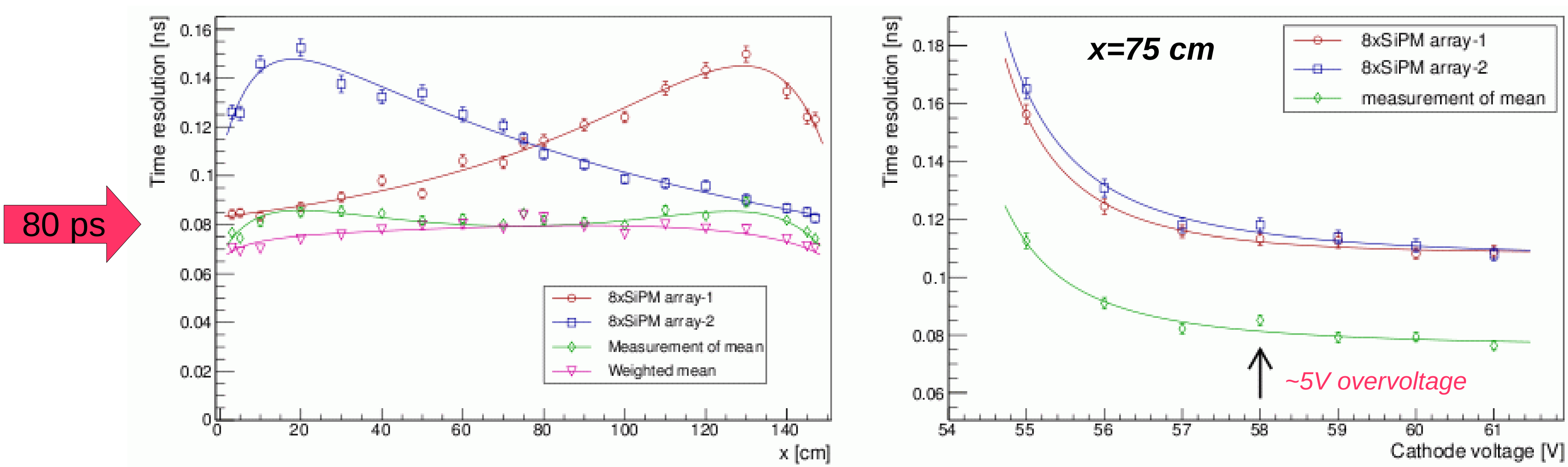

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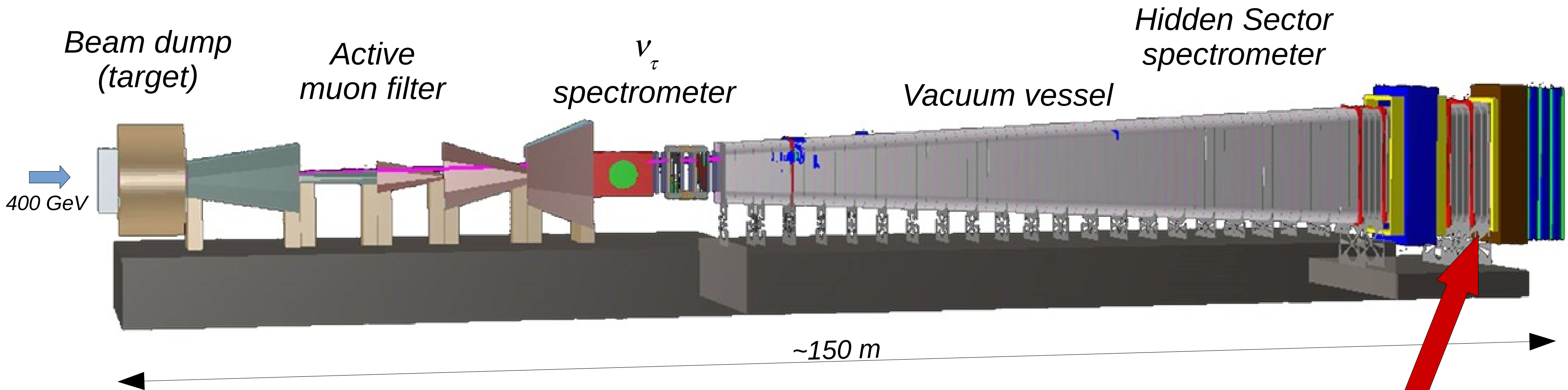
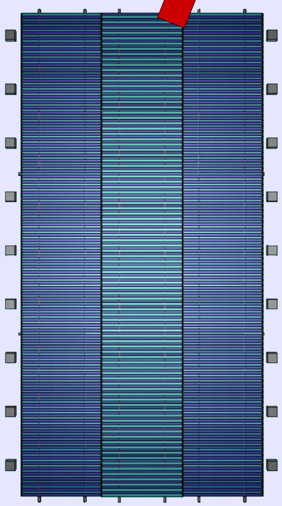
SHiP experiment at CERN SPS (approval in 2020)

The SHiP Experiment is a new general-purpose fixed target facility at the CERN SPS to search for hidden particles as predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe

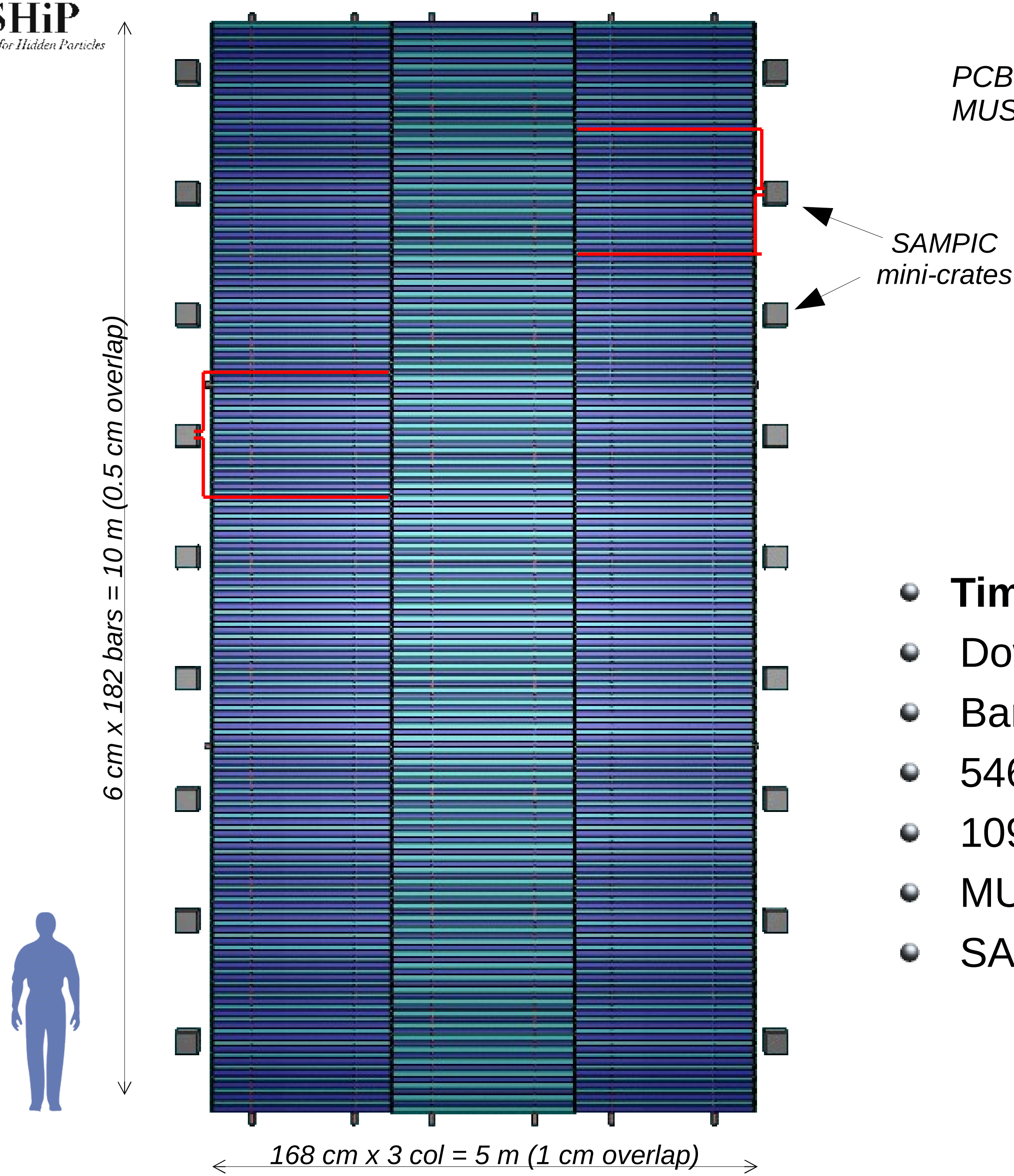


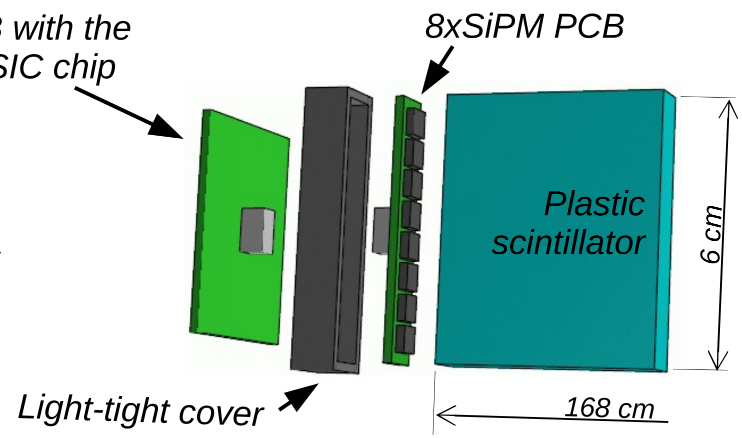
Timing Detector

- Purpose: reduction of combinatorial background by tagging particle belonging to a single event
  - Source of background: products of μ and ν interactions
- Detector can be used for PID of few GeV particles
- Time resolution < 100 ps
- Active surface: 5 m x 10 m
- Material: plastic scintillator; light readout: array of SiPMs or PMT
- Trigger-less readout DAQ => SAMPIC based system is proposed



Timing Detector in SHiP (construction in ~2023)

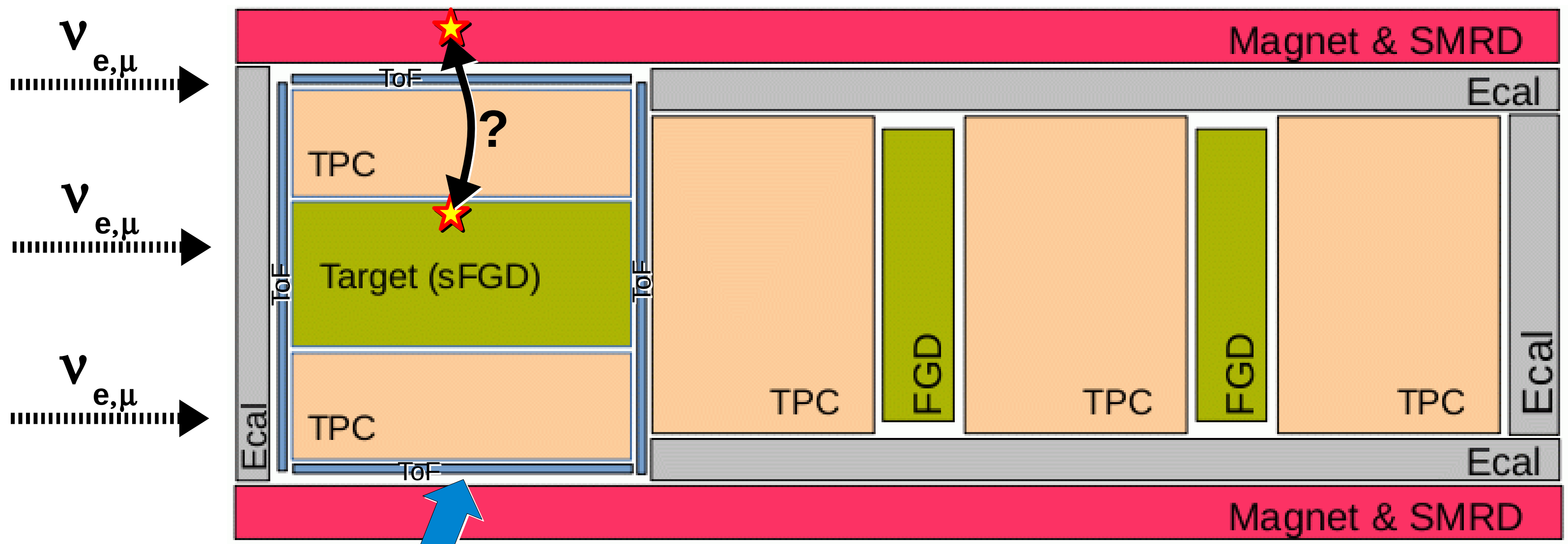


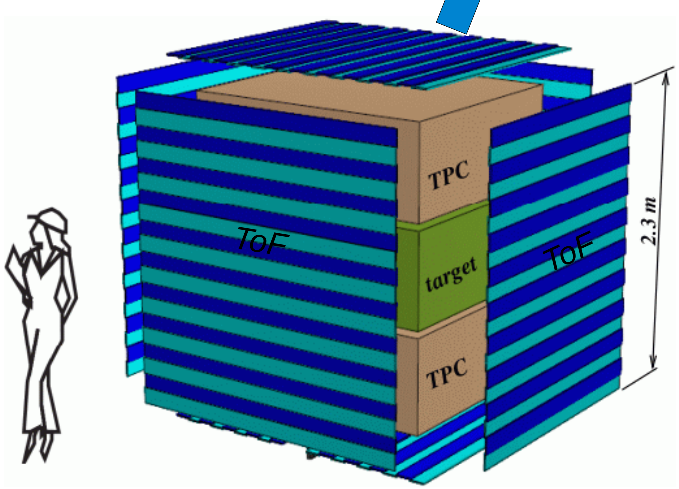


- **Time resolution < 100 ps**
- Downstream of the decay vessel
- Bar's size ***168 cm x 6 cm x 1 cm***
- 546 bars x 2 = 1092 channels
- 1092 x 8 = 8736 SiPMs
- MUSIC for the Front-end
- SAMPIC for the DAQ (~1 kHz phys. rate)

Upgrade of Near Detector of T2K at JPARC (2019-2021)

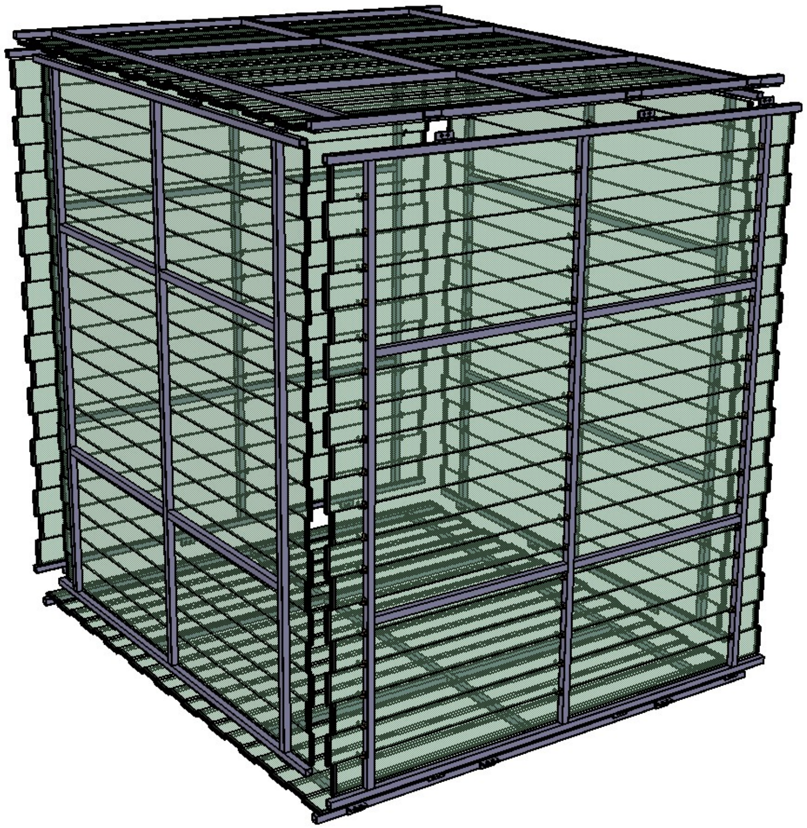
The goal of T2K is to study neutrino flavor oscillations using an off-axis neutrino beam of JPARC. ND280 detector is used to study charge current neutrino interaction aiming for neutrino cross section measurements and reduction the systematic uncertainty for the neutrino oscillation study. Super-Kamiokande is used as a far detector.

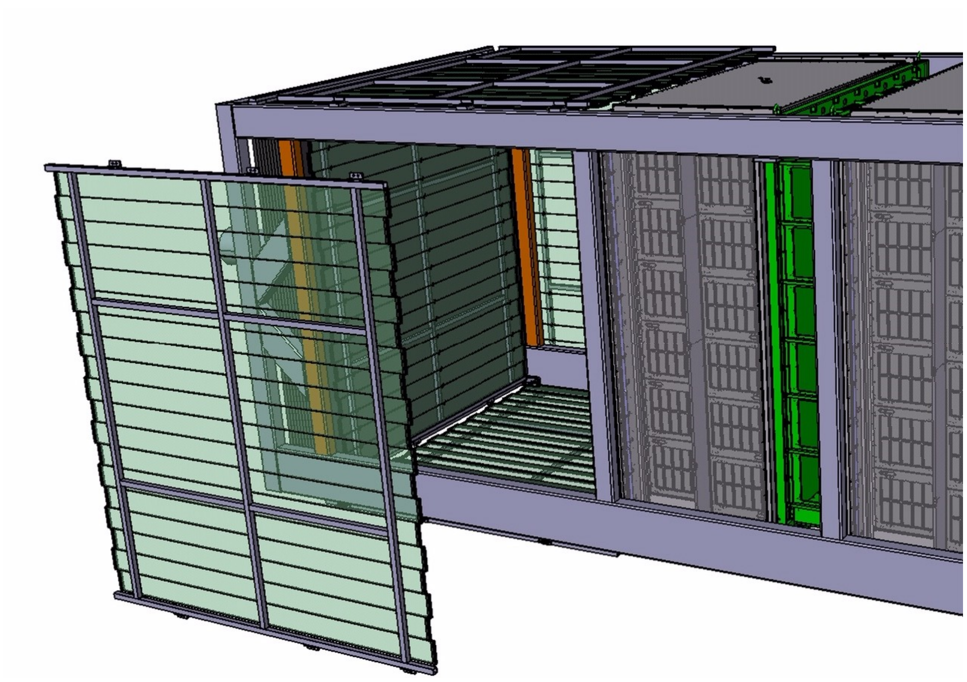


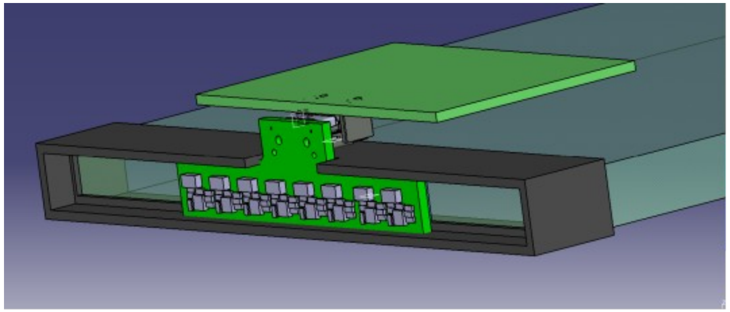


- 6 ToF planes surround the target and two TPCs
- Flight direction of ν interaction products: time resolution required 500 ps
- Improvement of PID: time resolution < 200 ps
- Precise timing stamp for the time calibration of the sFGD target

ToF detector for ND280 upgrade (construction in 2019)

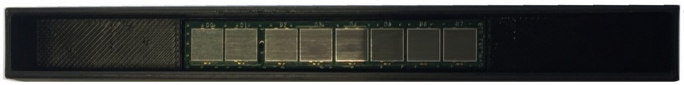


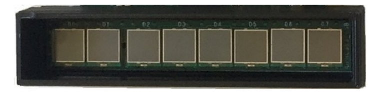


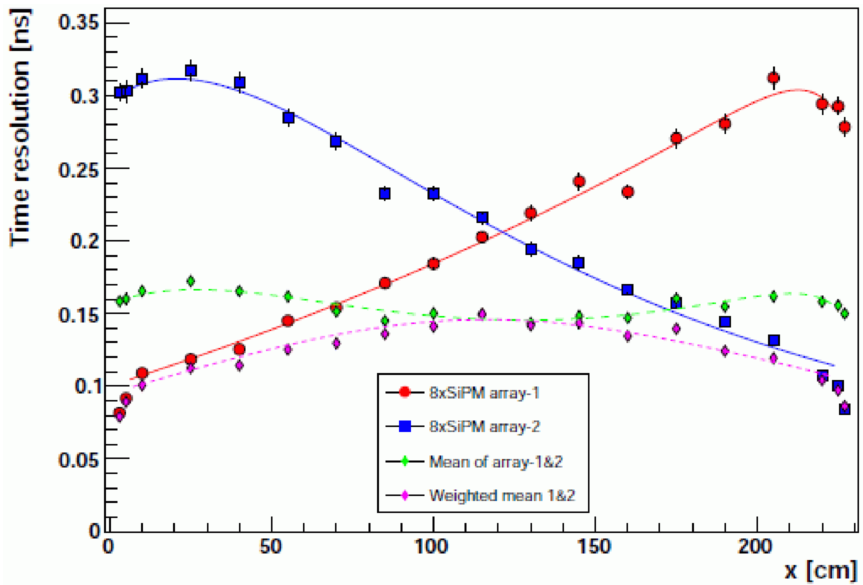


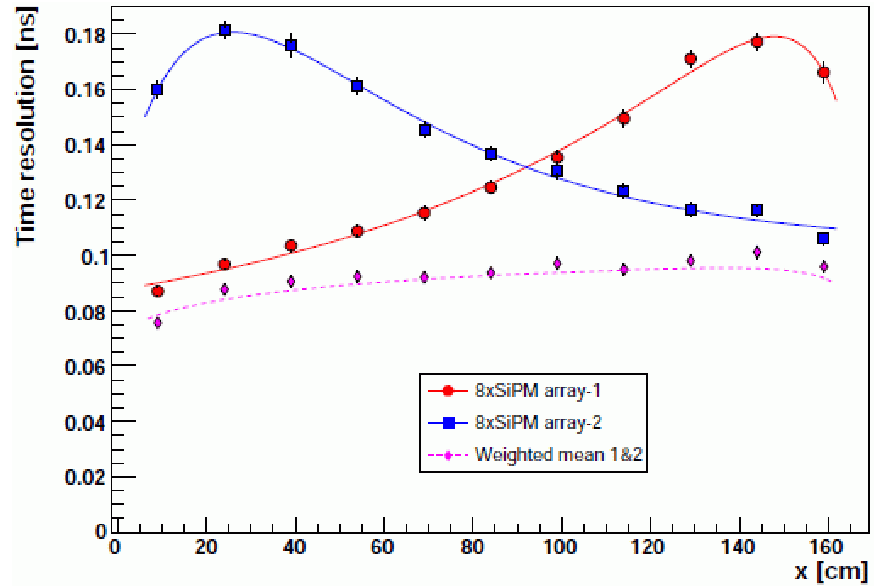
- 6 ToF modules, 20 bars each
- **Time resolution ≈ 200 ps**
- Bar's size ***230 cm x 12 cm x 1 cm***
- 120 bars x 2 = 240 channels
- 240 x 8 = 1920 SiPMs
- 256ch SAMPIC module for DAQ

Time resolution along the bar with 8-SiPM array









- Bar size: ***230 cm x 12 cm x 1 cm***
- Time resolution
  - Required: < 200 ps
  - Measured: ~150 ps

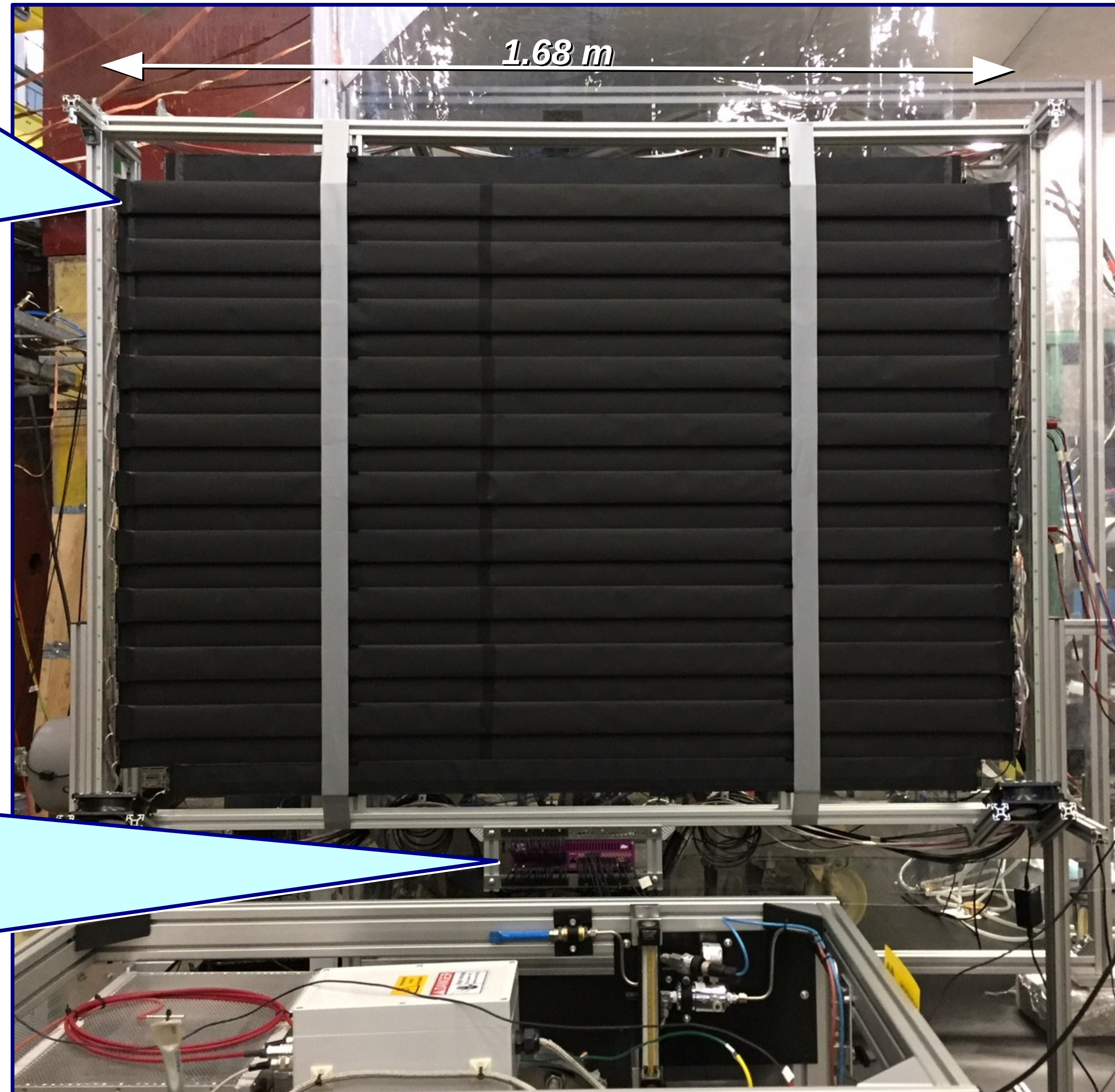
- Bar size: **168 cm x 6 cm x 1 cm**
- Time resolution
  - Required: < 100 ps
  - Measured: ~85 ps

Detector prototype (22 bars / 44ch)

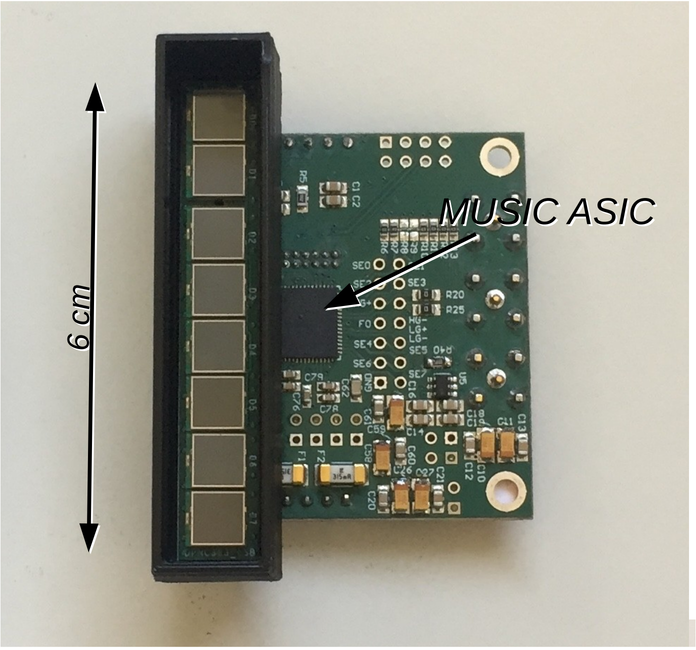
Readout by SiPM-arrays

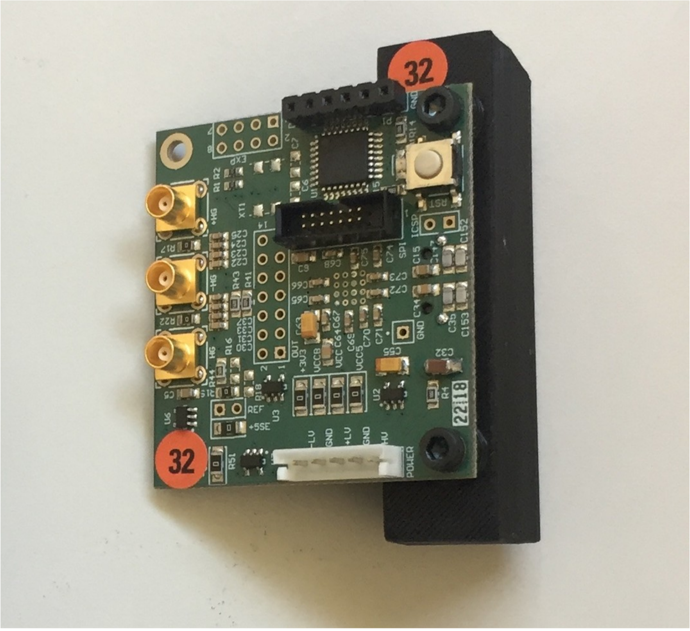
64ch SAMPIC module

Testbeam Aug 15 – Sep 19, East hall T10 of CERN PS

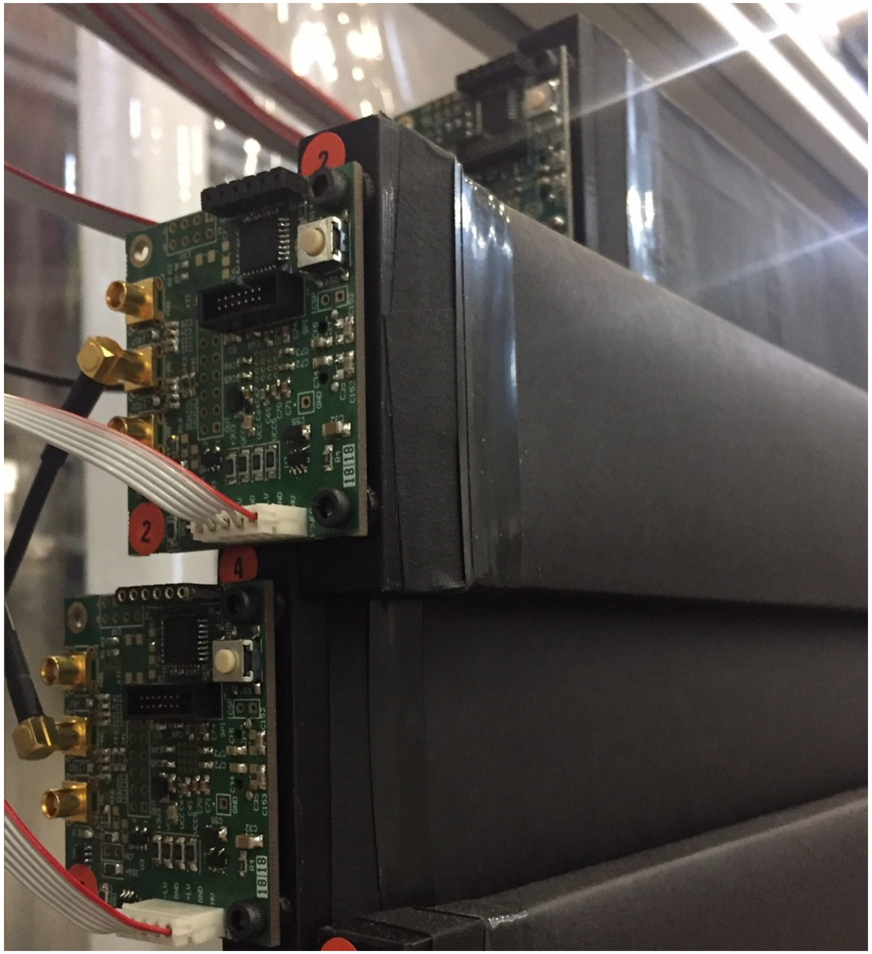


2 side readout, ~90 ps time resolution

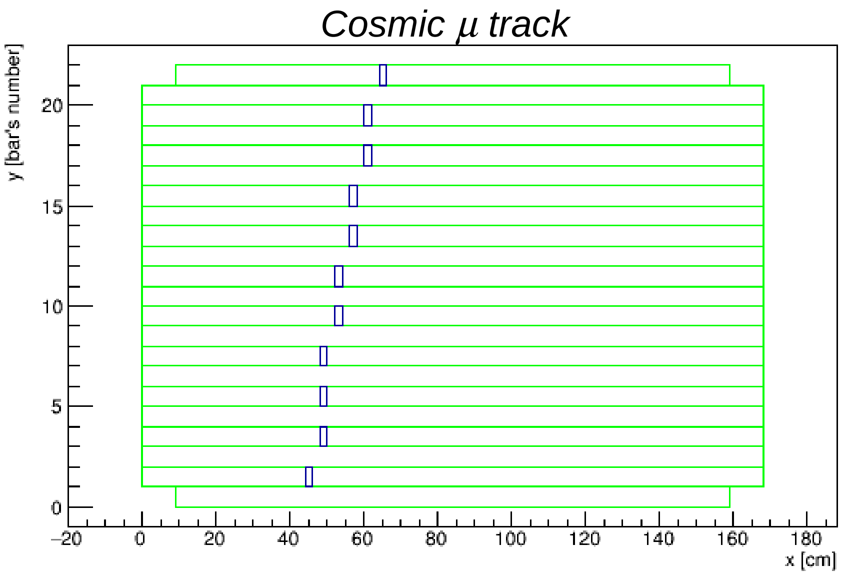


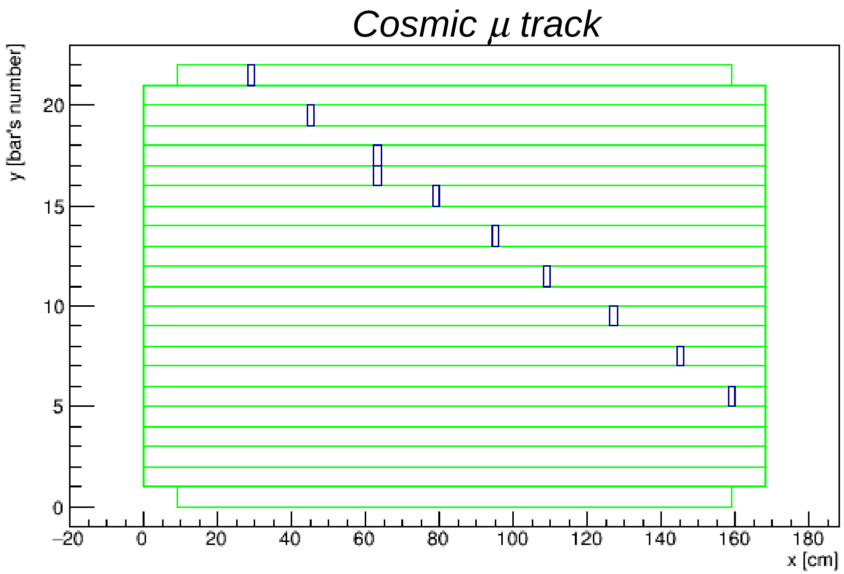


- Plastic scintillator bar EJ200 with a size 168 cm x 6 cm x 1 cm
- Array of 8 SiPM is attached to both ends
- Size of each SiPM 6 mm x 6 mm
  - Hamamatsu S13360-6050PE
- eMUSIC v2 is used for the readout

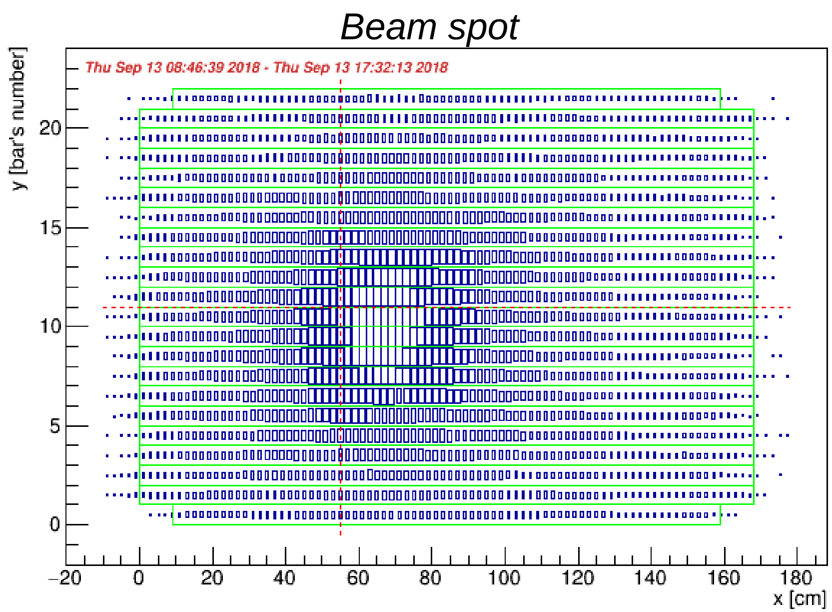


Detector prototype (22 bars / 44ch)



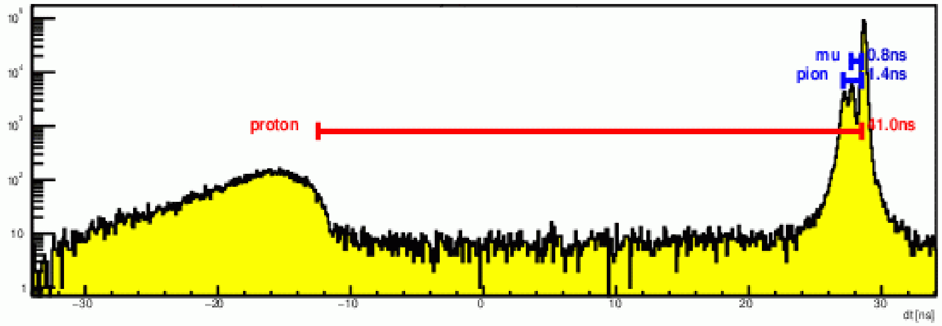


- Cosmic tracks to be used for calibration
- Two side readout for every bar
  - $(t_1+t_2)/2$ for the interaction time
  - $(t_1-t_2)/2$ for the position along the bar
- ToF was used to monitor the beam spot position with respect to HP-TPC

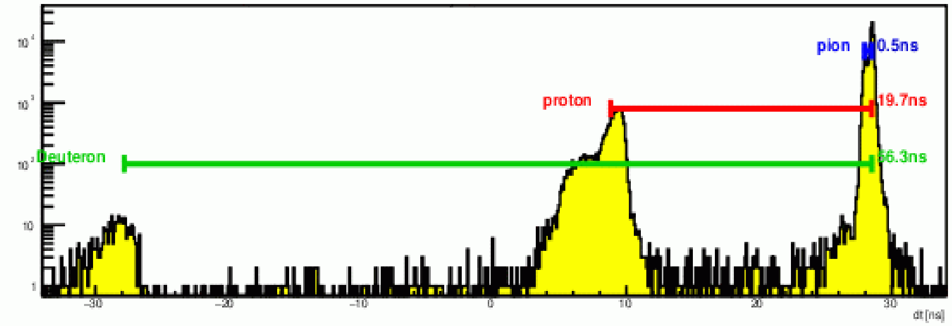


PID *vs* beam momentum (10m flight distance)

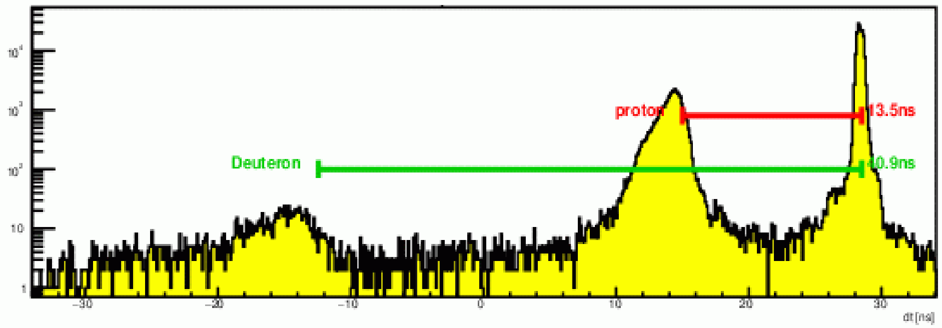
0.5 GeV/c



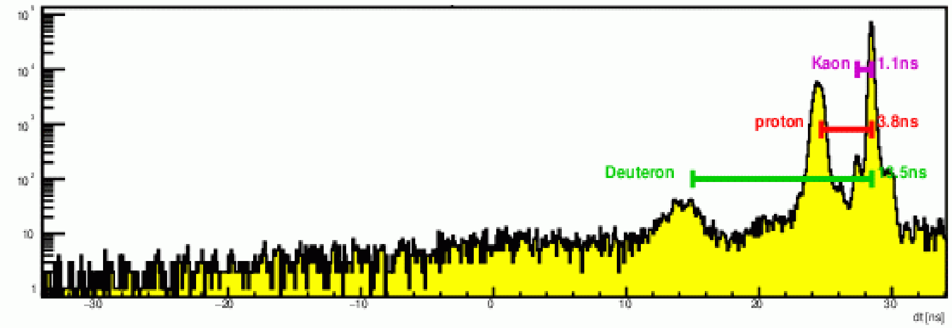
0.8 GeV/c



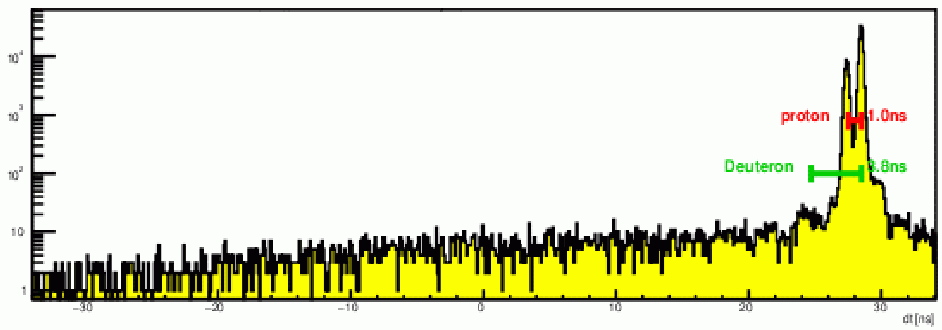
1 GeV/c



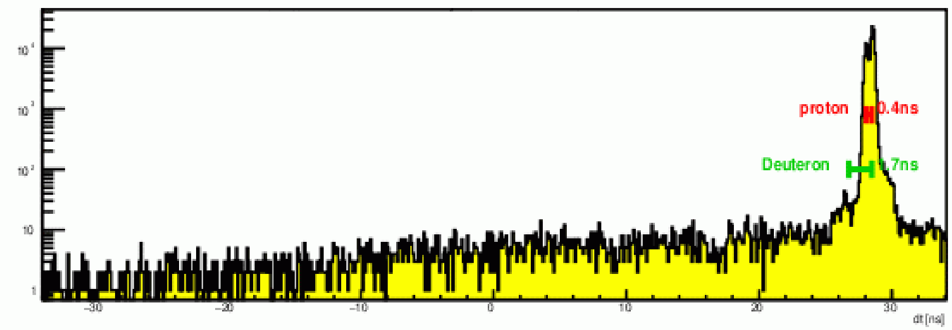
2 GeV/c



4 GeV/c

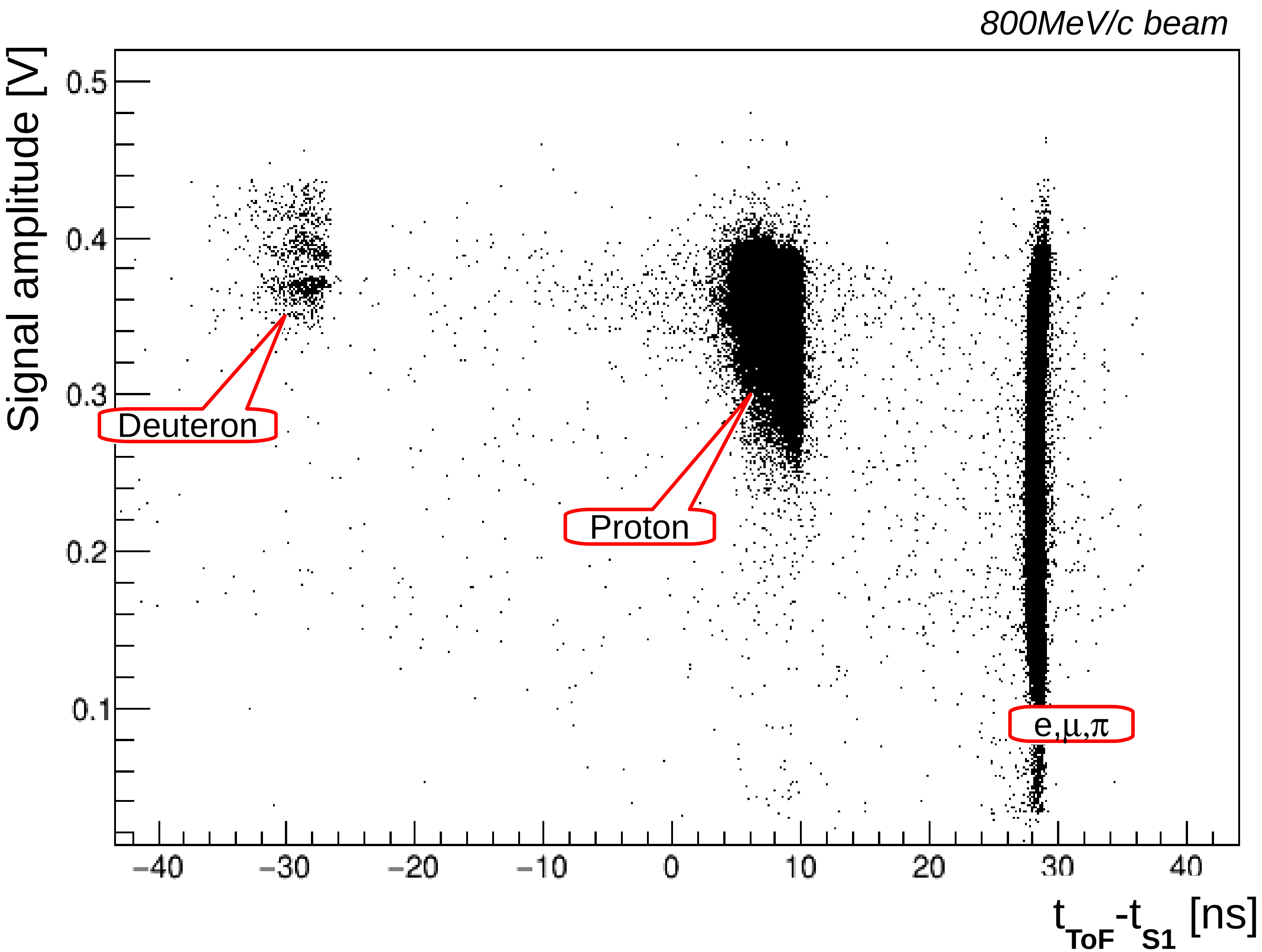


6 GeV/c



Non-calibrated data

Heavier particle provide larger light yield



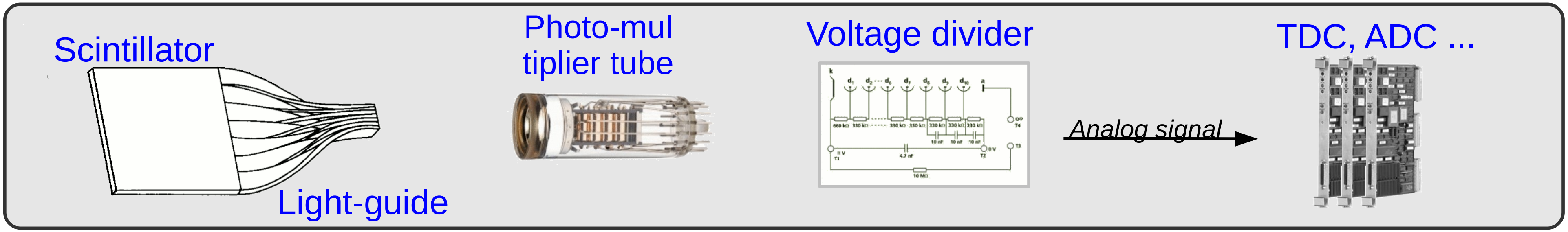
- Can be used as an additional information for PID

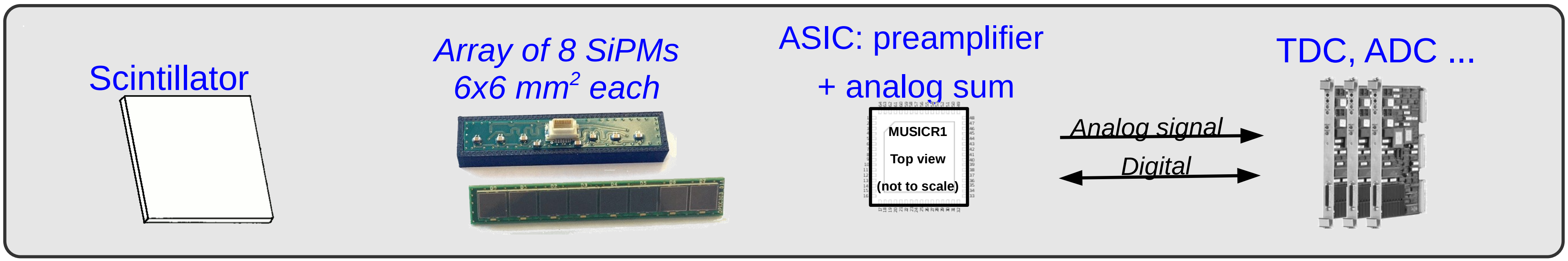
Summary

- **Array of large-area SiPMs** to be used for **direct replacement of PMT**
  - Advantages of SiPM: compactness, mechanical robustness, high PDE, low operation voltage, insensitivity to magnetic field, low material budget
  - SiPM-array coupled to the ends of a long plastic scintillator bar
- ToF system for the **ND280 upgrade of T2K at JPARC**
  - 120 bars, size of a single bar 230 x 12 x 1 cm^3
  - Required time resolution <200ps
  - Measured time resolution (8 SiPMs array) ~150ps
  - Construction is planned for year 2019
- Timing detector for the **SHIP experiment in CERN SPS**
  - 546 bars, size of a single bar 168 x 6 x 1 cm^3
  - Required time resolution <100ps
  - Measured time resolution (8 SiPMs array) ~80ps
  - Construction is planned for year 2023
- 22 bars **prototype successfully operated** in testbeam areas last summer

Backup slides

The original idea behind of this work





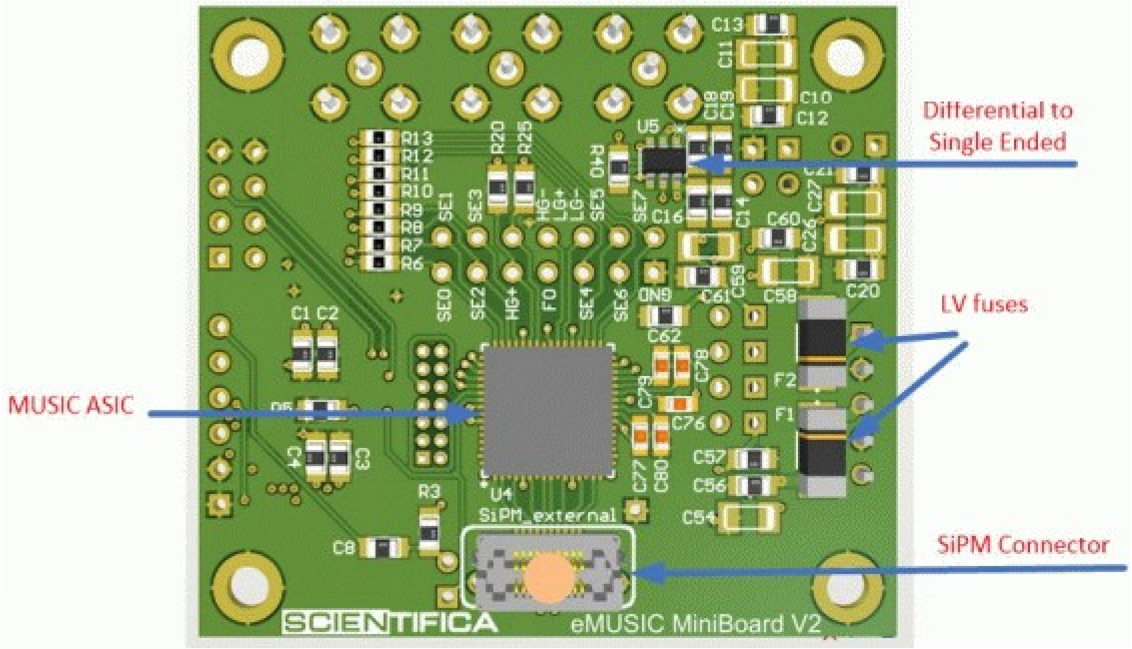
Advantage of SiPM-array *vs* PMT

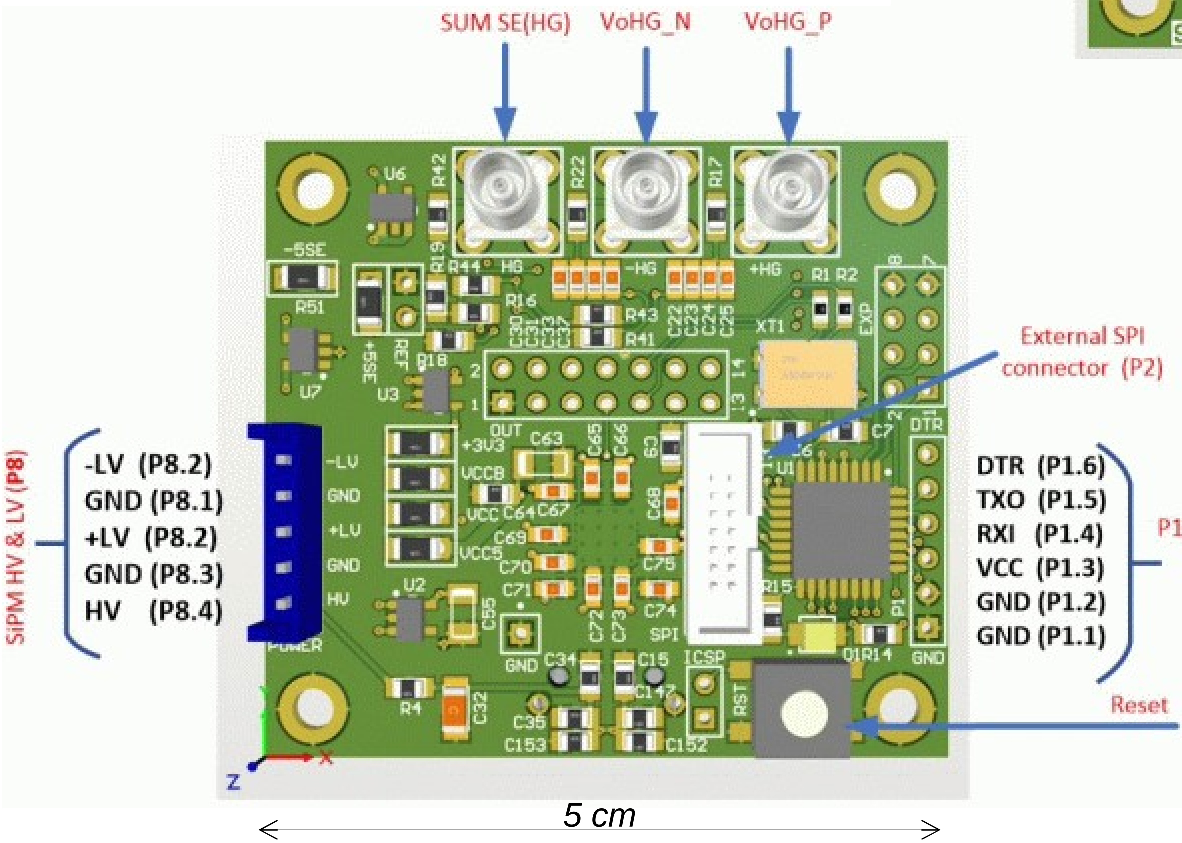
- Compactness
- Low bias voltage ~50 V
- High photon detection efficiency ~40%
- Easily scalable system
- In general any SiPM shape can be ordered from a producer company
- Can be directly attached to a scintillator surface
  - no need in a complex shape light-guide which provides an adiabatic connection
- Can be used in magnetic environment
  - PMT requires ferromagnetic housing which make the construction bulky

Comparison to MRPC

- No constrains for planarity. Barrel shape detector as an example
- Minimum expenses for maintenance
- Assembling is easy: no clean room or skilled manpower is required
- Low voltage: 50V *vs* few kV

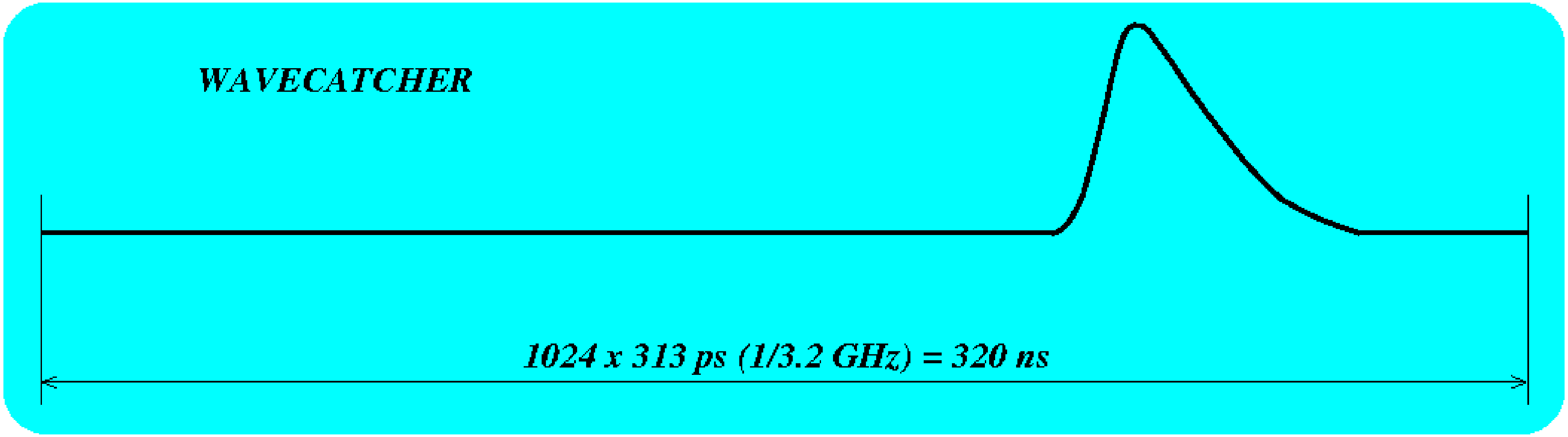
- ASIC: Multiple Use SiPM Integrated Circuit (MUSIC)
- ASIC provides analog outputs of 8 individual SiPMs and also the sum
- Tunable pole-zero cancellation for the SiPM recovery time
- Individual offsets and overall gain can be configured

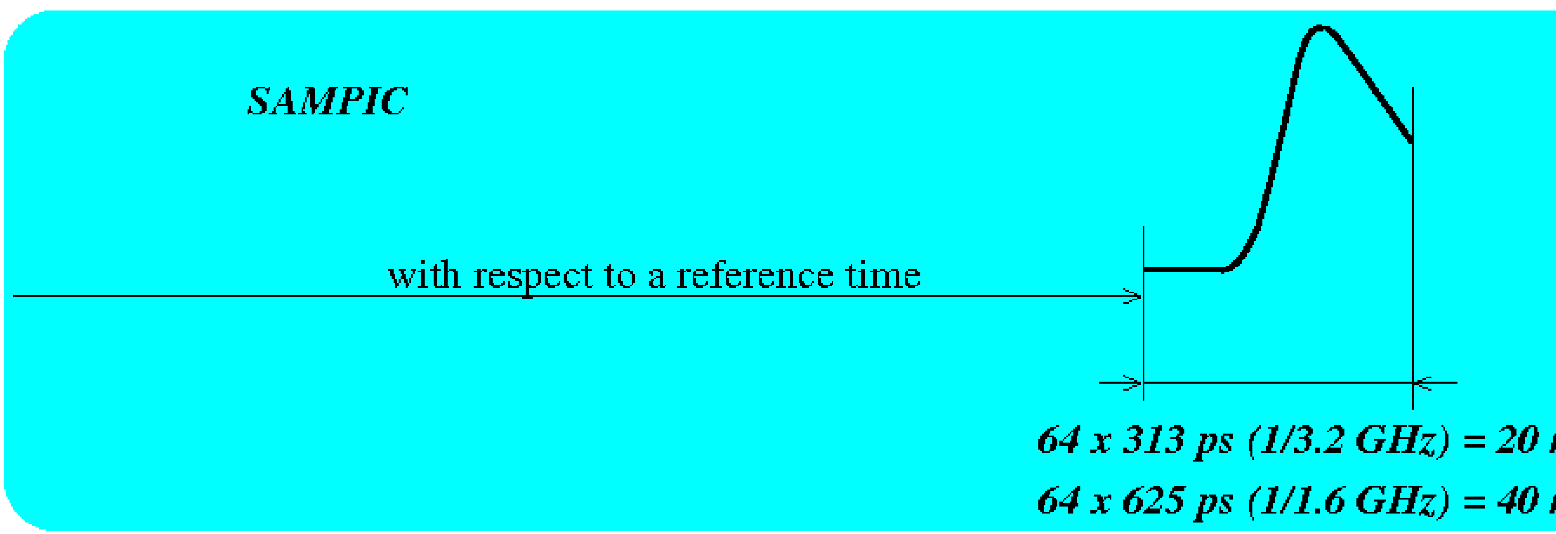




- Communication to MUSIC either directly (SPI connector) or via micro-controller
- Micro-controller can talk to PC via UART interface (USB) and can store all settings and calibration values for SiPMs
- 3 options for the analog output

Waveform recorded by SAMPIC and WAVECATCHER

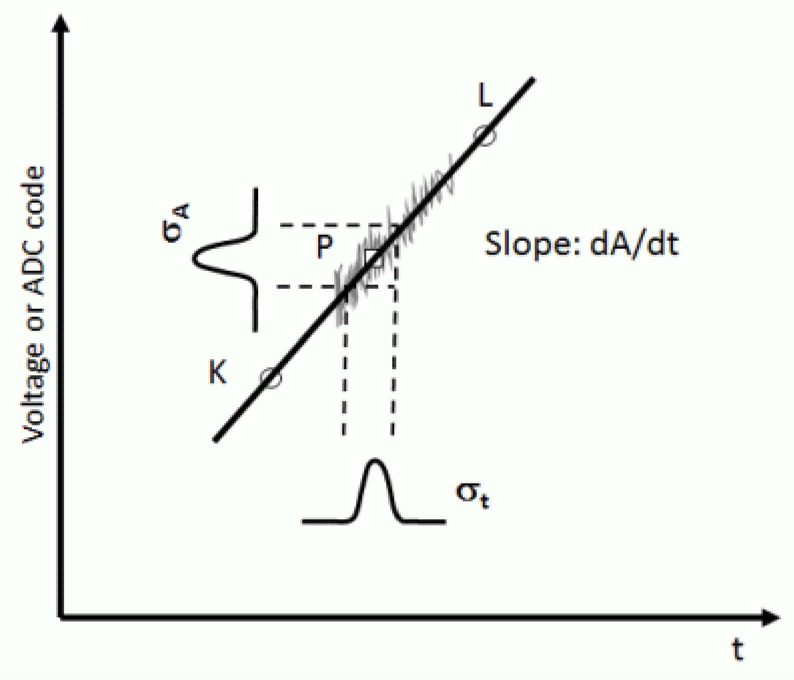




ToT information (signal width) is provided in new version

Was used in the 3.2 GS/s mode

Choice of plastic material (3)



- Time precision measurement

$$\sigma_t^2 = \left(\frac{\sigma_A}{dA/dt}\right)^2 + Const$$

- 'Fast' plastic (steep slope) should be chosen only if there are no other contributions smearing the front edge of a signal

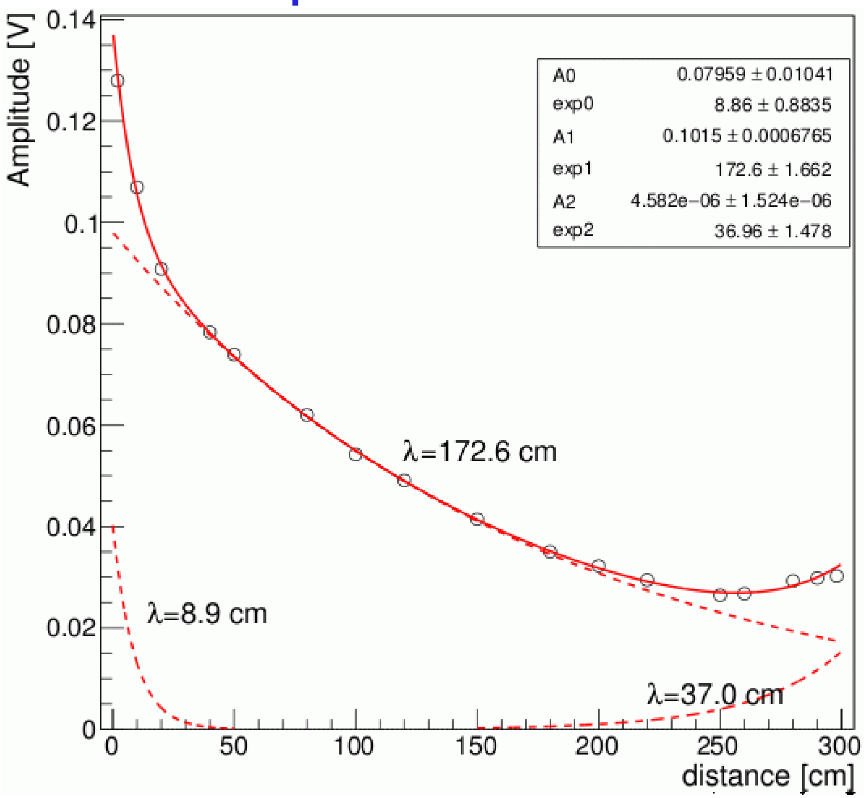
Time resolution of a scintillator counter

$$\sigma_t(l) = \sqrt{\frac{\sigma^2_{sci+PMT}}{N(l)} + \frac{(\sigma_{length} \cdot l)^2}{N(l)} + \sigma^2_{el}}$$

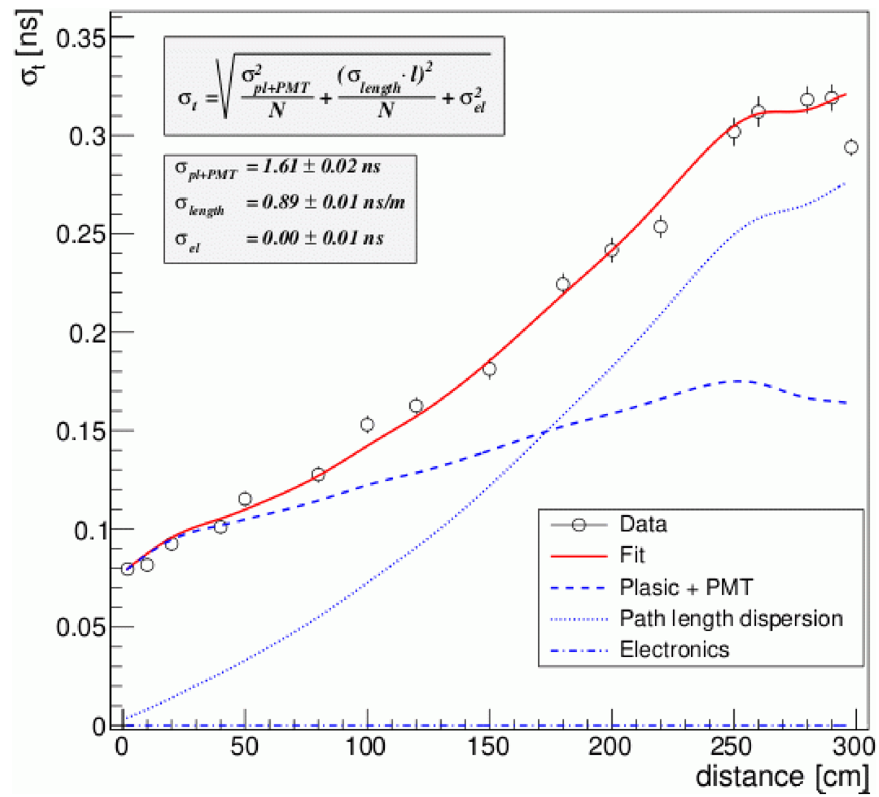
- $\sigma_{sci+PMT}$ is a decay time of the scintillator and a time jitter of PMT
- σ_{length} is a time spread of the light transmission
- σ_{el} is an uncertainty due to electronics
- N_e is the number of p.e. $N_e = N_0 e^{-l/\lambda}$

Time resolution: phenomenological fit

Amplitude vs Distance



Time resolution vs Distance



- At large distance the resolution is dominated by a contribution from the photon dispersion length => better electronics can not help
- Last point does not fit to the simplified formula (light reflection)

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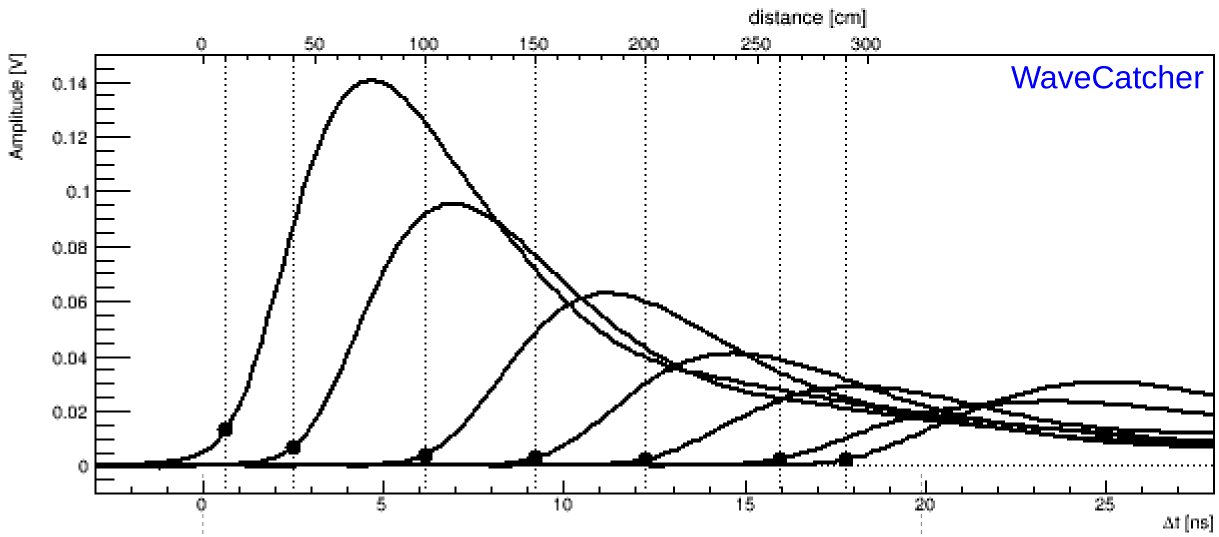
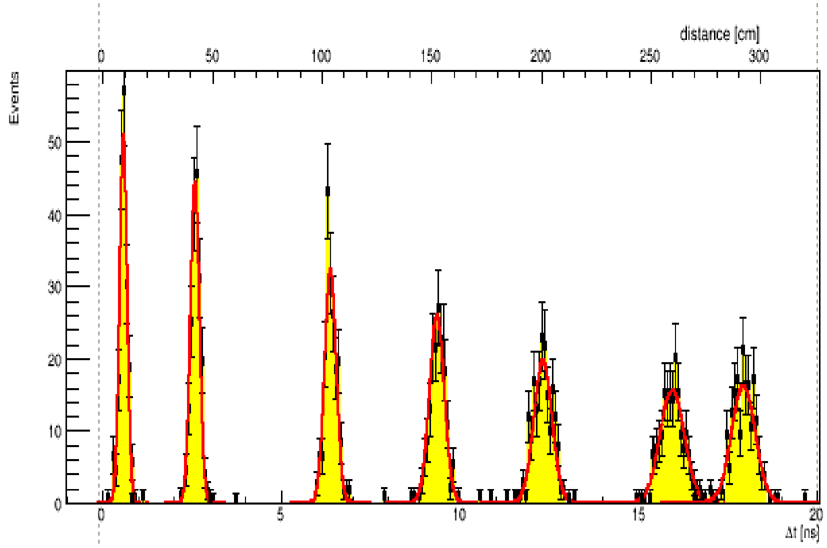
Time measurement w.r.t. reference counter

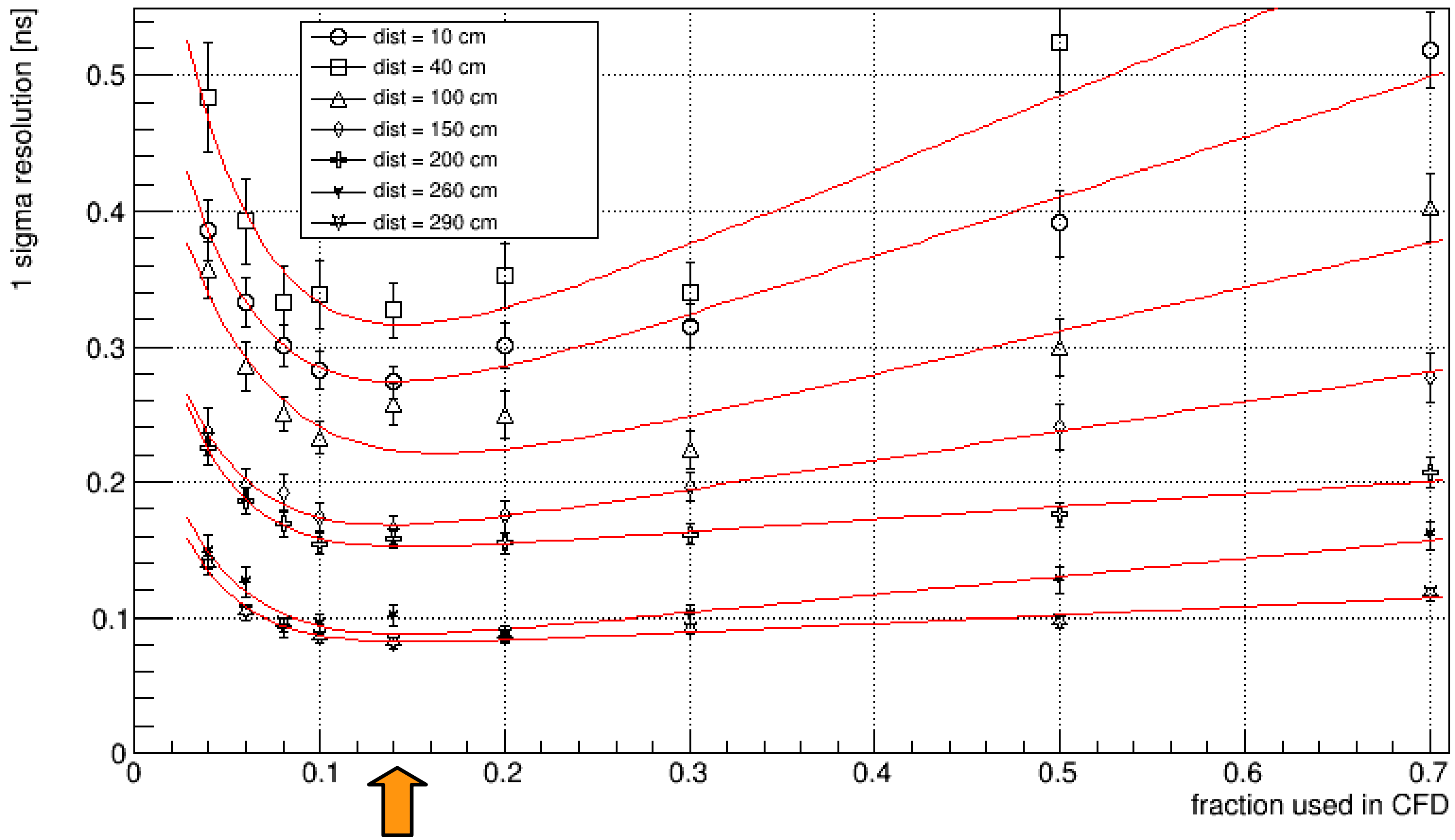


- Digital constant fraction discriminator (d-CFD) technique is used



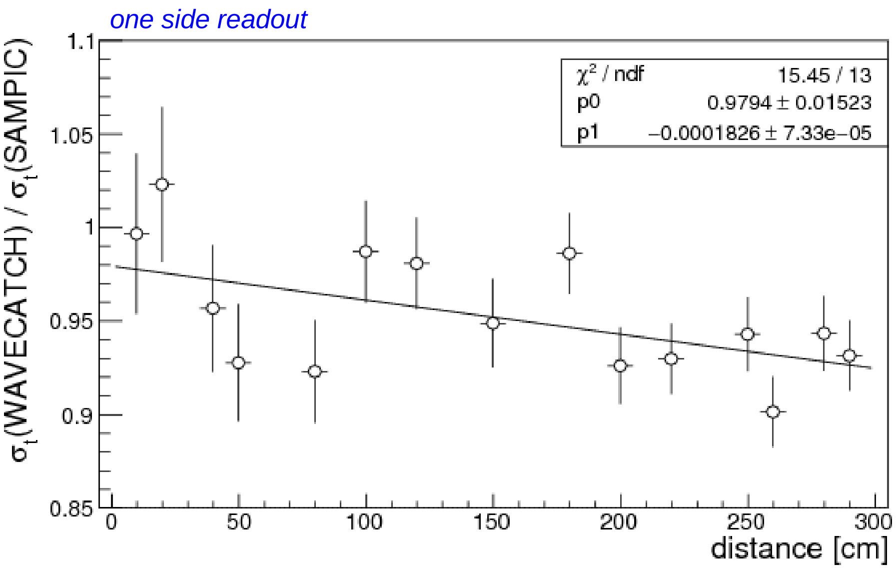
- Uncertainty of the reference counter to be subtracted in quadrature
- Signal improves when it is close to the far end because of the reflection

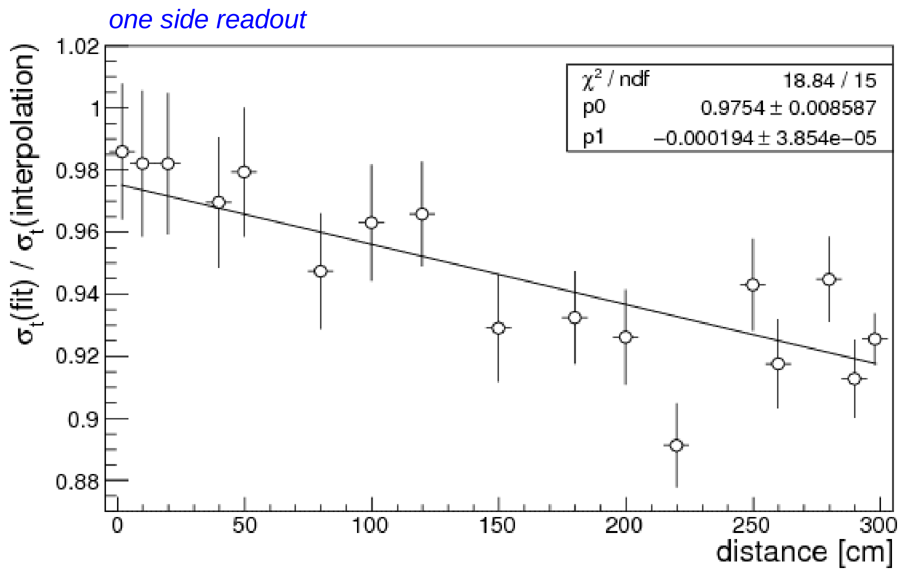
Optimization of the threshold of d-CFD (SAMPIC)



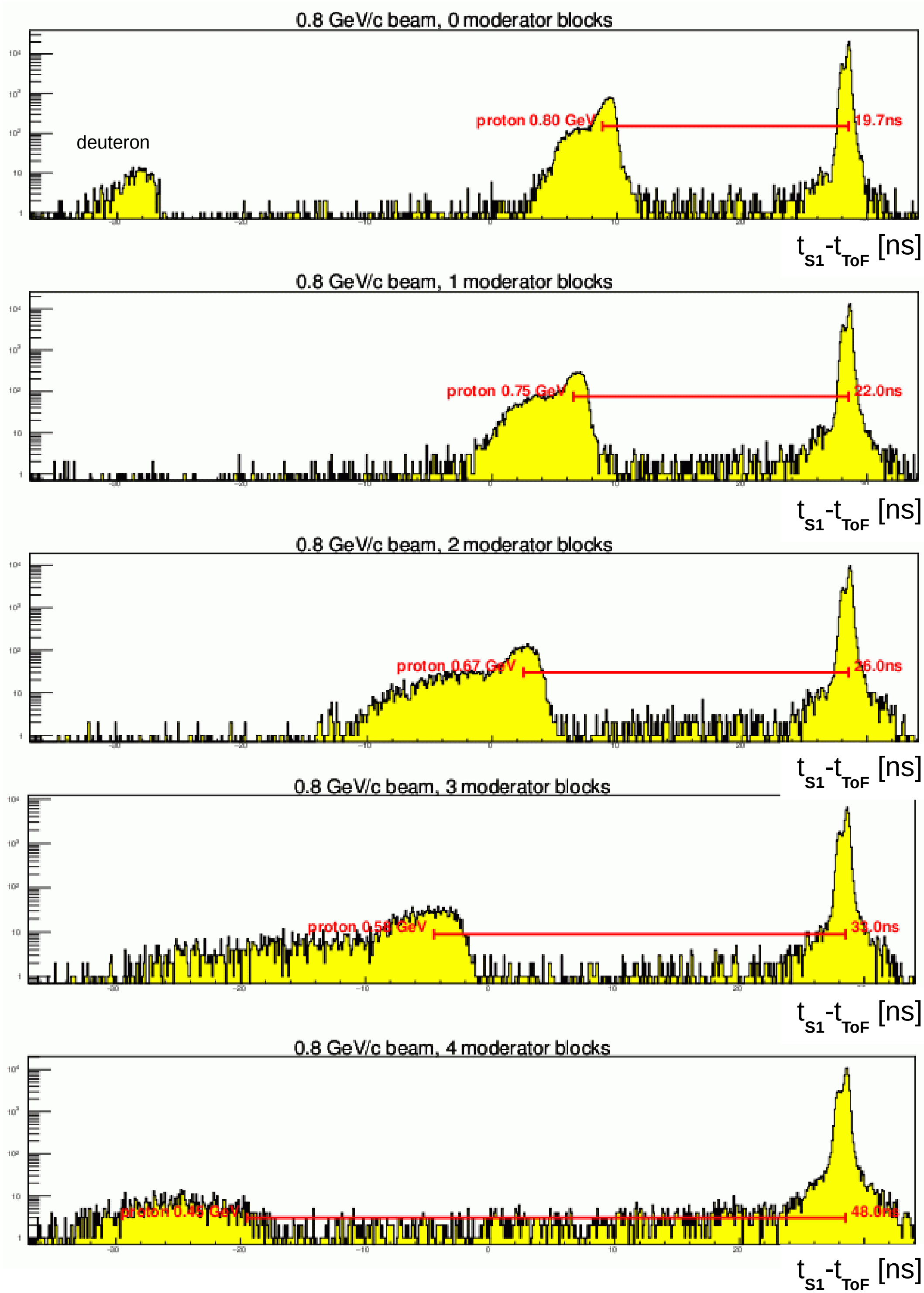
- Threshold (fraction) of d-CFD is a subject of optimization
- Can be calculated on firmware and software levels
- 14% fraction was used in the analysis

Time resolution: WaveCatcher vs SAMPIC (2)





- The time resolution is 5% better at the 3 m distance for data taken with WaveCatcher. No difference at smaller distances
- Fit of the waveform (8 points of the rising edge) can improve the resolution



PID *vs* moderator

- Proton peak moves away from e,mu,pi because of energy lose in moderator

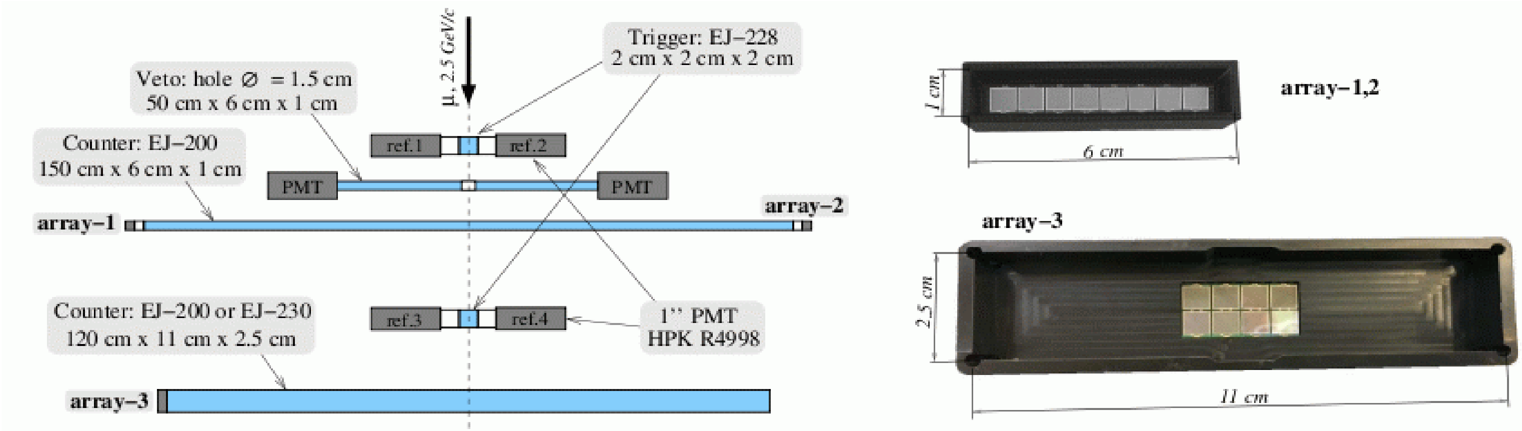


Figure 1. *Left*: schematic top view of the experimental setup. Outputs of all PMTs and SiPM-arrays were connected to a single acquisition module. *Right*: holders with the SiPM arrays.

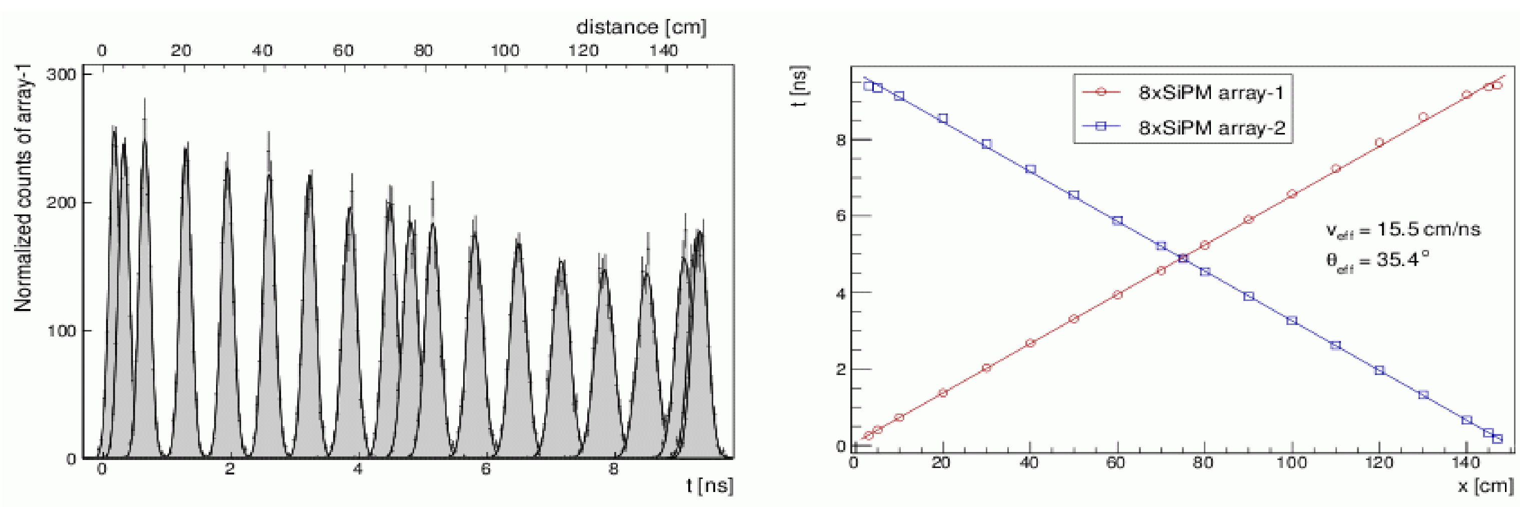
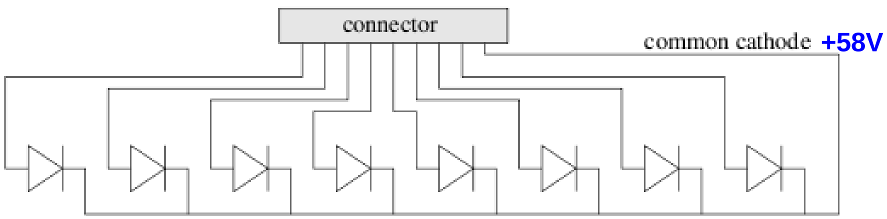


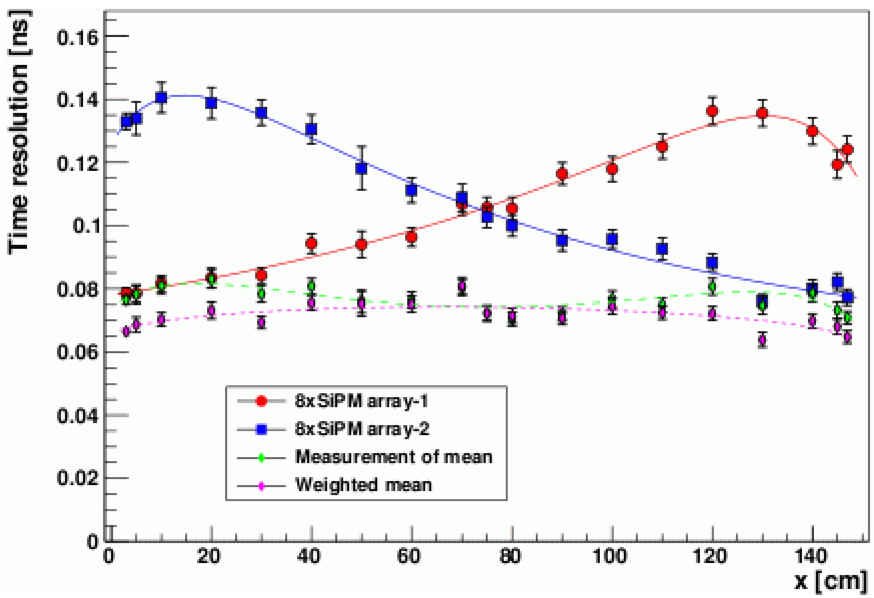
Figure 3. Measurements done with the 150 cm × 6 cm × 1 cm bar. *Left*: superposition of distributions of time registered by the array-1 for different positions of an interaction point along the x axis. Every distribution is approximated by a Gaussian function. *Right*: the mean value of the function for both SiPM arrays is shown as a function of the interaction position x along the bar.

C.Betancourt et al, JINST 12(2017) P11023 [1709.08972]

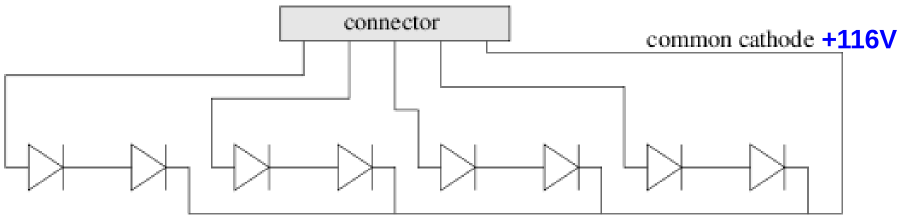
Time resolution with the 150 cm bar

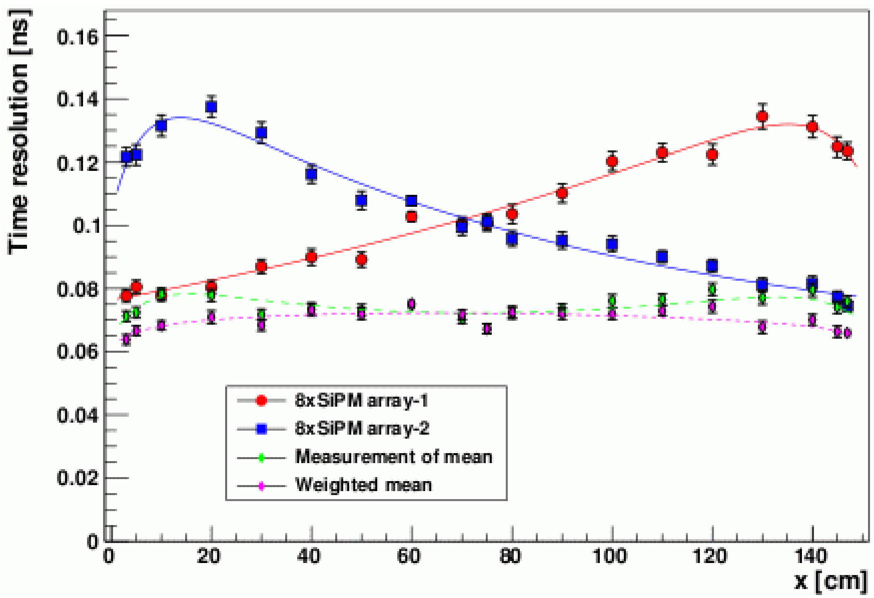
All SiPMs connected in parallel





Connection by pairs in series





- No difference in precision whether parallel or series (by pairs) connection is used => Bars with 2x8=16 SiPMs per PCB can be designed for ND280
- Time resolution for the 2.3 m long bar is ~100 ps