Deep Diffused Avalanche Photodiodes for Charged Particle Timing

Matteo Centis Vignali[1], CERN EP-DT Fellow
on behalf of $(see next page)

19.02.2019
15th Vienna Conference on Instrumentation, Vienna

[1] matteo.centis.vignali@cern.ch

Authors

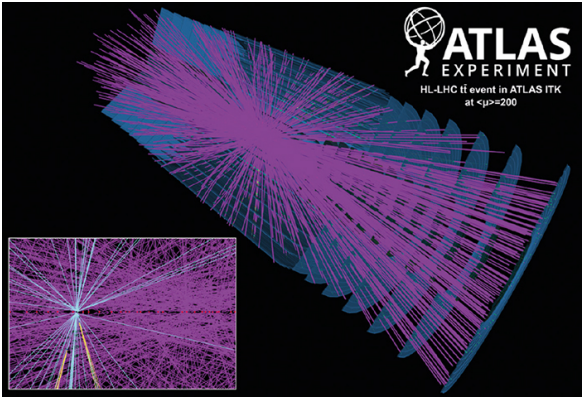
- **CERN, Geneva, Switzerland**:
  P. Almeida, M. Centis Vignali, Y. Gurimskaya, I. Mateu, M. Moll, S. Otero Ugobono*, M. Wiehe$^{\diamond}$
- **Lancaster University, Lancaster, UK**:
  W. Holmkvist
- **LIP, Lisbon, Portugal**:
  M. Gallinaro*
- **Princeton University, Princeton, USA**:
  B. Harrop, C. Lu, K. T. McDonald
- **Radiation Monitoring Devices, Watertown, USA**:
  M. McClish
- **University of Bern, Bern, Switzerland**:
  L. Franconi
- **University of Pennsylvania, Philadelphia, USA**:
  F. M. Newcomer
- **University of Virginia, Charlottesville, USA**:
  S. White*

* also Universidade de Santiago de Compostela, Santiago de Compostela, Spain
$^{\diamond}$ also University of Freiburg, Freiburg, Germany
* also CERN

Motivation: Minimum Ionizing Particle Timing

- Tracking
- Calorimetry
- PID
- **Counteract HL-LHC pile-up**
  200 p-p collisions per bunch crossing
  collisions time spread $\approx$ 180 ps
  time resolution on track $\approx$ 30 ps
  $\Rightarrow$ disentangle primary collisions
- Different devices: silicon detectors, gas detectors, etc.
- Many active groups

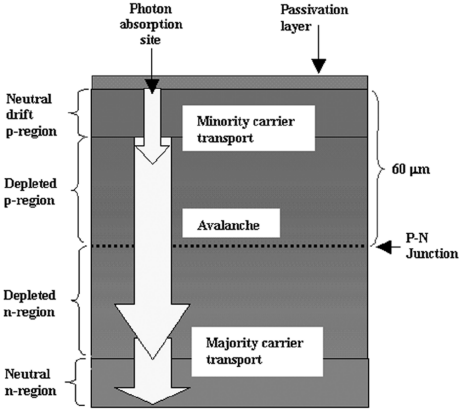
HL-LHC: With the current vertex resolution a significant fraction of the vertices will not be resolved



Technical proposals for MIP timing detectors: ATLAS collaboration, CMS collaboration

Deep Diffused Avalanche Photo Detectors

- Charge multiplication
- Gain: ≈ 500
- Bias: ≈ 1800 V
- Never fully depleted
- Die dimensions: $2.8 \times 2.8\,\mathrm{mm}^2$ and $10 \times 10\,\mathrm{mm}^2$
- Nominal active area: $2 \times 2\,\mathrm{mm}^2$ and $8 \times 8\,\mathrm{mm}^2$
- Thickness: $230 - 280\,\mu\mathrm{m}$
- Custom fabrication process
- Produced by Radiation Monitoring Devices (RMD)

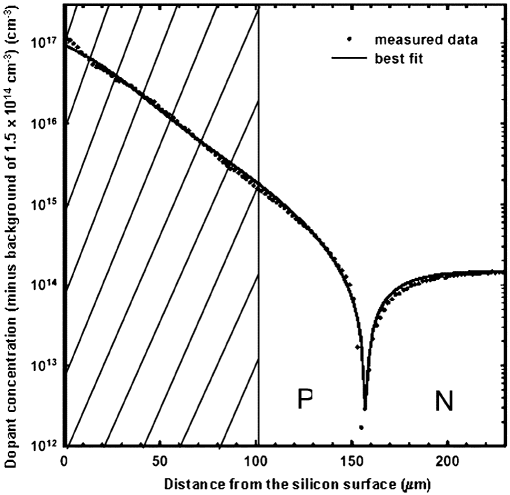


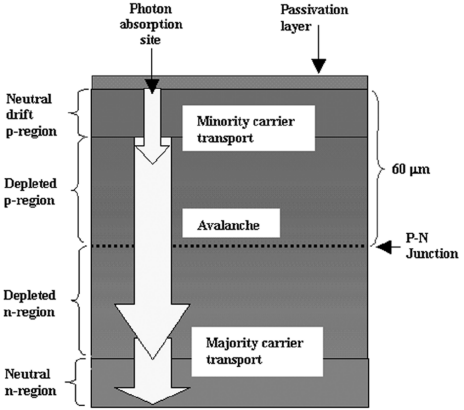
- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006

Deep Diffused Avalanche Photo Detectors

Doping profile



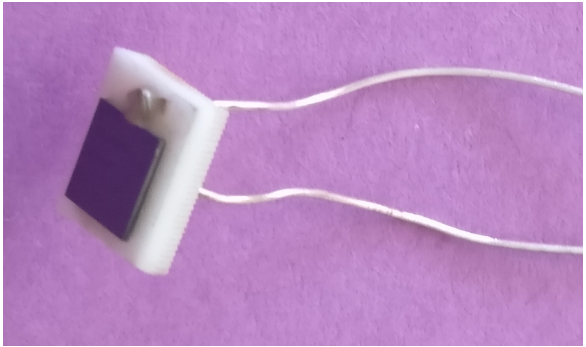


- Maximum of electric field at pn-junction
- Field exceeds 200 kV/cm enabling impact ionization

M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006

Radiation Hardness Study Using 2×2 mm^2 APDs

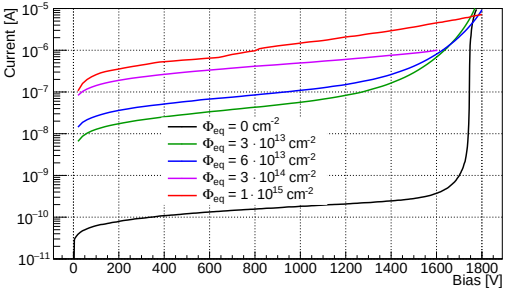
$2 \times 2\,\mathrm{mm}^2$ APDs



- Packaged
- Irradiated in Ljubljana (reactor neutrons)
- Characterized using a pulsed infrared laser
- $\Phi_{eq} = 0,\ 3 \cdot 10^{13},\ 6 \cdot 10^{13},\ 3 \cdot 10^{14},\ 10^{15}\ \mathrm{cm}^{-2}$
- Annealing of ≈ 70 min @ 21°C
- Sensor irradiated to $\Phi_{eq} = 3 \cdot 10^{14}\ \mathrm{cm}^{-2}$ is quite unstable

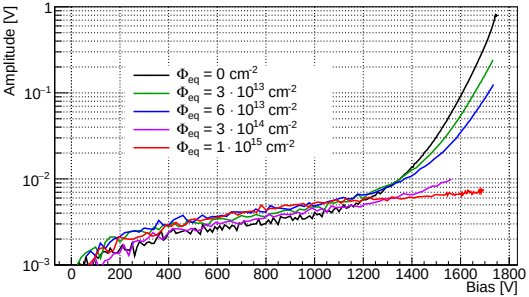
N-irradiated 2×2 mm^2 APDs, $-20°$C

Dark Current



- Increase with irradiation
- Change of shape

Signal, IR laser, 15 MIPs

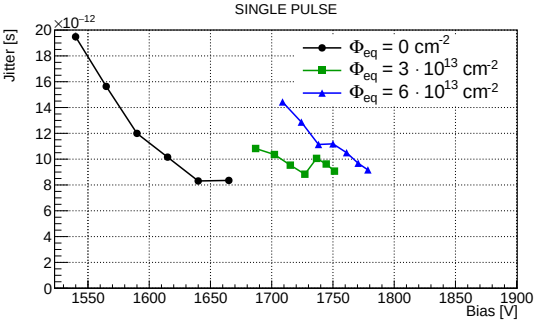


- Decrease with irradiation
- $\Phi_{eq} = 10^{15}$ cm^{-2}: little to no gain

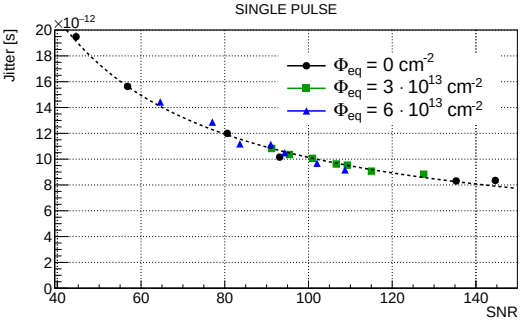
The gain is reduced by irradiation

N-irradiated 2×2 mm^2 APDs, $-20°$C, IR Laser, 0.8 MIPs

Jitter vs Bias Voltage



Jitter vs Signal to Noise Ratio



- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: jitter of 8 - 10 ps
- $\Phi_{eq} = 10^{15}$ cm^{-2}: low SNR
  Jitter $\approx$ 0.5 ns

- Jitter scales as 1/SNR

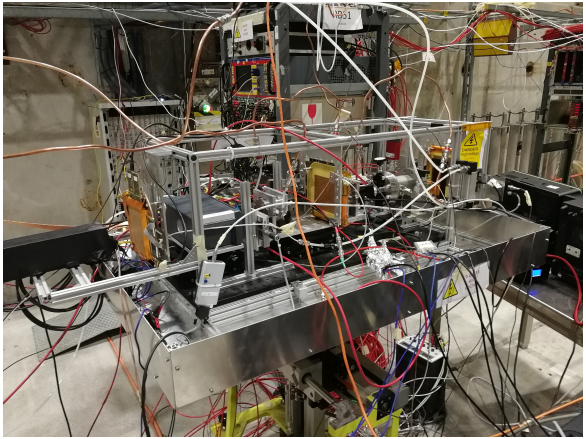
Time resolution maintained at least up to $\Phi_{eq} = 6 \cdot 10^{13}$ cm^{-2}, higher bias required

Radiation hardness estimated to be $\Phi_{eq} \approx 10^{14}$ cm^{-2}

Beam Test of 8×8 mm^2 APDs

Acknowledgments

The authors would like to thank the **RD51*** and **PICOSEC** collaborations for the possibility to participate in the May and August 2018 beam tests.
We are particularly grateful to **Eraldo Oliveri**[1], **Francisco Iguaz Gutierrez**[2], and **Lukas Sohl**[3].
We would like to thank **Francisco Garcia Fuentes**[4] and **Rui De Oliveira**[1] for the help in preparing the sensors and PCBs.

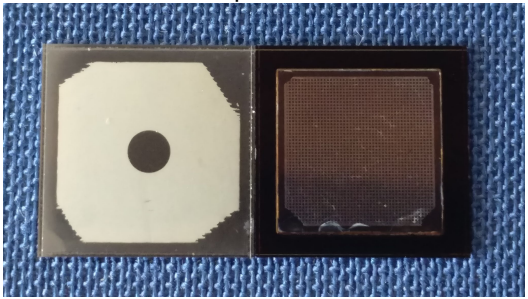


* RD51 website
[1] CERN, Switzerland
[2] Synchrotron SOLEIL, France
[3] CEA Saclay, France
[4] HIP, Finland

8×8 mm^2 APDs

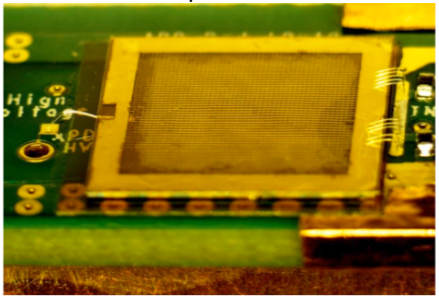
Uniformity of response improved through metallization or mesh readout

DC coupled readout



- Aluminum deposited on both sides
- Metallization on single dies at CMi-EPFL

AC coupled readout

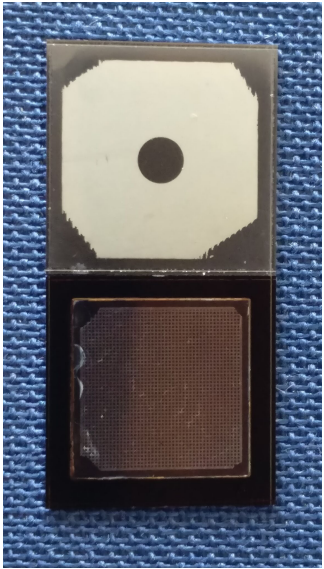


- Mesh on Kapton layer
- Sintered gold on back side
- Studied in previous beam tests ($\sigma_{\Delta t} = 19$ ps)
  S. White, CHEF 2013
  J. Va'vra, NIMA 876 (2017) 185-193

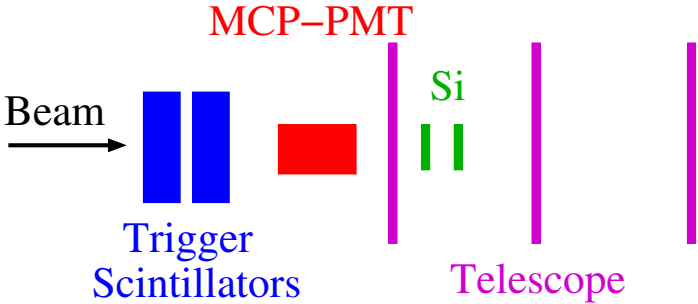
Today's Data

- 2 metallized 8×8 mm^2 APDs
- 1775 V
- Room temperature

- 1st run:
  - Full sensor illumination
  - Homogeneity, efficiency, time resolution
- 2nd run:
  - Incomplete sensor illumination
  - Higher statistics on detector
  - Detailed homogeneity study



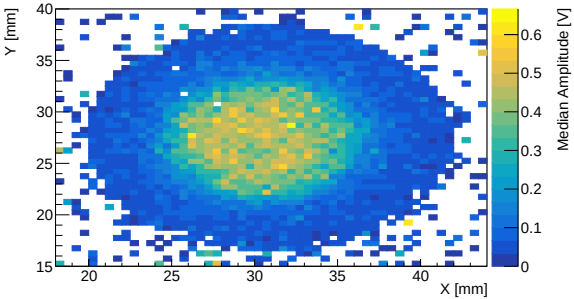
Beam Test Setup



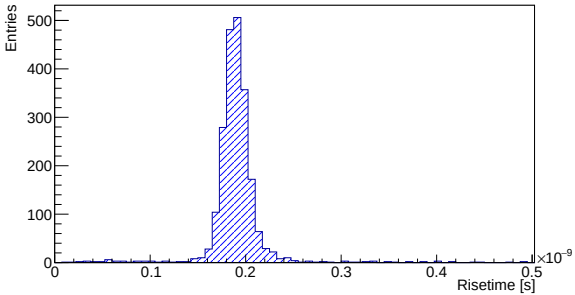
- 100 GeV μ, CERN North Area, H4 beamline
- Amplifier: CIVIDEC 2 GHz 40 dB
- Oscilloscope: Agilent 2.5 GHz 10 Gs/s
- Readout configuration not optimal for timing (due to mechanical constraints)
- Tracking and timing provided by RD51
- MCP-PMT signal shaped to have a few points on leading edge

MCP-PMT Time Reference, 100 GeV μ

Median Amplitude



20 to 80% Risetime (within geom. cuts)



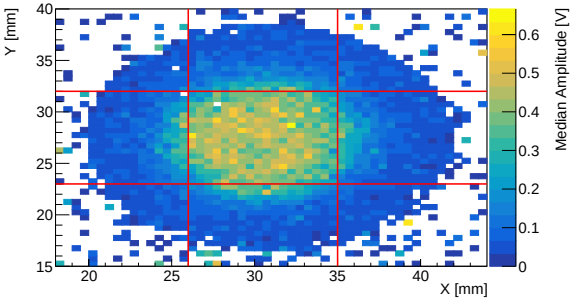
- Higher signal toward detector center
- Coverage of photocathode with Č light
  L. Sohl, NIMA (2018)

- Average 190 ps
- Values outside peak:
  few points on leading edge

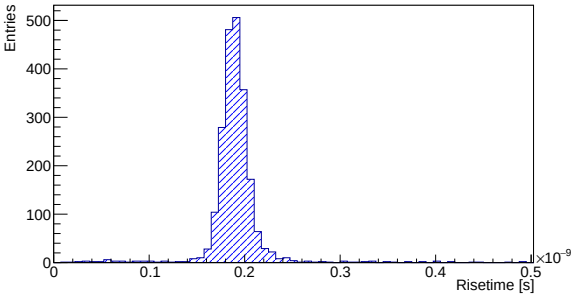
Time resolution better than APDs

MCP-PMT Time Reference, 100 GeV μ

Median Amplitude



20 to 80% Risetime (within geom. cuts)



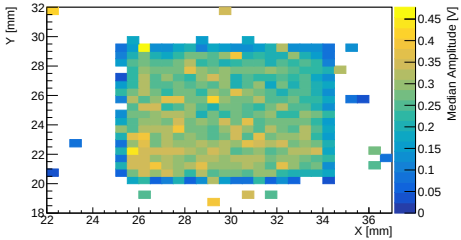
- Higher signal toward detector center
- Coverage of photocathode with Č light
  L. Sohl, NIMA (2018)

- Average 190 ps
- Values outside peak:
  few points on leading edge

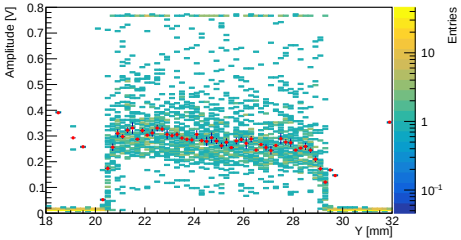
Time resolution better than APDs

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

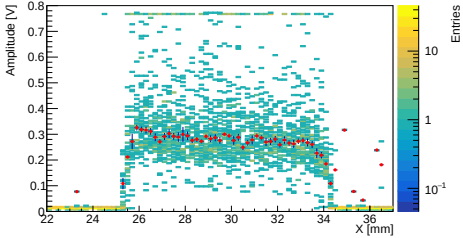
Median Amplitude



Section Y (between vertical lines)



Section X (between horizontal lines)

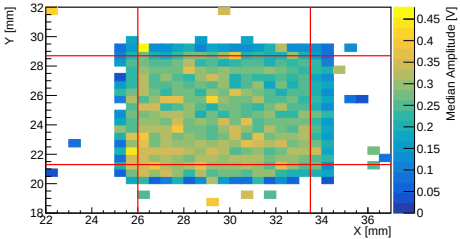


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

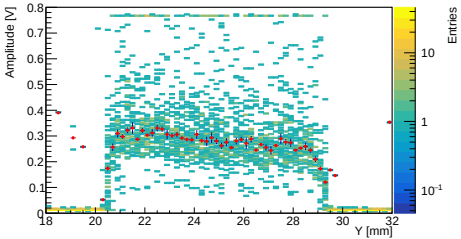
Amplitude uniform over the detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

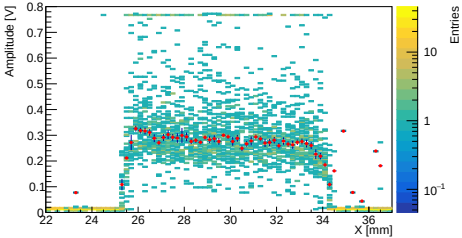
Median Amplitude



Section Y (between vertical lines)



Section X (between horizontal lines)

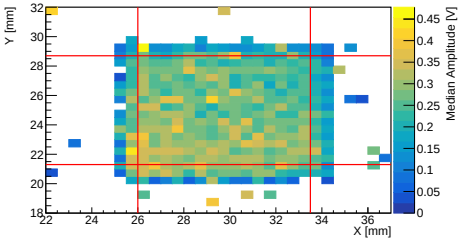


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

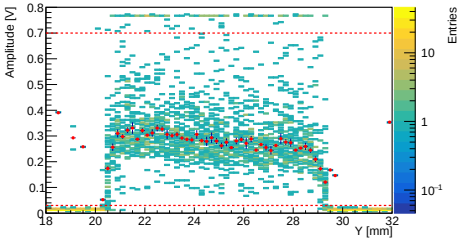
Amplitude uniform over the detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

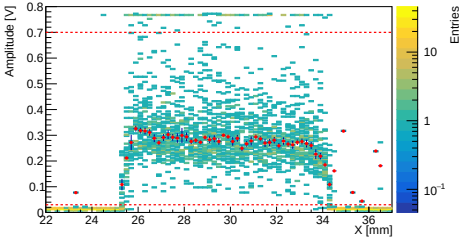
Median Amplitude



Section Y (between vertical lines)



Section X (between horizontal lines)

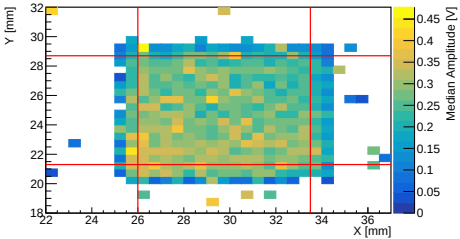


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

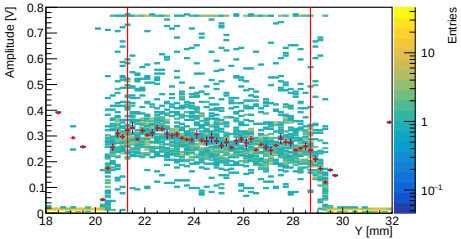
Amplitude uniform over the detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

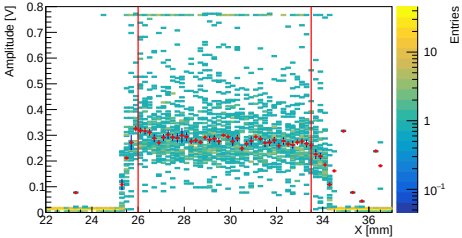
Median Amplitude



Section Y (between vertical lines)



Section X (between horizontal lines)

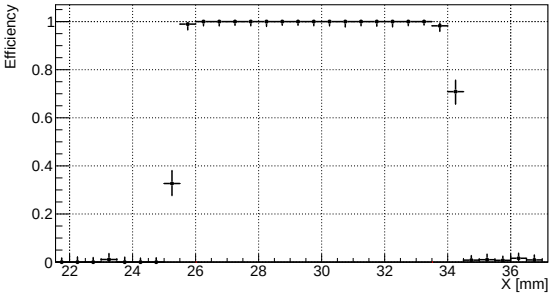


Red points: Median amplitude, excluding events below threshold or saturating the scope scale

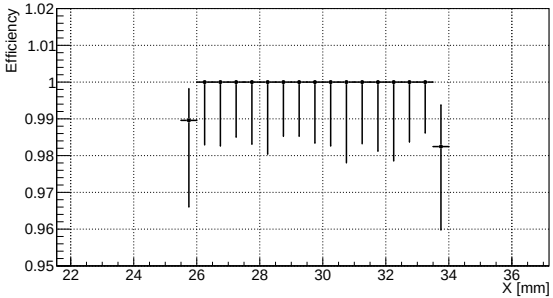
Amplitude uniform over the detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

Detection Efficiency



Zoom



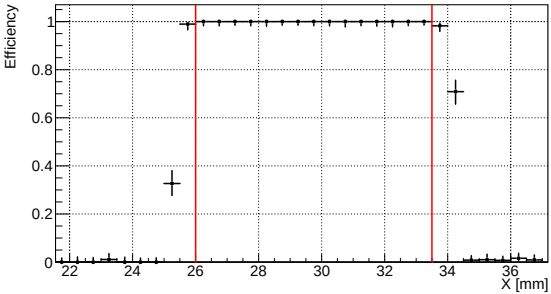
$$\text{Efficiency} = \frac{\text{Number of events above threshold}}{\text{Number of tracks}}$$

Threshold = 30 mV

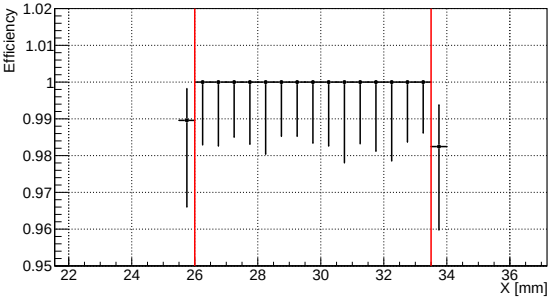
Detection efficiency above 99%

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

Detection Efficiency



Zoom



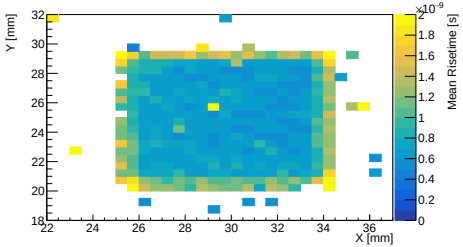
$$\text{Efficiency} = \frac{\text{Number of events above threshold}}{\text{Number of tracks}}$$

Threshold = 30 mV

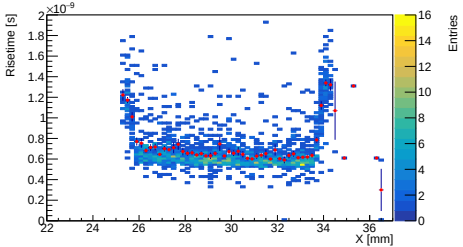
Detection efficiency above 99%

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

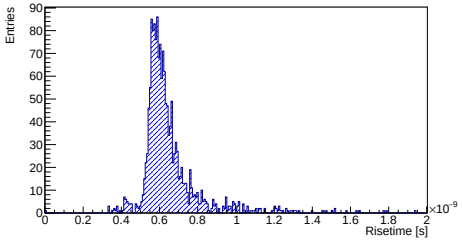
20 to 80% Risetime



Section X (between horizontal lines)



Distribution (within geom. cuts)



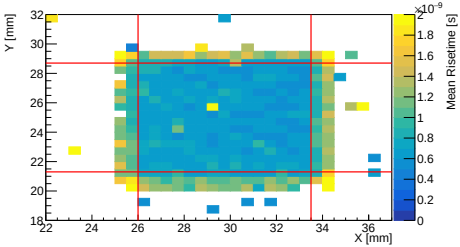
Red points: Average risetime

- Longer risetimes at detector edges
- Most probable value: ≈ 600 ps
- Tail in distribution to be understood

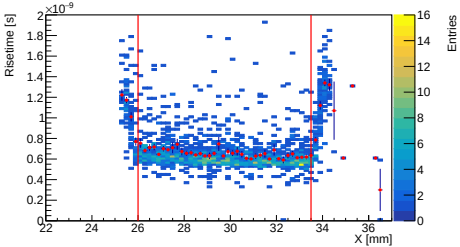
Risetime uniform over the detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

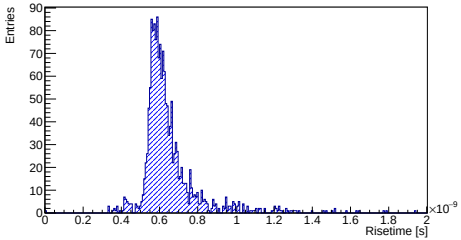
20 to 80% Risetime



Section X (between horizontal lines)



Distribution (within geom. cuts)



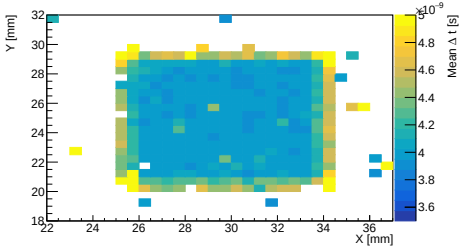
Red points: Average risetime

- Longer risetimes at detector edges
- Most probable value: ≈ 600 ps
- Tail in distribution to be understood

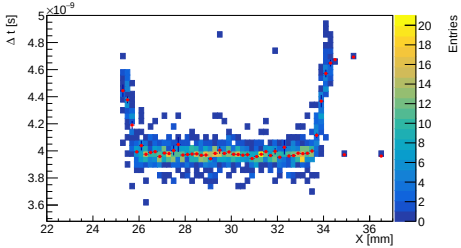
Risetime uniform over the detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

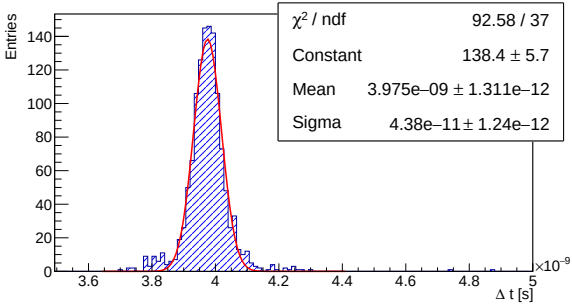
Time of arrival Δt



Section X (between horizontal lines)



Distribution (within geom. cuts)



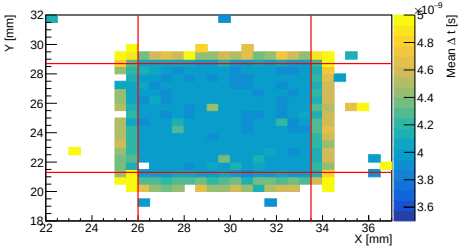
Red points: Average Δt

- Algorithm: CFD, 2 pt interpolation
- Uniform over the detector
- Tails at detector edges

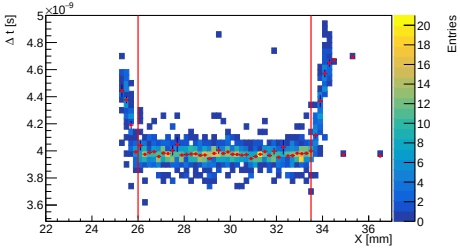
Time resolution of 44 ± 1 ps over a 8 × 8 mm^2 detector

Metallized 8 × 8 mm^2 APD, 1775 V, 100 GeV μ

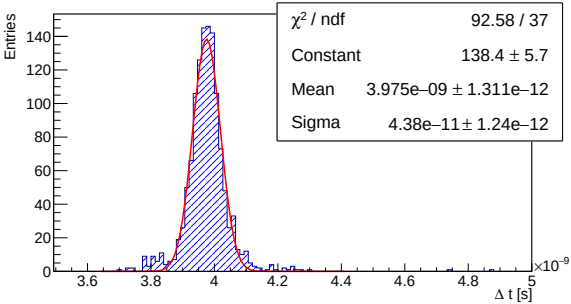
Time of arrival Δt



Section X (between horizontal lines)



Distribution (within geom. cuts)



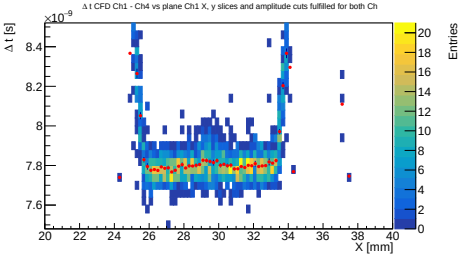
Red points: Average Δt

- Algorithm: CFD, 2 pt interpolation
- Uniform over the detector
- Tails at detector edges

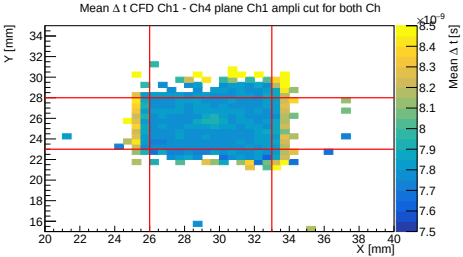
Time resolution of 44 ± 1 ps over a 8 × 8 mm^2 detector

Homogeneity study (Different sensor)

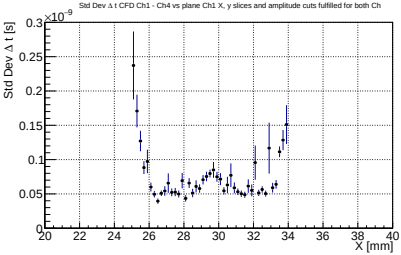
Δt Section on X (between horizontal lines)



APD metallized, mean Δt, 1775 V



Std. Dev. of Δt (not a fit)



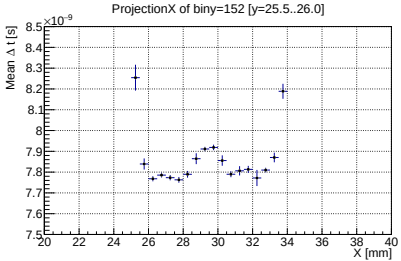
Red points: Average Δt

- CFD, 2 pt interpolation

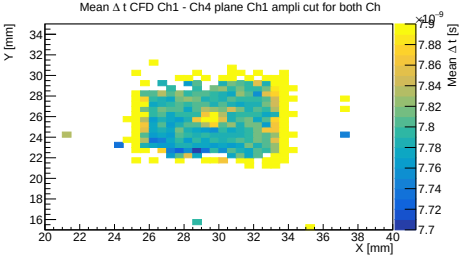
Region of broader Δt at detector center

Homogeneity study (Different sensor)

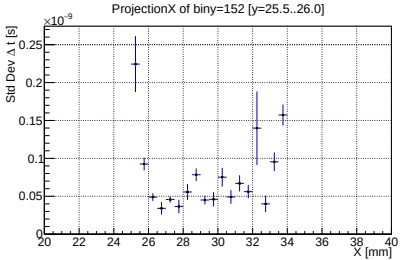
Mean Δt vs X for one bin [25.5,26] mm



Mean Δt (zoomed Z to see effect)



Std. Dev. Δt vs X for one bin (no fit)

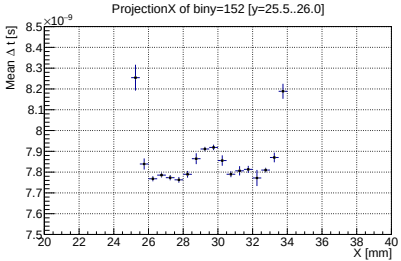


- Different Δt at detector center
- Std. dev. is similar to the rest of the detector
- Position corresponds to the hole in the metallization of p-side

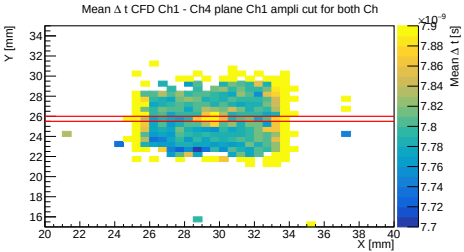
Remedy: change metallization pattern

Homogeneity study (Different sensor)

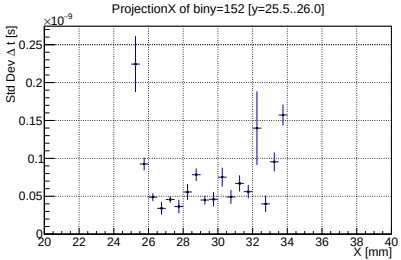
Mean Δt vs X for one bin [25.5,26] mm



Mean Δt (zoomed Z to see effect)



Std. Dev. Δt vs X for one bin (no fit)

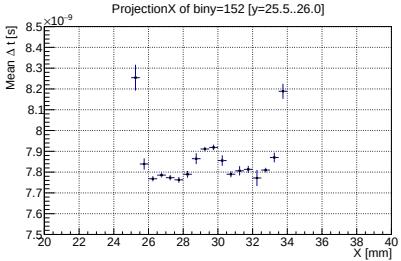


- Different Δt at detector center
- Std. dev. is similar to the rest of the detector
- Position corresponds to the hole in the metallization of p-side

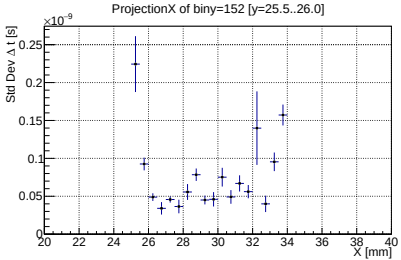
Remedy: change metallization pattern

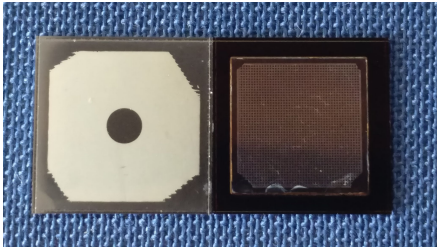
Homogeneity study (Different sensor)

Mean Δt vs X for one bin [25.5,26] mm



Std. Dev. Δt vs X for one bin (no fit)





- Different Δt at detector center
- Std. dev. is similar to the rest of the detector
- Position corresponds to the hole in the metallization of p-side

Remedy: change metallization pattern

Summary

Radiation Hardness Study Using 2×2 mm^2 APDs

- Radiation effects studied using a pulsed IR laser
- Jitter ≤ 10 ps maintained until at least $\Phi_{eq} = 6 \cdot 10^{13}$ cm^{-2}
- Detectors expected to work until $\Phi_{eq} \approx 10^{14}$ cm^{-2}

Beam Test of 8×8 mm^2 APDs

- Today's data from two metallized APDs
- Uniform response with efficiency > 99%
- Time resolution for metallized APD is 44 ps at 1775 V
- Readout scheme not optimal at beam test $\Rightarrow$ better performance expected

Future studies

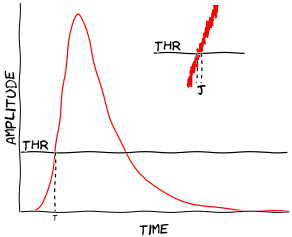
- Improve readout scheme and perform timing measurements using a radioactive source
- Study stability of metallized APDs

Backup Material

Timing

$$\Delta t = t_2 - t_1 \qquad \sigma^2_{\Delta t} = \sigma^2_{t_1} + \sigma^2_{t_2} \qquad \sigma^2_t = \sigma^2_J + \sigma^2_{TW} + ...$$

Jitter



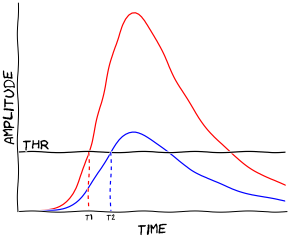
The noise influences the time at which the threshold is crossed

$$\sigma_J = \sigma_n / \frac{dV}{dt} \propto \frac{t_{rise}}{SNR}$$

Countermeasures:

- Reduce rise time
- Improve noise figure

Time walk



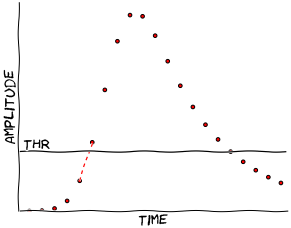
Variations in the amplitude influence the time at which the threshold is crossed

Countermeasures:

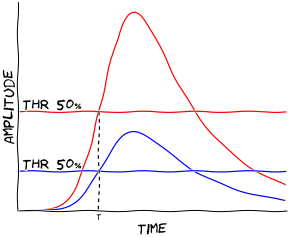
- Algorithm e.g. CFD

Timing

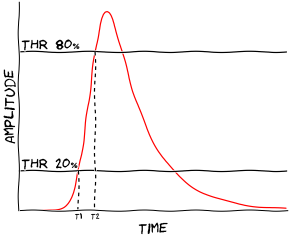
2pt interpolation



Constant Fraction Discrimination



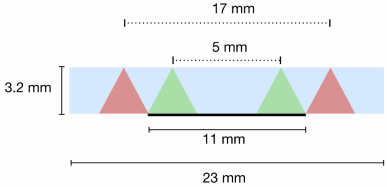
20-80% Rise time

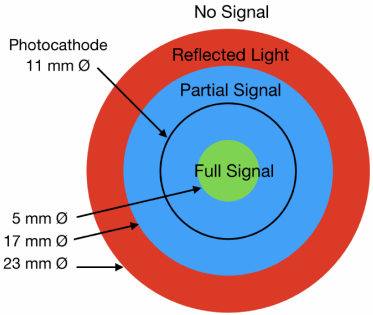


MCP-PMT Signal Map

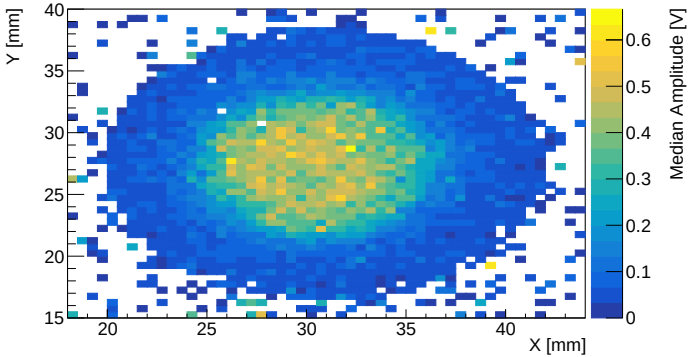
Sketches from L. Sohl contribution at the 14th Pisa Meeting on Advanced Detectors (2018)

https://agenda.infn.it/event/17834/contributions/83549/

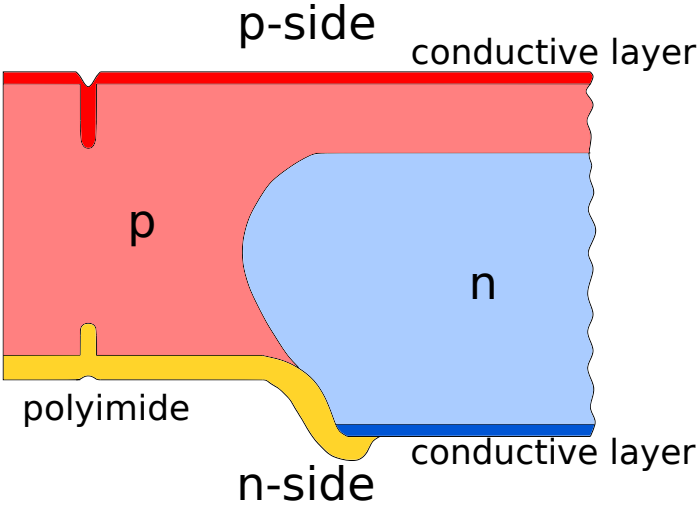




This work



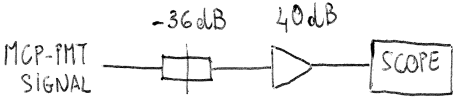
APD Section (Not to Scale)



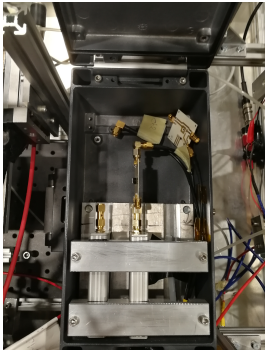
Beam Test Setup

- Sensor box placed downstream first tracking GEM
- Coating on detectors and PCBs to reduce discharges
- Amplifiers: CIVIDEC 2 GHz, 40 dB
- Data acquisition: Agilent 2.5 GHz, 10 Gs/s
  - Ch1: APD
  - Ch2: APD
  - Ch3: Telescope bit pattern (Trigger)
  - Ch4: MCP-PMT
- Temperature, bias, and current logged

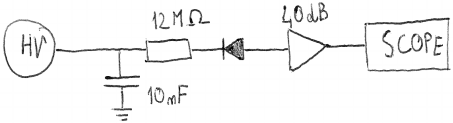
MCP-PMT readout and shaping



Sensor box



APD readout



Analysis

Analysis:

- Extract signal properties (ampli, risetime, tCFD, ...)
- The signal is selected in a window around the peak
- Points preceding the selection are used for baseline
- The leading edge is isolated to extract risetime and tCFD
- The tracking info is extrapolated to each plane
- Only events with one track are used