SiPMs for direct detection of charged particles: Response and timing performance for the future ALICE 3 at LHC

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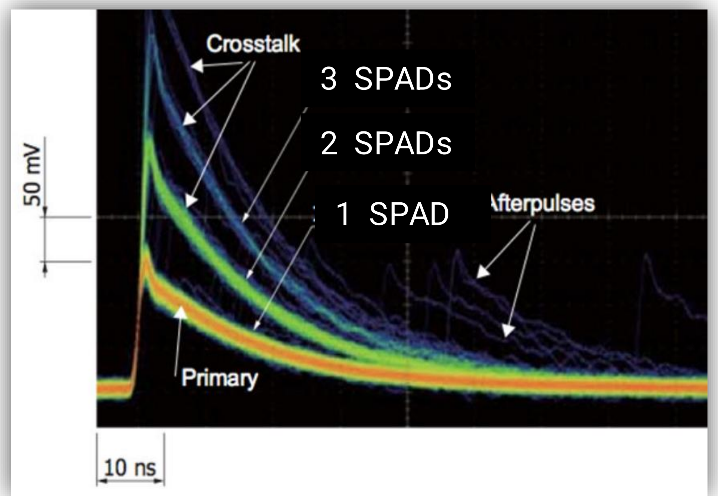
on behalf of the ALICE Collaboration

Silicon PhotoMultipliers (SiPMs)

SPADs Single-Photon Avalanche Detectors in Geiger mode (gain **10^6**) above breakdown $V_{OV} = V_{bias} - V_{breakdown}$



SiPM: array of few mm^2 of 10^2-10^4 SPADs.

Noise

- avalanches triggered by thermally generated charged carriers → **Dark Count Rate (DCR)**
- avalanches generated because of the primary one → **Cross Talk (CT)**

SiPM performance studied when directly traversed by MIP [1][2]:
expected: 1 SPAD fired (+CT) per event
observed: several SPADs fired

SiPM are able to **directy detect charged particles**!

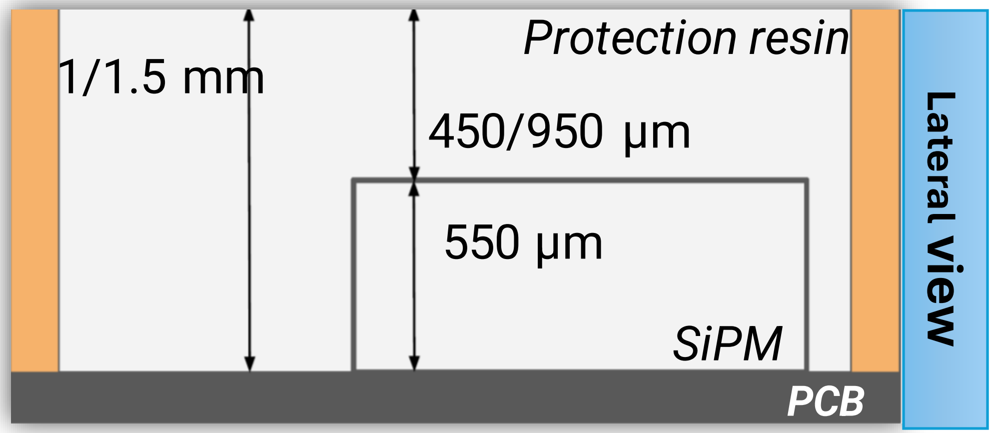
→ ***Cherenkov effect in the standard protection layer!***

[1] Carnesecchi F., et al., JINST 17 P06007 (2022)
*[2] Carnesecchi F., et al., Eur. Phys. J. Plus **138**, 337 (2023)*

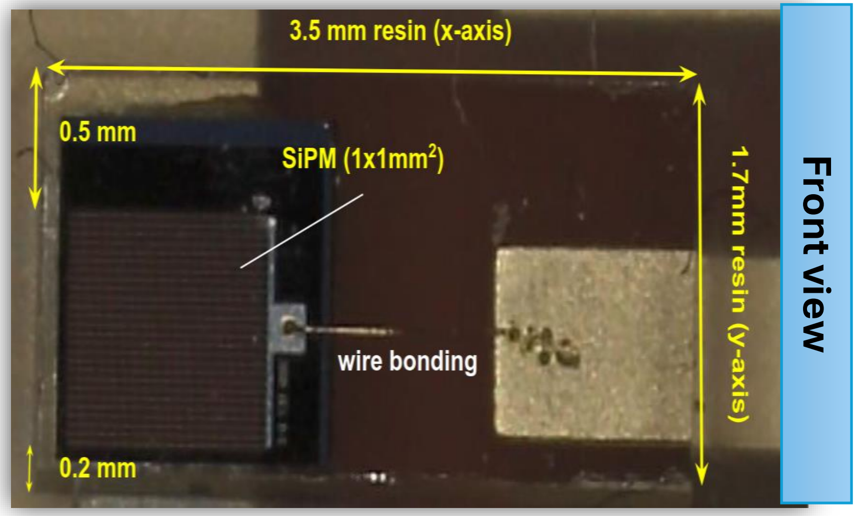
SiPM under study

FBK NUV-HD-RH available **SiPMs with different protection layers** (resins):

- 1 mm Si resin (**SR1**)
- 1.5 mm Si resin (**SR15**)
- 1 mm Epoxy resin (**ER1**)
- Without resin (**WR**)



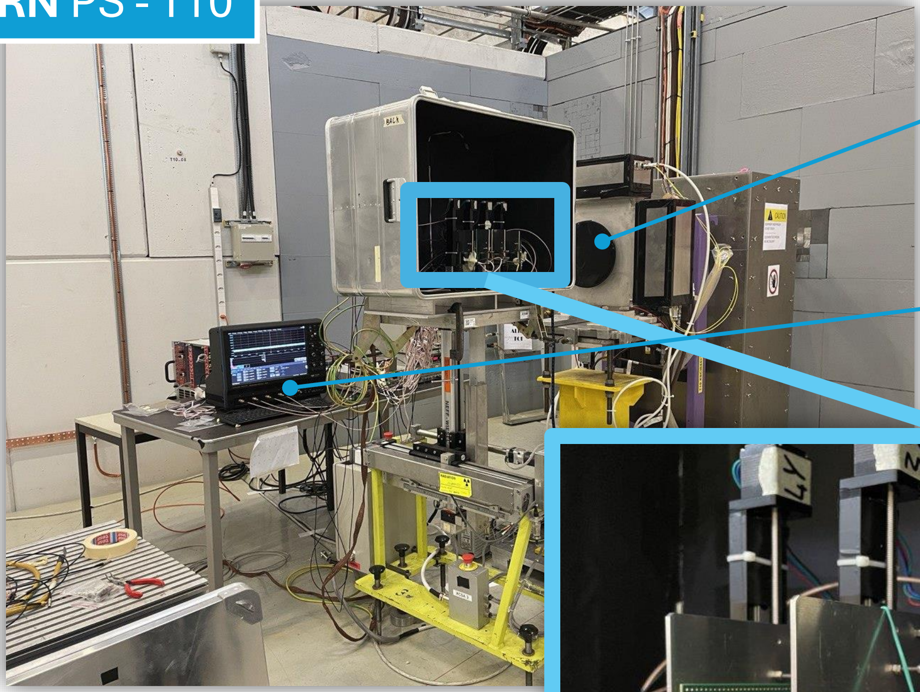
[3] Carnesecchi F., et al., Eur. Phys. J. Plus **138**, 788 (2023)

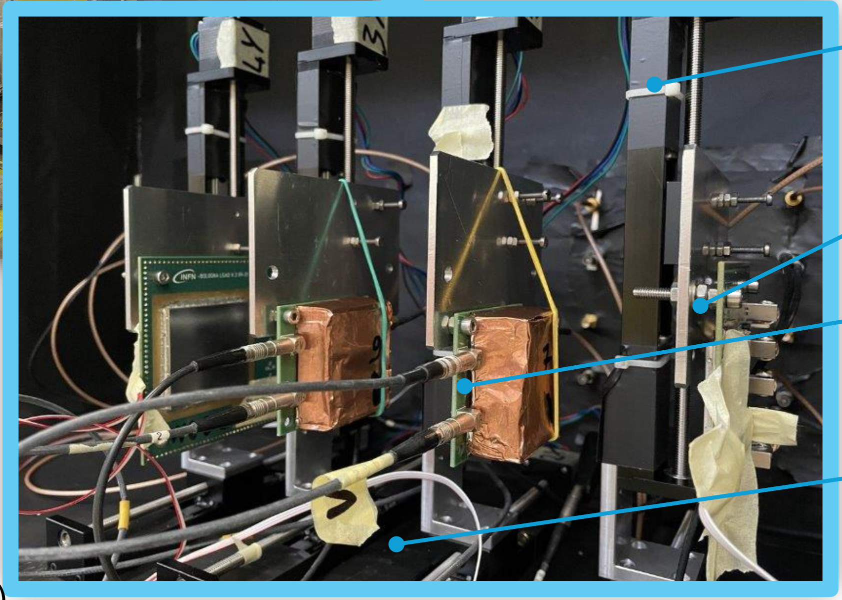


Active area	Pixel pitch	#SPADs	Fill Factor	V_{bd}
1×1 mm^2	20 µm	2444	72%	33.0±0.1 V

Beam test setup

CERN PS - T10





Beam
Protons/pions of 10 GeV/c

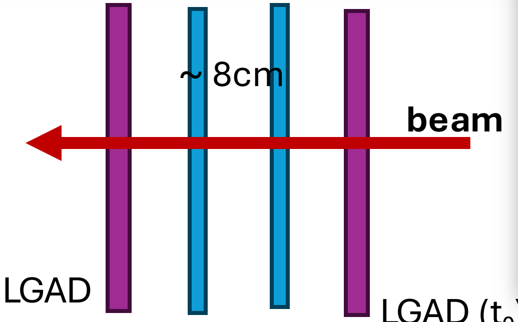
Data acquisition
Lecroy 9490M-MS digital oscilloscope 4 GHz bandwidth

Micropositioners
remotely controlled with ~ 10 μm precision

Trigger and t_0
25 μm and 35 μm thick FBK 1 × 1 mm² LGAD prototypes[4]

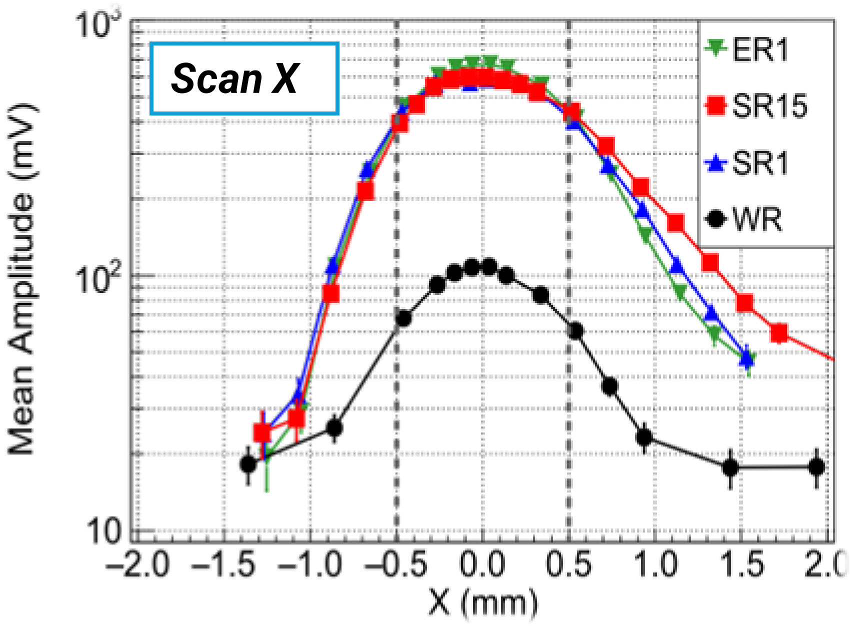
Front-end
XLEE39 amplifiers ~ 40 dB

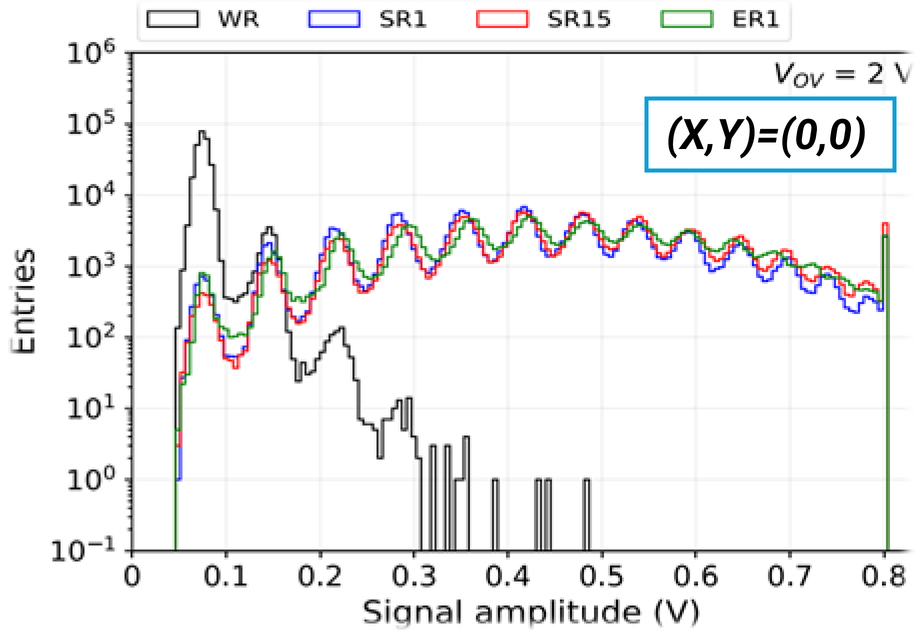
Dark box
temperature ~25-28°C



*[4] Carnesecchi F., et al., Eur. Phys. J. Plus **138**, 990 (2023)*

Signal with and without protection layer





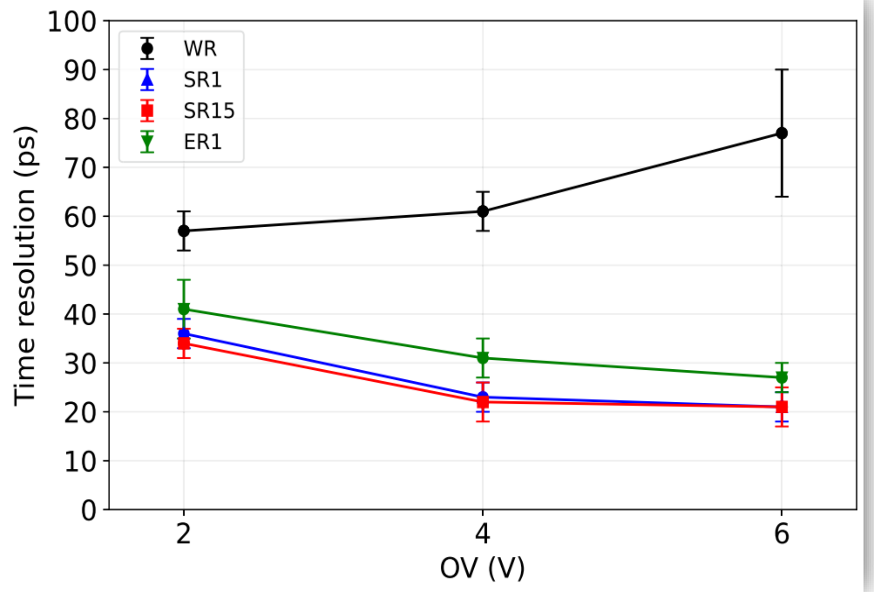
- **SiPMs with protection layer** → **multi SPADs events** → higher average signals wrt WR
- **SiPM without protection layer** mainly single SPAD events → up to 4-5 SPADs compatible with CT

*High **efficiency** of **SiPM with protection layer: >99%** events with ≥3 SPADs firing at 2 V OV .*

Timing in the center of the position scan

σ_{SiPM} VS OV

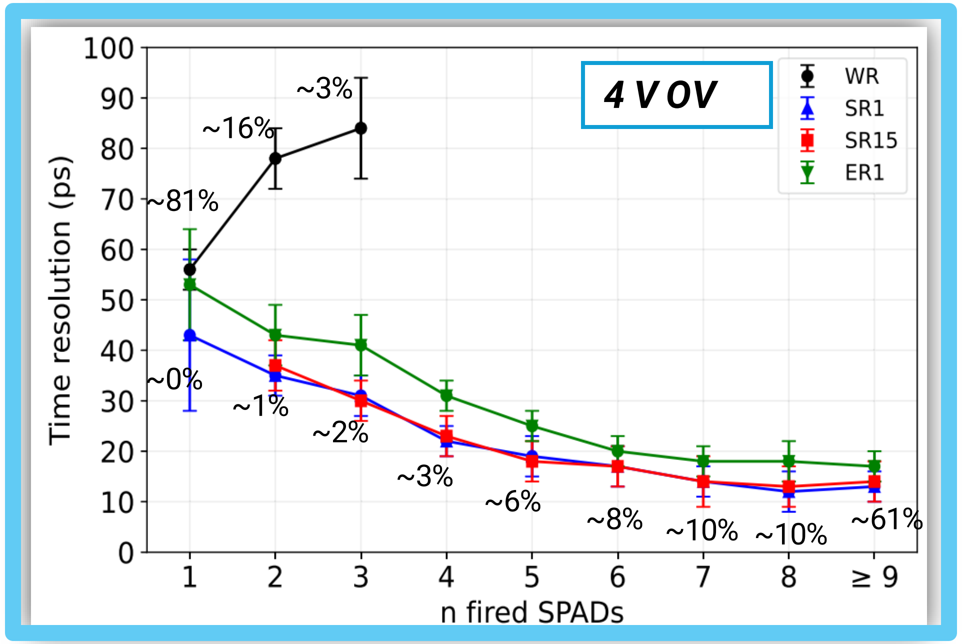
- SiPM **with protection layer** behave similarly
  → O(**20-30**) **ps** reached
- SiPM without protection layer → worsening of time resolution with OV may be due to increase in DCR



σ_{SiPM} VS fired SPADs

- SiPM with protection layer → improvement of σ_{SiPM} as $1/\sqrt{n_{SPADS}}$
- WR → affected by DC and CT

Intrinsic time resolution of around 20 ps for more than 5 SPADs firing, corresponding to >80% of total events!



Conclusions

Up to now established photon detectors usually coupled to scintillators or Cherenkov radiators for a variety of applications because of

- *high efficiency*
- *insensitivity to magnetic fields*
- *low cost*

now SiPM can **directly detect charged particles** showing:

- increased **efficiency**, if compared to simple geometrical fill factor
- **time resolution improving** with n fired SPADs

Moving SiPM from photosensors only to combined charged particle detectors, from space experiments to colliders!

BACK UP SLIDES

Lower beam momentum

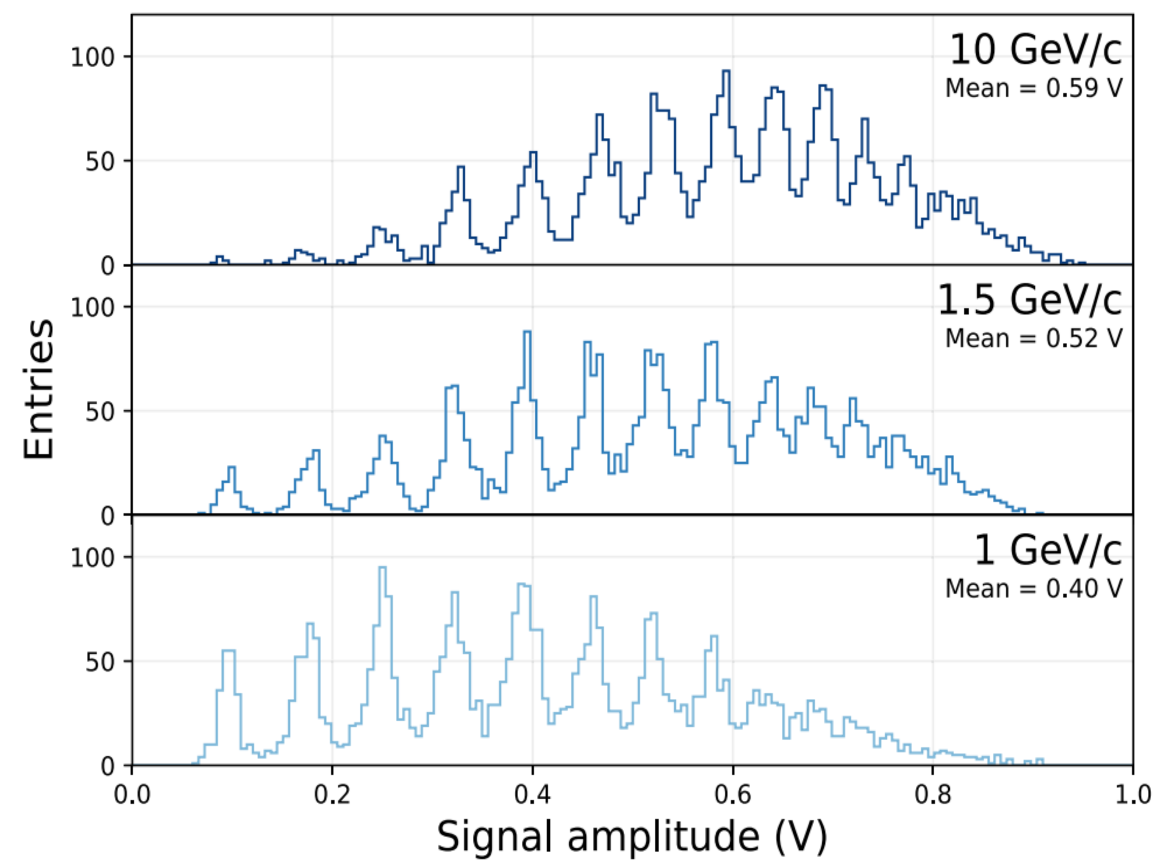
At low momentum, selected only protons using TOF-PID (purity ~ 83%)

Lower momentum

Light reduced approaching Cherenkov threshold of 0.8 GeV/c

lower #fired SPADs

smaller signal

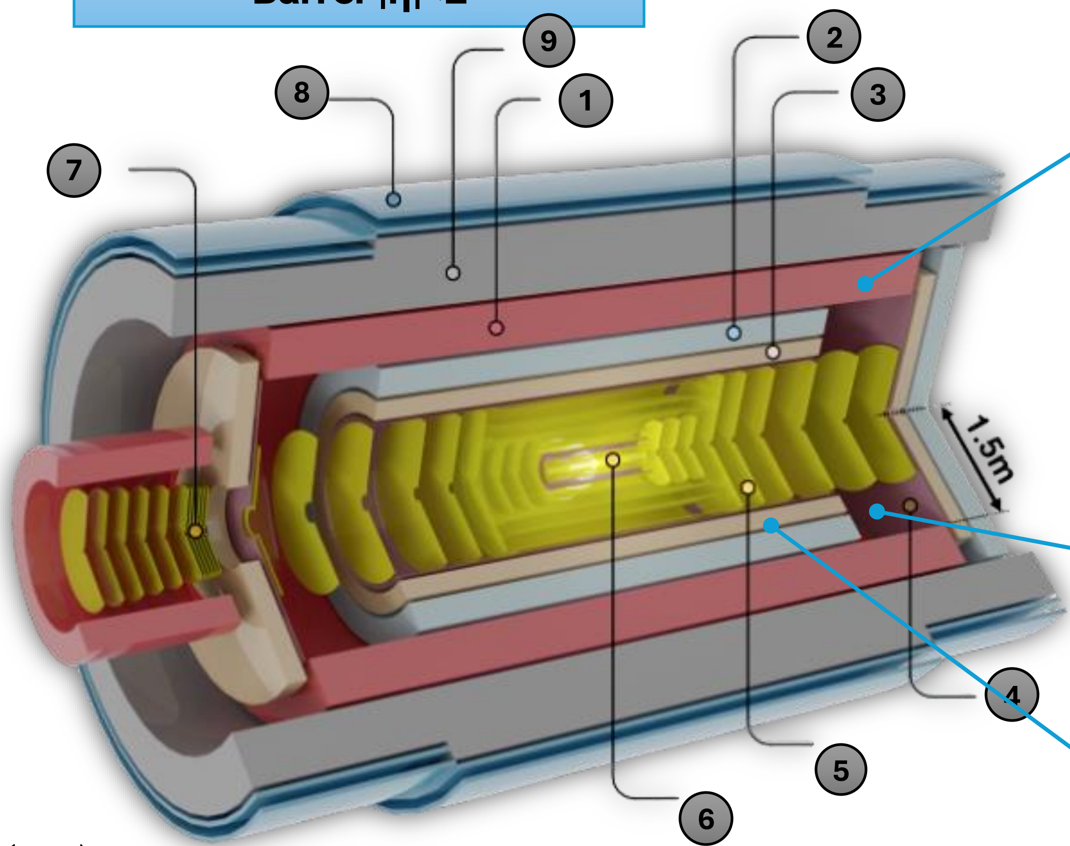


A possible application of SiPMs: ALICE 3 outer TOF layer

A compact next-generation detector for the LHC to study high-energy proton-proton (pp) and nuclear (AA and pA) collisions[5] .

1. Magnet
2. ECAL *Electromagnetic calorimeter*
3. RICH *Ring Imaging Cherenkov Detector*
4. **TOF *Time of Flight detector***
5. Outer tracker
6. Vertex tracker
7. FCT *Forward Conversion Tracker*
8. Muon chambers
9. Absorber

One benefit of using SiPMs could be merging the TOF and the RICH detectors.



Magnet
Under study, with central field of 2T

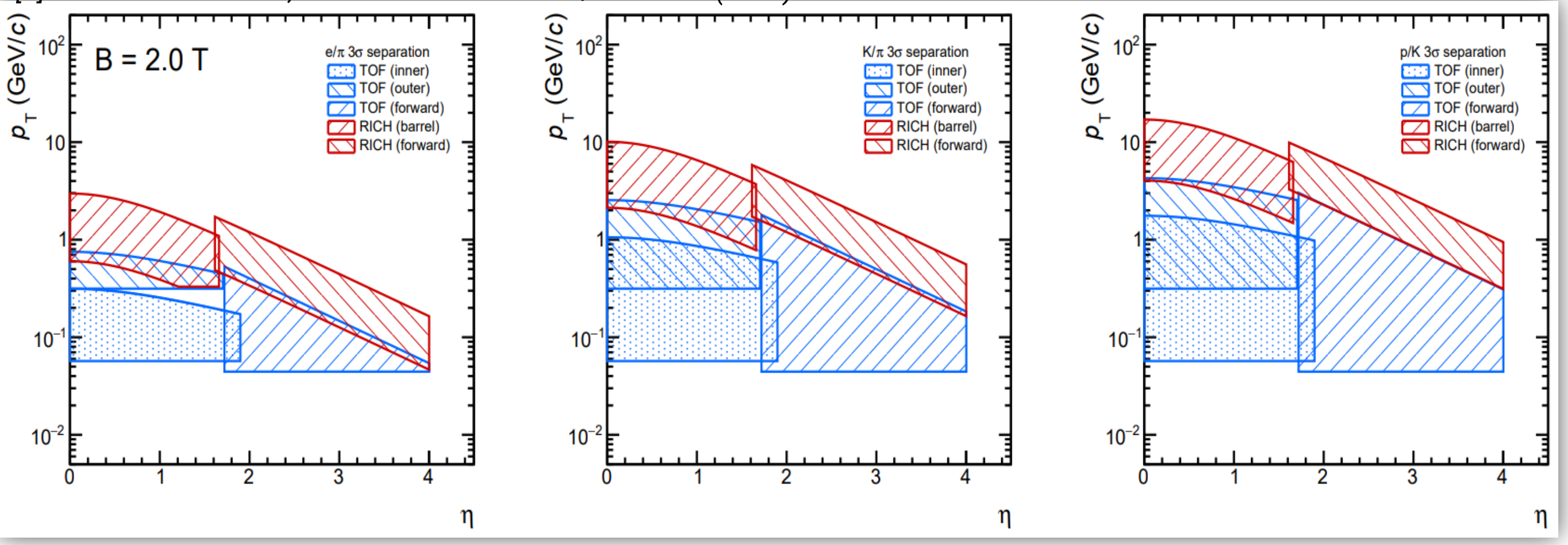
RICH
With n ~ 1.006 – 1.03 and σ_θ ~1.5 mrad

[5] ALICE Collaboration, CERN –LHCC-2022-009/LHC-I-038 (2022)

TOF specifications

	iTOF	oTOF	Forward TOF
Radius (m)	0.19	0.85	0.5-1.5
Surface (m^2)	1.5	30	14
Time resolution (ps)	**20**	**20**	**20**

[5] ALICE Collaboration, CERN –LHCC-2022-009/LHC-I-038 (2022)



Other candidates:

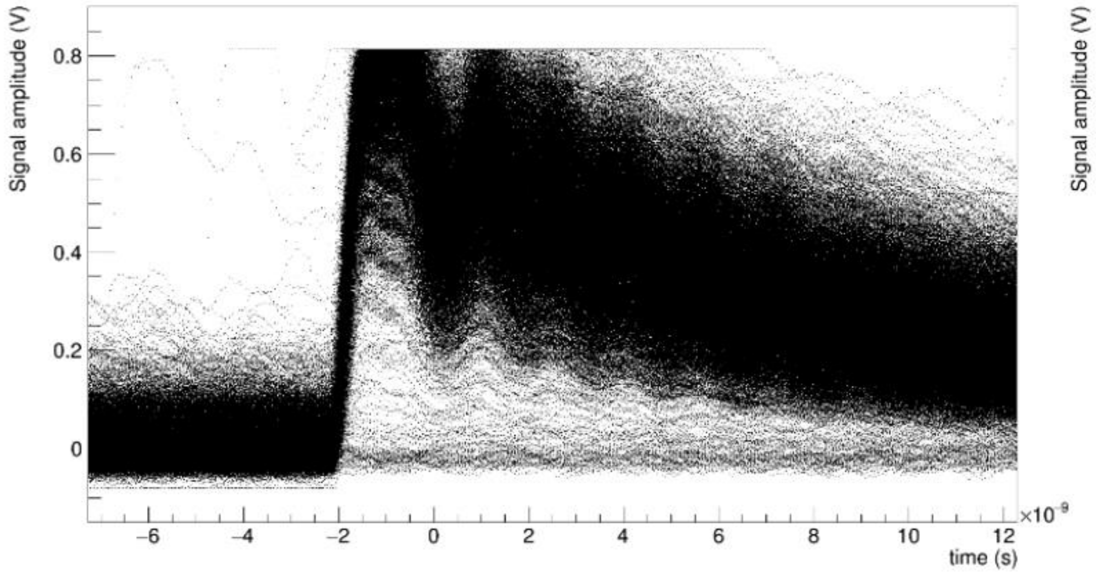
- ➢ CMOS MAPS with additional gain layer (**CMOS LGADs**)
- ➢ Low-Gain Avalanche Diodes (**LGADs**)

Backup slides

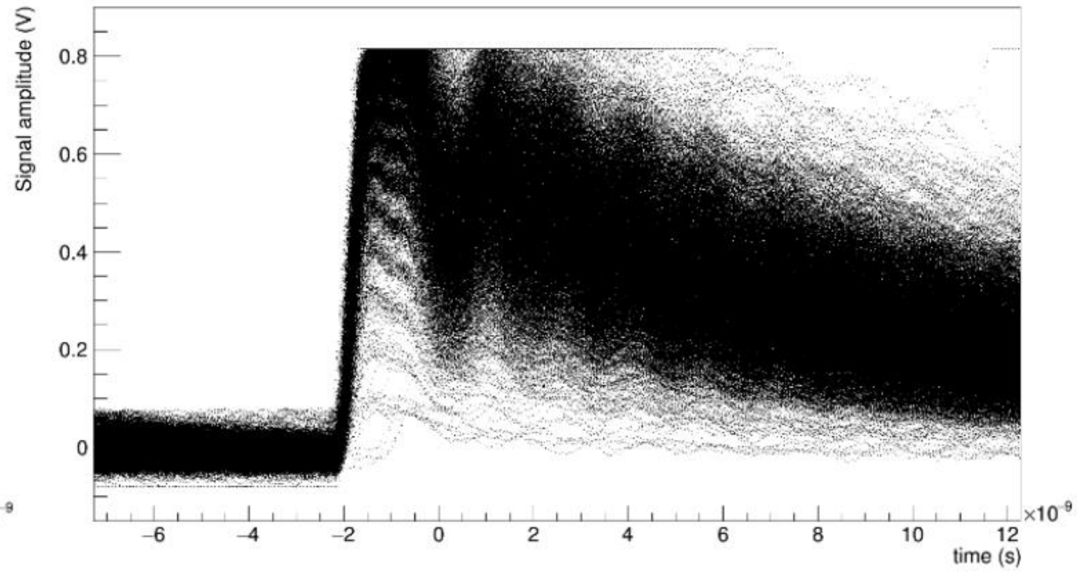
SIGNALS on oscilloscope

recovery time < 10 ns

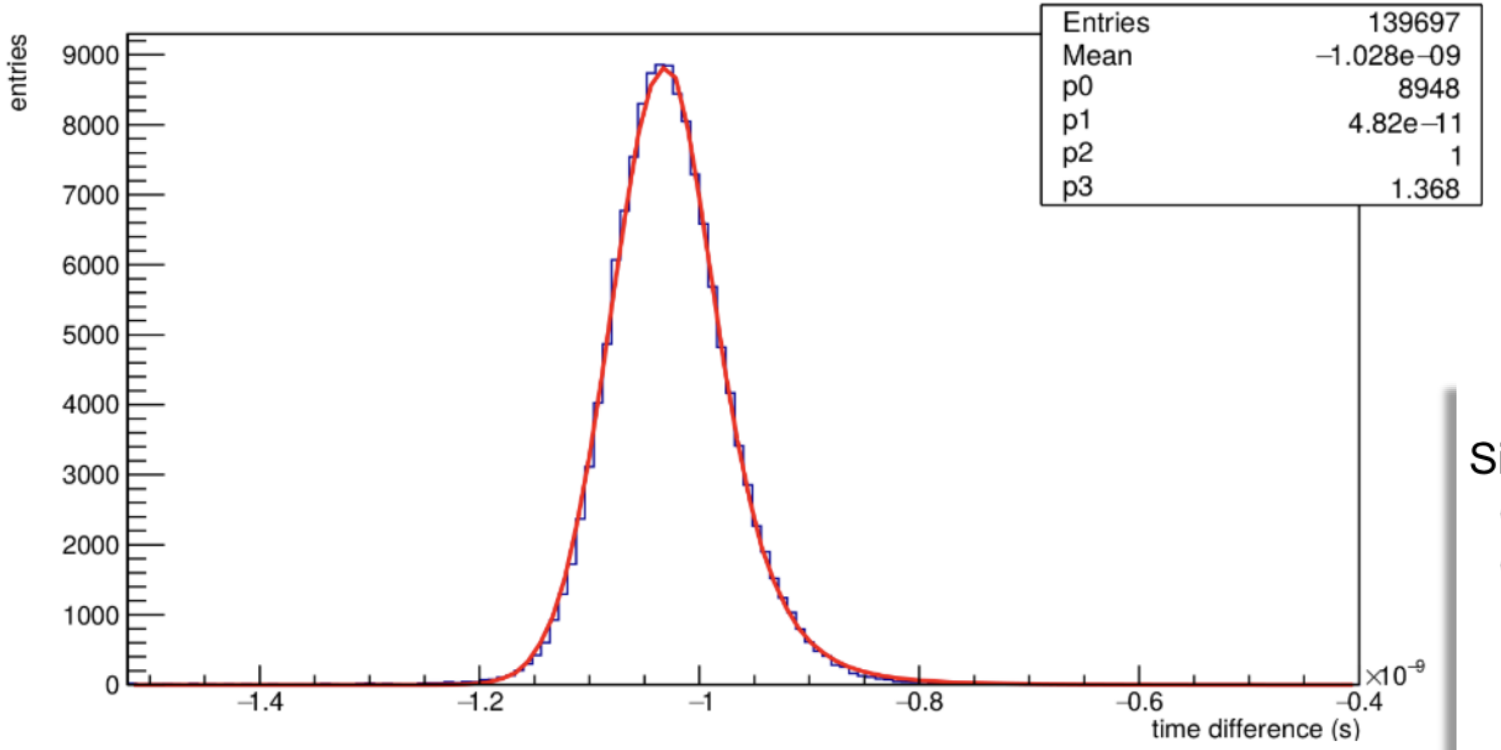
BEFORE SELECTION



AFTER SELECTION



Time resolution



Signal thresholds:

- 50% CFD LGAD
- 50% single SPAD amplitude

$$\sigma_{SiPM} = \sqrt{\sigma_{fit}^2 - \sigma_{LGAD}^2}$$

with $\sigma_{LGAD} \simeq 31$ ps (*)

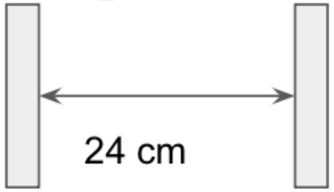
Time resolution and % events

	SR15		SR1		ER1		WR	
n	σ (ps)	F_n (%)	σ (ps)	F_n (%)	σ (ps)	F_n (%)	σ (ps)	F_n (%)
1	-	$\sim$0	(43 ± 15)	$\sim$0	(53 ± 11)	$\lesssim$1	(56 ± 4)	$\sim$81
2	(37 ± 5)	$\sim$0	(35 ± 4)	$\lesssim$1	(43 ± 6)	$\sim$1	(78 ± 6)	$\sim$16
3	(30 ± 4)	$\lesssim$1	(31 ± 4)	$\sim$1	(41 ± 6)	$\lesssim$3	(84 ± 10)	$\sim$3
4	(23 ± 4)	$\lesssim$2	(22 ± 3)	$\lesssim$3	(31 ± 3)	$\sim$5	-	-
5	(18 ± 4)	$\lesssim$4	(19 ± 4)	$\lesssim$5	(25 ± 3)	$\sim$8	-	-
6	(17 ± 4)	$\sim$5	(17 ± 4)	$\lesssim$7	(20 ± 3)	$\lesssim$12	-	-
7	(14 ± 5)	$\lesssim$8	(14 ± 3)	$\lesssim$10	(18 ± 3)	$\lesssim$13	-	-
8	(13 ± 4)	$\sim$9	(12 ± 4)	$\sim$11	(18 ± 4)	$\sim$10	-	-
$\geq$9	(14 ± 4)	$\sim$71	(13 ± 3)	$\sim$63	(17 ± 3)	$\sim$48	-	-

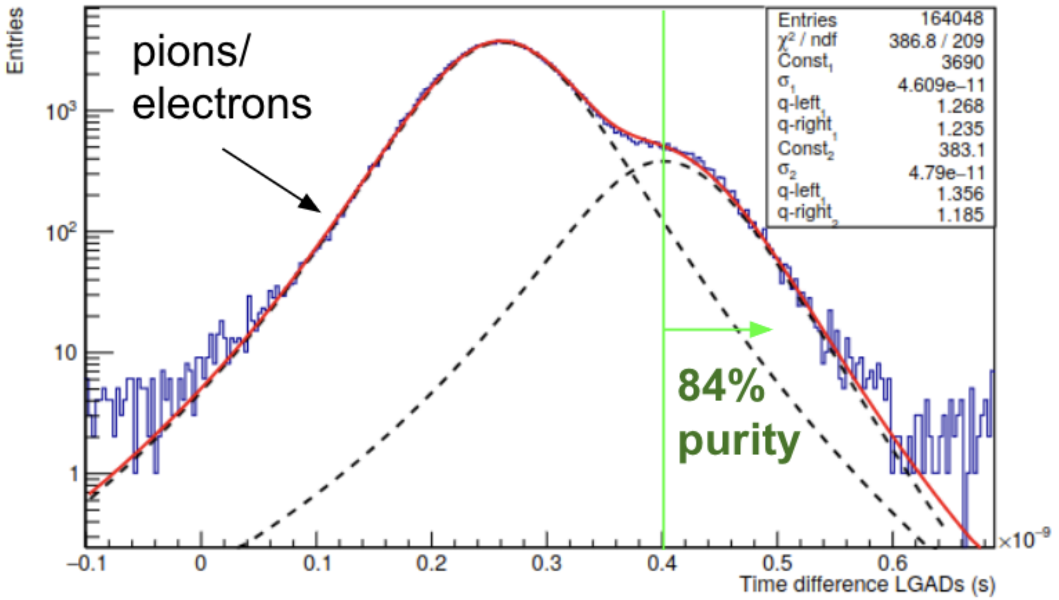
Table 1: Time resolution with respect to a selected number n of firing SPADs of different type of SiPMs at 4 V OV. The percentage F_n is the rounded mean fraction of events with a signal corresponding to n SPADs with respect to the total. The last value of WR is intended to be for signals with $\geq$3 SPADs firing.

Cherenkov effect: energy dependence (I)

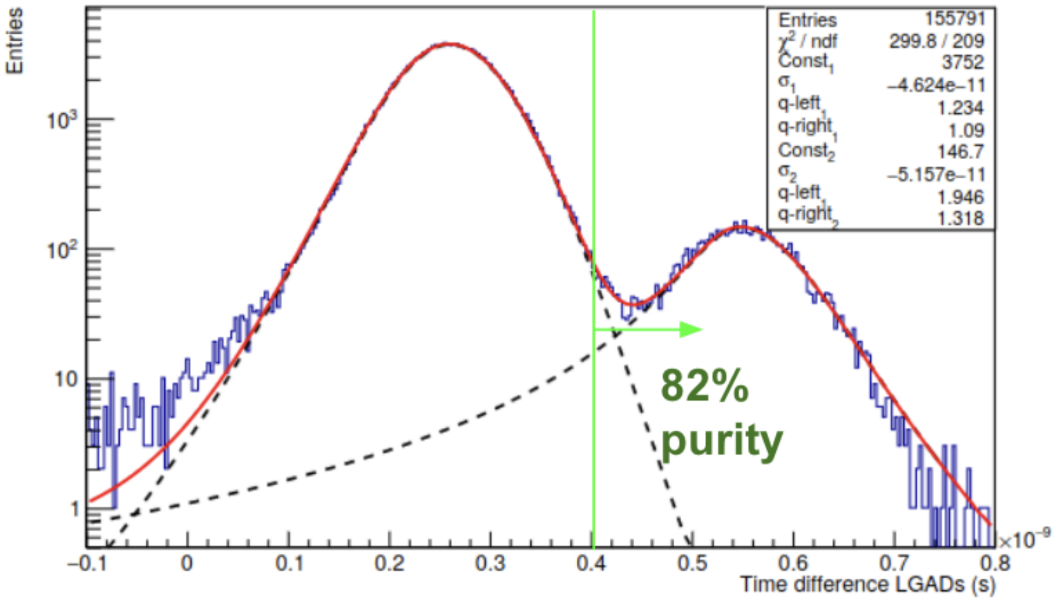
- selection based on timing (TOF) provided by the two LGADs
- TOF allows selection of protons



1.5 GeV/c

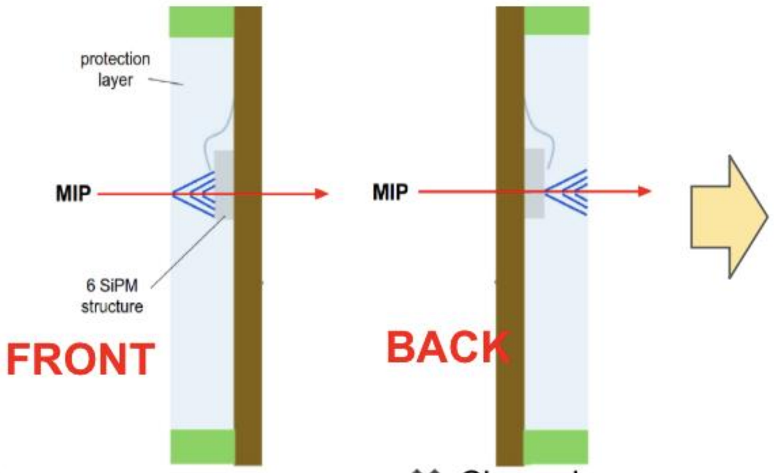


1 GeV/c



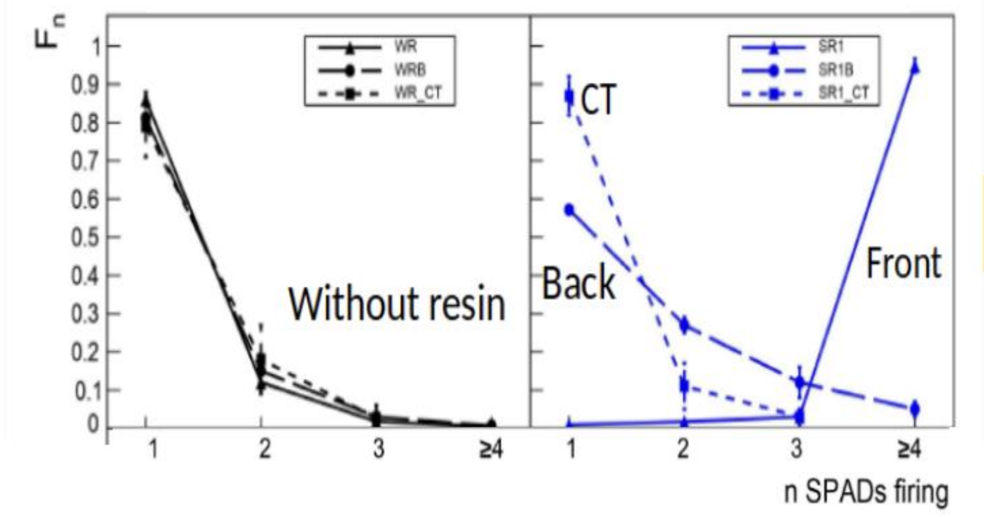
Understanding the direct detection of charged particles with SiPMs

Carnesecchi, *et al.* (2023):
https://doi.org/10.1140/epjp/s13360-023-03923-4



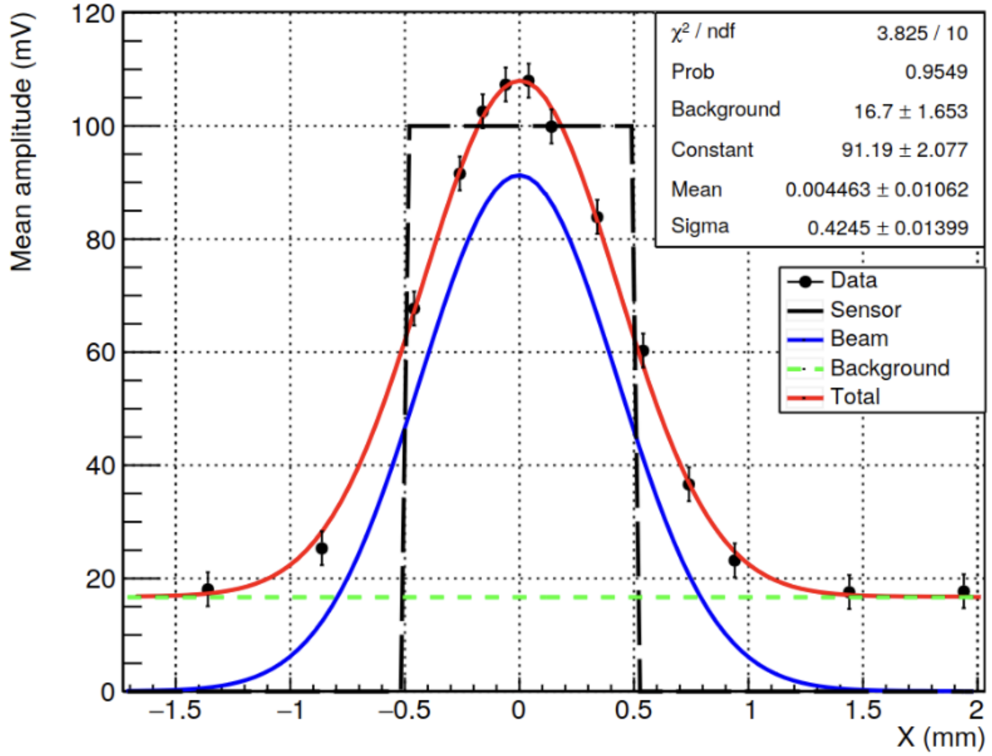
FRONT	BACK
✔ Cherenkov	✖ Cherenkov
✔ Bulk	✔ Bulk
✖ SiPM WR	✖ SiPM WR

$$F_n = \frac{\text{events with n SPADs firing}}{\text{events with} \geq 1 \text{ SPADs firing}}$$



Cherenkov effect!

WR position scan



Area of beam: 1 mm x 1 mm
in agreement with LGADs
triggered area.