Particle identification with the cluster counting technique

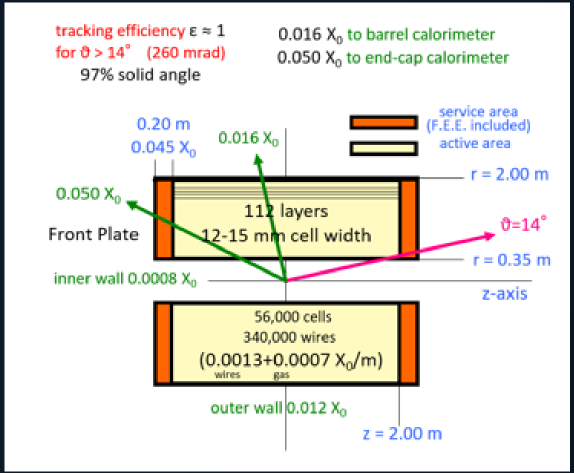
Federica Cuna for the cluster counting team

Outline

- The IDEA drift chamber: an innovative tracker with high particle identification potential
- The cluster counting technique: a promising method for the particle identification
- The simulations results with Garfield++ and Geant4: first hint of great results
- Beam tests for the validation of the great expectations

The IDEA drift chamber

The IDEA drift chamber (DCH) is the tracker of FCC-ee and CEPC. It is designed to provide efficient tracking, high precision momentum measurement and excellent particle identification by exploiting the application of the cluster counting technique.



- **He based gas mixture** (90% He – 10% i-C_4H_{10})
- **Full stereo configuration** with alternating sign stereo angles ranging from 50 to 250 mrad
- 12÷14.5 mm wide square cells 5 : 1 field to sense wires ratio
- 56,448 cells
- 14 co-axial super-layers, 8 layers each (112 total) in 24 equal azimuthal (15°) sectors

- **Gas containment – wire support functions separation**:
  the total amount of material in radial direction, towards the barrel calorimeter, is of the order of 1.6% X0, whereas in the forward and backward directions it is equivalent to about 5.0% X0, including the endplates instrumented with front end electronics.
- **Cluster timing**:
  allows to reach spatial resolution < 100 μm for 8 mm drift cells in He based gas mixtures (such a technique is going to be implemented in the MEG-II drift chamber under construction)
- Cluster counting:
  allows to reach dN/dx resolution < 3% for particle identification (a factor 2 better than dE/dx)

The cluster counting technique

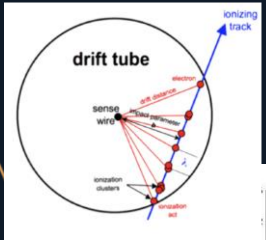
The traditional technique: dE/dx

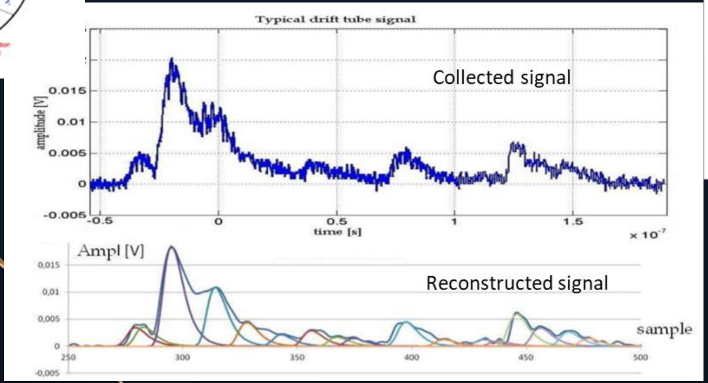
Using the information about energy deposit by a track in a gaseous detector, particle identification can be performed.

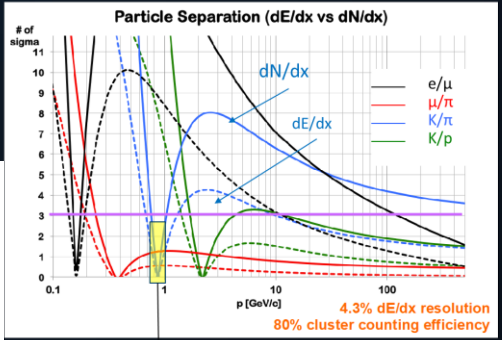
The large and intrinsic uncertainties in the total energy deposition represent a limit to the particle separation capabilities.

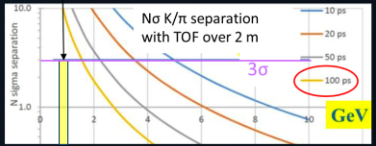
The cluster counting technique : dN/dx

The method consists in singling out, in ever recorded detector signal, the isolated structures related to the arrival on the anode wire of the electrons belonging to a single ionization act.

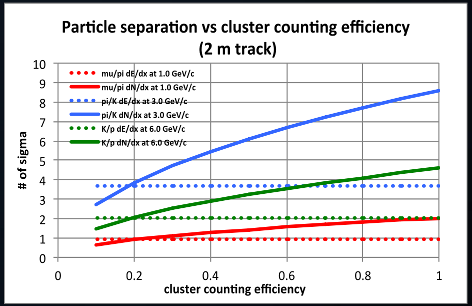








Analytical evaluation by F.Grancagnolo



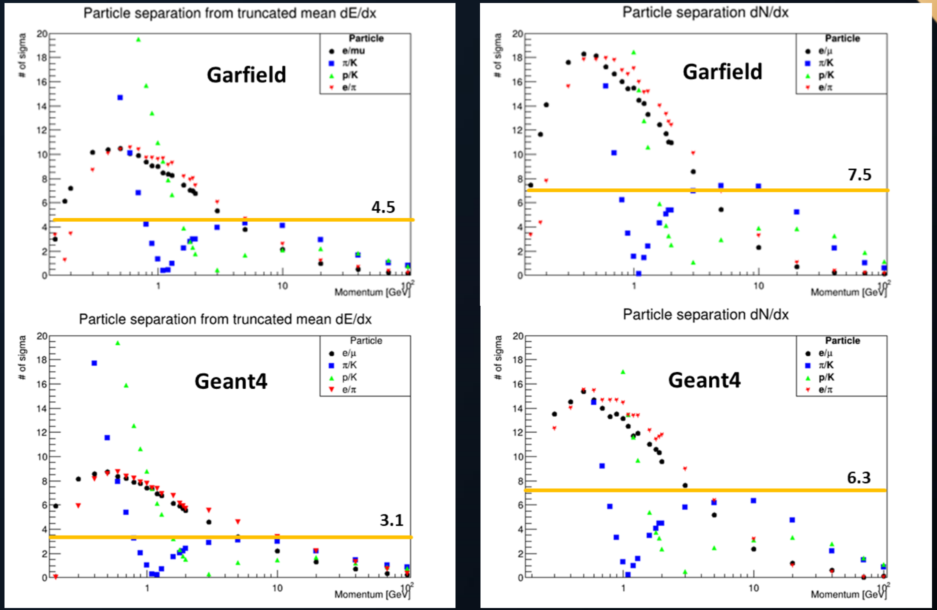
- 80% cluster counting efficiency.
- Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)
- Could recover with timing layer

Simulation results with Garfield++ and Geant4

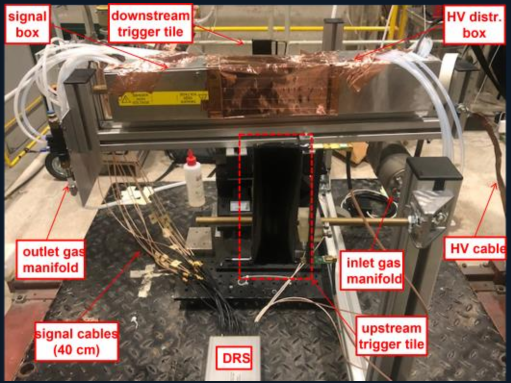
A simulation of the ionization process in 1 cm long side cell of 90% He and 10% iC_4H_{10} has been performed in **Garfield++** and **Geant4**.

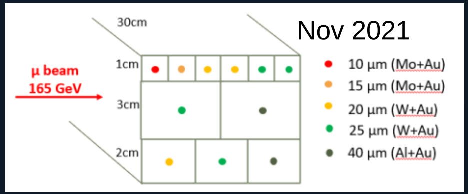
Three different algorithms have been implemented to simulate in Geant4, *in a fast and convenient way*, the number of clusters and clusters size distributions, using the energy deposit provided by Geant4.

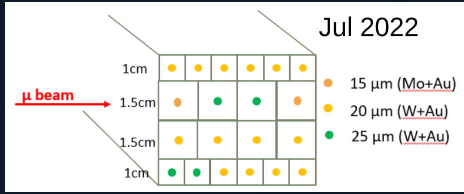
The simulations confirm the predictions: a factor 2 better than dE/dx !



Beam tests to validate the simulations results

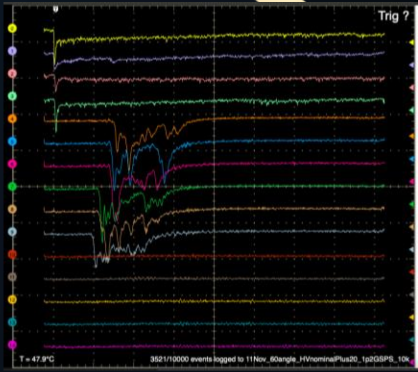


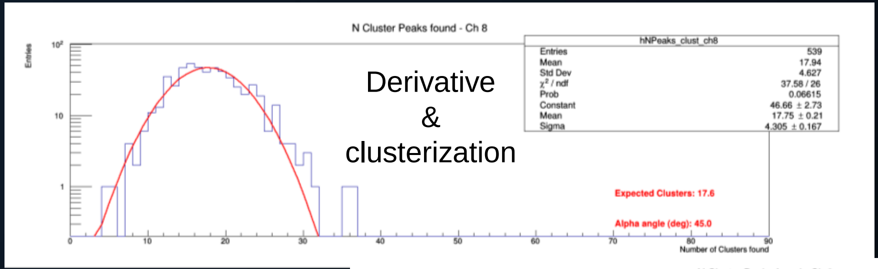




A “minimal” setup

- A pack of drift tubes
- DRS for data acquisition
- Gas mixing, control and distribution (He and iC_4H_{10})
- 2 trigger scintillators





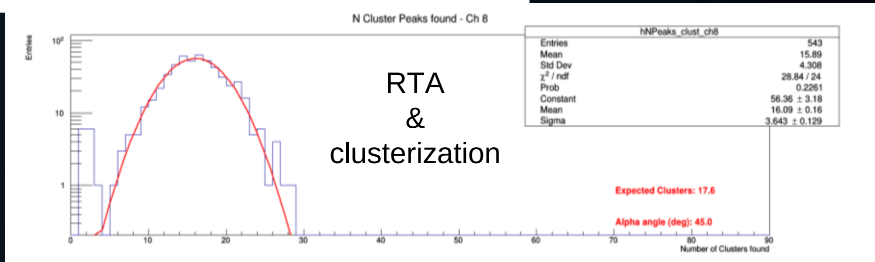
Poissonian nature

Two algorithms for peaks finding:

- Derivative algorithm
- Running template algorithm (RTA)

An algorithm to associate the peaks found in clusters:

- Clusterization algorithm



Thank you

The cluster counting team

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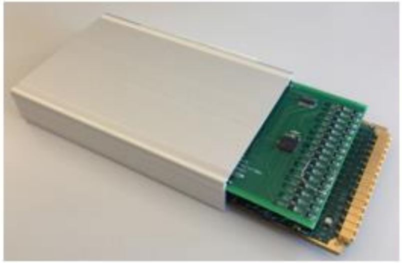
Backup

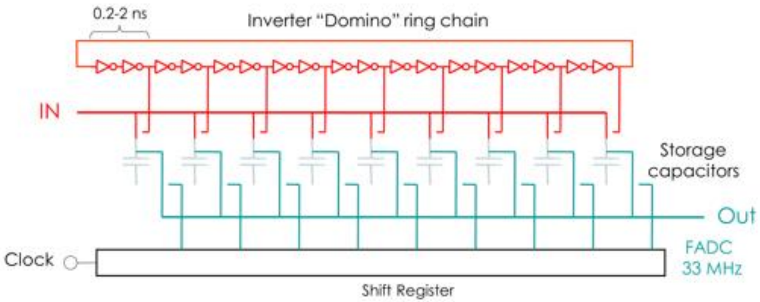
The DAQ system: WDB wave dream board

16 ch **D**rs4 **REA**dout **M**odule

Special thanks to the MEG collaboration

16 channels data acquisition board designed and used by the MEG2 experiment at PSI (μ → e + γ)





- **Analog switched capacitor array**: analog memory with a depth of 1024 sampling cells, perform a "**sliding window**" sampling.

- **500MSPS ↔ 5GSPS sampling speed** with 11.5 bit signal-noise ratio
  - 8 analog channels + 1 clock-dedicated channel for sub 50ps time alignment

- Pile-up rejection O(~10 ns)
- Time measurement O(10 ps)
- Charge measurement O(0.1%)

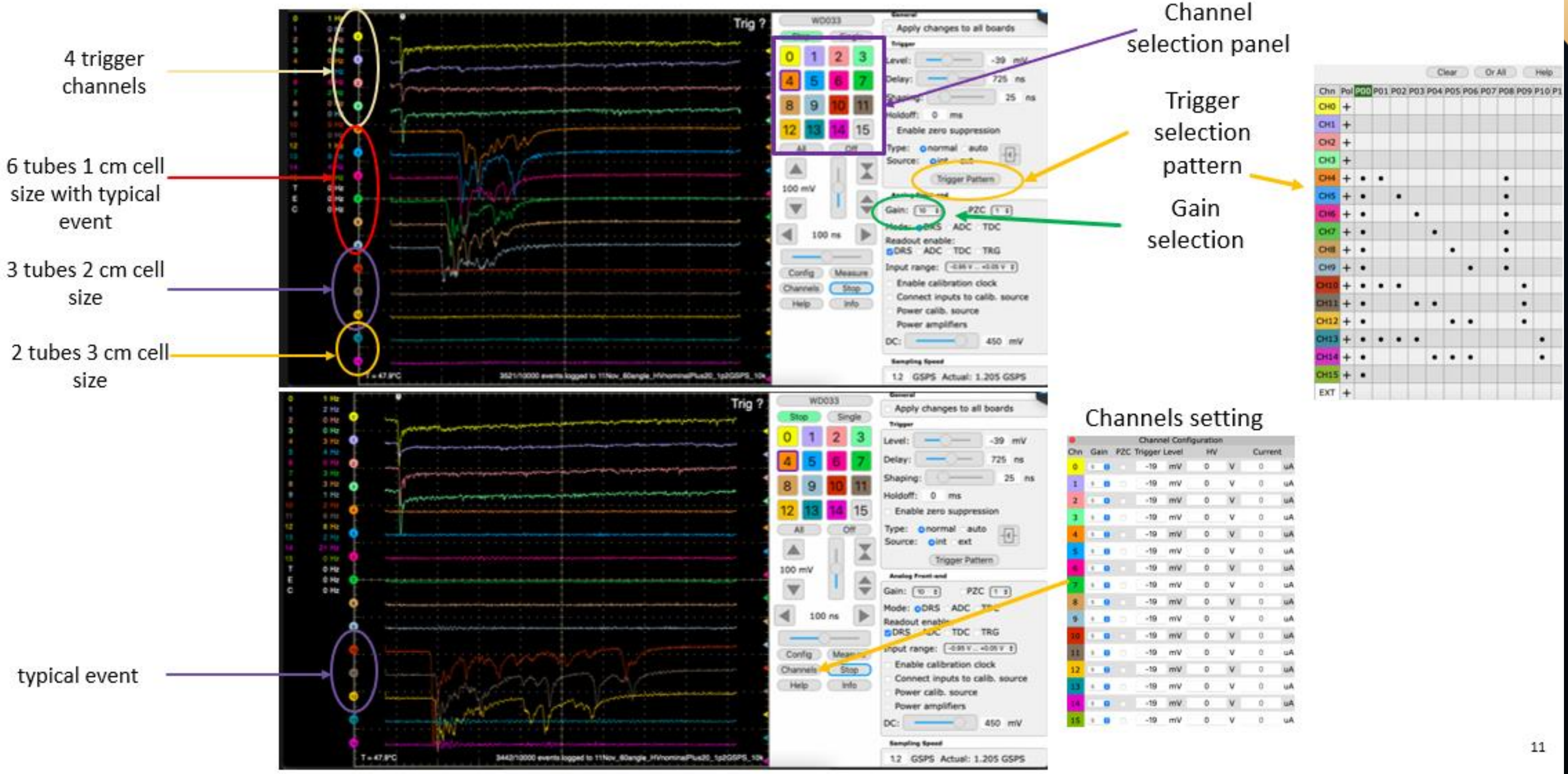
The data files have been converted in root format to accomplish the data analysis.
Data at different configuration have been collected:

- 90%He-10%iC_4H_{10}
- 80%He-20%iC_4H_{10}
- HV nominal (+10,+20,+30,-10,-20,-30)
- Angle 0° ,30 °,45 °,60 °

Details at: Application of the DRS chip for fast waveform digitizing, Stefan Ritt, Roberto Dinapoli, Ueli Hartmann, *Nuclear Instruments and Methods in Physics Research A 623 (2010) 486–488*

The DAQ system: an oscilloscope interface

WDB interface is similar to the interface of an oscilloscope with 16 channels



Preliminary results: an efficient algorithm to count electrons

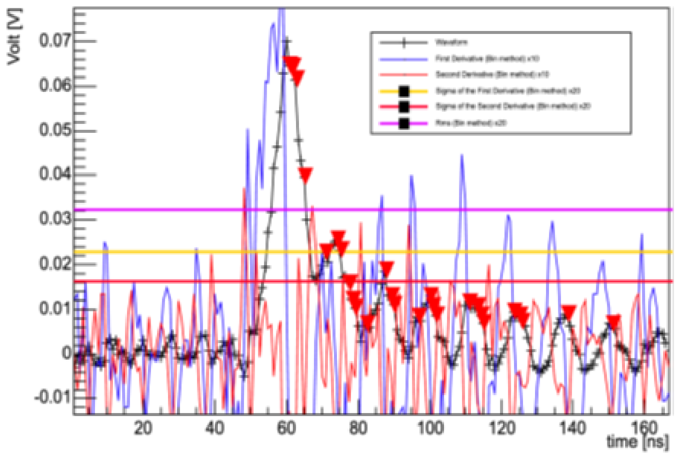
The first and second derivative algorithm (DERIV)

Requirements for a good peak candidate in the bin position [ip]:

1. Amplitude constraint:
   - Amplitude[ip]>4*rms
   - Amplitude[ip]- Amplitude[ip-1]>rms || Amplitude[ip+1]-Amplitude[ip-1]>rms
2. First derivative constraint:
   - Fderiv[ip]< $\sigma_{der1}/2$
   - Fderiv[ip-1]> σ_{der1} ||Fderiv[ip+1]<- σ_{der1}
3. Second derivative constraint:
   - Sderiv[ip]<0

0°, nominal HV+20, 90%He-10%iC_4H_{10}

Tube with 1 cm cell size and 20 µm diameter

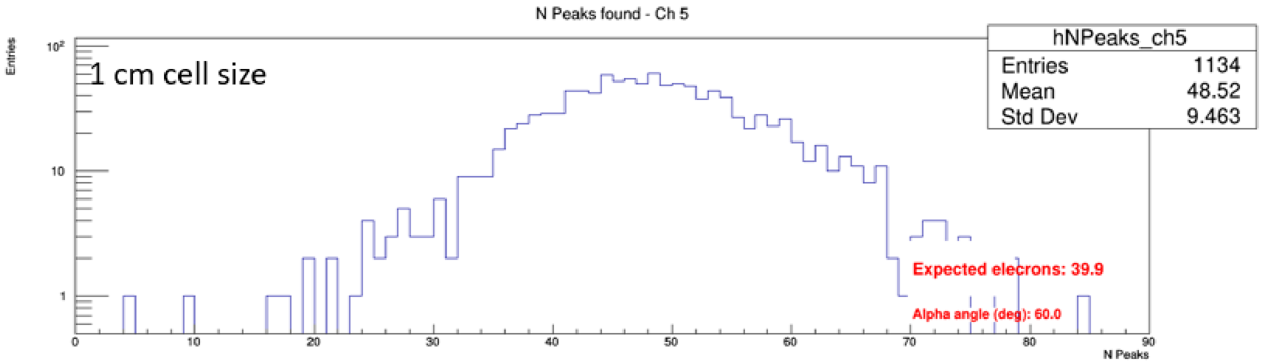


Expected number of electrons peaks:

Npeak=δcluster/cm(M.I.P.)*drift tube size[cm]*1.3(relativistic rise)*1.6 electron/cluster*1/cos(α)

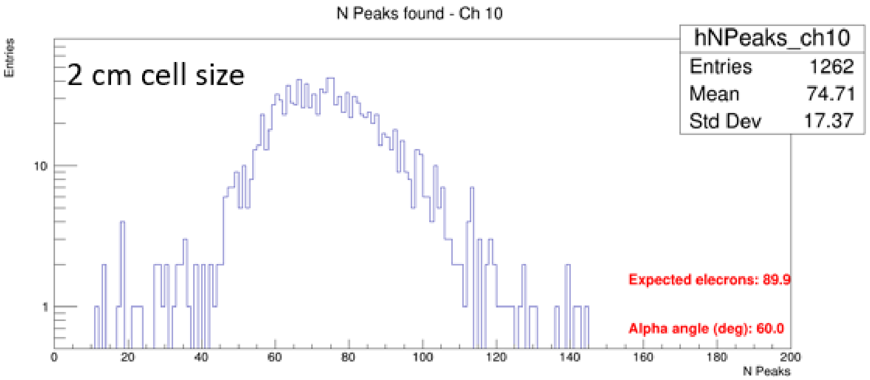
- δcluster/cm(M.I.P.) changes from 12 to 18 respectively for 90%He and 80%iC_4H_{10}
- Drift tube size changes from 0.8 to 1.8 respectively for 1 cm and 2 cm cell size tube.
- α is the angle of the muon tracks to the detector

The first and second derivative algorithm: results



90%He-10%iC_4H_{10}
60°
nominal HV+20

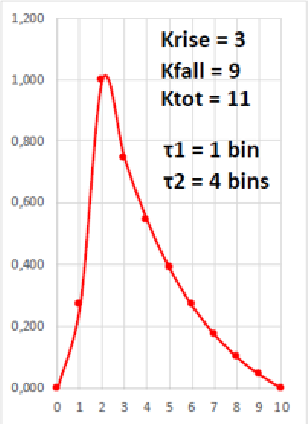
The mean values are compatible with the ones expected!

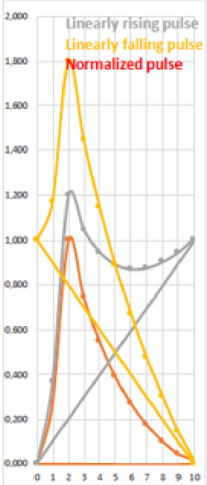


The running template algorithm (RTA)

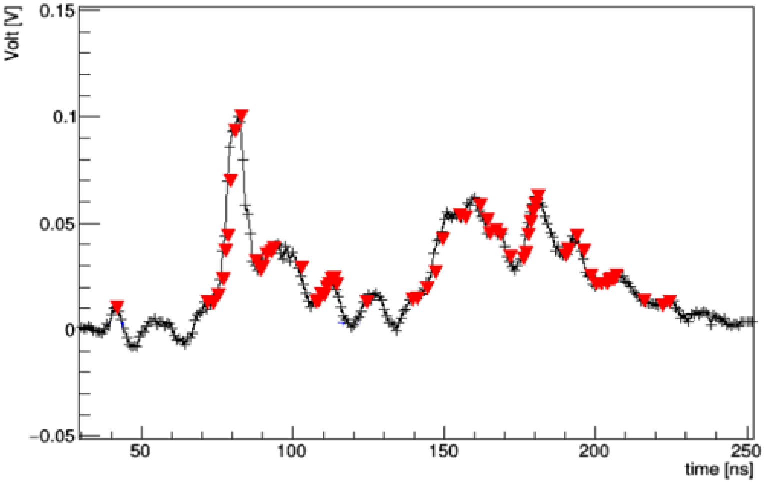
- Define an electron pulse template based on experimental data.
- Raising and falling exponential over a fixed number of bins (Ktot).
- Digitize it (A(k)) according to the data sampling rate.
- Run over Ktot bins by comparing it to the subtracted and normalized data (build a sort of χ2).
- Define a cut on χ2.
- Subtract the found peak to the signal spectrum.
- Iterate the search.
- Stop when no new peak is found.

k	A(k)
0	0.0
1	0.269
2	1.0
3	0.744
4	0.545
5	0.390
6	0.269
7	0.175
8	0.102
9	0.044
10	0.0

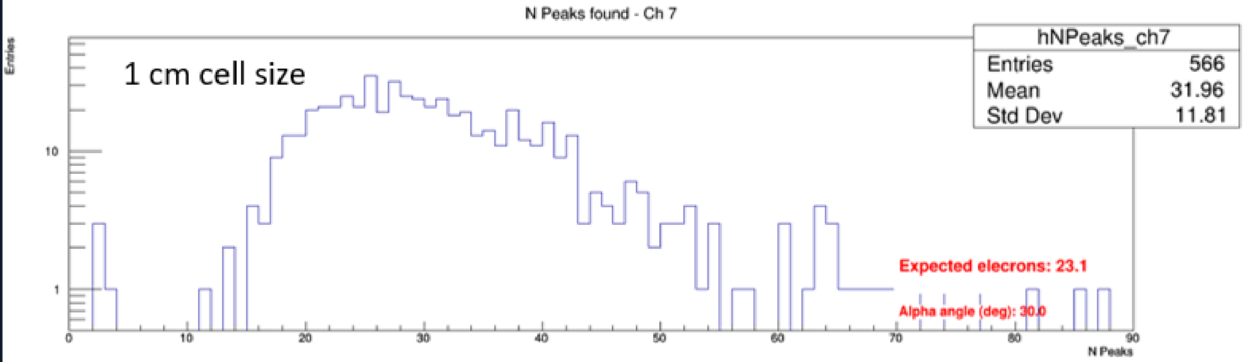




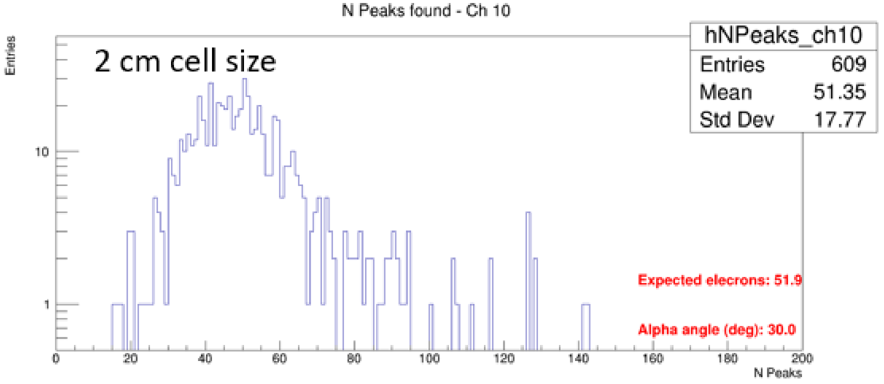
30°, nominal HV+20, 90%He-10%iC_4H_{10}
Tube with 1 cm cell size and 20 μm diameter



The running template algorithm (RTA): results



90%He-10%iC_4H_{10}
30°
nominal HV+20



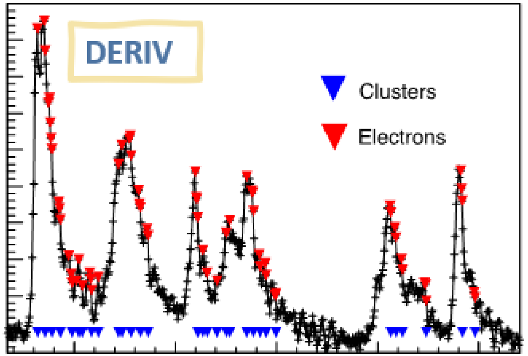
The mean values are compatible with the ones expected!

A single clusterization algorithm

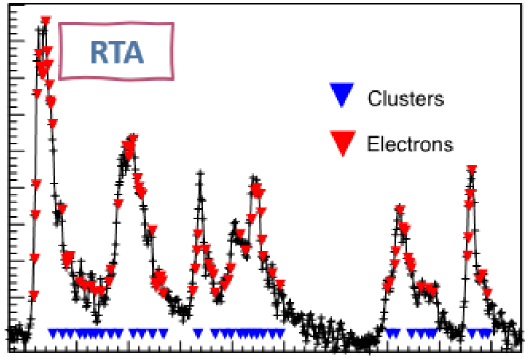
Once find the electron peaks, clusterization of the electron peaks into ionization clusters has been implemented:

1) Association of electron peaks consisting in consecutive bins (difference in time == 1 bin) electrons to a single electron in order to eliminate fake electrons.
2) Contiguous electrons peaks which are compatible with the electrons diffusion time (2.5 ns or 3 bins) must be considered belonging to the same ionization cluster.
3) Position of the clusters is taken as the position of the last electron in the cluster.

2 cm drift tube Track angle 45°

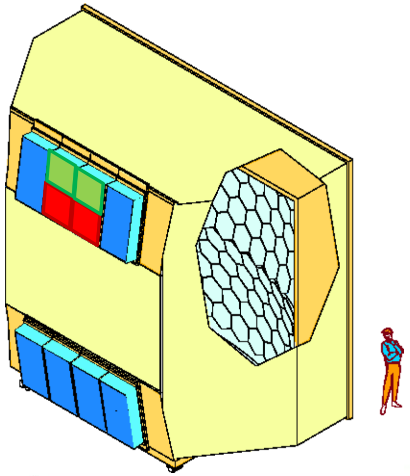


2 cm drift tube Track angle 45°



SINGLE PHOTON DETECTION WITH MPGDS

Daniele D'Ago on behalf of COMPASS RICH group

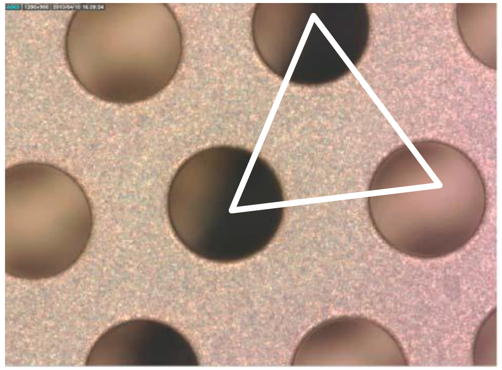


Cover large area with photon detectors in COMPASS RICH ($\sim 1.4\ m^2$)

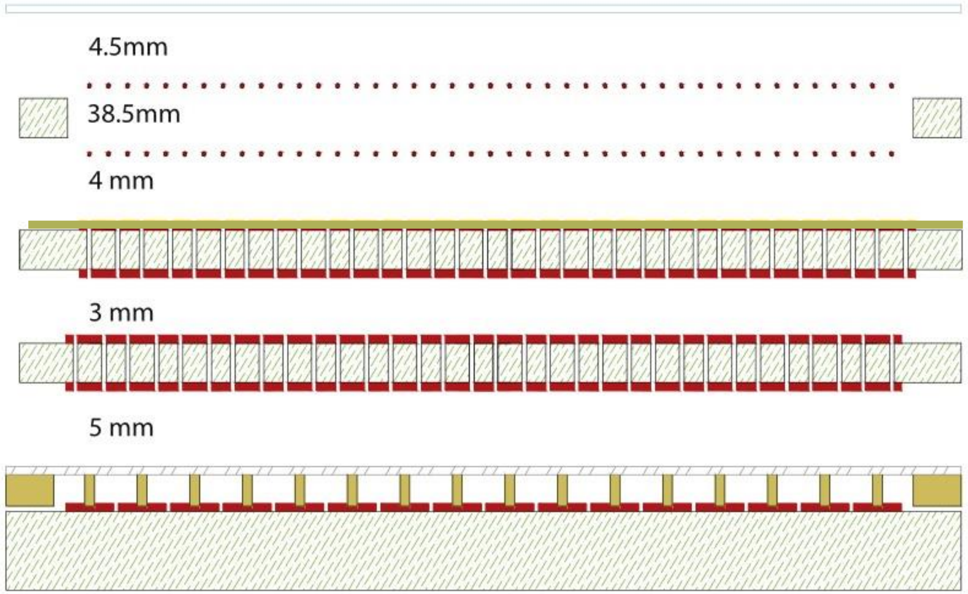
Why MPGDs?

> Reduced ion and photon backflow to photocathode > reduced aging and improved electrical stability

> Faster signal development > higher rate capabilities



Dielectric Thickness: 400 μm
Hole Ø: 400 μm
Hole in triangular pattern
Hole pitch: 800 μm
No rim



600x600 mm^2 Photon detectors composed of two equal segments

Fused silica window

2 layers of THGEM (staggered) first THGEM coated with CsI > reflective photocathode

1Micromegas
Suppresses Ion backflow (3%)

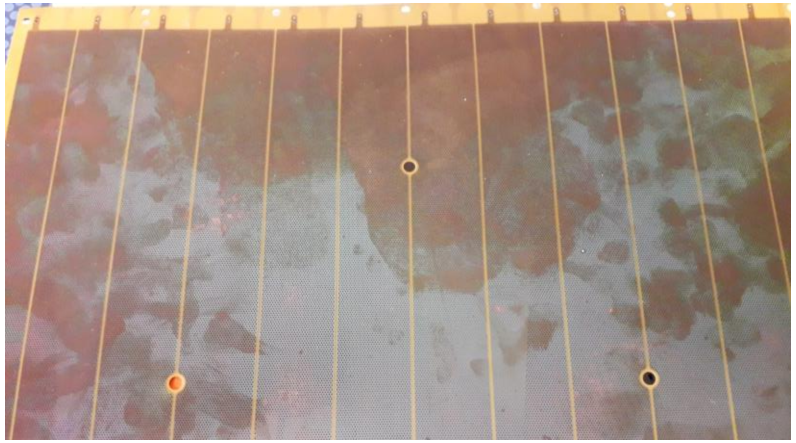
Gas Mixture: $Ar:CH_4 = 50:50$

Bulk Micromegas
Stainless steel, woven mesh
Anodic distance: 128 μm
Wire Ø: 18 μm
Wire pitch: 63 μm

POWERING AND READOUT

Electrode segmentation is essential. Each sector biased via 500 MΩ resistor.
> discharges affect single sector
> operating conditions restored in ~10 s

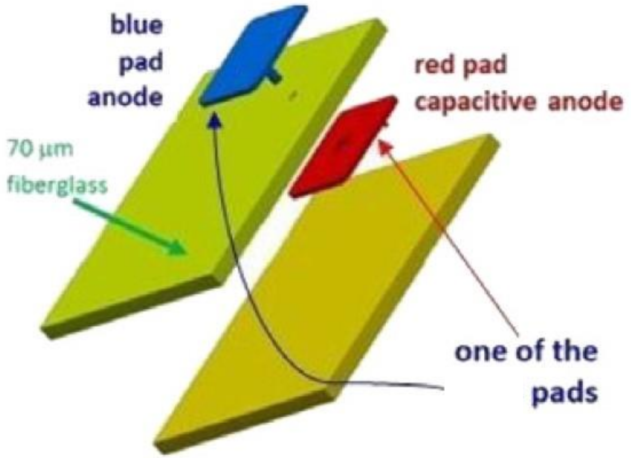
Voltages rescaled according to p and T fluctuations > stability of gain (~6%)

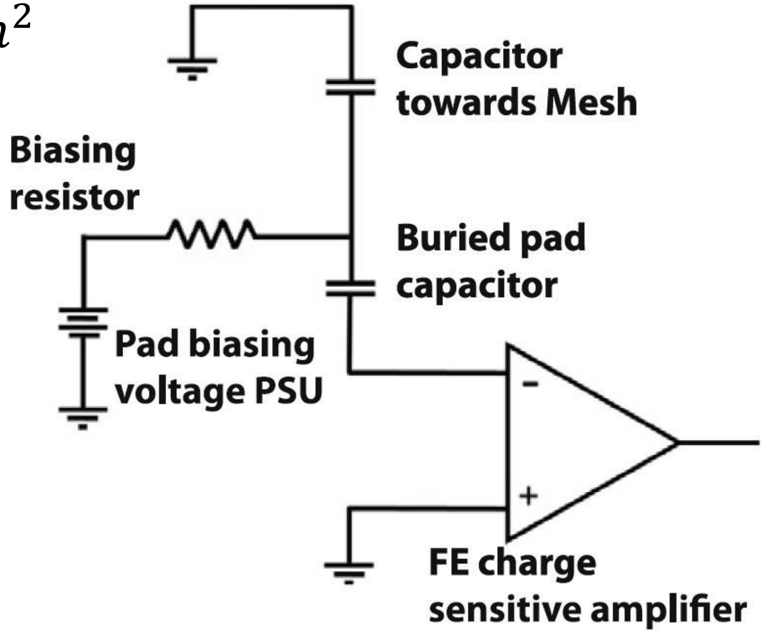


Large number of HV channels (~100) > compromise between cost and flexibility

“resistive” MM:
470 MΩ in series with each pad
Signal collected by buried pad and read with APV25 chip

Readout pad size: 7.5 x 7.5 mm^2
Readout pad pitch: 8 mm





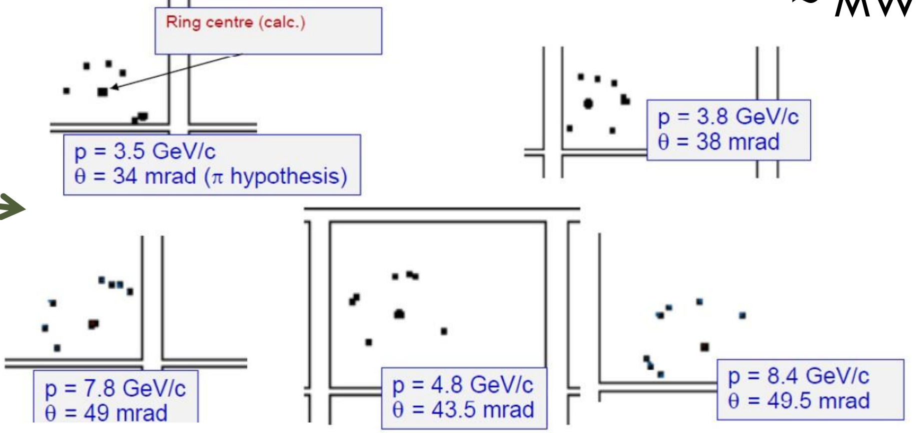
PERFORMANCE

MPGD-based PDs used during COMPASS runs 2016, 2017, 2021, 2022

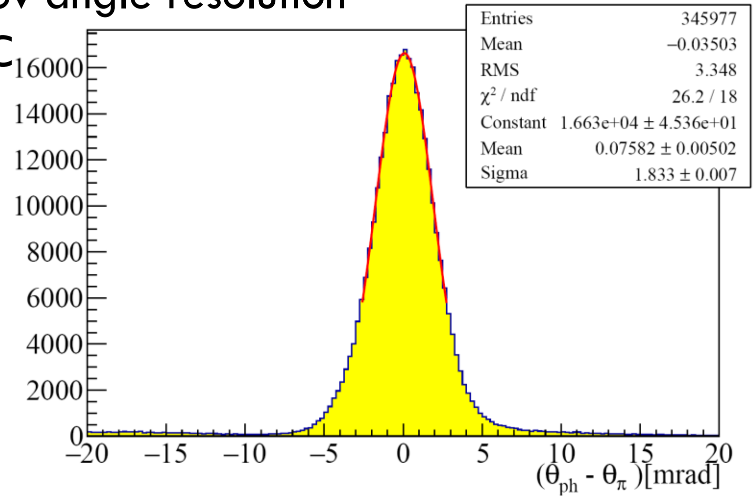
IBF: 3%

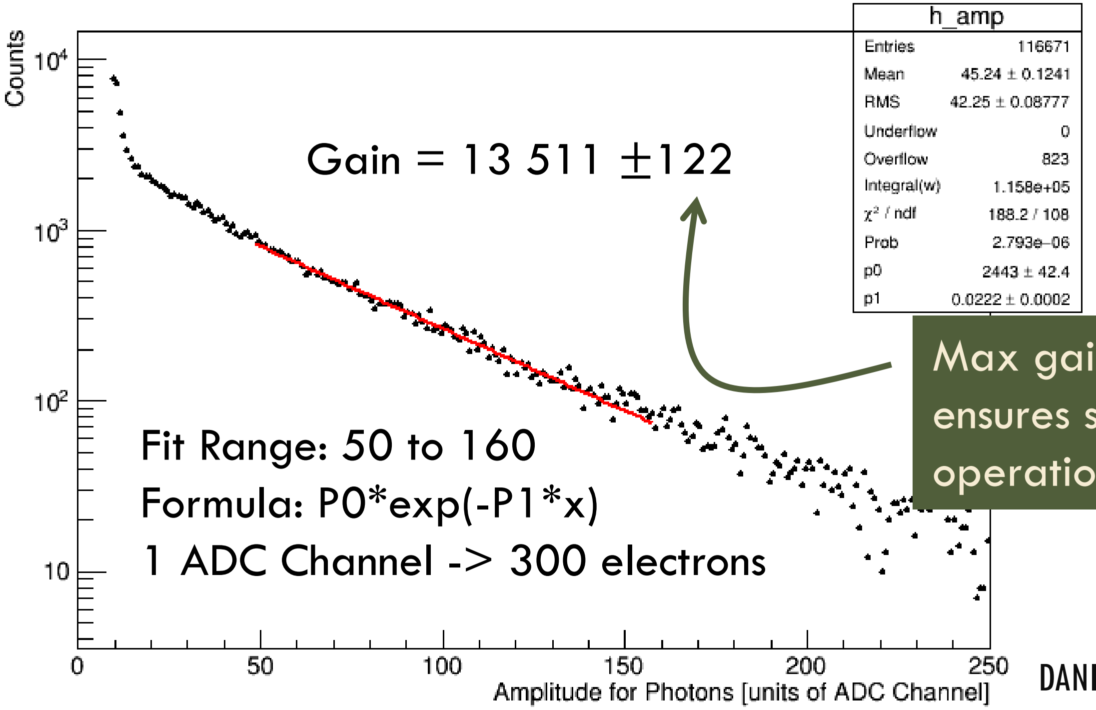
Electronic noise: 900ENC

Cherenkov rings in MPGD PDs
- no background subtraction



Cherenkov angle resolution ~ MWPC





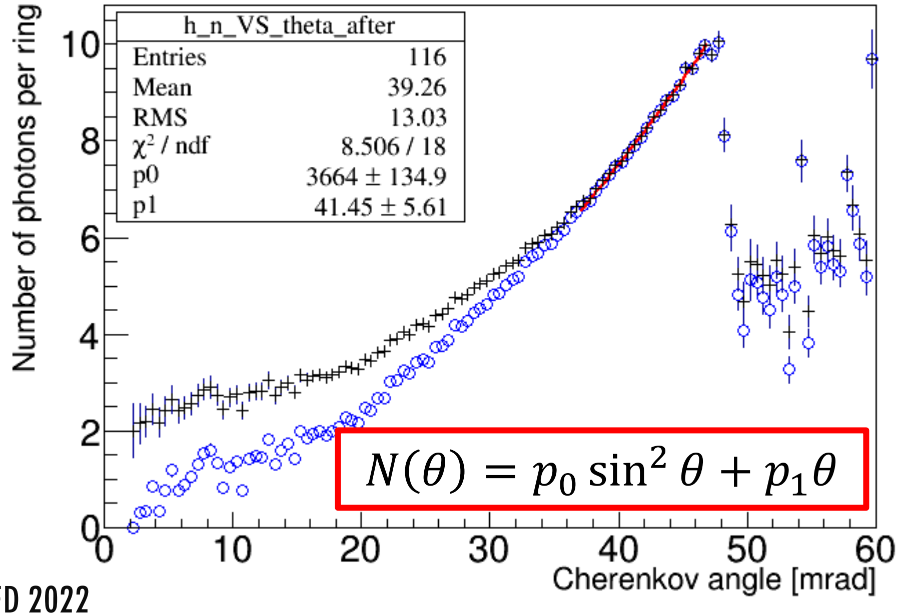
Gain = 13 511 ±122

Max gain that ensures stable operation

Fit Range: 50 to 160

Formula: P0*exp(-P1*x)

1 ADC Channel -> 300 electrons



$$N(\theta) = p_0 \sin^2\theta + p_1\theta$$

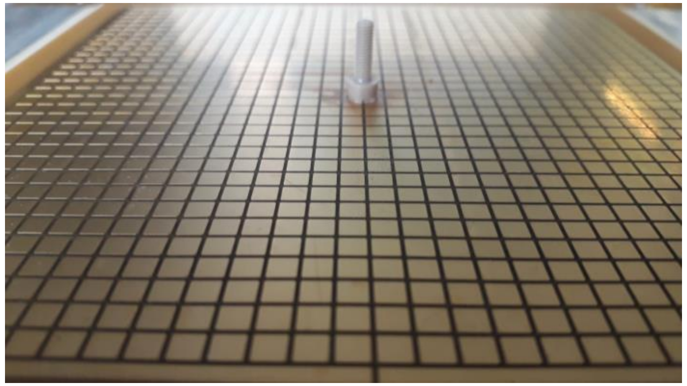
+ data points

○ Poissonian correction

At saturation: 11 photons

A LOOK TO THE FUTURE

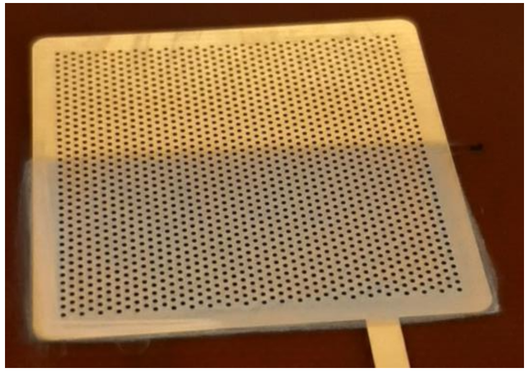
For exporting the technology to shorter radiator (e.g. collider experiment) > Improve space resolution



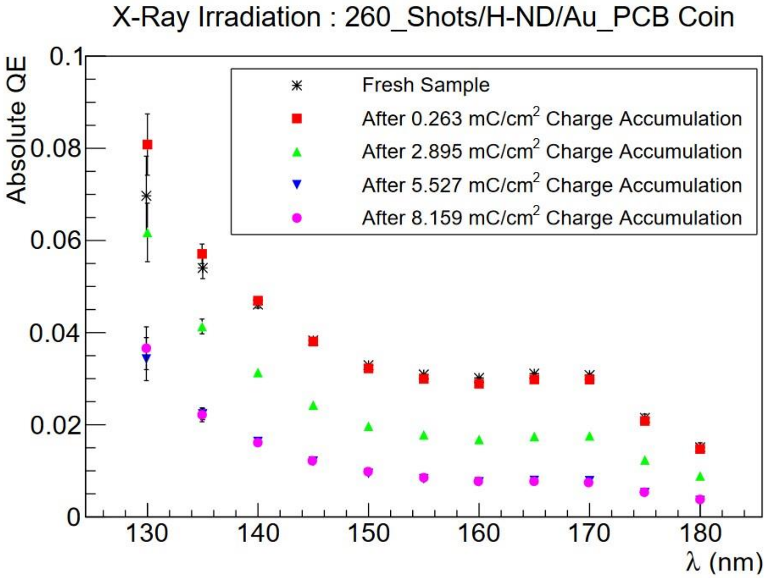
Reduced readout pad size (3x3 mm^2)

A prototype was produced and tested, promising results
> non uniformity among pads requires careful design of anode plane

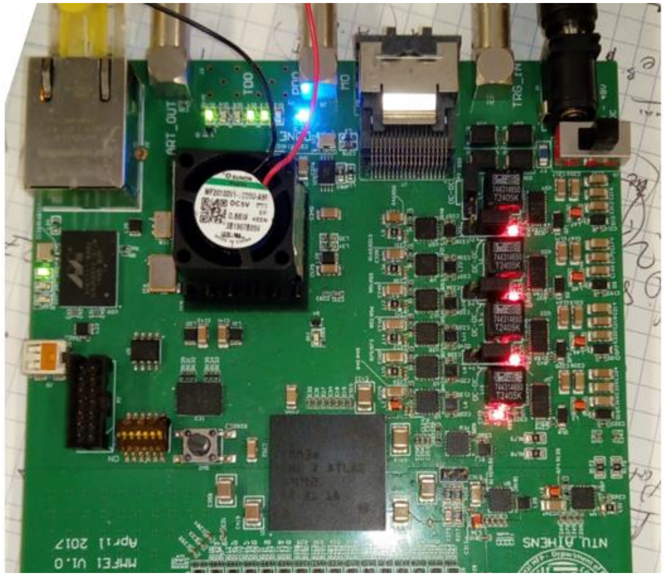
How low can we go in pad size?



Novel photocathode: hydrogenated nanodiamond powder
> Robust to ion bombardment
> Easier to handle compared to CsI
> QE comparable with CsI

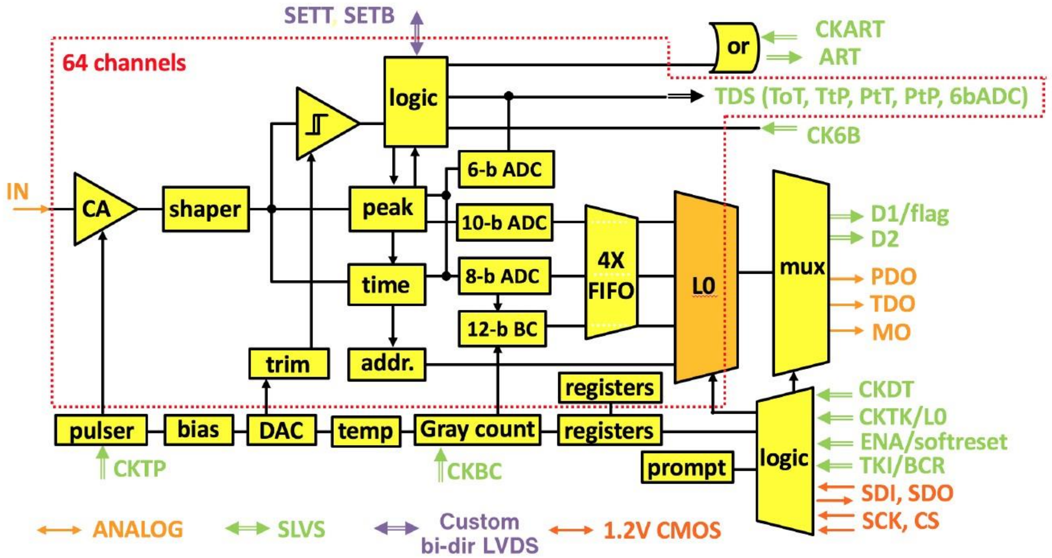


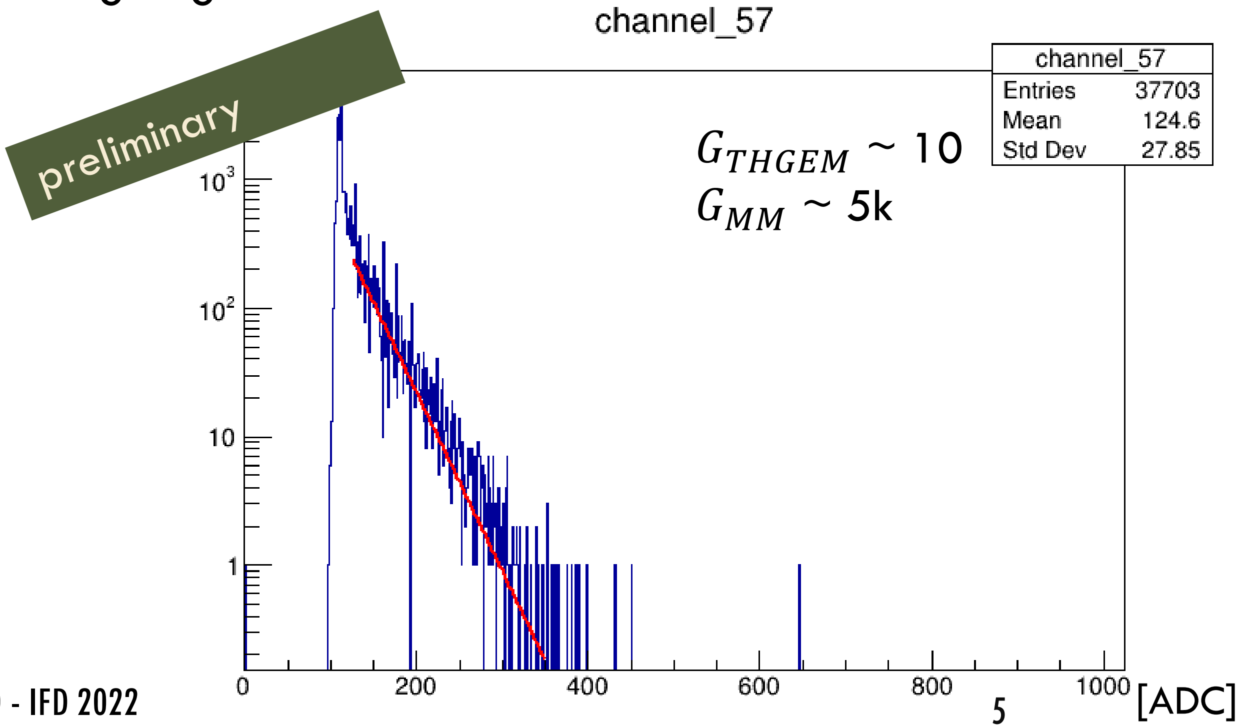
A LOOK TO THE FUTURE



Single photon detection requires extremely low noise electronics

New Front-end electronics: VMM3a, designed for ATLAS NSW (MM and sTGC)
> Compatible with triggerless DAQ
> Each channel: CSA, Shaper, Discriminator, Digitizer
> Output fully digital (time stamp, amplitude, n of channel, …)
> First tests with UV photons ongoing in Trieste





IFD2022 - INFN Workshop on Future Detectors

Istituto Nazionale di Fisica Nucleare

TWO SHOTS ON

1. *THE NEW NEUTRON HODOSCOPE*
2. *RIBs CHARACTERIZATION FOR FRAISE, THE NEW FRAGMENT IN-FLIGHT SEPARATOR AT INFN- LNS*

PAGANO EMANUELE VINCENZO (LNS-INFN) E*
MARTORANA NUNZIA SIMONA (LNS-INFN & UNICT)
COLLABORAZIONE CHIRONE

* speaker

NArCoS

FRAISE: a new FRAgment In-flight SEparator
Approved inside POTLNS PON

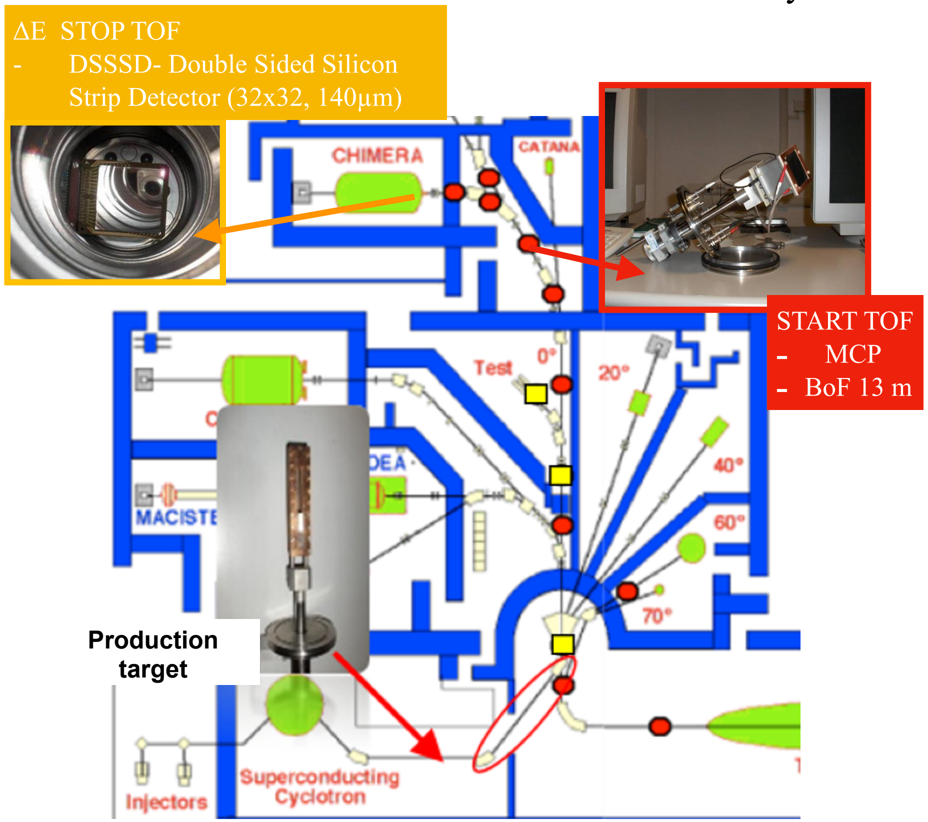
What we did @FRIBs facility

At INFN-LNS RIBs were produced, from 2001 to 2019, using the FRIBs (in Flight Radioactive Ion Beams at LNS) facility through the In-Flight fragmentation employing a maximum beam power of 100 W

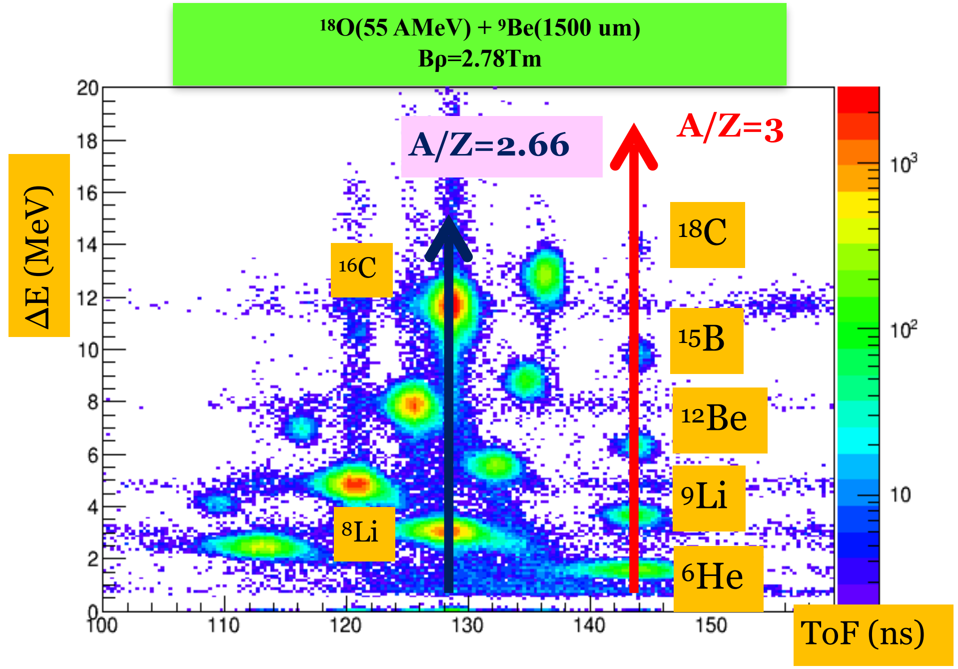
As known the produced beam is a *«cocktail beam»*, we need :

- Diagnostics system DSSSDs + plastic scintillators, to achieve an optimal transport from the production target to the final user point
- Tagging device for the CHIMERA array (ΔE-ToF method for PID identification, MCP-DSSSD system)

RIBs produced: from ^{6}He to ^{68}Ni with max intensity of ≈ 10^{5} pps



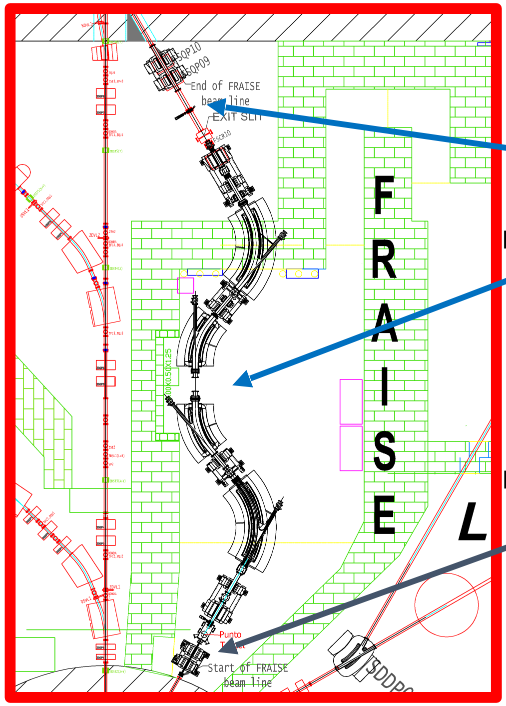
Lombardo I. et al., Nucl. Phys. B Proc. Suppl., 215 (2011) 272



Characteristics:
MCP: up to 10^{5} pps, Δt ≈ 200-300 ps;
DSSSD: max rate 200 kHz (light ions), 30 kHz (medium and heavy ions).
Worsening of performances in ≈ 1 week;
Time resolution Δt <≈1 ns ;

FRAISE: a new FRAgment In-flight SEparator
Approved inside POTLNS PON

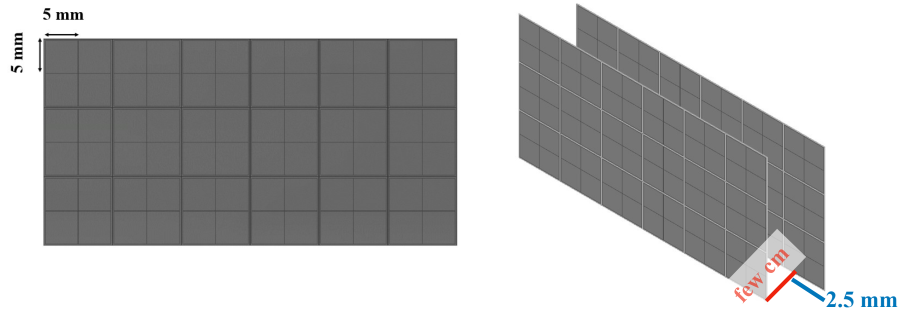
The building of a new fragment separator FRAISE (Fragment In- Flight Separator) is ongoing at INFN-LNS to provide high intensity (10^3 –10^7 pps) RIBs using the In-Flight Fragmentation method and employing a primary beam power of 2-3 kW. We expect an increasing up to two order of magnitude to the respect of the preset situation.



100 μm thick fully depleted SiC rad-hard multi-pad sensors: up to 10^7 pps over the whole system with $\Delta t \approx 200$ ps (≈0.1% precision on energy for 20 m base-of-flight) if 200 μm inter-pad dead zone, 10% dead area

Some examples (E/A≈ 50 MeV)

Nuclide of interest	Intensity* (kHz)
^{8}B	3100
^{14}Be	3
^{13}N	23000
^{14}O	1400
^{16}C	14000
^{17}F	170000
^{19}O	2300
^{34}Ar	8200



New radiation-hard tagging systems are needed to measure features of RIBs:

- Need of a point-to-point measurement of cocktail intensity, relative composition (PID), energy distribution, 2D profile, angular distribution during optimization
- Monitoring of beam properties, start time for event-by-event ToF/energy measurement during data taking

- Front-end: Custom multi/channel ASIC with charge preamplifier configuration and analog pre-processing optimized for amplitude and time measurements
- Full waveform digitizers and synchronization with CHIMERA/FARCOS DAQ

Martorana N.S., Il Nuovo Cimento 44 C (2021) 1
Martorana N.S. et al., Il Nuovo Cimento 45 C (2022) 63
Russo A.D. et al., Nucl. Instrum. Methods B, 463 (2020) 418
Russotto P. et al., J. Physics: Conf. Ser., 1014 (2018) 012016
F. Risitano, Tesi di Laurea Magistrale, Università degli Studi di Messina, Italy

NArCoS (Neutron Array for Correlation Studies)

Idea for a new Neutron Hodoscope

To realize a prototype of detector able to detect at the same time charged particles and neutrons with high energy and angular resolution for reaction studies and applications

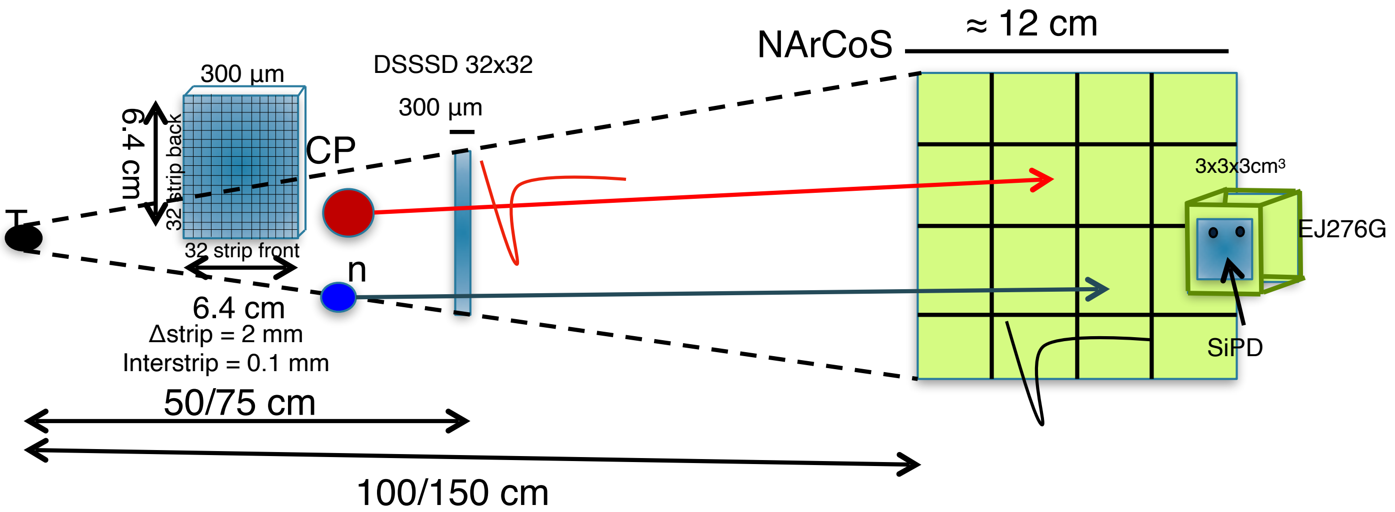
Detector

- Candidate: The plastic scintillator EJ276-Green Type (ex EJ299-33) (3x3x3cm³)
- 1 cluster: 4 consecutively cubes -> 3x3x12 cm³
- Neutron detection efficiency ≈ 50% for the prototype
- Reading the light signal: Si-PM and digitalization
- <u>Modular, reconfigurable (in mechanic and electronic)</u>
- Discrimination of n/γ from PSD (but also light charged particles)
- Energy measurement from ToF (Δt≤0.5 ns with L_{ToF}≈1÷1.5m)

TOF measured using the RF of the CS or with an ancillary MCP (low intensity exotic beams)

Physic cases

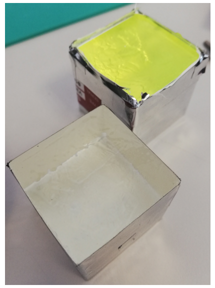
- Neutron-particles correlations (HBT)
- Reaction Dynamics and time scale
- Symmetry Energy in EoS of nuclear matter
- Nuclear structure of unbound exotic nuclei
- In medium nuclear interaction
- Nuclear astrophysics (neutron stars and nucleosynthesis processes)
- Medical application (neutron production cross section, differential cross sections)

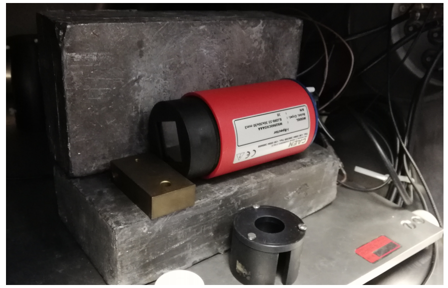


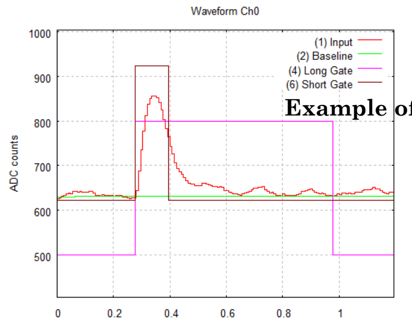
PSD studies using sources

- **Detector Configurations:**
  - EJ-276G + PMT
  - EJ-276 + i-Spector
  - EJ-276G + i-Spector
- **Lab measurements with radioactive sources:**
  - Vacuum Chamber
  - Pb shield
  - Gamma sources: ^{133}Ba, ^{137}Cs, ^{60}Co, ^{152}Eu
  - Alpha source: ^{241}Am
  - Digitizer from CAEN

E.V.Pagano, G. Politi, A. Simancas et al., in preparation



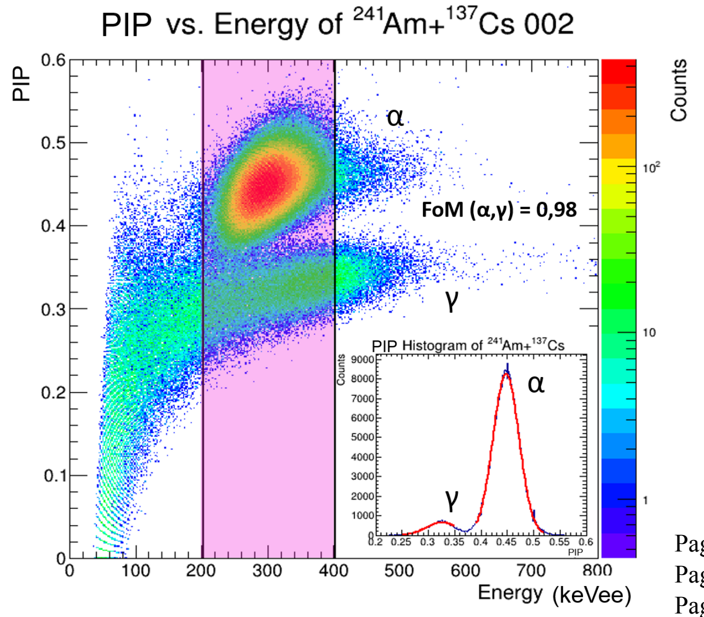




Example of signal and integration windows

Particle Identification Paramenter

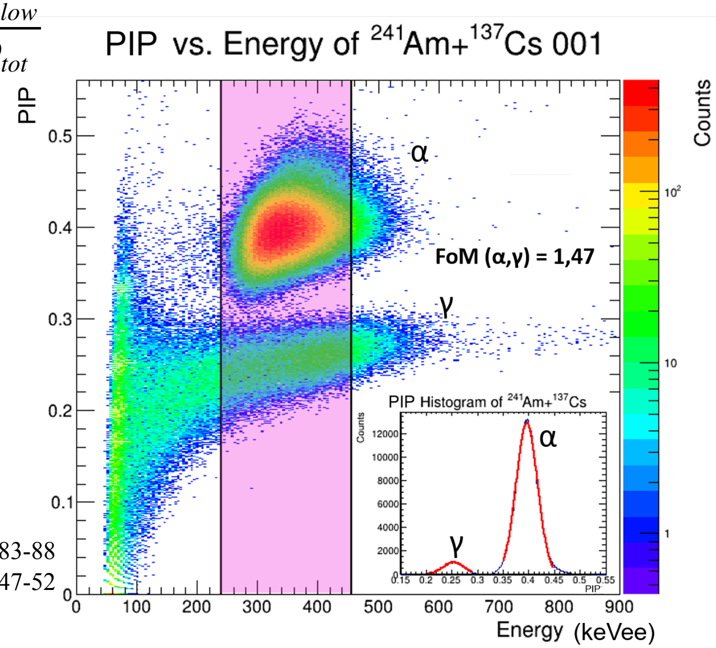
$$PIP = 1 - \frac{Q_{fast}}{Q_{tot}} = \frac{Q_{slow}}{Q_{tot}}$$



EJ-276 + i-Spector

Results

Detector	FoM
i-Spector + EJ-276	0.98
i-Spector + EJ-276G	1.47
PMT + EJ-276G	1.03



EJ-276G + i-Spector

Pagano E.V. et al., N.S., Nucl. Instrum. Methods A, 889 (2018) 83-88
Pagano E.V. et al., N.S., Nucl. Instrum. Methods A, 905 (2018) 47-52
Pagano E.V. et al., IL NUOVO CIMENTO 41 C (2018) 181
Pagano E.V. et al., JPS Conf. Proc. 32, 010096 (2020)
Pagano E.V. et al., IL NUOVO CIMENTO 43 C (2020) 12
Pagano E.V. et al., J. Phys.: Conf. Ser. 1643 (2020) 012037
Pagano E.V. et al., IL NUOVO CIMENTO 45 C (2022) 64

The LHCb RICH Upgrade

Federica Borgato on behalf of the Italian RICH groups

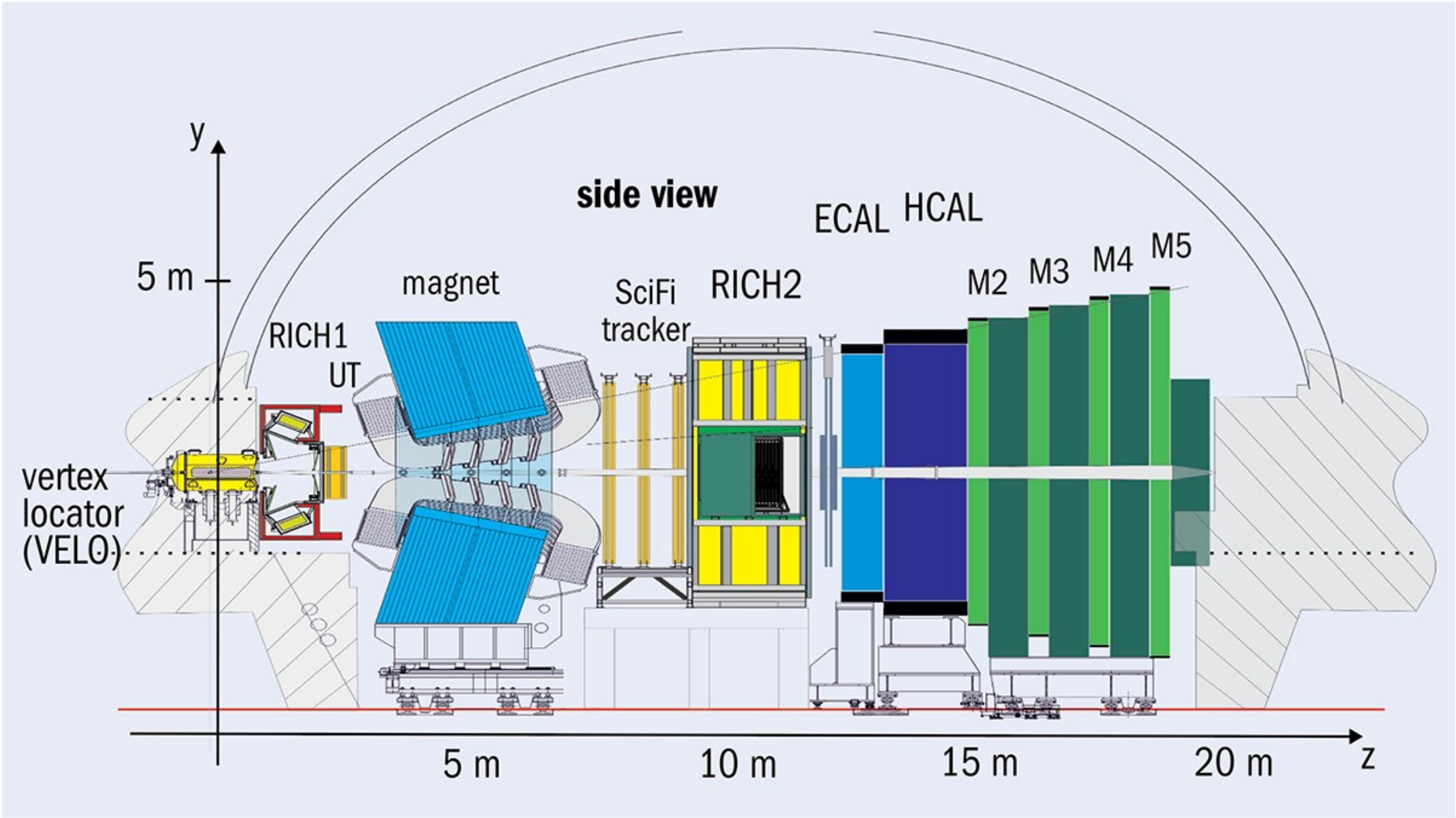
INFN Workshop on Future Detectors, 18th October 2022

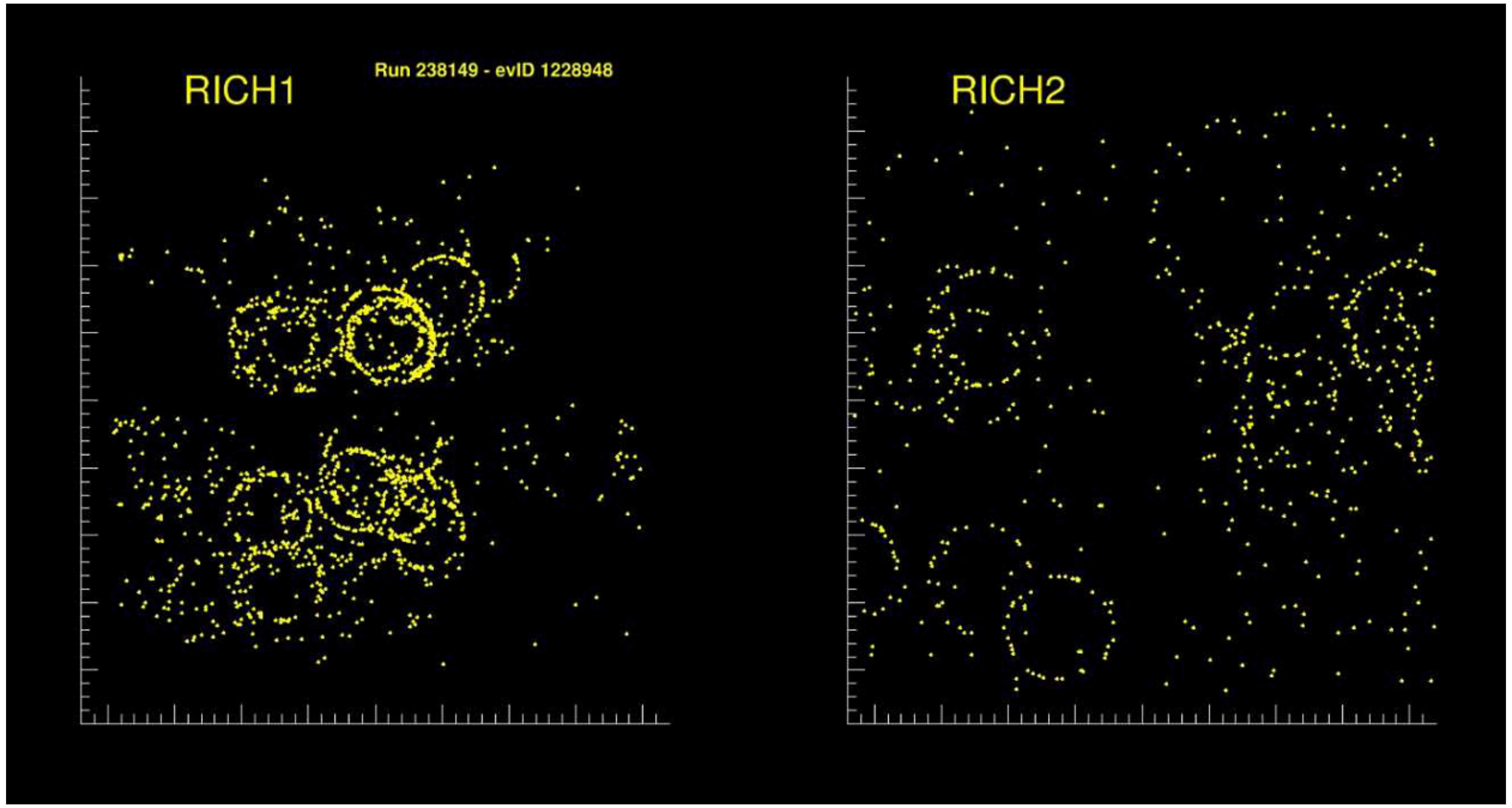
INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

The LHCb RICH detectors

LHCb relies on the **Ring Imaging Cherenkov** (RICH) **detector** system for the charged hadron identification in the momentum range [2;100] GeV/c.

The **Cherenkov light** produced by those particles is redirected by an **optical system** towards the **photodetector planes**, composed by **Multi-Anode PMTs**, and outside the acceptance of the spectrometer.





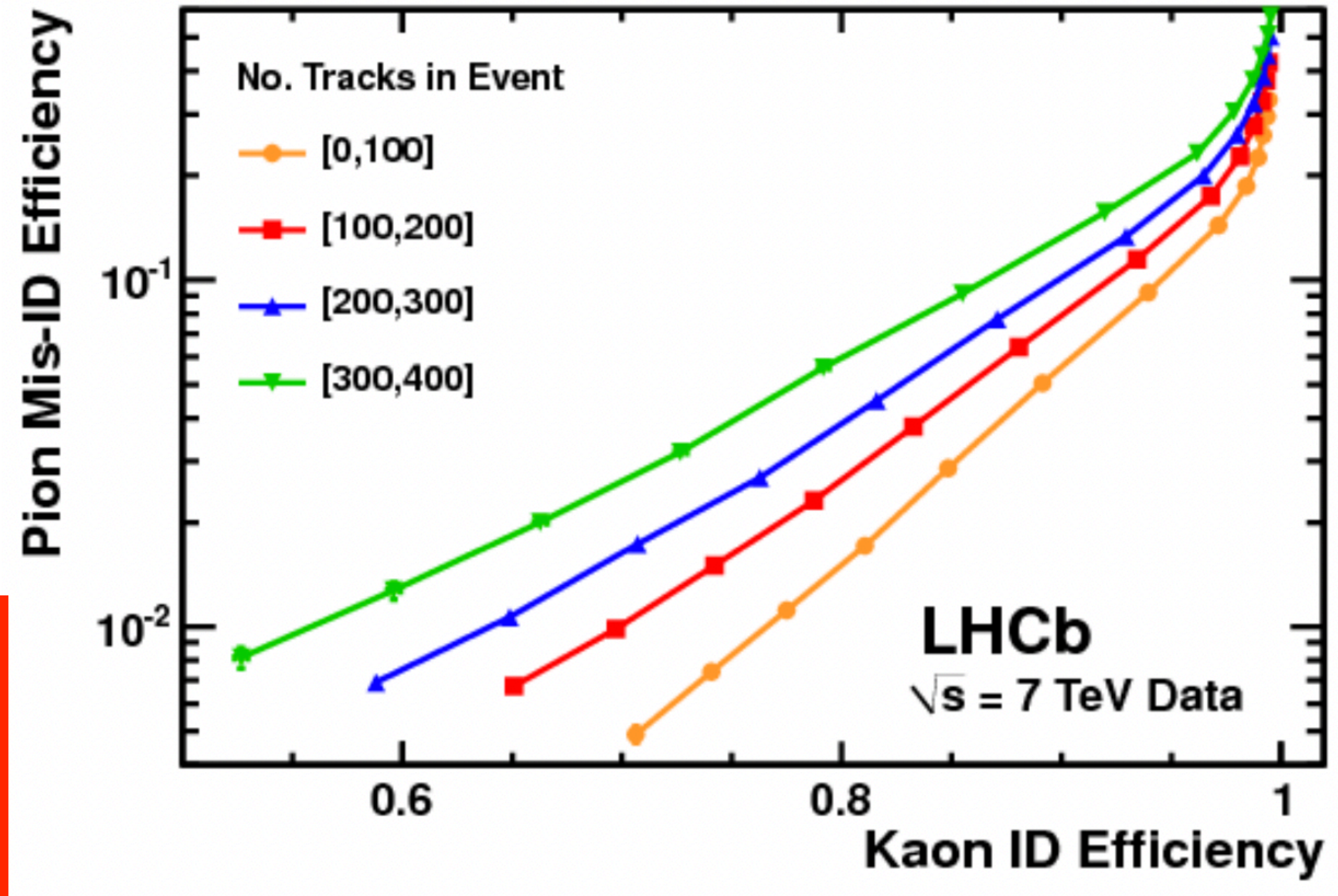
The **commissioning** of the current **RICH detector** (Upgrade 1a) is ongoing.

Upgrade 1a	Long Shutdown 2
Upgrade 1b	Long Shutdown 3
Upgrade 2	Long Shutdown 4

The LHCb RICH in Upgrade 1b/2

The **PID** performance is affected by **high detector occupancy**

→ In **Upgrade 1a** the expected maximum occupancy is ≈**30%** and very non-uniform



Upgrade 2 conditions:

- Keep or reduce maximum occupancy in the detector, make it more uniform, zooming into the high-occupancy central region
- Improve Cherenkov ring angle resolution

Many requirements for Upgrade2!

- Reduce occupancy → Reduce pixel size to focal length ratio, extend readout to include timing, change optical design
- Improve Yield → New photo-sensors with enhanced overall photo-detection efficiency
- Improve pixel size error → Reduce pixel size to focal length ratio
- Improve chromatic error → Improve $\sigma_{chromatic}/\sqrt{N}$
- Improve emission error → New optical design

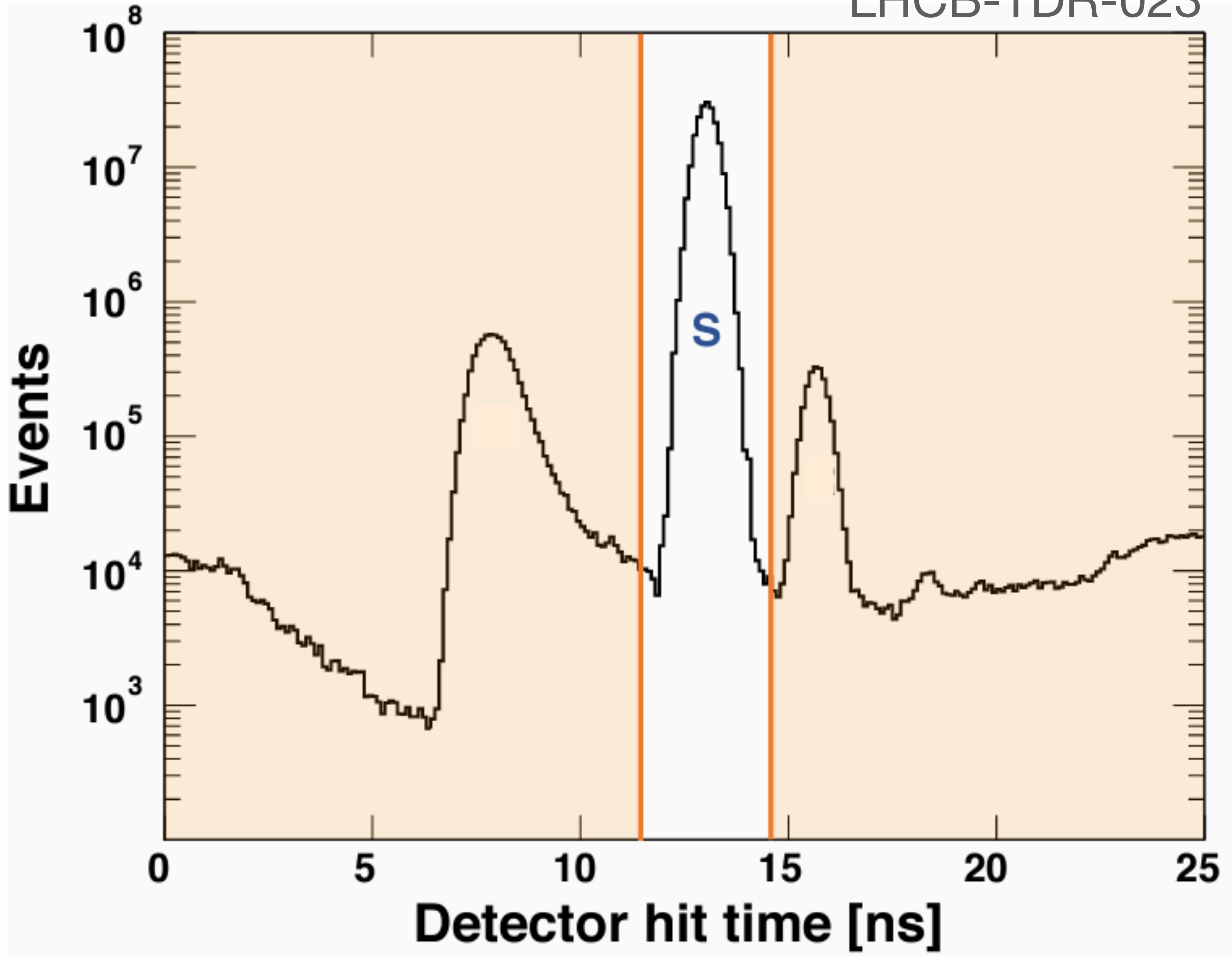
RICH PID with timing in Upgrade 1b/2

Cherenkov photons from a given track arrive almost **simultaneously** (about tens of ps) and it is possible to **predict the time of arrival of photons** from a track with an **excellent precision**.

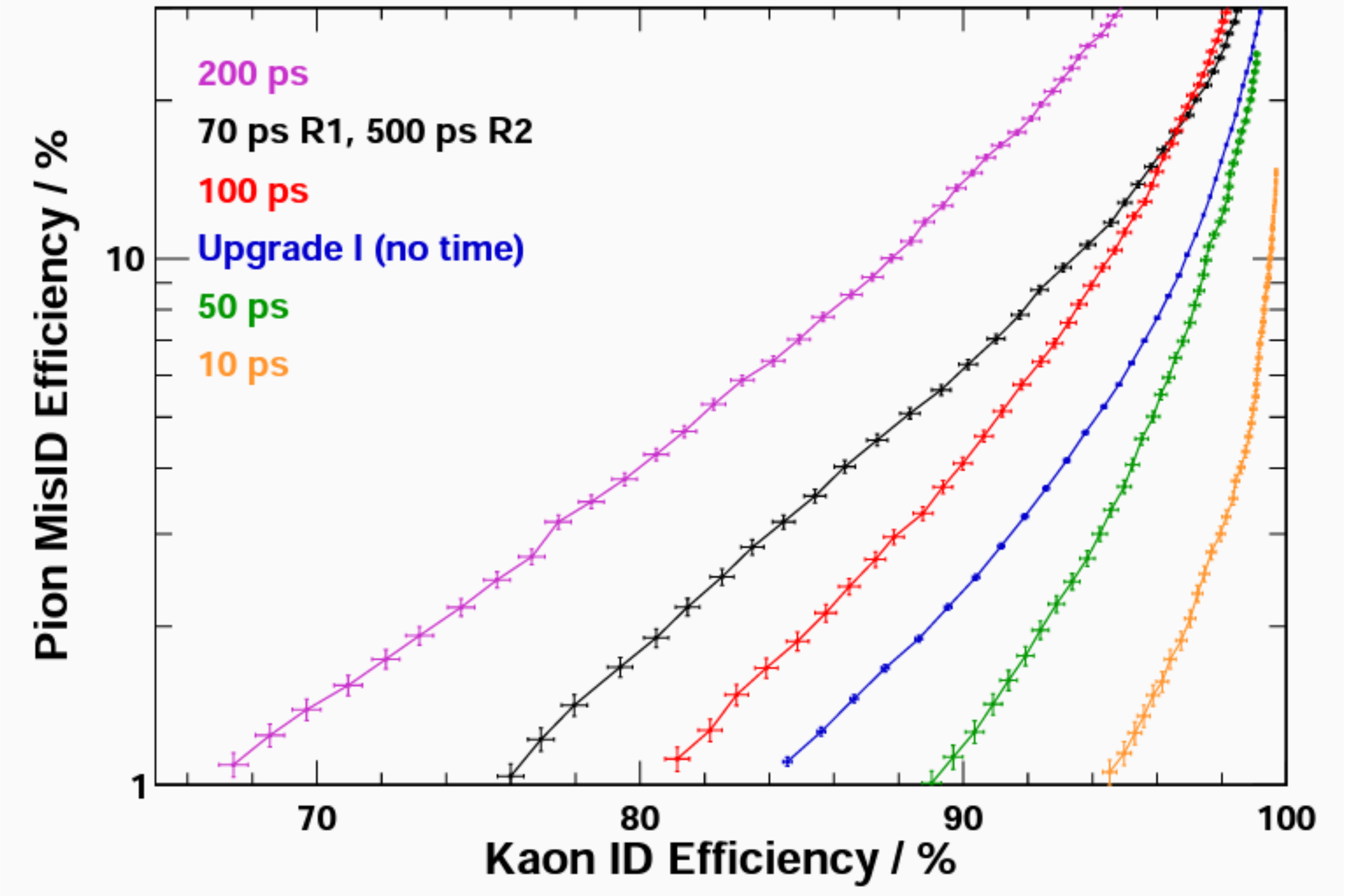
Using a **fast timing information** would allow to **improve the RICH PID performance**:

- **Nanosecond-scale time shutter** around the expected RICH detector hit time (Upgrade 1a-b)
- **10 picosecond-scale timestamp of photon hits** to be compared to the predicted time in the event reconstruction (Upgrade 2)

LHCB-TDR-023

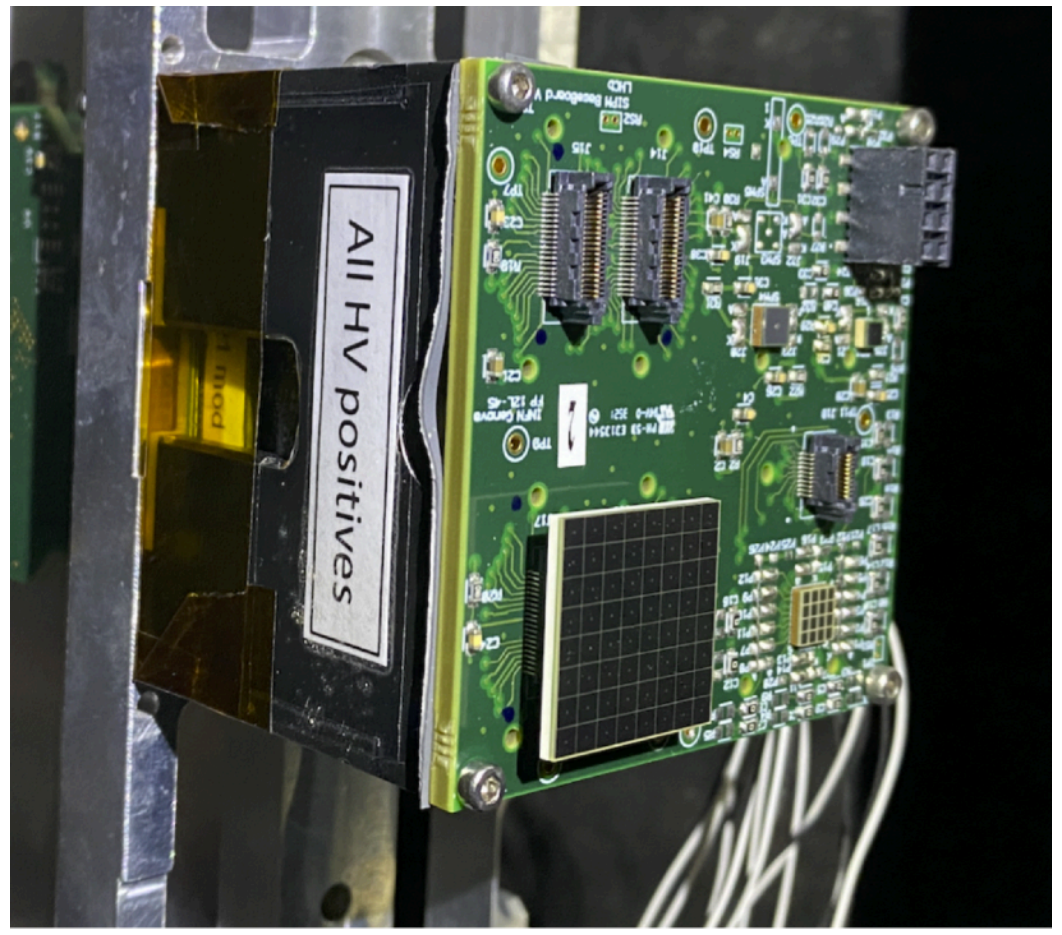


LHCB-TDR-023



Photodetectors for Upgrade 1b/2

	SiPM	MCP-PMT	MaPMT
Time resolution [ps]	100	20	200
Pixel size	<1mm	<1mm	≈3mm
Bias voltage [V]	10-70	$\approx 10^3$	$\approx 10^3$
Dark count rate	✗	✓	✓
Radiation Hardness	✗	✓	✓
Gain Aging	✓	✗	≈



SiPM

PROs
- High photon detection efficiency
- Good single photon time resolution
- Able to sustain high photon rates
- High granularity

CONs
- Radiation hardness
- High noise (dark count rates)

R&D ongoing to improve those aspects!

MCP-PMT

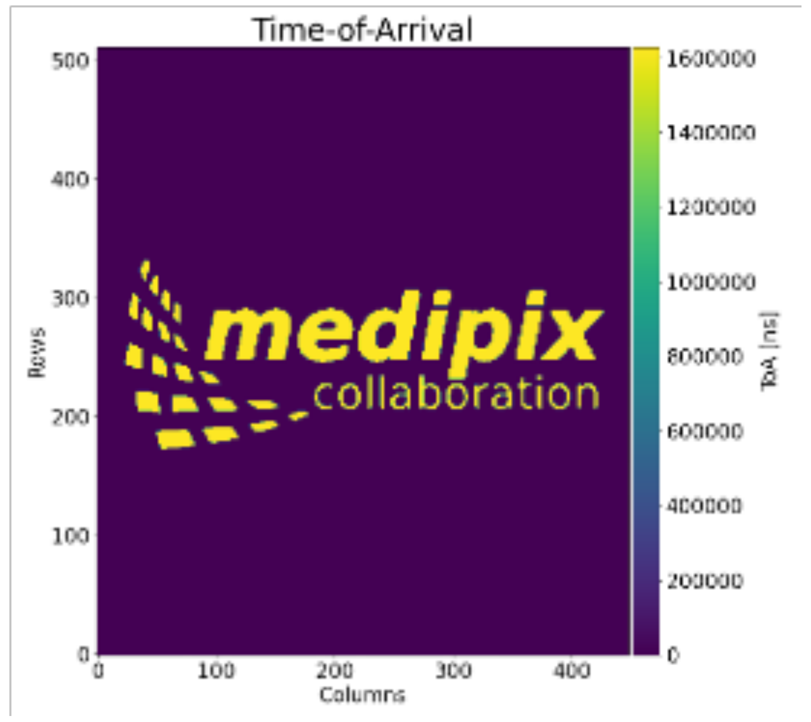
Hybrid vacuum photo-detector development:
Photocathode + MCP multiplication +
Timepix4 anode in vacuum tube

PROs
- Simultaneous excellent time and space resolution
- Low noise at room temperature
- Large active area

CONs
- High bias voltage
- Current saturation at high rates
- Ageing

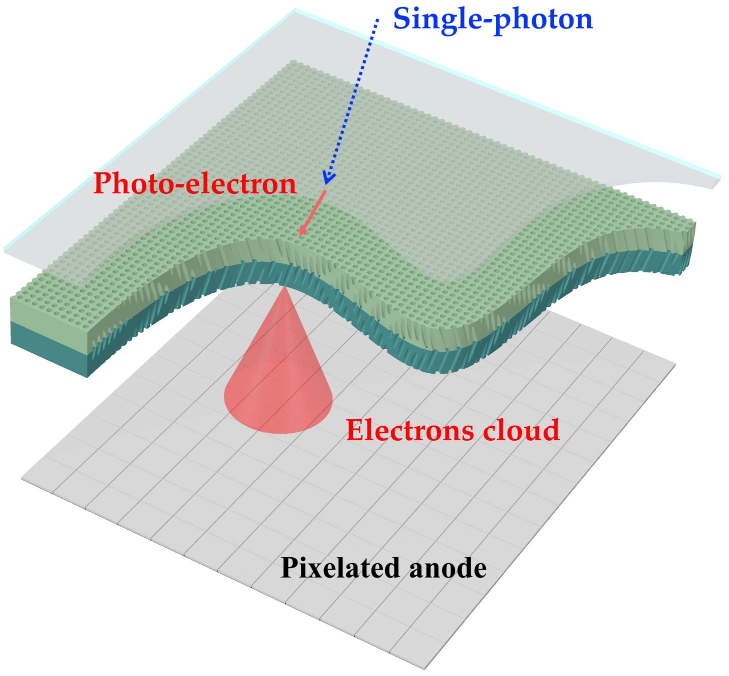
Hybrid MCP development

- Hybrid vacuum photo-detector development
  - Photocathode + MCP multiplication + Timepix4 anode in vacuum tube
  - Funded by ERC: 4DPHOTON (INFN, CERN, UniFE)
- Timepix4 ASIC productions: v0 (Q1-2020), v1 (Q4-2020), v2 (Q4-2021)
  - v2 bare ASIC extensively tested; first tests with Si sensor in summer 2022
  - ASIC, read-out electronics, software and expertise available to the INFN community (MEDIPIX4 project in CSN5)



Advantages:

- On-detector signal processing and digitization with large number of active channels (~230 k pixels), with limited number of external interconnections (~200)
- Longer lifetime due to low gain operation
- Excellent timing (<100 ps) and position (5-10 μm) resolutions
- Timing resolution and radiation hardness can be improved with next generation ASICs (e.g. PicoPix project at CERN for future VeloPix2 ASIC, 20-30 ps TDC LSB, or Timespot)



JINST 13 C12005 2018

Cons:

- Saturation at high rates and ageing for large integrated charge

IFD 2022

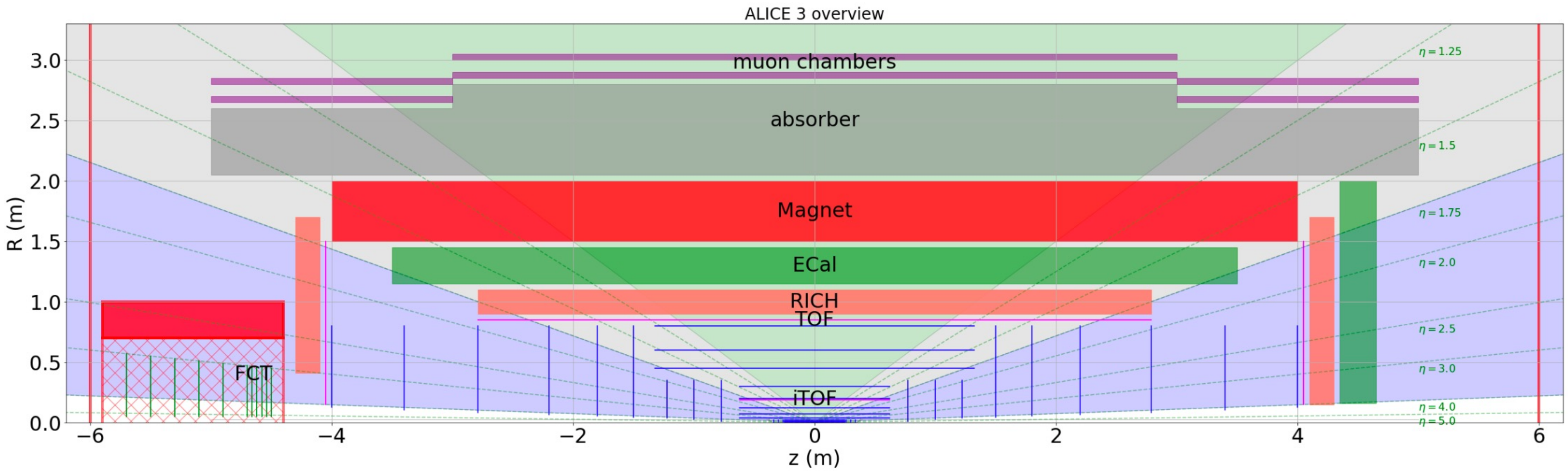
INFN Workshop on Future Detectors, 17 - 18 October 2022, Bari

SiPM studies for the ALICE 3 Aerogel RICH detector

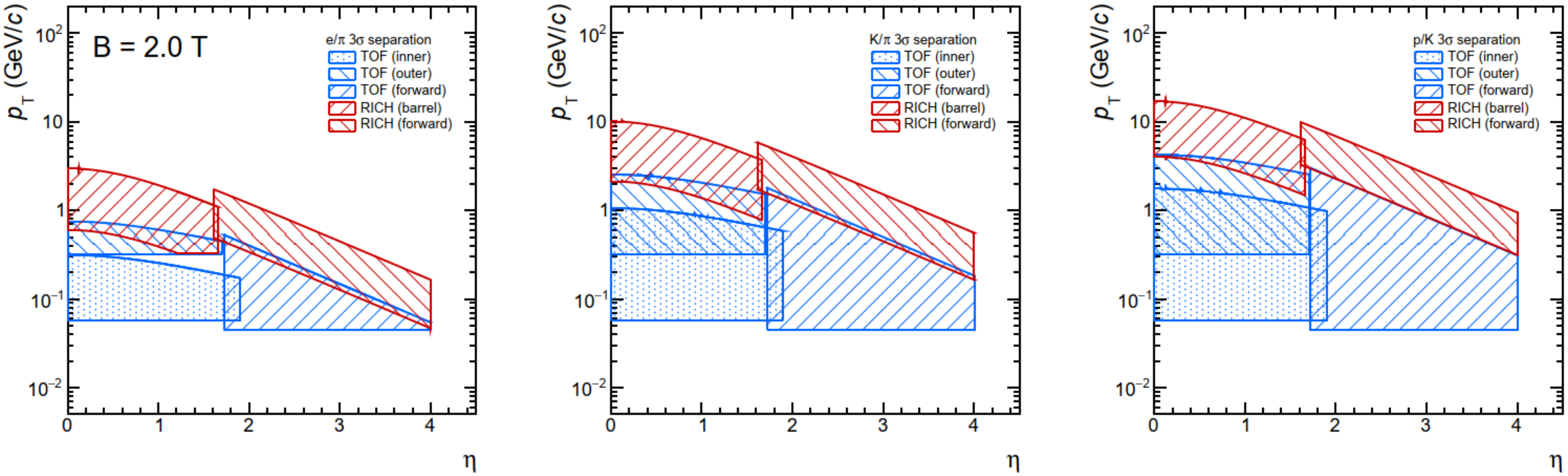
A. R. Altamura[a], D. Di Bari[b], A. Di Mauro[c], E. Nappi[a], N. Nicassio[b], G. Volpe[b]

[a]*INFN, Bari, Italy*
[b]*University and INFN, Bari, Italy*
[b]*CERN, Geneva, Switzerland*

RICH system in the ALICE 3 layout

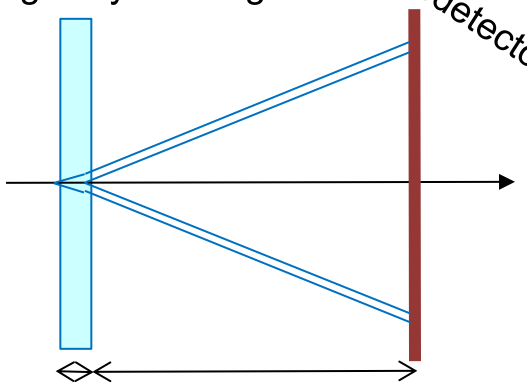


Extend electron and charged hadron ID at momenta higher than the TOF range

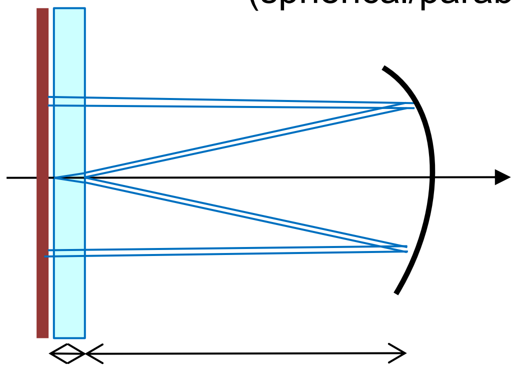


Layout options and photon detector

Baseline layout:
- No aerogel focusing
- Aerogel layer @ 0.9 m from IP
- Photodetector @ 1.1 m
- Aerogel ~ 32 m^2, p.d. ~ 39 m^2



Mirror layout:
- With or w/o aerogel focusing
- aerogel layers @ 0.95 m from IP
- photodetector @ 0.9 m
- Aerogel ~ 33 m^2, p.d. ~ 32 m^2



→ **pro's:**
- **Reduce/suppress geometric aberration** depending on mirror:
  - flat: doubling of gap
  - cylindrical: focusing in one direction + doubling of gap
  - parabolic: full focusing
- **reduce p.d. area by 60%**

→ **con's:**
- ~ 20% photon loss due to double crossing of aerogel and mirror reflection
- spherical aberration and mirror alignment to be taken into account

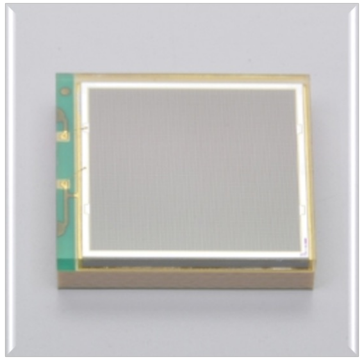
Photon detector main requirements
- Single photon sensitivity in the visible range (Photon Detection Efficiency (PDE) > 40-50%)
- Integration fill factor > 90%
- Pixel ~ 3x3 mm^2
- Time resolution σ < ~ 100 ps
- Magnetic field B ≤ 2 T
- Expected radiation load: NIEL ~ 10^{12} 1-MeV n_{eq} /cm^2

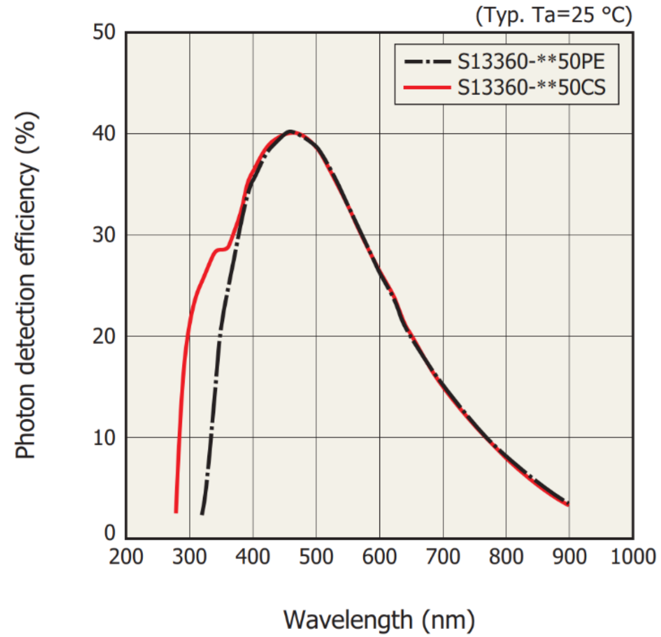
The photon detector

Significant enhancement on the semiconductor process over past decades, excellent improvement of CMOS SPAD performance → renewed interest for the **development of digital-SiPM** for large area coverage in HEP applications (e.g.: development ongoing in Sherbrooke University and FBK)

- **R&D on digital SiPM based on CMOS Imaging technology**
  - Reduce cost
  - Explore solutions for:
    - noise performance improvement (beyond online/offline time gate)
    - radiation hardness improvement (1-2 orders of magnitude, 10^{12} 1-MeV n_{eq} /cm^2 required)
    - TOF applications (MIPs detection with time resolution ~ 20 ps)

- **Backup option: commercial SiPM**
  - Example: SiPM HPK 13360 3050CS
  - 3x3 mm^2 pixel (3600 SPADs with 50 μm pitch)
  - Dark count rate (DCR) ~ 50 kHz/mm^2
  - 50 ps time resolution
  - Above 10^{11} 1-MeV n_{eq} /cm^2 → DCR increasing

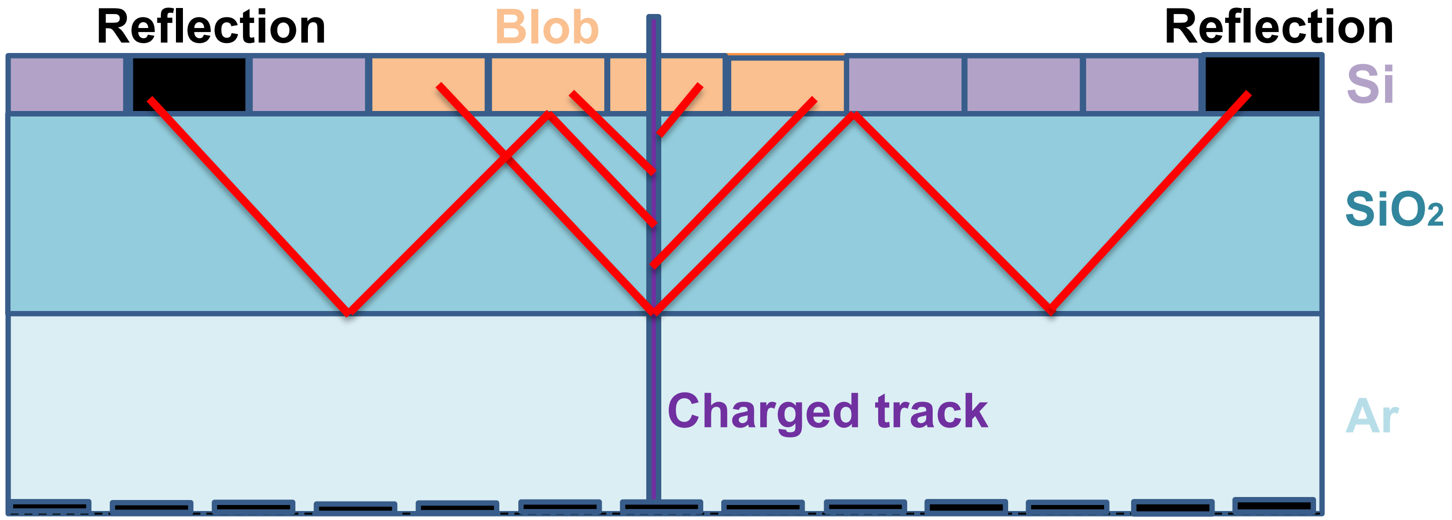




A step forward: Cherenkov-based TOF system

Reflection background

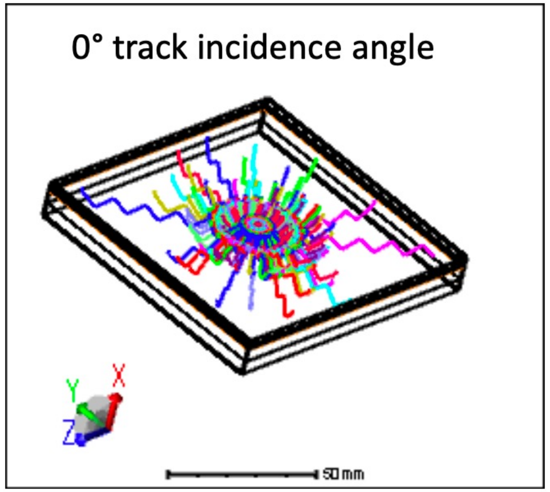
About 30% of photons reflected at SiO_2 - Si
Total reflection at SiO_2 - Ar

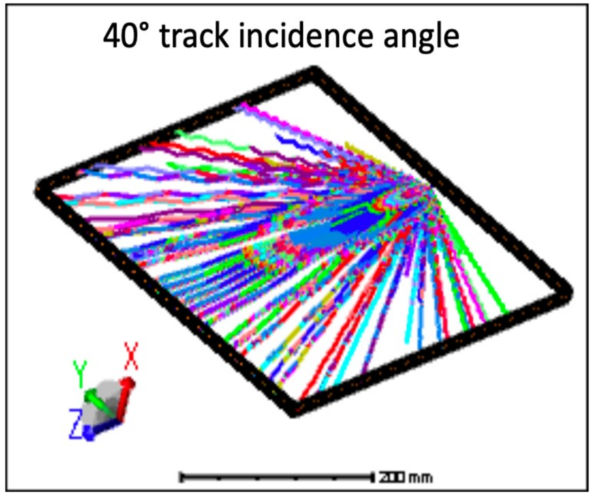


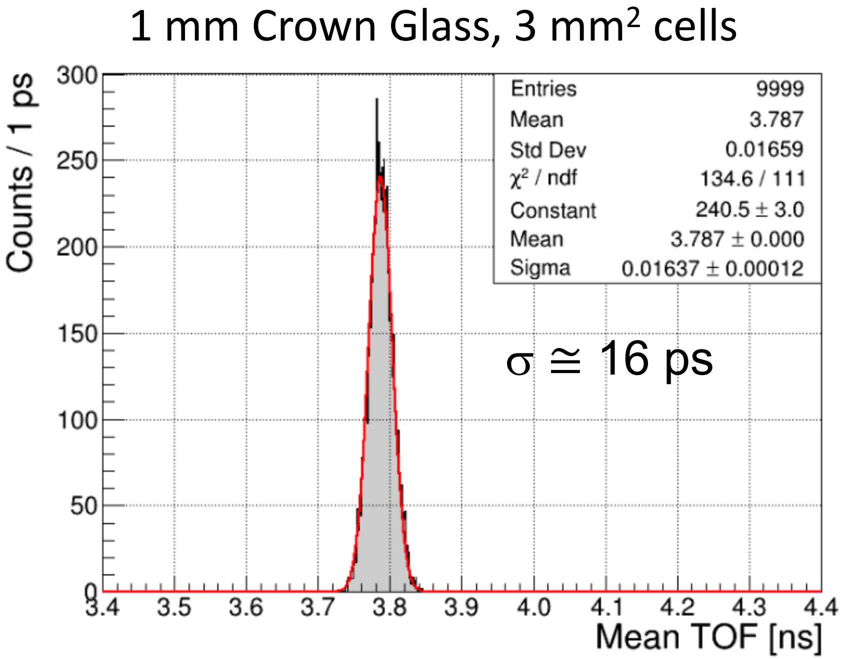
Track time resolution

Determined by single photon resolution and blob size

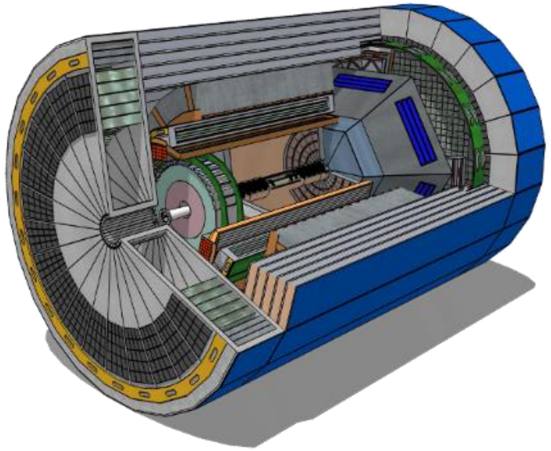
$$\sigma_{\theta_t}^{trk} = \frac{\sigma_t^{\gamma}}{\sqrt{N_{blob}}}$$

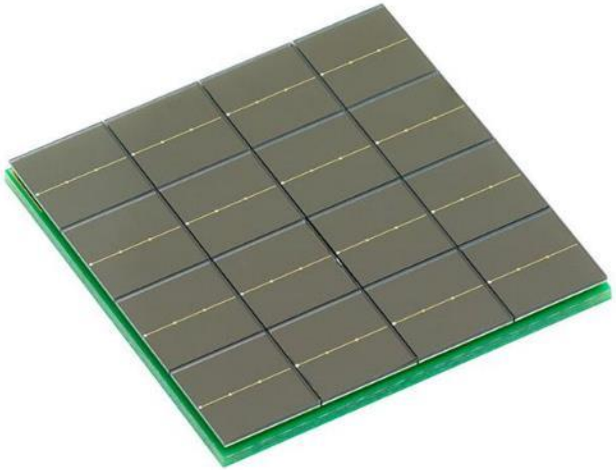






A SiPM-based optical readout system for the EIC dual-radiator RICH





R&D on SiPM as potential photodector for dRich

Luigi Rignanese rignanes@bo.infn.it

The EIC

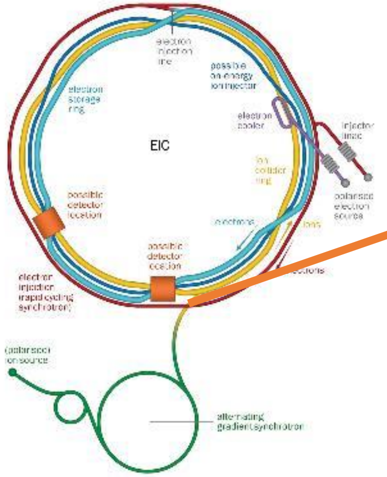
The **E**lectron **I**on **C**ollider (**EIC**) will be a large-scale innovative **particle accelerator** planned to be built at **Brookhaven National Laboratories** in Long Island, New York (**U.S.A**.). Constitutes the **major project** in the **nuclear physics** field.

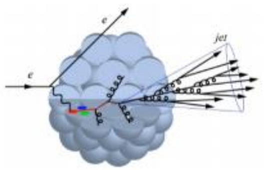
Highly **polarized electrons** collide with **protons** and **nuclei** providing access to those regions in the nucleon and nuclei where their structure is dominated by gluons.
Polarized beams in the **EIC** will give unprecedented access to the **spatial** and **spin structure** of the **proton**, **neutron**, and **light ions**

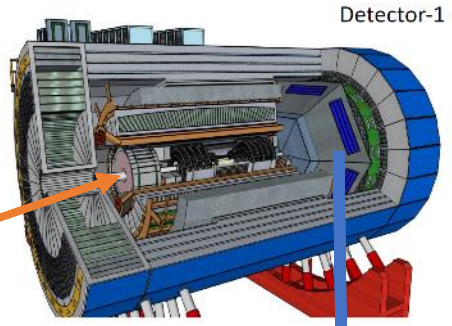
The **EIC** covers a **center-of-mass** energy range for **e+p** collisions of **√s** of **20** to **140 GeV**
The **first beam** operations are expected to start in the **early 2030s**.

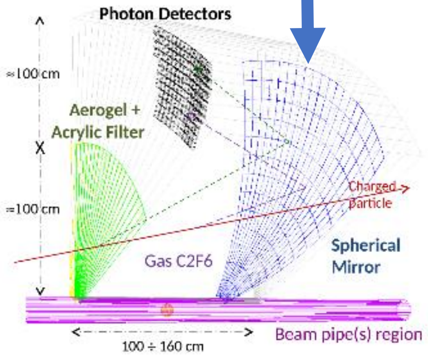
The EIC detectors are in the interaction regions where space is constrained due to the requirements of high luminosity and will have:

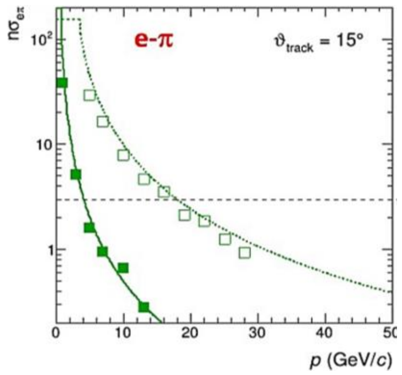
- Tracking and Vertexing Detector Systems
- **Particle Identification Detector Systems**
- Calorimeter Detector Systems











A dual-radiator (**dRICH**) is in charge for the forward **P**article **Id**entification **PID.**
It is c compact and cost-effective solution for continuous momentum coverage (3-60 GeV/c).
It shows interesting capability in the elcttron-pion separation.

Radiators are made in aerogel (n ~ 1.02) and C2F6 (n ~ 1.0008).

Mirrors: large outward-reflecting, 6 open sectors.

The Photon Detectors is made by 3x3 mm^2 **SiPMs** arranged in **six** 0.5 m^2 / sector for a total of **3 m^2** surface (~ 300 k channels). The SiPM technology allows **single-photon** detection inside high B field (~ 1 T). SiPMs have **fast time resolution** but there are consideration on **dark noise** and **radiation hardness**.

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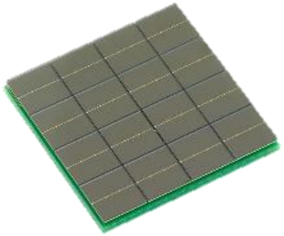
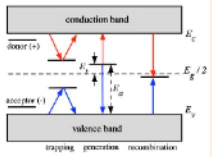
SiPMs are a valuable option for the **dRICH** optical readout:

- **Cheap**
- Low voltage operation
- **Excellent time resolution**
- Single photon detection
- **Insensitive to magnetic field**
- High spatial resolution
- **High noise as Dark Count (DCR)**
- **Prone to radiation damage (10^{11} n_{eq}/cm^2)**

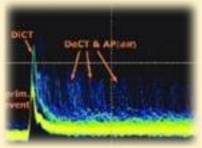


DCR is reduced by a factor 40 every 30° C of temperature reduction. The dRICH SiPMs will be operated at **-30° C.**



Radiation damage is produced by Non-ionizing Energy Loss (**NIEL**) leading to **displacement** damages and build up of **crystal defects** that results in:

- Increased **DCR**
- Increased **After Pulses**
- Change in **charge collection**

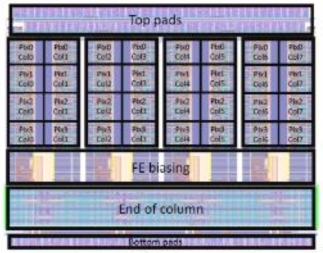


Performance can be recovered by using **annealing techniques**. High temperature re-order out-of-lattice atoms to their former positions reconvening performance
https://arxiv.org/pdf/1805.07154.pdf,
https://www.osti.gov/pages/servlets/purl/1477958,
https://ieeexplore.ieee.org/document/9059772,
https://arxiv.org/abs/1804.09792

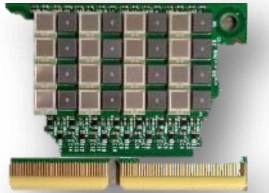
3x3 mm² SiPMs from different vendors and with different cell sizes are mounted in matrixes were studied to evaluate their performance after irradiation and annealing.

Vendor	Version	Cell size (μm)	V_{BD} (V)	DCR (kHz/mm²)
Hamamatsu	S13360-3050VS	50	53	55
Hamamatsu	S13360-3025VS	25	53	44
Hamamatsu	S14160-3050HS	50	38	160
Hamamatsu	S14160-3015PS	15	38	78
FBK	NUV-HD-CHK	40	31	50
FBK	NUV-HD-RH	15	31	40

FBK matrix



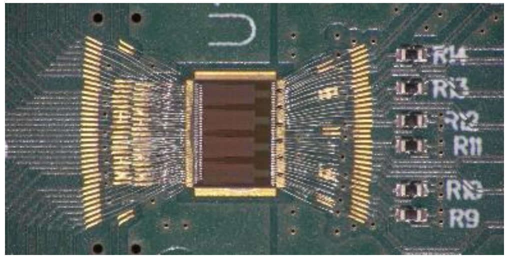
ALCOR scheme



Hamamatsu matrix

The **ALCOR-ASIC** (developed by INFN-TO) is a **32-pixel** matrix mixed signal with a dual polarity **frontend** for **amplification** and **conditioning.**

Each pixel features
- dual-polarity front-end amplifier
- 2 leading-edge discriminators
- 4 TDCs based on analogue interpolation



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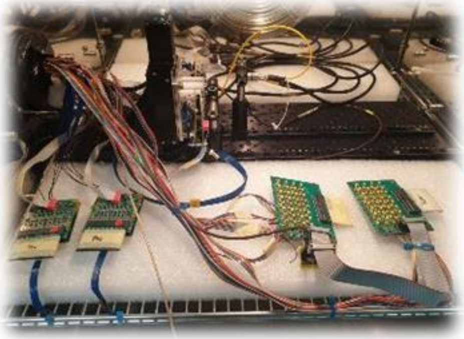
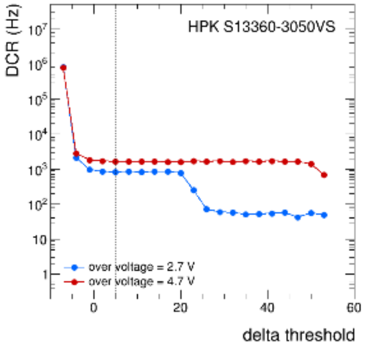
INFN

To mimic the **operative conditions**, sensors are tested in a **climatic chamber** at **-30° C**.
3 different automated measures are performed in parallel on the matrixes:
- Dark Count Rates (**DCR**)
- Current over Voltage curves (**IV**)
- Light response (**PDE**)

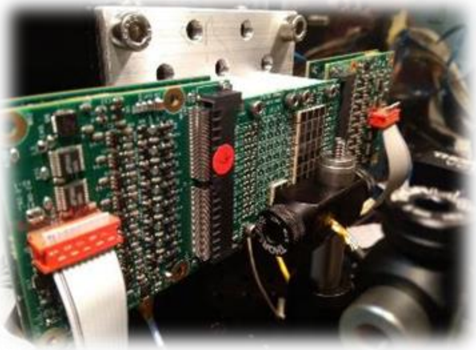


Test set-up

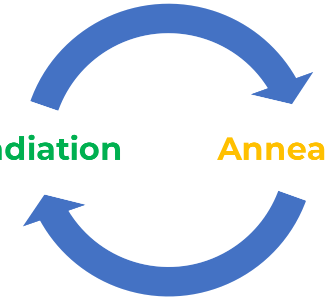


DCR is measured by the full dressed **ALCOR redout**. The ASIC streams **TDC** hits to an **FPGA** through a LVDS. **Threshold** and bias **voltage scan** are used to automatically compute the threshold level and the bias voltage.
IV curves are measured by a Keithley 2450 **SMU** and a **multiplexer** (up to ***64 SiPMs***) to measure the **Dark Current.**

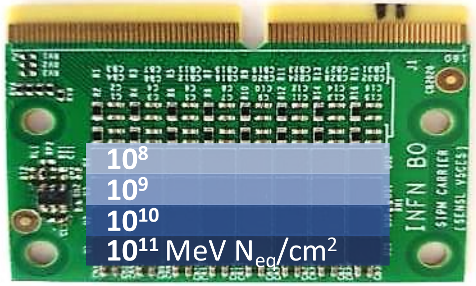
For the PDE, a sensor's matrix is mounted on a 2-axis stage. The fixed **LED** source (λ = 570 nm) is powered with a pulser at **1 MHz** for **50 ns**. The number of **counts** measured in **coincidence** with the pulser is compared to the same measure of a **reference sensor** to evaluate **losses** in the **PDE** after the **irradiation/annealing**



Trento Institute for Fundamental Physics and Applications



Detectors are **characterized before** and **after** the **irradiation** at **TIFPA**.
Irradiation at **INFN TIFPA** facility in Trento with **148 Mev protons**.
Differential approach to test **different levels** of damage (**10^8-10^{11} n_{eq}/cm^2**).
After the **annealing** they are **characterized** again.



The **annealing** is performed in a **temperature-controlled oven** at **150°** C for **200 hours** in Ferrara.

More than **150 SiPMs** undertook this **cycle**.

Current annealing
If directly polarized, **current** flows into the **SiPM**, **heat** is generated and contributes to the **annealing**. For a small sample of devices, a new method of direct current annealing is tested @**175°** C for **2.5 hours**.

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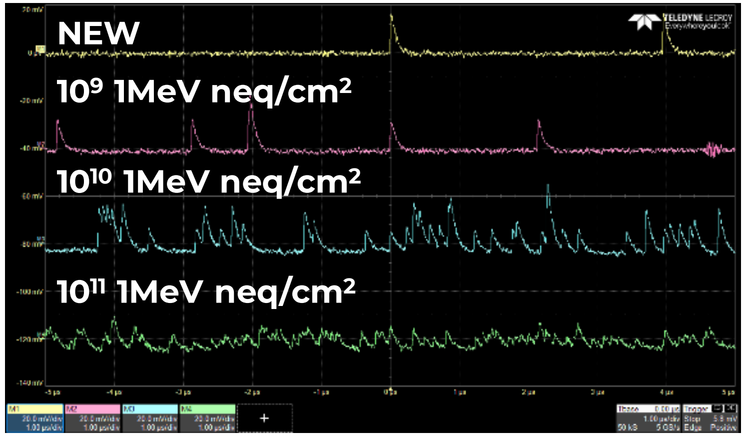
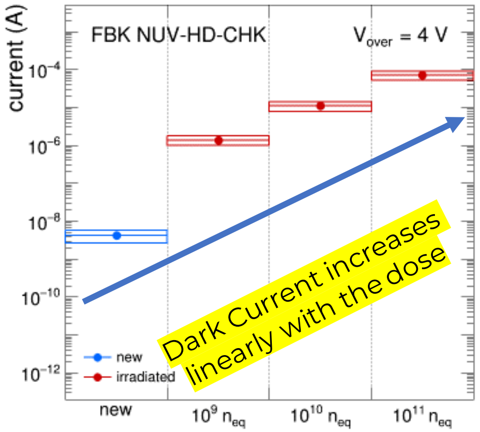
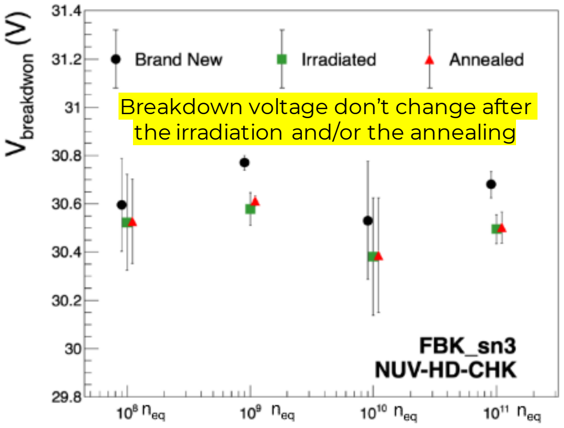
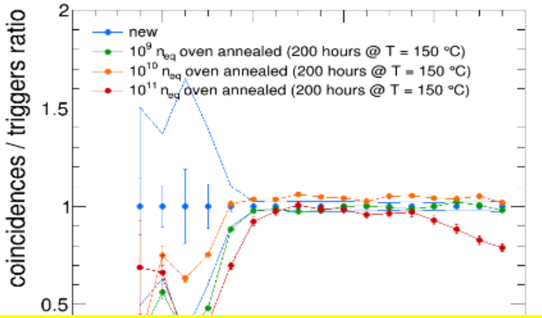
Results



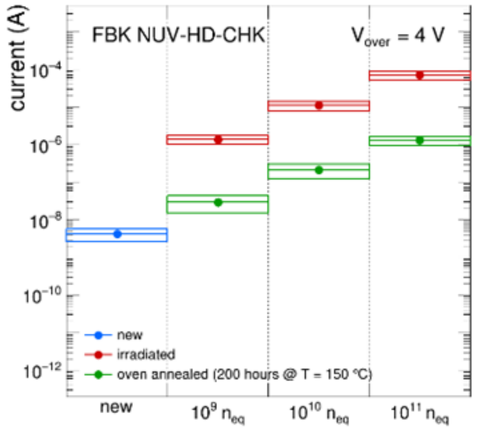




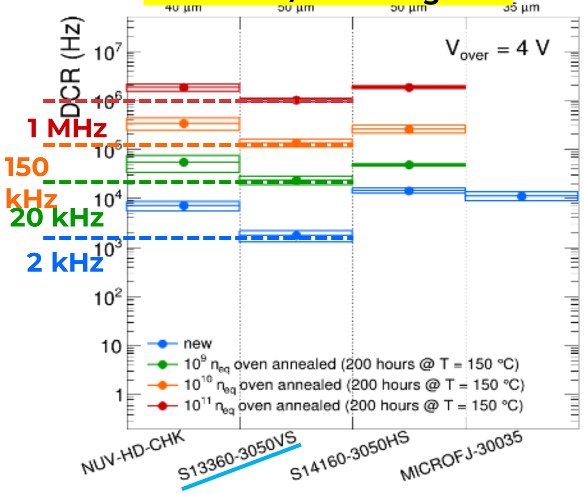


Up to 10^{10} n_{eq} there are **no damage** to the **optical window** or in the **photon-ions conversion**.
At 10^{11} n_{eq} saturation in ALCOR

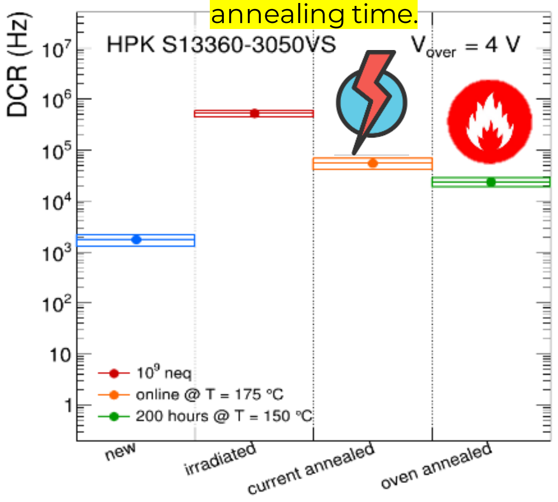
200 hours @ 150°C oven annealing reduces the **dark current** by a factor **≈100**.



Hamamatsu S13360-3050 shows **less DCR** at **any irradiation/annealing level**



DCR decreases with current annealing without reaching the oven but in **1/10** of the annealing time.



Conclusions and what's next

SiPMs show to be a good candidate for photon detection in the dRich for EIC.

HPK series **13** seems to cope with radiation damage up to 10^{11} n_{eq}/cm^2 thanks to the **annealing**.
Direct current annealing allows **in-situ DCR** induced by radiation damage reduction.

Neutrons irradiation run at **LENA**.
3x3cm 256 SiPMs matrix with **ALCOR** readout and **active** liquid cooling.

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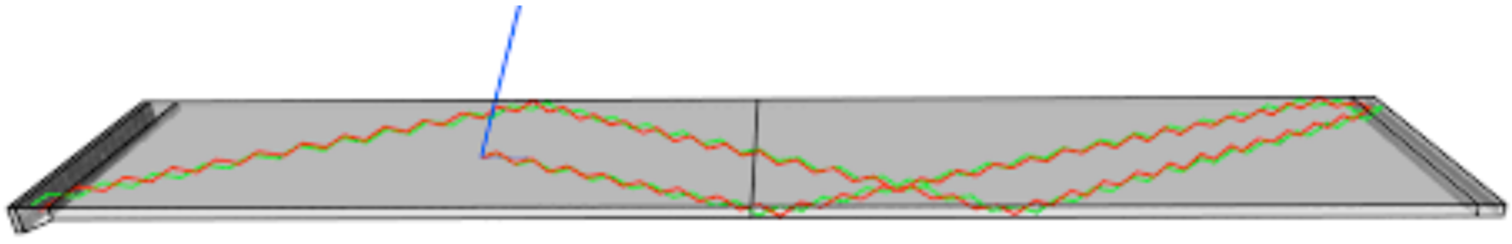
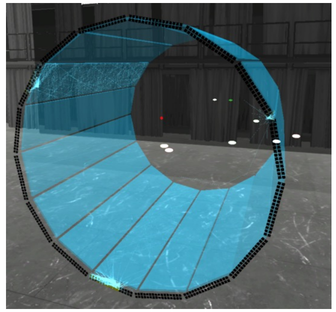
SiPM development for the TOP detector upgrade of the Belle II experiment

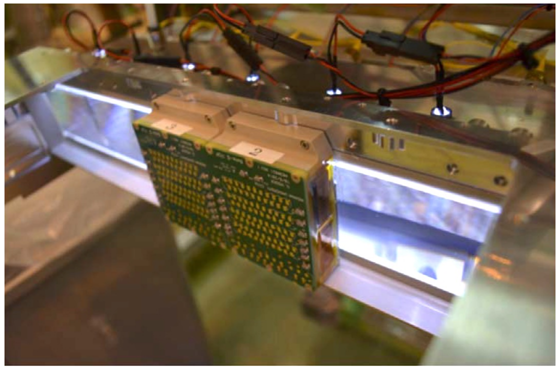
Flavio Dal Corso[a], Roberto Stroili[a,b], Ezio Torassa[a]
INFN Padova[a], Univ. Padova[b]

The **T**ime **O**f **P**ropagation is the particle identification detector in the barrel region of the Belle II experiment
The detector uses quartz bars acting as Cherenkov radiators and MCP-PMTs as photodetectos.





For every TOP module 32 MCP-PMTs 16ch 1 in^2 are optically coupled to the prism

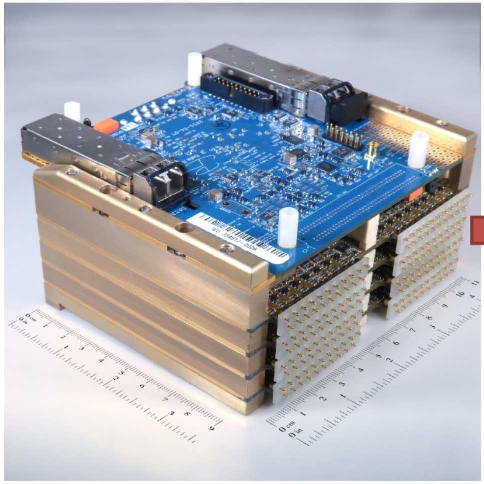


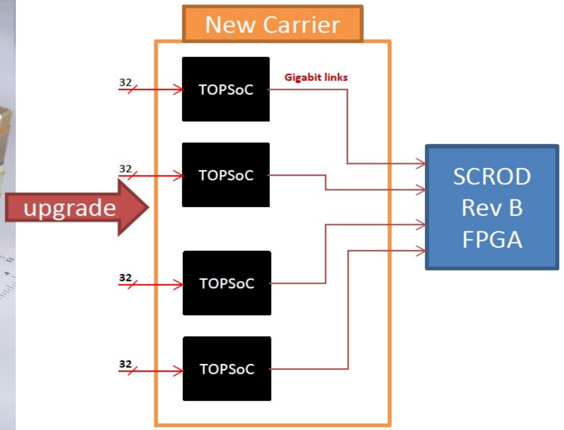
Three generations of MCP-PMT are currently installed in the TOP detector. Long shutdowns of the SuperKEKB accelerator in 2023 and 2027 will be used to upgrade the detector with the last generation of MCP-PMT.

Many improvements in SiPM production technology have been achieved in the last years. Using SiPM as a photodetector is the backup plan for the 2027 upgrade and the primary option for following upgrades with higher luminosity and higher background.

Electronics upgrade

Replacement of MCP-PMT with SiPM will require to upgrade the electronics.



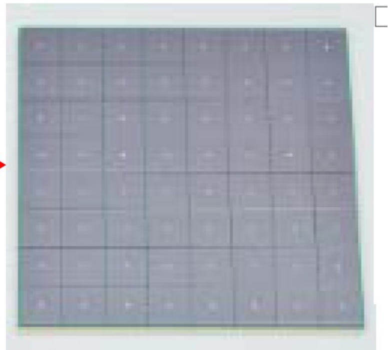


IRSX **ASIC 8-channel** 250 nm CMOS will be replaced with TOPSoC **ASIC 32-channel** 130 nm CMOS.

The total number of channels will be increased from 8192 to 32768. Developments of new boards are ongoing at the University of Hawaii

MCP-PMT
16 ch, 1 in^2

MPPC (SiPM array)
64 ch 3x3 mm^2



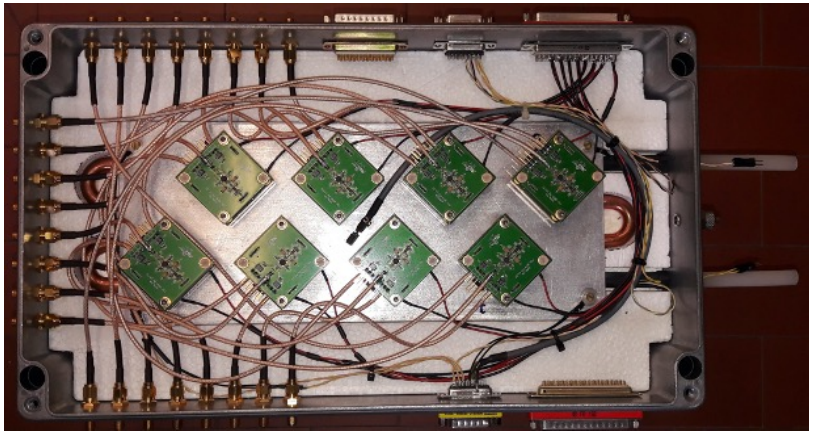
SiPMs compared to MCP-PMTs have higher dark count rate (DCR).

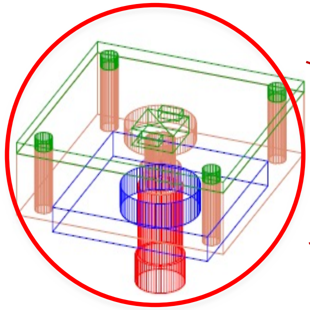
Radiation damages will increase DCR, the effect can be mitigated by lowering the temperature.

SiPM test in Padova: setup

Tests are ongoing in Padova to measure the characteristics of the SiPMs in the market 1) for different temperatures 2) before and after irradiation.

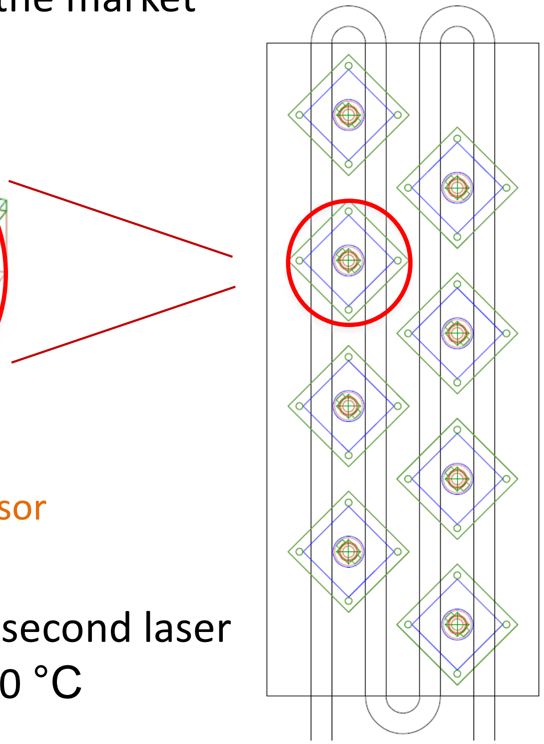
Dark box with SiPM blocks





PCB Amplifier
PCB SiPM with T sensor
PCB peltier

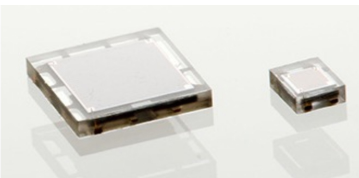
SiPMs illuminated with picosecond laser
T from +20 °C to -50 °C



Cooling plate (glycolate water)

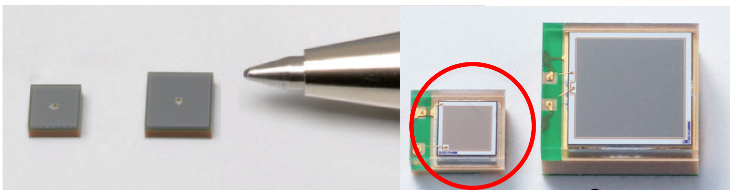
Available SiPMs to be tested

OnSemi (35μm)



1x1 - 3x3 mm^2

Hamamatsu (15-25-50 μm)

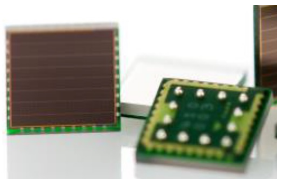


1.3x1.3 - 3x3 mm^2

FBK (15μm)

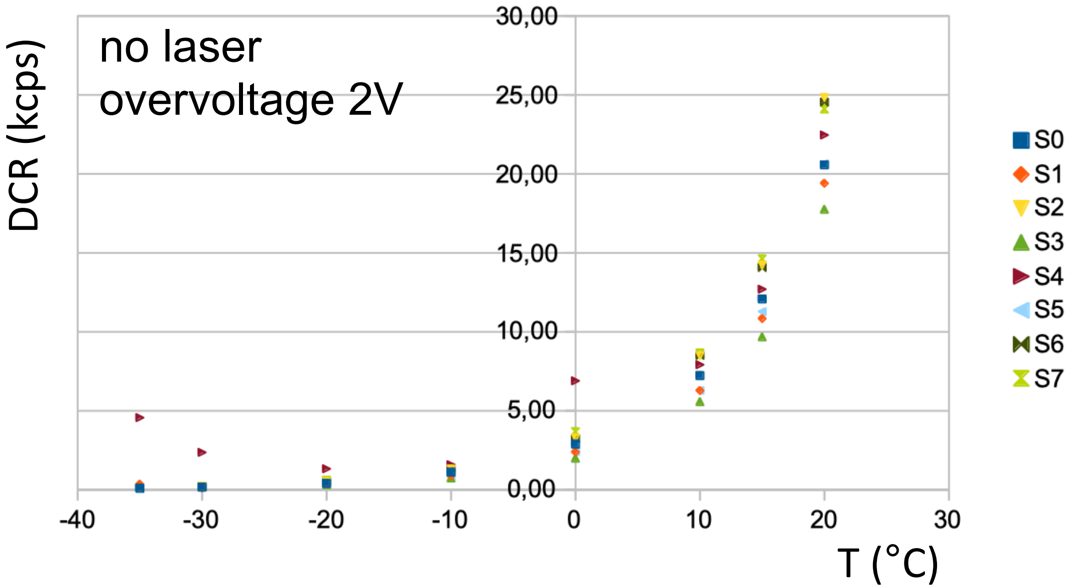
1x1 - 3x3 mm^2

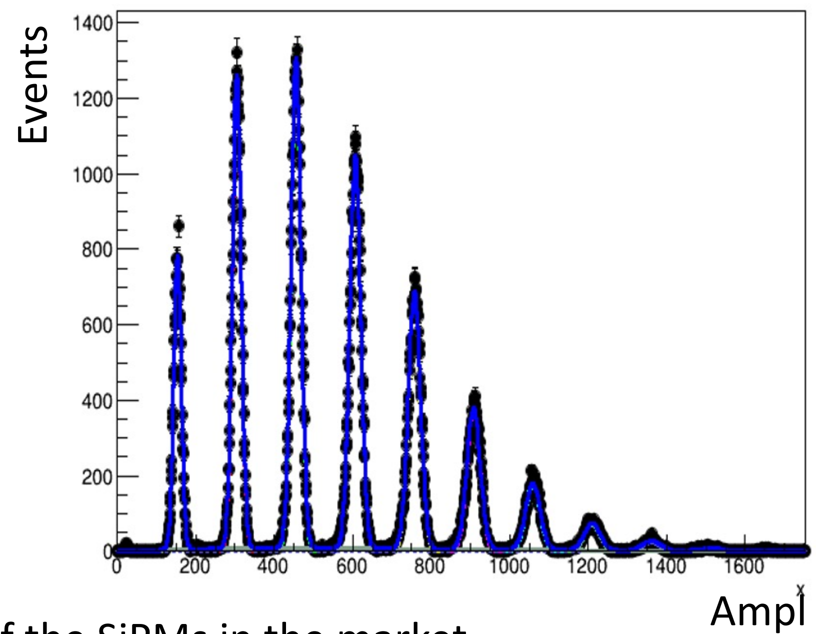
Ketek (15-35 μm)



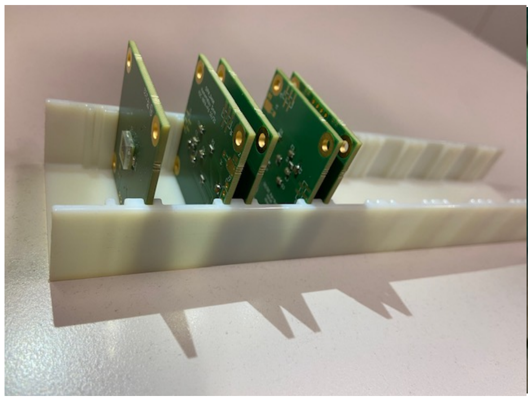
3x3 mm^2

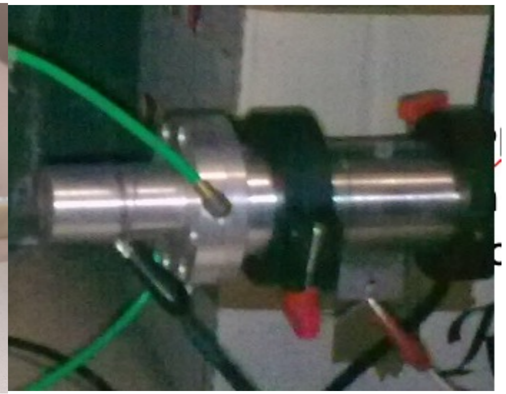
SiPM test in Padova: first results





Tests are ongoing in Padova to measure the characteristics of the SiPMs in the market
1) for different temperatures 2) before and after irradiation.





In November 2022 SiPMs will be irradiated at the LNL CN neutron beam facility with neutron fluxes from $1x10^{+09}$ to $5x10^{+11}$ neutrons/cm^2

SiPM development in collaboration with FBK is inside the AIDAinnova project in the framework of WP 8 task 8.4.1.

Nuova Officina Assergi

INFN LNGS

a new reality for novel SiPM-based detector production

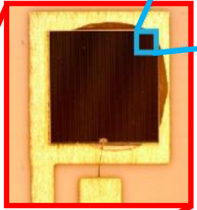
Lucia Consiglio
INFN LNGS

New SiPM technology for light detection

Why SiPMs?

- Higher Photon Detection Efficiency
- Higher fill factor
- Operated with low bias
- Lower cost

1cm^2



SPAD: single photon avalanche diode 30 μm pitch

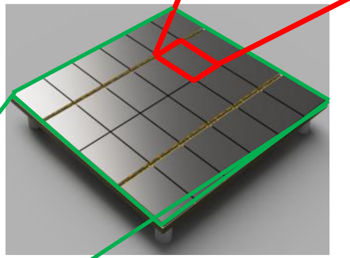
94 900 SPADs

Challanges

- Large area cryogenic SiPMs
- Low noise cryogenic electronics
- Technological transfer for photosensor massive production

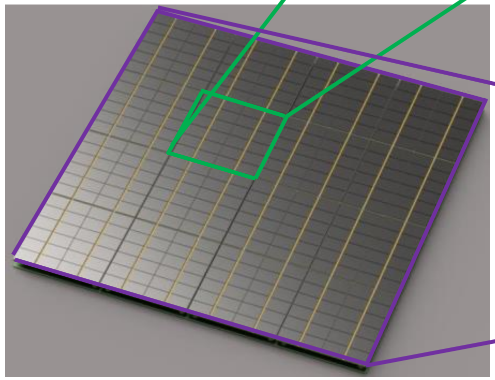
Tile: 24 SiPM array integrated with signal preamplifier

Photo Detection Module (PDM)



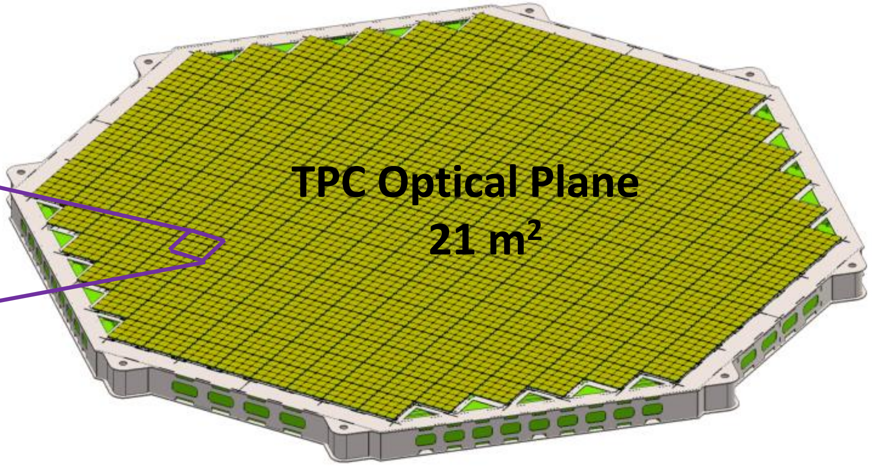
5 x 5 cm^2

Photo Detection Unit (PDU)



20 x 20 cm^2

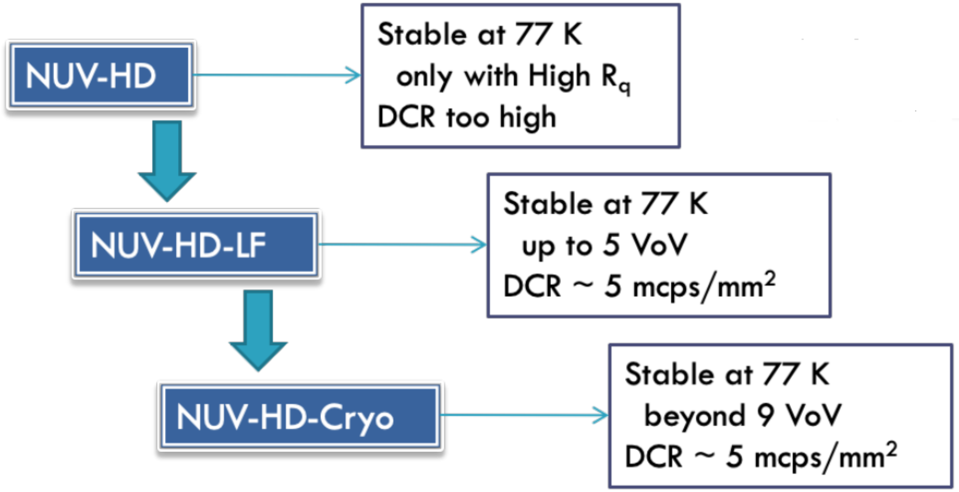
16 tiles ->4 readout channels

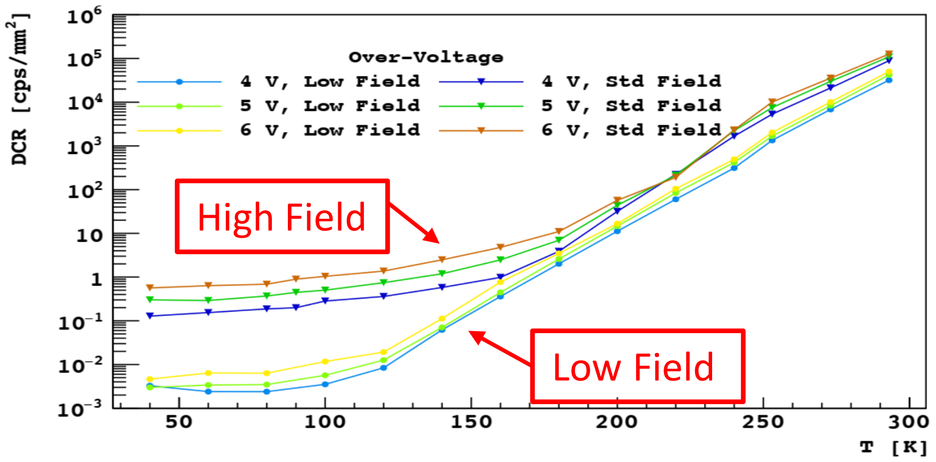


DarkSide-20k top and bottom planes equipped with 528 PDUs

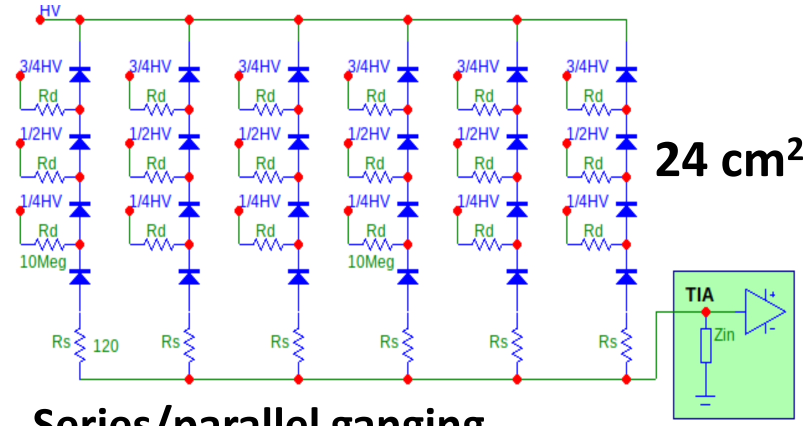
STEP 1
SiPM development

Custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK)





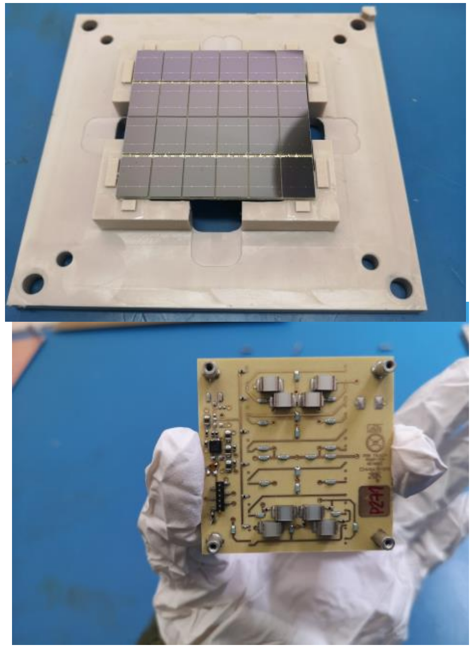
STEP 2
Electronics design



Series/parallel ganging
Reduce Cin@TIA and preserve BW

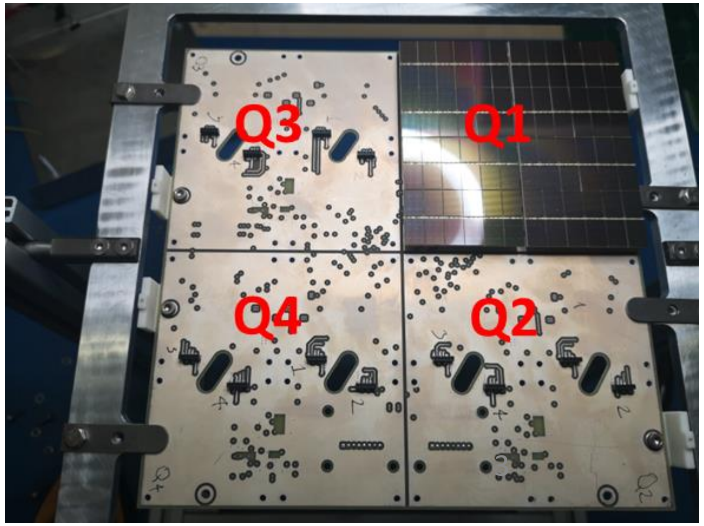
SiPM = current generator + huge output capacitance (~60pF/mm^2)
Transimpedance amplifier (TIA)
High Bandwidth and Low Noise

4 PDMs readout as a single analog channel



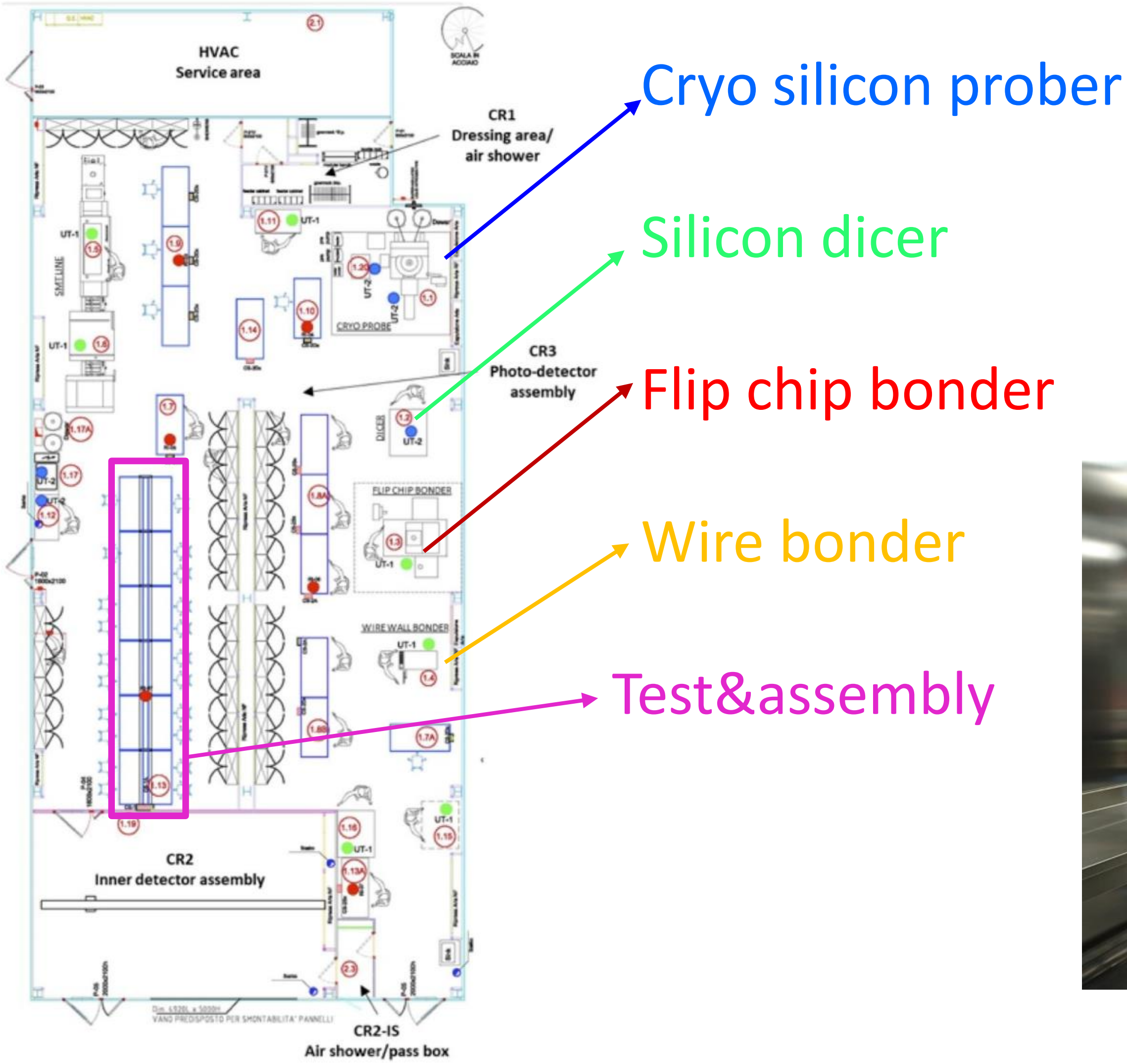
TILE + 1 TIA

Photo Detection Module (PDM)



STEP 3 NOA clean room

420 m^2 clean area in LNGS (PON/RESTART Regione Abruzzo) for packaging, test and assembly of SiPM-based detectors



- Cryoprobe installed and wafer test started.
- Flip chip bonder final installation foreseen by November 2022

Milestones & perspectives in NOA

- A unique infrastructure enhancing the high-tech capability INFN LNGS
- Support for integration of large arrays of radiopure SiPM-based photodetectors
- Start up operations in the beginning of 2023

DarkSide-20k PDU assembly (2023-2025)

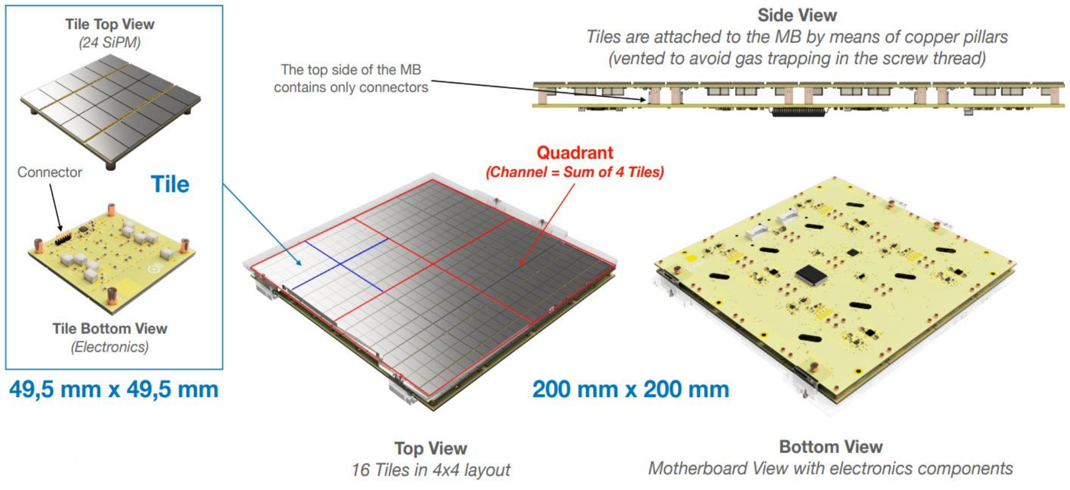
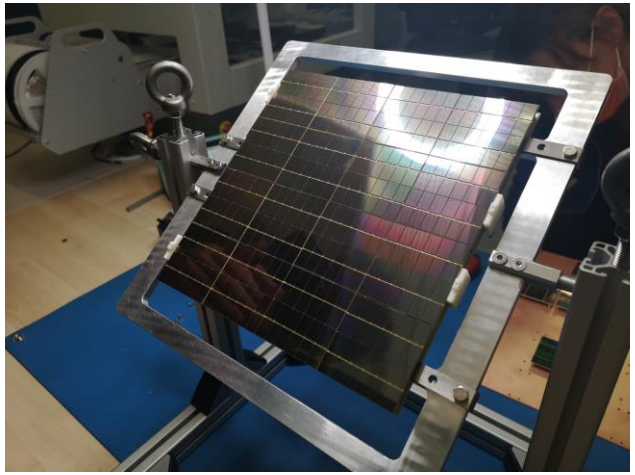


Photo Detection Unit prototype



What's Next?

- Production and test of photo-detectors for low background experiments.
- Start a network of collaborations to share laboratories and infrastructures

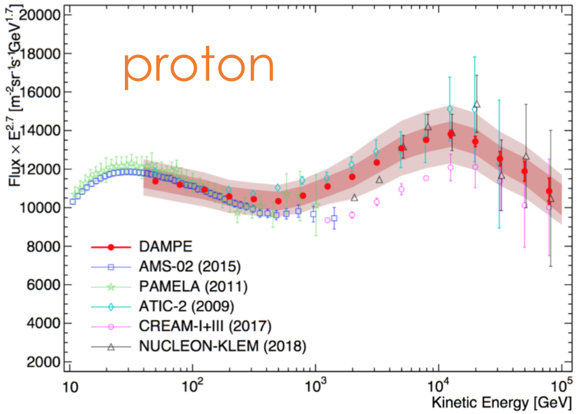
Particle Identification in Space Experiments with Scintillator Detectors

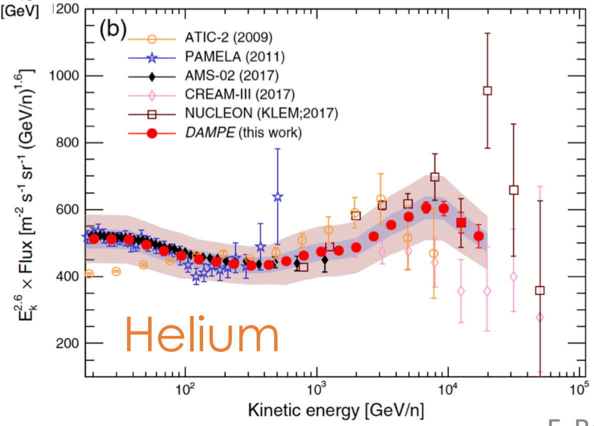
Felicia Barbato

Charge Identification of cosmic rays

Motivation

Identify cosmic rays species to measure the flux and address origin, acceleration and propagation problem





Principle of operation

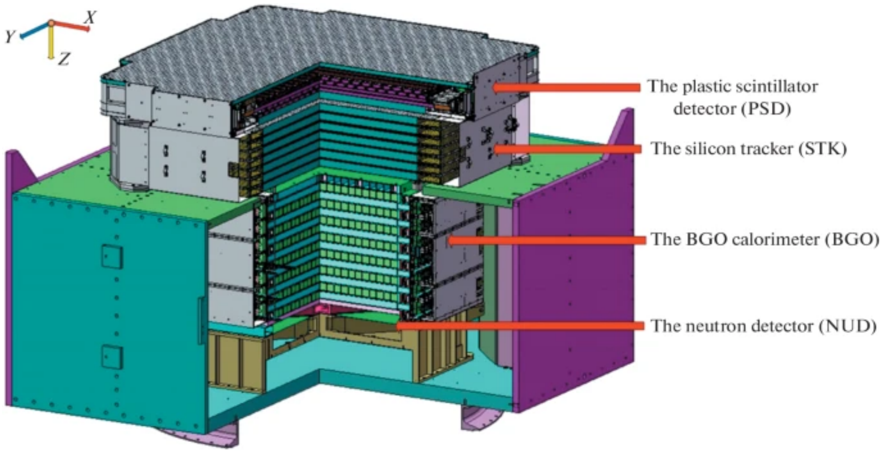
$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

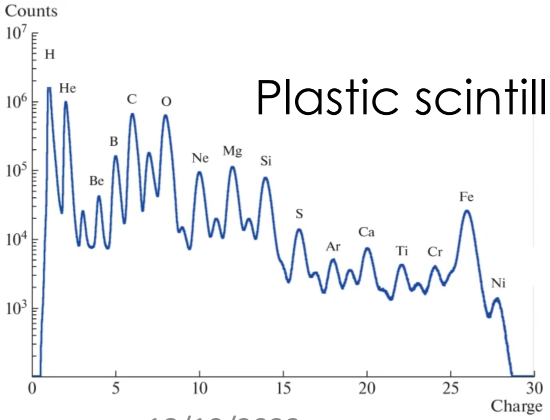
Bethe Bloch formula

Ionization energy loss of charged particles

Plastic Scintillator Detector

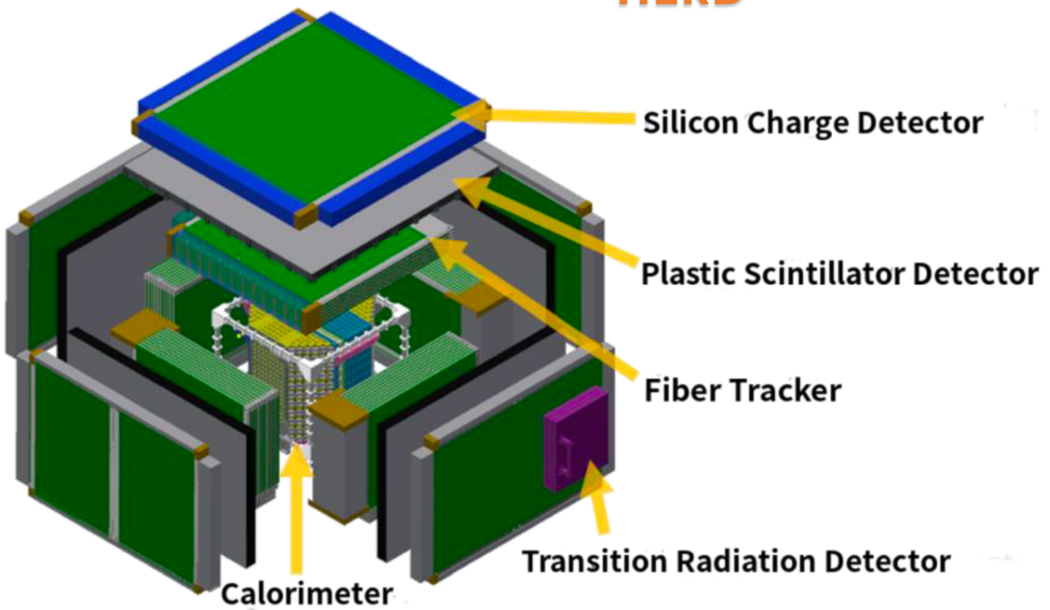
DAMPE

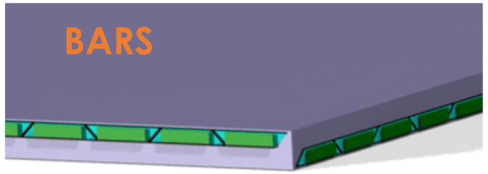




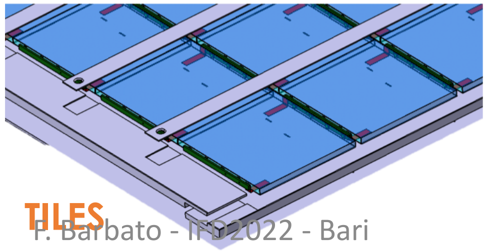
Plastic scintillator bars + PMTs

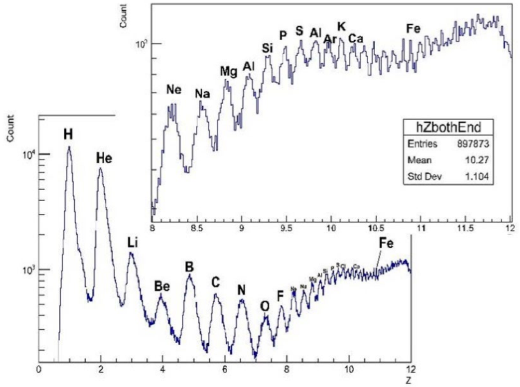
HERD



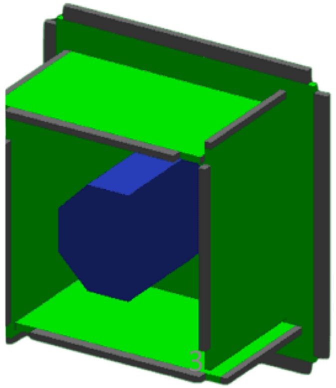


Plastic scintillator + SiPM



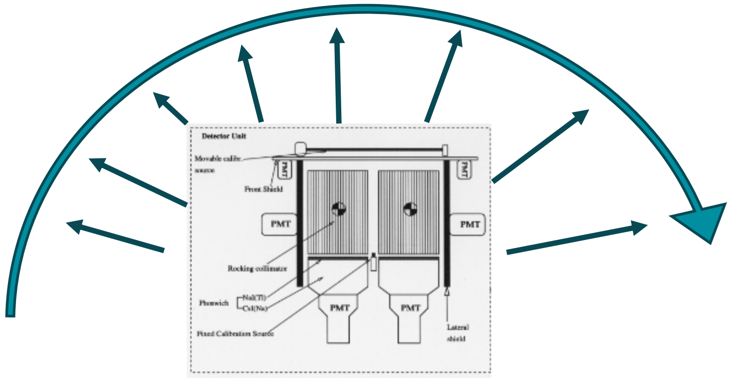


High hermeticity



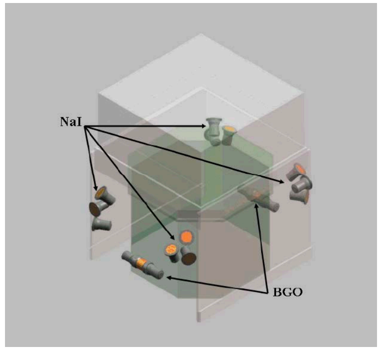
Gamma-ray identification

Beppo-Sax



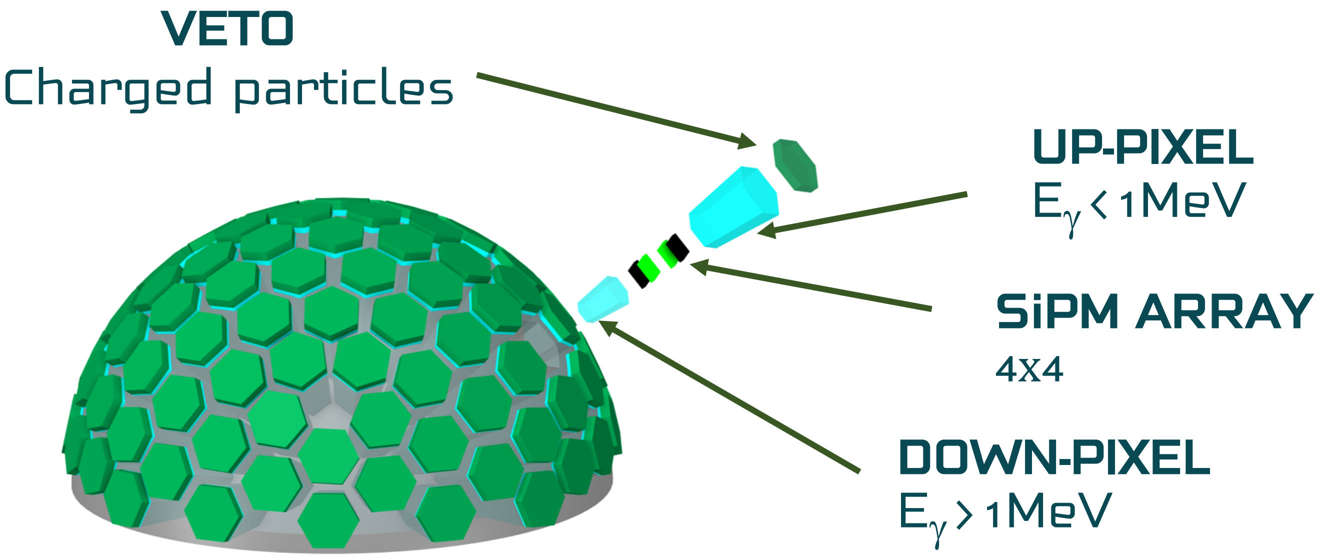
- Phoswich technique with collimators
- Orientable mechanics
- One module

Fermi-GBM

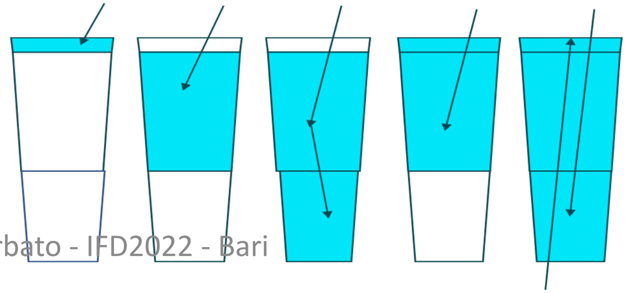


- Triangulation over 12 pixel (ø 12.7 cm)
- Different orientation
- One module

Crystal Eye

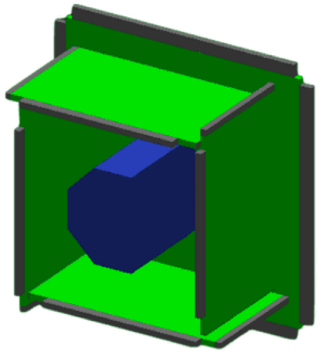


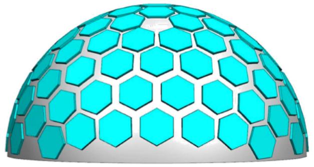
- Charge distribution over 112 pixel (ø ~ 5cm)
- Compact photosensors (simplified phoswich, no need for pulse shape discrimination)
- Compact hemispherical design (no need for orientable mechanics)



a – Down-going hard X-ray
b – Down-going LE g-ray
c – Down-going ME g-ray
d – Down-going LE charged particle
e – HE charged particle

Scintillators + SiPMs





PROS

- Compact design
- Low power consumption
- Easy redoundancy
- No sensitivity to magnetic fields

CONS

- Non space qualified
  - packaging issue
  - radiation damage
- high dcr

OPEN DISCUSSION ABOUT FUTURE

Gamma-ray identification with Imaging Atmospheric Cherenkov Telescopes

Di Venere Leonardo

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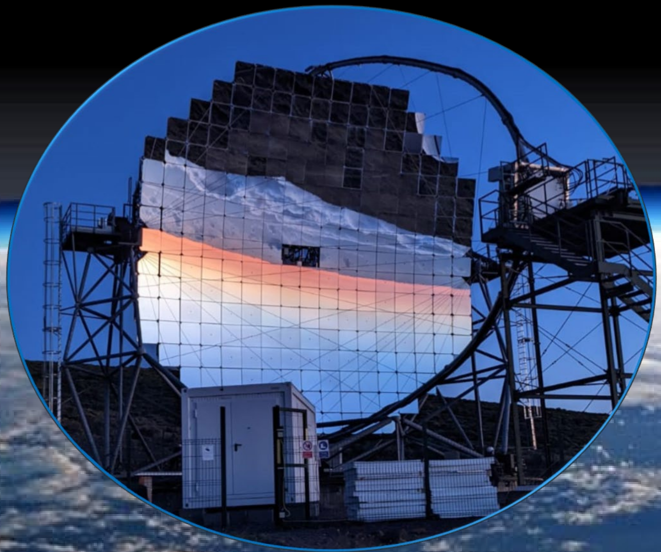
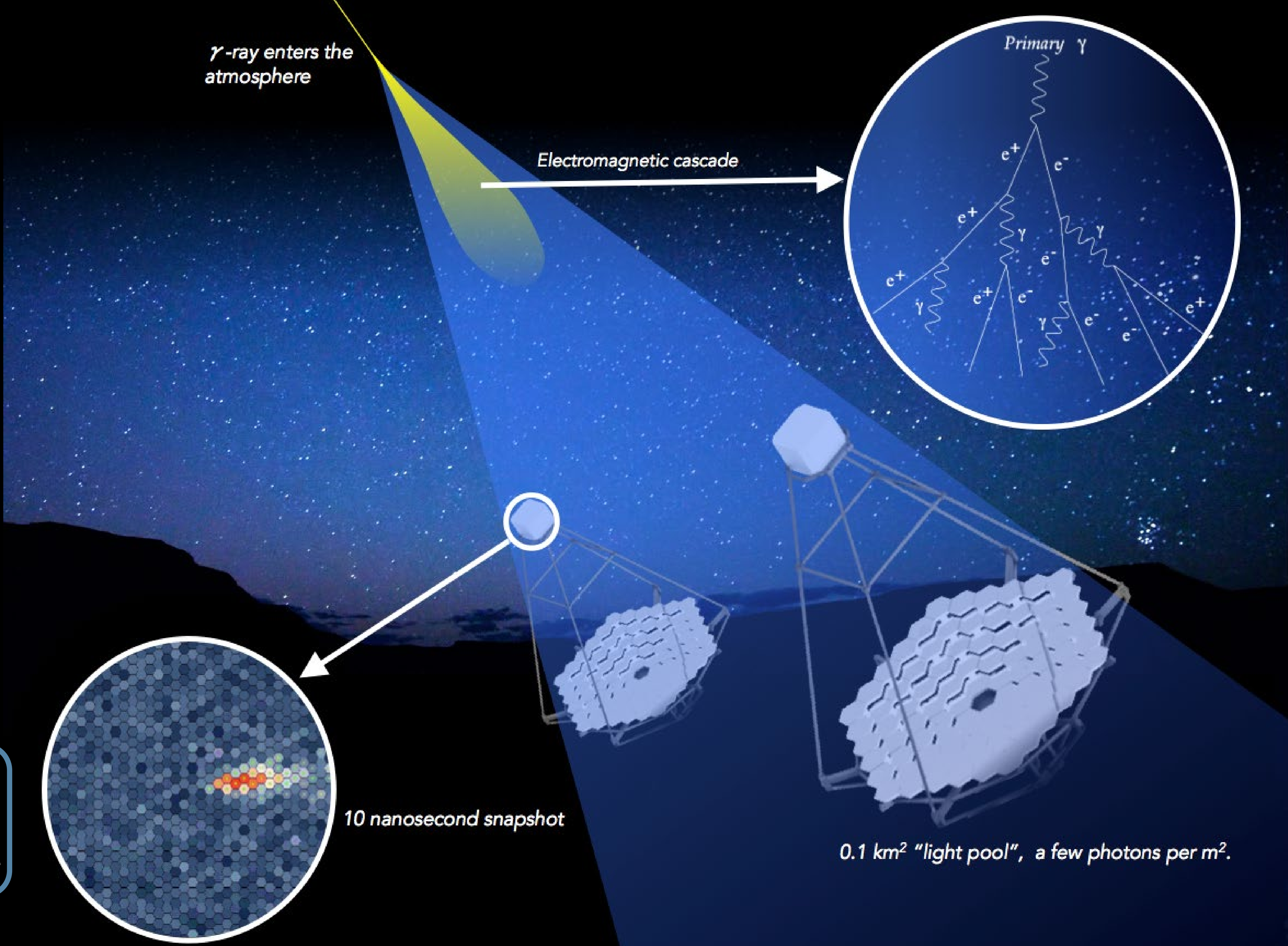


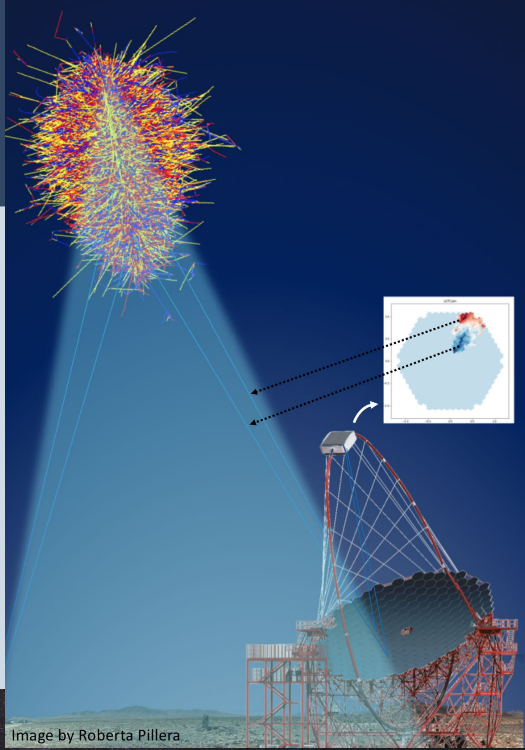
Imaging Atmospheric Cherenkov Telescopes

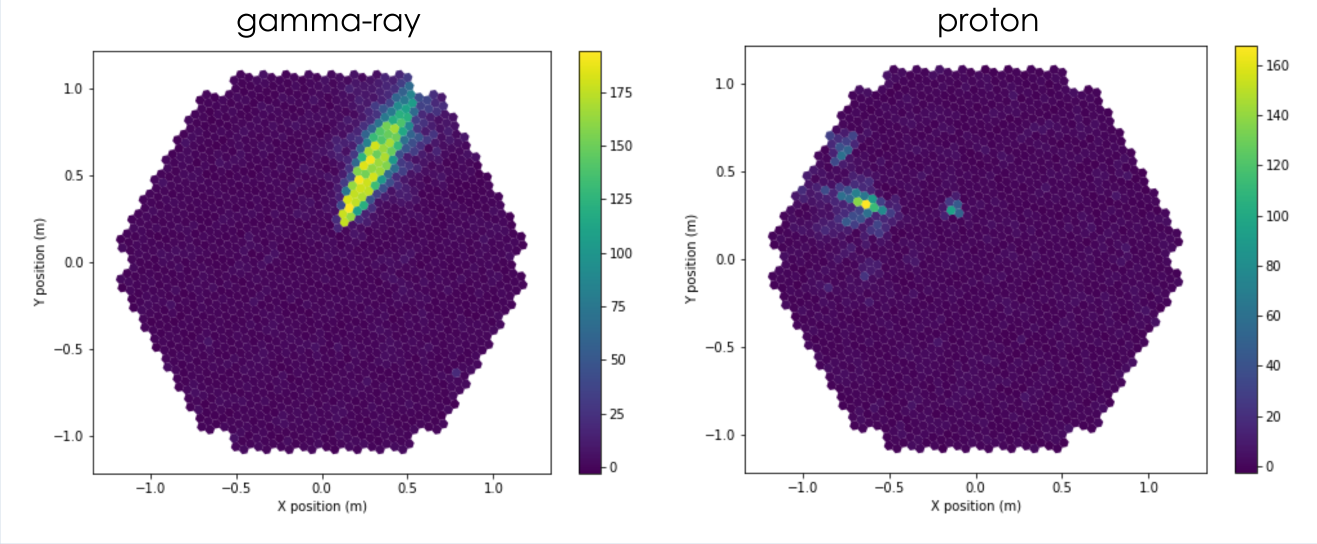
TeV gamma-ray ideal to probe the most energetic Universe



Particle identification

- Gamma rays and cosmic rays produce particle showers in atmosphere which emit Cherenkov light
- Shower images detected by fast high-resolution cameras
- ML algorithms used for the particle identification and the measurement of direction and energy of the primary particle

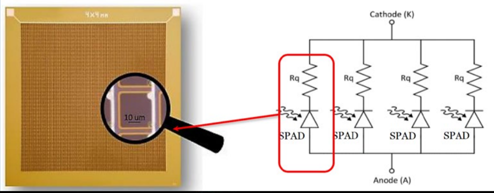


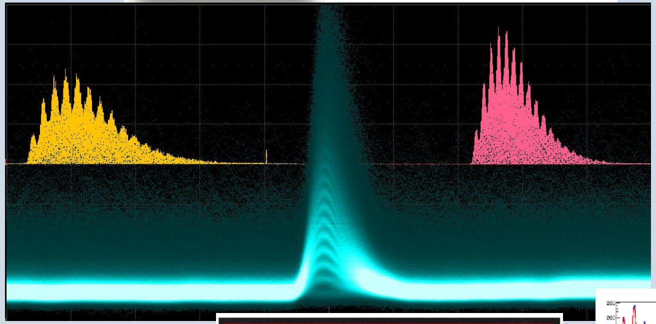


Di Venere L.

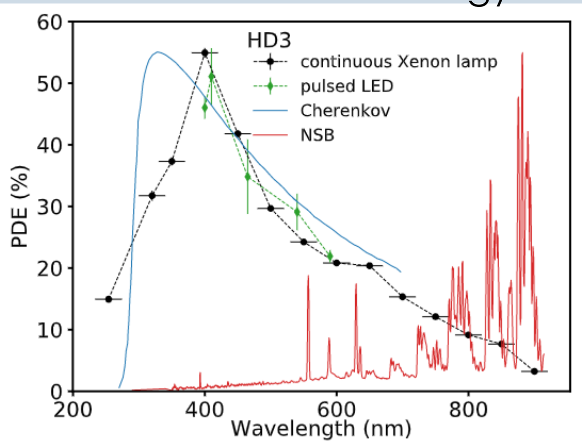
IACT camera

- Need to detect faint (down to few p.e.) and fast (~tens of ns) Cherekov light
- Need to deal with night sky background (NSB) light
- Photon detectors:
  Photomultiplier Tubes (PMT) → Silicon Photomultipliers (SiPM)
- Pros:
  - Single p.e. resolution
  - NSB tolerant → Operable under full moon
  - High PDE (> 50% peak)
  - Small pixels → easy to make arrays
  - Low bias voltage (<100V)
- Cons:
  - High sensitivity to NSB in > 550 nm range
  - Correlated noise
  - high dark count rate →
    usually below the NSB rate

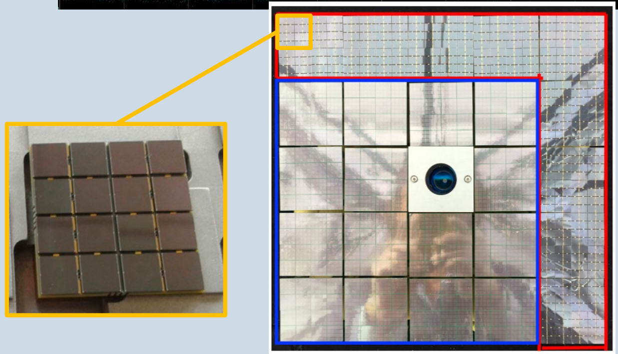


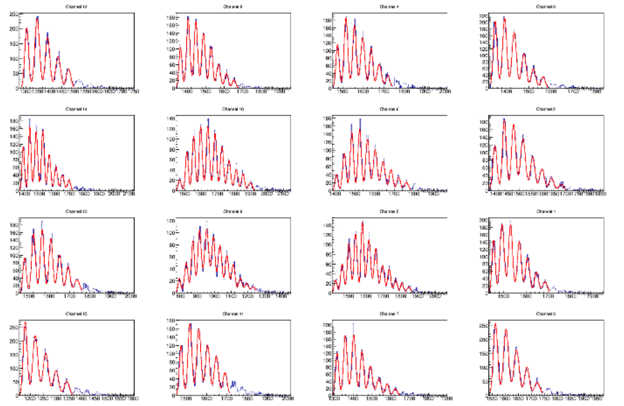


FBK NUV-HD technology



Ambrosi+2022 Submitted to NIMA

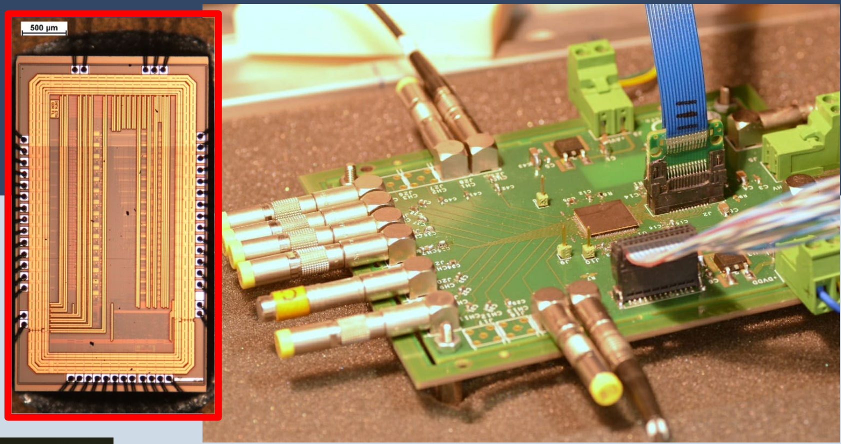




Di Venere L.

Ambrosi+2022 https://doi.org/10.1016/j.nima.2022.167359

Fast and single p.e. resolution frontend electronics

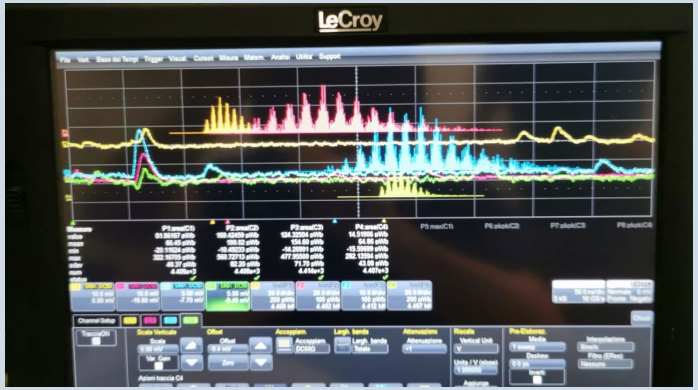


SMART: a **S**iPM **M**ultichannel **A**sic for high **R**esolution Cherenkov **T**elescopes

Features:

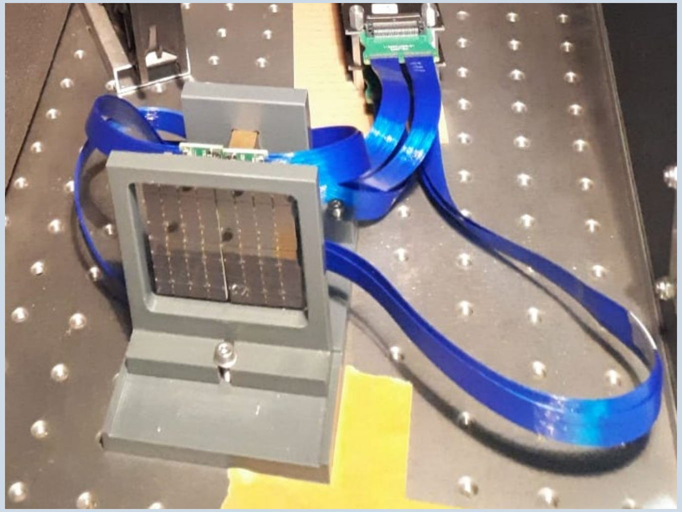
- 16-channel trans-impedance amplifier
- Fast path gain: 1-3 mV/ph
- Tail suppression: pulse duration ~ 10ns
- Power consumption: 20mW/channel
- SiPM bias fine tuning: LSB = 12.5mV
- Slow path output & 10 bit ADC: LSB = 2MHz
- Output dynamic range:
  - 900 mV without external PZ
  - 600 mV with external PZ

- ~800 ASICs tested @INFN Bari



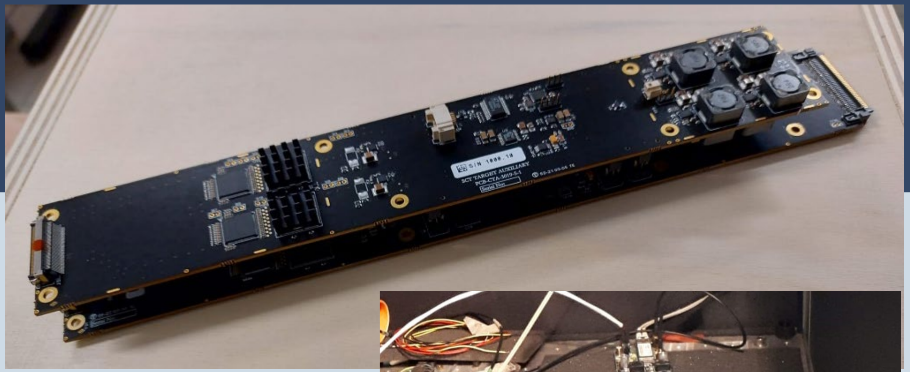
Designed by F. Licciulli & G. De Robertis at the Electronics CAD INFN Bari

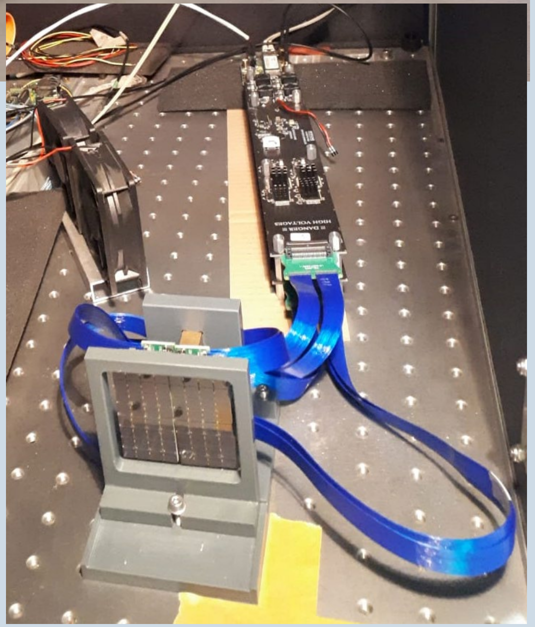
Contact: francesco.licciulli@ba.infn.it



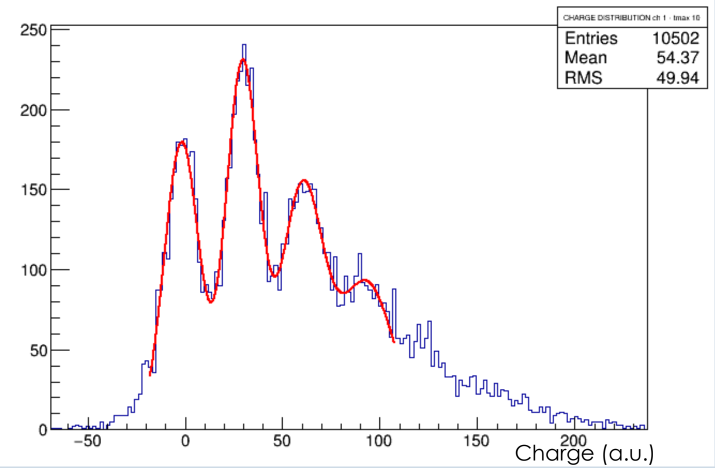
Readout electronics

- Readout electronics to digitize fast signals and generate trigger signals at pixel level → TARGET ASICs
  - CTC ASIC: 16-channel 1GSa/s digitizer
    - Analog buffer with 16k cells per channel →16 us storage depth
  - CT5TEA ASIC: 16-channel trigger ASIC
    - Channels are summed in groups of 4 to obtain 4 trigger pixels per ASIC





Single p.e. spectrum



Rate scan