Report on

IPRD23
Siena, Italy 25-29 Sept. 2023

E. Giulio Villani

Outlook

- The IPRD conference
- Selected presentations
- Summary & conclusions

SIENA is in Tuscany about 50km south of Florence

An ancient Etruscan settlement, it became Roman colony under the name of *Sena Julia*

Its importance grew in Middle Ages until became a municipality in 12th century: it flourished in XIV century

Frequent confrontations with neighbouring towns, it was taken over by Florence in 16th century

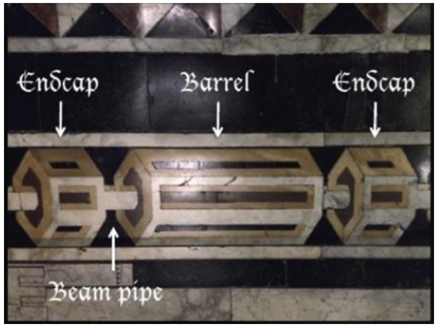
Piazza del Campo, that dates back to 14th century, is the heart of the city. The location of the ancient roman forum it boasts 14th century gothic buildings

The horse race (Palio) is held here, 2nd of July and 16th of August

The Duomo, 14th century: one of the best roman-gothic architectural examples.

It hosts works by Nicola Pisano, Donatello, Pinturicchio

An interesting innovative project in A.D. 1300 (floor panels of the Duomo)



From the Basilica di San Domenico

Orto de Pecci (medieval garden)

16th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD23)

The Seminar is the sixteenth in a series devoted, over a time span of 40 years, to detectors and experiments for high-energy particle physics and astrophysics.

The previous ones were held in San Miniato* (1984, 1986, 1988, 1990, 1993, 1996, 1998) and in Siena (2002, 2004, 2006, 2008, 2010, 2013, 2016, 2019).

The Seminar is focused on advanced technologies in particle physics at collider experiments, and in cosmic ray and astrophysics experiments, including balloon-borne, space-based and ground-based experiments.

The participation of representatives from industry will make it possible to discuss future applications of basic research.

https://web.bo.infn.it/sminiato/siena23.html

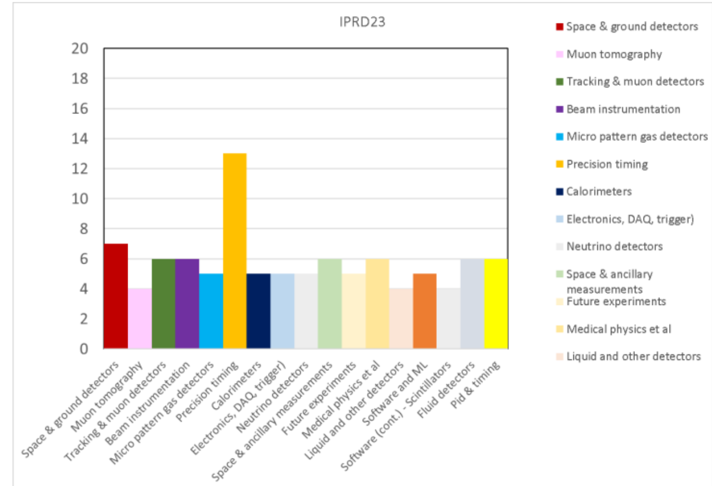
* Around 50 km NE of Siena

MAIN TOPICS

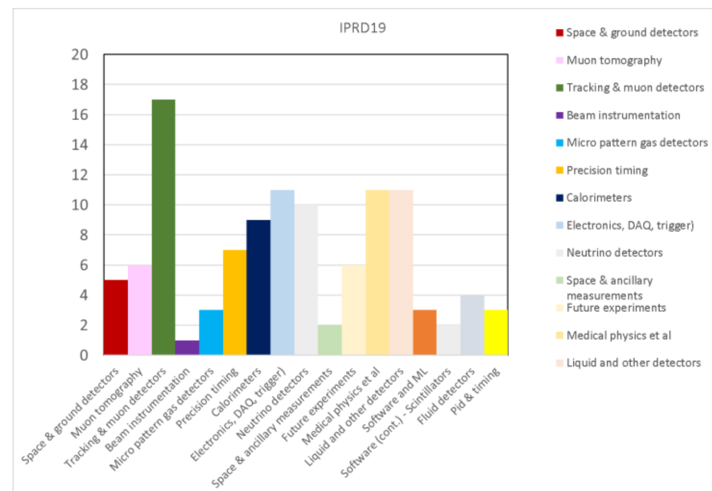
•Tracking detectors
•Calorimeters
•Detectors for X and gamma ray astrophysics
•Cosmic ray experiments in space, on the Earth's surface, and underground
•Neutrino experiments
•Radiation-hard detectors and electronics
•Muon-tomography of archaeological and geophysical structures
•Detectors for medicine and biology
•Large X-ray and muon systems for homeland security control
•Simulations and new computing methods, including machine learning techniques
•Detectors for environmental controls
•Outreach

ATTENDANCE

Attendance will be limited to approximately one hundred and fifty participants.



Registered participants: 129
Talks: 98



Registered participants: 112
Talks: 111

- Rather diversified range of topics, covering detectors for many applications
- Very good technical level of talks and posters
- Selected presentations:
  - Fast timing , including PPD contribution
  - Solar Neutrino
  - Muon tomography in archaeology

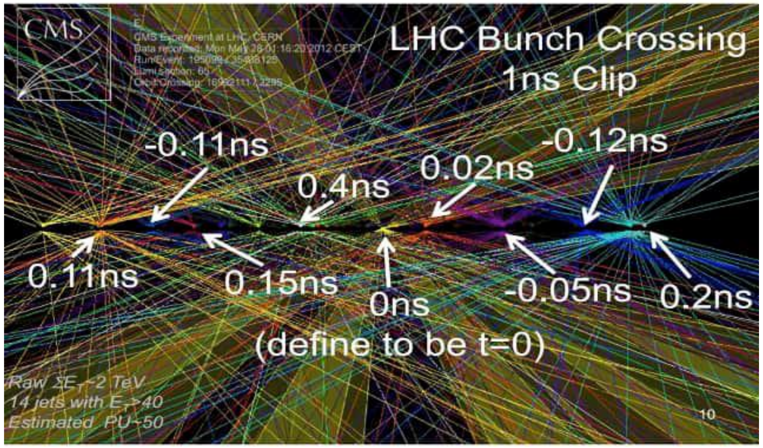
Particle Physics

Characterization of Teledyne e2v LGADs

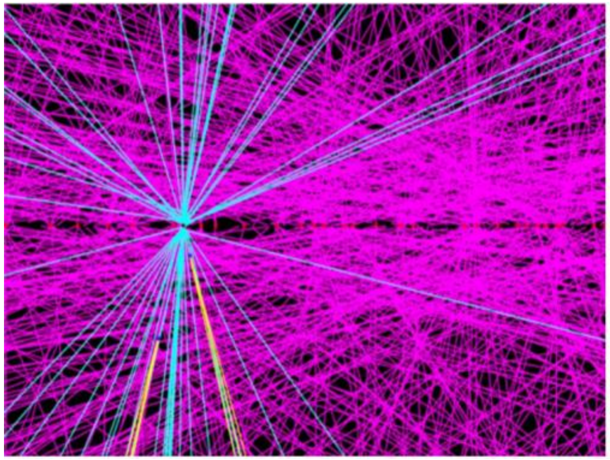
EG Villani

IPRD23 Siena, Sep. 2023

Introduction: Timing for HL-LHC



Interaction time of many pp vertexes happening in the same bunch crossing at LHC in the case of ≈50 overlapping events. The vertexes are spaced 10's of ps apart



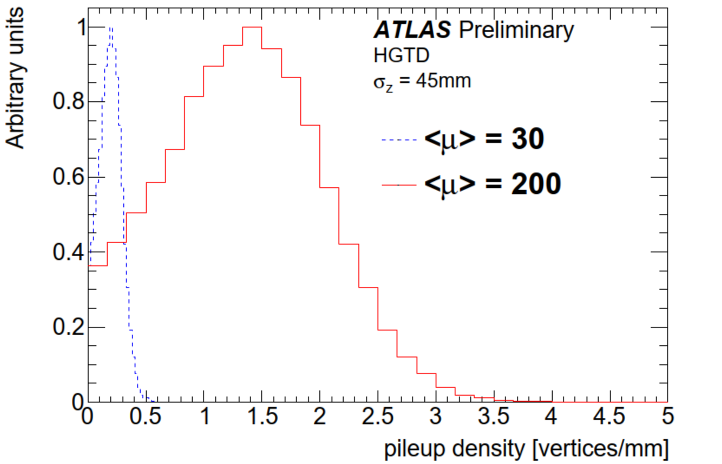
ATLAS simulation of spatial events at HL-LHC with < μ >= 140 pileup

At the nominal luminosity of the LHC the average number of pp interactions in a single bunch crossing (pileup) is approximately 23

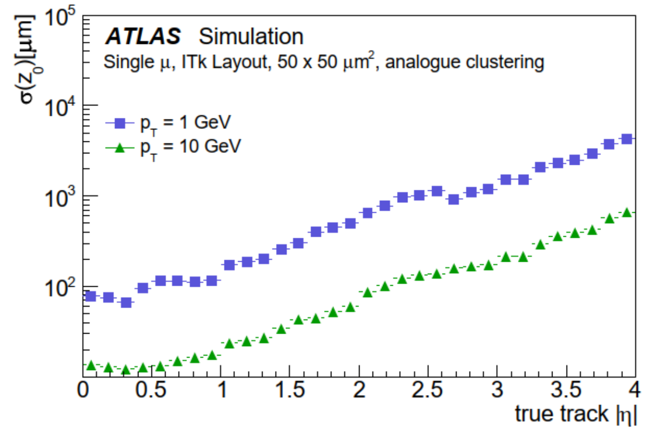
The planned luminosity upgrade to HL-LHC will increase this number to about 200

The increased spatial pileup line density (number of collisions / unit length along the beam axis) will lead to misidentified tracks

Introduction: Timing for HL-LHC



Simulation of HL-LHC local pileup vertex densities for two values of < μ >= 30 and < μ >= 200 ≃ 1.44 vertices/mm MPV

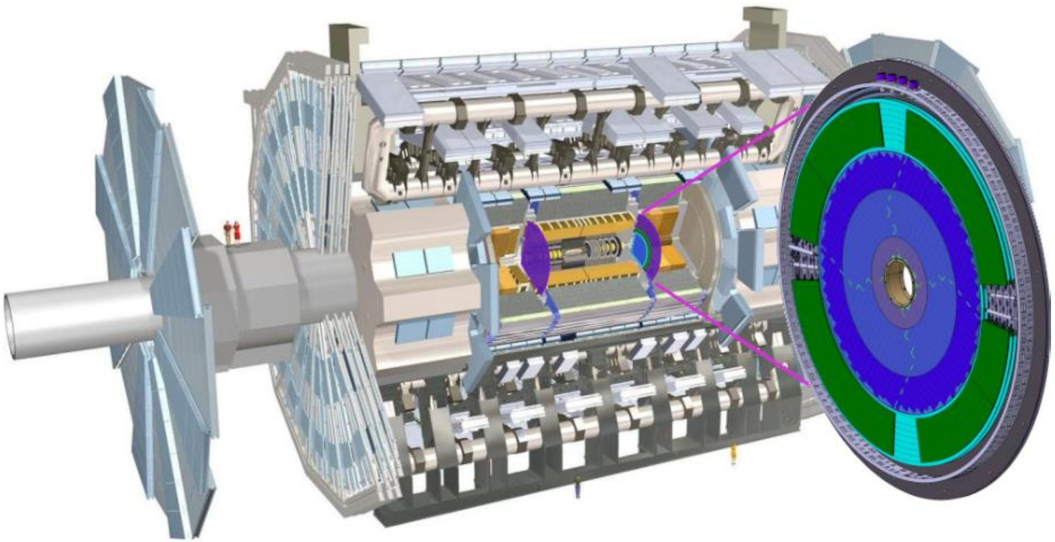


Resolution of the longitudinal track impact parameter, z0, as a function of η for muons of pT = 1 GeV and pT = 10 GeV using ITk alone

Track reconstruction becomes particularly critical at high η, when resolution becomes larger than distance between vertices

One solution to suppress the detrimental effect of pileup on reconstruction is to separate vertices in time rather than in space

Introduction: Timing for HL-LHC



Position of the HGTD within the ATLAS Detector. Positioned at $z = \mp 3.5$ m along the beamline, on both sides of the detector

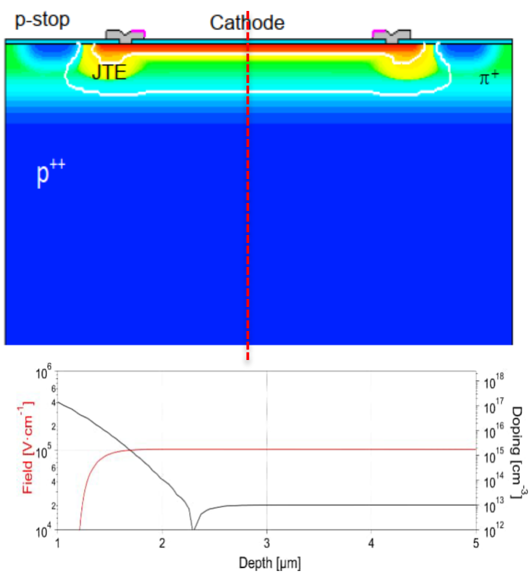
Mechanical parameter	value
Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	$\pm$ 3.5 m
Weight per end-cap	350 kg
Radial extension:	
Total	110 mm < r < 1000 mm
Active area	120 mm < r < 640 mm
Sensor parameter	**value**
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 μm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	30 x 15 pads (4 cm × 2 cm)
Modules	8032
Collected charge per hit	> 4.0 fC
Average number of hits per track	
$2.4 < \|\eta\| < 2.7$ (640 mm > r > 470 mm)	≈ 2.0
$2.7 < \|\eta\| < 3.5$ (470 mm > r > 230 mm)	≈ 2.4
$3.5 < \|\eta\| < 4.0$ (230 mm > r > 120 mm)	≈ 2.6
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \|\eta\| < 4.0$	$\approx$ 35 ps (start), $\approx$ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	$\approx$ 30 ps (start), $\approx$ 50 ps (end)

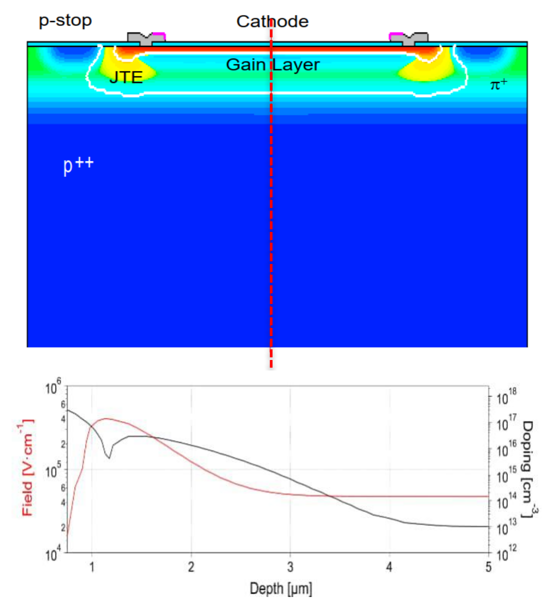
The HGTD[1] in ATLAS will be placed the gap region between the barrel and the end-cap calorimeter. Two instrumented double-sided layers on two cooling/support disks on each end-cap.

Timing sensors used are based on **L**ow **G**ain **A**valanche **D**etector (LGAD) technology

[1] ATLAS Collaboration, Technical Design Report: A High-Granularity Timing Detector 2562 for the ATLAS Phase-II Upgrade, tech. rep. CERN-LHCC-2020-007, CERN, 2020, URL: 2563 https://cds.cern.ch/ record/2719855.

Teledyne e2v LGAD design

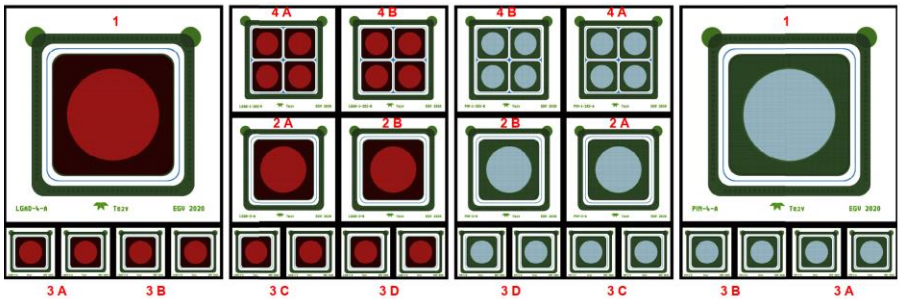




A standard PIN silicon sensor consists essentially of a pn junction. At depletion it shows an ~ uniform electric field F

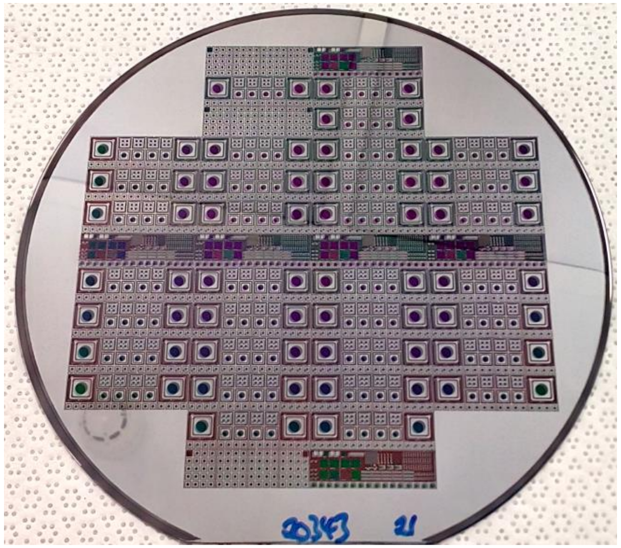
In the LGAD device an additional p^+ doped layer (gain layer or GL) is implanted near the pn junction. When depleted the GL creates an electric field high enough to start impact ionization, leading to charge multiplication by a factor G

Teledyne e2v LGAD design



Cell layout	Cathode diameter	Laser hole diameter	Cathode to p-stop	p-stop width	p-stop to Guard Ring	Guard Ring width
1	4000	3020	156	6	152	332
2	2000	1510	78	6	76/96	166
3	1000	755	39	6	38/48/58/68	83
4	1000	755	39	6	38/68	166

Size of Run I cells [um]



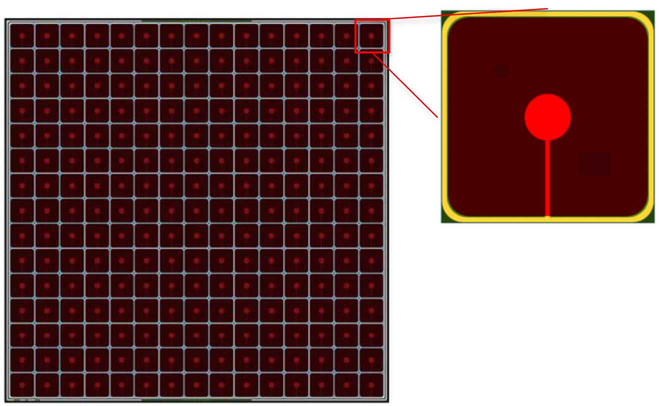
Wafer	GL dose	GL energy
19,20,21	1.00	1.00
17,18	1.07	1.00
15,16	0.92	1.05
12,13,14	1.00	1.05
9,10,11	1.07	1.05
7,8	1.15	1.05
4,5,6	1.00	1.11
2,3,24	1.07	1.11

Normalized values of GL 11B doping

Two runs of LGAD fabrication with Teledyne 2ev (Te2v) :

Run I included 1,2, 4 and 2x2 of 1x1 mm^2 cells

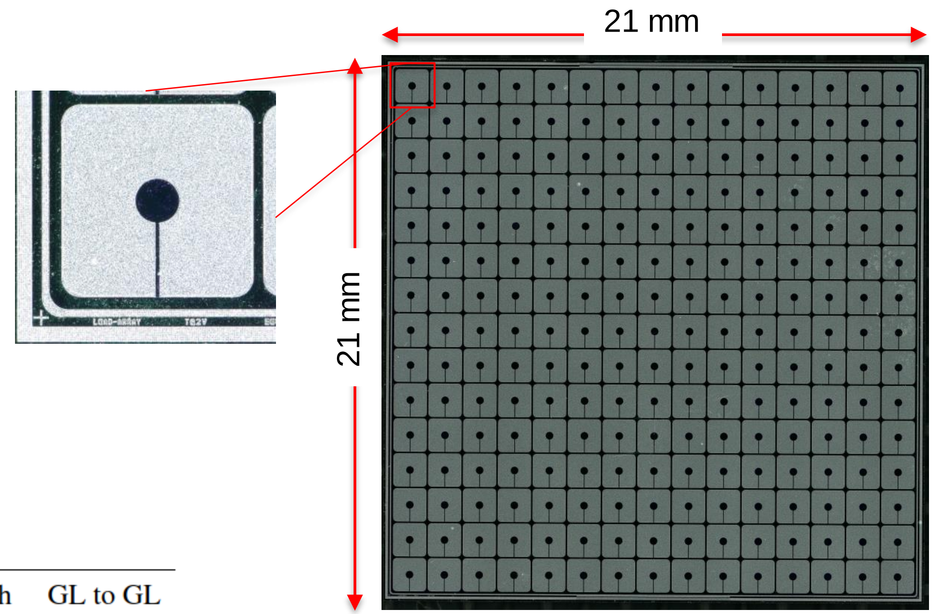
Teledyne e2v LGAD design



Cathode diam.	Cath to GR	Cath to p-stop	p-stop width	Cath to Cath	GL to GL
1300	83	30	6	66	86

Size of Run II cells [um]

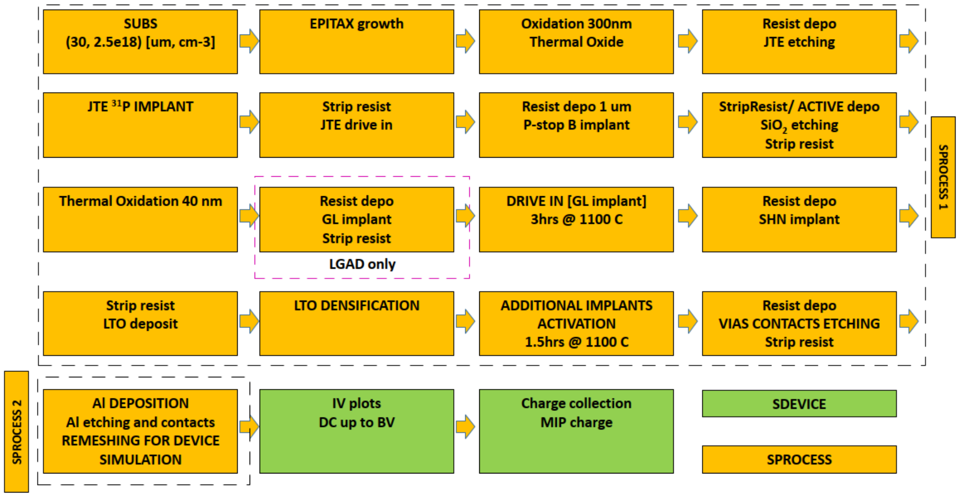
Second fabrication (Run II) included array of 15 x 15 cells of 1.3 x 1.3 mm2

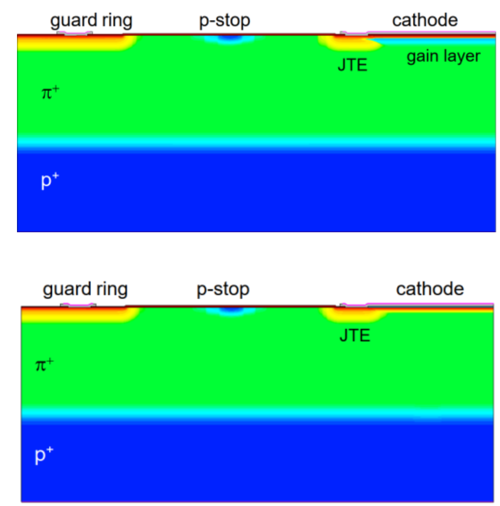


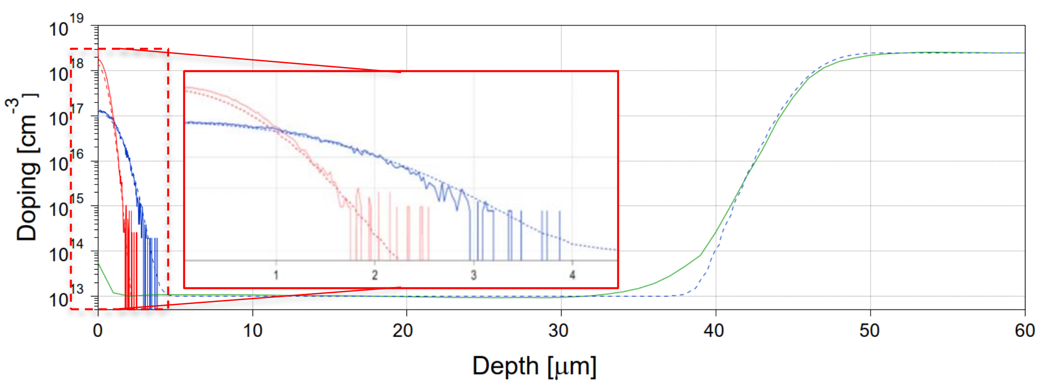
Wafer	GL dose	GL energy
1	1.00	1.00
2	0.95	1.07
3	1.00	1.07
4	1.00	0.93

Normalized values of GL 11B doping

Teledyne e2v LGAD TCAD simulation fabrication process

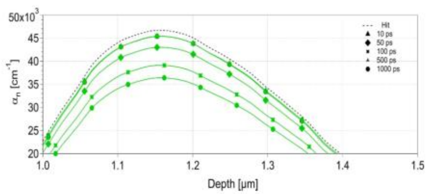




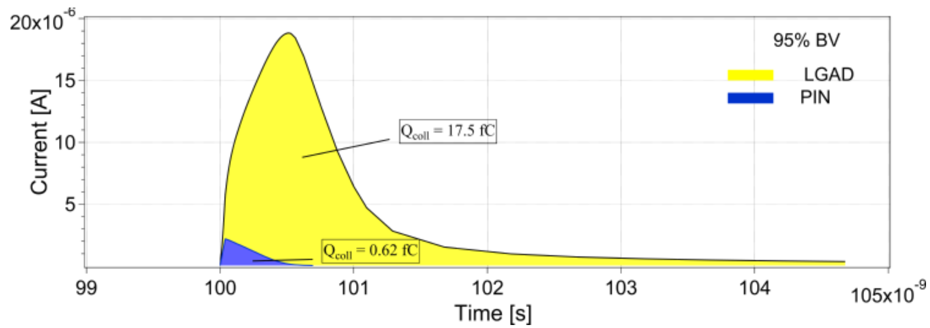


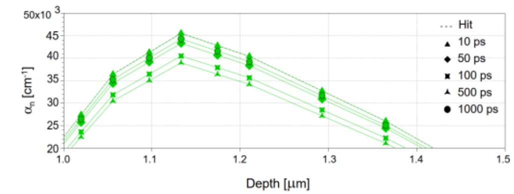
Full process simulation using Synopsys TCAD to predict doping profiles compared with SIMS measurements

Teledyne e2v LGAD TCAD simulation
Charge collection and gain

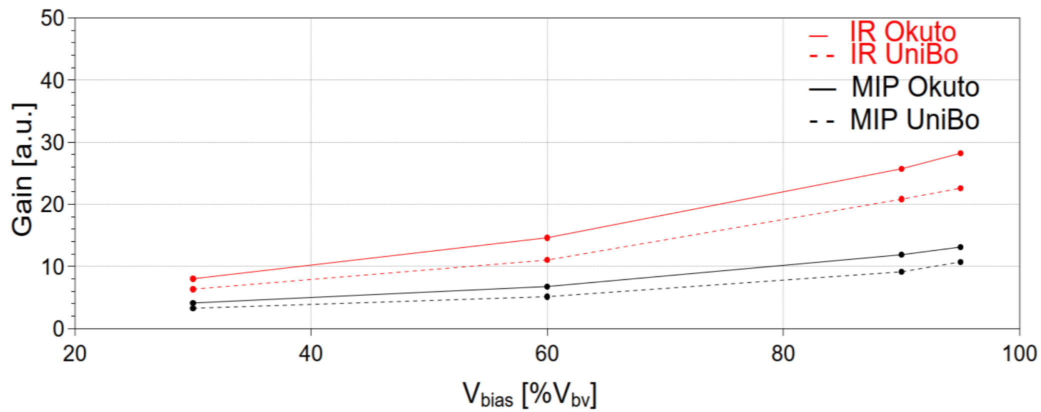


$\alpha_n(t)$ during MIP injection





$\alpha_n(t)$ during Laser injection

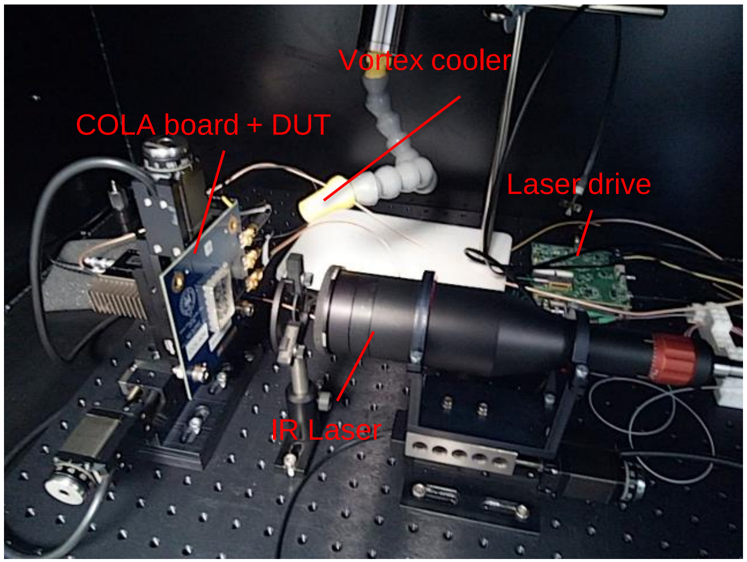


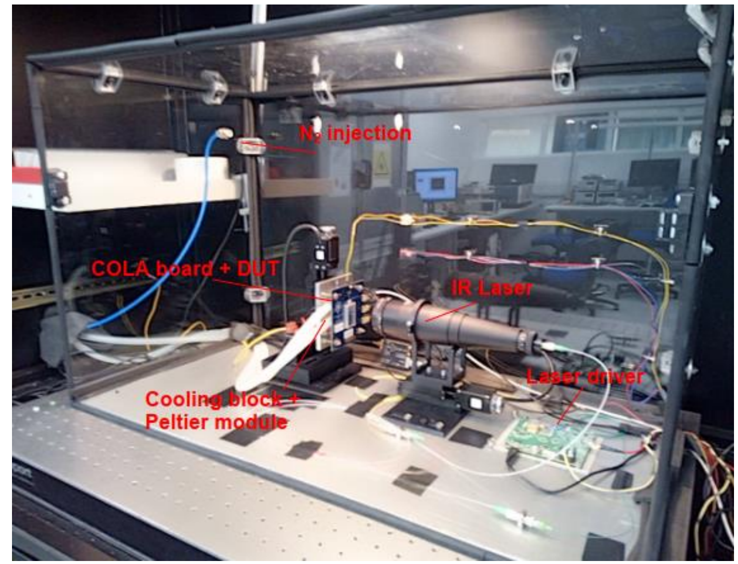
Transient simulation to estimate charge collection and gain performed both using Laser (1064 nm) and MIP injection

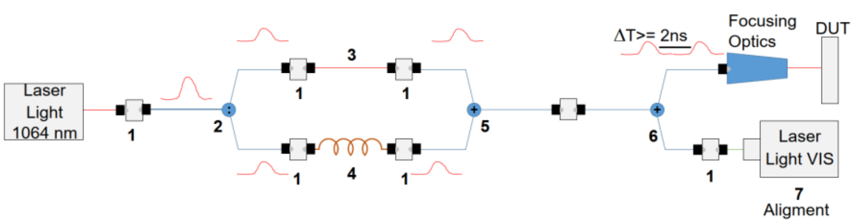
Gain obtained from ratio of collected charge by LGAD vs. bias compared to charge collected by PIN diode under same biasing conditions

Evidence of gain suppression is observed

Teledyne e2v LGAD Test setup

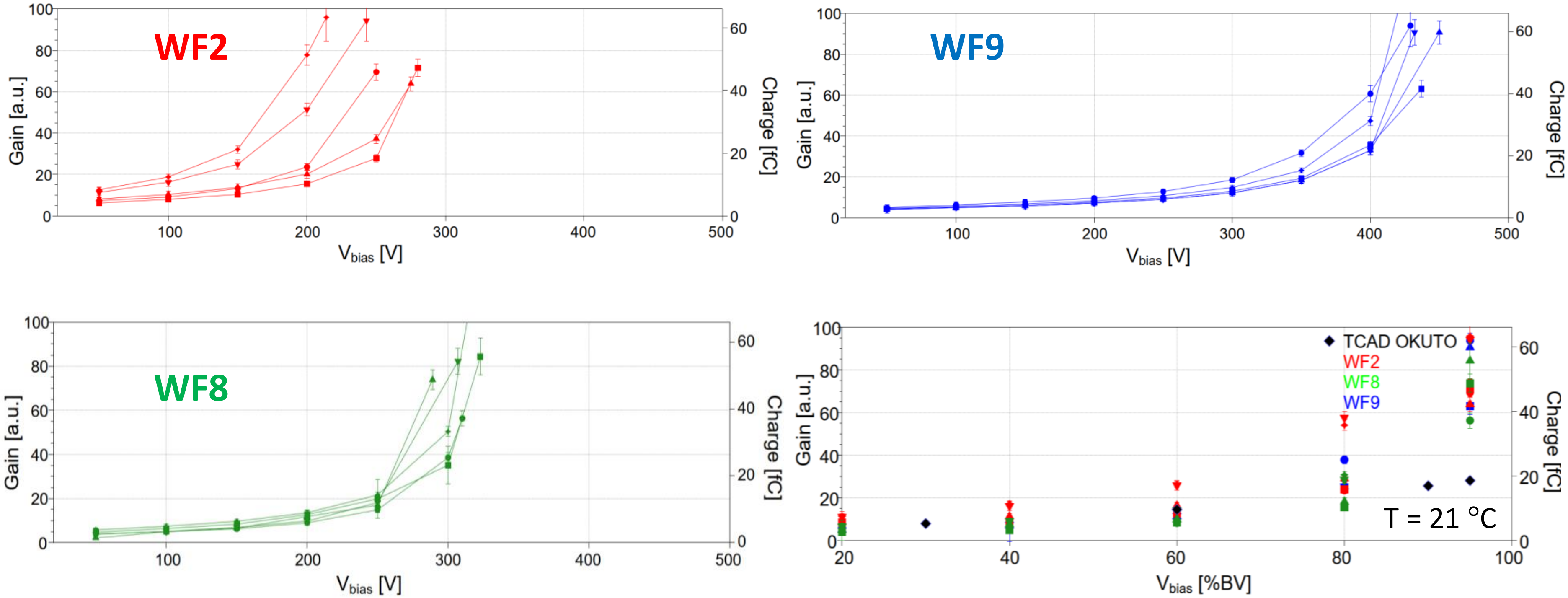






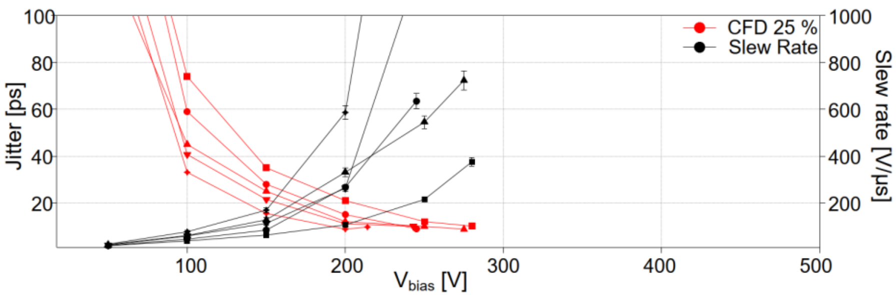
Infrared Laser (1064 nm -15 ps) charge injection
Gain measured as ratio of collected charges LGAD/PIN
Jitter measured using Split Recombine method at different CFD
Coolers to test irradiated sensors

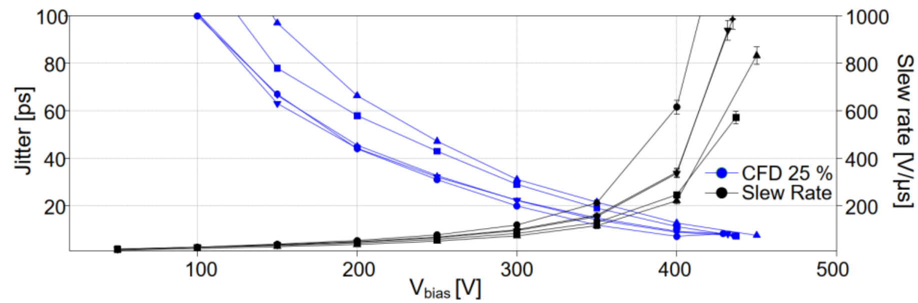
Teledyne e2v LGAD test results – Charge collection and Gain

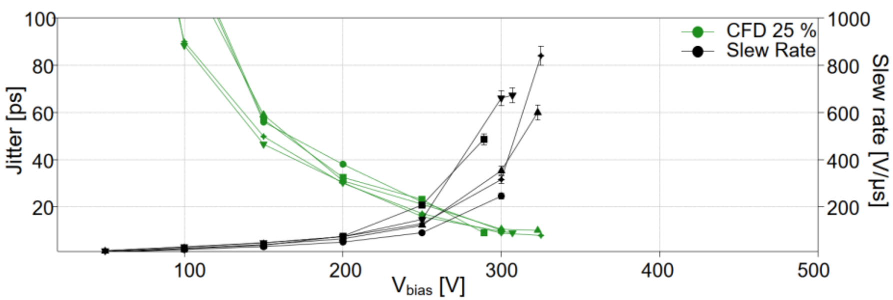


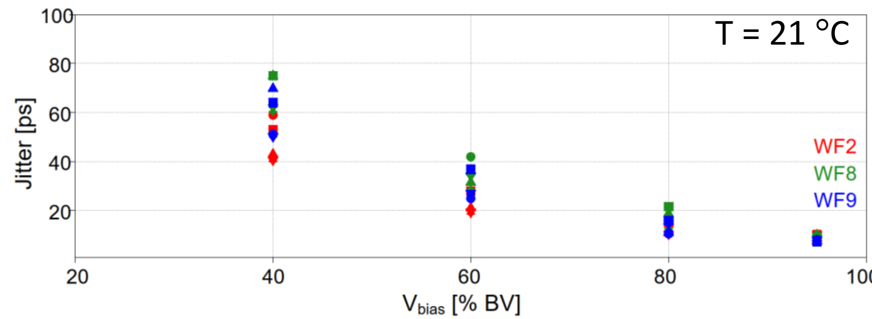
Gain plots using laser injection ~ 0.7 fC
Plot of gain vs. V_{bias}/V_{bv} shows similar trend for all flavours tested
TCAD comparison shows good prediction up to ~ 80 %V_{bv}, lower predicted gain above

Teledyne e2v LGAD test results – timing results



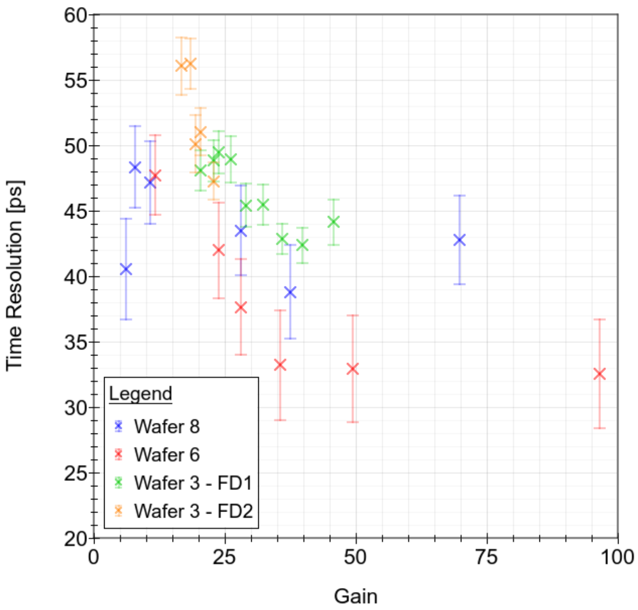


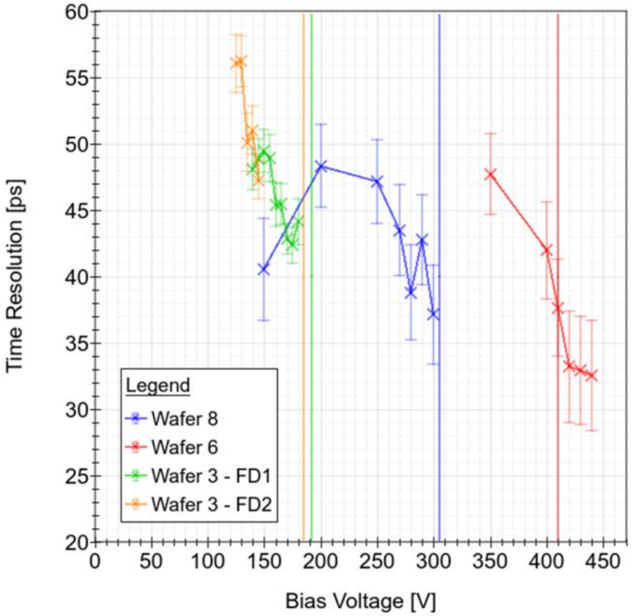




Jitter plots using laser injection ~ 0.7 fC
Minimum jitter ~ 10 ps @ 90-95% of BV using CFD = 25 %

Teledyne e2v LGAD test results – timing results





Timing plot using 90Sr setup
For non-irradiated sensors time resolution of approximately 33 ∓ 4 ps

Summary and conclusions

- The increased pileup at HL-LHC represents a challenge for track reconstruction.

Using Ultra Fast detectors with time resolution of around 30 ps would help disentangle the tracks. The High Granularity Timing Detector (HGTD) in ATLAS has been designed for this purpose. It uses Low Gain Avalanche Detector (LGAD) as timing sensors

- This projects described the two runs of LGAD fabrication with Teledyne e2v. First run of individual cells designed to investigate achievable performances using the technology, the second a full LGAD array to HGTD specs

- TCAD simulations have been used in all phases of sensor design, including fabrication and charge collection. Gain prediction match test results up to 80 % of BV

- Test results indicate time resolution for non-irradiated sensors of around 34 ps using MIP and around 10 ps jitter using IR Laser light. Neutron Irradiated sensors show jitter of around 25 ps up to 1e14 fluence (ongoing tests)

- Initial tests done to investigate possible uses of LGAD for Low Let particles detection.

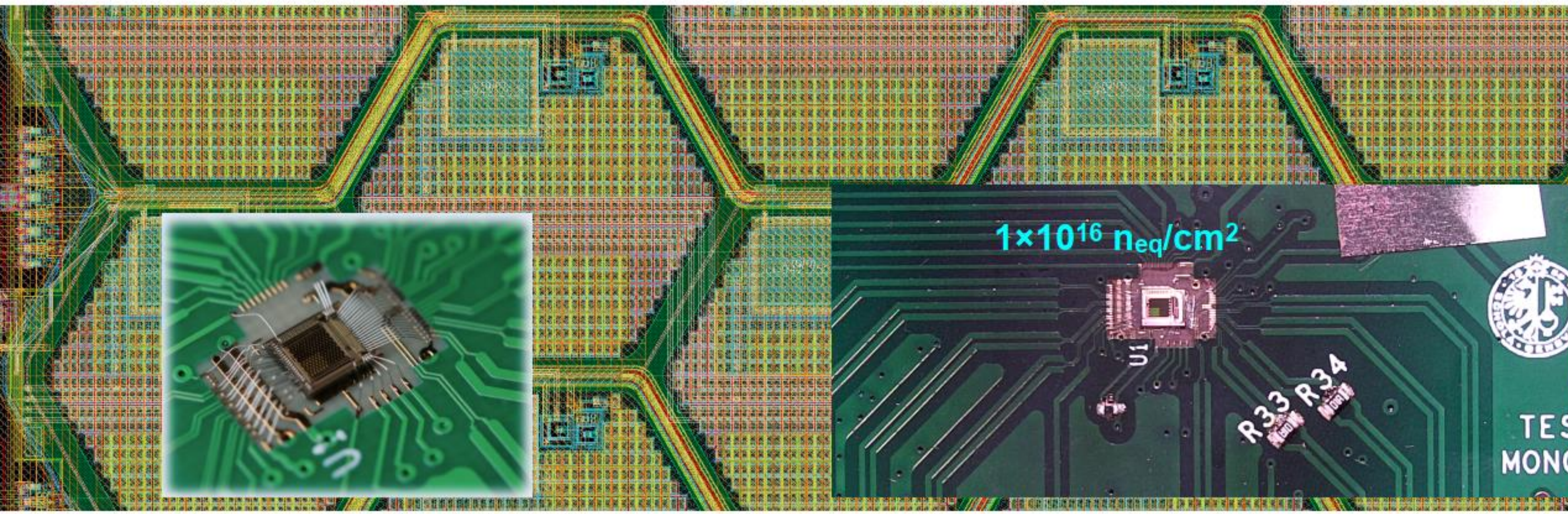
THANK YOU

E. G. Villani - IPRD23 - Sep2023

Fast timing

The MONOLITH project: towards **picosecond timing** with monolithic silicon

Giuseppe Iacobucci — Université de Genève



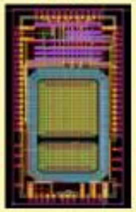
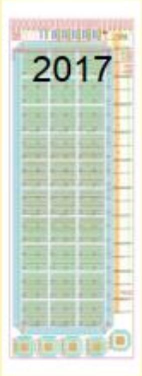
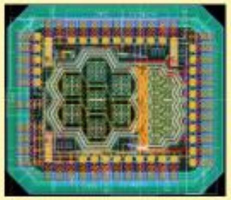
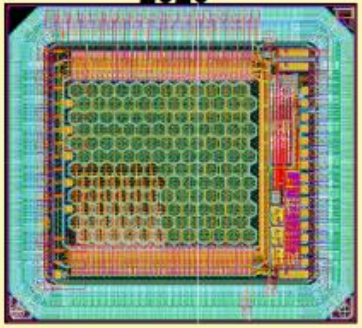
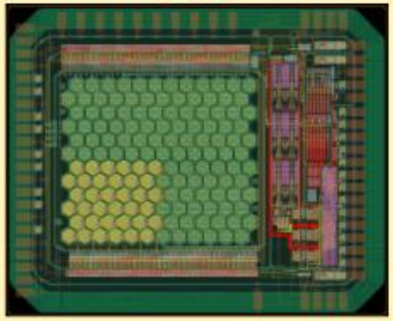
UNIVERSITÉ DE GENÈVE

Swiss National Science Foundation

erc European Research Council

Fast timing

Monolithic prototypes in SiGe BiCMOS (without internal gain layer)

2016	2017	2018	MONOLITH prototype 1 2020	**MONOLITH prototype 2 2022**
				
200ps	**110ps**	**50ps**	**36 ps**	
• 1 mm² pixel • Discriminator	• 30 pixels 500x500µm² • 100ps TDC +I/O logic	• Hexagonal pixels 100µm and 200µm pitch • Discriminator output	• Hexagonal pixels 100µm pitch • 30ps TDC + I/O logic • 4 analog channels	• Matrix of 12x12 hexagonal pixels • 100µm pitch • improved electronics • 50µm epitaxial layer (350Ωcm)

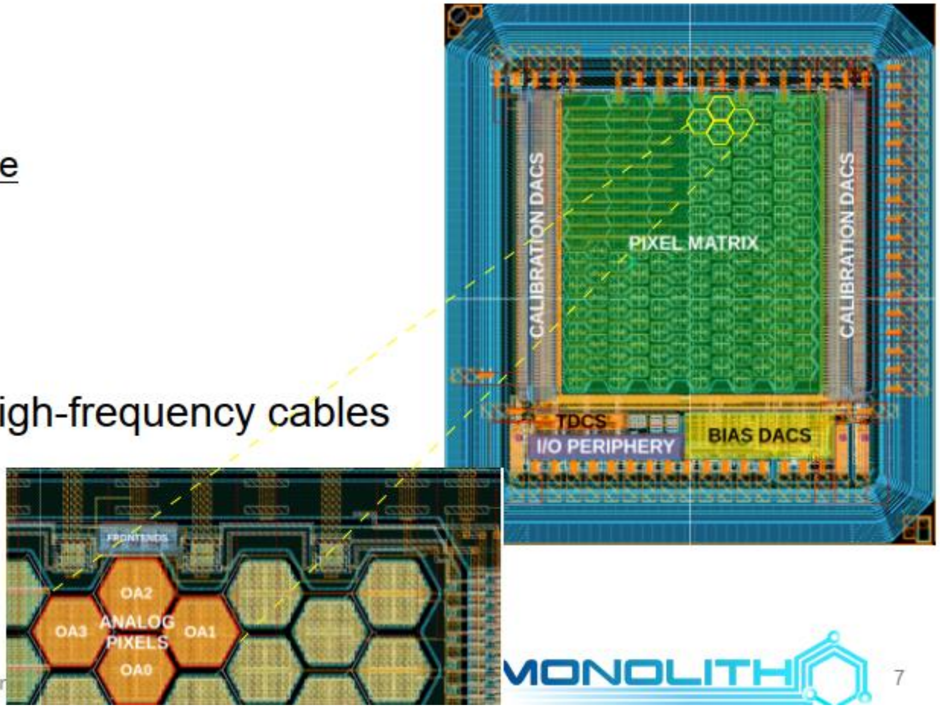
evolution of 2020 prototype

The MONOLITH Project

European Research Council
Established by the European Commission

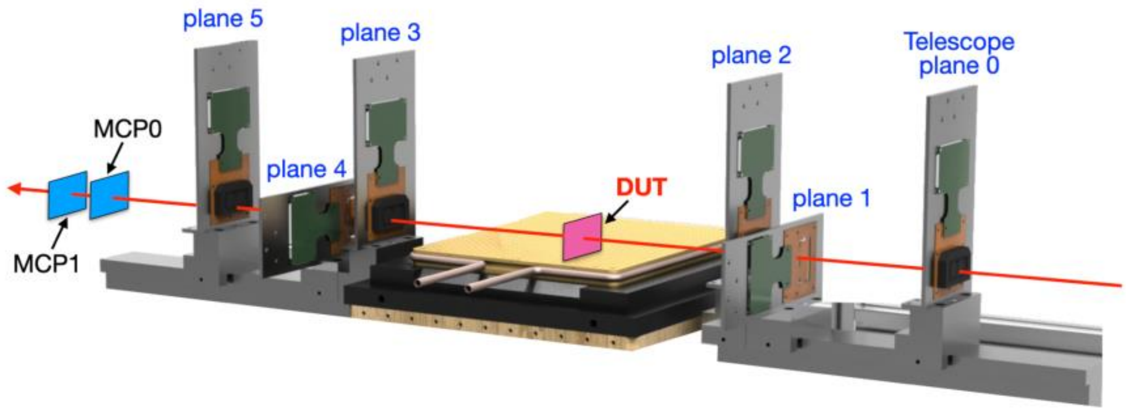
Funded by the H2020 ERC Advanced grant 884447,
July 2020 - June 2025

- Same matrix configuration as prototype1, but
  - **Substrate**: 50Ωcm → 350Ωcm epilayer, 50μm thick on low-res (1Ωcm)
    - ➡ smaller pixel capacitance
    - ➡ depletion 23μm → 50μm
    - ➡ larger voltage plateau
    - ➡ can operate sensor with <u>v_{drift} saturated everywhere</u>
  - **Preamp and driver** voltage decoupled
    - ➡ was limiting optimal amplifier operation
    - ➡ was creating cross-talk, removed
  - **Optimised FE layout**, **differential output**, high-frequency cables
    - ➡ better rise time (600ps → 300ps)



Test Beam: Experimental Setup

Mid October SPS testbeam with 120 GeV/c π to measure **efficiency** and **time resolution**

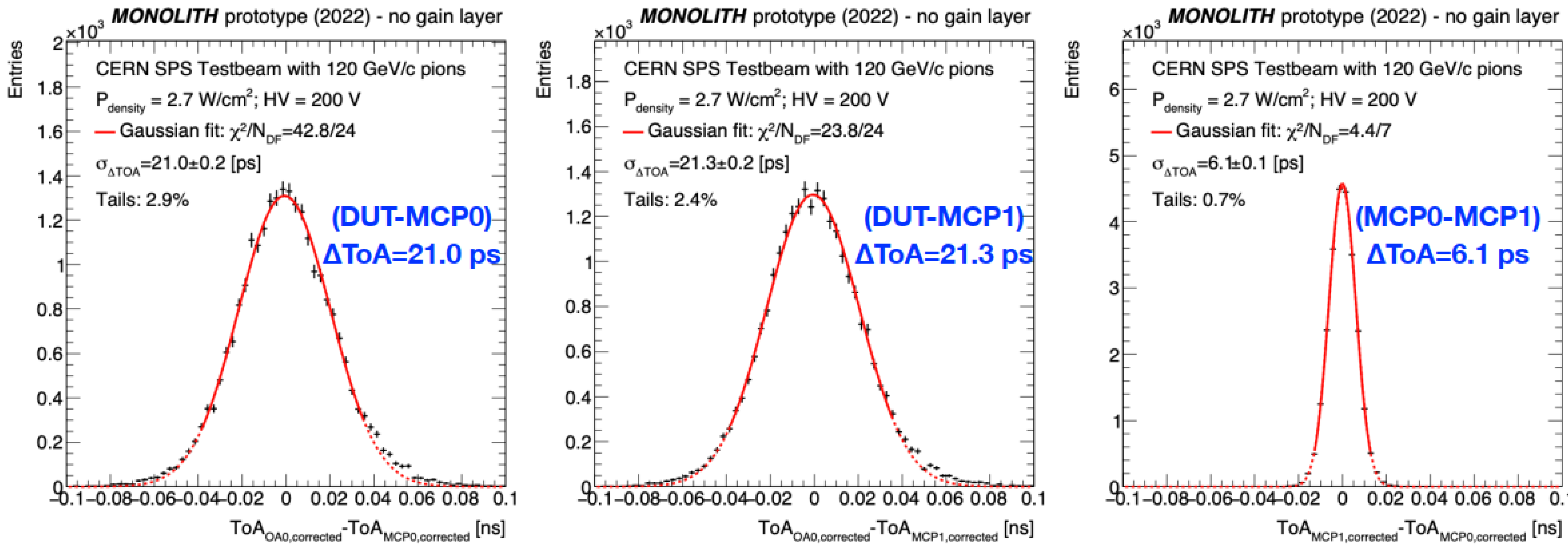


UNIGE FE-I4 telescope to provide spatial information ($\sigma_{x,y} \approx 10$ μm)

Two MCPs ($\sigma_t \approx 5$ ps) to provide the timing reference

Lots of data taken: results in **JINST 18 (2023) P03047**

prototype2 (2022) — no gain layer



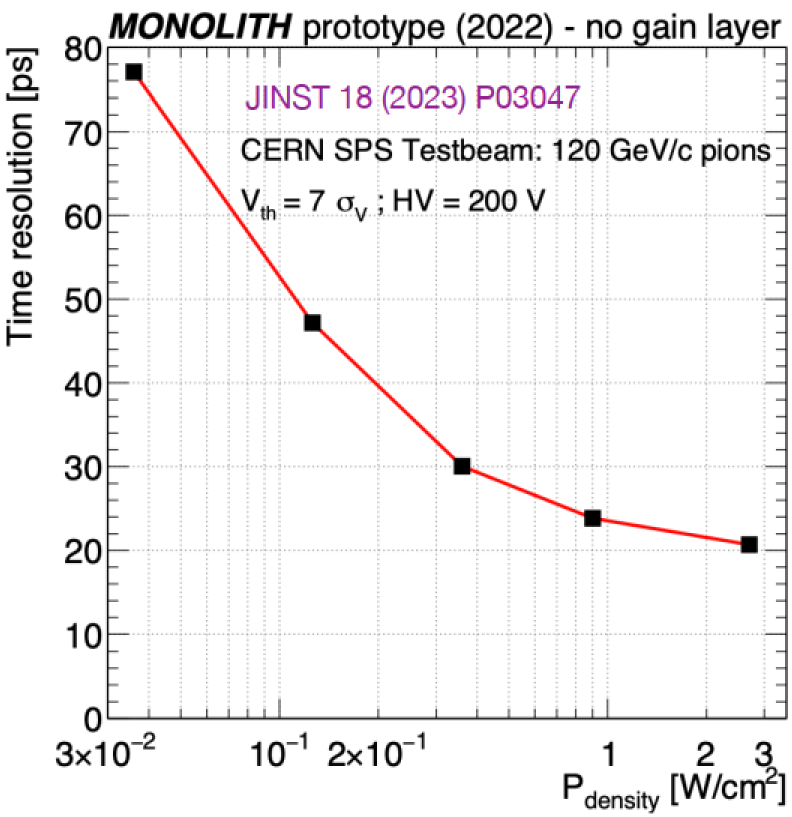
- Simultaneous fit to extract time resolutions of the DUT, MCP0, MCP1:

Fit results: MCP0 $\sigma_T = (3.6 \pm 1.5)$ ps
MCP1 $\sigma_T = (5.0 \pm 1.1)$ ps

$\sigma_T = (20.7 \pm 0.3)$ ps

non-Gaussian tails ≈ **3%**

prototype2 (2022) — no gain layer



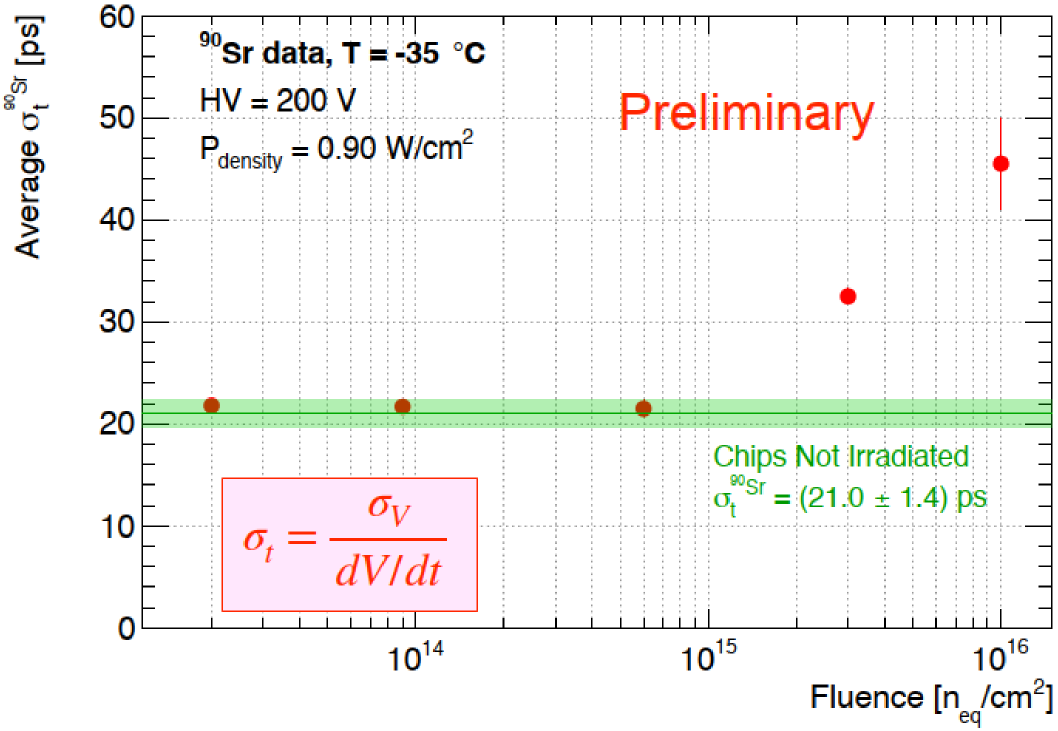
DUT operated at $HV = 200$ V and $V_{th} = 7\sigma_V$		
$P_{density}$ [W/cm^2]	Amplitude MPV [mV]	Time Resolution [ps]
2.7	48.6 ± 0.5	20.7 ± 0.3
0.9	35.8 ± 0.5	23.8 ± 0.3
0.36	22.6 ± 0.4	30.1 ± 0.4
0.13	14.2 ± 0.3	47.2 ± 0.7
0.04	16.2 ± 0.3	77.1 ± 0.9

20 ps at 2.7 W/cm²
50 ps at 0.1 W/cm²

Without gain layer.

Radiation hardness of SiGe HBTs

MONOLITH **prototype2 (2022) - no gain layer**



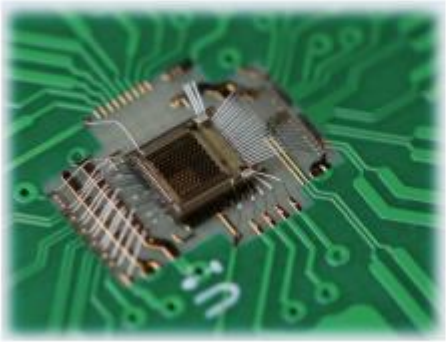
Excellent news from radiation tolerance studies:

The time jitter with ^{90}**Sr** increases **from 21ps** (unirradiated) **to 46ps** (at 10^{16} n_{eq}/cm^2) at **HV = 200V** and **0.9 W/cm²**

Summary

A monolithic prototype ASIC without gain produced in SiGe BiCMOS provided:

- **Efficiency of 99.8%** and **time resolution of 21 ps**
- **Laser** measurement: down to 2.5 ps.



After proton fluence of **10^{16} 1MeV n_{eq}/cm^2**:

- Increasing HV from 200 V to 325 V gives **Efficiency up to 99.7 %** and **time resolution of 40 ps**

This performance was obtained **without gain layer**

SiGe BiCMOS is a serious candidate for future 4D trackers (and much more)

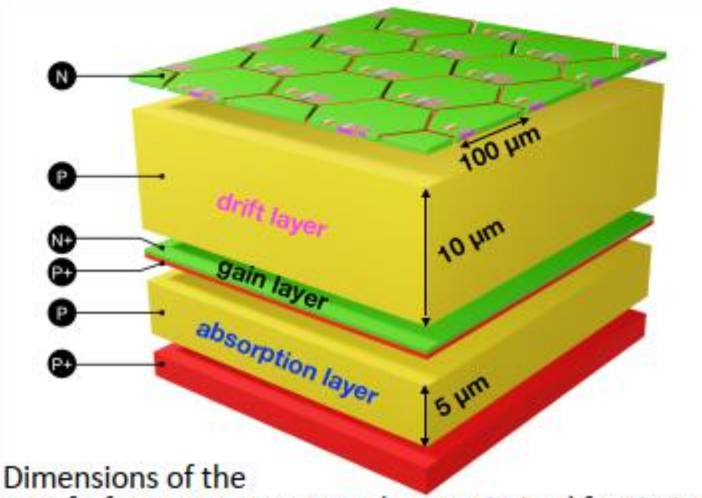
PicoAD Sensor Concept

PicoAD:

Multi-Junction Picosecond-Avalanche Detector© with continuous and deep gain layer:

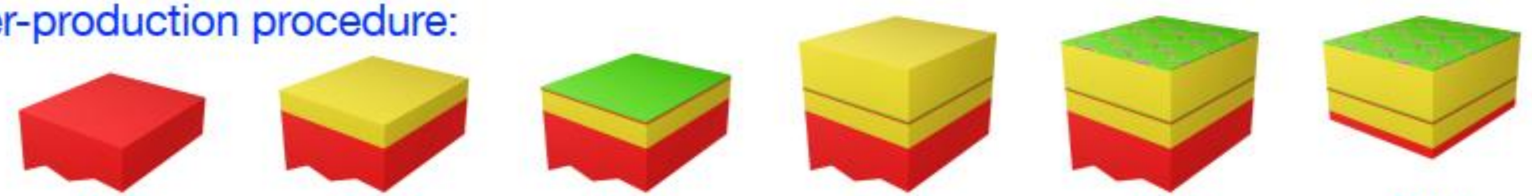
- De-correlation from implant size/geometry
  → **high pixel granularity and full fill factor**
  (high spatial resolution and efficiency)
- Only small fraction of charge gets amplified
  → **reduced charge-collection (Landau) noise**
  (enhance timing resolution)

© G. Iacobucci, L. Paolozzi and P. Valerio. Multi-junction pico-avalanche detector; European Patent EP3654376A1, US Patent US2021280734A1, Nov 2018



Dimensions of the proof-of-concept prototype (not optimised for timing)

Wafer-production procedure:



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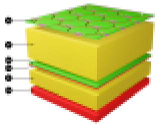
Fast timing

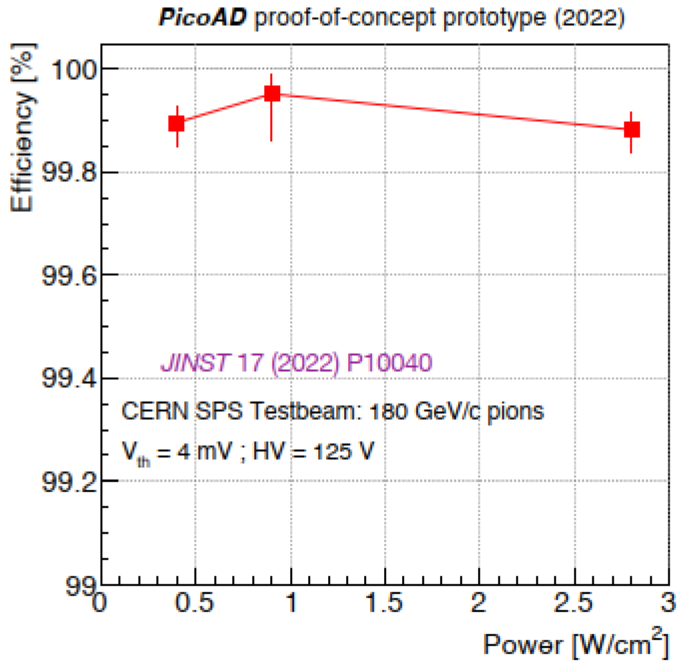
Testbeam PicoAD p.o.c.: Detection Efficiency

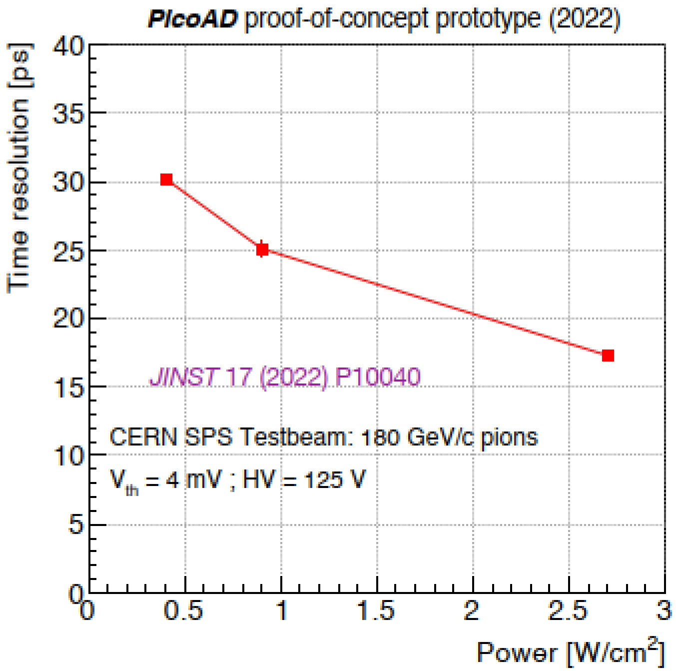
PicoAD



99.9% for all power consumptions

17 ps at 2.7 W/cm²
30 ps at 0.4 W/cm²

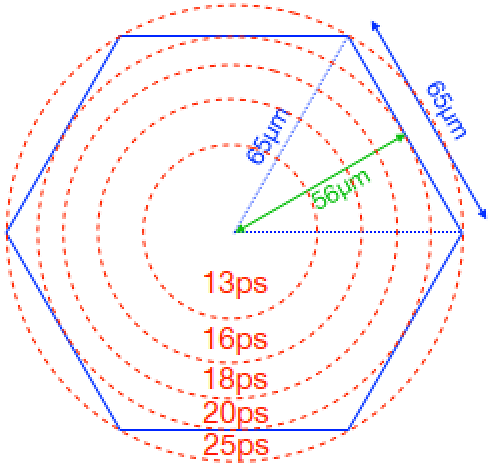


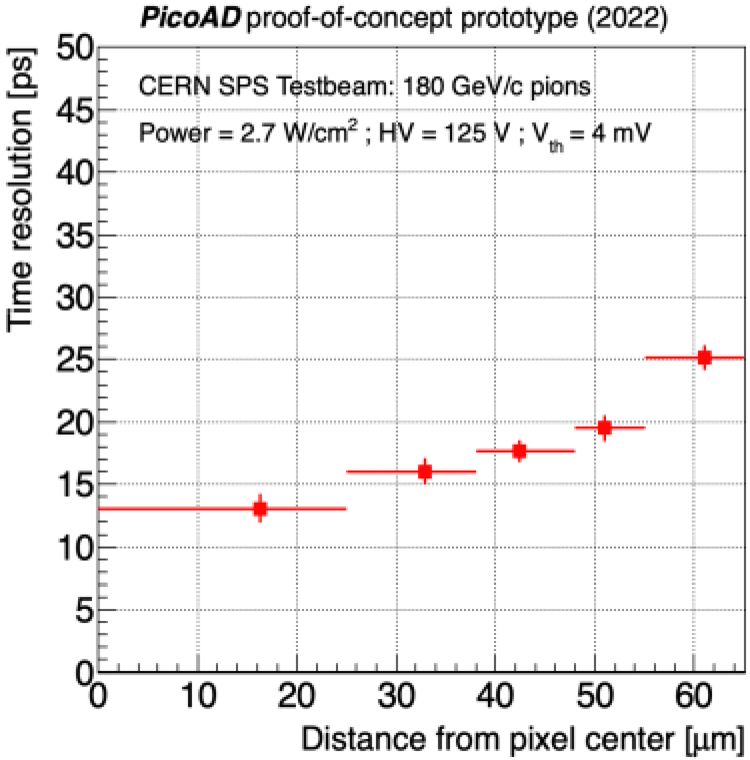


Testbeam PicoAD p.o.c.: Time Resolution

PicoAD

Pixel surface divided in 5 radial areas:

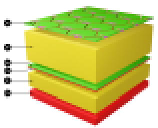




Time resolutions: **13 ps** at the pixel center
25 ps at the pixel edge

To be improved in future prototypes.

PicoAD p.o.c. — Summary & Outlook



The PicoAD© sensor works *(JINST 17 (2022) 10 P10032 ; JINST 17 (2022) 17 P10040)*

Testbeam of the monolithic proof-of-concept ASIC provided:

- **Efficiency = 99.9 %** including inter-pixel regions
- **Time resolution σ_t = (17.3 ± 0.4) ps**
  13 ps at center and **25 ps** at pixel edge
  (although sensor not yet optimized for timing)

New PicoAD prototypes optimised for timing back from foundry in **October 2023**

Deliverable of MONOLITH ERC project:

- Full-reticle monolithic ASIC in **Summer 2025** with 50µm pitch and 10ps timing

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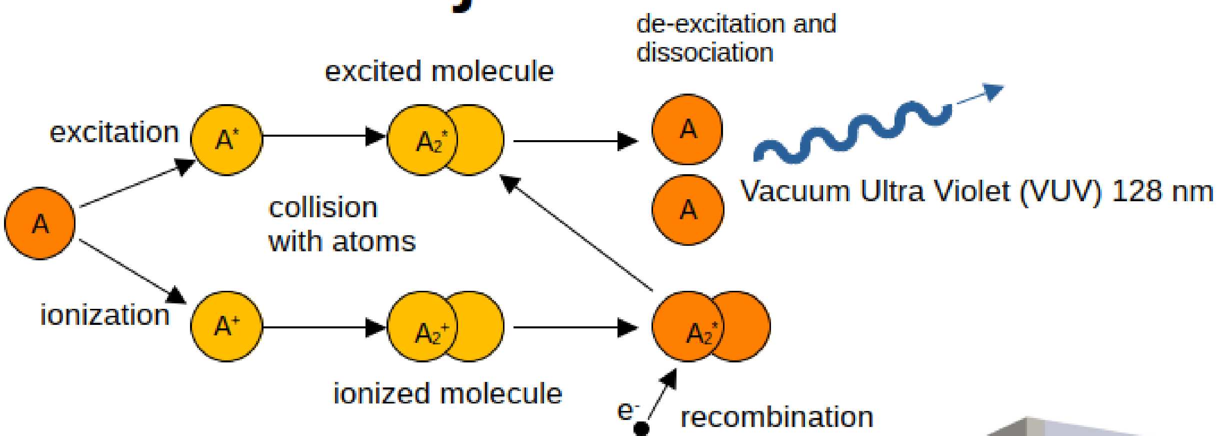
SoLAr: A future LAr TPC to detect MeV-scale neutrinos

Jan Kunzmann, on behalf of SoLAr collaboration
jan.kunzmann@unibe.ch

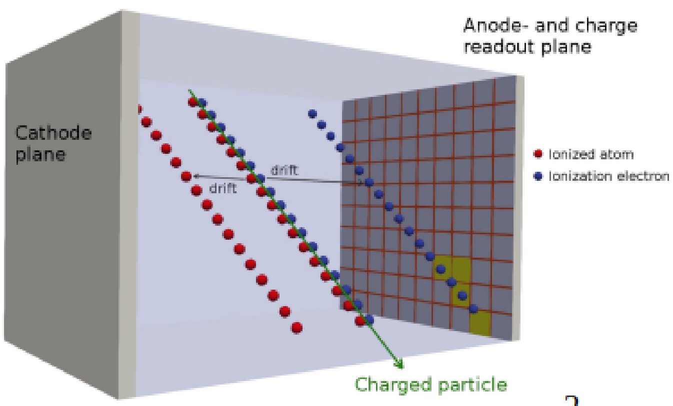
University of Bern
LHEP

IPRD 2023, Siena

Time Projection Chamber



- An electrical field drifts the electrons to the anode plane.
- On the anode plane is an electrical 2D readout.
- The scintillation light is used to measure drift time of the electrons.
- This gives the distance of the track to anode plane.
- A TPC is able to do 3D track reconstruction.



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https://argoncube.org/LArTPCs.html

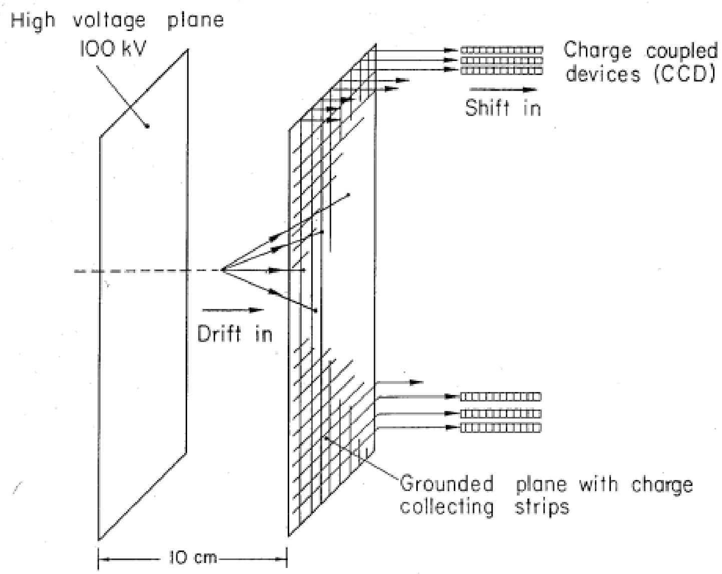


Fig. 9

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

SoLAr Solar neutrinos in Liquid Argon

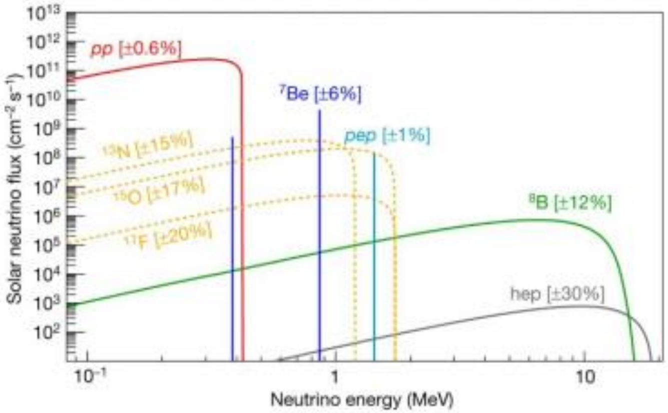
Novel detector concept:

- MeV-scale events are online detectable in space and time.
- The detector concept can be used for a large LAr-TPC.
- A true 3D reconstruction is possible with a pixelated charge readout anode plane.
- An array of VUV (Vacuum Ultra Violet) SiPMs (Silicon Photon Multiplier) on the same anode plane is capable to do 3D reconstruction from light.
- The combination of the two readout systems will be able to do online localized triggering to deal with the high data rates.

S. Parsa et al., SoLAr: Solar Neutrinos in Liquid Argon. arXiv:2203.07501. August 25, 2022

Physics motivation:

- The detection of the Solar hep neutrinos and other low MeV energy scale particles.
- Supernova neutrino bursts will be detectable.



The Borexino Collaboration. Comprehensive measurement of pp-chain solar neutrinos. Nature 562, 505–510 (2018).

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SoLAr

Main challenges for MeV energy scale physics

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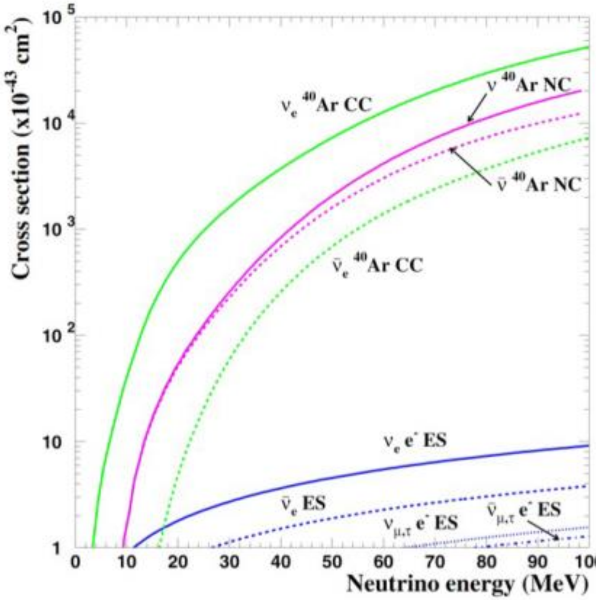
- An excellent energy resolution is essential.
- For the full detector size a good MeV energy calibration is needed.
- The low-energy background needs to be identified efficently.
- Neutrino flavors have to be tagged.
- Neutrino directions should be reconstructed.
- An efficient event reconstruction is needed for the online triggering.



Supernova Neutrinos at the DUNE Experiment, Amanda Weinstein and for theDUNE Collaboration 2020 J. Phys.: Conf. Ser. 1342 012052

For low energy the cross section of neutrinos with liquid argon decreases. A good detection and identification is needed.

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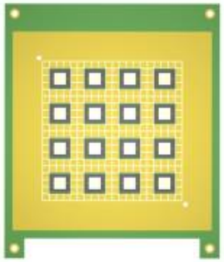
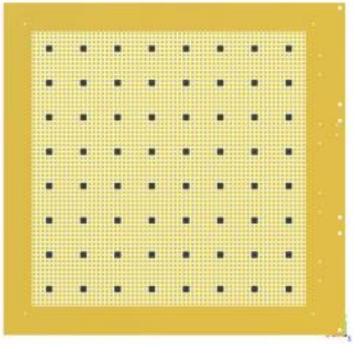
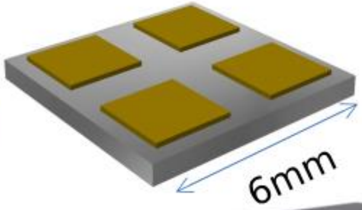
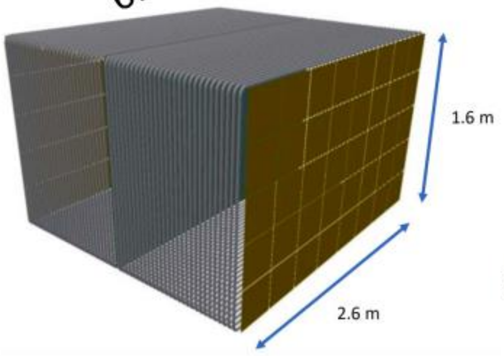
Road map of SoLAr

- Small scale SoLAr prototype-v1 @Bern **(successful test in October 2022)**
  - 7 cm x 7 cm anode plane (3 stacked PCB)
  - 16 VUV SiPMs with ceramic package and pins
  - 4 LArPix-v2a chips
- Small scale SoLAr prototype-v2 @Bern **(successful test in July 2023)**
  - 30 cm x 30 cm (1 PCB)
  - 64 SMD packaged VUV SiPMs
  - 20 LArPix-v2b chips (space for 64 chips)
- Small scale prototype with improved SiPMs (charge pads on top)
  - R&D and collaboration with Hamamatsu and/or FBK
  - Test of alternative readout chips
- Mid scale, SoLAr Demonstrator @Boulby (2025-2028?)
  - Few-ton scale LAr detector underground (Boulby, UK, 1100 m overburden)
  - 30 × 30 cm^2 readout anode tiles (≈ 6400 pixels/tile)
  - First measurement of flavor tagged solar neutrinos in LAr









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SoLAr Electric field simulation around SiPMs

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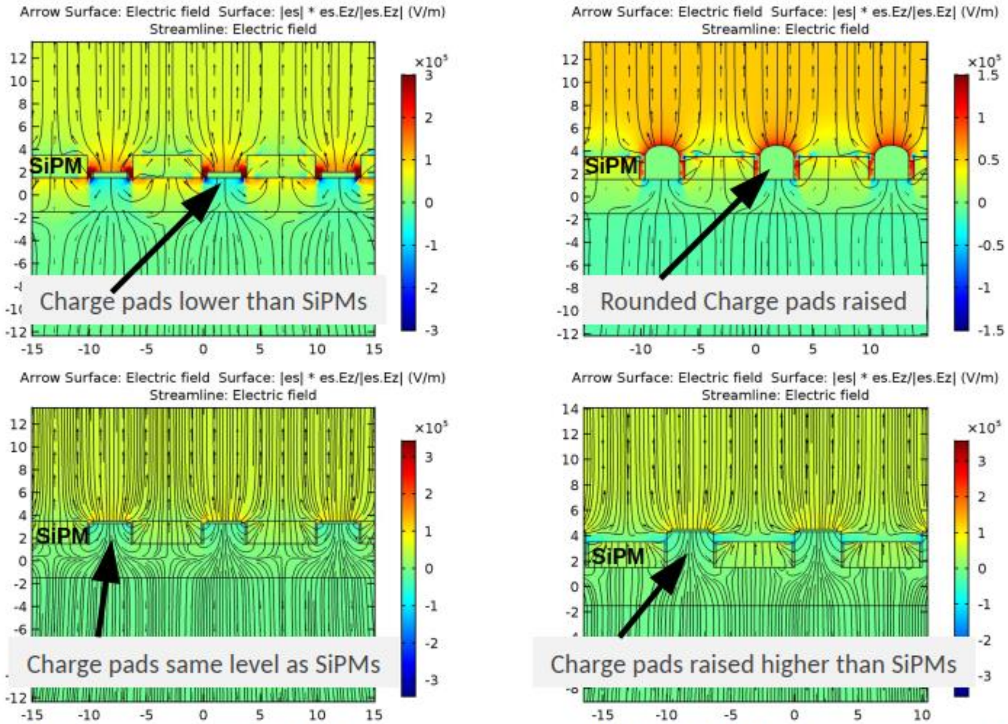
- Simulations of the electric field performed with Comsol for different heights of charge pixels.
- A homogeneous electric field can be realized even with SiPMs on the anode plane.
- To float the SiPMs on a different negative voltage level could deflect more electrons towards the charge pixels.



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by Nikola McConkey and Guilherme Ruiz Ferreira

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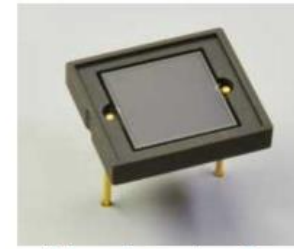
SoLAr prototype-v1

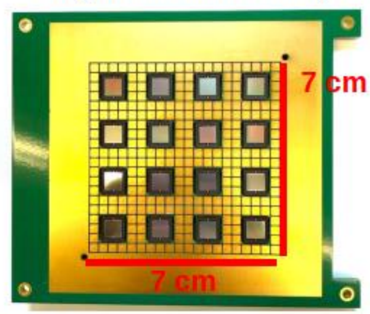
- A small scale LAr TPC with an anode plane that collects the charge on pixels and the light in VUV pin SiPMs directly.
- The set-up allowed to put the SiPMs on a floating voltage level.
- The test set-up is used to
  - Investigate charge accumulation on SiPMs.
  - Check for crosstalks between the readouts.
  - Observe cosmic muon tracks.

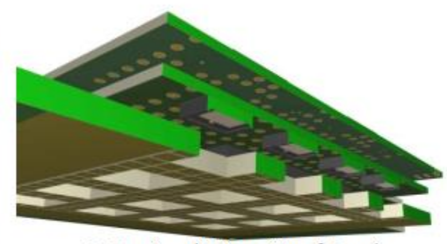
- SiPM type: Hamamatsu S13370-6050CN
- Ceramic packaged with pins
- 15 % PDE for 128 nm, VUV



link to the product flyer

- On a single PCB the pins would interfere with the LArPix ground pads
- A stackup of 3 different PCBs that are soldered together solves the problem





C. Tognina (University of Bern)

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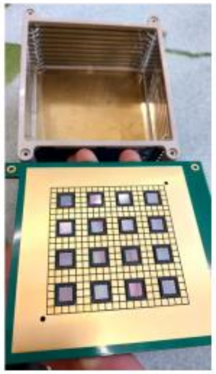
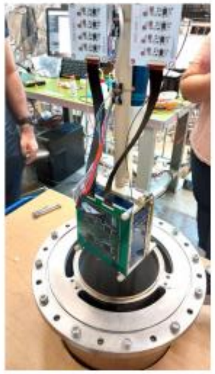
Final design of the SoLAr prototype-v1

- The TPC took cosmic rays measurement in Bern from 24.-26. October 2022 (~24 h operation).
- Continuous measurements are performed.
- The data taking is split into runs of about 10 min.
- A few 10 min runs with different floating voltage levels for the SiPMs were performed.

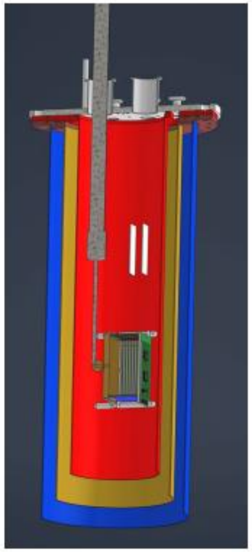


Inside the TPC

SoLAr-v1 TPC



Insertion into cryostat



Drawing of a cut through the cryostat

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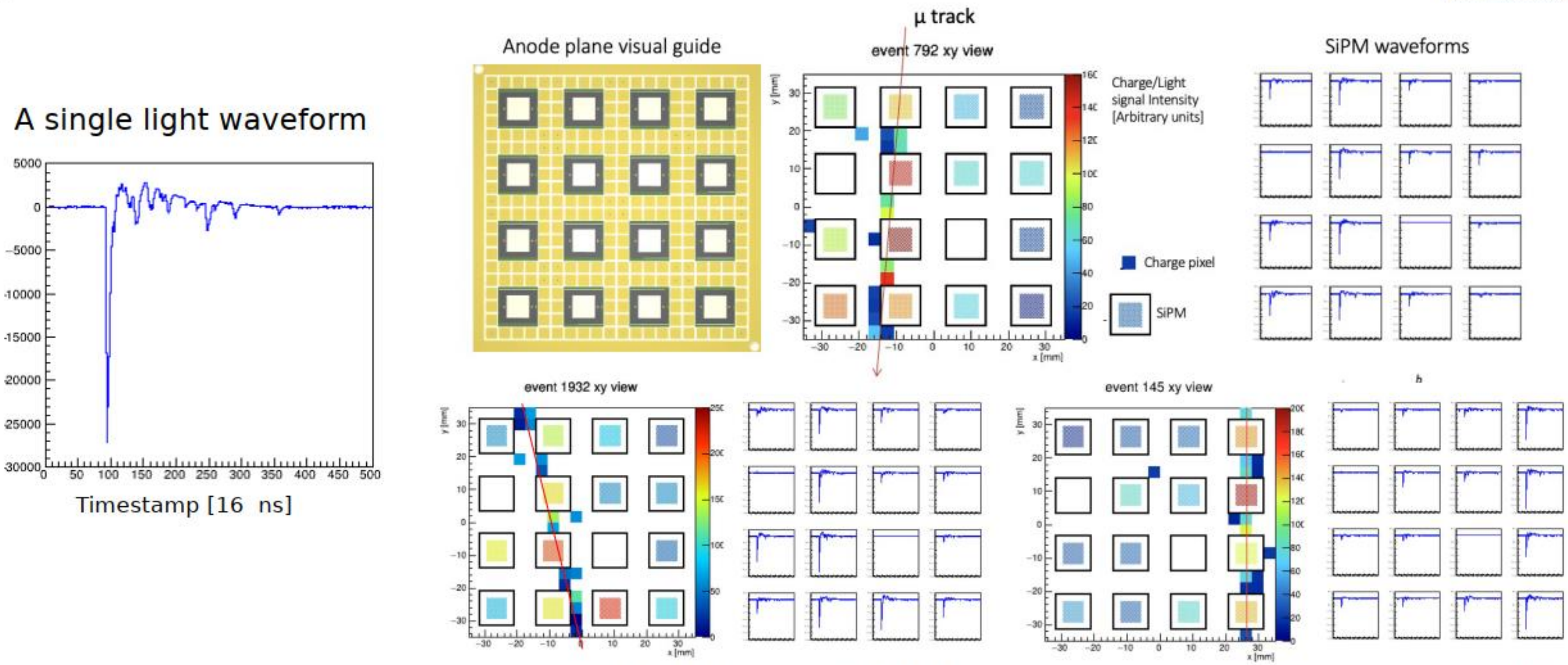
First results of the SoLAr prototype-v1 cosmic run



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SoLAr Final design of the SoLAr prototype-v2

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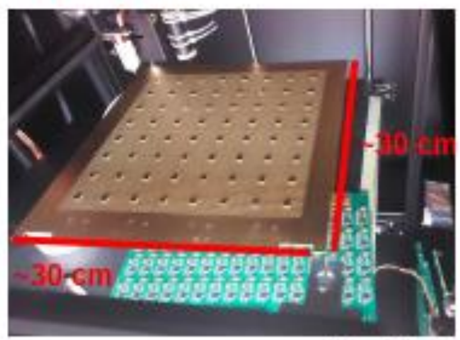
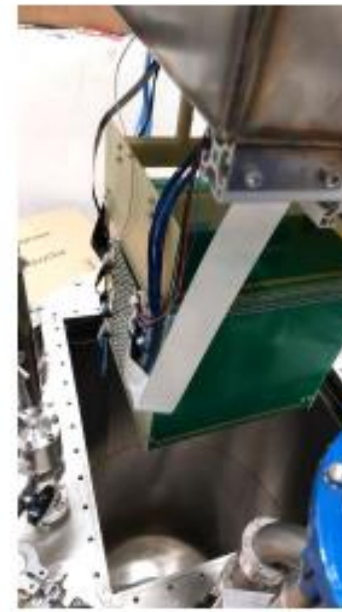
- One single PCB with LArPix and VUV SiPMs routed.
- 64 SMD Hamamatsu VUV SiPMs
- The test set-up is used to
  - Investigate charge accumulation on SMD SiPMs
  - Check for crosstalks between the readout
  - Observe longer cosmic muon tracks



Warm SiPM test in a blackbox

Inner view of the TPC



Insertion into cryostat

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SoLAr Final design of the SoLAr prototype-v2

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- Cosmic rays were tracked in Bern from 3. to 10. July 2023.
- The SoLAr prototype-v2 tile was assembled in a single cube setup.
- The test was performed in the single module cryostat at Bern.

CAD drawing of the cube TPC

The cube TPC assembled and hanging on the top flange

The laboratory at University of Bern with the LAr cryostat

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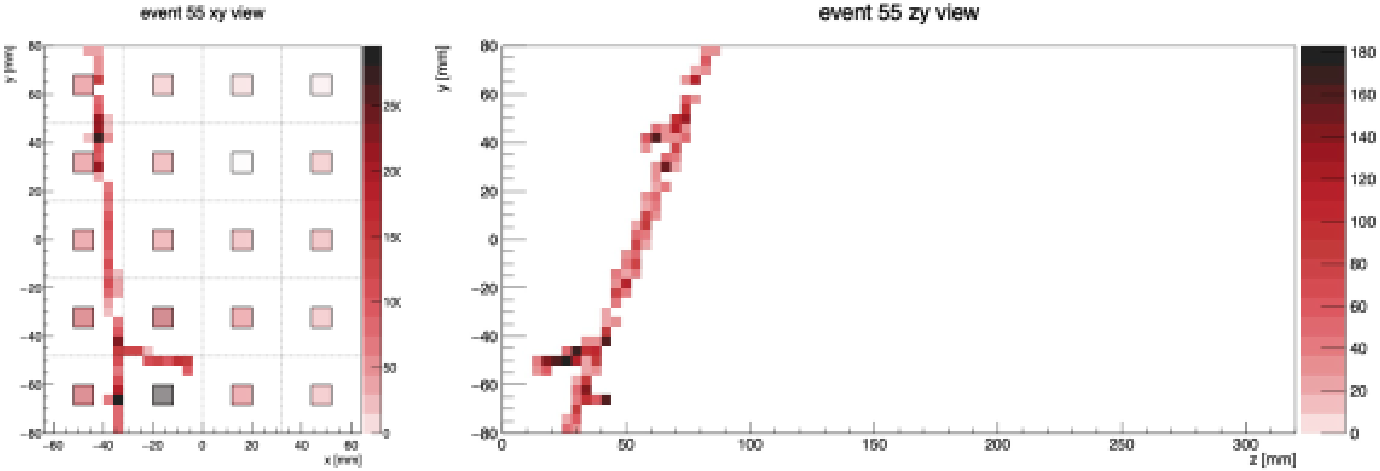
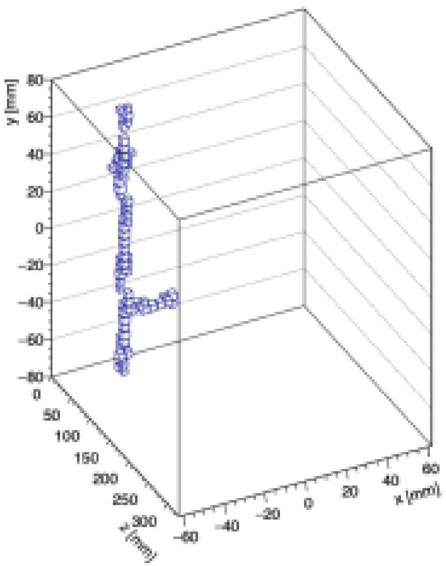
Light and charge combined 3D display of a cosmic muon track

- Anode plane is located at z=0
- SiPMs are visualized as square boxes in the xy view
- SiPMs relative light intensity is presented as fill color (arbitrary units)





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Outlook

- Future R&D and prototyping program aims to benchmark new technology and delivers a SoLAr cell unit with charge pads implemented on the surface of a VUV SiPM device.
- Simulation efforts in progress (understanding background sources, developing mitigation strategies, quantifying the sensitivity to solar neutrinos > 5 MeV).
- A medium scale demonstrator @Boulby would aim to satisfy the requirement of tracking and calorimetric resolutions for low neutrino energy physics.
- Integrate the SoLAr design concept in the DUNE Module of Opportunity.

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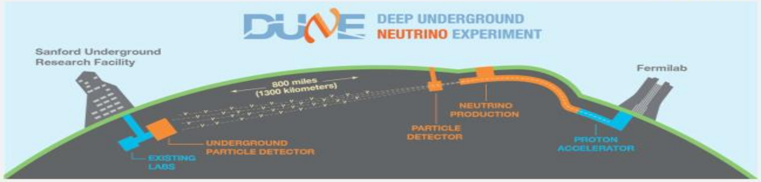
Deep Underground Neutrino Experiment (DUNE)



Long baseline oscillation experiment (1285 km)

- Measure unoscillated ν beam at near detector (ND)
- Measure oscillated ν beam at far detector (FD)

Main goals

- Explore CP violation in the leptonic sector
- Resolve the hierarchy of ν mass eigenstates
- Non-beam physics (e.g. supernova ν)

How to improve uncertainties?

- Unprecedented intensity ν_μ ($\bar{\nu}_\mu$) beam: 2.4 MW
- High detector mass: 4x10kt FD, 67t ND
- Reduce systematic errors with advanced near detector

Absorption muography as a support technique for non-invasive research and three-dimensional localization of tombs in archaeological sites: a case study from Palazzone Necropolis (Perugia - Italy)

Diletta Borselli[1,2], Tommaso Beni[2,4], Lorenzo Bonechi[2,3], Massimo Bongi[2,3], Roberto Ciaranfi[2], Vitaliano Ciulli[2,3], Raffaello D'Alessandro[2,3], Livio Fanò[1,5], Catalin Frosin[2,3], Sandro Gonzi[3], Luca Lombardi[4], Laura Melelli[1], Andrea Paccagnella[2,3] and Maria Angela Turchetti[6]

[1]University of Perugia, Department of Physics and Geology, Italy, [2]INFN-FI, Florence, Italy (borsellid@fi.infn.it), [3]University of Florence, Department of Physics and Astronomy, Florence, Italy

[4]University of Florence, Department of Earth Sciences, Florence, Italy

[5]INFN-PG, Perugia, Italy

[6]Ministry of Culture Regional Directorate of Museums Umbria, Necropolis of Palazzone, Perugia, Italy

University of Perugia

INFN FI, PG

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MiC DIREZIONE GENERALE MUSEI

Direzione Regionale Musei Umbria

Volumni Hypogeum

Absorption muography at the Palazzone necropolis (Perugia-Italy)

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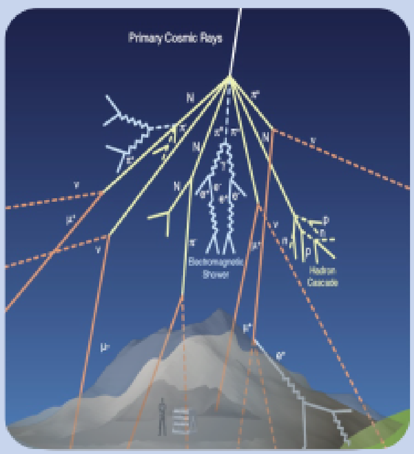
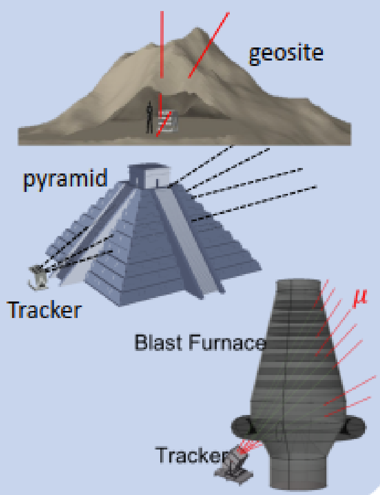
The Technique:

Muon radiography is an imaging technique that allows to create 2D or 3D images of the target density distribution through measurements of atmospheric muon absorption in the target. The detectors used are charged particle trackers.

The Muon Radiography Technique

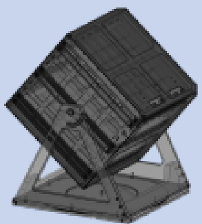
- ✓ Same operating principle as X-ray radiography
- ✓ Non-invasive technique
- ✓ Atmospheric muons free source
- ✓ Many fields of application:



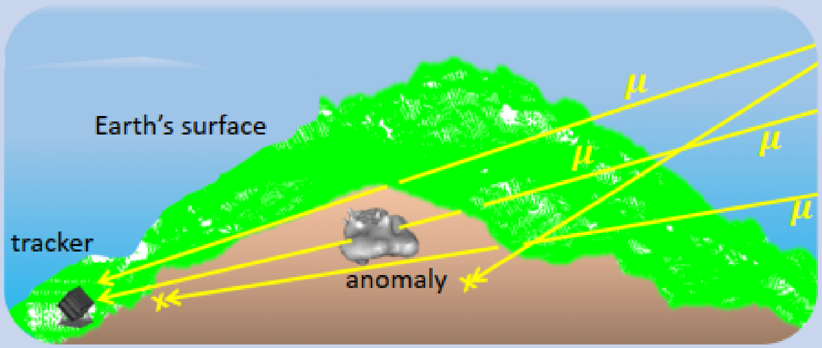


Search for low density anomalies within an archaeological site

- ✓ mapping of cavities in the areas
- ✓ possibility of finding unknown cavities
- ✓ possibility of re-evaluating the archaeological site



tracker



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First use of muon tomography: L.W. Alvarez et al., Search for Hidden Chambers in the Pyramids, Science 167 (1970) 832.

Absorption muography at the Palazzone necropolis (Perugia-Italy)

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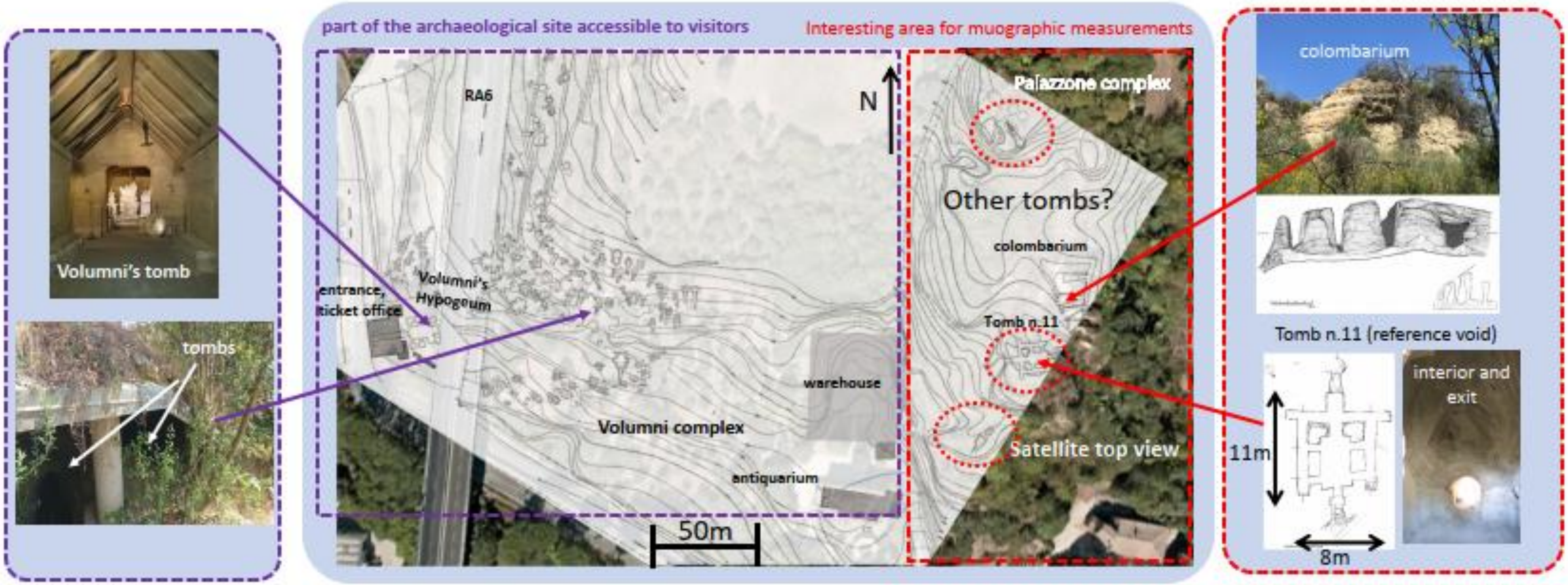
Archaeological site:

The archaeological site is only partially known: the area not accessible to the public (east area) may contain tombs not yet discovered



Interesting area for muographic measurements:

- not open to the tourist route, not fully inspected
- known voids including the very large tomb n.11, reference void for the technique

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2

Muon tomography

Absorption muography at the Palazzone necropolis (Perugia-Italy)

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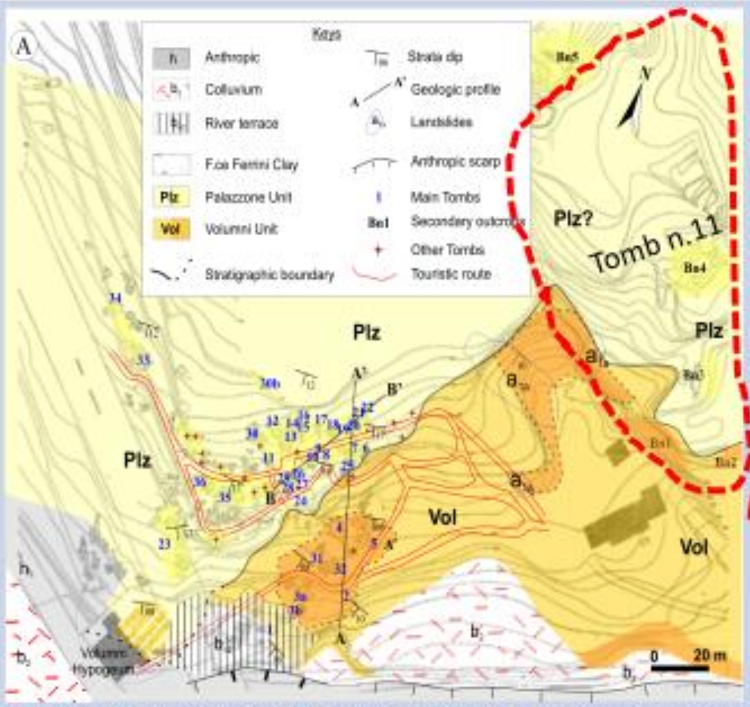
Palazzone as an Archeo-Geosite



Ref: Melelli L. et al. ARCHAEO-GEOSITES IN URBAN AREAS: A CASE STUDY OF THE ETRUSCAN PALAZZONE NECROPOLIS (PERUGIA, CENTRAL ITALY). Alpine and Mediterranean Quaternary, 31(2):207–219, 2018

Two main lithologies: Volumni Unit and Palazzone Unit.

Volumni complex: prevailing gravel conglomerates

Palazzone complex:
prevailing sand with conglomerate

Tomb n.11

Sample of material inside the tomb no 11 (Palazzone Unit):
Density $\rho = (2.061 \pm 0.006)\text{g/cm}^3$

The area monitored with the muographic measurements is mainly within the Palazzone Unit with density range 1.8-2.3 g/cm³

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3

Absorption muography at the Palazzone necropolis (Perugia-Italy)

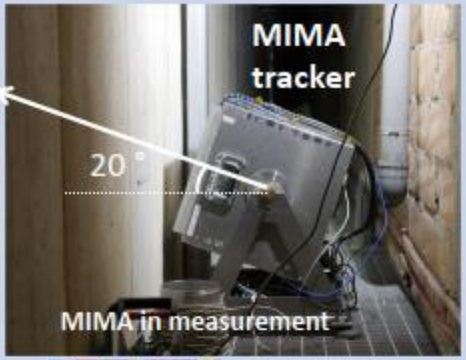
Installation of the MIMA tracker at the necropolis :

Installation: 13/05/2022

2 months of data collection

MIMA is inside the warehouse and «looks» at the Palazzone hill

Satellite View



The MIMA muon tracker (**M**uon **I**maging for **M**ining and **A**rchaeology)

Developed between 2016 and 2017 at the INFN in Florence

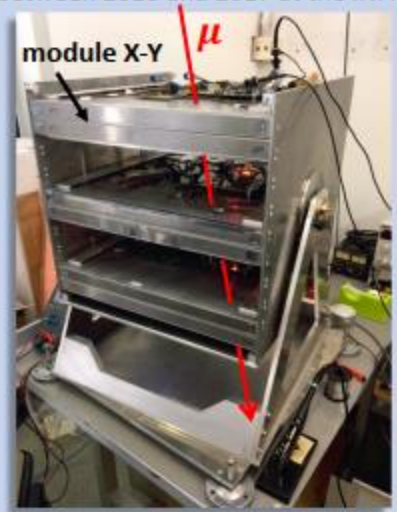


Image from: G. Baccani et al 2018 JINST 13 P11001, doi: 10.1088/1748-0221/13/11/P11001

- **plastic scintillator (triangular section);**
- **spatial resolution 1.5 mm;**
- **angular resolution 0.3 °;**
- **cube (50 x 50 x 50) cm³;**
- **light sensor: SiPM**

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Absorption muography at the Palazzone necropolis (Perugia-Italy)

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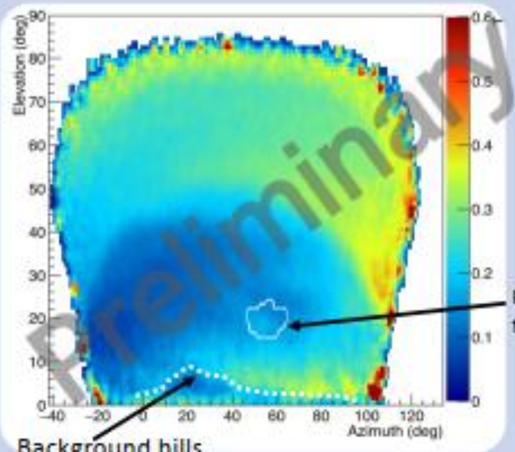
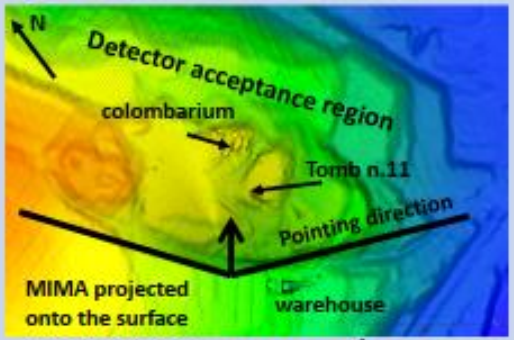
Measured muon transmission:

Measured Transmission



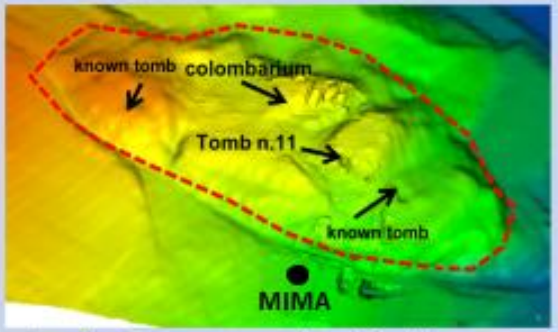
- The measured transmission increases to the right consistently with the decrease in the thickness of the hill

The dependence on the conformation of the hill remains →comparison with simulations to find unknown cavities



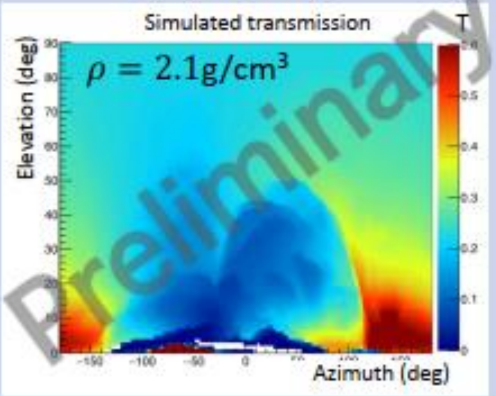
the colors reproduce the altimetry

Geometry for simulation and simulated transmission



- Vegetation removal process

Beni T. and et al. Laser scanner and UAV digital photogrammetry as support tools for cosmic-ray muon radiography applications: an archaeological case study from Italy. Sci Rep, (Under review September 2023).



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Absorption muography at the Palazzone necropolis (Perugia-Italy)

2D angular density maps: searching for low density signals

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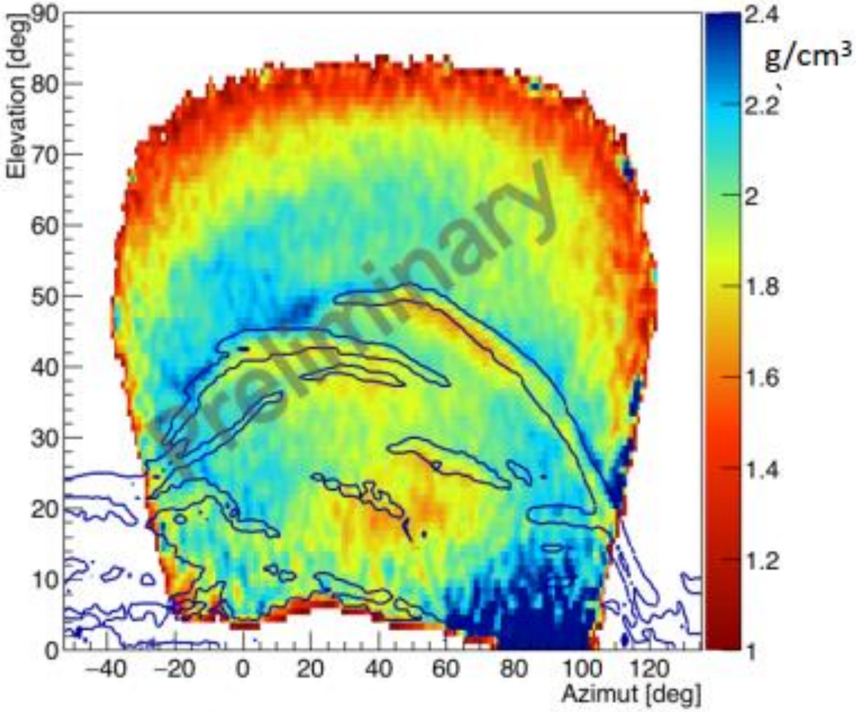
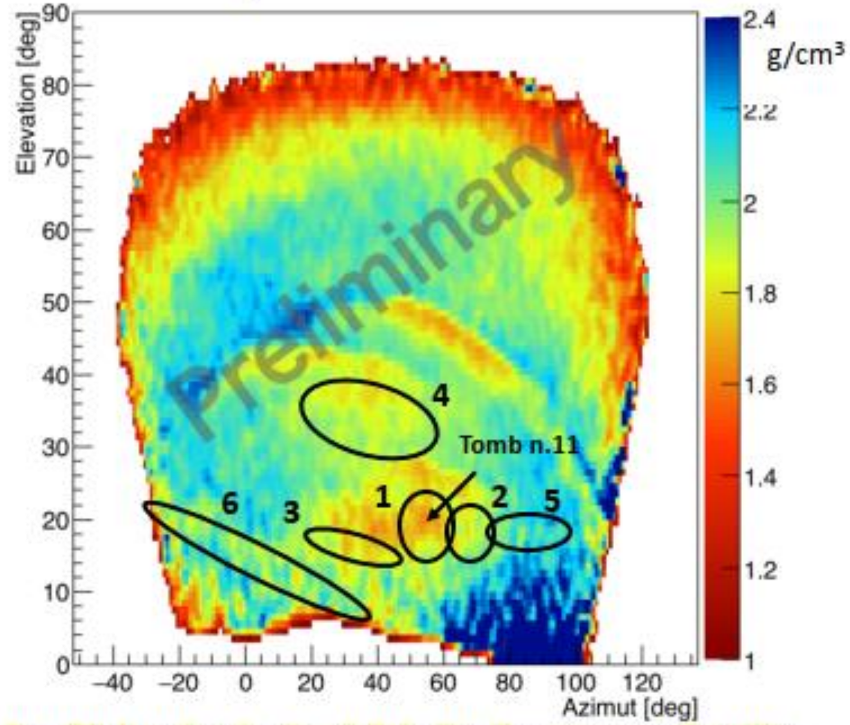
The densities found reflect the values of the materials that make up the Palazzone hill



The lines represent the artefacts that are due to the conformation of the hill and the presence of residual vegetation in the simulation geometry



Possible low density signals linked to the presence of cavities

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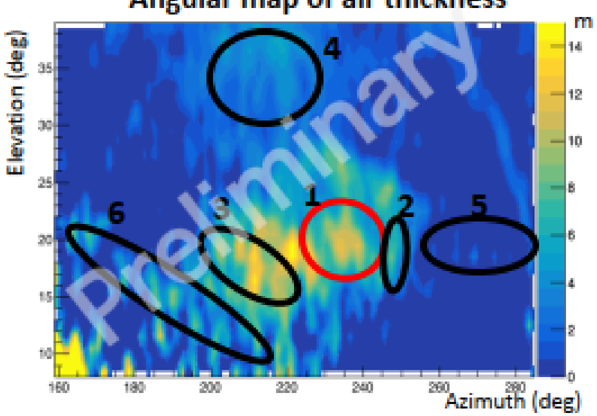
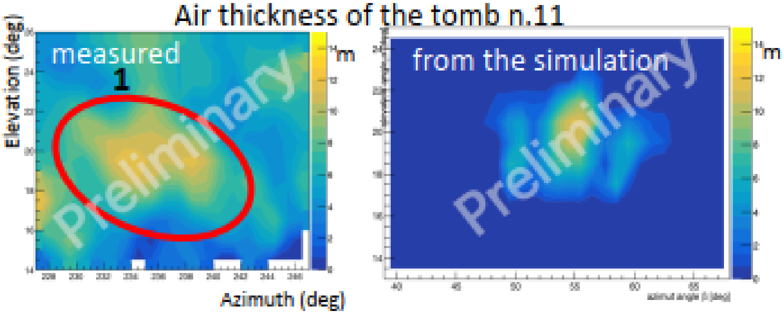
Three-dimensional reconstruction of low density signals: procedure

Angular map of air thickness



The air thickness of some signals is not negligible

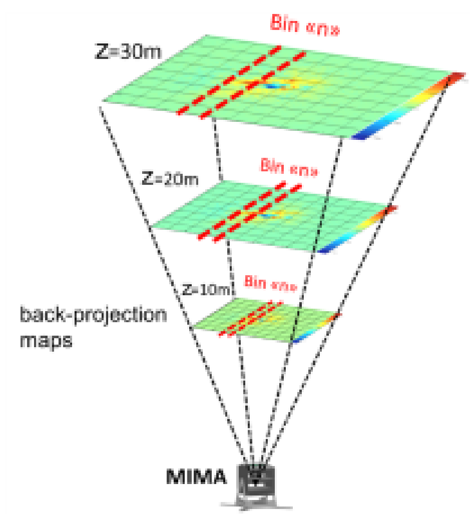
Air thickness of the tomb n.11



The air thickness found for tomb n. 11 is compatible with the real ones

The three-dimensional reconstruction is underway and takes advantage of the back-projection technique which is an image focusing technique

✓ with this technique it is possible to locate the face of the cavity closest to the detector



Ref: Bonechi,L.*et al.* A projective reconstruction method of underground or hidden structures using atmospheric muon absorption data. *J. Instrum.* **10**, P02003. https://doi.org/10.1088/1748-0221/10/02/p02003 (2015).

Ref: Borselli, D., Beni, T., Bonechi, L. *et al.* Three-dimensional muon imaging of cavities inside the Temperino mine (Italy). *Sci Rep* **12**, 22329 (2022). https://doi.org/10.1038/s41598-022-26393-7

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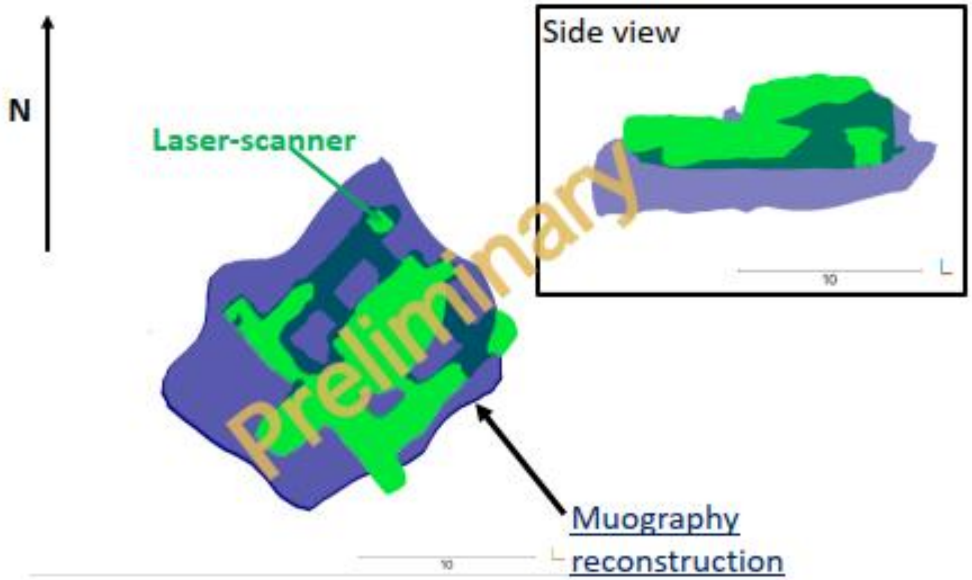
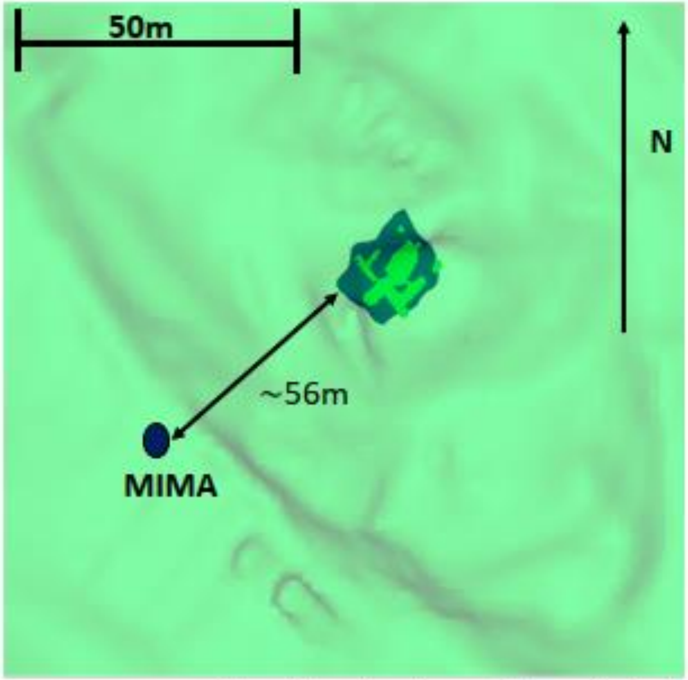
3D reconstruction of the known cavity (Tomb no. 11): test of the technique

With the back-projection technique the signal of Tomb n.11 is reproduced in 3D quite faithfully both in position and in volume at a distance from the detector of 56 m.





the other signals are being studied with the back projection technique

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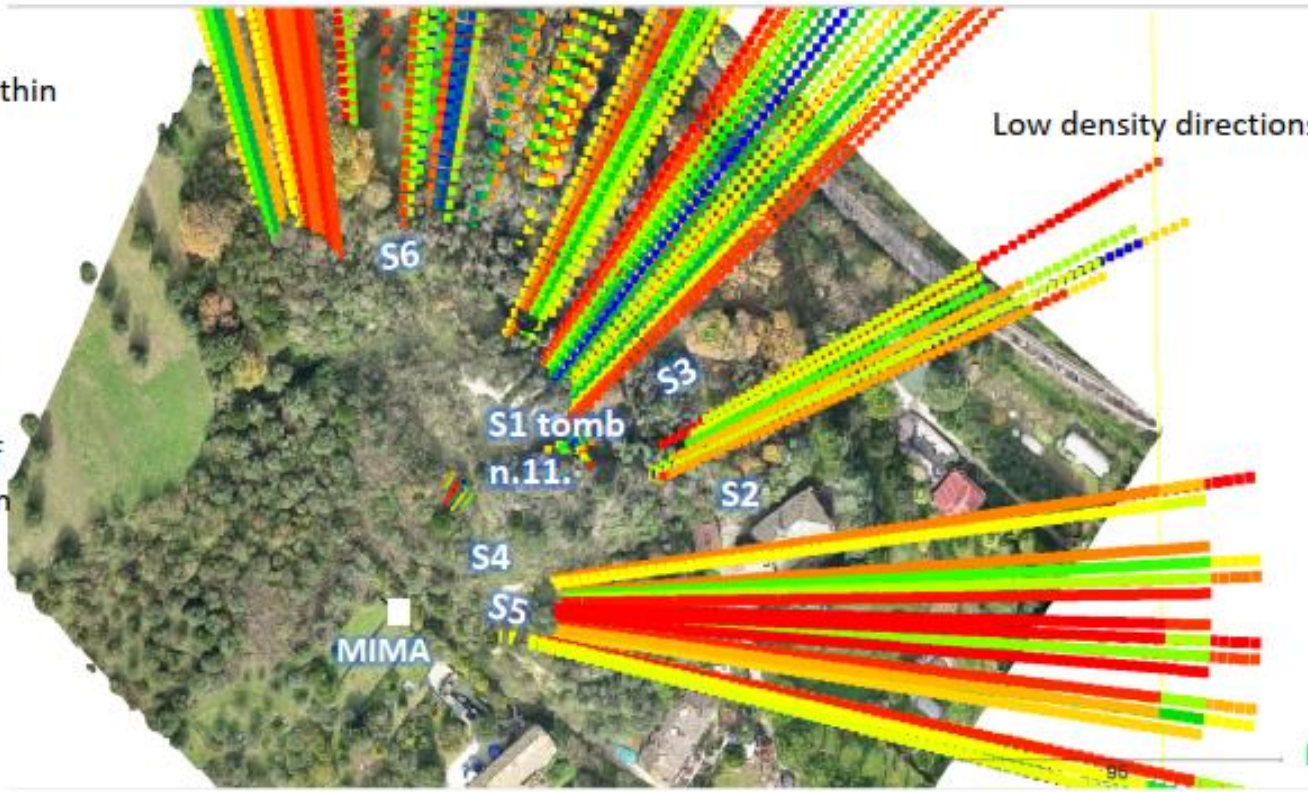
Preliminary research of the areas most likely to find access to cavities

The Etruscan tombs in this archaeological site are all within 5 m of the surface

We can suppose that along these directions in the areas where low density rays are closest to the surface, the probability of the presence of entrances leading to unknown cavities is greatest.



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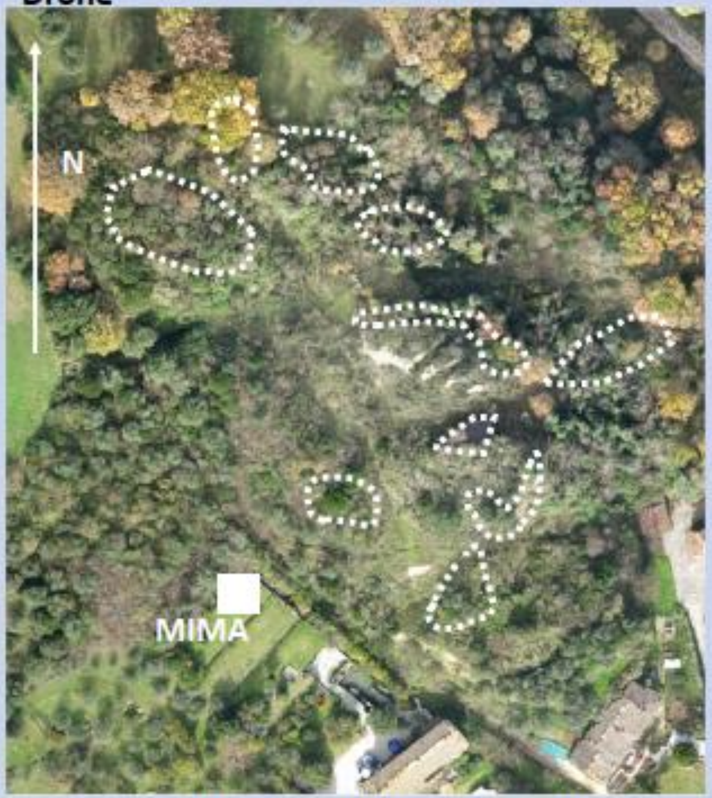
Inspection to search for cavities in the identified surface areas

Drone



areas with higher probability to find cavities

Some cavities found in the areas identified by the muography

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Conclusions:

The muographic measurement at the necropolis of Palazzone was carried out:

- two-dimensional absorption, density and cavity thickness maps were created
    - low-density artifacts are evident due to the imperfect geometry of the simulation
    - the areas of potential signal of cavities external to the artifacts have been defined
- the back-projection algorithm was applied for a three-dimensional reconstruction of the know cavity for a test of the technique with a good precision
- the surface areas most likely to have access to cavities have been defined
- through an inspection, in most of the areas, the presence of cavities found confirmation

Future Developments:

- Application of the 3D reconstruction technique also for other low density signals
- Carry out targeted inspections with archaeologists

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Conclusions – IPRD23 Conference

Very good conference, with many interesting talks

Interdisciplinary approach, with detectors for different applications and useful discussions with attendants

Excellent location, with superb catering

Proceedings published in JINST

THANK YOU