Envisaging the
future of particle
detection

TIMESPOT

Adriano Lai
INFN Sezione di Cagliari

Mini-symposium of High Energy Physics in Cagliari, December 11th 2019

Frontiers in Particle Physics

*and the (street)light-**SPOT** effect…*

Personal (incomplete, intentionally irreverent) view

Exploring the Darkness
Dark particle searches, under the light-spot?

Exploring the Wideness
Gravitational waves, after 30 years, now we learned how to do it !

Exploring the Deepness
Where does the SM fail ?
Higher Luminosities (interaction rates)
Higher Energies (new colliders ?)
New Concept of experiments ?

Is it time to look for a change in basic paradigms of scientific methodology ??

… and in the meantime ?

Street-light effect

L'**effetto lampione** o **street light effect**, è un tipo di distorsione osservativa, che consiste nel cercare qualcosa dove è più facile trovarla.[1][2] Questo tipo di ricerca viene anche detto "ricerca dell'ubriaco", a causa dell'esempio che comunemente si usa per spiegare questo fenomeno.

L'espressione è stata coniata da David H. Freedman, ma la metafora risale almeno al 1964 quando Abraham Kaplan ne parlò chiamandolo il "principio della ricerca dell'ubriaco".[3]

L'esempio della ricerca dell'ubriaco ha numerose versioni, che seguono tutte la stessa struttura:

Un poliziotto vede un ubriaco che cerca qualcosa vicino ad un lampione e gli chiede cosa abbia perso. 'un mazzo di chiavi',risponde l'interpellato. Il poliziotto allora decide di aiutarlo ma dopo alcuni minuti di ricerca infruttuosa chiede all'ubriaco se sia sicuro di aver perso le chiavi vicino al lampione. L'ubriaco risponde di no, e che in realtà le ha perse nel parco. 'Perché le cerchi qui allora, chiede il poliziotto. "... ma perché qui è illuminato!".

Ludwik de Laveaux: Parigi, Place de l'Opéra, 1892

La storiella dell'effetto lampione è in realtà collegata alla tendenza umana a condurre la ricerca della verità attraverso vie semplici evitando la complessità. È difficile trovare un oggetto dove è scuro quindi cerchiamolo dov'è la luce. La ricerca sarà più semplice.

Constatava Galilei che la natura fa uso, in tutte le sue opere, dei mezzi « più immediati, più semplici e più facili». [4] per cui la storia della scienza sino ad oggi è stata il tentativo di ridurre a semplice ciò che appare complesso. [5]

Si è parlato anche dell'eleganza della scienza quando si presenta nella sua semplicità:

> «Che significato possiamo attribuire alla parola "eleganza" in ambito scientifico? Qualcosa di efficace e creativo. Da un lato, capita infatti che una soluzione proposta sia così semplice e chiara da produrre nell'osservatore un'esclamazione di stupore. Dall'altro, la scienza più alta, teorica o sperimentale che sia, riflette sempre una notevole immaginazione creativa. [6]»

«La riducibilità del complicato al semplificato» è stata messa in discussione nel 1947 da Warren Weaver con la sua opera *Scienza e complessità* dove si prospettava il superamento della visione unitaria di un fenomeno che sarà studiato dalla ricerca scientifica contemporanea non più come un'unità elementare ed isolabile, come nell'idea classica di scientificità, ma secondo un modello della complessità, basato sull'idea di relazione e organizzazione della realtà [7].

The crossroad in the desert

… Someone searches the keys under the light spot …
… Someone collects the physics cases around …
… someone stands wondering if physics should be re-founded …
… someone died waiting …
… someone is engaged to develop NEW TECHNIQUES and instruments of discovery…

The crossroad in the desert (2)

Positive attitude

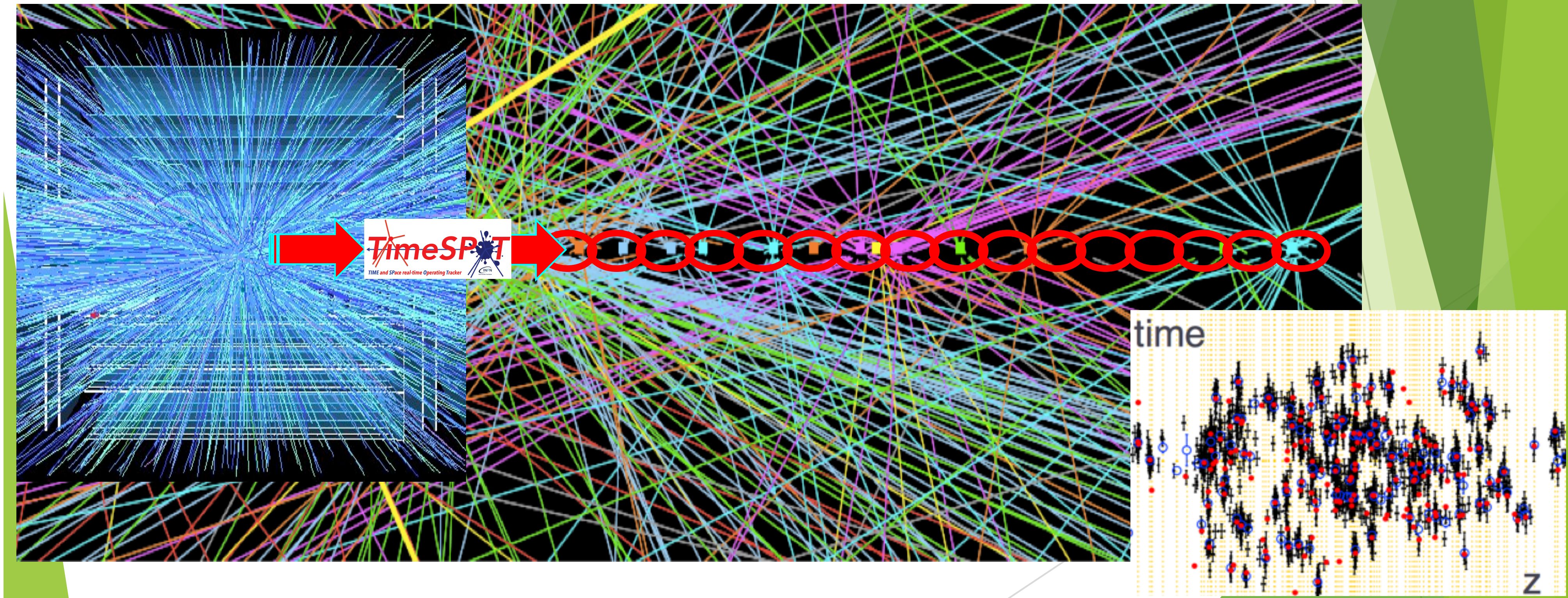
... and, what matters more, HE IS HAPPY !!

Frontiers in particle detection

R&D is a must ! And failure IS an option

Many channels to be investigated. In our specific case:

- Study of new processes for detection of (extremely) small amounts of energy deposit (≈meV) → AXIOMA (2016-18)
- New tracking techniques and vertex detectors: pixel with timing at very high time resolutions → TIMESPOT (2018-20 + 2021)



Structure, organization and objectives of TimeSPOT

Main target:

Develop and realize a demonstrator consisting of a complete yet simplified tracking system, integrating about 1000 read-out channels (pixels), satisfying the following characteristics:

- **Space resolution: O (10 μm)**
- **Radiation hardness: > some 10^{16} 1 MeV n_{eq}/ cm^2 (sensors) and > 1 Grad (electronics)**
- **Time resolution: ≤ 50 ps per pixel (target = 30 ps or better)**
- **Real time track reconstruction algorithms and fast read-out (data throughput > 1 TB/s)**

Activities are organized in 6 work packages: **P.I.: A. Lai, INFN Cagliari**

1. **3D silicon sensors: development and characterization (GF. Dalla Betta Trento)**
2. **3D diamond sensors: development and characterization (S. Sciortino Perugia)**
3. **Design and test of pixel front-end (V. Liberali Milano)**
4. **Design and implementation of real-time tracking algorithms (N. Neri Milano)**
5. **Design and implementation of high speed readout boards (A. Gabrielli Bologna)**
6. **System integration and tests (A. Cardini Cagliari)**

Money: 1 M€
Time: 3 (+1) years

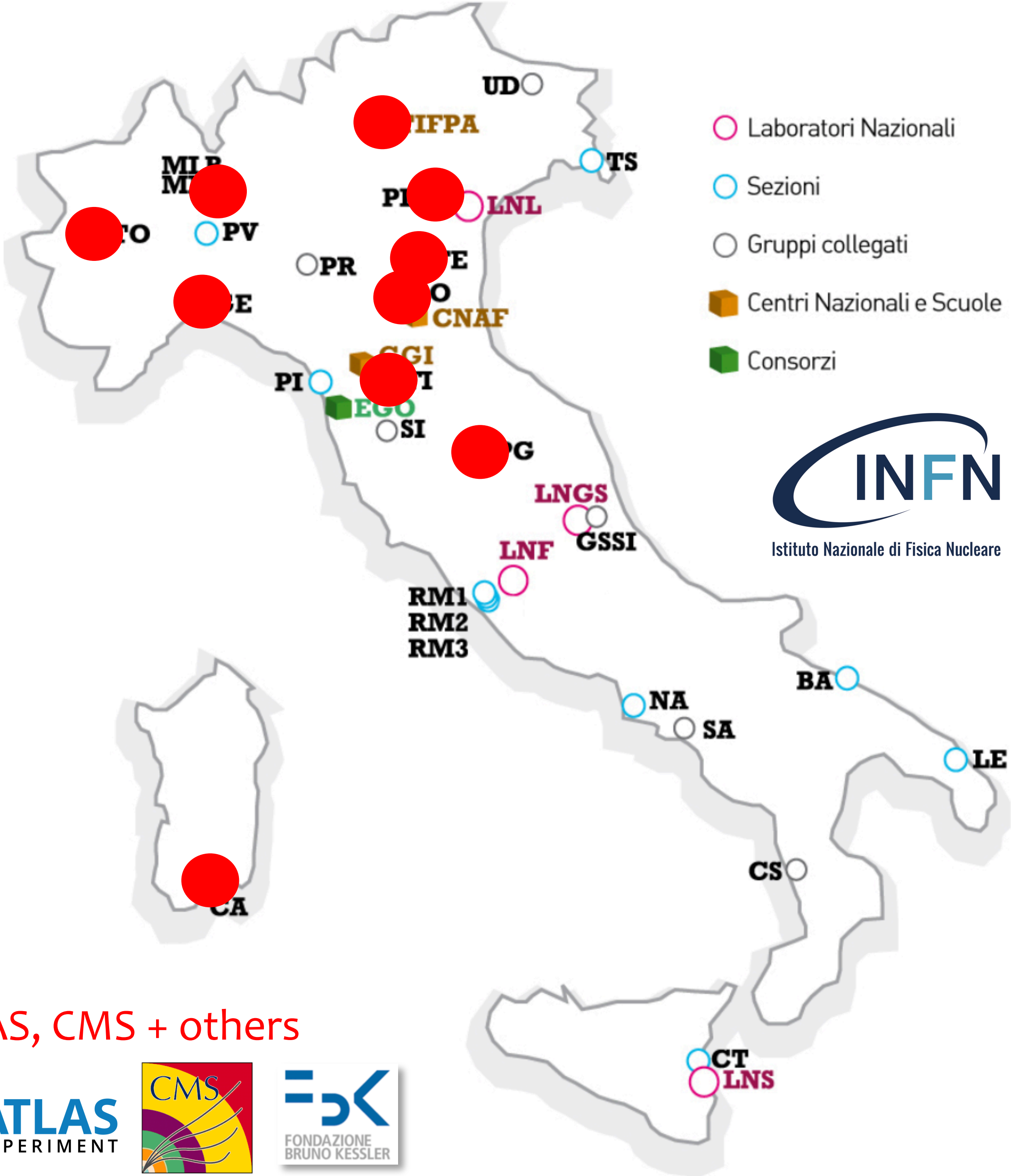
TimeSPOT

TIME and SPace real-time Operating Tracker

Places & people:

Sezioni INFN:

Bologna,
Cagliari (RN)
Genova
Ferrara
Firenze
Padova
Perugia
Torino
TIFPA (Trento)



≈ 60-70 heads,
≈ 20-25 FTE.
People from LHCb, ATLAS, CMS + others

TimeSPOT

TIME and SPace real-time Operating Tracker

TIMESPOT Cagliari Team:

Mauro Aresti	AdR
Davide Brundu	PhD student 3rd year (since December ‘19)
Sandro Cadeddu	INFN staff
Alessandro Cardini	INFN staff
Andrea Contu	INFN staff
Michela Garau	PhD student 1st year
Adriano Lai	INFN staff
Andrea Lampis	PhD student 1st year
Angelo Loi	PhD student 3rd year
Rolf Oldeman	UniCA staff
Gian Matteo Cossu	External collaborator (graduated July 2019)
Ludovica Ricciardi	Undergraduate student

INFN

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Sezione di Cagliari

Additional (satellite, for now) activities

Proposal Title and Acronym
INSTANT
(Imaging iN Space–Time ANd Tracking)

This proposal responds to challenges in the following domains:
Sensors, front and back end electronics

Coordinator's name and email address
Adriano Lai
adriano.lai@ca.infn.it

Consortium Composition Table

	Organization full name	Organization short name / PIC number	Organization type[1]	Contact person name	Contact person email
Coordinator	Istituto Nazione di Fisica Nucleare Sezione di Cagliari – Italy	INFN 999992789	Research Infrastructure	Adriano Lai	adriano.lai@ca.infn.it
Partner 1	Fondazione Bruno Kessler – Trento – Italy	FBK 999625450	Research & Technology Organization	Maurizio Boscardin	boscardi@fbk.eu
Partner 2	Università di Milano - Italy	UMIL 999995796	University	Nicola Neri	Nicola.neri@mi.infn.it
Partner 3	Univesrity of Manchester – Great Britain	UNIVERSITY OF MANCHESTER 999903840	University	Cinzia Da Via	Cinzia.da.via@cern.ch
Partner 4	Università di Trento – Italy	UNITN 999841954	University	Gian Franco Dalla Betta	Gianfranco.dallabetta@unitn.it

TimeSPOT
TIME and SPace real-time Operating Tracker

ATTRACT
INSTANT

Development a Tera-fps video-camera for ionizing radiation, capable of embedded stereo-scopic image reconstruction (tracking) and to sustain extremely high radiation doses and event rates.

Selected for 1st phase (100 k€)
2nd phase selection: end 2020 (5-6 M€)

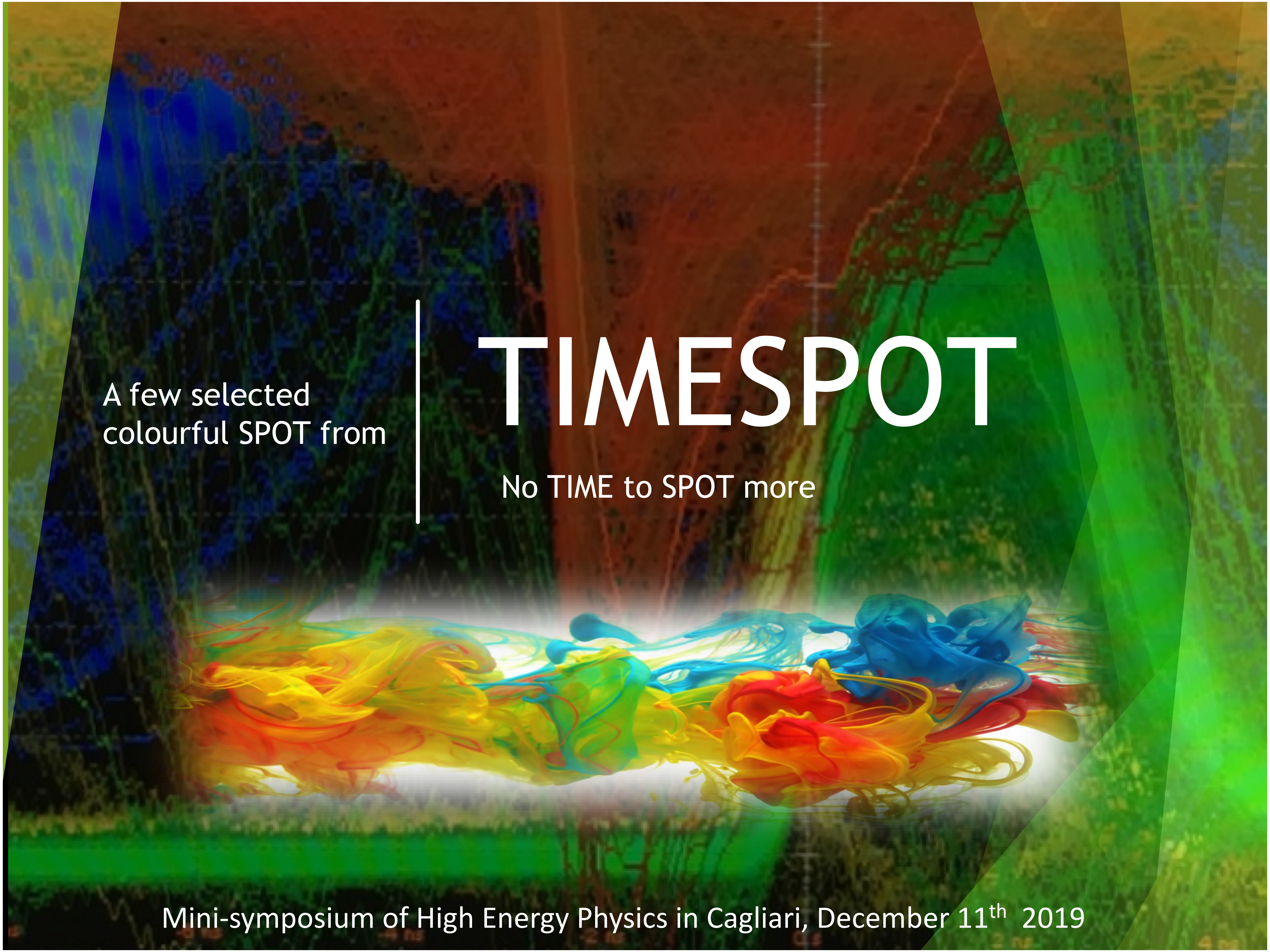
AIDA 2020

AIDA++

Cagliari & Trento
Responsible Institutes for 3D + timing

(100-200 k€, still under finalization: April 2020)

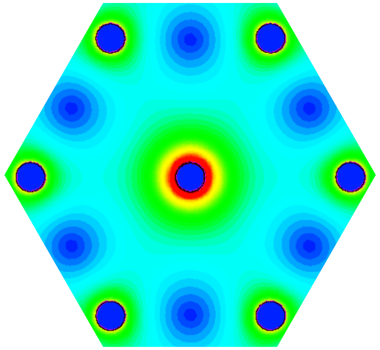
Exploring also other sources of financing
INFN: still far in the future


A few selected colourful SPOT from
TIMESPOT
No TIME to SPOT more
Mini-symposium of High Energy Physics in Cagliari, December 11th 2019

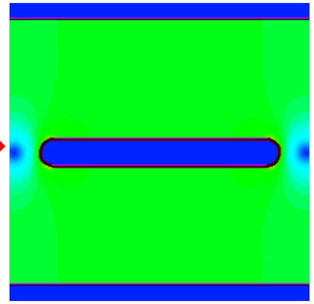
3D Trench geometry and Pixel characteristics

The starting (break-through) point

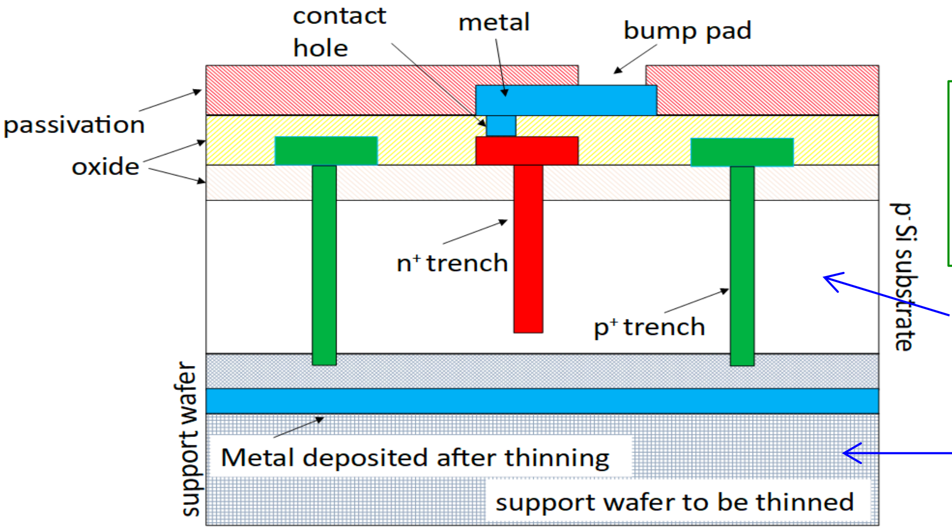
Electric field map



Column geometry (e.g. ATLAS IBL)



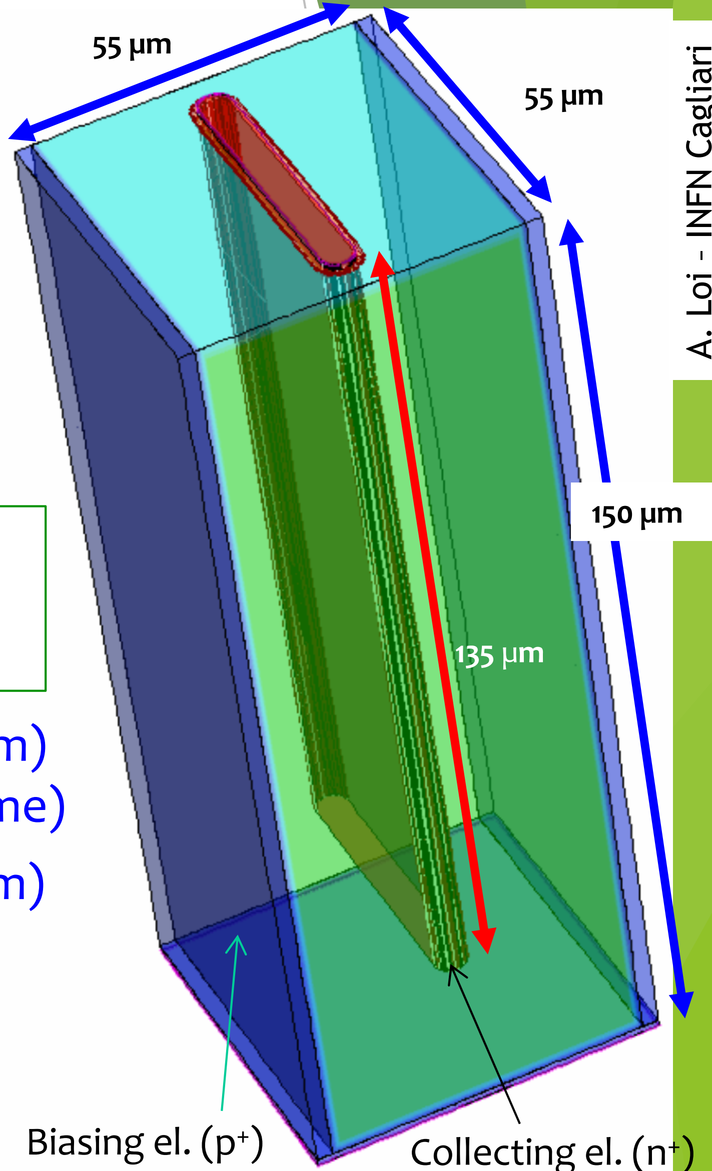
Trench geometry (TIMESPOT)



Single-Side production method

HR Si (~ 5kΩ cm) (sensitive volume)

LR Si (<Ω cm)

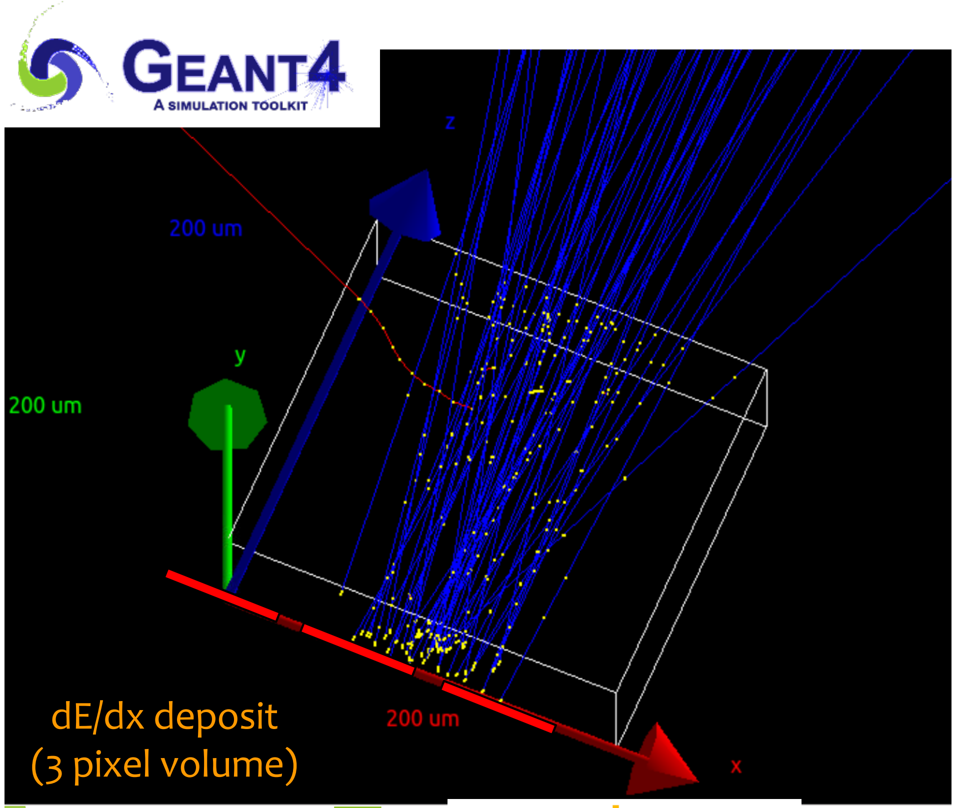


A. Loi - INFN Cagliari

- **Total charge deposit for MIP ≈ 2 fC**
- **Full depletion @ few Volts, Velocity saturation @ > 30 V**
- **Pixel capacitance (from simulation) ~140 fF**

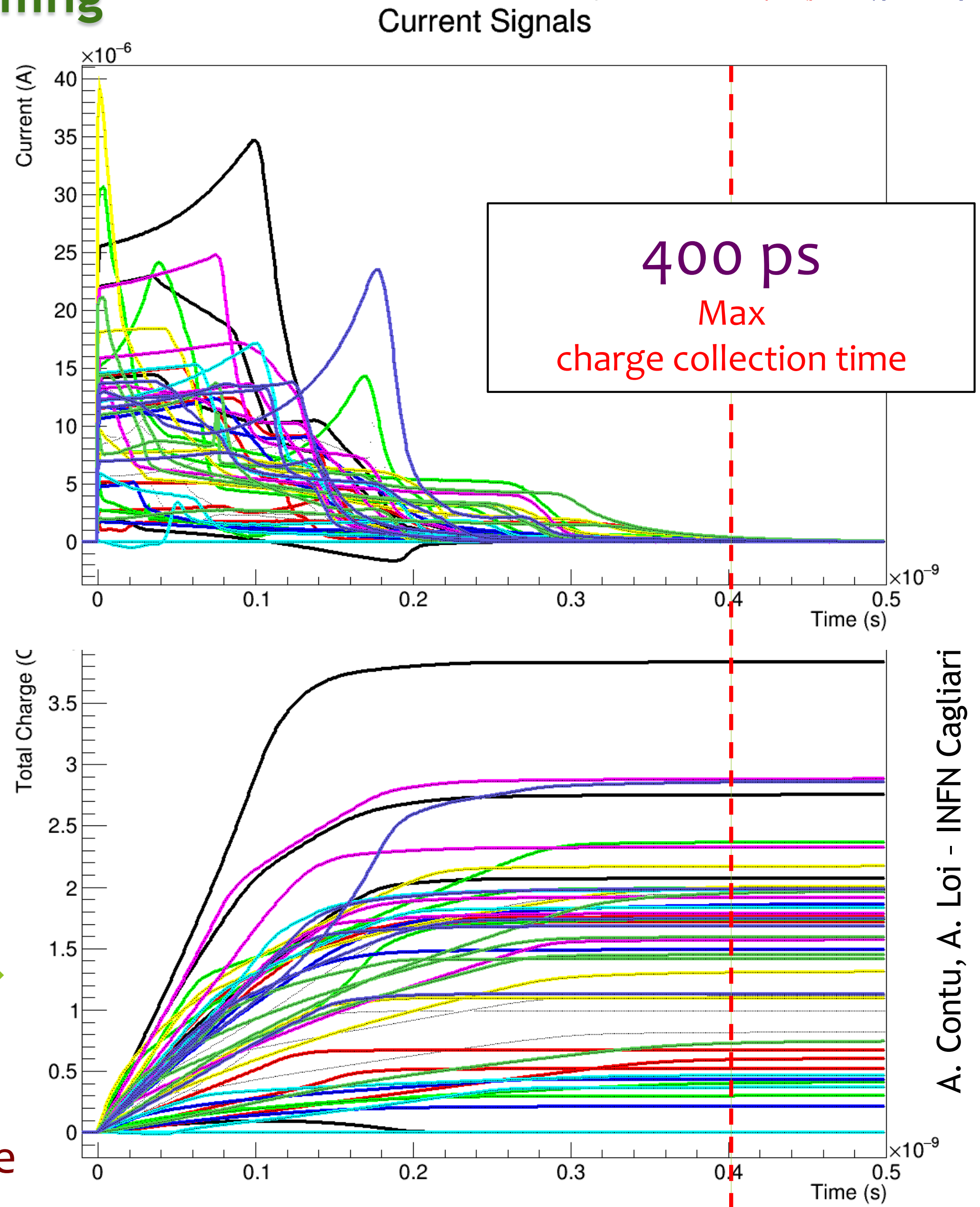
Full sensor model and signal

Sensor performance in terms of timing



TCoDE
TimeSPOT Code for Detector simulation

https://github.com/MultithreadCorner/Tcode

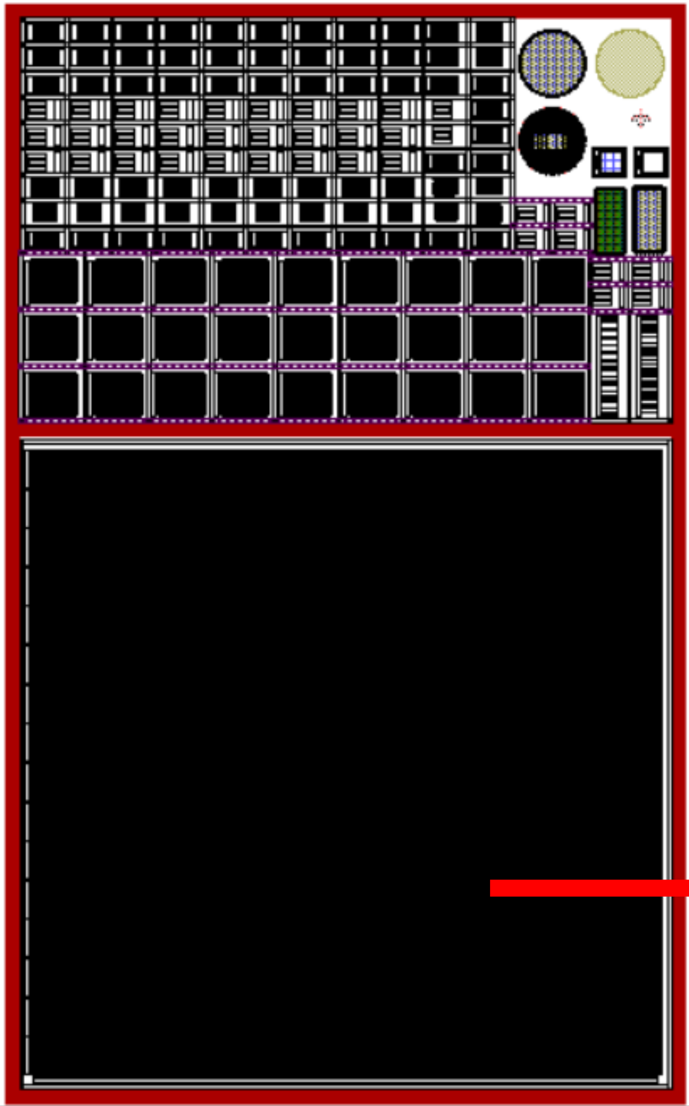


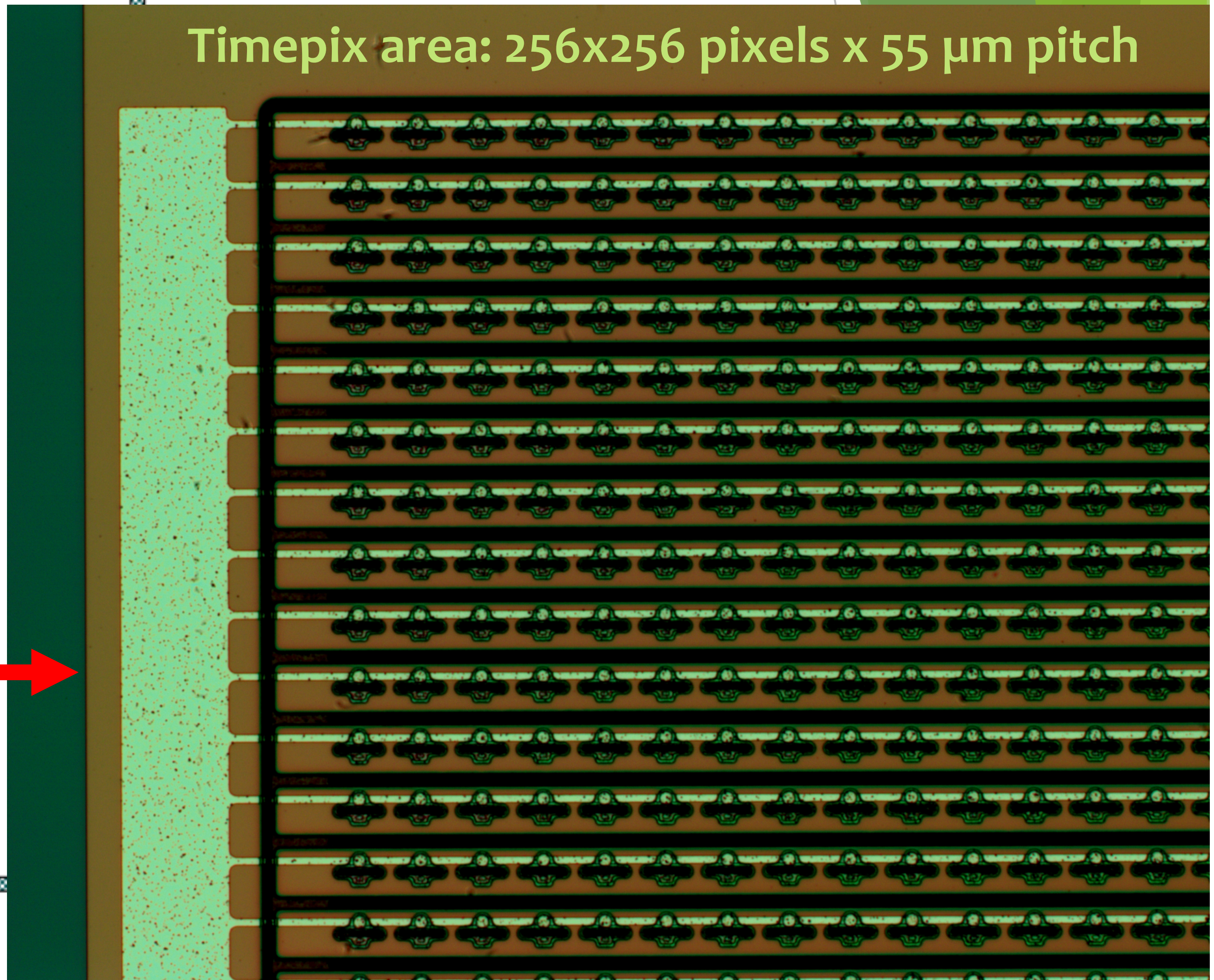
A. Contu, A. Loi - INFN Cagliari

1st 3D-trench batch

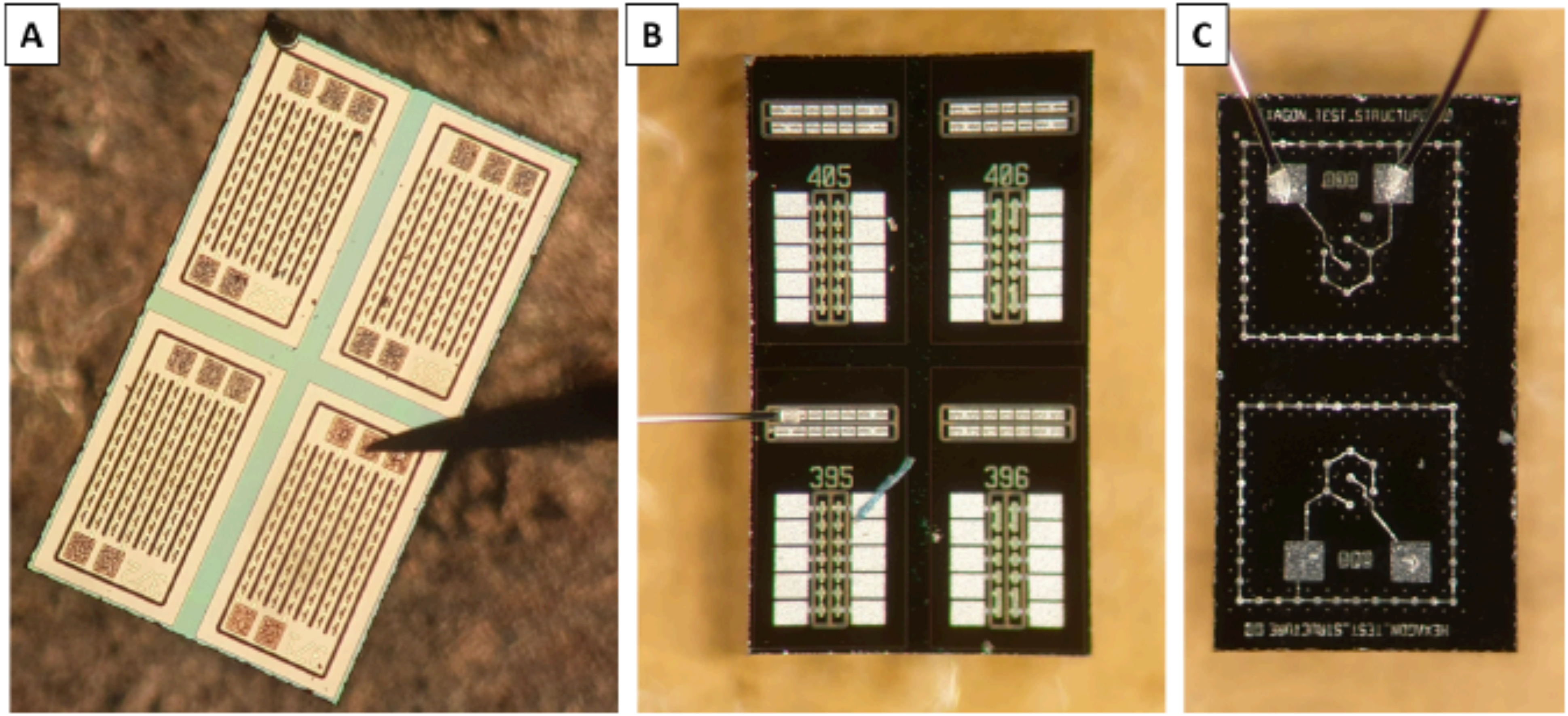
15 June 2019

G. Forcolin – INFN Trento, M. Boscardin – FBK





3D structures under test
In lab & under-beam measurements

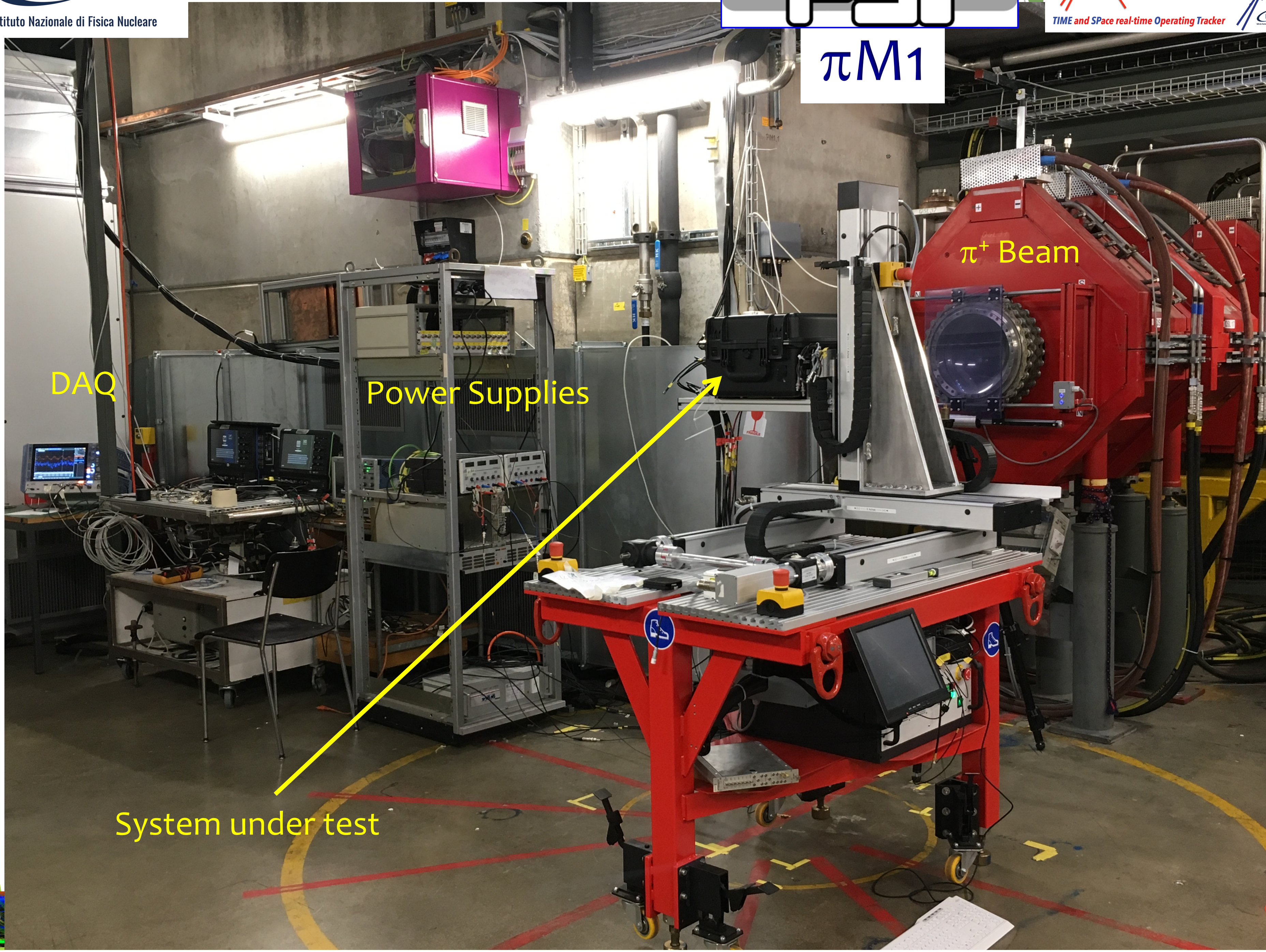


(A) Pixel-strip (10 pixels connected on the same read-out pad); **(B)** Single and double pixel; **(C)** Hexagonal (column) pixel device, based on FBK 3D Double Side Technology.

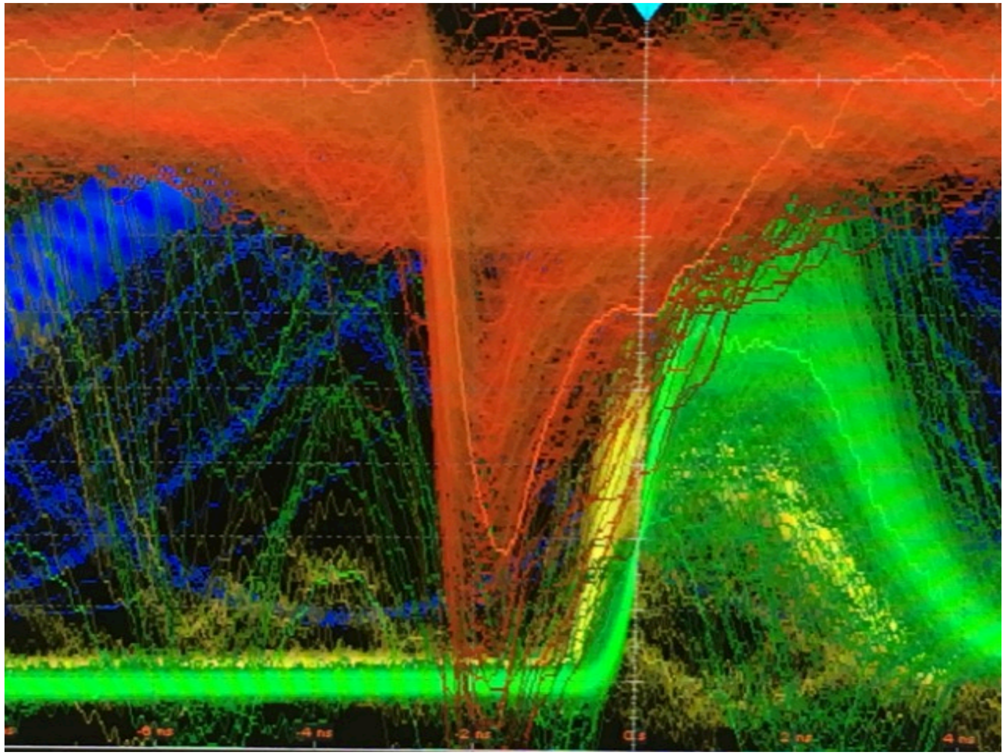
Devices are connected to electronics by wire bonding (Al, 25 μm diameter, ~ 5 mm length)

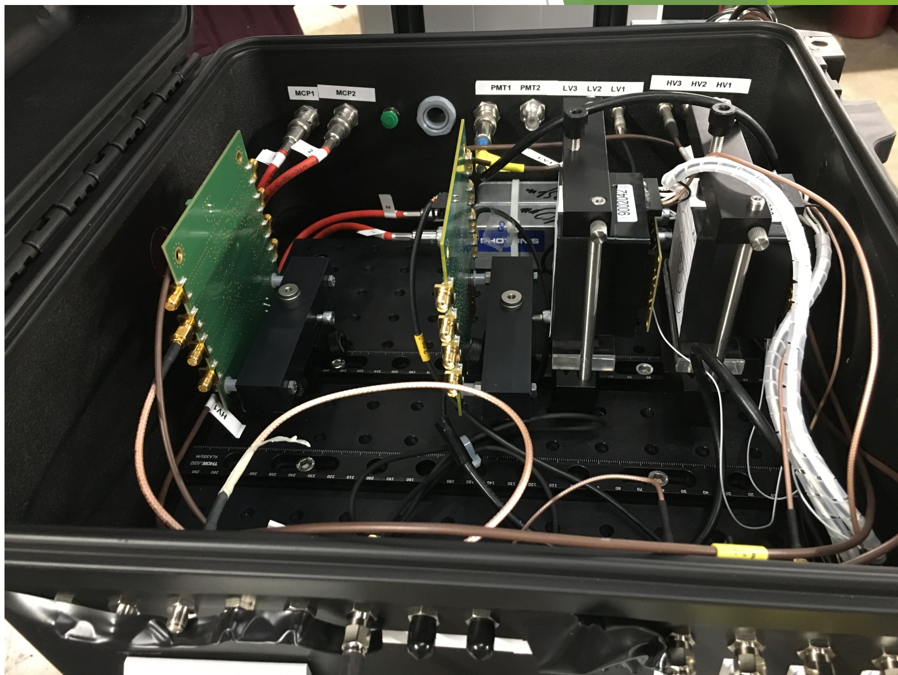
Tests beam @ PAUL SCHERRER INSTITUT PSI

$\pi M1$

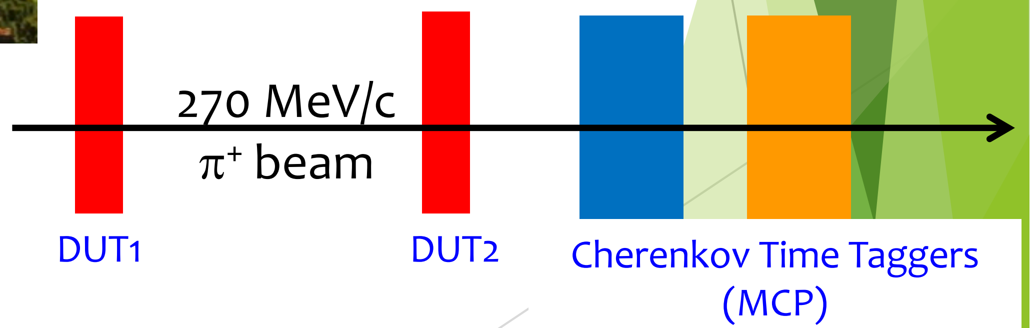


Tests beam @ PSI πM1
System under test & procedure



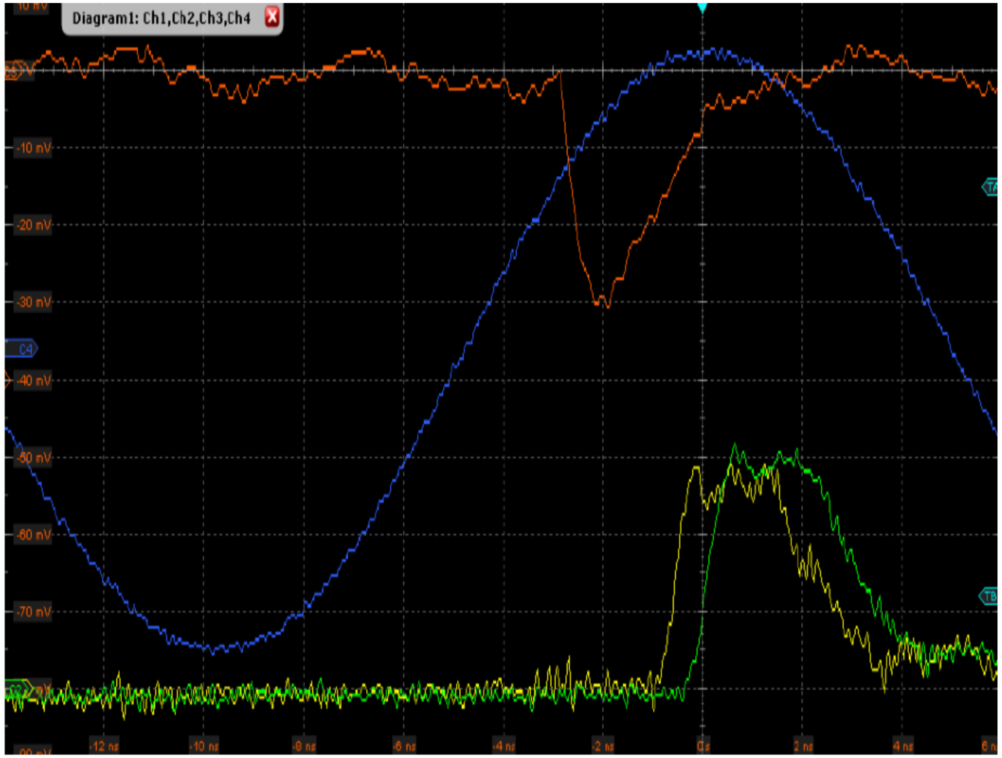


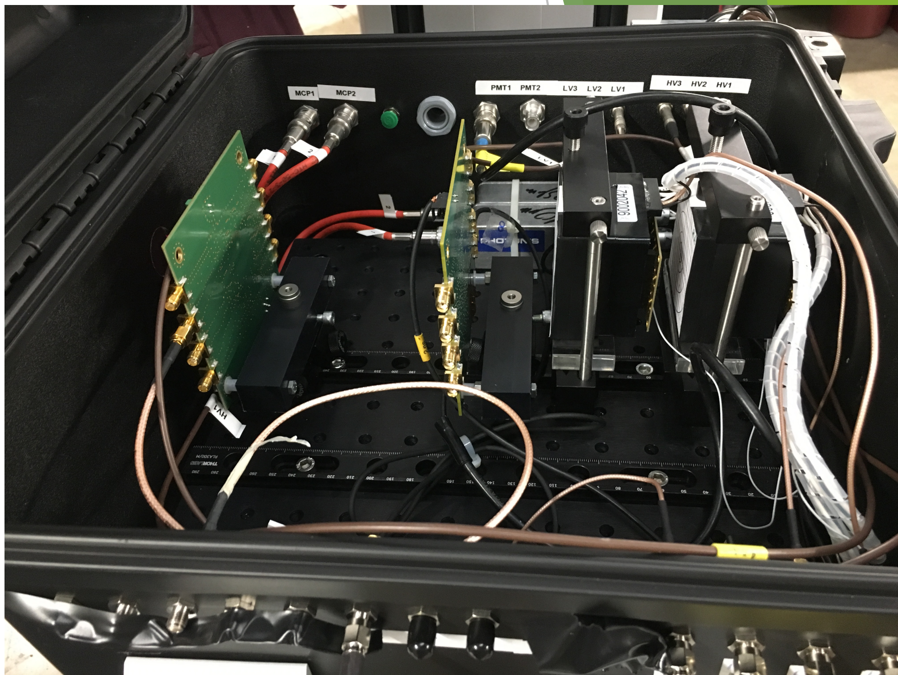
- Trigger is on DUT;
- Waveforms of DUT, MCP1 and MCP2 (and RF) are entirely acquired by the scope;
- DUT time is calculated by applying a numerical CFD algorithm, taking time at 35% of the DUT waveform maximum;
- MCP1 and 2 average time is calculated and used to measure Δt w.r.t. DUT time.



Several structures were interchanged and tested (both 3D silicon and diamond)
3 different RO electronics in various combinations

Tests beam @ PSI πM1
System under test & procedure





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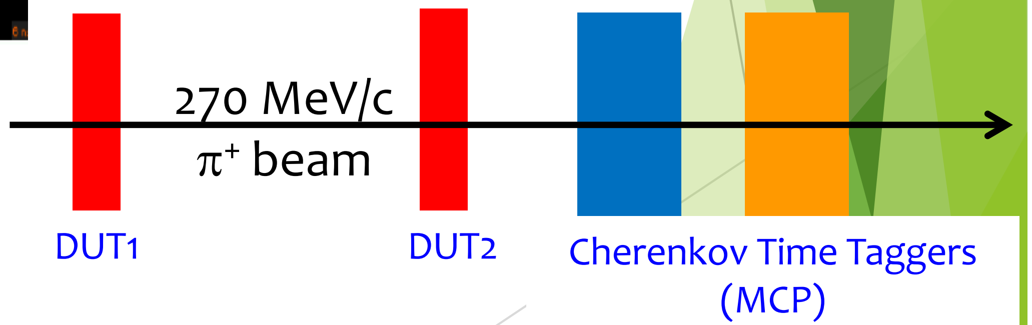
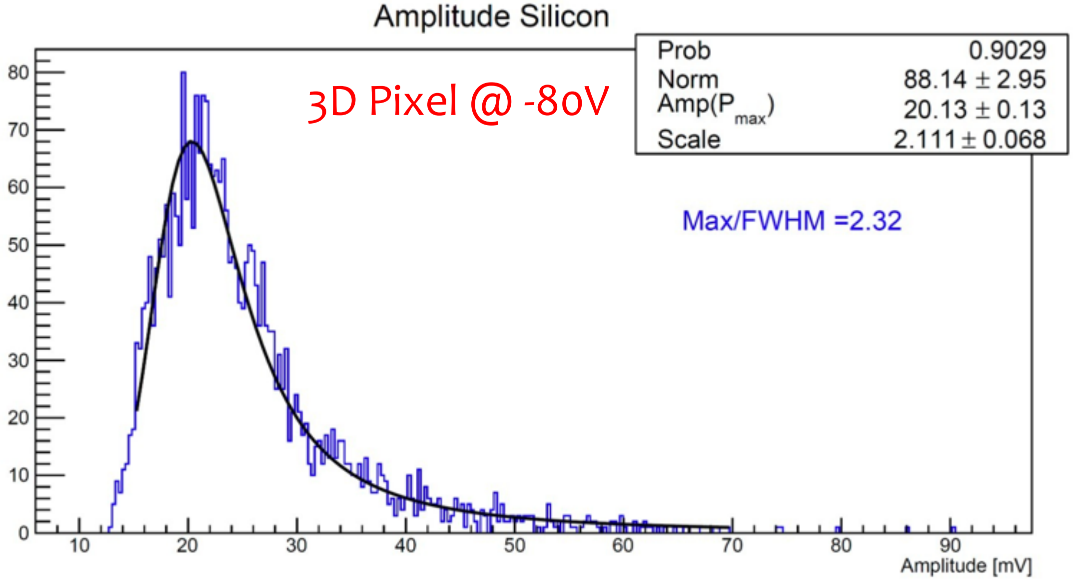
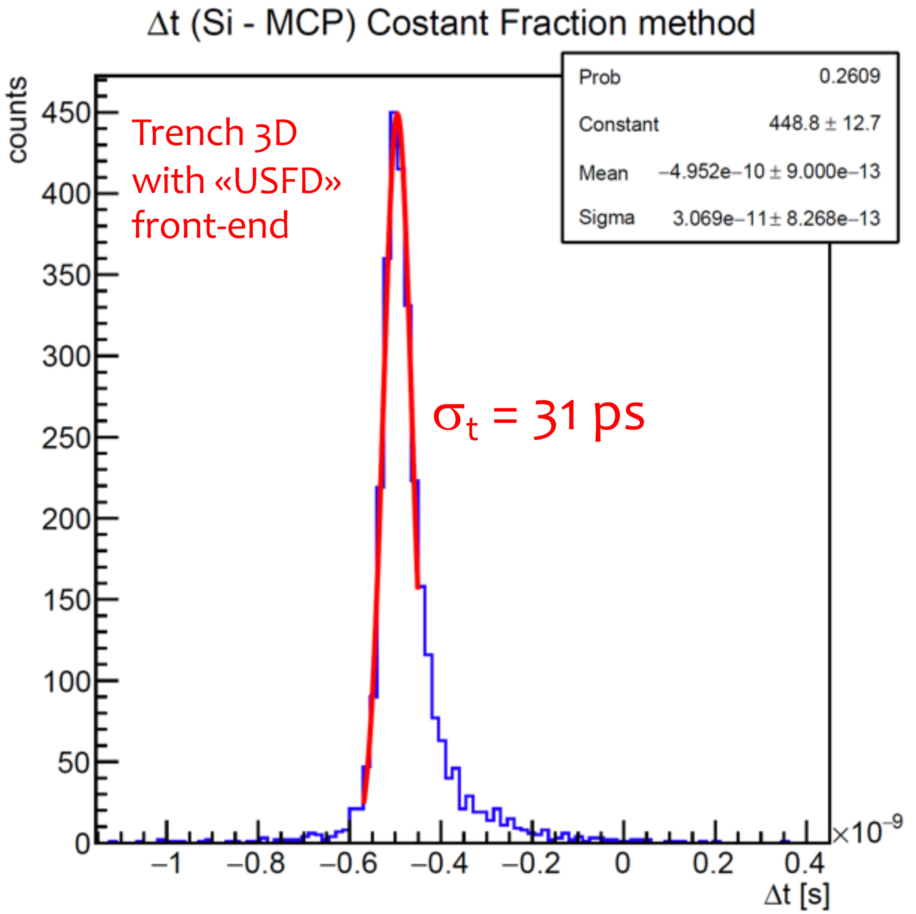


Several structures were interchanged and tested (both 3D silicon and diamond)
3 different RO electronics in various combinations

Time resolution
of TIMESPOT 3D trench pixels



Noise (gauss) + Signal (Landau) fit
MIP MPV ~ 20 mV



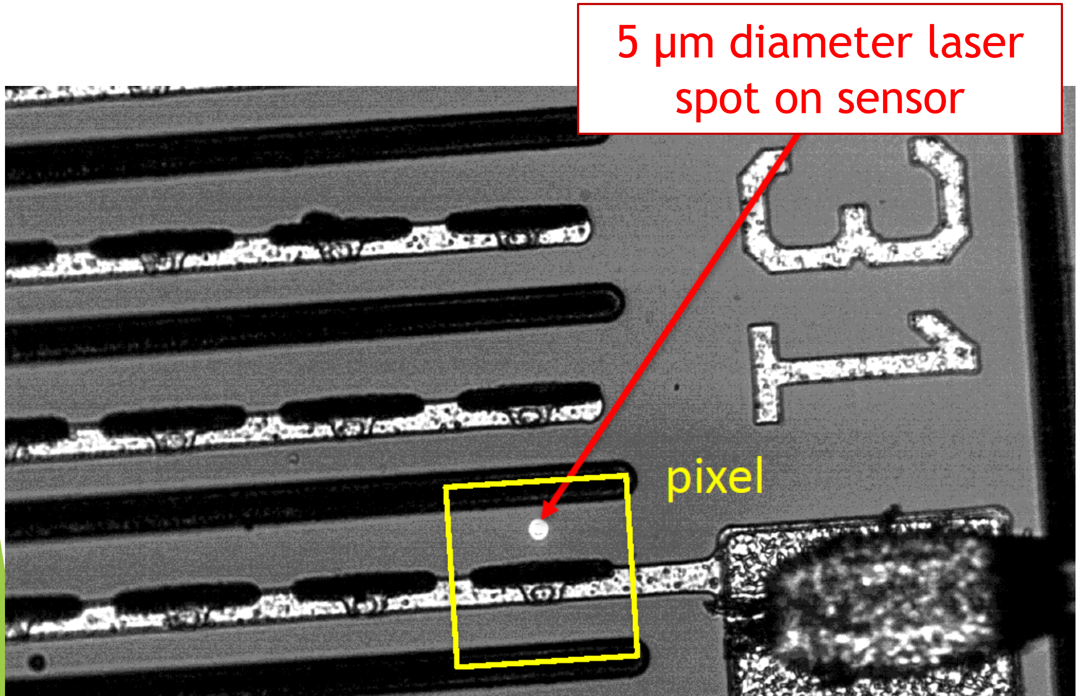
Comparing different read-out boards is easy to argue that the measurements are limited by front-end performance and extrinsic (EMI) noise.

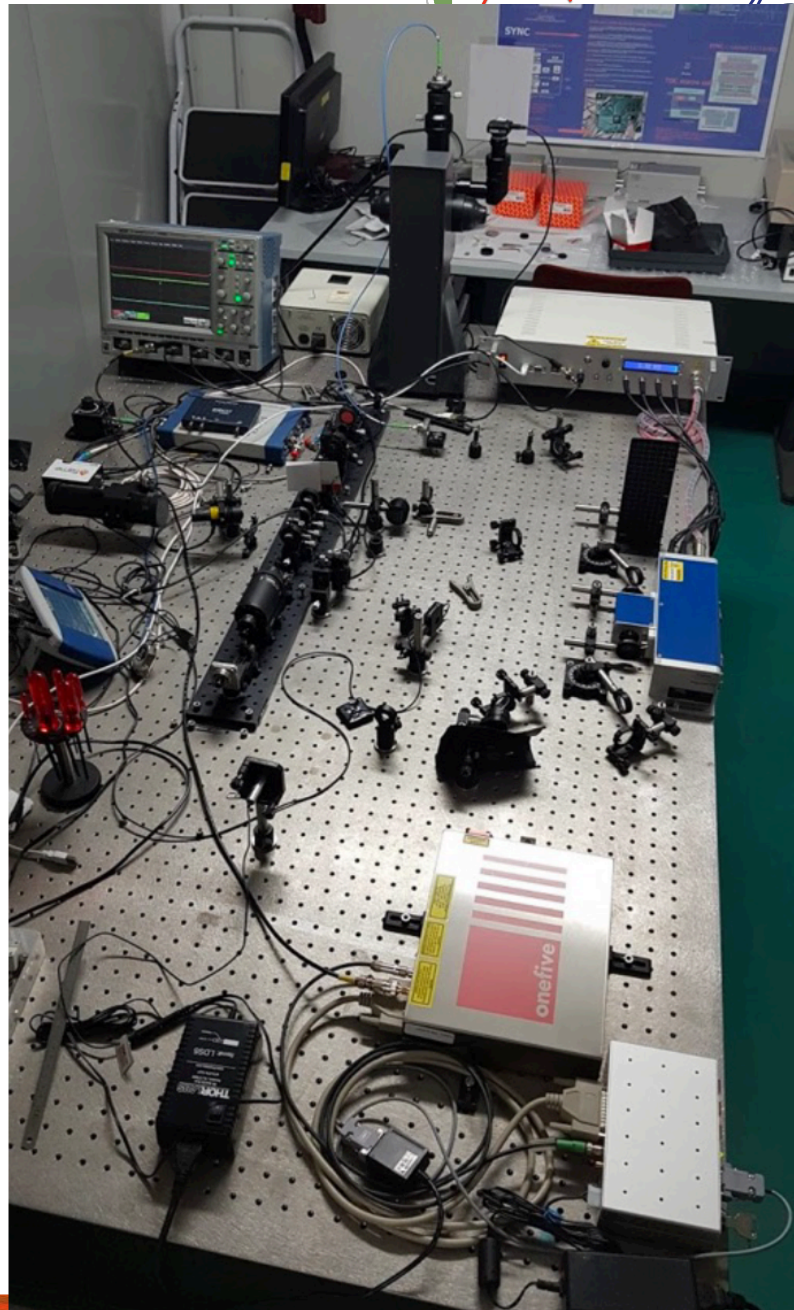
Analysis work is on the way to deconvolve system contributions.
σ_t tends to be lower (25 ps? Less?)

Time resolution becomes **~29 ps** after deconvolving time-tagger jitter

Cagliari Laser setup

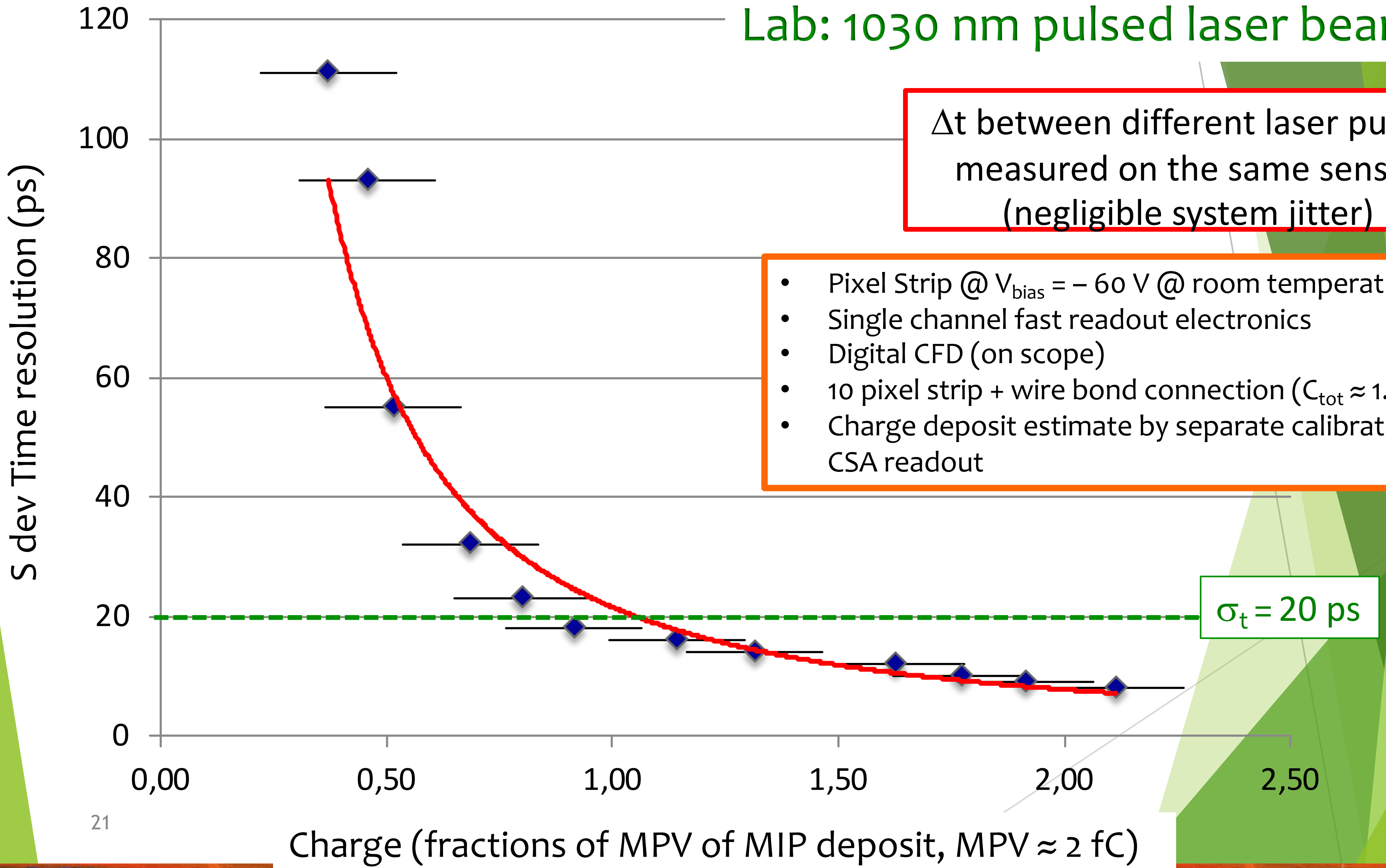
- 1030 nm, 100 fs, 40 MHz pulsed laser
- Pulse-picker to select pulses from 40 MHz to single
- Monomode fiber to microscope
- Optical filters for light intensity attenuation
- Pin-hole for collimation
- Microscope with IR camera





M. Aresti – INFN Cagliari

Even better (1): Time response vs Charge



Lab: 1030 nm pulsed laser beam

Δt between different laser pulses measured on the same sensor (negligible system jitter)

- Pixel Strip @ $V_{bias} = -60$ V @ room temperature
- Single channel fast readout electronics
- Digital CFD (on scope)
- 10 pixel strip + wire bond connection ($C_{tot} \approx 1.5$ pF)
- Charge deposit estimate by separate calibrated CSA readout

Istituto Nazionale di Fisica Nucleare

Even better (2): Cable loss evaluation and recovery

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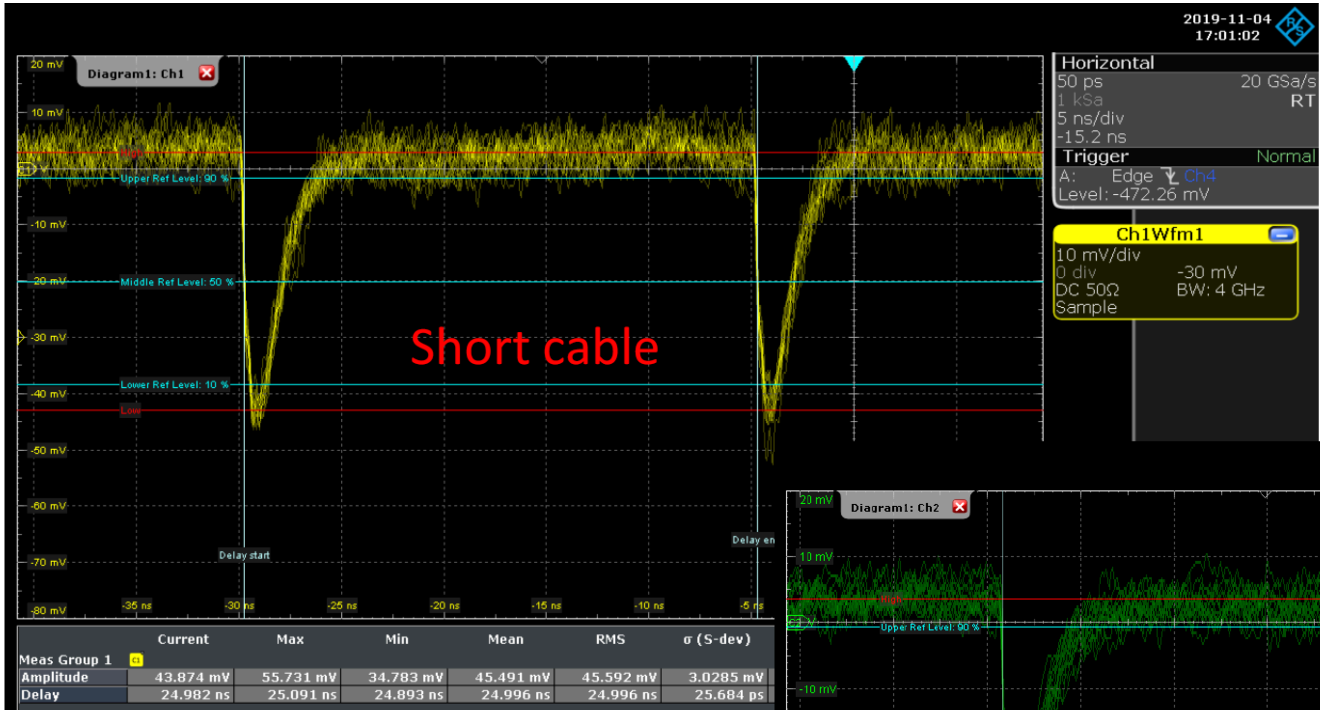
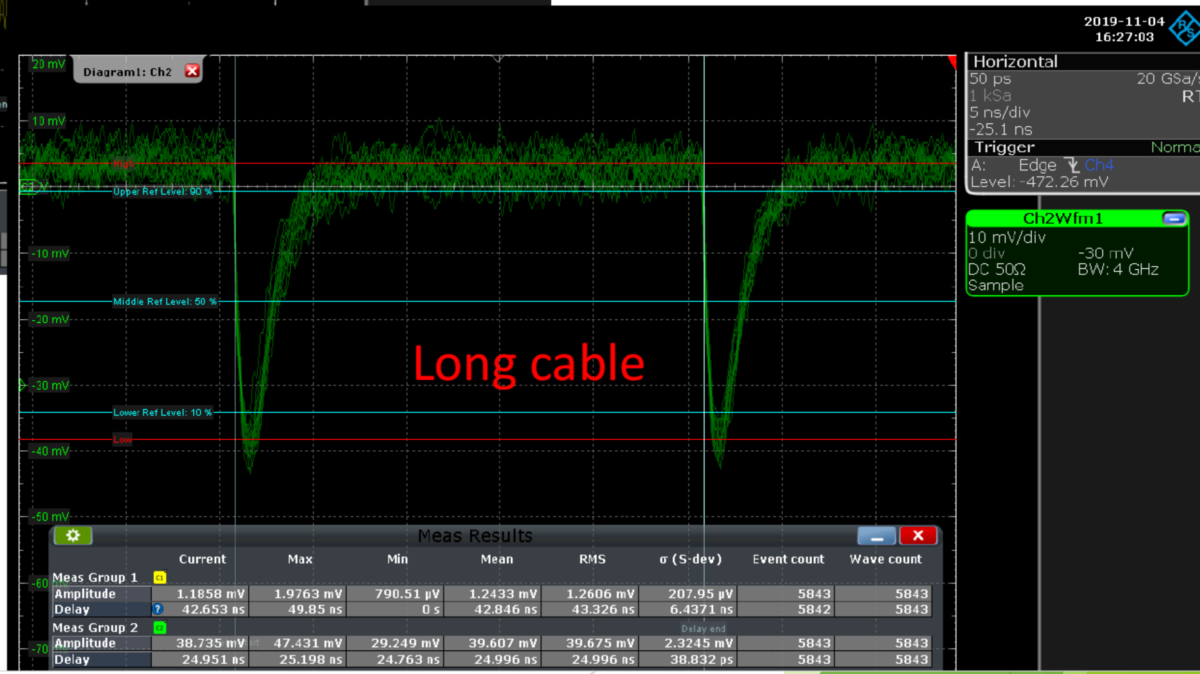
TIME and SPace real-time Operating Tracker



Laser pulse energy release in pixel corresponds to approximately **1.3 MIP** (calibrated using long cables, as in PSI, and comparing to PSI amplitudes measured on 3D pixels)



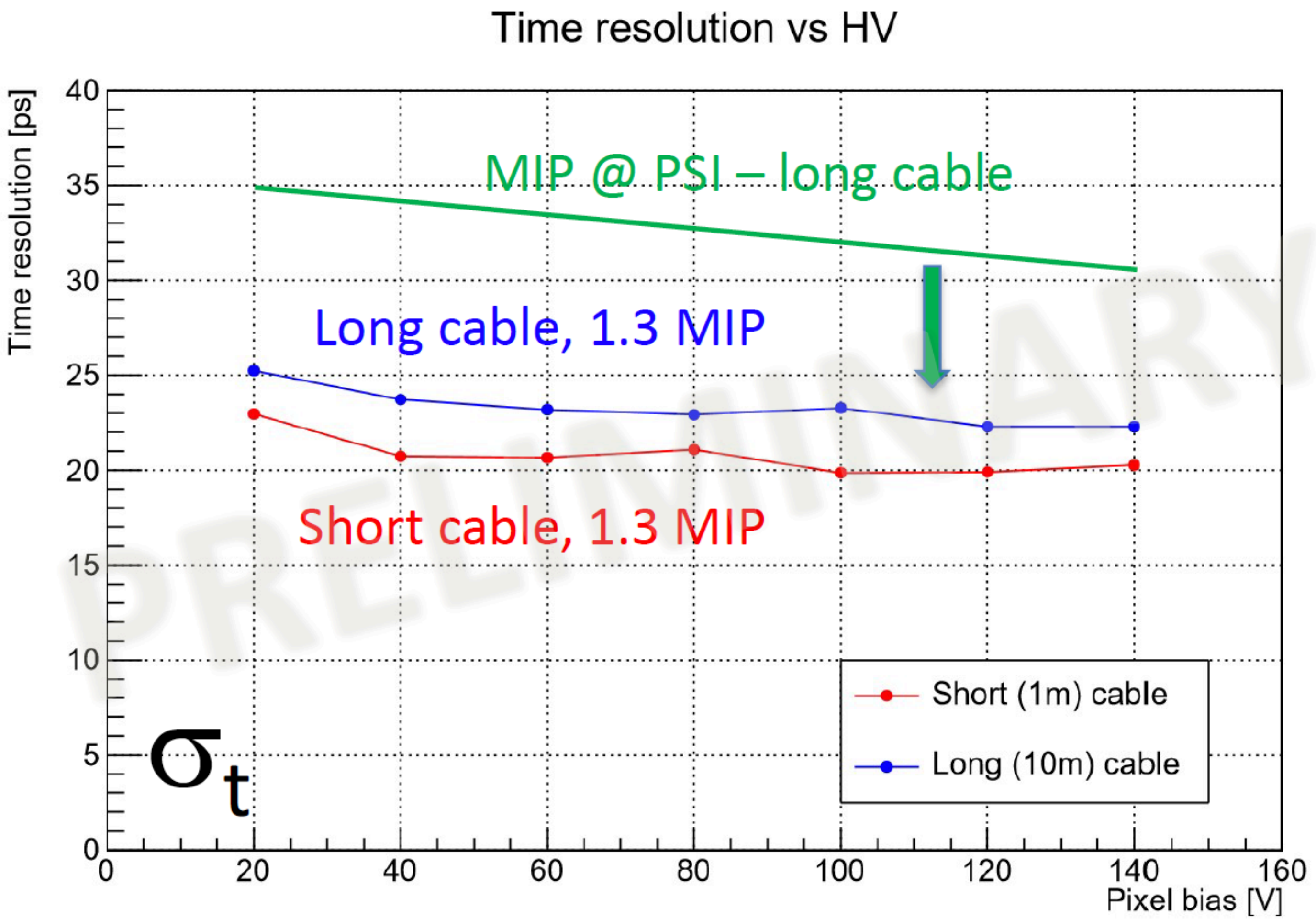
Waveforms are reconstructed and analysed as for the beam test data

LHCb Week, 04DEC2019

A. Cardini – INFN Cagliari

Even better (2):
Cable loss evaluation and recovery

A. Cardini – INFN Cagliari



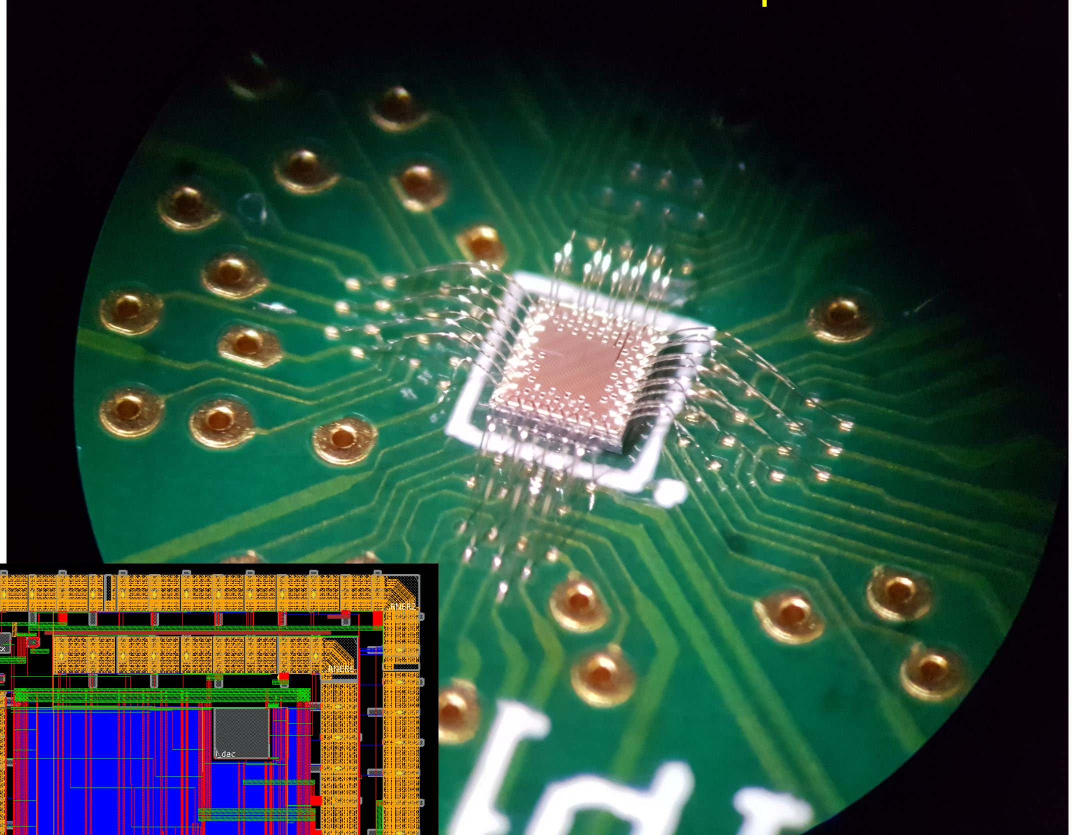
Impact of cable characteristics on measured sensor timing performance (in addition to better EMI setup)

1^{st} prototype in 28-nm CMOS
(presently under test)

INFN Cagliari, Torino Milano

- Main purpose: gain confidence on 28-nm CMOS and test technology performance.
- All cells are kept independent and directly accessible from external pins (with a few exceptions)

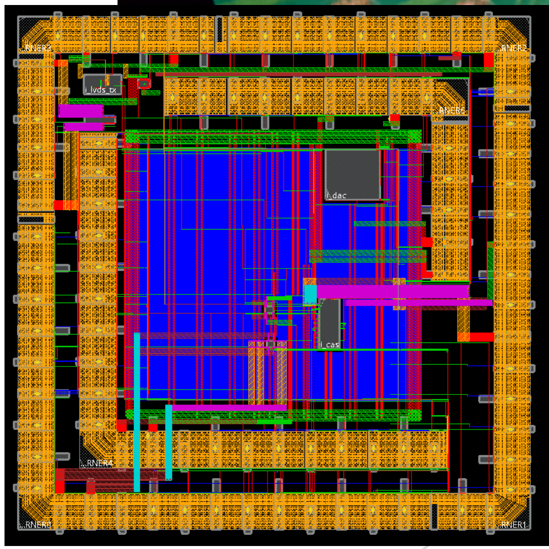
  → strongly pad-limited



Encapsulated chip prototype. 75 µm bonding pitch
Bonded at Milano workshop

Integrated cells:

- 3 different TDC solutions
- 6-bit DAC + SPI I/F
- 8-channels CSA+Discriminator
- Programmable power (and speed)
- General purpose OPAMP
- LVDS Tx/Rx



Total area 1.5x1.5 mm²
mini@sic

TDC

Simulation and tests

TDC schemes (prototipo zero)

	DCO (dithering)	Tapped delay	Time Amplifier
Size (μm^2)	23 x 22	27 x 22	23 x 21
LSB (ps)	190	50	22
RMS (ps)	47	15	37
Power Active (μW)	1200	1200	65
Power Standby (μW)	10	10	34

Test TDC_TAP (preliminary)

DCO_CTRL	2° counter	LSB	RMS
0	Yes	51	15
1	Yes	61	18
2	Yes	79	23
3	Yes	89	26
0	No	101	29
1	No	122	35
2	No	158	46
3	No	178	51

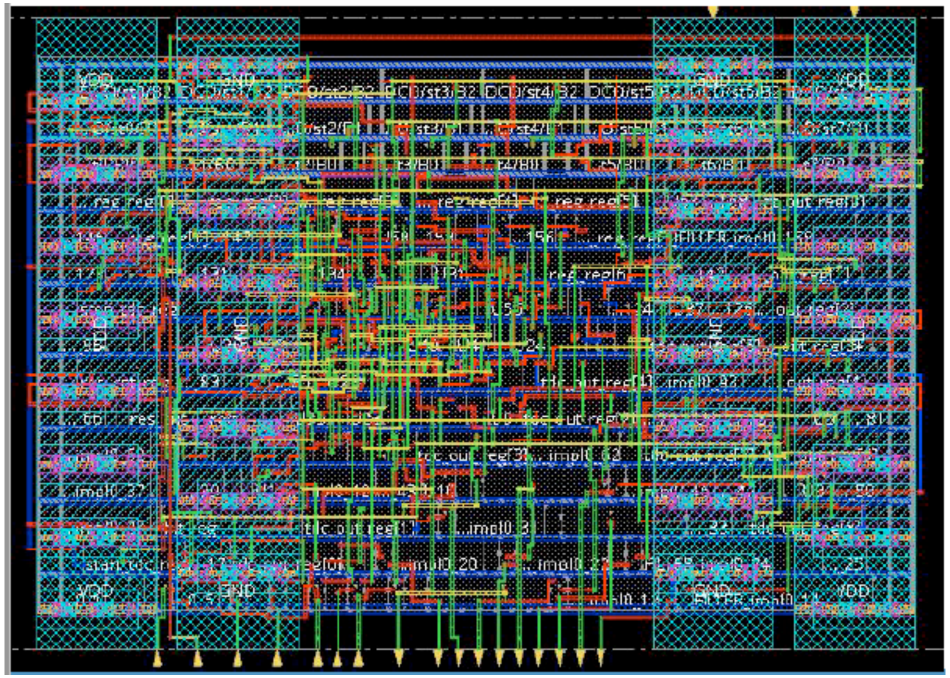
DCO_CTRL	2° counter	LSB	RMS
0	Yes	78	82
1	Yes	79	76
2	Yes	101	75
3	Yes	111	76
0	No	122	84
1	No	148	114
2	No	194	110
3	No	214	84

S. Cadeddu, L. Riccardi - INFN Cagliari

Next TDC

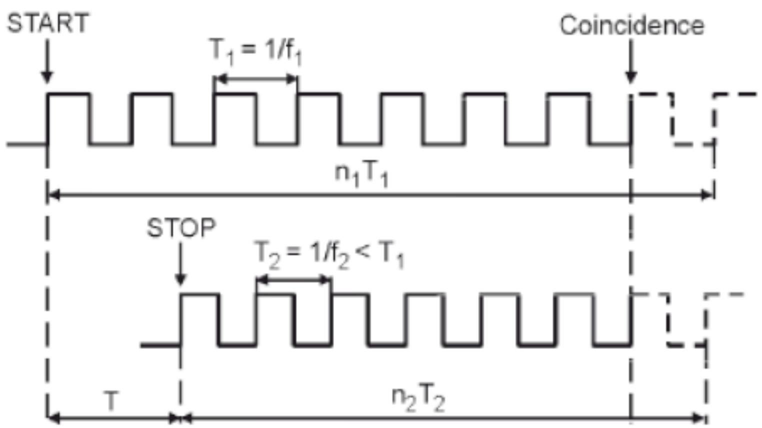
S. Cadeddu - INFN Cagliari

Increase resolution down to 4-5 ps (LSB ~ 20 ps !!)



Interpolated–tapped scheme
~ 40 ps LSB, 10 ps rms
Size: 22x15 µm²

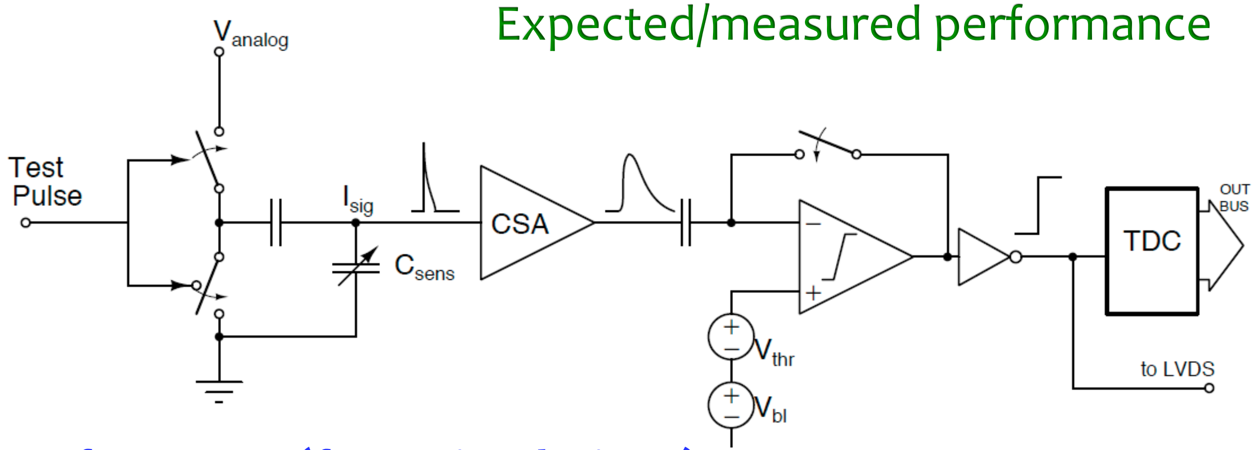
Vernier TDC (under design)
Possible to reach required resolutions
Time conversion can be kept below 1 clock cycle



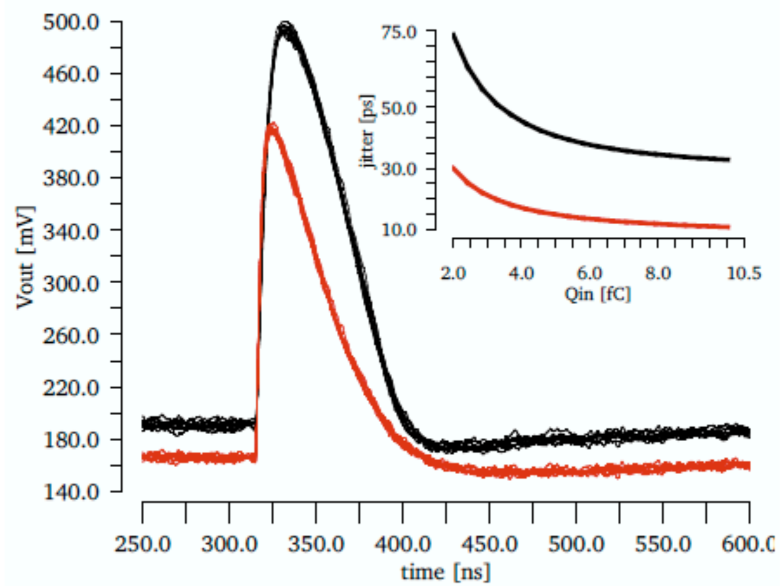
CSA + Discriminator

L. Piccolo - INFN Torino

Expected/measured performance



Expected performance (from simulations)



Input Signal	Delta-like		Sensor	
Power [μW]	4.1	7.2	4.1	7.2
G [mV fC^{-1}]	190	168	150	124
σ_n [mV]	2.8	2.0	2.8	2.0
ENC [e]	94	77	120	103
t_{pk} [ns]	16.4	7.7	18.2	10.2
t_A [ns]	2.1	2.1	4.2	3.5
TOT [ns]	100	98	79	78
SR [mV ns^{-1}]	53	98	39	68
σ_j [ps]	54	21	74	30
σ_p [ps]	66	65	67	66
σ_{mm} [ps]	33	26	40	29

Measured performance of low current version are x2 less than expected due to lower gain. Still under investigations (amplifier biasing or external board contribution?)

PrototipoZero: 1st results

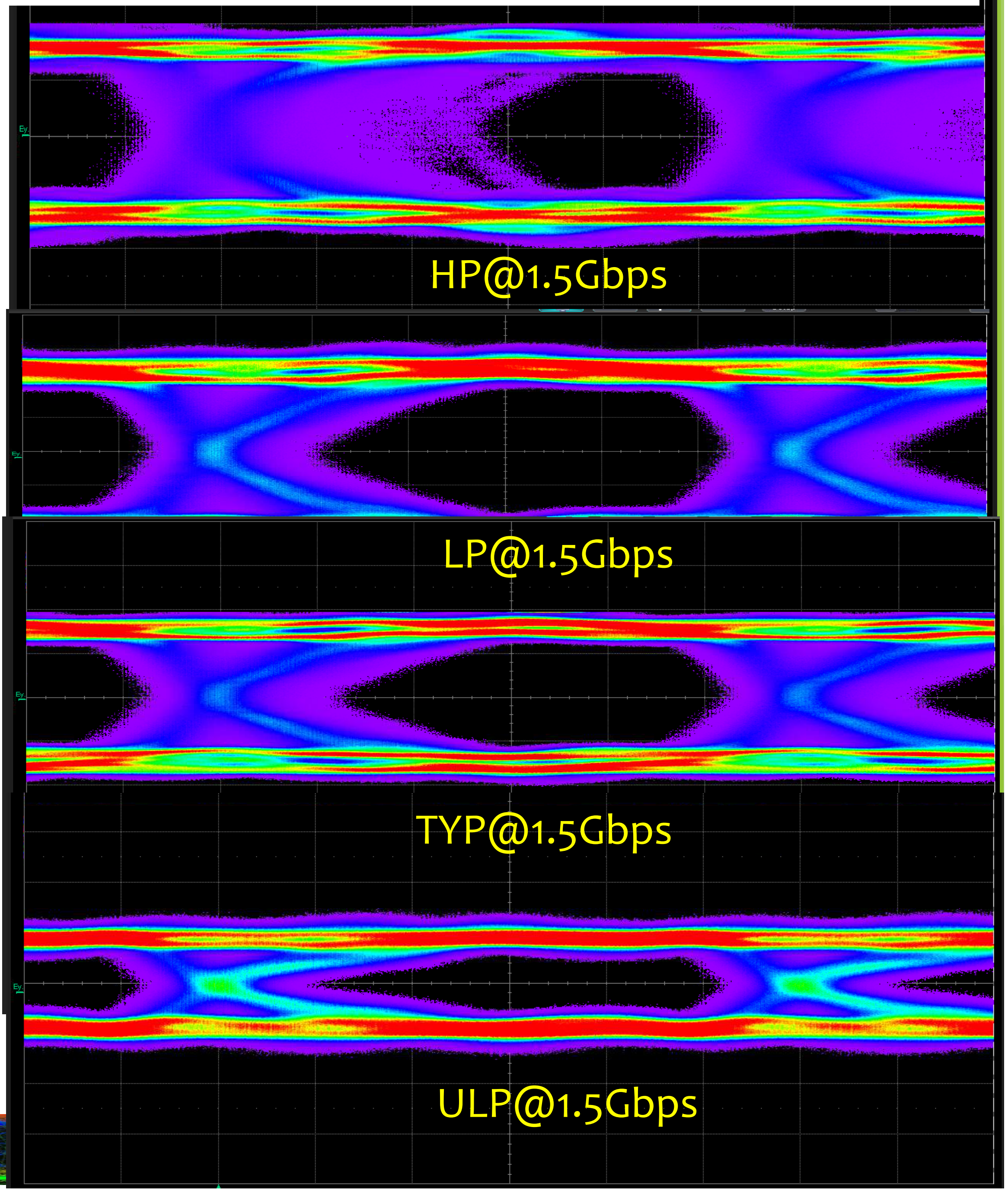
LVDS transmitter and receiver in loopback configuration.
ATLAS AM08 design
(Designers: G. Traversi & F. De Canio, Milano-Pavia CMS group)

The loopback have a nice eye (Bit Error Ratio < 10^{15} @ 1.5 Gbps and low-power mode). AM08 specs is 1.0 Gbps.

This is a very good result by considering that PrototypeZero is wire-bonded and without decoupling capacitors

The LVDS link is “silicon proof” in all modes @1.5 GBps:

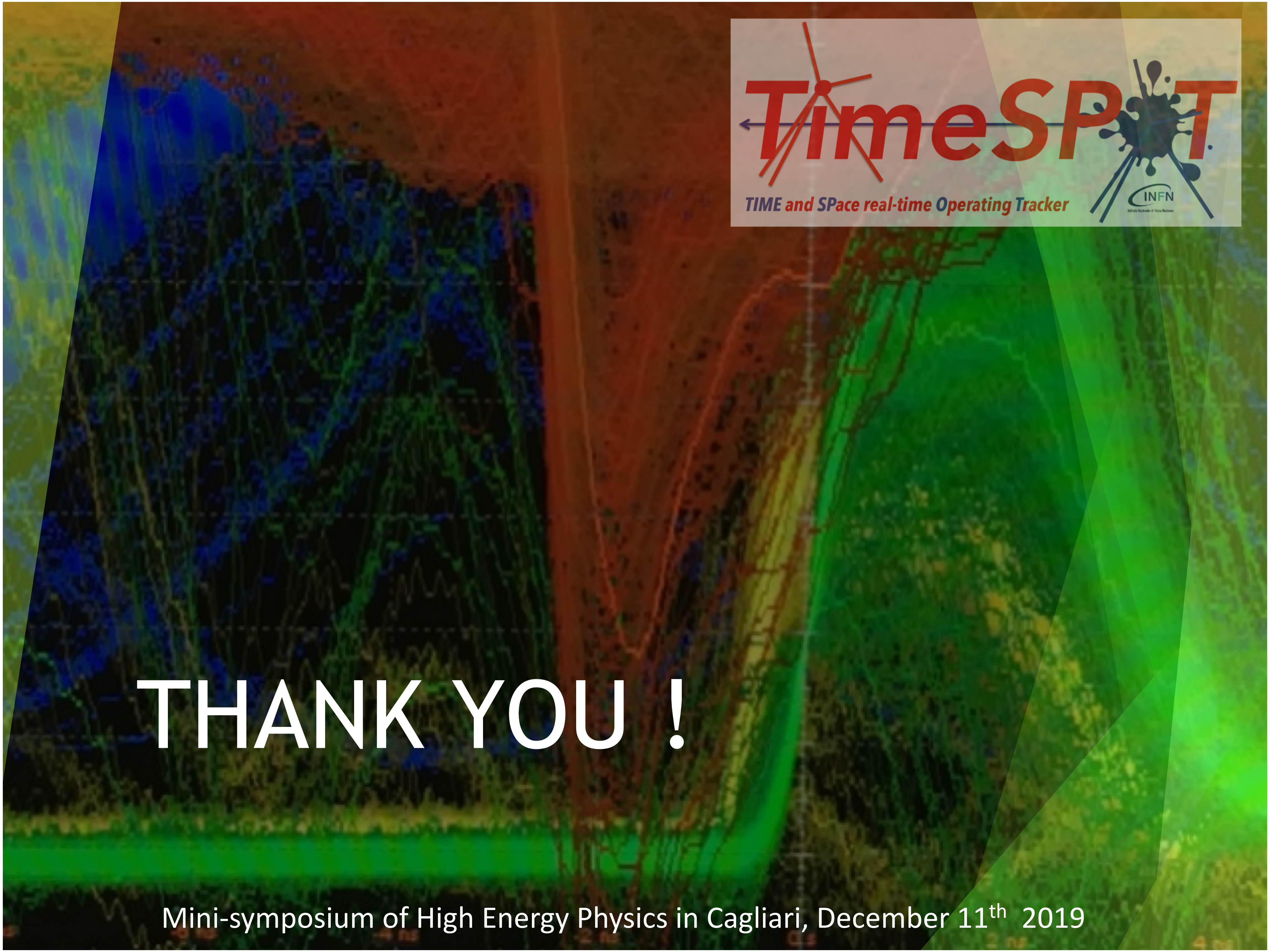
- Ultra-Low-Power (ULP, 1.6 mA),
- Low-Power (LP, 2.7 mA),
- Typical (TYP, 4.1 mA)
- High Power (HP, 8.1 mA)



TIMESPOT

Conclusions

- We are living a „crisis age“ in HEP (which is not necessarily bad!)
- Crisis is time for decisions and a new start – just „waiting“ can be deadly
- Starting a completely new route is always a risk – worth to be taken !
- Exploring new experimental techniques has for physicists the same level of importance as starting new experiments from a „physics case“ – and makes you happy !
- TIMESPOT has a system approach to the experimental challenge of the next generation of HEP experiments
- It is starting to produce very valuable results on sensors and electronics developments
- The recent result on sensors (σ_t < 30 ps) is a world record for silicon devices detecting ionizing particles
- Its potential impact on future detector systems is ready to be exploited and is now in our hands



TimeSPOT

TIME and SPace real-time Operating Tracker

INFN

THANK YOU !

Mini-symposium of High Energy Physics in Cagliari, December 11th 2019