4D Tracking at High Intensity

A new technique for future experiments at colliders: results and open challenges

Adriano Lai

TimeSPOT
TIME and SPace real-time Operating Tracker

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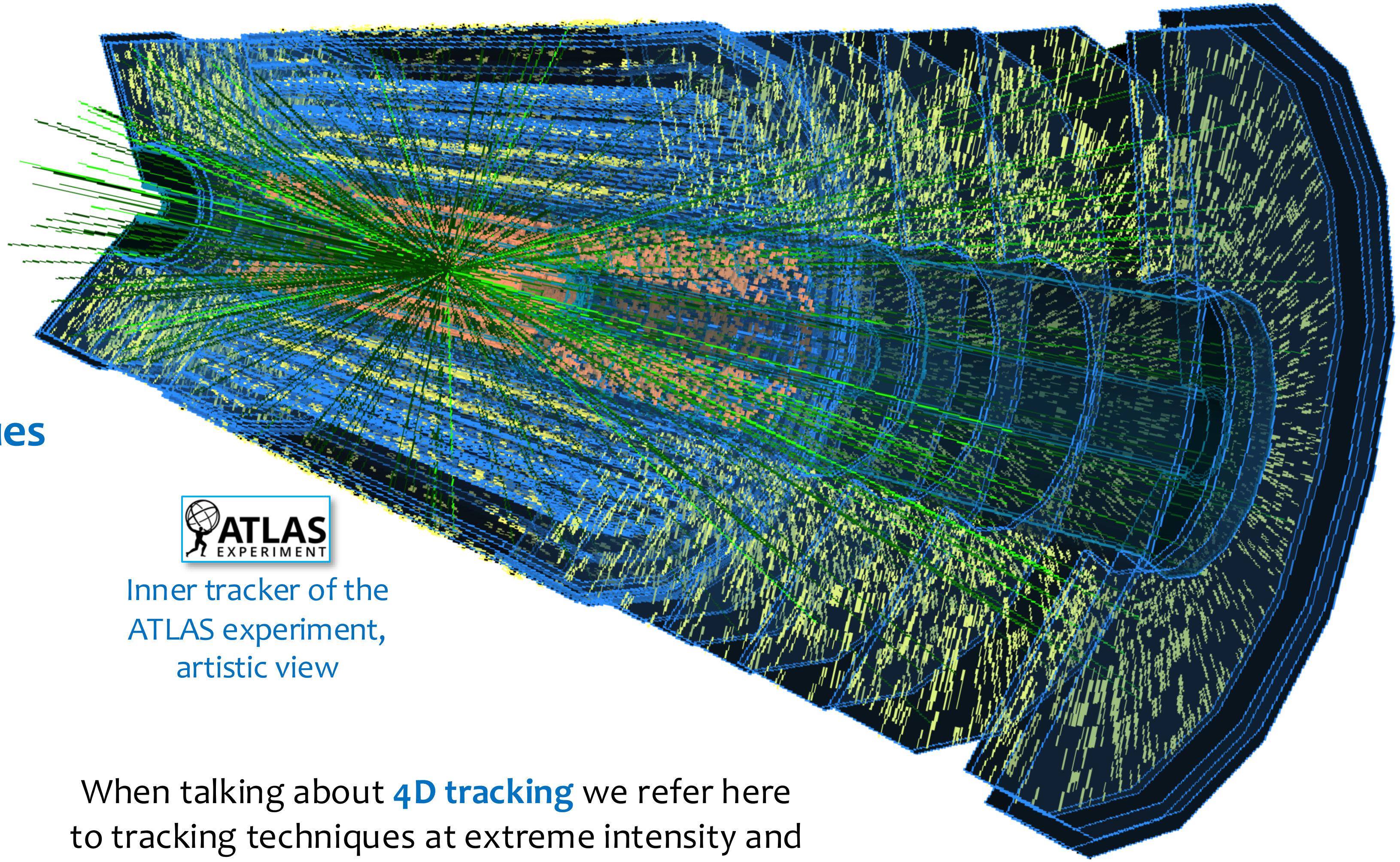
IGNITE
INFN Istituto Nazionale di Fisica Nucleare
INFN Ground-up iNITiative for μElectronics developments

Topics

1. **Why 4–Dimensional Tracking?**
2. **Development of novel techniques and instrumentations**
3. **Timing sensors**
4. **Timing electronics**
5. **Results**
6. **Challenges**
7. **Conclusions**



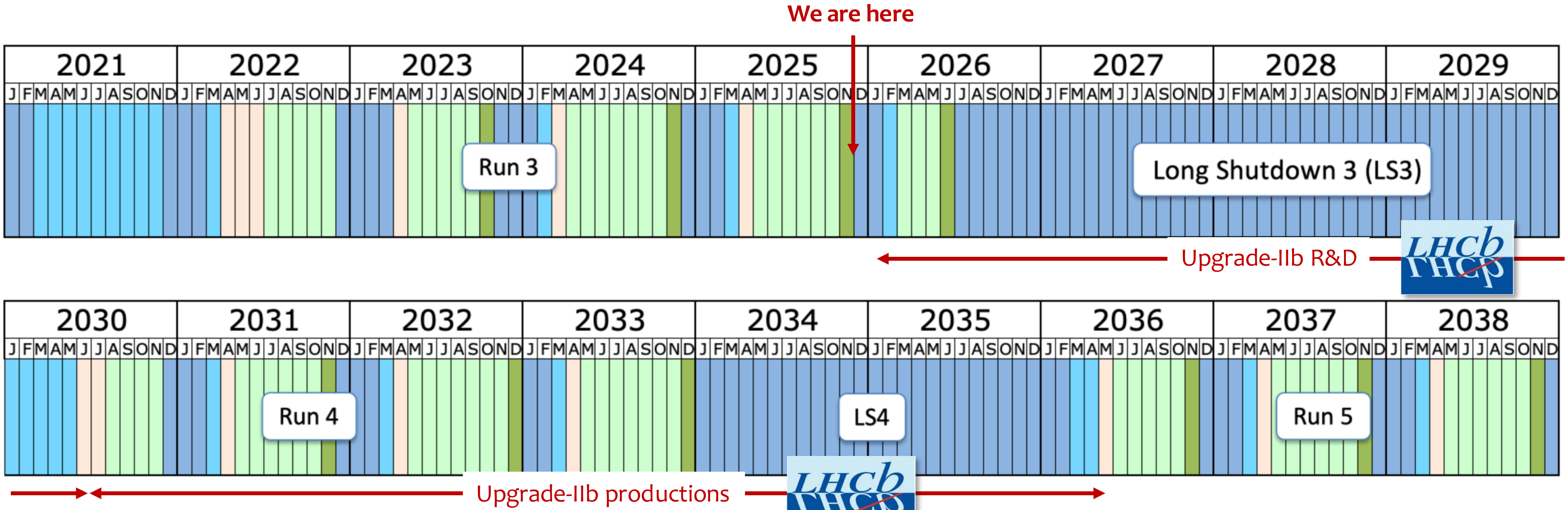
Inner tracker of the ATLAS experiment, artistic view

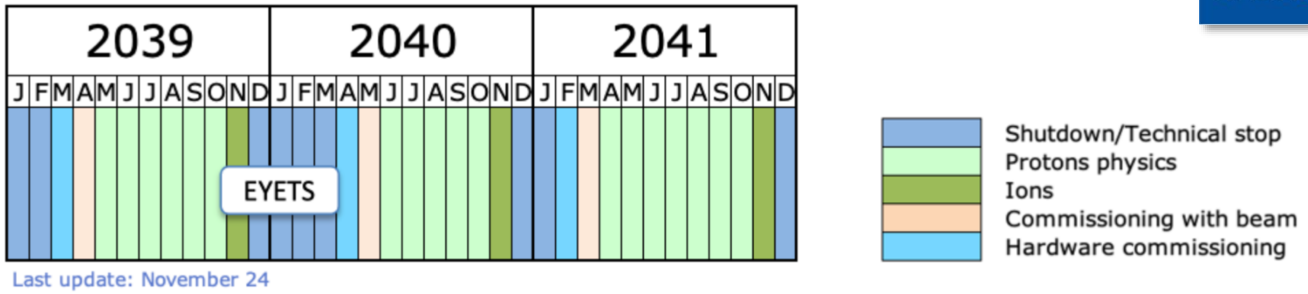
When talking about **4D tracking** we refer here to tracking techniques at extreme intensity and pile-up of events per detection area (1-10 GHz/cm^2). This experimental conditions are typical of **inner trackers** of the next generation of collider experiments, requiring **time resolution of tens of ps and space resolution of tens of μm and below**.

High resolution space-time tracking (&imaging): Physics and applications…

1. **4D tracking for extreme luminosity colliders (HL-LHC, FCC-hh, Muon Collider)**
2. **Tagged / monitored neutrino beams**
3. Medical imaging TOF-PET and "Ultra-Fast PET" (10 ps)
4. Beam Diagnostic for high-intensity accelerators and plasma accelerators (EuPRAXIA, AWAKE)
5. High brilliance XFEL / Xsouces and ultrafast X-ray imaging
6. Fusion Diagnostics (ITER, DTT, advanced tokamak)
7. Time-resolved electron microscopy (UTEM, 4D-STEM)
8. High energy astrophysics and Cherenkov telescopes
9. Muography and geophysics (vulcanos, pyramids, infrastructures)
10. Space-time dosimetry in hadron therapy and beam monitoring

Near future of collider physics (R&D ongoing)





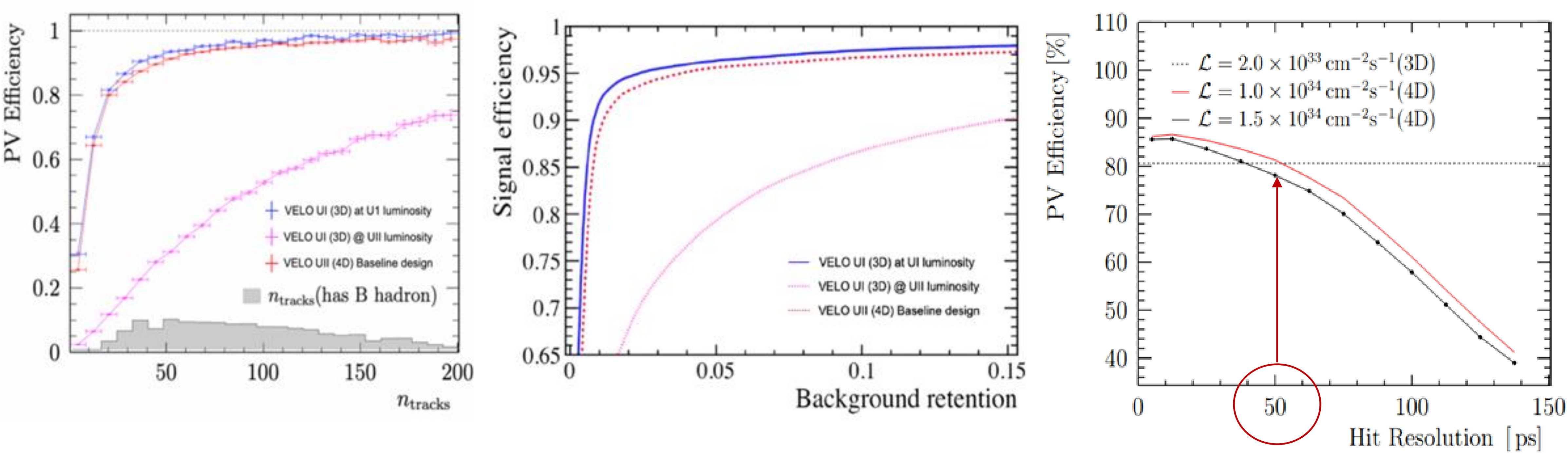
Commissioning: 2034, Data Taking: 2036

A second initiative (nuSCOPE) intends to profit of ongoing 4D-tracking developments for the Upgrade for a «new» experimental technique in ν-Physics

«Far» future experiments (beyond the '40s) will demand timing in tracking (es FCC – if any – and μ-colliders)

4D-Tracking in Hi-Lumi: the LHCb Upgrade-II

LHCb: an experiment dedicated to studies on rare decays, CP violation in the barion sector, heavy ion physics



Timing in the inner tracker is mandatory!

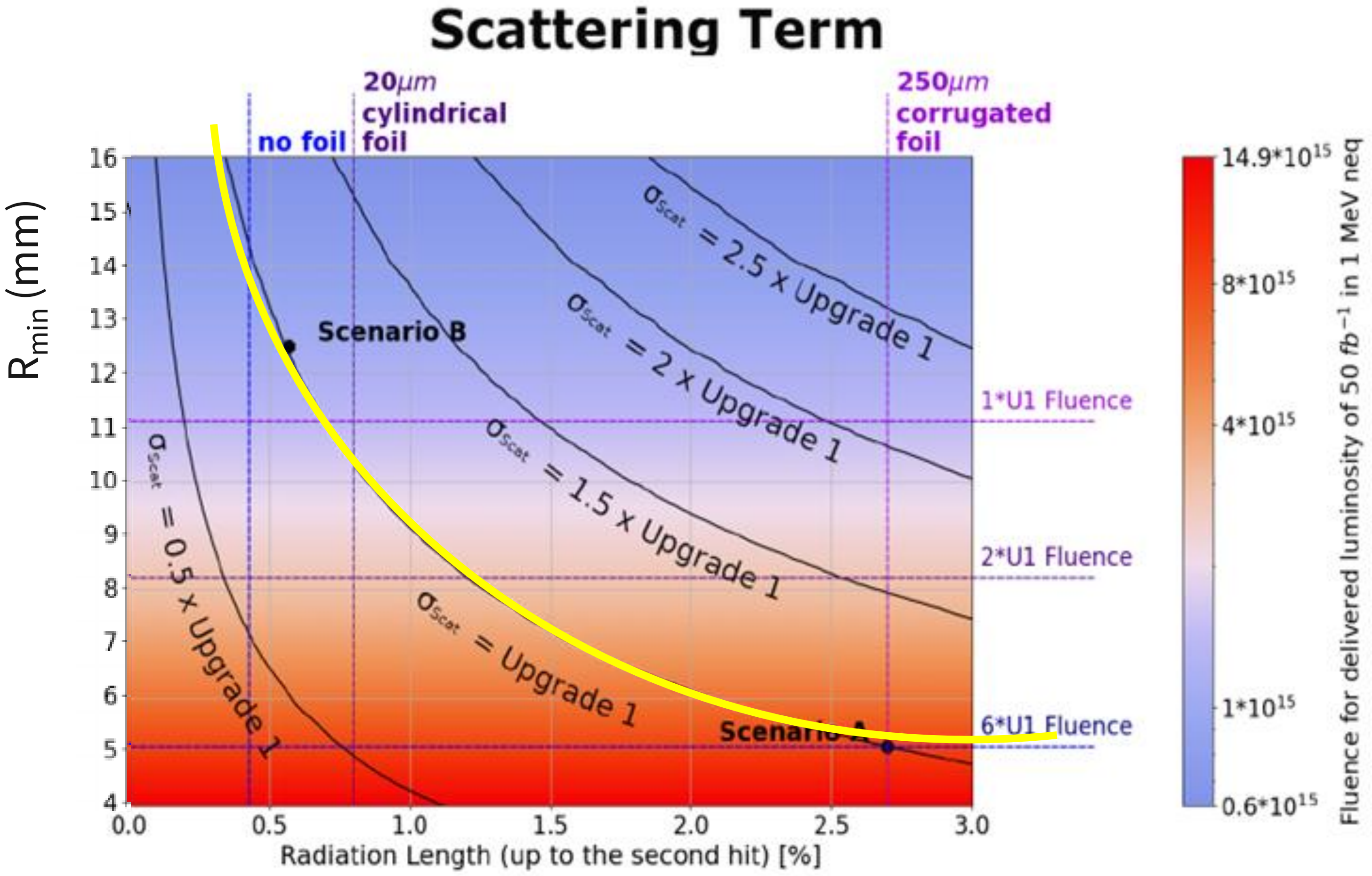
- Necessary to keep the same performance (and possibly better) at a x6 pile-up wrt U1 (μ=7 → μ=40)
- For reconstruction efficiency, a resolution of ≈20 ps per track is required, which translates in at least **50 ps per hit**
- Such performance should be kept **along the aging process** (fluence, dose) of the detector (= some margin in «native» timing should be considered when the detector is «young») → **30-40 ps rms required on the full chain (sensor to TDC)**

From VELO U1 to VELO U2 (aka TV)

Concurrent Requirements

Experimental specifications are to be studied in a **multi-parameter space,** optimizing concurrent requirements:

1. Distance from collision point (IP) decides pixel area (the closer the larger it can be) and radiation level (fluence / hit rate).
2. Going to larger R_{min} (min distance from IP) for less Fluence demands improving spatial resolution **(smaller pixel and less material budget)**
3. **Spacial resolution is crucial for tracking, which finally is made in space**



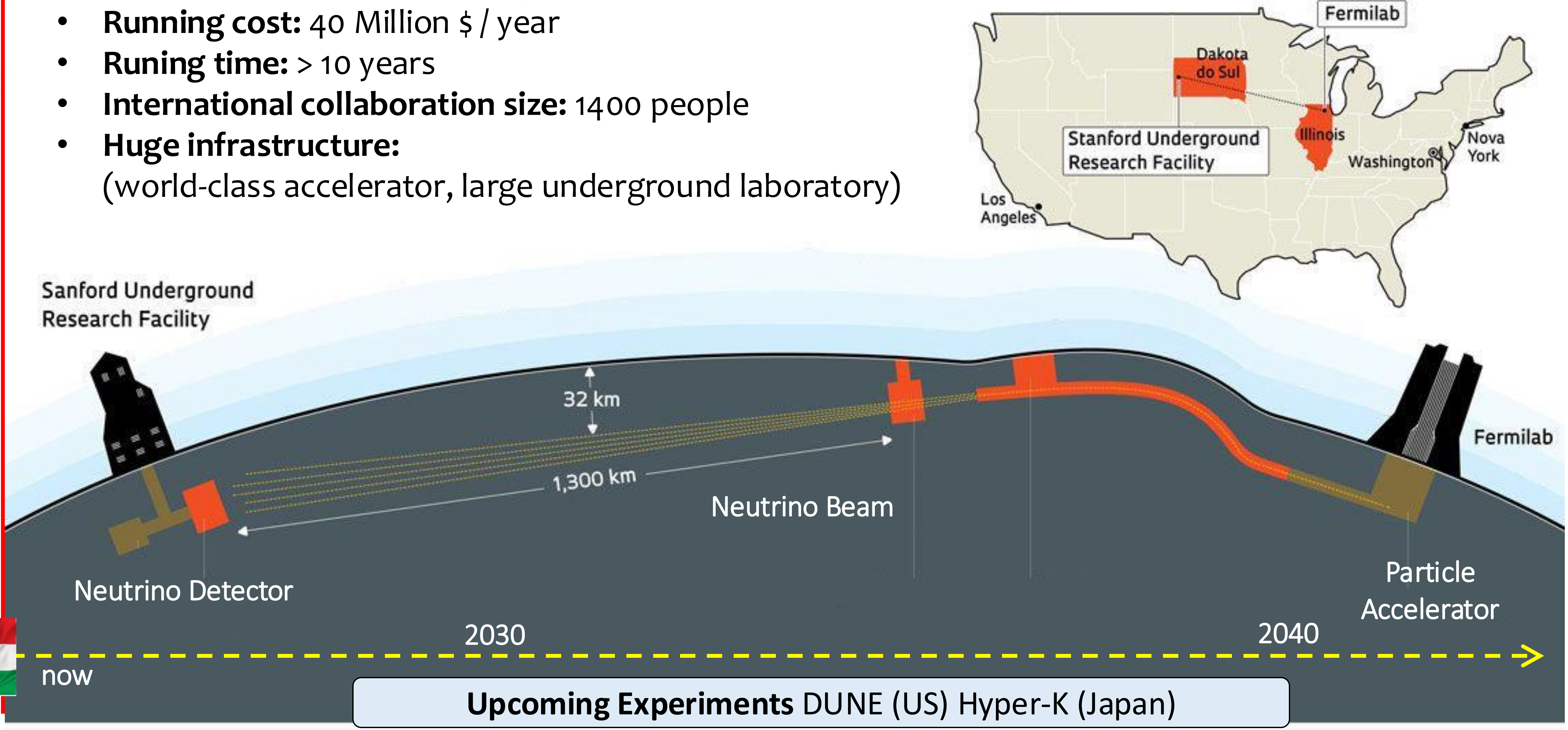
Present preference/choice (Scenario X, SX):
R_{min} = 7.2 mm, Fluence = 5 10^{16} n_{eq}/cm^2, Cylindrical Foil

Something «completely» different

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

A colossal endeavour:

- **Construction cost:** 3 billion $ (phase 1)
- **Running cost:** 40 Million $ / year
- **Runing time:** > 10 years
- **International collaboration size:** 1400 people
- **Huge infrastructure:**
  (world-class accelerator, large underground laboratory)



Upcoming Experiments DUNE (US) Hyper-K (Japan)

Standing challenges in ν physics

Beyond DUNE and Hyper–K

Increasing **sample size**
Reducing **modelling uncertainties**

Longer term:
Scaling-up DUNE or Hyper-K appears not feasible
(beam power, detector size)

X 10 – 100

now - - - - 2030 - - - - 2040 - - - ->

Present Experiments

Upcoming Experiments DUNE (US) Hyper-K (Japan)

What is next?

?

÷ 10

?

Medium term:

Modeling uncertainties jeopardize the success of next-to-come multi-billion-dollar experiments.
➔ Improve **Cross section precision** from **30% to a few** %

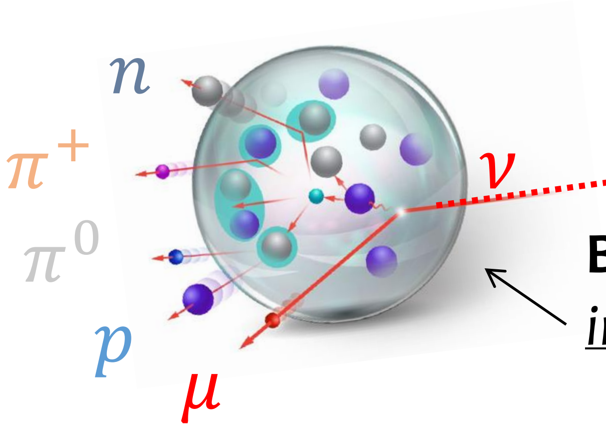
Both **problems are identified** in international **roadmaps** (e.g. European Strategy, P5)

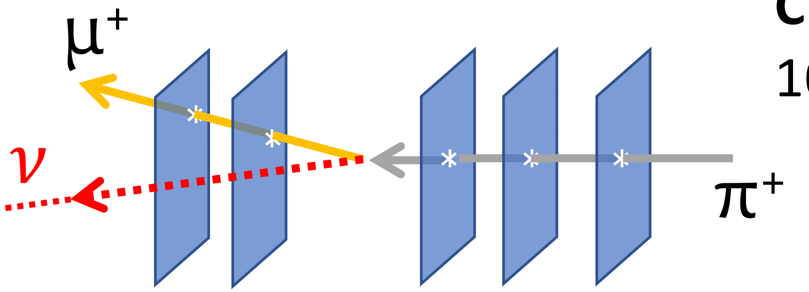
A solution: Neutrino Tagging

Neutrinos are detected/studied through their **interaction** with the detector matter

ν interaction are **complex** processes

ν energy resolution ~20%





Challenge:
$10^{10\text{-}11}$ π+/s

But:

<u>interaction</u> *is **only half the story***

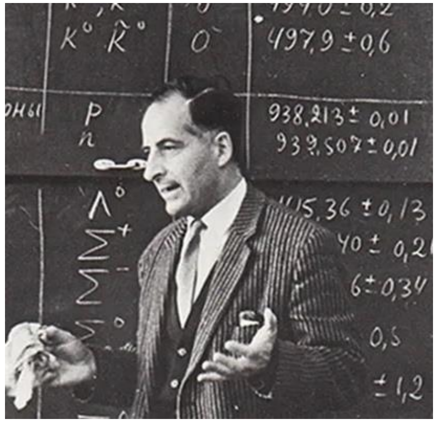
*the **other half** is the <u>neutrino **production**</u>*

Production process are **precisely measurable** with trackers

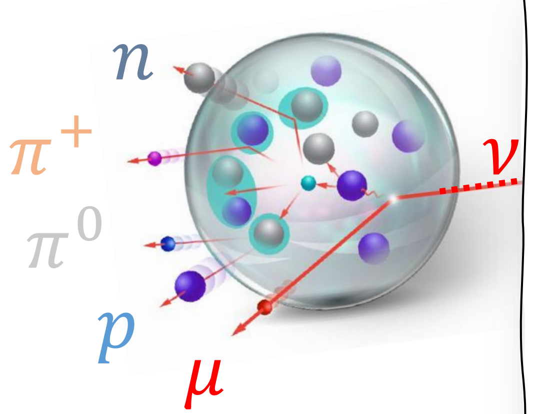
ν energy resolution <1%

Neutrino tagging brings together the two processes and **remove modeling uncertainties**

A solution: Neutrino Tagging



- **Neutrino Tagging** initially was thought as the ideal experimental setup (B. Pontecorvo, 1979) for the study on **ν** properties
- A tracker for full reconstruction of the cinematic of the process generating ν
- **Idea gradually abandoned as far too challenging**



Tagging Direct Neutrinos. A First Step to Neutrino Tagging.

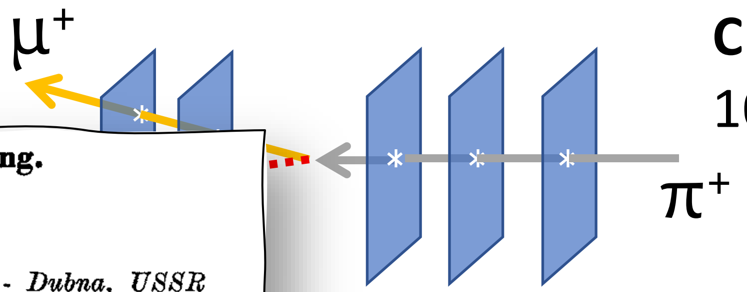
B. Pontecorvo

Laboratory of Nuclear Problems, Joint Institute for Nuclear Research - Dubna, USSR

(ricevuto l'1 Giugno 1979)

As it is well known, high-energy neutrino investigations are performed by using neutrino beams from π and K decays (π → μν, K → μν), that is by letting the pions and the kaons decay over a large distance (the so-called decay length).

The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation (π → μν, K → μν, K → eνπ, ...). Of course, in tagged-neutrino experiments the properties of neutrino beams (type, direction and energy) will be much better known than in the experiments performed so far. The main difficulty in designing such a facility is that the effective neutrino source (which is also the source of the charged particles to be detected in coincidence with the neutrino event) has a length equal to the decay length (of the order of hundreds of metres). In spite of the difficulties it seems that sooner or later such facilities will be available at various high-energy accelerators. Naturally such a « maximum » programme would provide an extremely useful facility.



Challenge: $10^{10\text{-}11}$ π^+/s

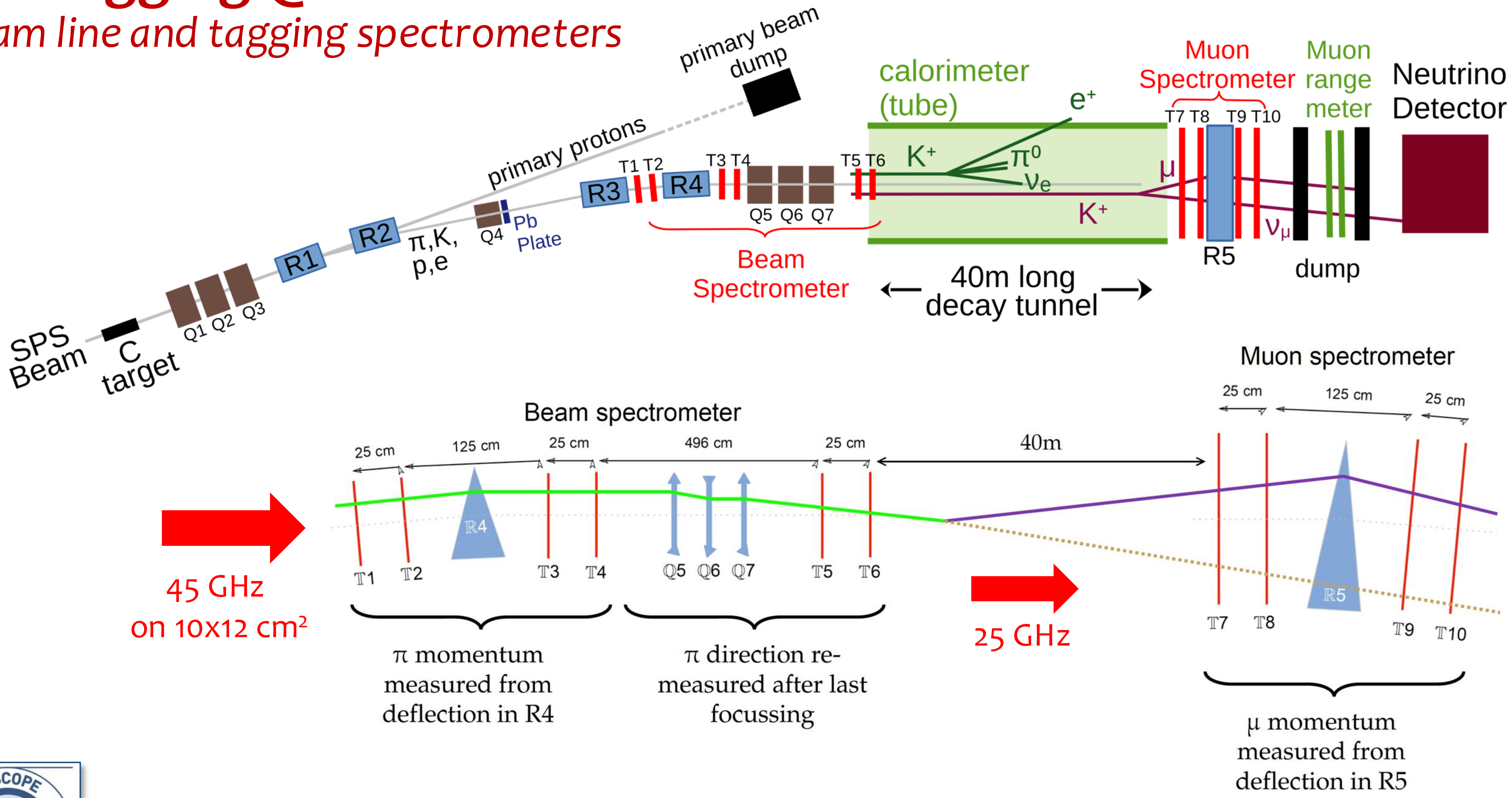
oduction process are **precisely measurable** with trackers

ν energy resolution <1%

NOW
HI-4D-tracking can enable full-scale tagged neutrino experiments

ν-tagging @nuSCOPE

Beam line and tagging spectrometers



M. Perrin-Terrin IN2P3/CNRS

Interested researchers are gathering in a proto-collaboration (nuSCOPE)
First collaboration meeting on 13-15 October at CERN: https://indico.cern.ch/event/1548855/

Tagged Long Baseline Neutrino Experiment

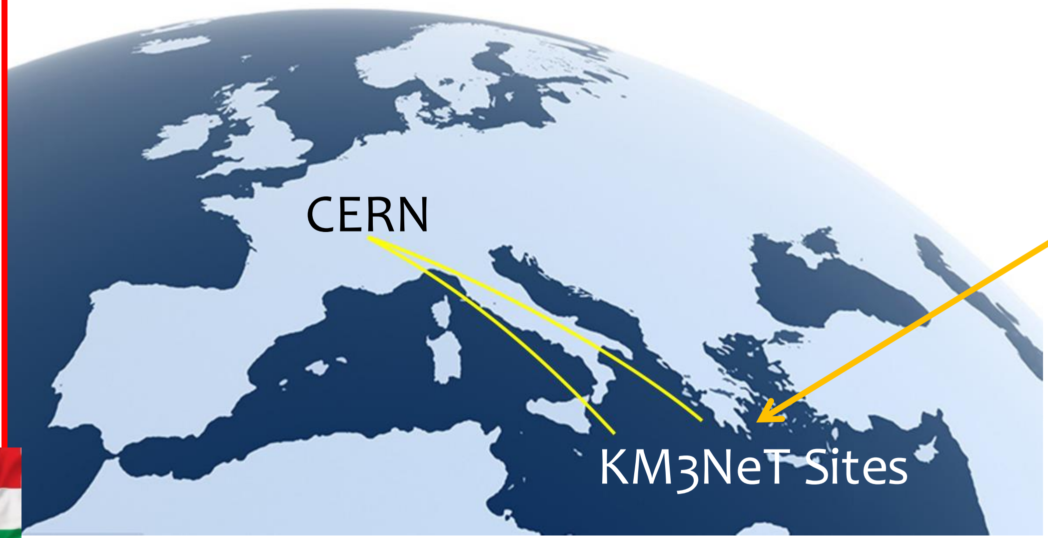
a long-term perspective for ν studies

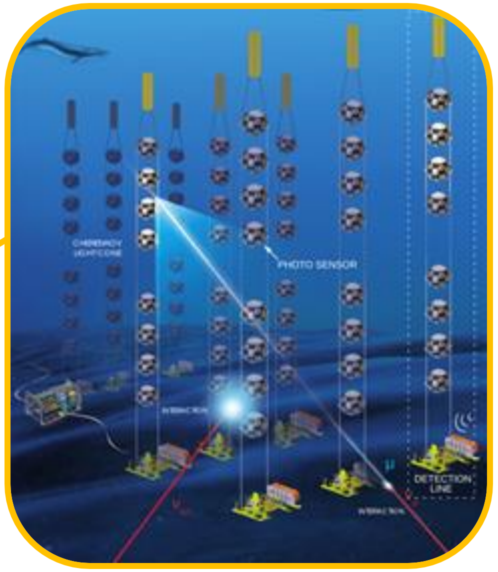
Experiments after DUNE/Hyper-K will need **even larger datasets**

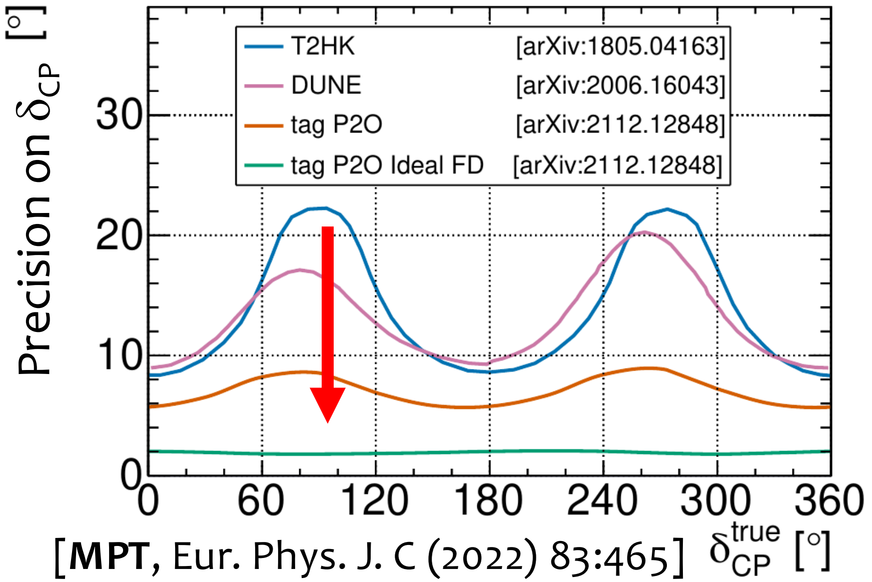
Scaling-up DUNE/HK seems **unfeasible** (extreme beam power)

<u>Alternative solution:</u> use megaton **open water neutrino detectors** (KM3NeT) with a **tagged beam**

- Neutrino tagging compensates coarse detector resolutions
- Huge detector grants large datasets (KM3NeT-ORCA: 7 Mton; DUNE 40kton)
- **Environmentally responsible** (modest beam power, no excavation)







[**MPT**, Eur. Phys. J. C (2022) 83:465]

Technical requirements and detector R&D

Main experimental requirements in HI4DT

for ν–tagging and comparison with LHCb VELO

Specifications [units]	Beam spectrometer	Muon spectrometer	LHCb VELO U2	NA62-GTK (since 2014)
Peak Rate [GHz/cm^2]	2	0.06	1-10 (a)	0.2
Peak Fluence [1MeV n_{eq}/cm^2]	1 x 10^{16}	6 x 10^{14}	5 x 10^{16}	4.5 x 10^{14}
Peak Dose [Mrad]	700	60	> 10^3	16
Hit time resolution [ps] (b)	< 40	< 100	< 50	< 130
Pixel pitch [μm]	300 (c)		45	300
Power density [W/cm^2] (d)	> 2		< 2	> 2
Material budget [X_0]	< 1%		0.8 %	0.5 %
Data troughput [Gbps/ASIC]	100	Not critical	100	Not critical

Notes:

(a) Depends on the chosen "Scenario". In the present option is around 5 GHz/cm^2

(b) Time resolution refers to the RMS on the full chain, considering the different contribution as added in quadrature **(sensor ⊕ front-end ⊕ TDC ⊕ reference clock)**

(c) When 3D silicon sensors are concerned (see next slides), pitch is constrained by the time resolution required

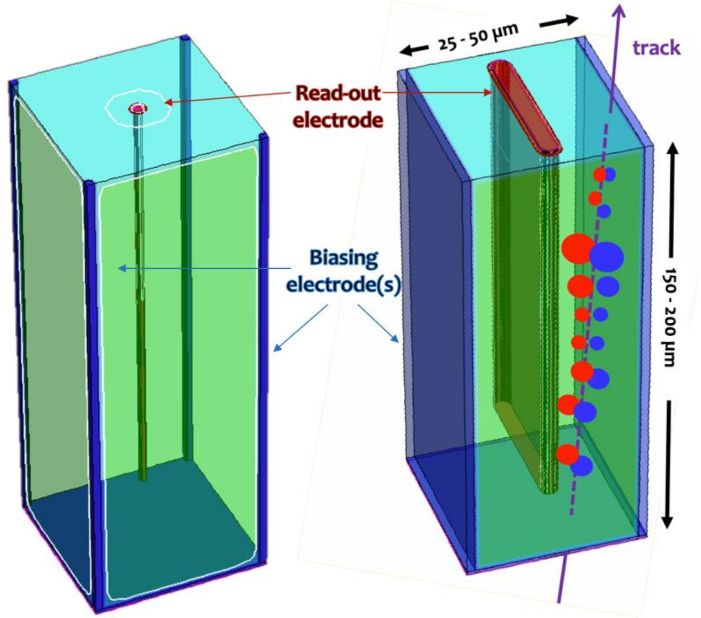
(d) Maximum power density depends on cooling techniques, that is on the capabilty to dissipate power in the Tracker structure

3D silicon sensors: strenghts and features

Concept (S. Parker et al., 1997): Perpendicular electrodes make Inter-electrode distance d independent of sensor thickness z

Sensitive volume and electrode shapes can be designed and modeled for maximum performance

High and uniform E field, Fast Charge Collection Time



columns trenches

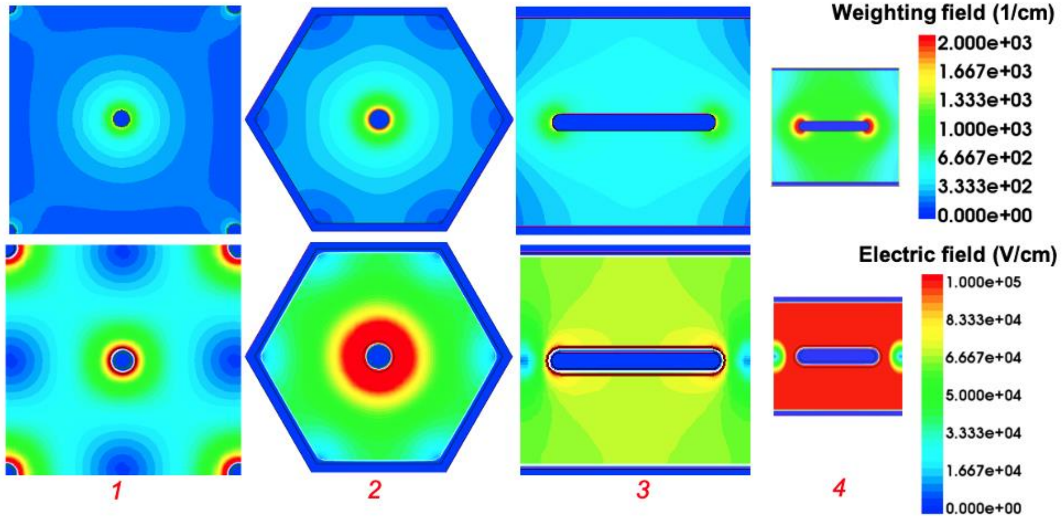
Column or trench aspect ratio ≈ 30:1

Deep Reactive Ion Etching
(MEMS technology)

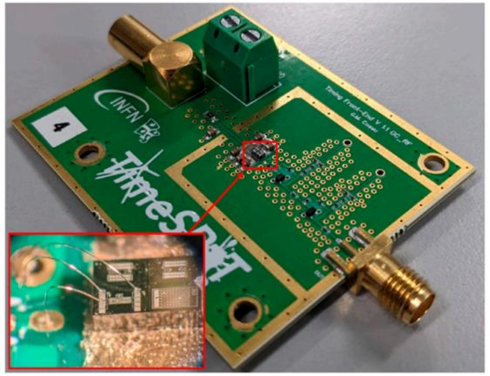
TimeSPOT

TIME and SPace real-time Operating Tracker

$$i = qE_w \cdot v$$



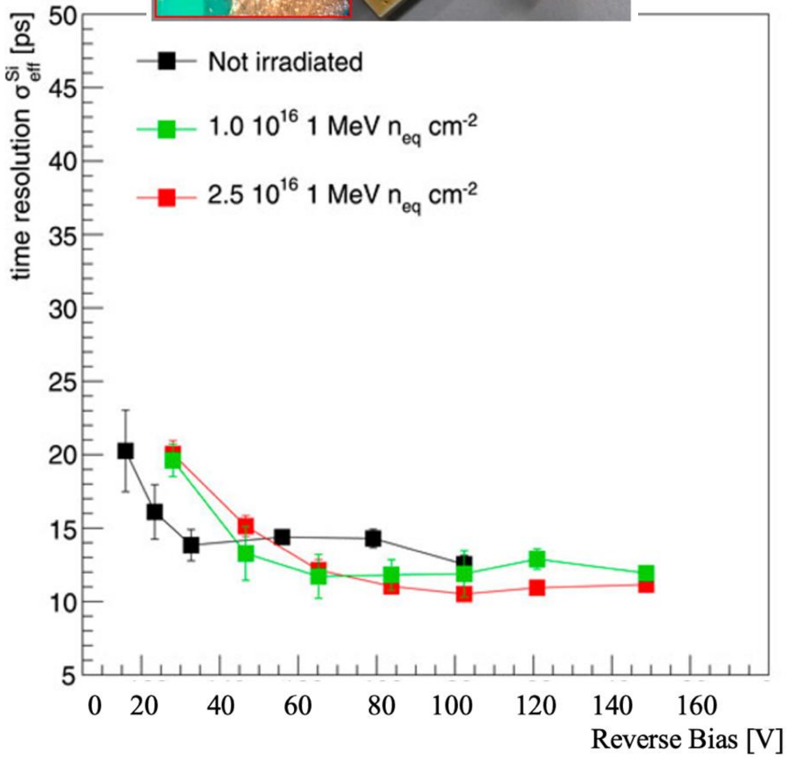
TCAD Sentaurus output: 2D model simulation of three different electrode **geometries** at bias voltage V_{bias} = –100 V

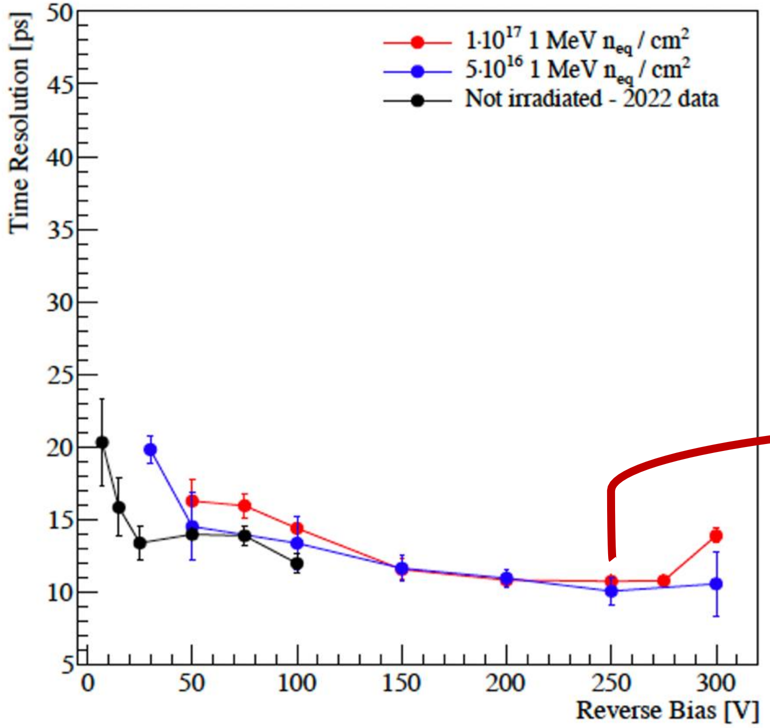


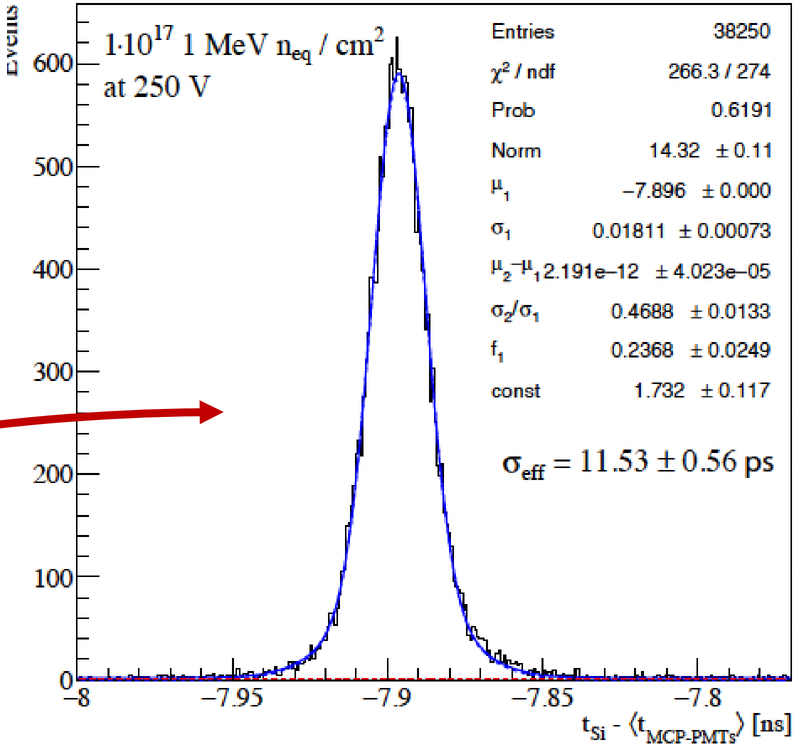
Sensors for 4D-tracking

55 μm pitch, 3D-trench silicon sensors

180 GeV/c π^+, CERN SPS (2020-23)







$2.5{\cdot}10^{16}$ 1 MeV n_{eq}/cm^2
σ_t ≈ 10 ps @ –150 Vbias [1]

$5{\cdot}10^{16}$ 1 MeV n_{eq}/cm^2
σ_t ≈ 11 ps @ –250 Vbias [2]

$1{\cdot}10^{17}$ 1 MeV n_{eq}/cm^2
σ_t ≈ 11.5 ps @ –250 Vbias [2]

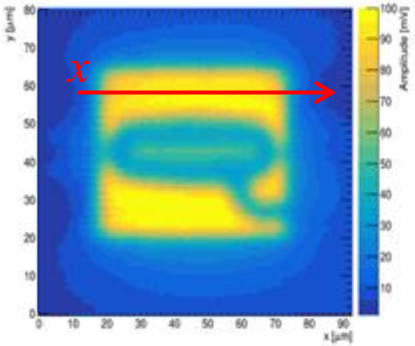
[1] *Characterisation of highly irradiated 3D trench silicon pixel sensors for 4D tracking with 10 ps timing accuracy* , Frontiers in Phys. 12 (2024)

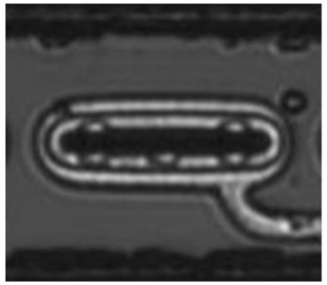
[2] *Characterisation of 3D trench silicon pixel sensors irradiated at $1{\cdot}10^{17}$ 1 MeV neq cm^{-2}* , Frontiers in Phys. 12 (2024) .

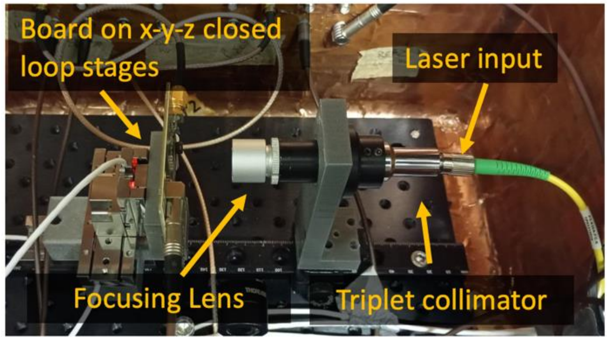
Beyond 10^{17}: CCE maps up to 10^{18}

Lab tests with red pulsed laser

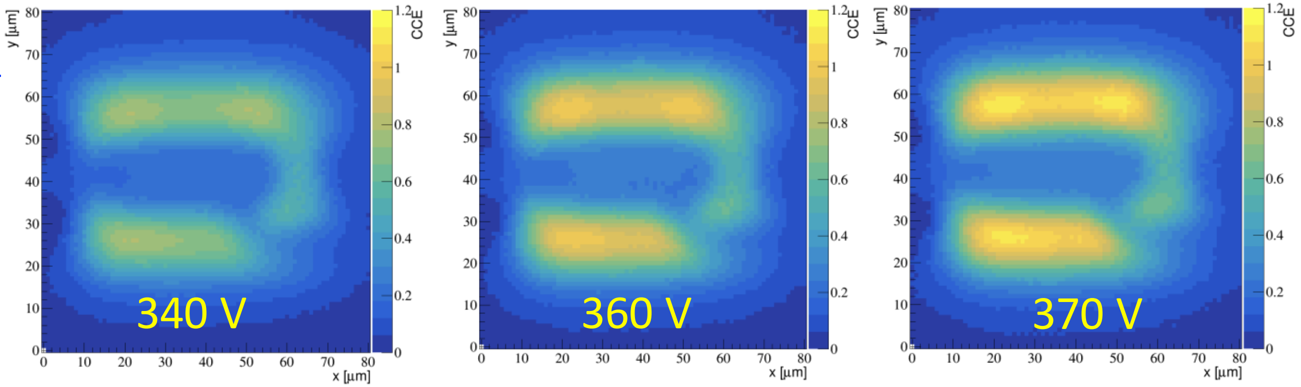
Not irradiated @50V (reference)





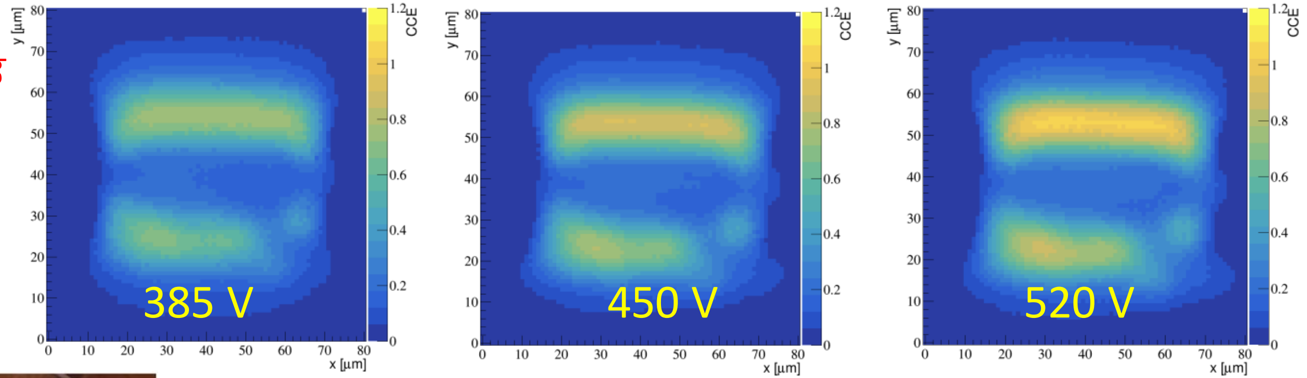


$5 \cdot 10^{17}$ 1 MeV n_{eq}/cm^2

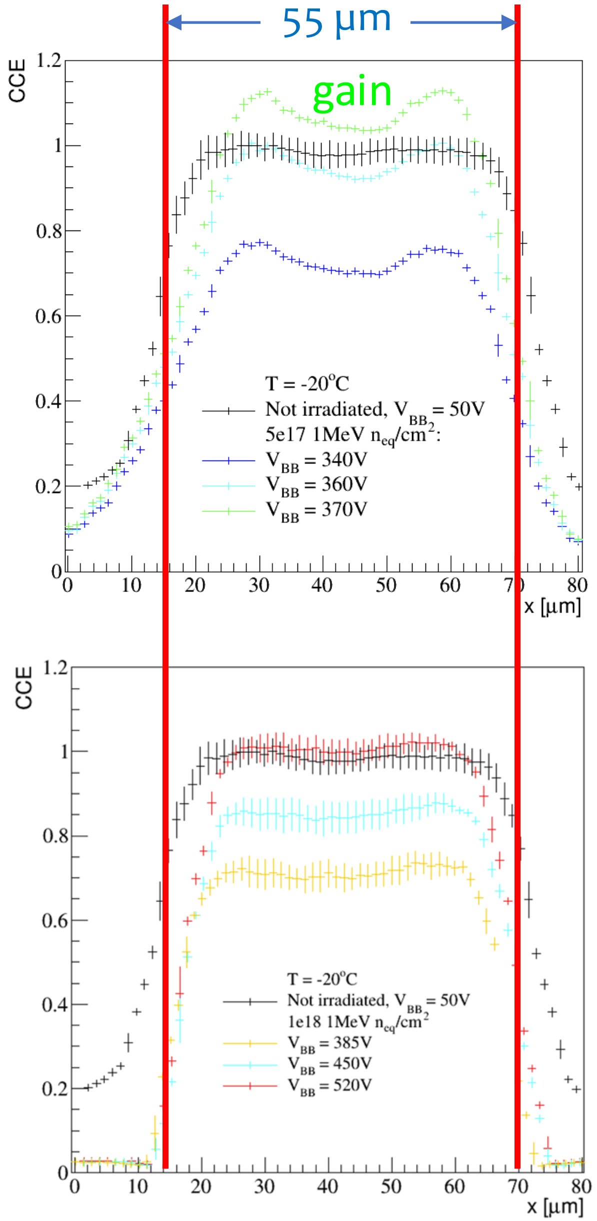


CCE recovered at V_{bias} < 370 V

$1 \cdot 10^{18}$ 1 MeV n_{eq}/cm^2



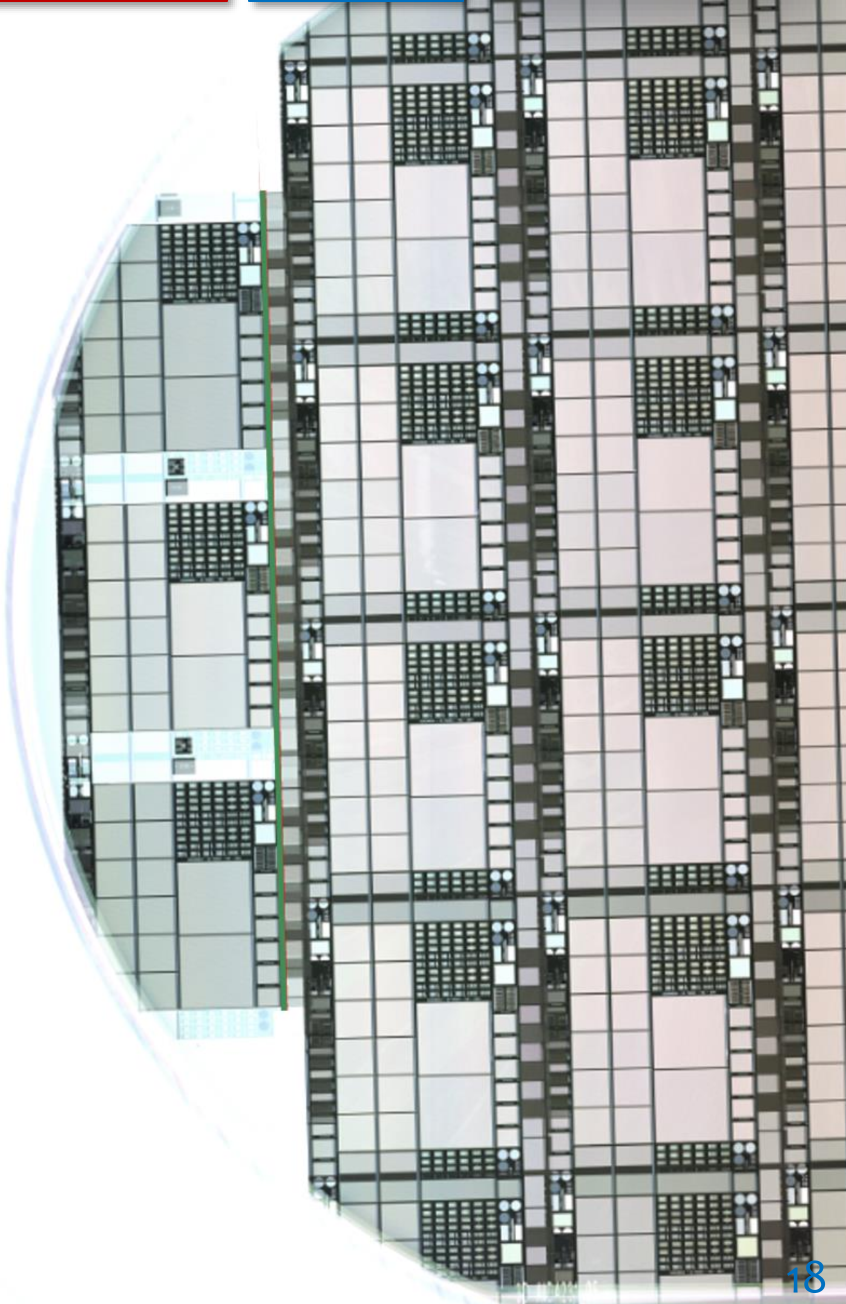
CCE recovered at $V_{bias} \approx$ 520 V



A (proven) effective method for pre-characterization at low temperature (–20 °C)

Edge regions not fully depleted (effcts in detetction efficiency?)

Remaining issues with 3D silicon sensors



1. While showing amazing performance in timing and radiation hardness, 3D-trench sensors are **still a young technology** (we are testing the 3rd batch ever produced). More «exercise» is necessary to obtain **better yield** in production on large size (order cm²) devices.

2. For 3D-trench, **55 µm pitch** is an **optimal size** for both timing and fabrication. Smaller ones start to give excessive capacitance and become difficult to produce (no space for bonding pad area).

3. **3D-column** sensors are **more mature** at the industrial level, as they have already faced the production phase for the inner trackers in ATLAS and CMS upgrades.

4. The high **performance** of 3D-trench, being more than needed, could be **traded with more robustness** in using 3D-column sensors

5. **Remark:** in 3D sensors the **pitch size directly influences the timing performance.** A too small pixel will have a too large capacitance. A «too large» pixel will have a too large CCT, becoming too slow for timing.

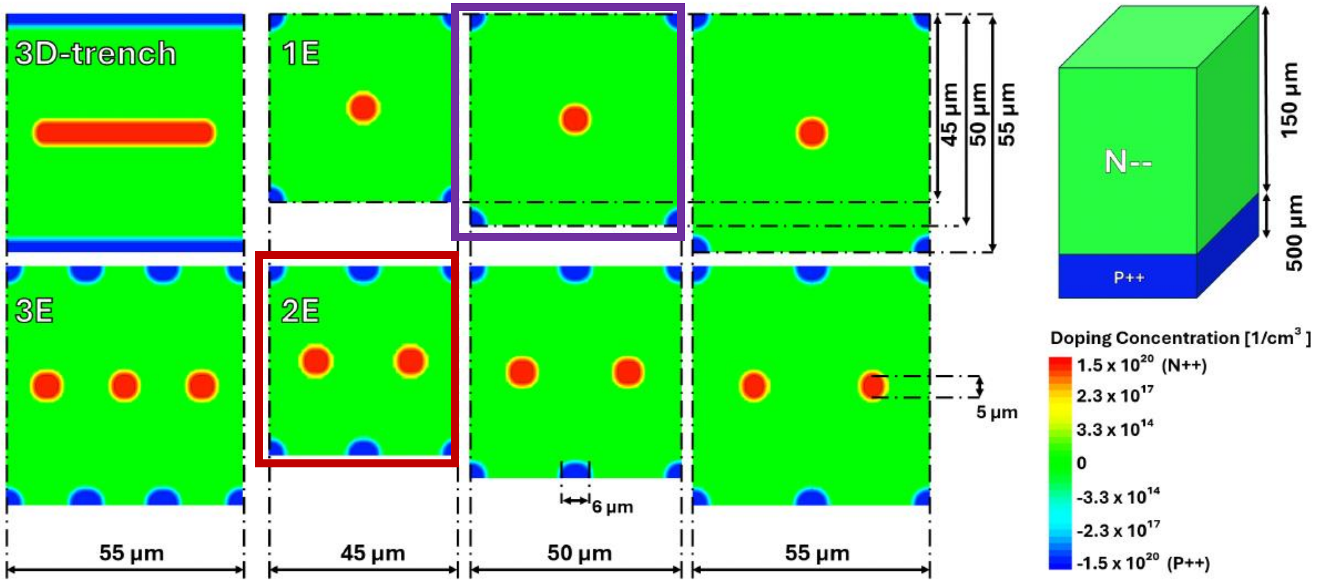
3D flavours: Columns & Trenches

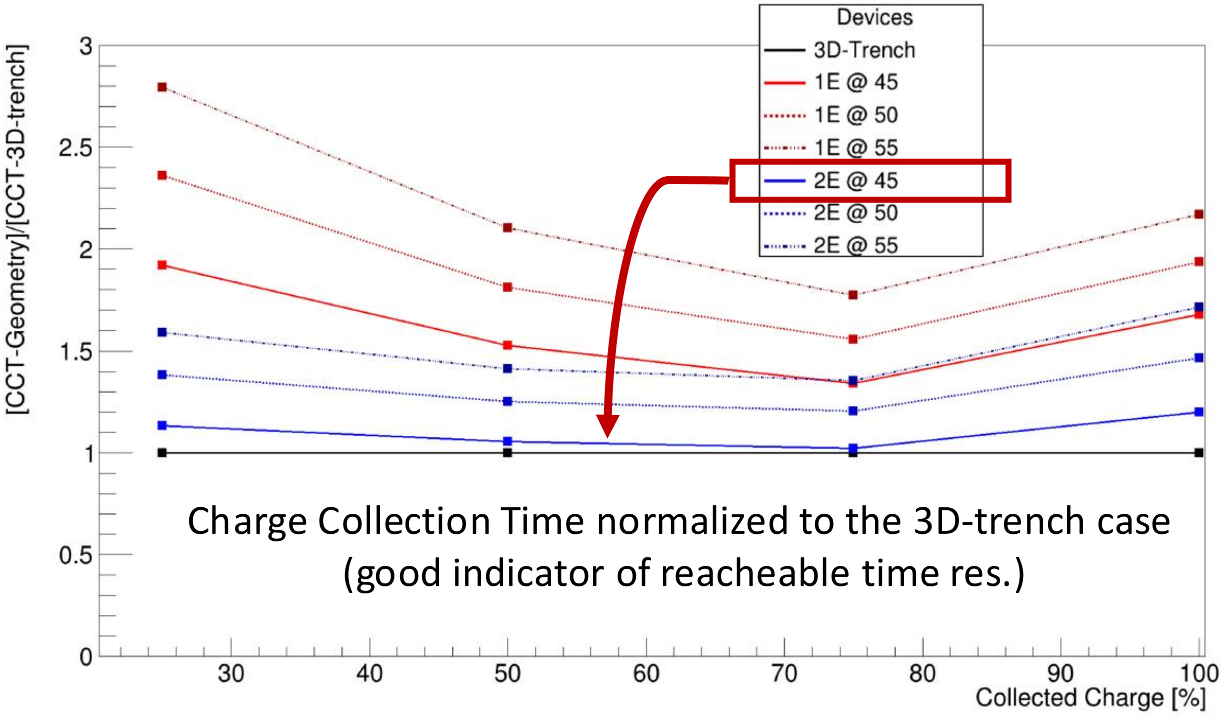
A. Loi et al, doi.org/10.3390/s25030926

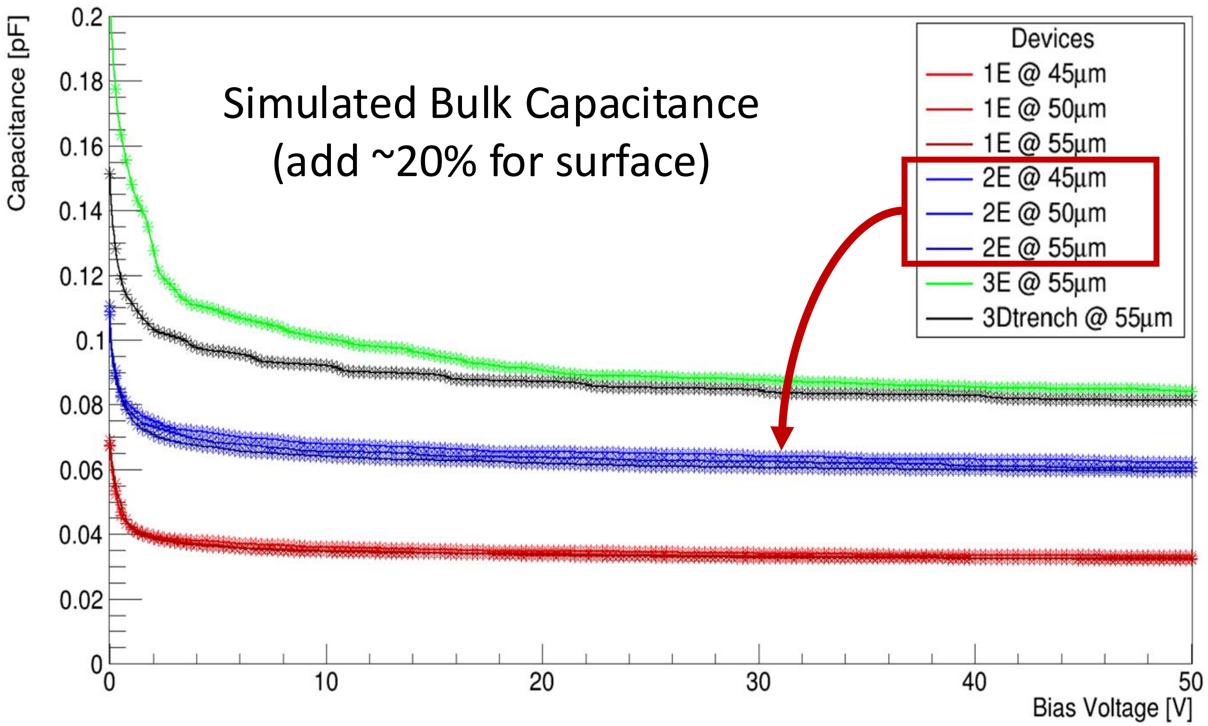
3D-trench (TimeSPOT, 55µm) best for timing
Techically difficult to be made of smaller pitch

Columns simpler to produce (ATLAS-CMS, yield > 50%)
45-2E comparable to 3D-trench up to 80% CCT, with less Capacitance

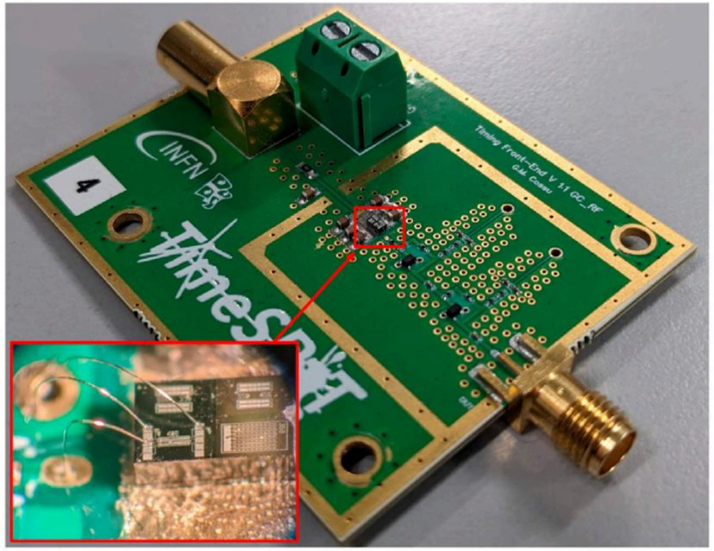
Idea to test also larger thickness (50µm, 200 µm depth)

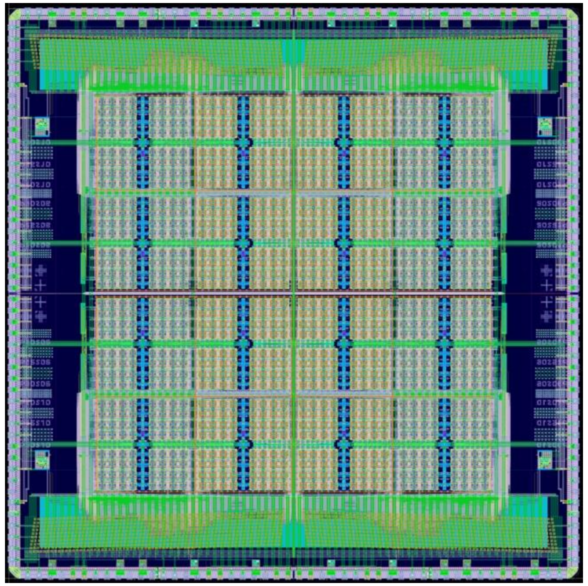






Electronics for 4D-tracking



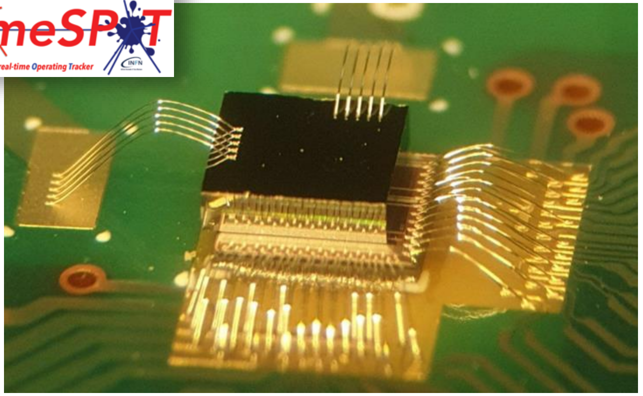


A super-fast sensor: is this enough for HI4DT?

1. Once «solved» the sensor, an even harder challenge is to be faced: the readout ASIC

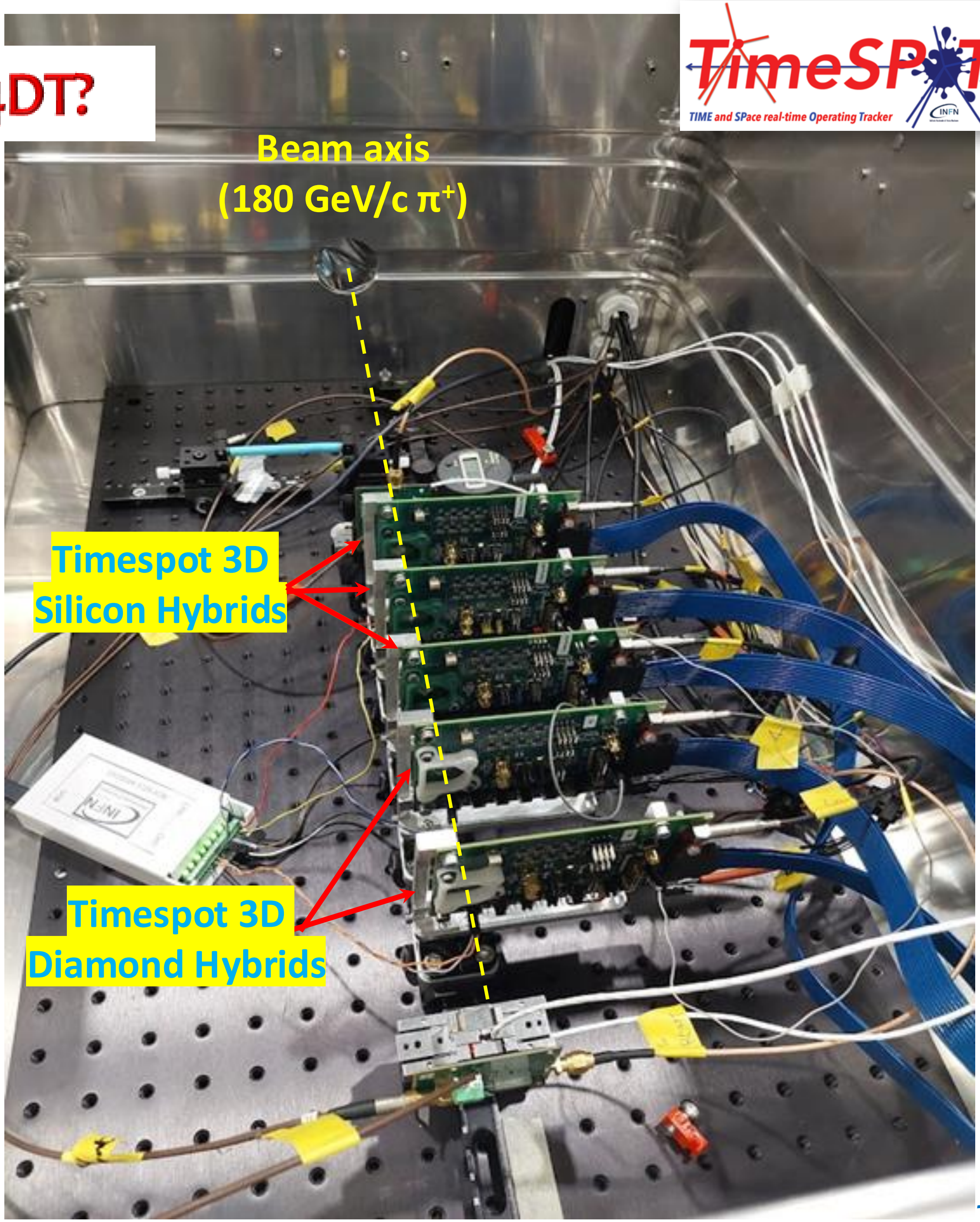
2. TimeSPOT also developed a first ASIC (32x32 pixels). This was not a complete success, especially due to performance disuniformity across its (small) area, with time resolutions ranging from 20 ps to even 100 ps.

3. This was an extremely instructive development step, indicating fundamental rules to follow in designing a large area, full precision device.

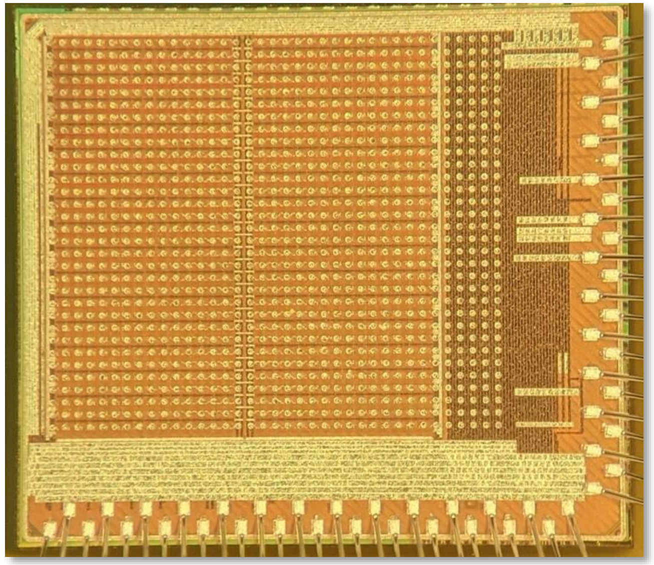


The hybridized Timespot1 ASIC (CMOS 28nm technology)

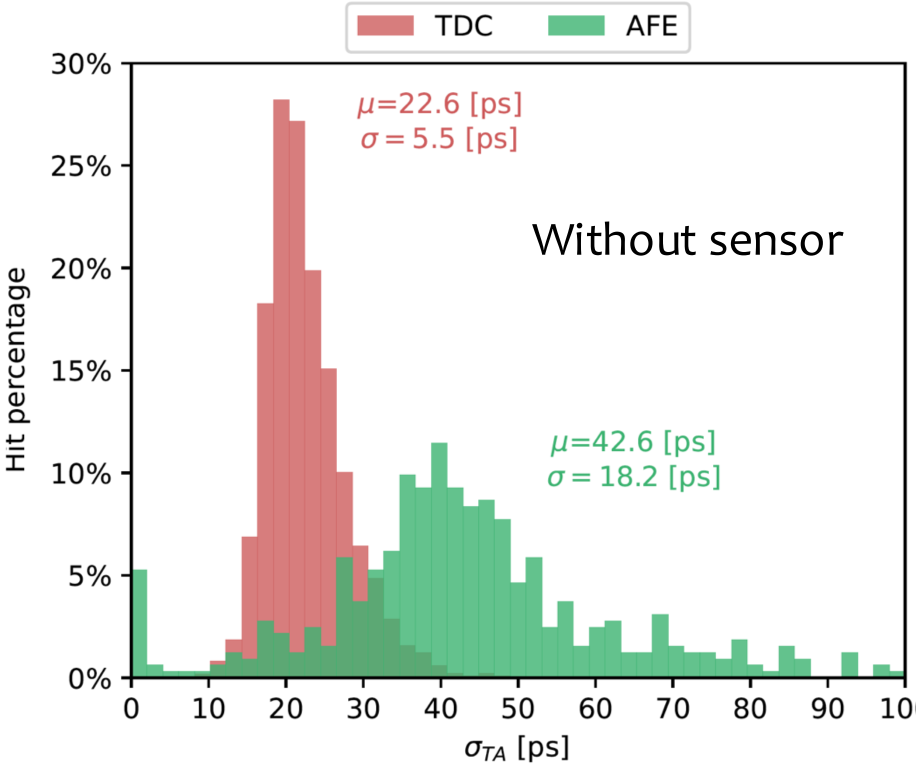
Test of the Timespot1 ASIC at SPS in a **5-station demotracker** (June 2023)

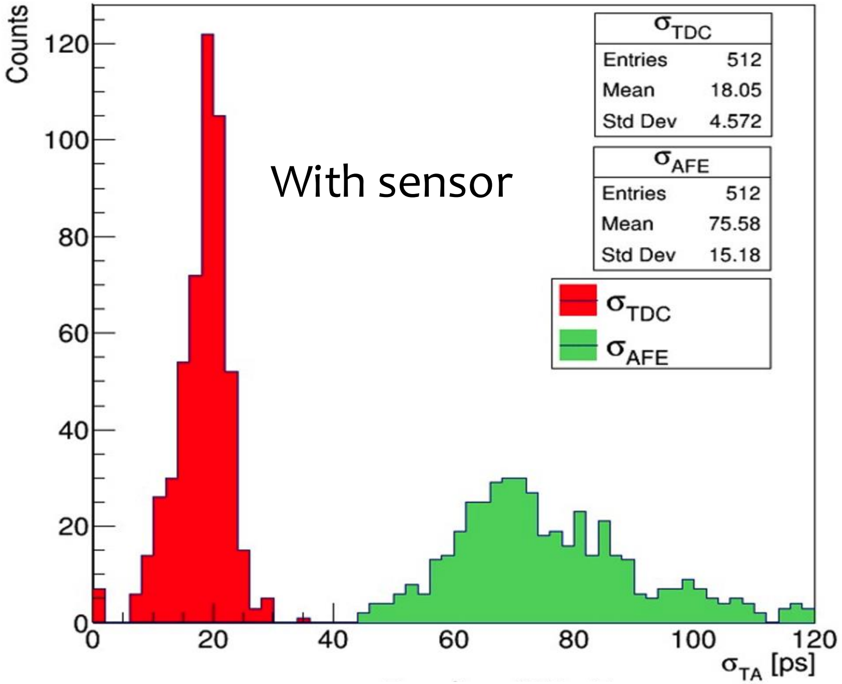


CMOS 28nm technology and power integrity



Timespot1 ASIC (2020-22)
1024 pixels, 55 µm pitch
CMOS 28 nm technology





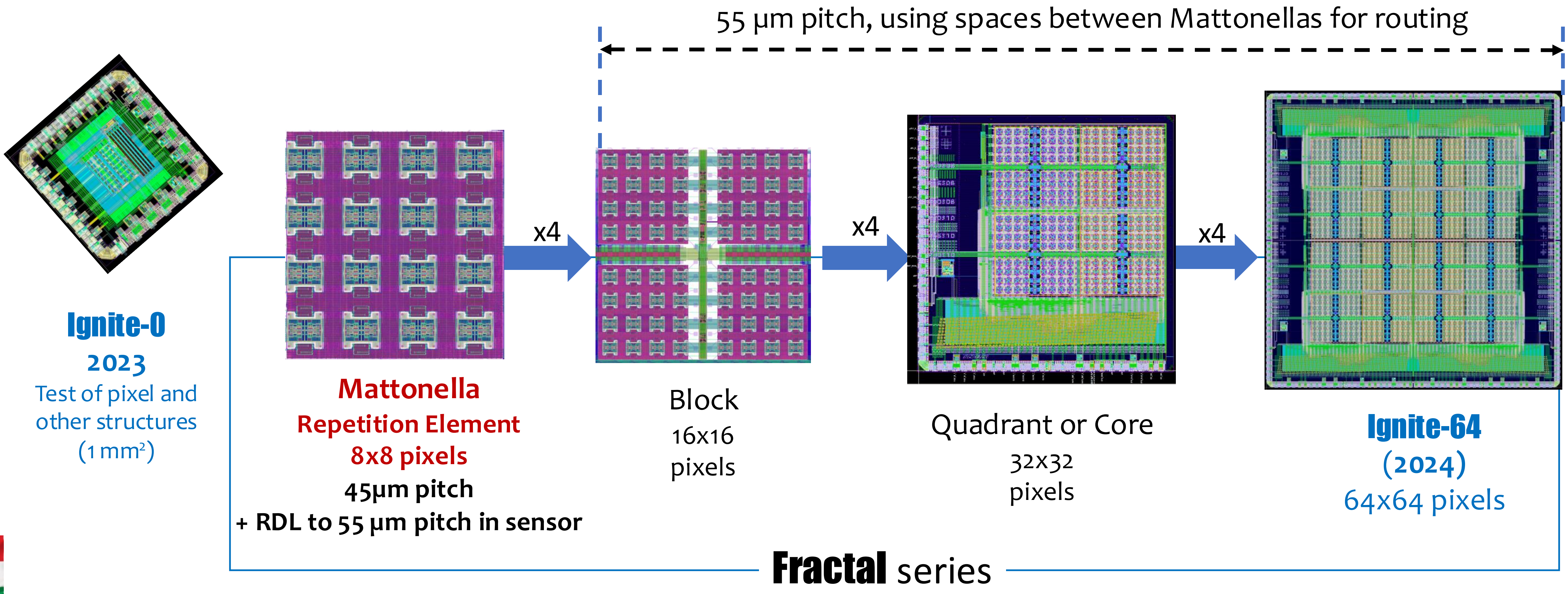
RMS distributions (1024 channels) of Analog Front End (at 10 µW power) and TDC. 2 fC input charge.

- The use of CMOS 28 nm is mandatory in HI4DT for its **high radiation hardness** and integration capabilities
- However such technology is mainly digitally oriented. Reduced head-room for bias (0.9 V)
- **Effect of parasitics is dominant:** connections have large capacitance and IR (Voltage) drop, higher than in 65 nm CMOS technology.
- This can affect considerably circuit performance and its uniformity
- **Special care must be taken in power distribution**, even across small distances (mm)

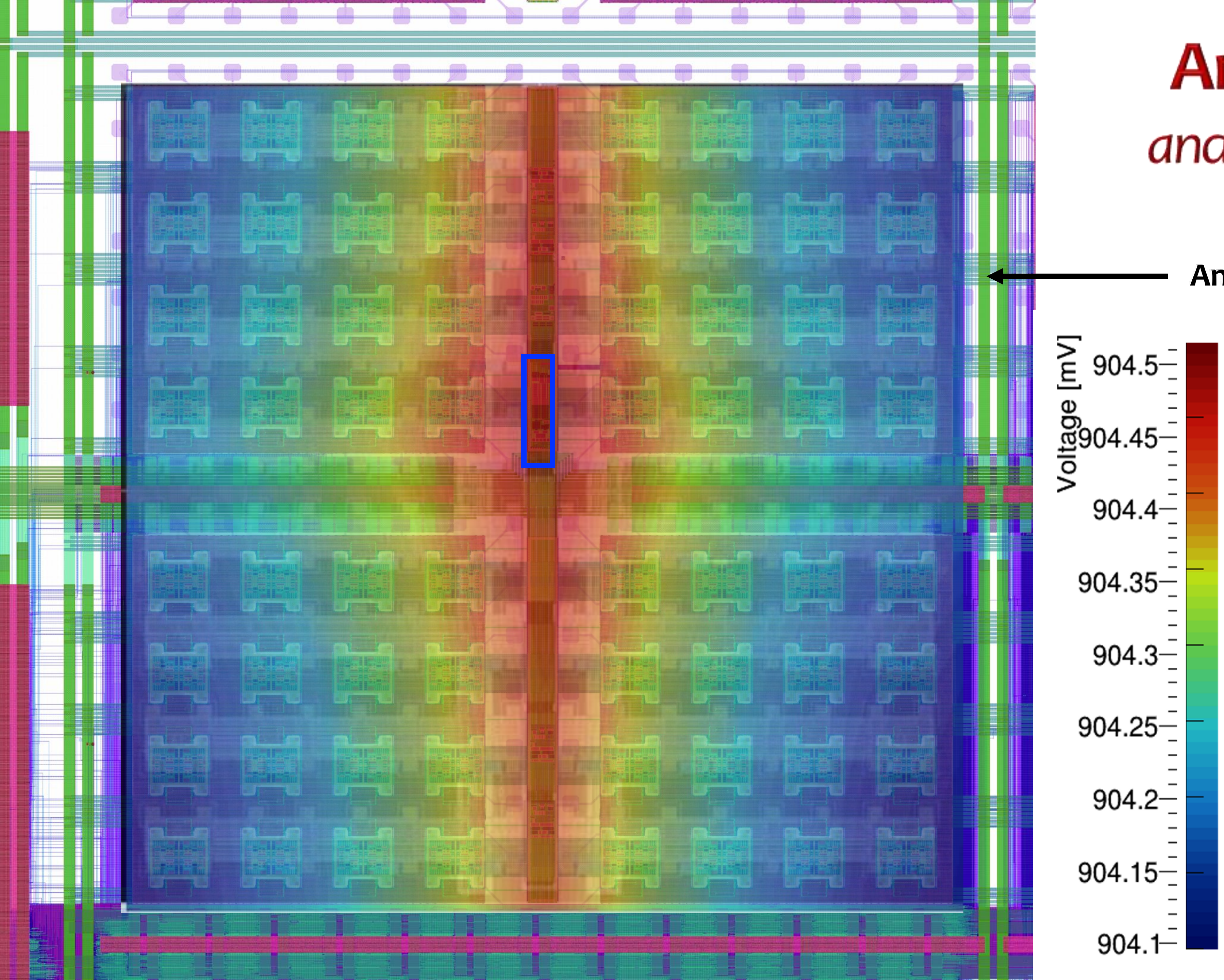
The IGNITE strategy: FractalDesign and vertical integration

keep it local !

The idea (**FractalDesign**) is to build the Large Area ASICs (1÷2 cm²) as repetion of a small structures, **small enough to be fully simulated, produced, and tested in a reliable way.** This sets the possible implementation of a series of scalable ASICs, using the same replica circuit

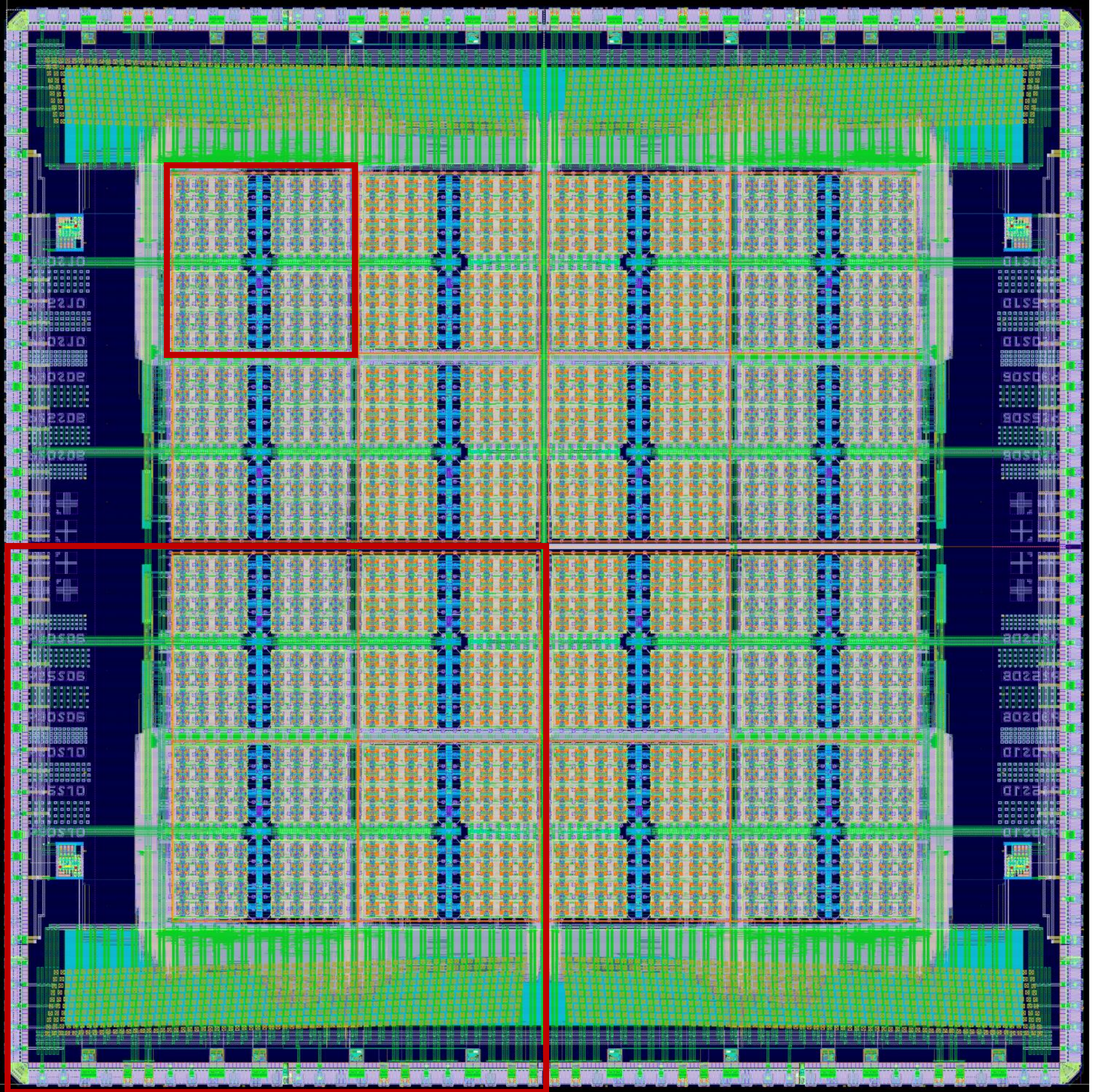


Analog Block
and power Integrity



Analog Block in **Ignite64** : *16x16 pixels*

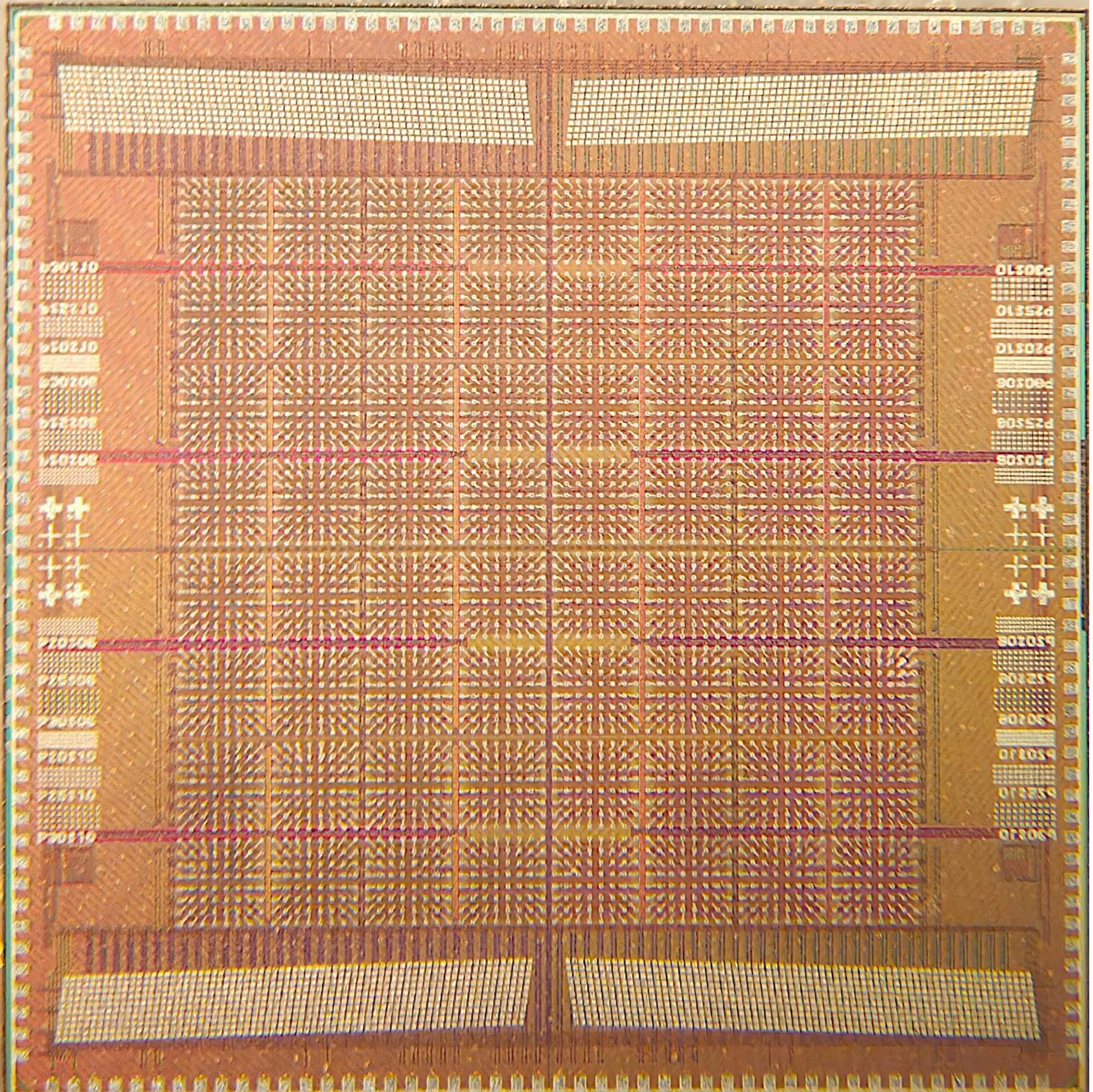
- **Power Integrity is decisive for timing performance**
- **LDO and power distribution with high Voltage integrity**
- **1.2 V in, 0.9 V out**
- **A single (small size: 27x59 μm^2) LDO limits voltage drop to max 0.4 mV**



Ignite64 (ASIC)

64x64 pixels

- Obtained by double-mirroring the Quadrant (4 totally independent Quadrants)
- 16 A-Blocks, 64 Mattonellas
- **Size: 5x5 mm² (sensitive area ≈ 3.52x3.52 mm²)**
- **Purpose:**
  - **Front-end test and characterization**
  - **Mattonella and A-Block (bias) test**
  - **Hybridization and timing sensor characterization onto AIDA-Innova sensors (FBK 3D-Trench and TI-LGAD, CNM 3D-DS columns, CNM I-LGAD)**
- **Slow read-out 4x(1.28 Gbps), a lab/testbeam device**
- Test of DBI structures (see next slides)



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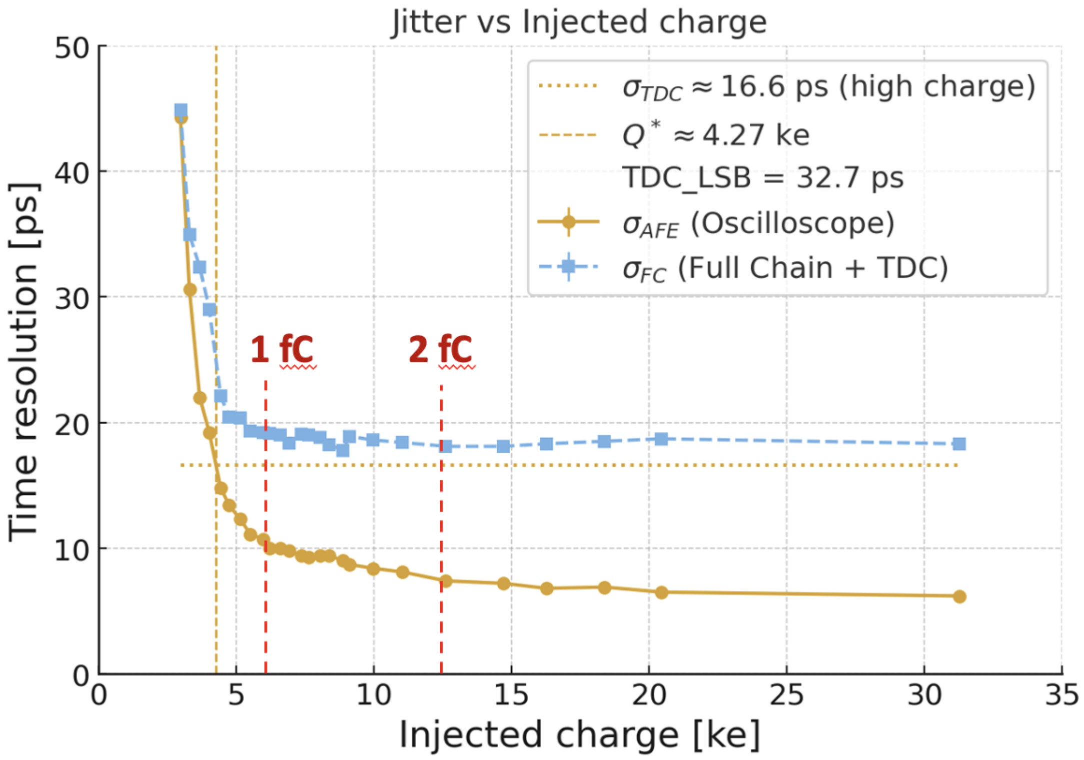
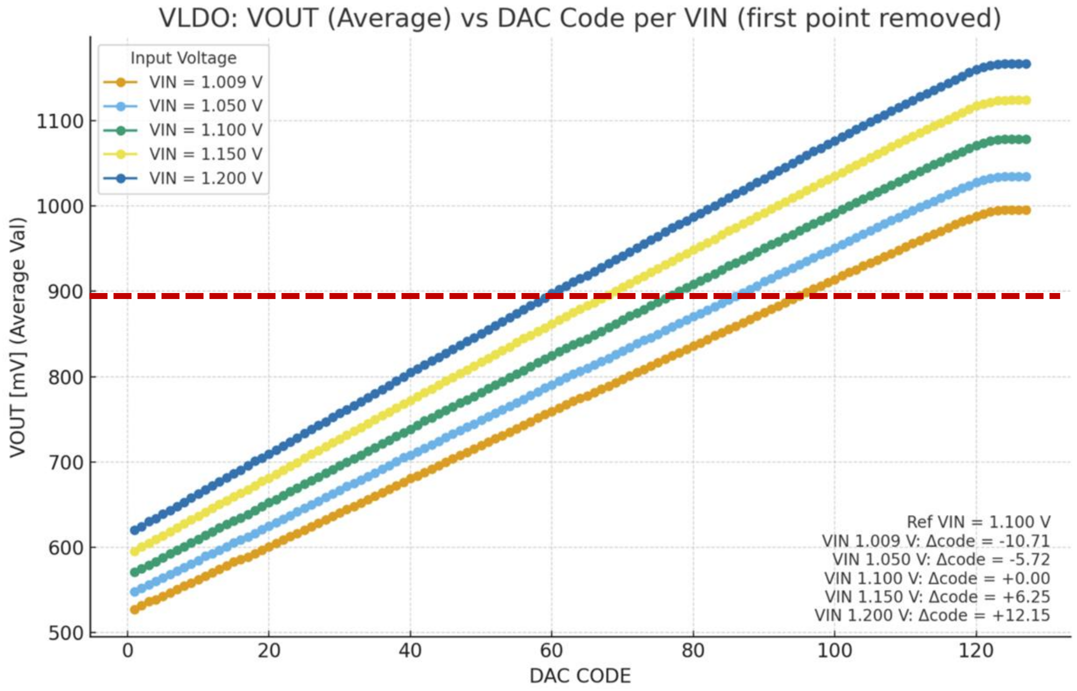
- Test of DBI structures (see next slides)

Submitted on 5th January 2025
Tests now in progress

Ignite32/64 tests (1)
Analog Front End (AFE)

First tests with built-in pulse system
- Before hybridization, no sensor (Cdet ~ 0)
- Achieved RMS time resolution **σ_t < 20 ps for Q ≳ 4 ke**
- Target: **σ_t < 30 ps for Q > 1 fC and Cdet ~ 100 fF**
- Massive tests on all channels ongoing. Response appears nicely uniform.



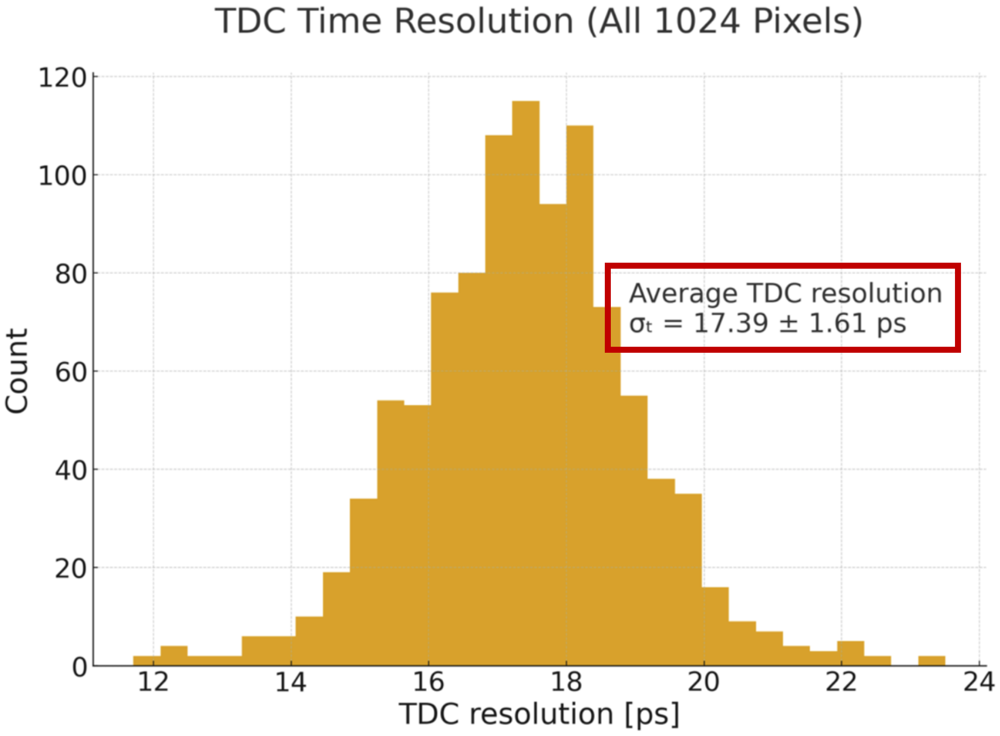


Distributed voltage regulator LDO (1 per each 16x16 channel block)
- Curves of V_{out} vs internal DAC code, at different V_{in}, showing proper circuit operation.
- Key analog circuit to ensure voltage integrity across the full matrix
- Internal custom DAC and LDO working

Ignite32/64 tests (2)

TDC (one per pixel)

- Achieved TDC LSB on the 32x32 matrix: a preliminary indication of achieveable performance stability
- Typical values are **nicely below 30 ps LSB** (theoretical resolution < 9 ns), exception made for **Mattonellas 4 to 7.**
- This is due to a **bug in the configuration interface** in those blocks (presently under study), which prevents individual selection of channels. Nothing related to intrinsic timing performance



Mattonella 0

27.8	27.9	28.4	27.7	28.7	26.1	27.6	27.2
26.3	28.3	28.3	28.5	27.5	28.3	27.9	26.6
28.3	28.2	27.6	28.5	26.4	27.8	26.5	26.2
27.6	28.6	26	28.2	26.9	26.7	28.5	29.1
29.5	27.3	26.2	26.2	27.3	27.9	26.8	27.8
27.3	26.8	28.9	26.2	28	26.8	26.9	28.6
28.2	28.2	26.7	28.8	28.3	28	26.6	31.2
27.7	27.3	29.2	26.9	26.2	26.1	27.9	28

Mattonella 1

26	28.2	28.5	27.5	26.6	28.3	28.6	28
28.5	26.4	26.3	28.2	27	28.8	26.2	27
28.2	28	28.8	27.5	28.9	26.7	29.6	26.4
29.1	26.2	27.7	27.9	27	28.7	28.1	28.4
26.1	28.2	28.5	27.4	27.2	26.8	26.8	28.6
29.2	27	28.1	27.3	26.3	28	30.7	27.7
26	27.4	28.2	26.1	26.8	27.9	28.3	27
29	27.3	28	27.9	29.5	26.3	27.2	28.5

Mattonella 2

26.6	28.4	28.3	27.8	28.5	27.2	27.3	26.2
27.1	26.6	29.8	26.4	29	26.7	28.3	26.6
28.2	26.2	28.2	26.2	28.2	27.2	28.5	26.4
27	26.1	26.1	26.1	27.6	27	31.4	26.4
27.9	29.7	27.5	26.3	28.1	29	28.6	27.8
28.2	28.1	28.5	28.7	29.2	26.9	26.4	28.5
27.2	27.7	28.6	28.7	26.1	28.8	27.8	27.5
29.9	27.1	26.3	27.2	28.2	27.5	27.5	27.9

Mattonella 3

27.5	27.3	28.8	28.1	26.5	27.1	26.9	26.6
27.6	28.7	28.4	28.5	27.2	26.9	27.6	28.7
26.1	29.1	27.7	26.7	26.3	26.2	30.8	27
26.4	28.6	27.6	27.8	26.7	26.4	27.5	26.9
27.4	26.4	28.4	28.2	27.6	26.5	26.1	27.9
26.3	26.8	27.3	28.6	28	26.6	29.1	26.1
28.1	28.6	28	28.1	26.1	26.1	26.7	28.9
27.9	27.3	26.4	28.9	27.8	27.6	27.2	28.2

Mattonella 4

28.1	37.3	43	34.7	39.1	27.6	27	26.3
41.7	36.1	35.5	28.9	37.1	28	27.3	64.7
42.7	37.2	27.2	44.8	40.5	26.7	26	50.1
35.9	30.6	68.6	58.9	27.9	28.7	34.6	28.3
42.9	36	25	45.4	40.7	45.9	27.3	27.5
41.7	55.5	26.8	31.6	47.5	59.1	27.2	52.6
57.8	47.5	64.9	24.8	69.3	33.7	31.9	39.3
40.5	31.8	31.4	31.2	25.4	60.1	28.1	37.6

Mattonella 5

28.1	40.2	62.8	31.4	32.1	48.8	31.3	31.8
30.7	33	34.1	33.3	29.4	30.1	26.6	61.4
44.8	46.7	35.9	25	28	62	30.7	26.9
31.2	26	47.6	25.8	39.5	45.6	71	26.6
28	47.8	29.9	35	36.7	33.1	40.6	38.3
29.5	25.6	52.9	27.3	40.7	46	41.7	38.9
58.5	43.4	35.6	35.1	28.6	29.7	31.2	52.6
29.8	28.6	46.7	25.3	26.8	40.7	38.6	26.7

Mattonella 6

51.5	29.8	29	26.9	29.3	40	40.8	45.1
43.7	52.3	43.3	34.5	32	51.9	55.1	29.2
27.6	28	64.6	39.1	38.5	45.8	34.4	47.3
29.5	44	30.3	53.2	39.9	48.1	56.1	62.8
31.3	28	48	32.1	30.2	53.2	32.4	25.4
33.8	35	35.2	27.7	53.4	39.9	53.9	30.6
64.1	28.3	50.8	27.5	55.6	67.1	27.6	40.3
34.7	42	29.2	28.2	32.9	49.5	42.7	47

Mattonella 7

45.6	30.3	51.3	64.7	30.5	28.9	53.1	50
31.8	27.1	44.4	42.6	28.4	50.3	24.7	53.9
33.4	37.7	35.6	44.3	38.2	33.2	44.5	50.4
26.2	41.1	77.1	40	37.8	46	29.3	63.7
32.4	45.7	33.2	50	27.3	70.8	42.5	41.9
29.1	50.7	30	24.8	27.1	26.5	38.8	57.1
27.5	50	25.1	48.7	47.5	74.9	34.7	28.6
48.8	44.3	25	35.2	49.6	26.2	25	54.9

Mattonella 8

27.7	28.5	29.9	26.7	26.9	26.8	26.8	26.5
27.7	29.1	29.3	26.1	27.9	27.6	28.1	28.3
26.6	31.9	27.8	25.2	29.2	28.6	26.6	28.9
26.3	26.1	26.8	26	27.4	27.2	28.5	26
28.2	28.4	26.2	26.2	27.8	28	26.6	26.3
27.6	26.1	26.2	27.2	29	27.6	28.6	27.9
28	26.9	28.6	26.5	26.3	27.4	26.7	26.8
28.7	26.6	28.1	28.1	26.3	28.2	26.5	26.1

Mattonella 9

28.3	26.4	26.6	27.6	27.5	27.7	27.3	27.6
27.6	26.9	28.4	27.2	27.7	26.6	29.2	28.7
26.8	26.6	29.2	28.5	28	27.9	27.4	28.5
29.2	28.5	26.4	27.2	27.8	26.6	26.5	28.5
26.8	28.3	26.6	28.6	27.8	29.5	29	28.3
27.5	28.3	26.8	28.5	28.8	26.1	27.5	27.8
27.7	29.5	28.1	27.8	28	26.7	27.9	25
27.7	28	27.5	28.1	28.1	28.5	26.3	28.3

Mattonella 10

28.1	26.9	28.5	28.7	28.8	26.1	26.2	28.7
27	26.1	27.3	26.1	27	26.5	28.3	27.5
27.1	27.8	28.9	31.1	28.6	27.9	28	28.3
27.6	28.3	29.2	29.1	27.2	28.7	27.8	25.3
27.6	28.5	27	28.1	28.6	26.3	26.3	27.7
28.2	27.7	26.8	27.3	27.3	26.9	26.1	28.3
27.4	27	29.9	27.7	28.5	28	26.5	26
28.5	26.8	28.3	27.5	28	27.4	29.1	27.3

Mattonella 11

27.1	27.7	26.2	28.4	28.2	27.1	26.5	27.8
27.5	27	30.3	27.3	29.1	28.4	27.2	26.9
27.3	28.5	27.2	31.3	27.2	27.2	29.1	27.1
28.2	31.3	26.8	28.9	26.8	26.4	26.4	27.8
27.4	26.5	28.7	28.1	27.8	28.5	26.9	27.5
27.9	26.9	32.8	26.5	29.1	28.3	26.2	28.1
26.9	28.1	26.5	28.5	28.9	26.8	27.2	26.8
27.1	28.2	27.4	28.2	28.2	27.4	26.1	26.3

Mattonella 12

29.7	27.6	27.8	26	28.2	26.5	26.1	26.8
27.2	27	28.6	27.9	27.2	27.6	27.9	29
28.2	28.9	26.7	26.7	28.7	27.1	26.4	26
28.5	28.4	28.7	26	26.2	26.8	27.9	27.7
28.5	28.1	27.6	27.4	28.3	27.9	28.1	26.2
26.9	27.5	27.2	27.6	26.6	29.6	26.8	26.5
26.2	26.7	28.5	29.2	27.8	27.6	26.1	28.2
29.8	27.3	26	26.5	26.1	27.8	26.3	28.4

Mattonella 13

27.5	28.9	27.7	31.8	26.7	26.9	28.1	27
28.2	27.4	26.1	28.3	27	27.9	27.8	26.3
26.9	26.8	28.8	27.8	26.5	26.9	28	28
27	28.9	28.7	29	28.7	27.6	26.5	26.7
26.5	28.4	26.7	28.4	26.8	28.7	27.6	31.9
27.4	27.9	27.5	26.4	27.8	26.4	29.9	26.6
26.2	26.7	27.7	32.1	28.7	27.3	28.9	27.8
27.9	30.8	28.9	26	30.2	27.1	28.5	27.8

Mattonella 14

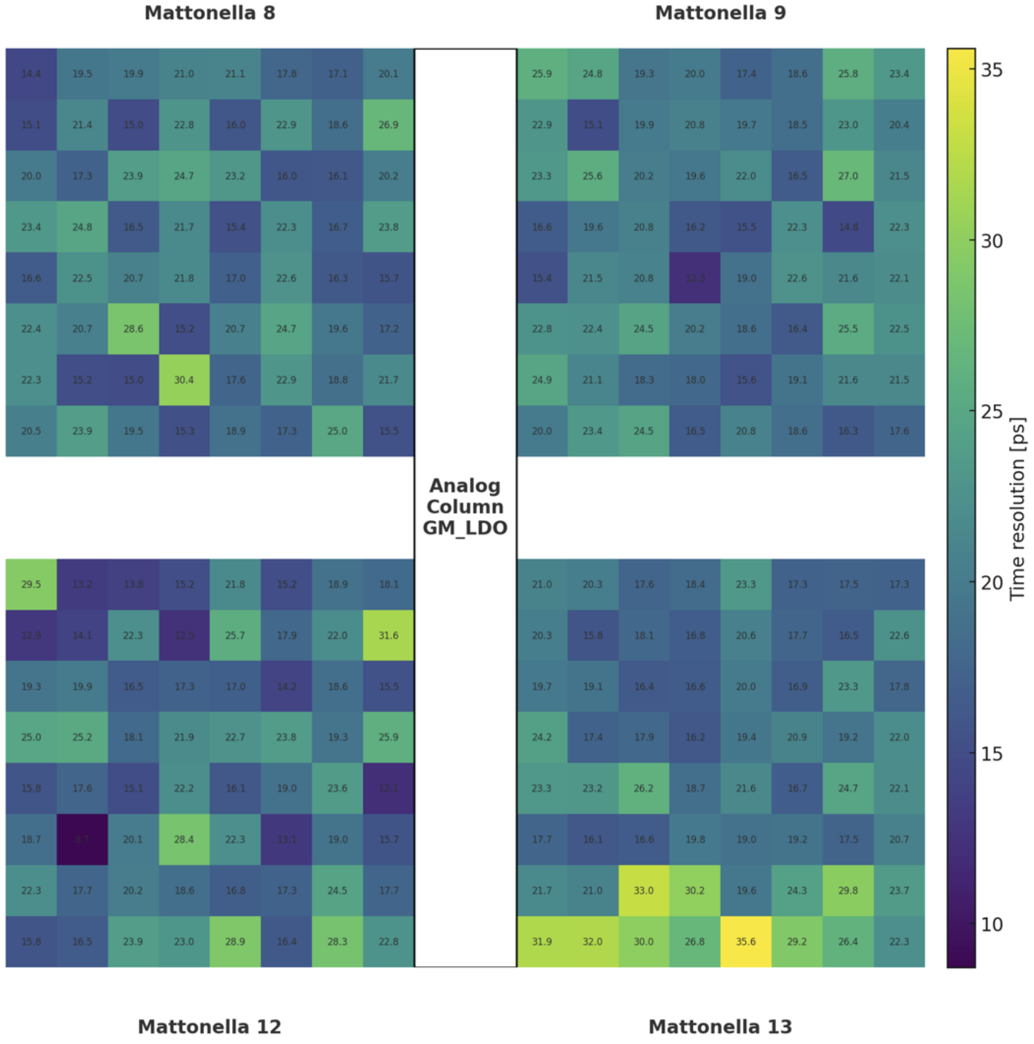
28	26.7	26.5	26.5	26.3	26	27.1	26
28.3	26.4	26.9	28.3	31.7	27.7	27.9	28
28	26.5	28.1	27.3	27.9	27.4	26.6	27.5
28.8	28.2	28.1	28.1	28.1	29	26.4	26.7
26.1	27	27	26.7	28.3	27.1	28.8	28.4
27.6	27.7	26.1	27.4	28.3	28.8	26.9	29
26.9	26.9	26.7	26.2	27.7	28.6	26.3	28.6
27.1	27	26.6	26.3	27.7	26.4	27.3	29

Mattonella 15

27.2	28.3	26.2	25.4	26.1	26.9	26.9	27.3
26.1	28.9	29.2	26.2	26.1	27.1	26.2	27.2
26.3	27.1	27.5	26.2	26.1	28.8	27.7	28.8
27.8	27	26.3	27.3	26.7	27.2	26.4	28.1
27.3	28.5	26.5	28.8	27.6	31.8	26.8	30.7
29.8	27.2	28.3	28.1	26.7	27.4	28.6	27.8
30	28	29.1	27.9	28	26.6	26.3	26.5
27.2	28.9	27.5	26.2	27.5	26.2	27.3	27.7

Ignite32/64 tests (3)

Full chain (AFE ⊕ TDC ⊕ Clock)

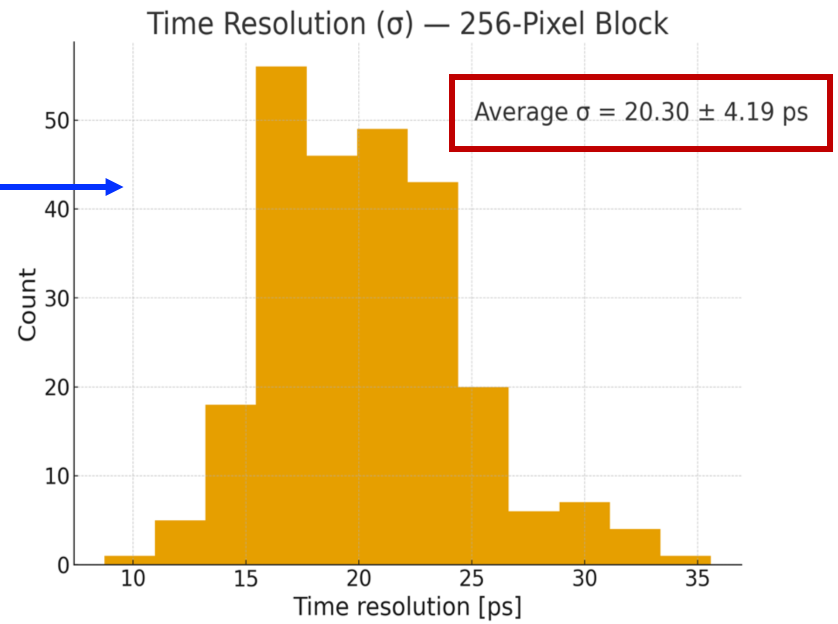


Full chain RMS time resolution per pixel on an Analog Block

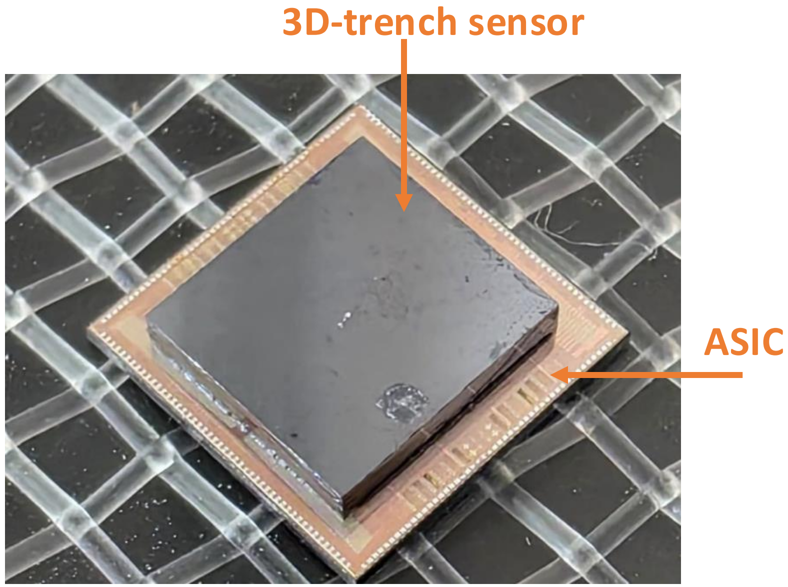
Timing performance with the full chain
AFE pulsed with 1 fC
Power 20 μW/pixel.

All internal DACs and LDO in use

Average Time resolution of the full Analog-Block is 20 ps



Tests on the hybridized prototype presently starting

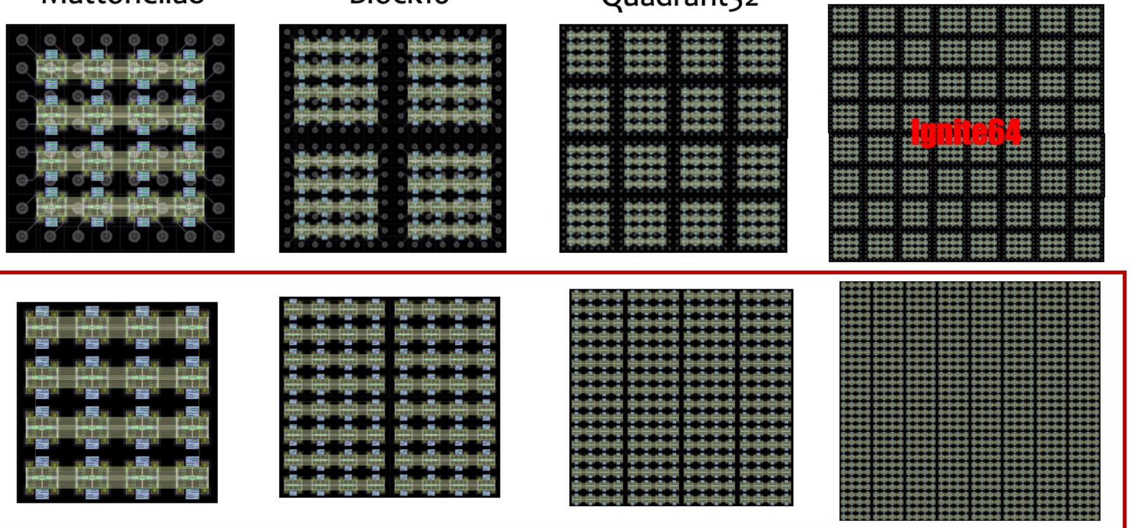


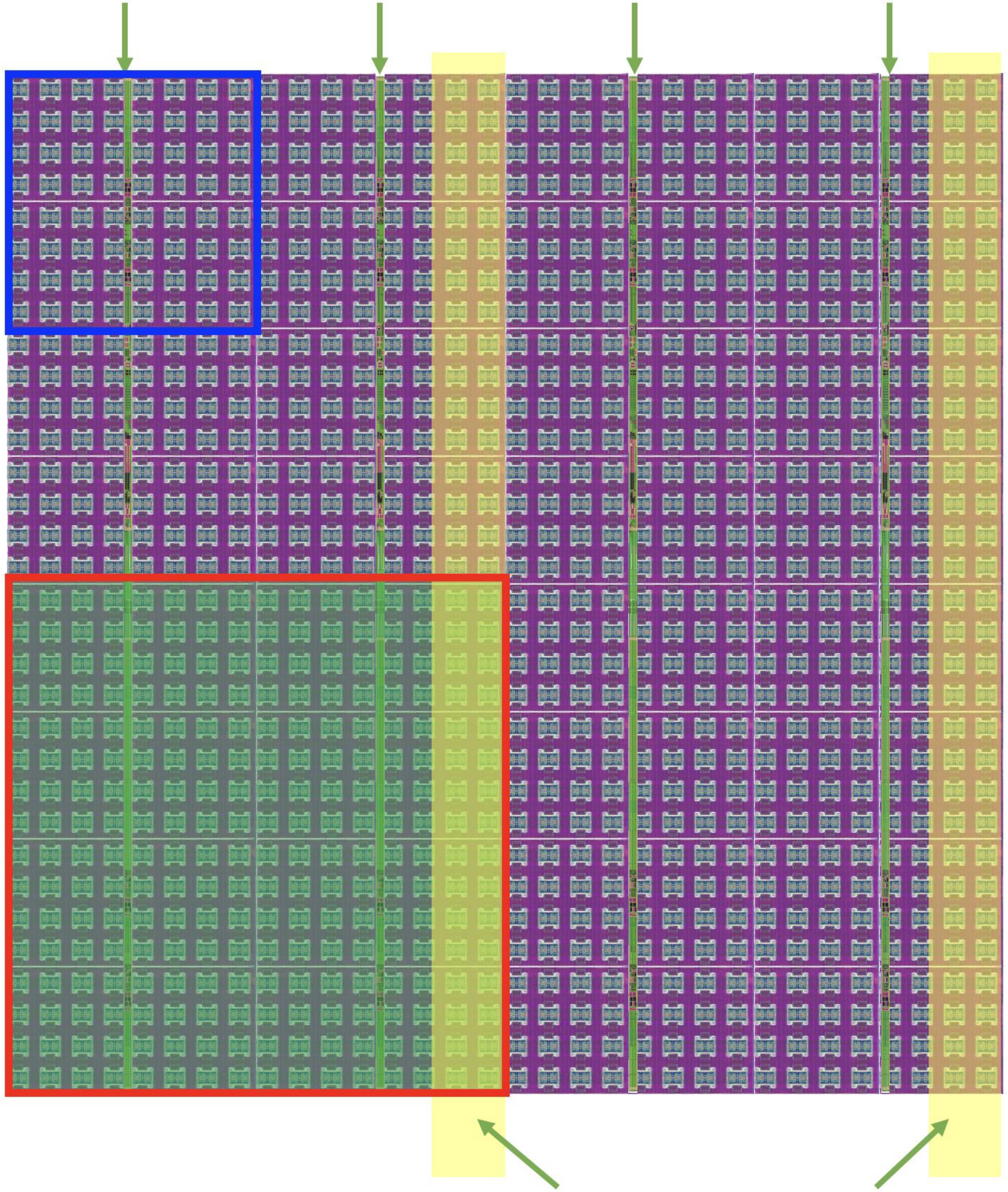
Large area ASIC: the Ignite-ER

Architecture

Example of an Analog 64x64 matrix, **45 µm pitch**

- **Analog Block** (module) is 16x16 (2x2 Mattonellas)
- A Digital Block (DB – aka Core32) covers the area of 32x32 pixels and is connected to the Analog Layer by DBI
- Each **Core32** concentrates data from 4x4 Mattonellas and send them on a Digital Column, which ensures communication to the ASIC periphery

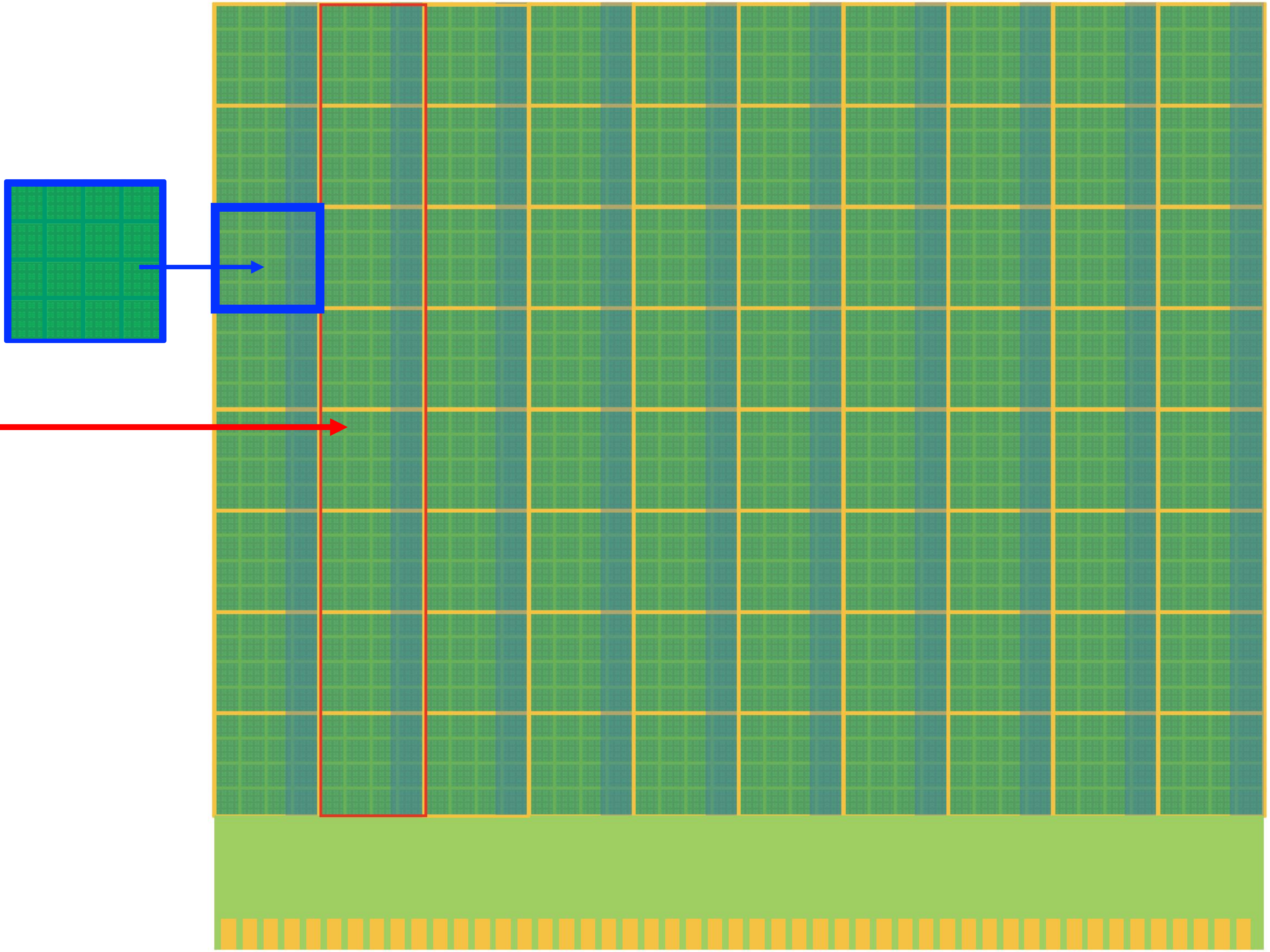




Ignite-ER

320x256 pixels

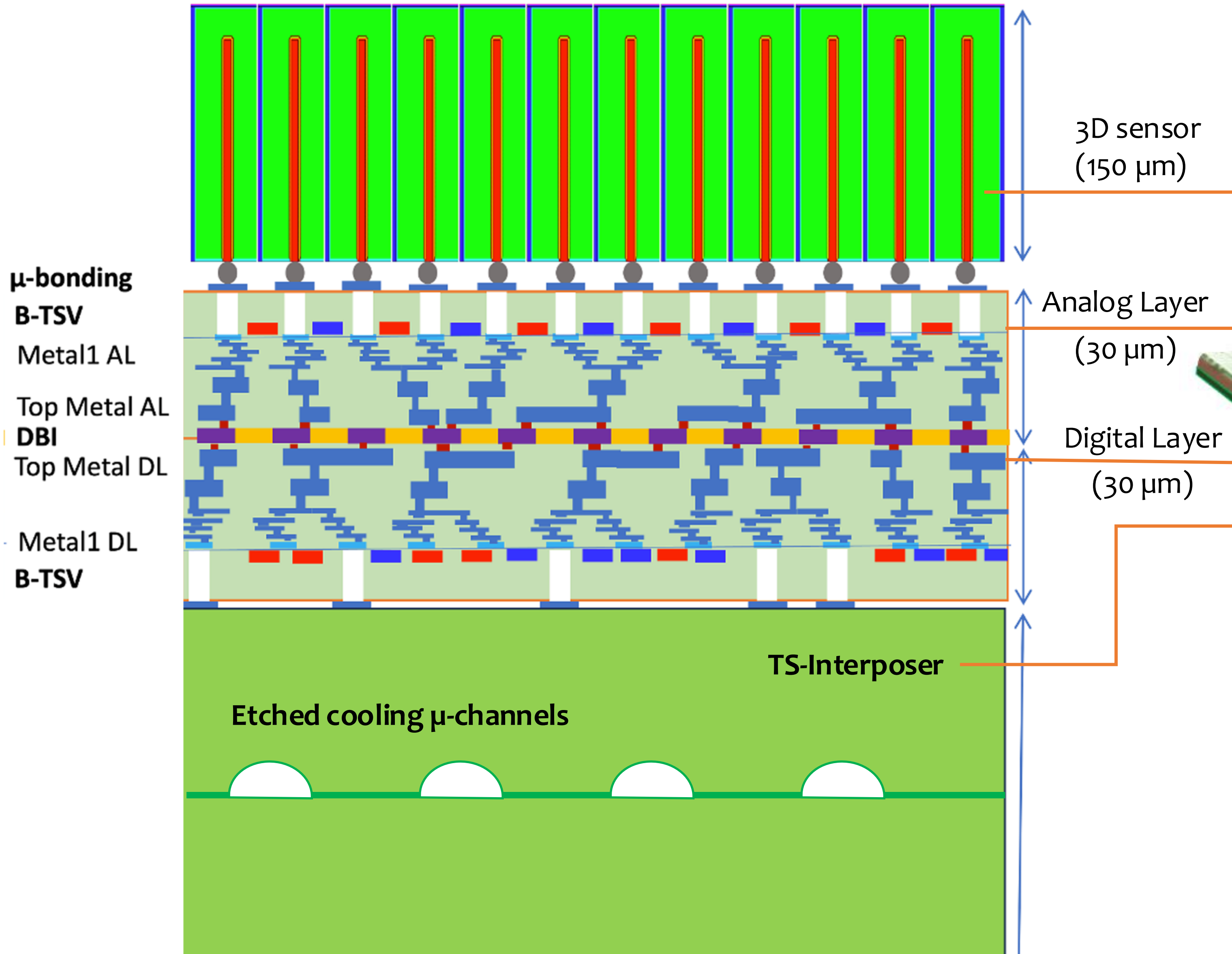
- A variable number of **Core32** make a Sector. In this version a Sector is made by 8 Core32
- Each Sector shares a unique Digital Column and a unique serializer and driver. **Sectors** are independent of each other
- 10 Sectors, completed by their periphery, make the **Ignite-ER** ASIC
- The cells implementing the Modular Units of the Digital Layer occupy a reduced area (<50%) of the full Layer, allowing space for very accurate power and clock distribution

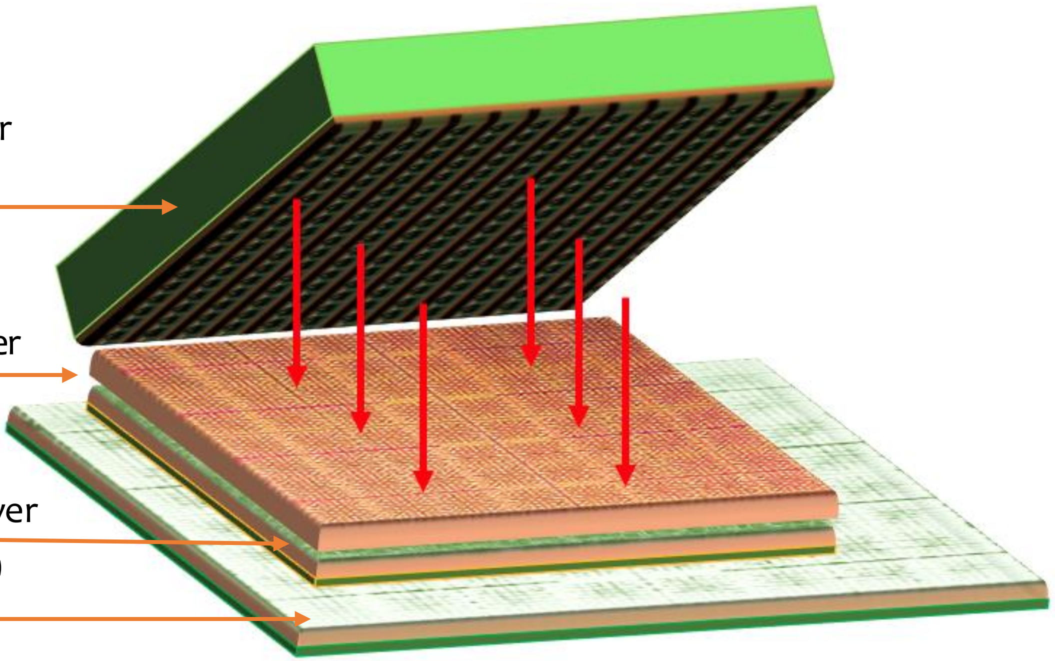


Vertical Integration: B-TSV(1) and DBI(2)

An enabling technology for high performance tracking

(1) Back-Through-Silicon-Vias
(2) Direct-Bonding-Interconnect





Implementation scheme of sensor-electronics 3D stacking (intentionally not to scale)

Conclusions & Perspectives

- The development of **High Intensity 4D-Tracking** techniques is urgent and vital for the future of collider Physics. Several applications in radiation imaging will profit of HI4DT techniques
- **Technology is at its limit** in both sensors and ASIC developments. Important test results are already there. The path ahead is still long and rough.
- On the sensor side, fundamental requirements are matched by the developed **3D-trench silicon sensors**. 3D-column can also be reasonably satisfactory, while providing more robustness in producion processes.
- Thanks to the **Fractaldesign** approach, the **Ignite64** (64x64 pixels, 55 μm pitch) show satisfactory results concerning analog functionalities, decisive for **space-time measurement performance**. The ASIC is presently being tested.
- Its extension, the **Ignite-ER** ASIC (320x256 pixels, 45 μm pitch), is programmed for **submission in Q2/2026**. It intend to enable **3D integration** for maximum space-time tracking **performance**.
- A second parallel devolpment at CERN (**LA-Picopix ASIC**) addresses similar problems with a more traditional 2D approach. The two projects could even possibly merge in the future.
- **Innovative experimental techniques are mandatory to open new horizons in high energy physics!**