OVERVIEW PIXEL WORKSHOP

- OVERVIEW OF THE WORKSHOP
- OVERVIEW OF THE FUTUR PROJECTS
- FOLLOW-UP AND NEXT STEP

BENJAMIN AUDURIER - GDR-INF ANNUAL WORKSHOP - NOV. 7TH 2023

OVERVIEW OF THE WORKSHOP

General presentation

INTENSITY frontier GDR-InF

Détecteurs à pixel : retour d'expérience et futures projets

19–20 sept. 2023
Fuseau horaire Europe/Paris

Entrer le texte à rechercher

- Accueil
- Ordre du jour
- Liste des contributions
- Inscription
- Liste des participants

Le but de ce workshop est d'offrir une plateform d'échanges pour la communauté française de physique des hautes énergies, impliquée ou intéressée par les projets de détecteur à pixel.

Le premier jour est dédié aux projets futures, le second aux retours d'expériences des projets plus avancés.

Le dîner du workshop aura lieu le mardi soir (19 septembre) à 20h00 au restaurant La Nautique sur le vieux port.

Ce workshop est co-parainé par les GDR-QCD et GDR-DI2I.

======== English version ========

This workshop aims to gather the actors within the high-energy French community involved or interested in detector projects based on pixels.

The first day is dedicated to projects in the far future, while the next day focuses on more advanced and installed detectors, with large discussion sessions for both days.

The workshop dinner will take place on Tuesday evening (September 19th) at 20:00 in the restaurant La Nautique at the vieux port.

This workshop is co-supported by the GDR-QCD and GDR-DI2I.

Commence le 19 sept. 2023, 12:30
Finit le 20 sept. 2023, 13:35
Europe/Paris

Antonin Maire
Benjamin Audurier
Dorothea vom Bruch
Jerome Baudot
Marlon Barbero
Michael Winn

Hotels_Marseille_Prado_and_Vieux_Port.pdf
Plan-d'accès-CPPM-Campus-de-Luminy.pdf

- Link to the indico page:
  - https://indico.in2p3.fr/event/29988/overview
- Inter-GDR workshop (GDR-Inf, GDR-QCD, QDR-DI2I)
- Objectives:
  - Gather French research groups involved in « past » and futur detector projects.
    - And have a nice diner …

General presentation

Tuesday

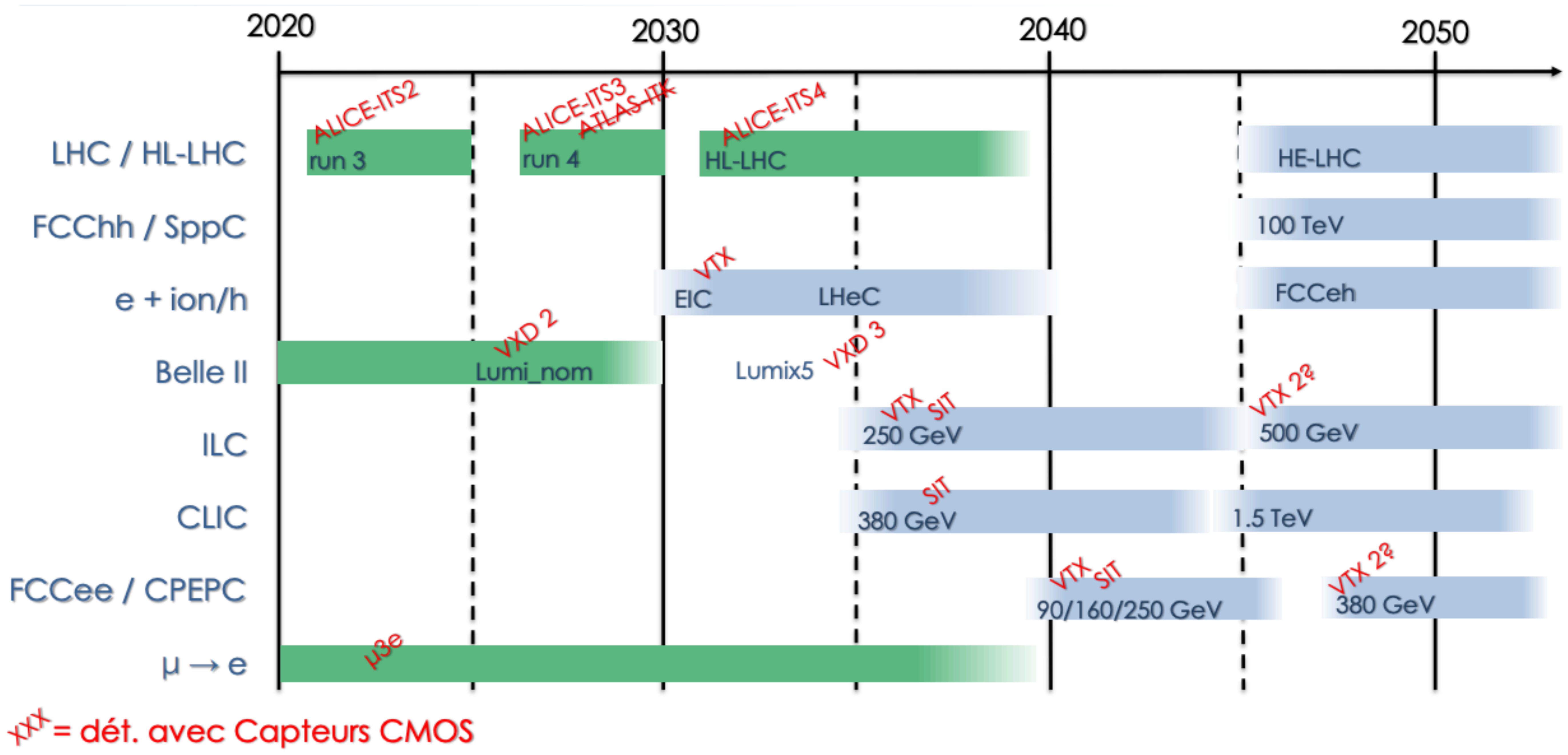
12:30 - 14:00	**Déjeuner**	
14:00 - 14:10	**Introduction au workshop**	
14:10 - 14:35	**LHCb trackers**	*Stefano Panebianco*
14:35 - 15:00	**ALICE 3**	*Antonin Maire*
15:00 - 15:15	**Belle II trackers**	*M. Carlos Marinas*
15:15 - 15:40	**pause café**	
15:40 - 16:05	**NA62 and NuTag**	*Mathieu Perrin-Terrin*
16:05 - 16:20	**FCC hh**	*Mohsine Menouni*
16:20 - 16:45	**FCC ee et technologies associées**	*auguste besson*
16:45 - 17:10	**pause café**	
17:10 - 18:10	**Discussion: futures projets**	

Wednesday

09:00 - 09:25	**ITK d'ATLAS**	*Francesco Costanza*
09:25 - 09:50	**Les Trackers de CMS**	*Gaelle Boudoul*
10:00 - 10:30	**pause café**	
10:30 - 10:50	**CBM**	*auguste besson*
10:50 - 11:15	**VTX**	*Roua Boudagga*
11:15 - 11:40	**ITS 3**	*Dr Serhiy SENYUKOV*
12:00 - 13:00	**Déjeuner**	

- Labs involved:
  - IPHC-CEA-CPPM-LAPP-IP2I-IFIC(Valencia)
- Short and effective workshop!

Objectives



Slide from J. Baudot - GT08 workshop

- Many CMOS based projects running in parallel:
  - ALICE ITS3 - ALICE 3 - LHCb UT - FCC - Belle II …
- Can we (French community) be more efficient?
  - Share of expertise.
  - Share of competences.
  - Save time.

Objectives

Tables to be updated with new projects

Etat-de-l'art / Besoins

	STAR PXL	ALICE ITS2	HL-ATLAS ITK	CBM MVD	ALICE ITS3	Belle-II Lnom	ILC VTX	FCCee VTX	CLIC SiTrack	FCChh SiTrack
Spatial res. (µm)	< 10	~5	10	~5	~5	< 10	≲ 3	3 – 5	7	~10
Mat. budget (%X0)	0.37	0.35	<1	~0,3	0.05	0.15	0.15	0.15	~1	~2
Hit rate (MHz/cm²)	O(0.1)	O(1)	200	15-70	2x better / ITS2	100	20	O(20)	O(0.1)	
Time figure (ns)	200.10^3	5.10^3	25	5.10^3		~100	10^2-10^4	10^2-10^3	5	$5x10^{-3}$
Rad.hard. (kGy) (n_{eq}/cm²)	2 10^{12}	30 $2x10^{13}$	500 10^{15}	30 /year < 10^{14} /y.		100 $5x10^{13}$	10 < 10^{12}	20 $5x10^{11}$	< 10 < 10^{12}	100 $5x10^{15}$
Sensor	**MIMOSA 28**	**ALPIDE**	**R&D MONOPIX MALTA**	**MIMOSIS**	**R&D**	**R&D**	**R&D**		**R&D**	
Techno (nm)	350	180	180 (150) modif.	180 modif.	65	180	180 / 65		180	
Pixel pitch (µm²)	20x20	28x28	33x33 36x36	27x30	target stitching	< 40x40	target 17x17		30x300	
Power (mW/cm²)	150	45	O(200)	< 55		target ~100	~3 Pow.Puls			

J. Baudot - Capteurs CMOS pour le vertexing/tracking - Séminaire GT08, Janvier 2020

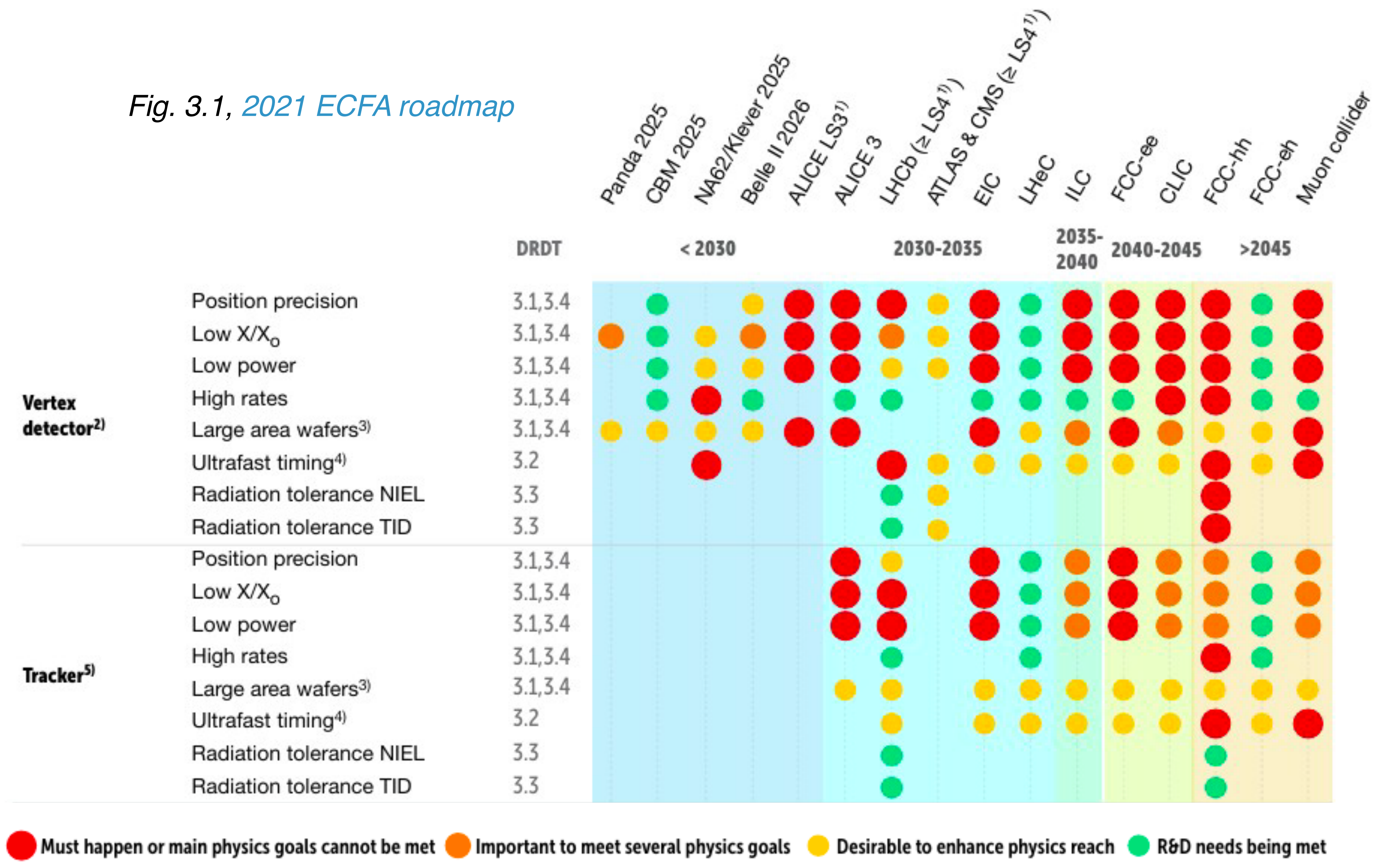


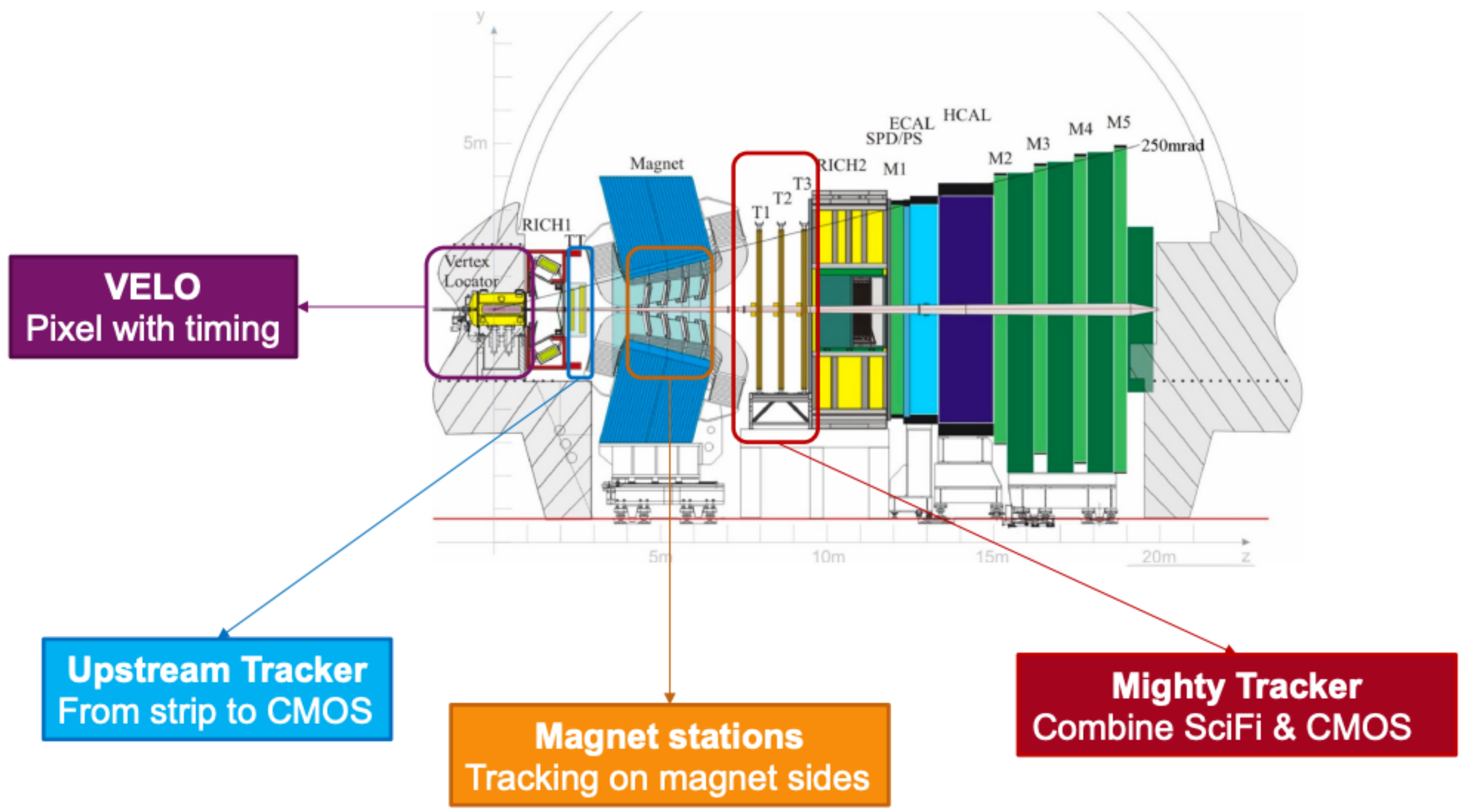
Fig. 3.1, 2021 ECFA roadmap

Slide from J. Baudot - GT08 workshop

- Different needs, but the R&D process can still be shared.

OVERVIEW OF THE FUTUR PROJECTS

Futur projects: Upstream tracker

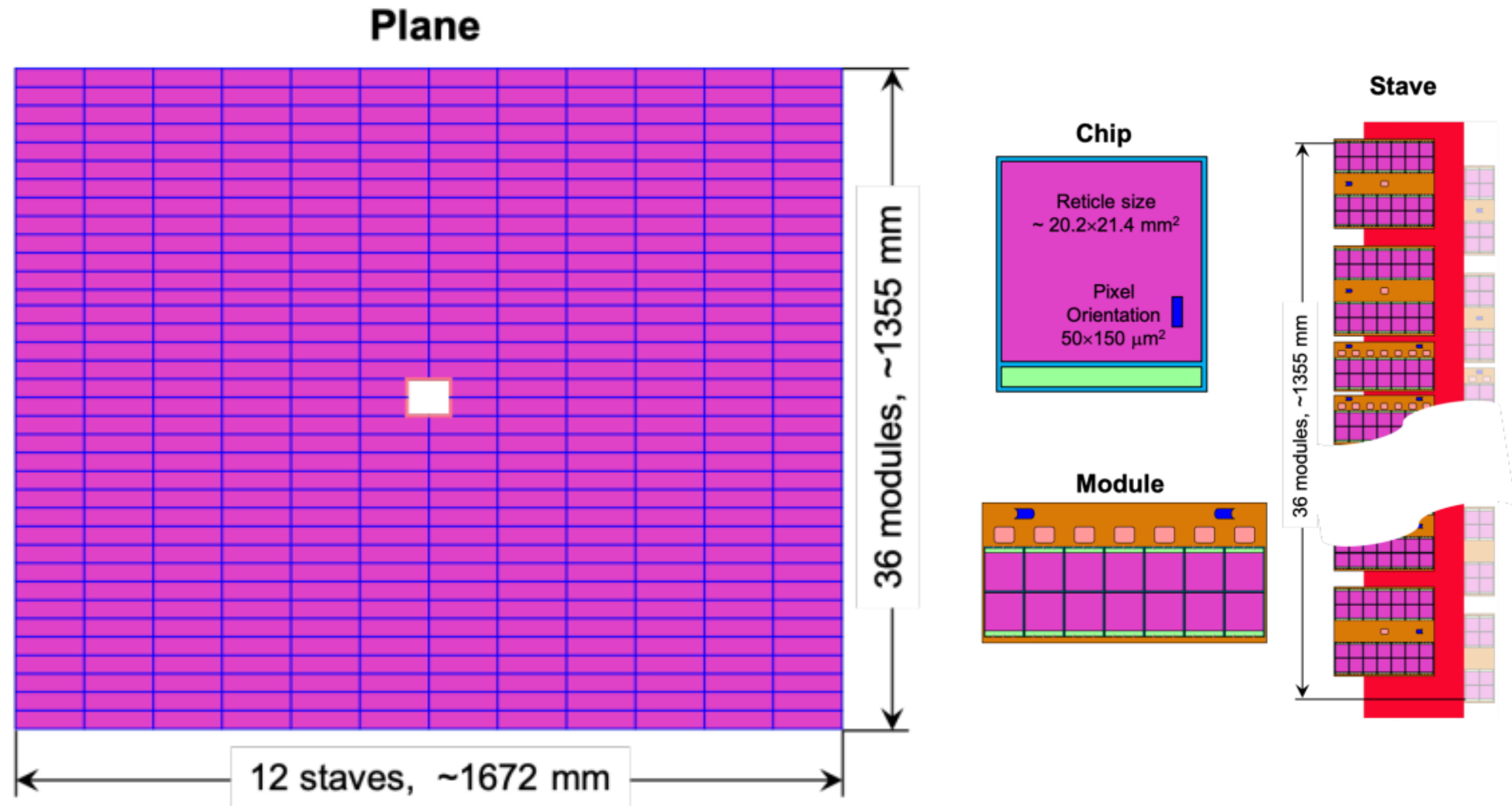


Preliminary specifications

- Concept presented within the F-TDR: well received by the LHCC
- First tentative list of specifications
- To be further consolidated and detailed: work in progress

Characteristics	Specification
Hit rate in hot event and region	160 MHz / cm² pp (~52.5 hits / cm² / BX for Pb/Pb)
Time resolution	O(1 ns) for BX tagging
Pixel size	O(30×30 μm²)
Power consumption	O(100-300 mW/cm²)
Radiation dose for 350 fb⁻¹	3×10^{15} 1-MeV n_{eq}/cm^2, 240 Mrad

Close to ATLAS CMOS outer layer specifications



Investigation of CMOS technologies

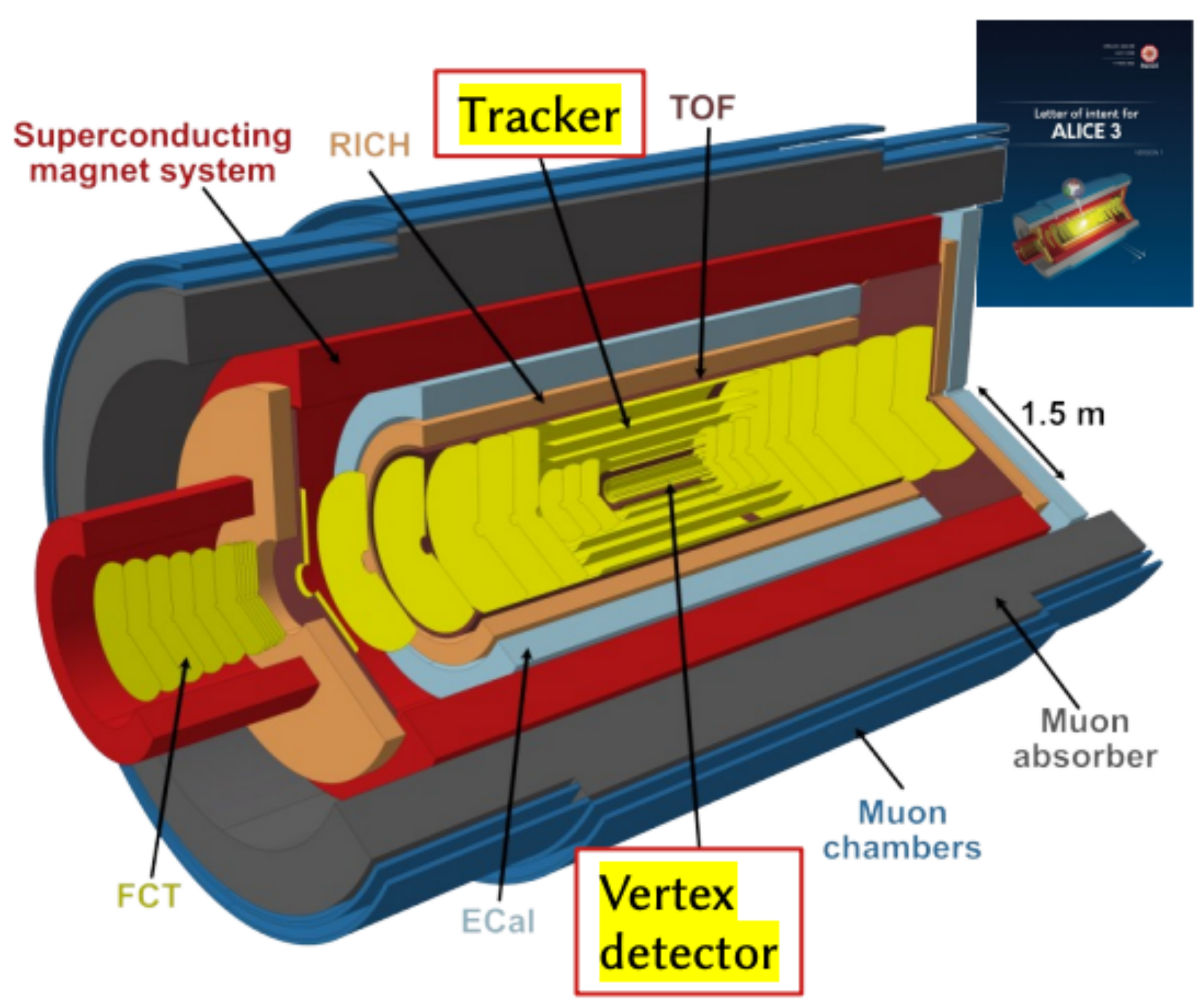
https://indico.cern.ch/event/1285479/contributions/5417480/attachments/2651634/4591280/2023-05-23_Migthy-UT_CMOS.pdf

- **MightyPix (AMS180nm)**
  Most advanced sensor : almost full functionality prototype
  Designed specifically for LHCb (readout)
  With the present demonstrated specs: not fully suitable for UT (readout rate, radiation dose)
  Interest in China to participate to the qualification and tests
- **MALTA family (TJ180nm)**
  Pixel size : 36.4 × 33 μm²
  98% "in-time" tagged data from test-beam without ToT (= less data to be sent - tbd)
  Proven 3 × 10^{15} 1-MeV n_{eq}/cm^2, 100 Mrad @ -20°C
  Malta 2 (2021): enlarged transistors for lower noise and higher gain
  Malta 3 (ongoing design): on-chip time tagging, serial output, daisy chain readout
  Strong interest from developers to include UT specifications
  Irfu participated to the chip qualification, LLR is joining the effor
- **DPTS (TJ65nm)**
  Large development group at CERN involved for ALICE ITS3
  Proven working after 1 × 10^{15} 1-MeV n_{eq}/cm^2 @ room temperatur
  Test vehicle for digital asynchronous readout
  Working point ~ 99% efficiency at acceptable fake-hit rate
  Strong interest from Irfu (and IPHC) to submit in ER2 (mid 2024)

Det	Pixel size	Bits per hit	Chip area	Data rate of the hottest chip
1	30 μm x 30 μm	31	4,72 cm²	15,3 Gbit/s
2	50 μm x 150 μm	29	4,23 cm²	10,8 Gbit/s
3	50 μm x 300 μm	29	19,66 cm²	27,2 Gbit/s

Futur projects: ALICE 3

ALICE3 LoI, CERN-LHCC-2022-009



Tracker,

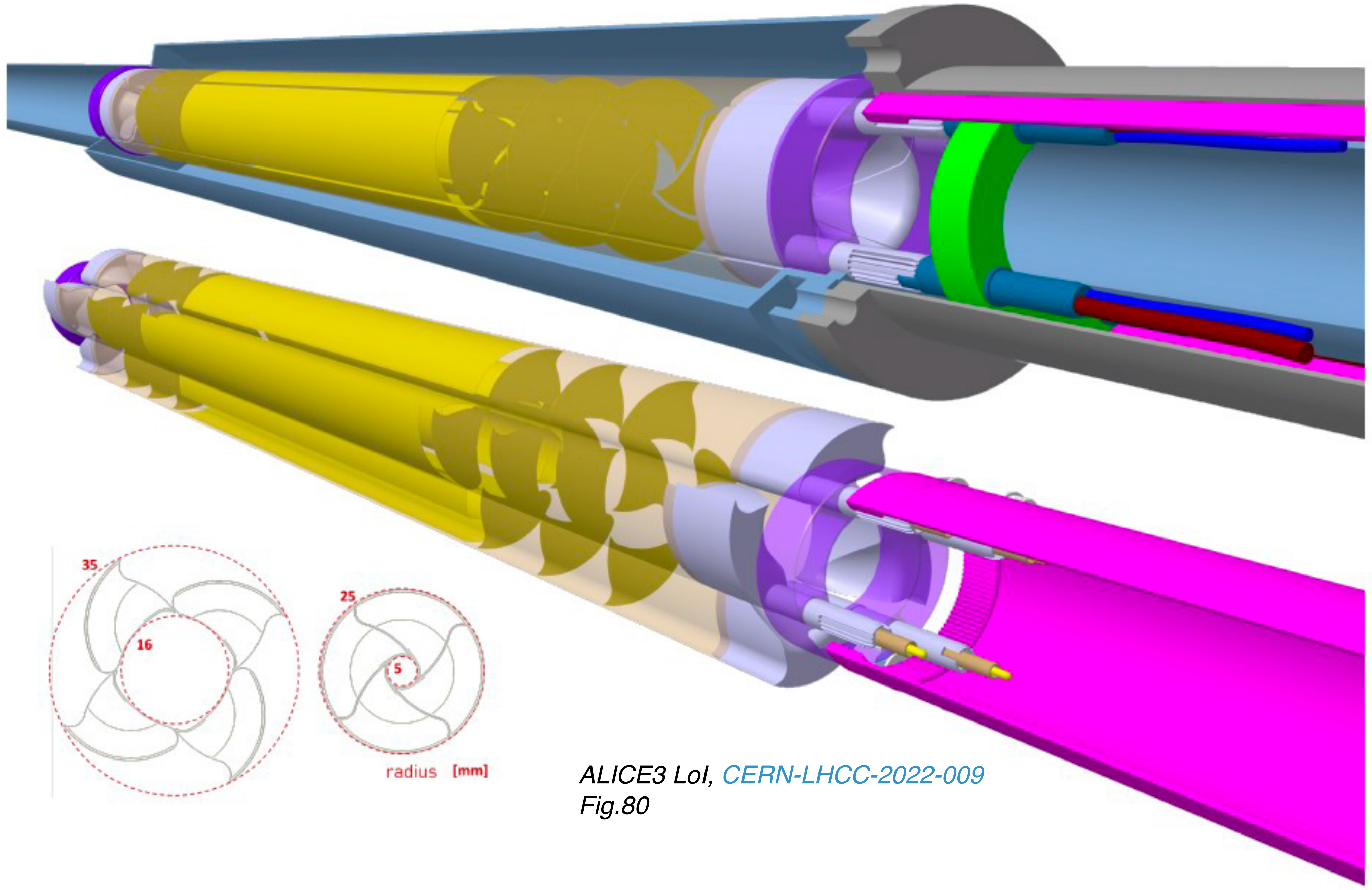
Compact ($R_{\text{outer TOF}} \approx$ 85 cm)

ultra-light (layer 0 ~ 0.1 % x/X_0)

All-Si (≈ 60 m²)

with high-performance tracking

(Axε, granularity, ...)



ALICE3 LoI, CERN-LHCC-2022-009
Fig.80

	Layer	Material thickness ($\%X_0$)	Intrinsic resolution (µm)	Barrel layers: Length ($\pm z$) (cm)	Barrel layers: Radius (r) (cm)	Forward discs: Position ($\lvert z \rvert$) (cm)	Forward discs: R_{in} (cm)	Forward discs: R_{out} (cm)
Inner tracker	0	0.1	2.5	50	0.50	26	0.005	3
	1	0.1	2.5	50	1.20	30	0.005	3
	2	0.1	2.5	50	2.50	34	0.005	3
(Middle tracker)	3	1	10	124	3.75	77	0.05	35
	4	1	10	124	7	100	0.05	35
	5	1	10	124	12	122	0.05	35
	6	1	10	124	20	150	0.05	80
Outer tracker	7	1	10	124	30	180	0.05	80
	8	1	10	264	45	220	0.05	80
	9	1	10	264	60	279	0.05	80
	10	1	10	264	80	340	0.05	80
	11	1				400	0.05	80

Table 8: Geometry and key specifications of the tracker.

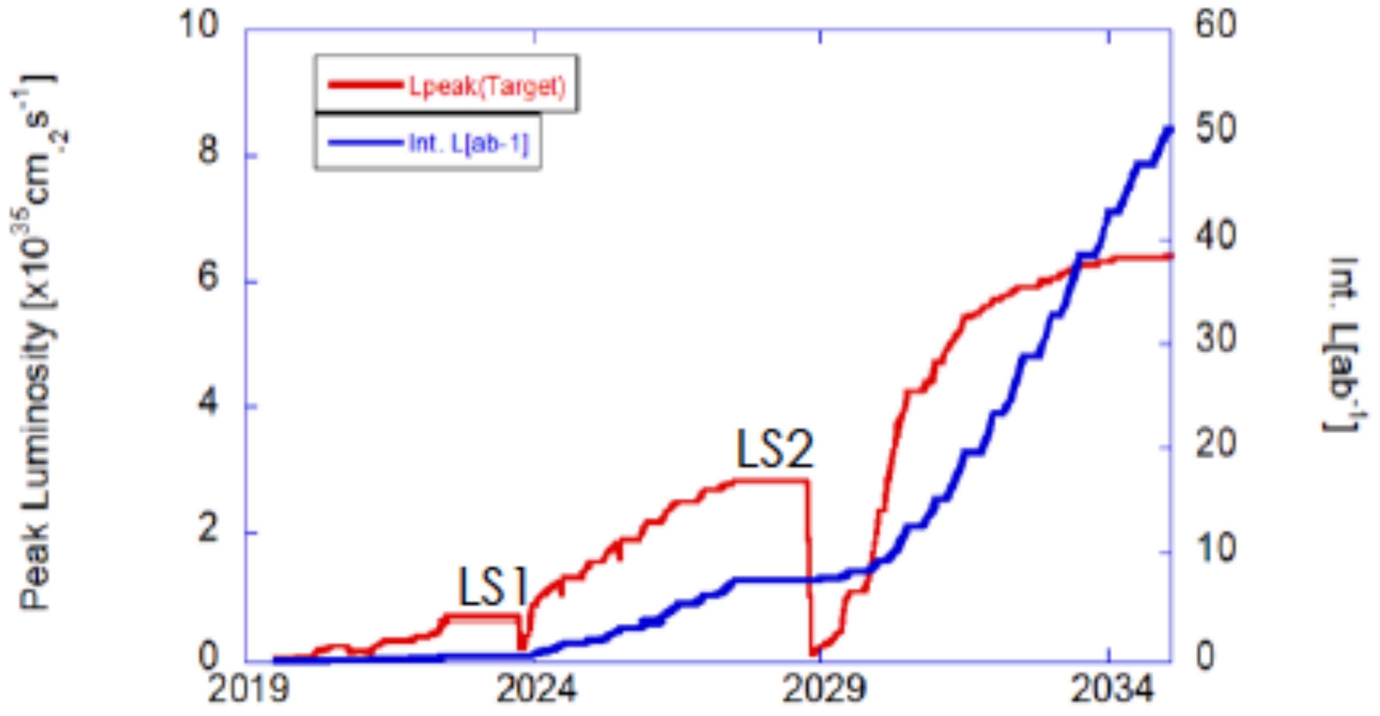
3 options :

- MAPS with gain layer
  (≈ ARCADIA project)
- Low Gain Avalanche Diodes (LGAD)
  (CMS MTD fwd, ATLAS HGTD)
- Single Photon Avalanche Diode (SPAD)

	Inner TOF	Outer TOF	Forward TOF
Radius (m)	0.19	0.85	0.15–1.5
z range (m)	−0.62–0.62	−2.79–2.79	4.05
Surface (m²)	1.5	30	14
Granularity (mm²)	1 × 1	5 × 5	1 × 1 to 5 × 5
Hit rate (kHz/cm²)	74	4	122
NIEL (1 MeV n_{eq}/cm²) / month	$1.3 \cdot 10^{11}$	$6.2 \cdot 10^{9}$	$2.1 \cdot 10^{11}$
TID (rad) / month	$4 \cdot 10^{3}$	$2 \cdot 10^{2}$	$6.6 \cdot 10^{3}$
Material budget ($\%X_0$)	1–3	1–3	1–3
Power density (mW/cm²)	50	50	50
Time resolution (ps)	20	20	20

Table 11: TOF specifications.

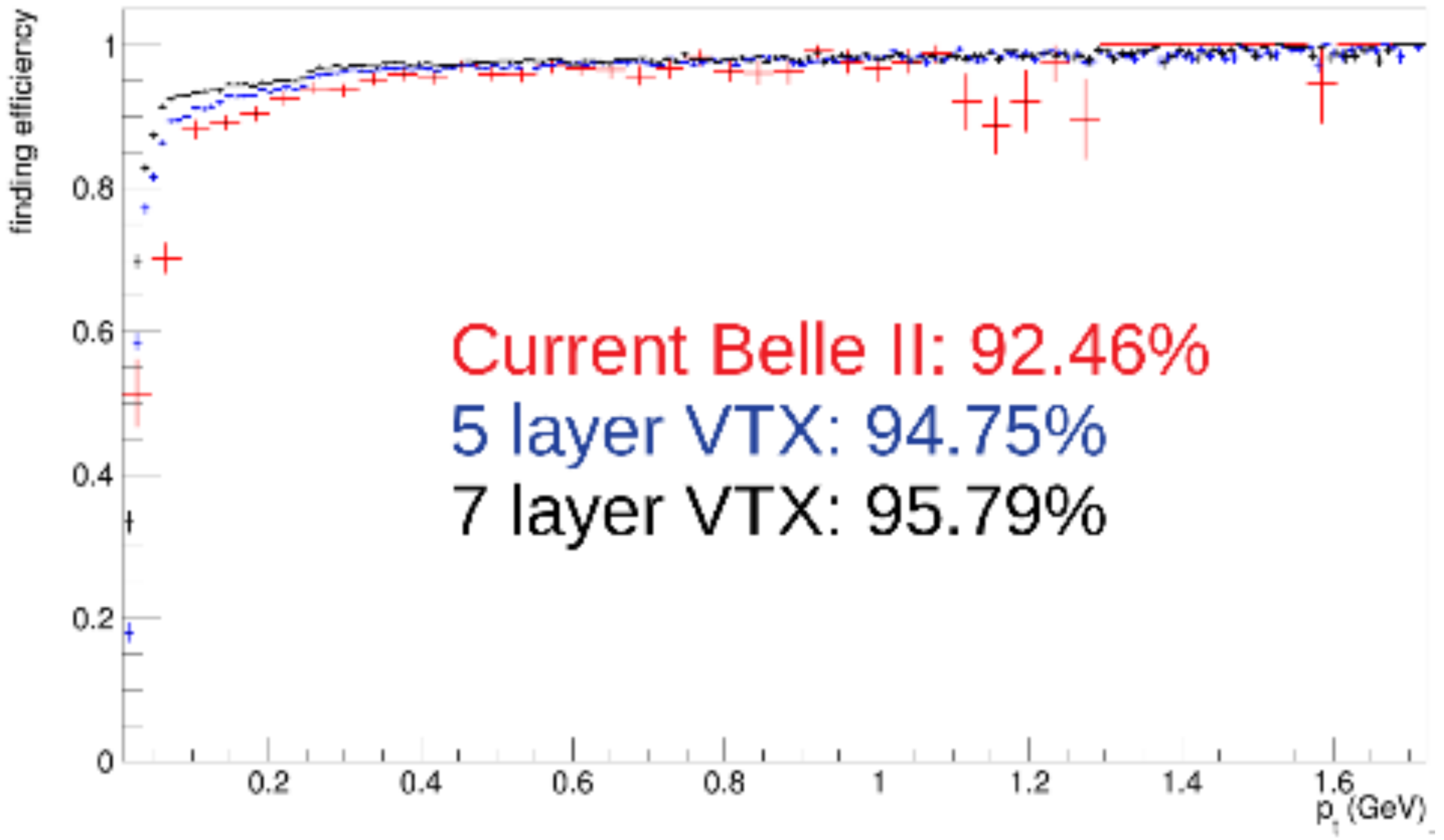
Futur projects: Belle II upgrade

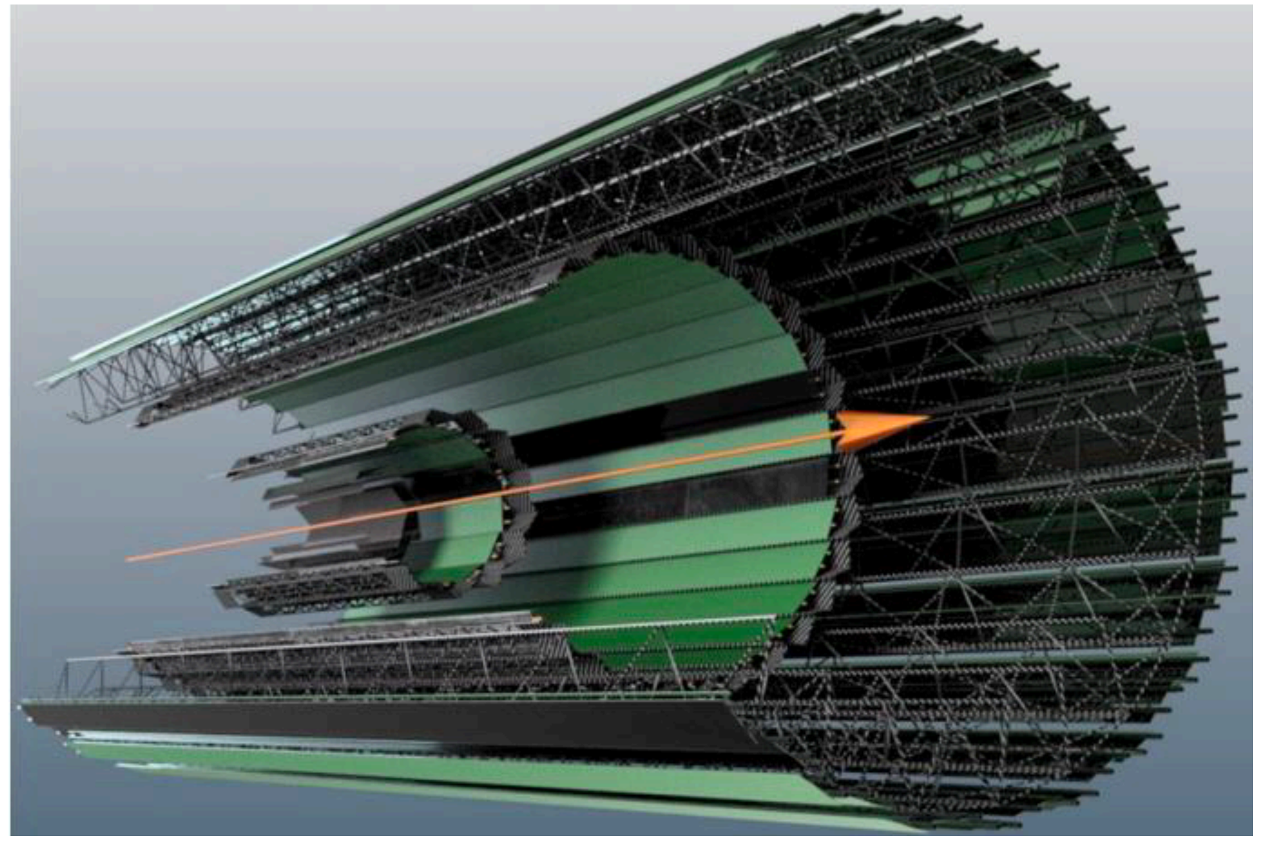


LS1: Actual detector consolidation
LS2: IR and detector upgrades

→ Currently: CDR preparation

- ✓ Fast sensor integration time : 25 to 100 ns
- ✓ High granularity (pixel pitch in the range 30-40 µm²)
- ✓ Low material budget ~ **2.5%X0** (sum of all layers)
- ✓ Hit rate: about 120 MHz/cm²
- ✓ TID : about 10 Mrad / year
- ✓ NIEL : about 5x10¹³ n_{eq} /cm²/year
- ✓ Limited power dissipation (maximum allowed of 200 mW/cm²)
- ✓ Same sensor type for all layers

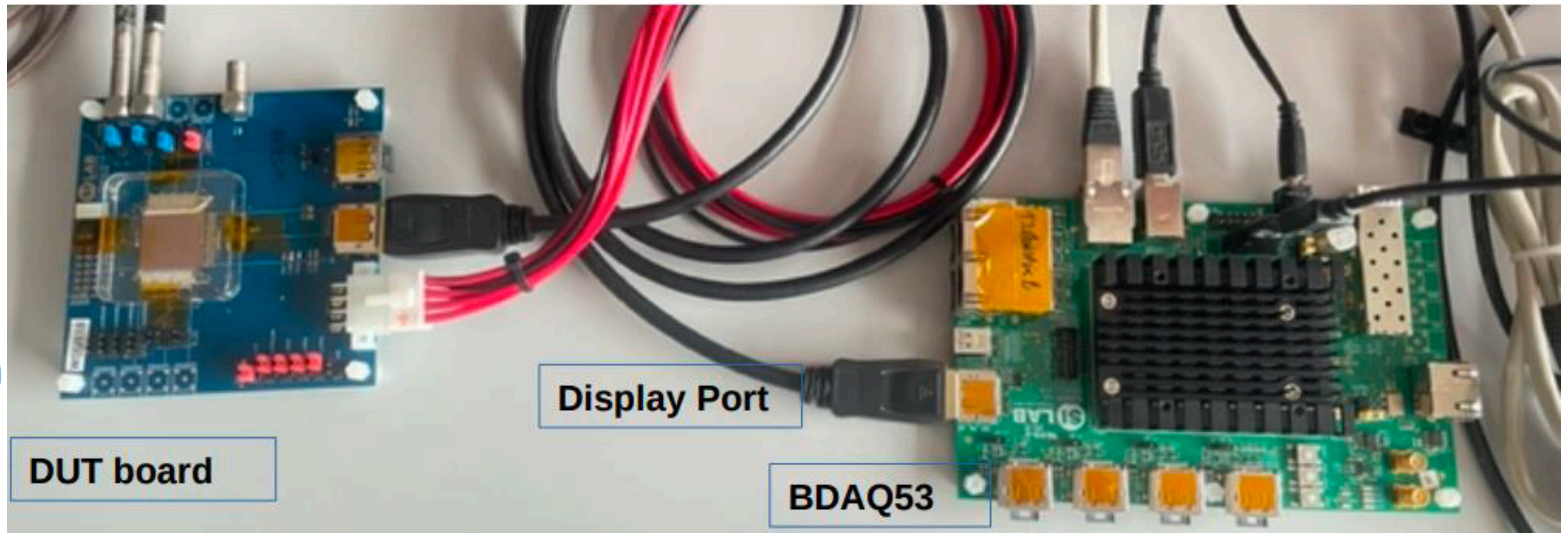




- 5 straight layers barrel, using CMOS pixel sensors
- Low material : 0.1% X_0 (L1+L2) - 0.4% (L3) - 0.8% X_0 (L4+L5)
- Moderate pixel pitch ~ 30 µm²
- Fast integration time 50-100 ns
- iVTX: innermost 2 layers, self-supported, air cooled
- oVTX: 3 outer layers, CF structure, water cooled
- Overall service reduction and operation simplification

Favored option: Obelix sensor (from TJ 180)

Tests ongoing with new beam test in June 2023



Futur projects: from NA62 to HIKE/NuTag

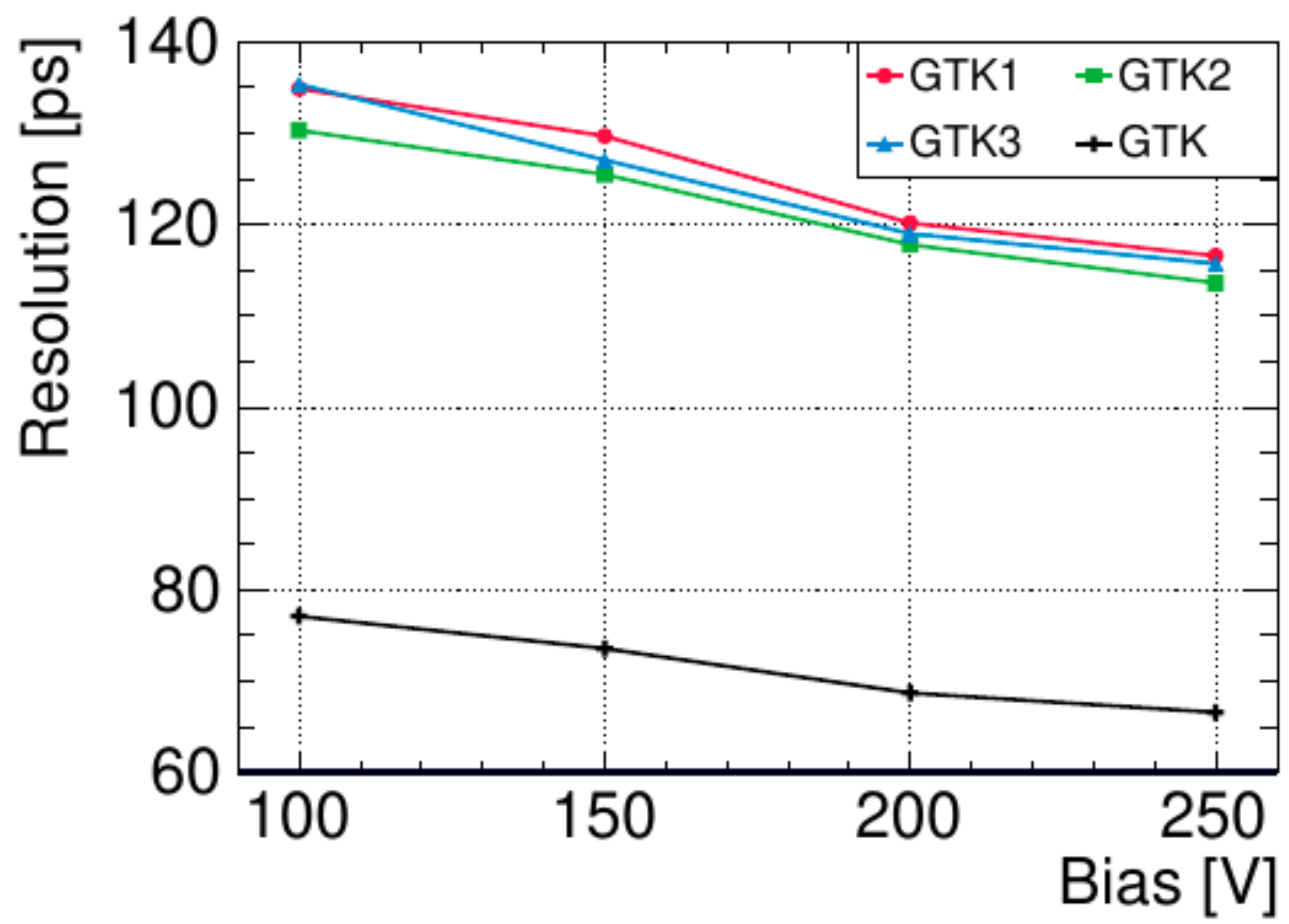
A GTK tracker module

now	2025	2031	2041
NA62	HIKE Construction	Phase 1 Data Taking	

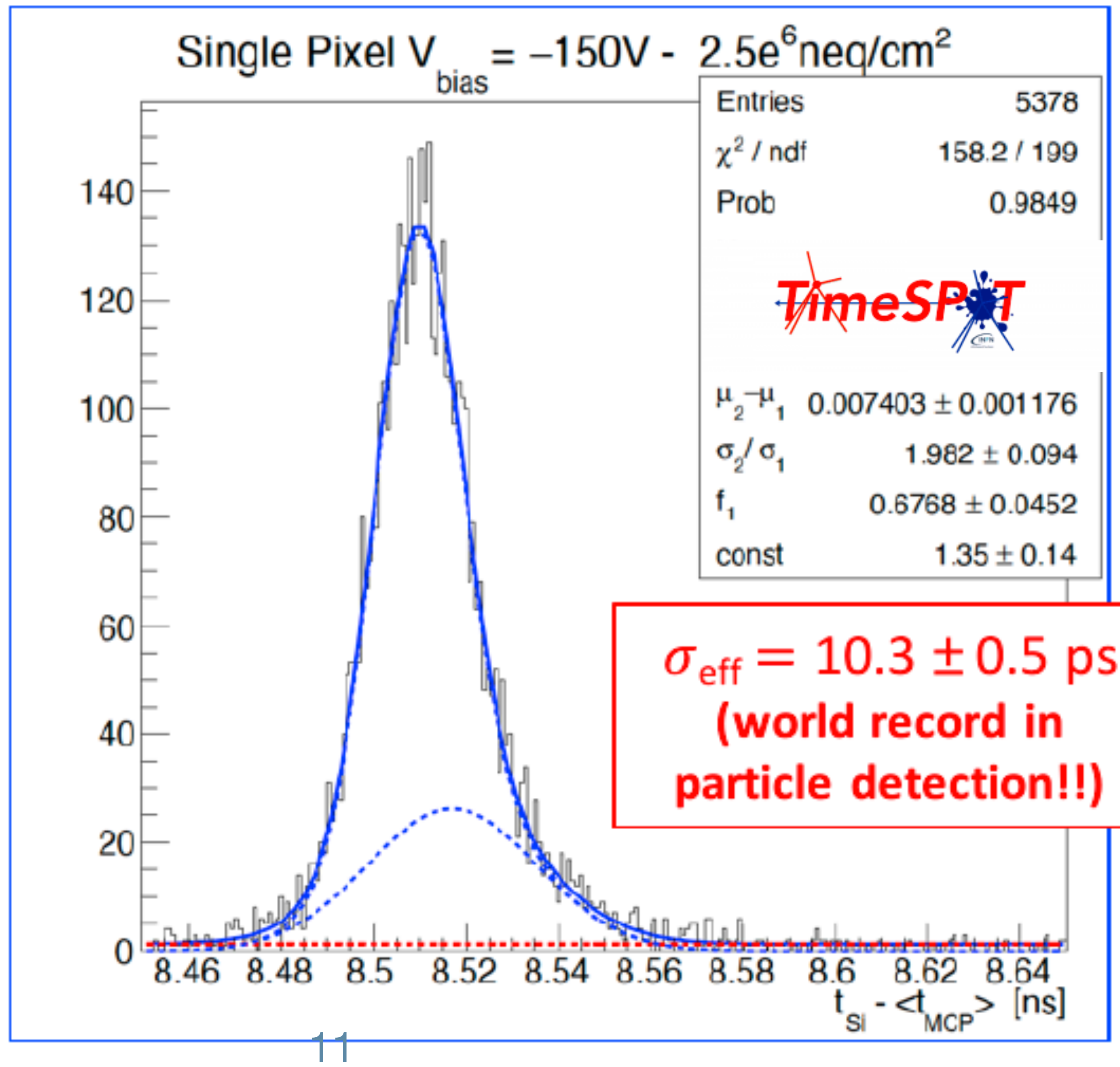
- **High intensity beam**
  - 4-6 times NA62
  - New beam tracker is needed

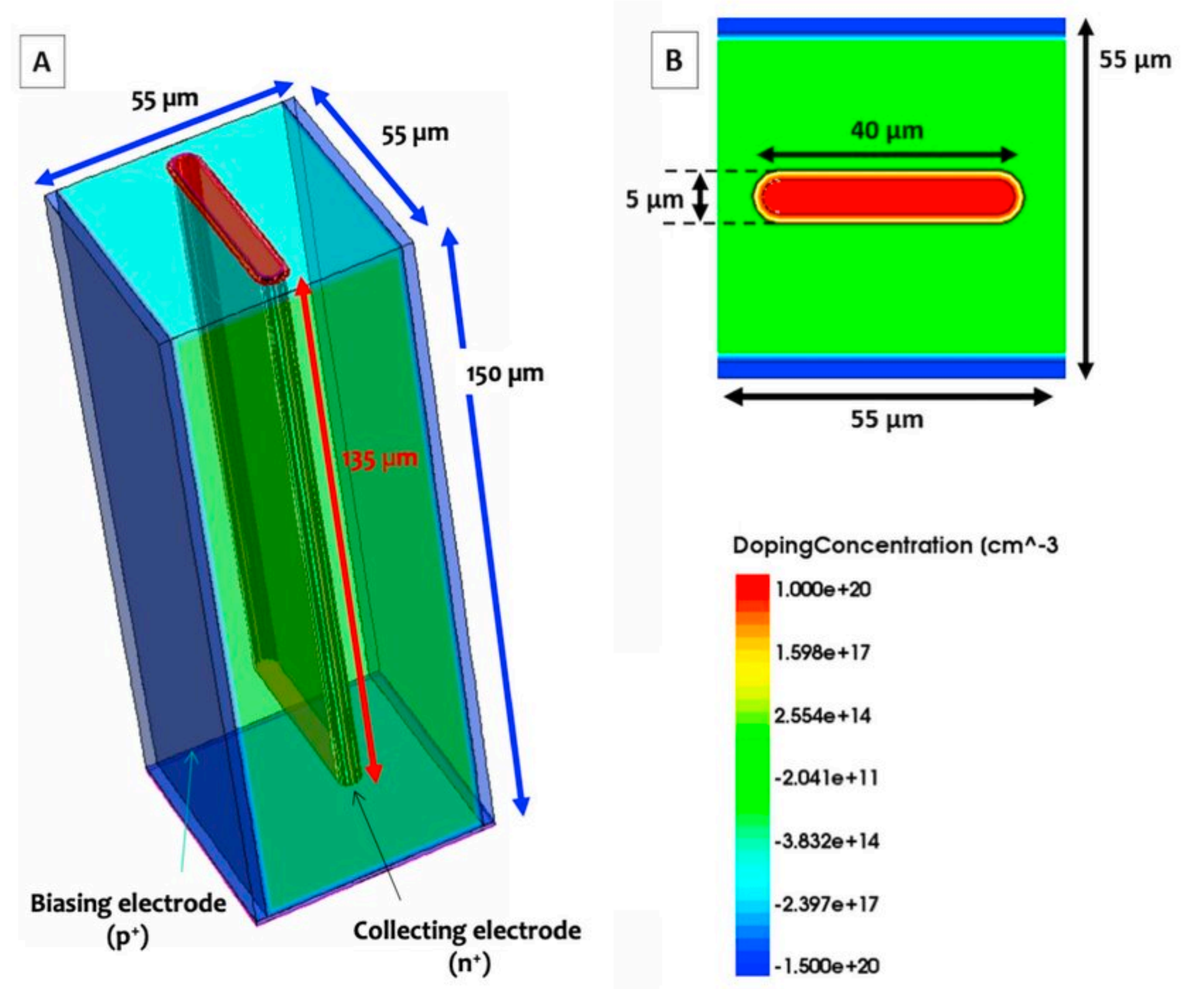
	NA62 GigaTracker	New beam tracker
Single hit time resolution	< 200 ps	< 50 ps
Track time resolution	< 100 ps	< 25 ps
Peak hit rate	2 MHz/mm^2	8 MHz/mm^2
Pixel efficiency	> 99 %	> 99 %
Peak fluence / 1 year [10^{14} 1 MeV n_{eq}/cm^2]	4	16

- NA62 tracker relies on time resolution for precision.
  ➡ Should be improve for futur projects !



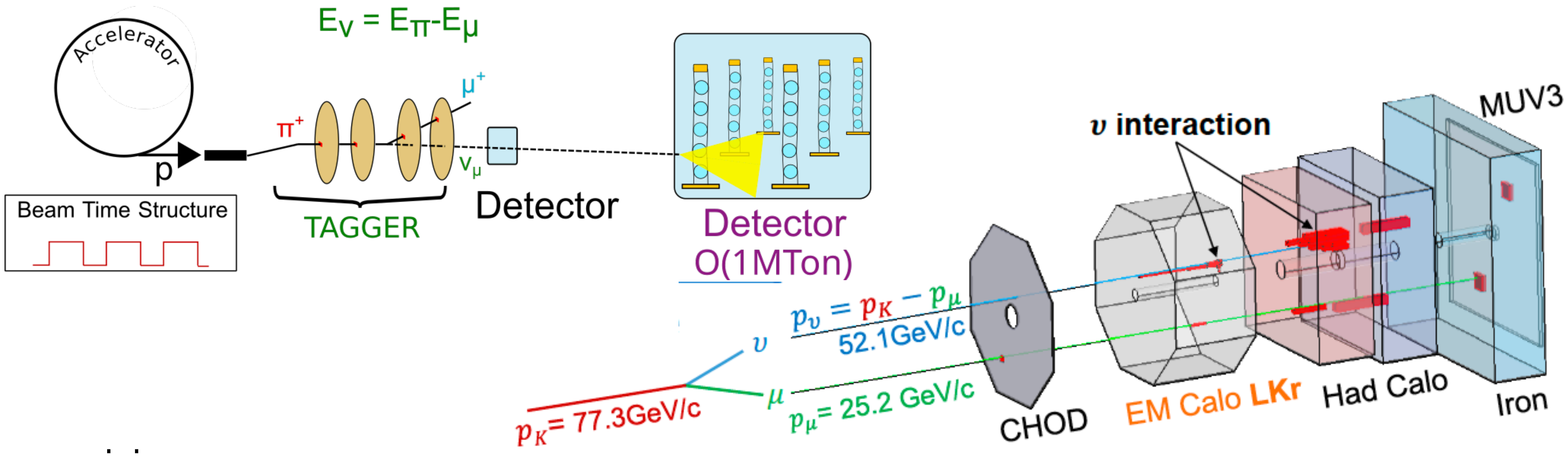
Favored option: GTK design with TimeSPOT pixels





Futur projects: from NA62 to HIKE/NuTag

A GTK tracker module



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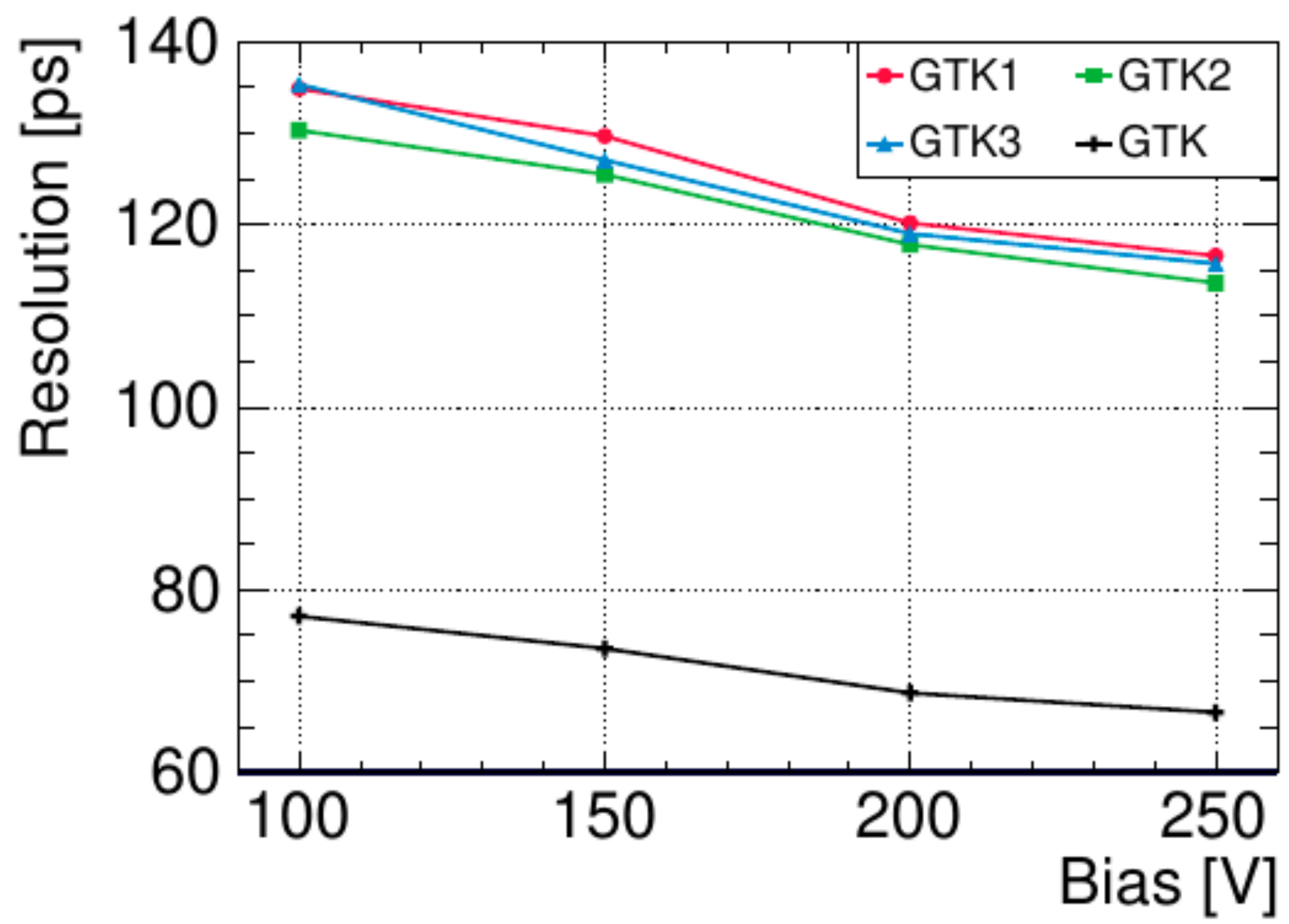
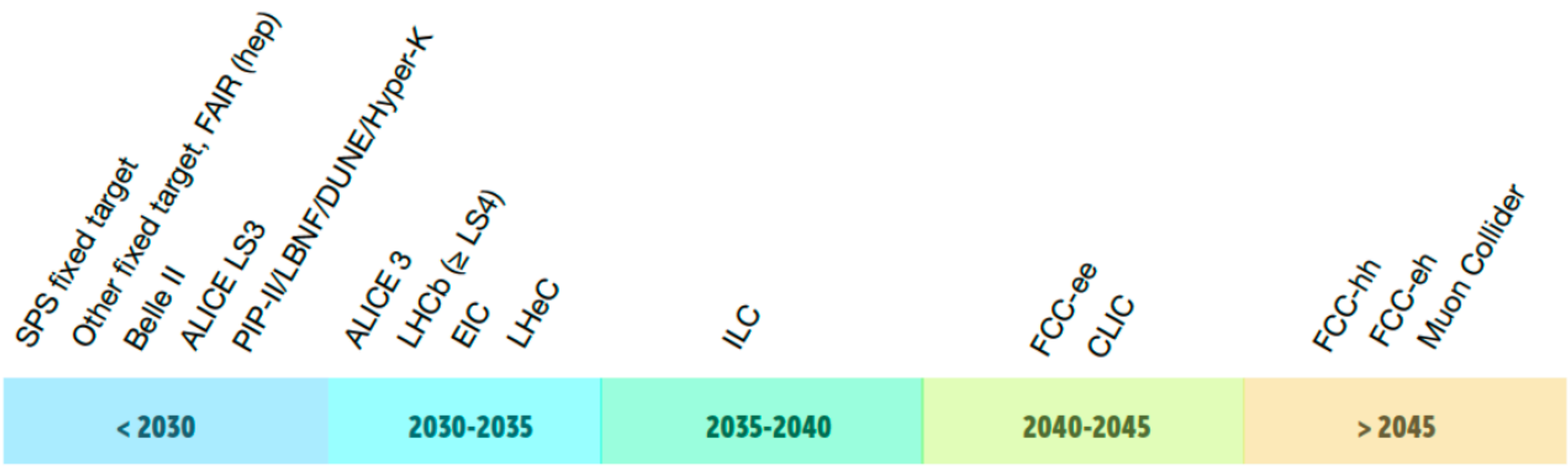


Need a tracker able to sustain very high beam particle flux 10-100 Mhz/mm², $10^{12}\pi^+$/s

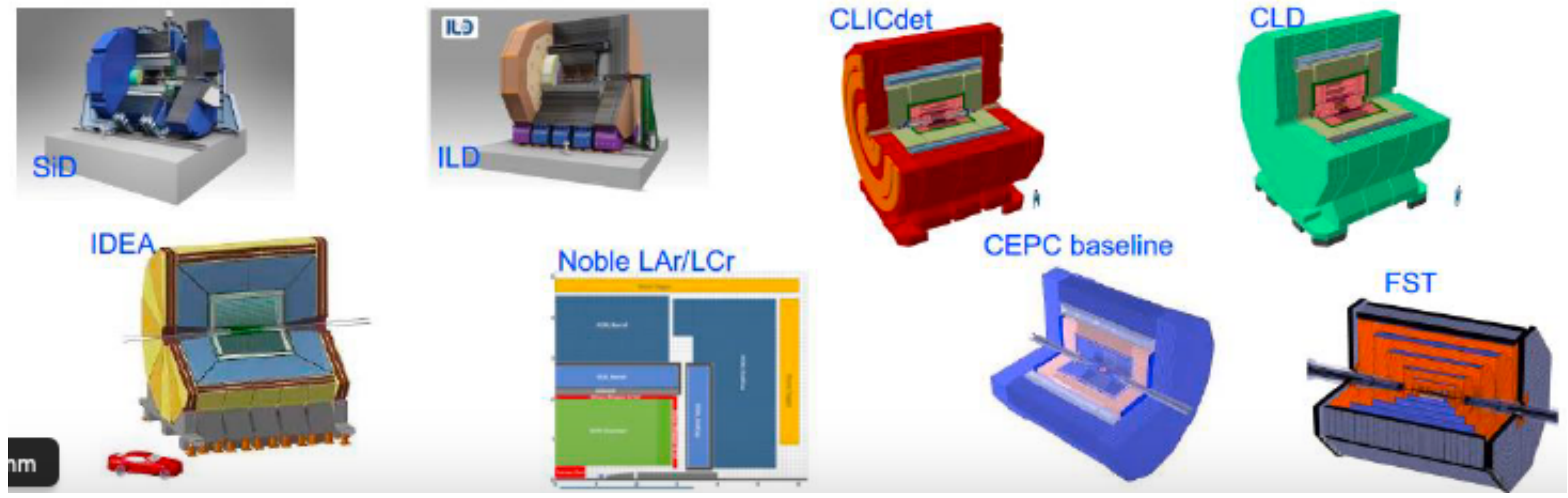
Specification	Neutrino Tagging	HIKE	NA62 (in operation)
Flux (MHz/mm²)	$\mathcal{O}(10-100)$	8	2
Fluence (n_{eq}/cm²)	10^{16-17}	$8 \cdot 10^{14}/y$	$2 \cdot 10^{14}/y$
Hit Time Reso. (ps)	< 20	50	200
Det. Efficiency (%)	> 99	> 99	> 99
Thickness (% of X_0)	< 0.5	< 0.5	< 0.5

- **TimeSPOT technology** can allow to build such tracker, but requires very advanced integration techniques
- **Cooling power** will ultimately determine the time resolution (>1.5W/cm²)
- **3D integration** is considered with an **active cooling plate** to distribute power, clock, data (10 Gbps/cm² with photonics intergrated circuits on cooling plate) and reach the desired efficiency and low material budget

Futur projects: FCCee



- Future e^+e^- collider physics program demands
  - ✓ Minimizing experimental systematic uncertainties
  - ✓ High acceptance/Hermiticity
  - ✓ Track momentum resolution: $\sigma_{p_T}/p_T^2 < 5 \times 10^{-5}\ GeV^{-1}$
    - CMS/40
  - ✓ Impact parameter resolution: $\sigma_{ip} \lesssim 5\mu m \oplus \frac{10\ \mu m.GeV}{p.sin^{3/2}\theta}$
    - CMS/4
  - ✓ Jet Energy resolution: $\sigma_E/E \sim 3-4\%$
    - ATLAS/2
  - ✓ General particle flow approach

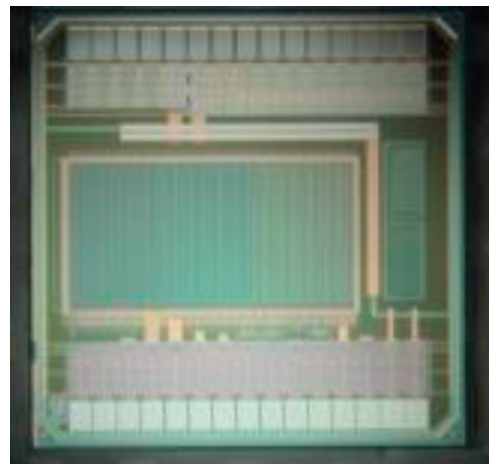


The physics requirements impose a hierarchy between the conflicting parameters

- ✓ the inner vertexing/tracking layers: Granularity and material budget first !
  - CMOS/MAPS Pixel sensors offer the best compromise
- ✓ Outer layers: less constrains in terms of granularity ⇨ Mat. Budget / Power / Time resolution
  - Specialized timing layers ?

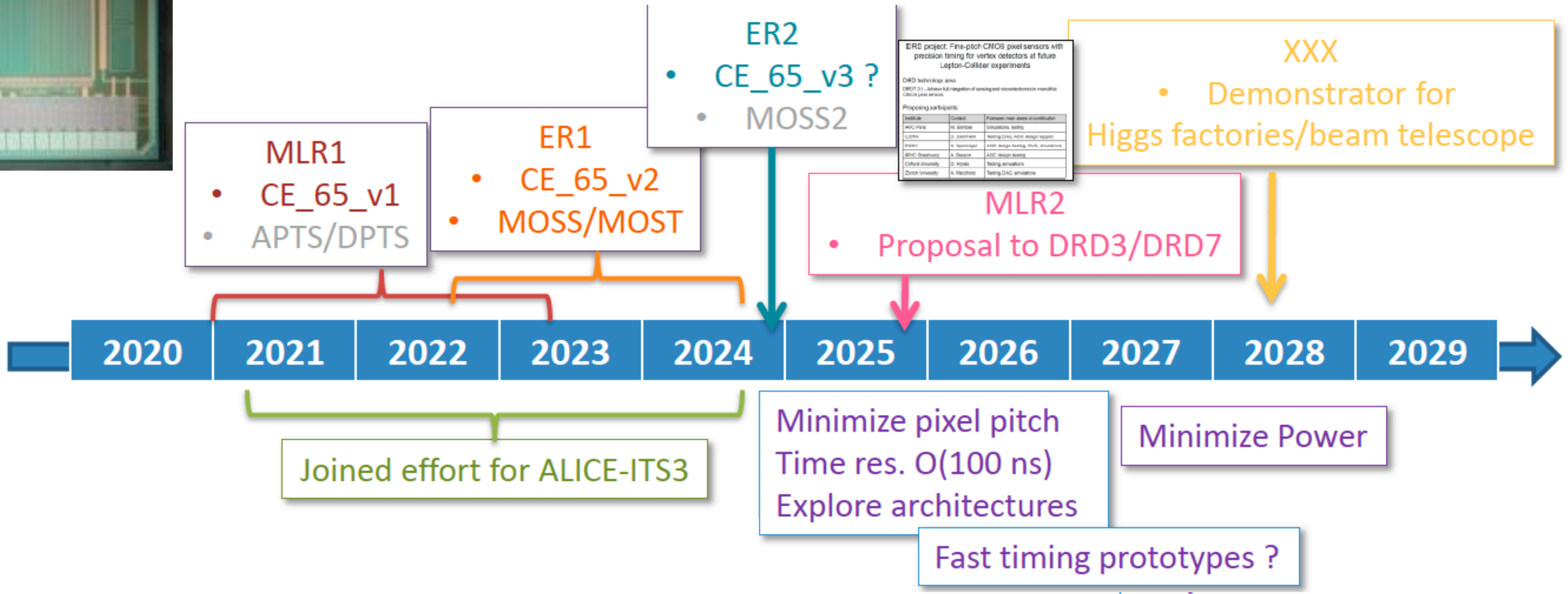
Example: TPSCo 65 nm CMOS technology

CE_65(IPHC) prototypes



65 nm feature size technology

- ✓ Main driver: CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades
  - Privileged relation between CERN with the foundry



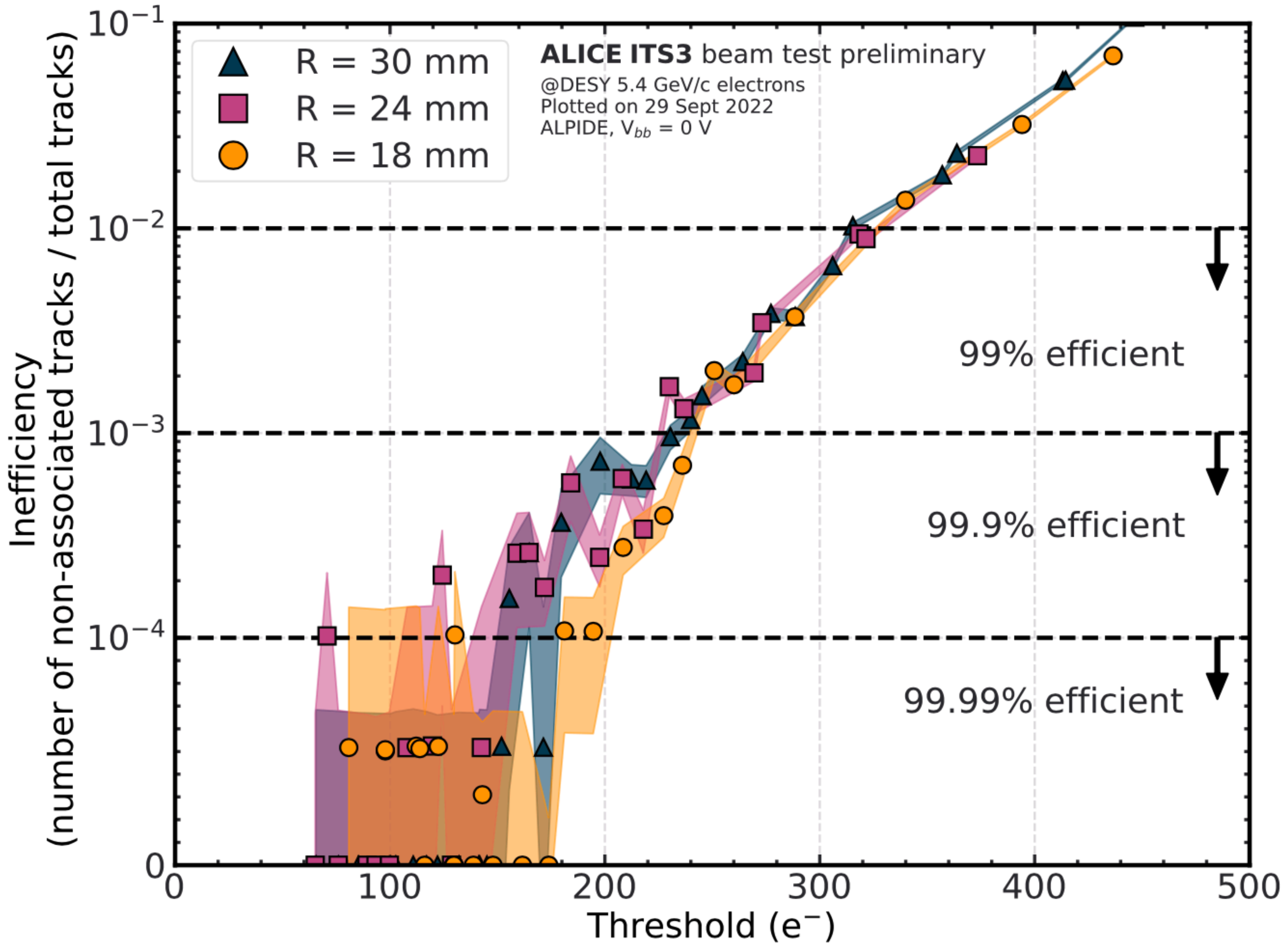
Synergies: Mid-term projects are still the way to go

- ✓ CBM (Mimosis), ALICE ITS-3, Belle-2 upgrade (Obelix), LHCb, EIC, etc.
- ✓ provides invaluable milestones

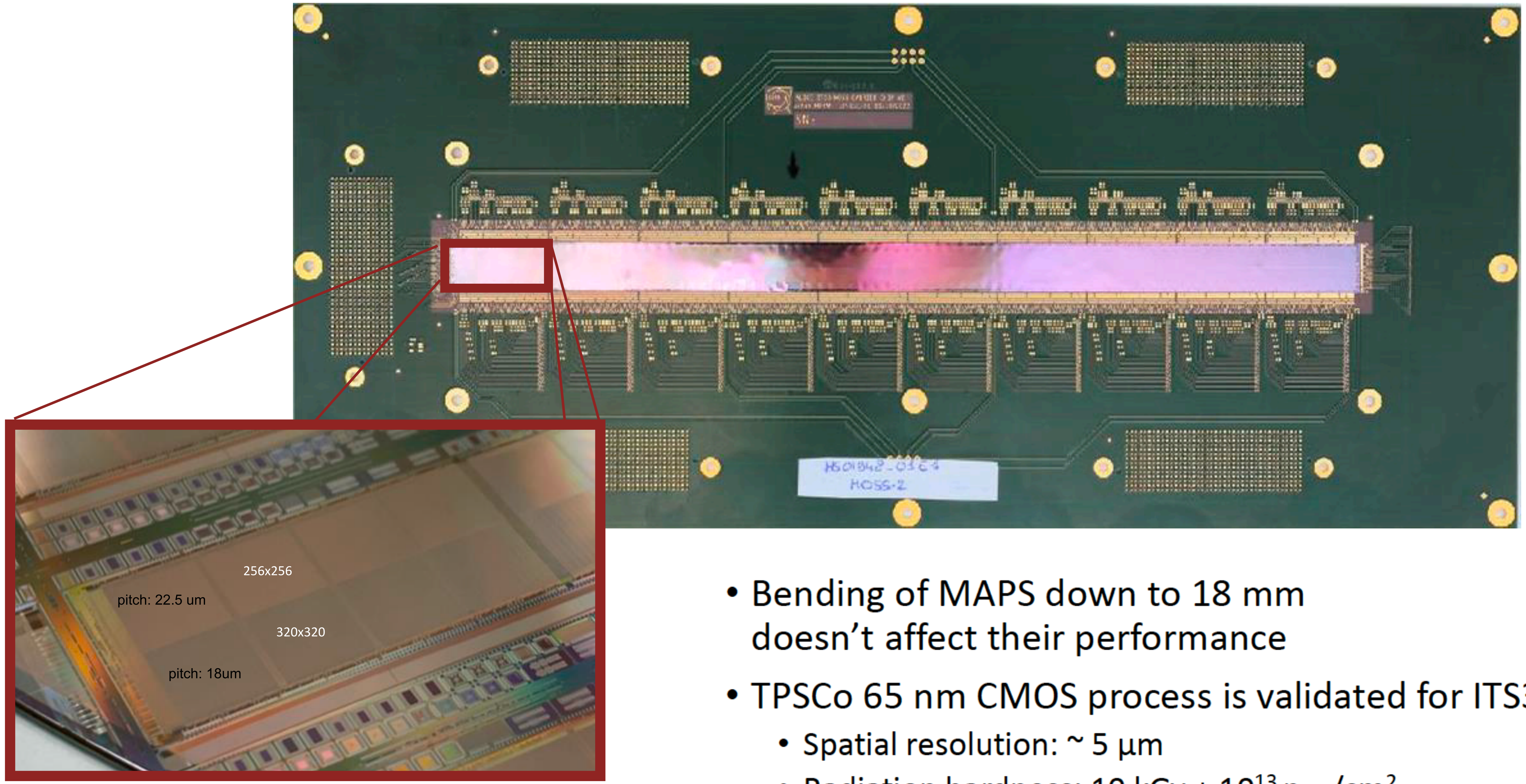
« RETOUR D’EXPÉRIENCE »

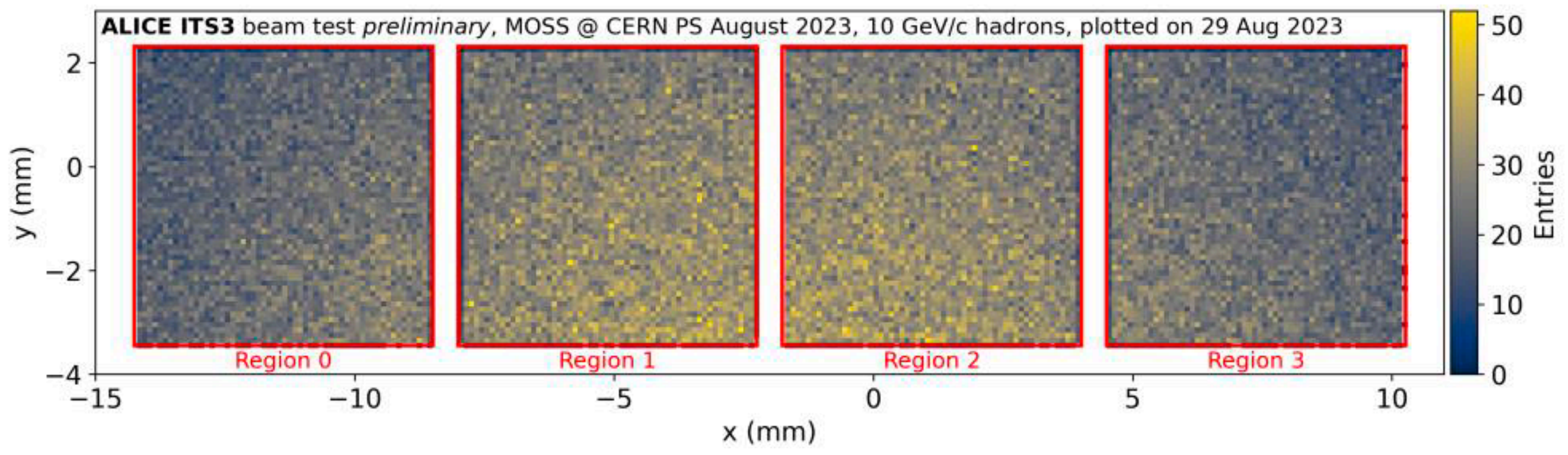
On the TPSCo 65 nm CMOS technology: ITS3

In 2021 *μITS3* – assembly of 3 ALPIDE sensors bent to ITS3 radii (18, 24, 30 mm) along rows – tested and also showed excellent detection efficiency not depending on the radius



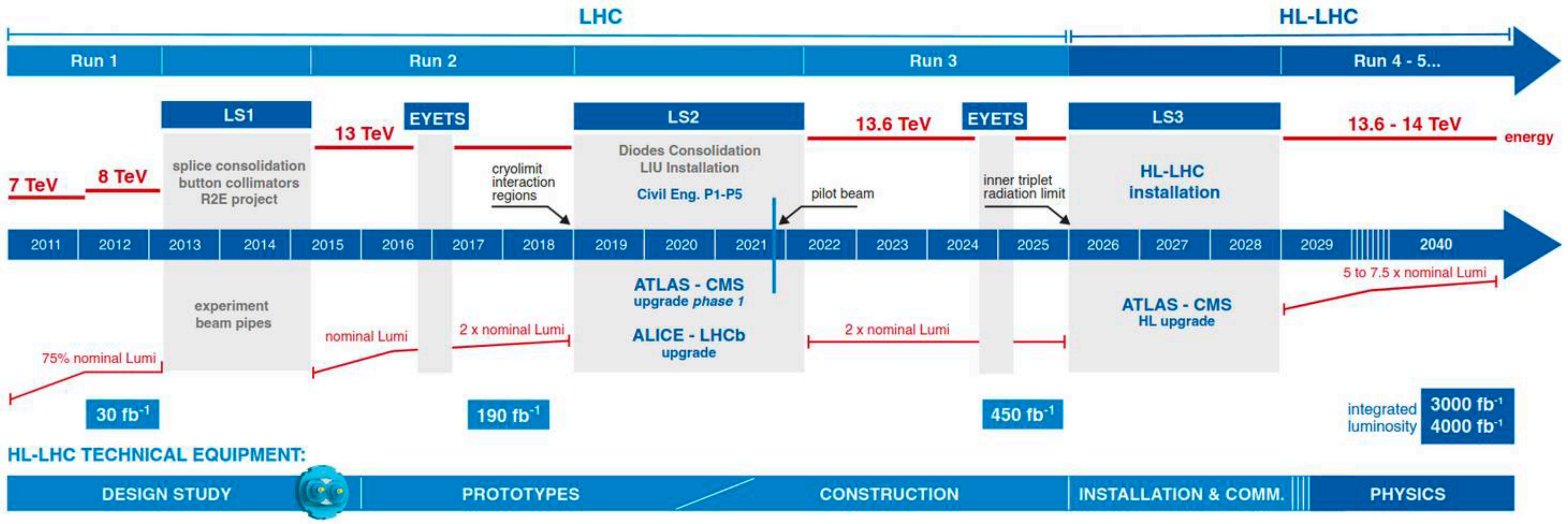
- Next: test MOnolithic Stitched Sensor (MOSS)



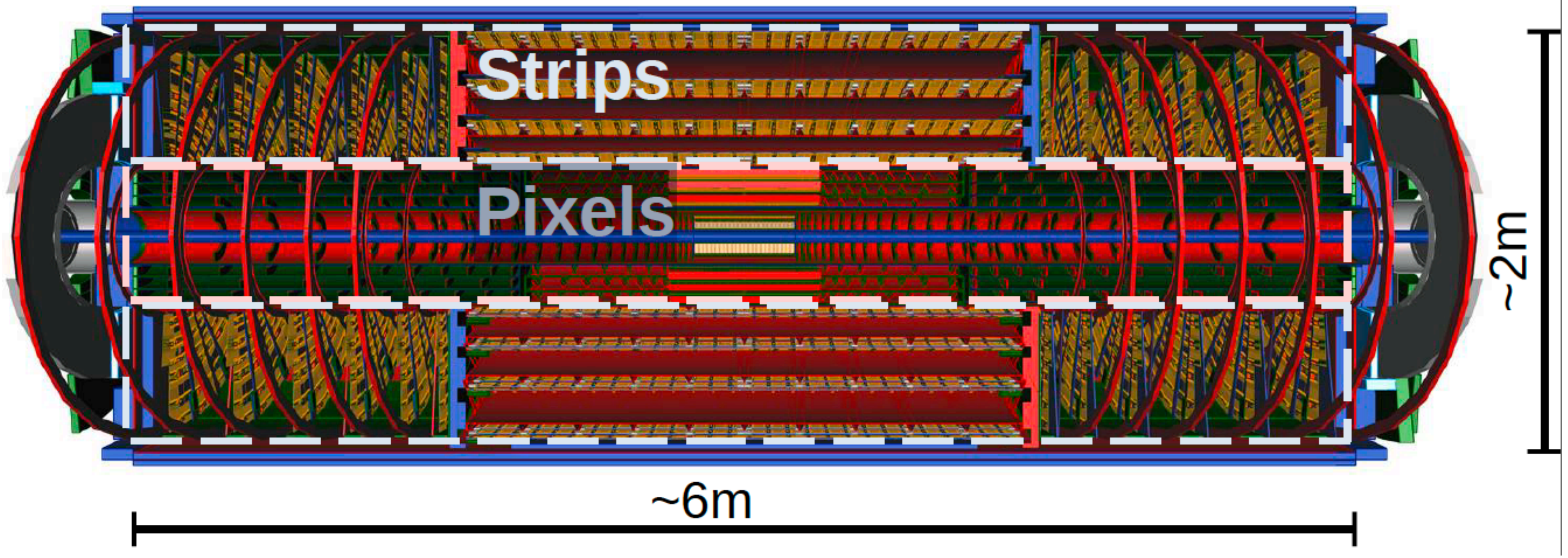


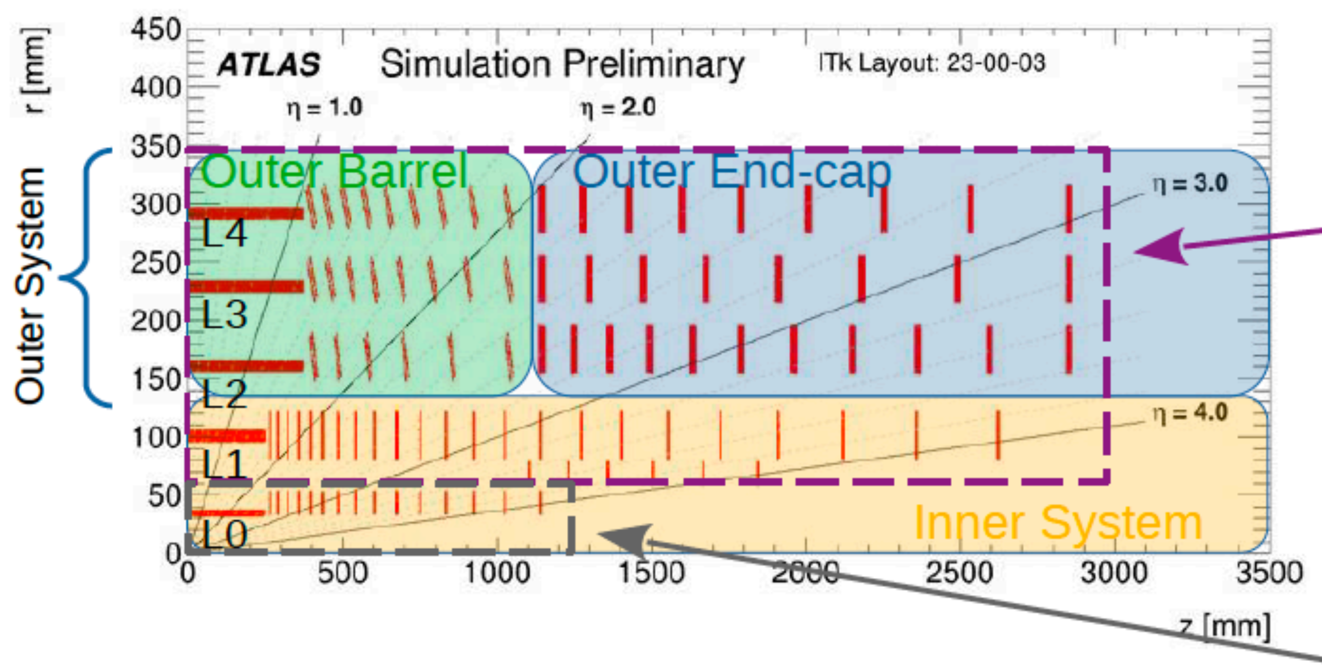
- Bending of MAPS down to 18 mm doesn't affect their performance
- TPSCo 65 nm CMOS process is validated for ITS3:
  - Spatial resolution: ~ 5 μm
  - Radiation hardness: 10 kGy + 10^{13} n_{eq} /cm^2
- First stitched prototypes work and being tested
- ER2 submission in preparation: final full scale sens prototype
- TDR to be presented to LHCC in November 2023

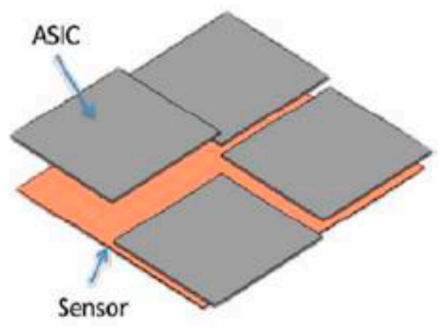
Another ongoing project: ATLAS



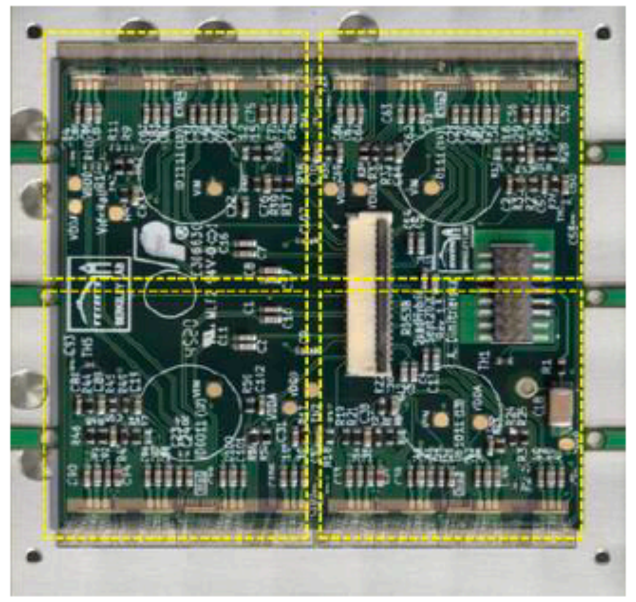
ATL-PHYS-PUB-2021-024



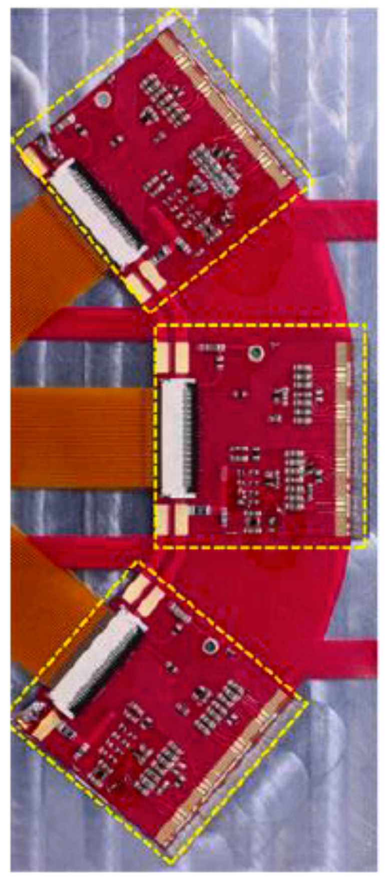




L1-4 planar quad module (single sensor)

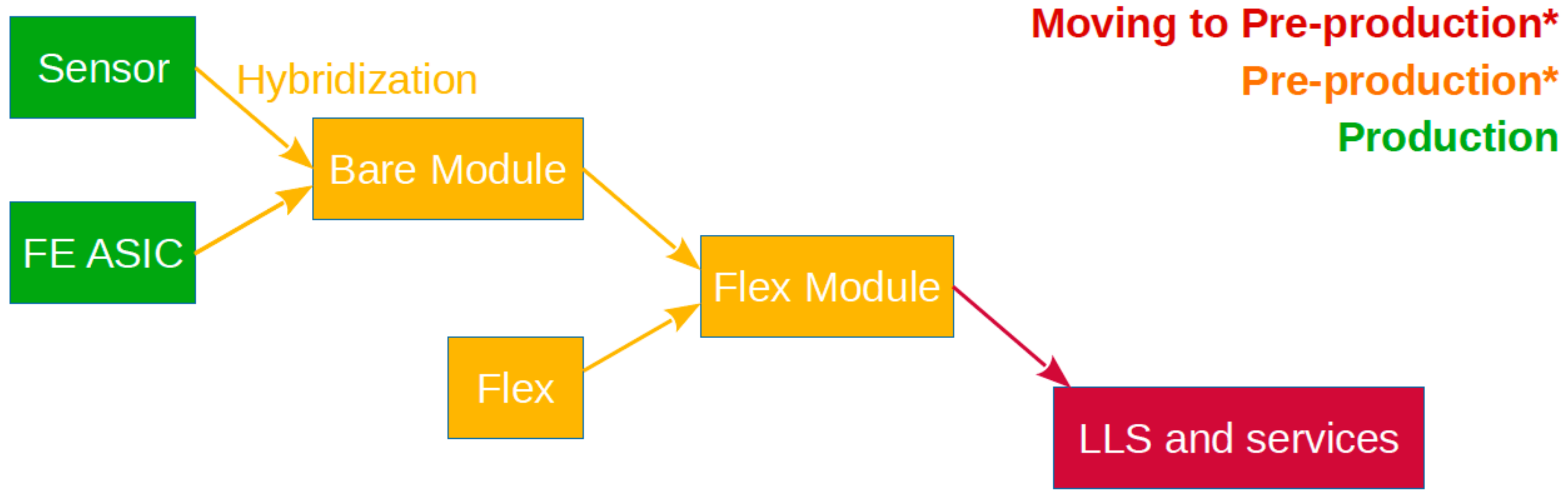


L0 3D single module (triplet PCB)

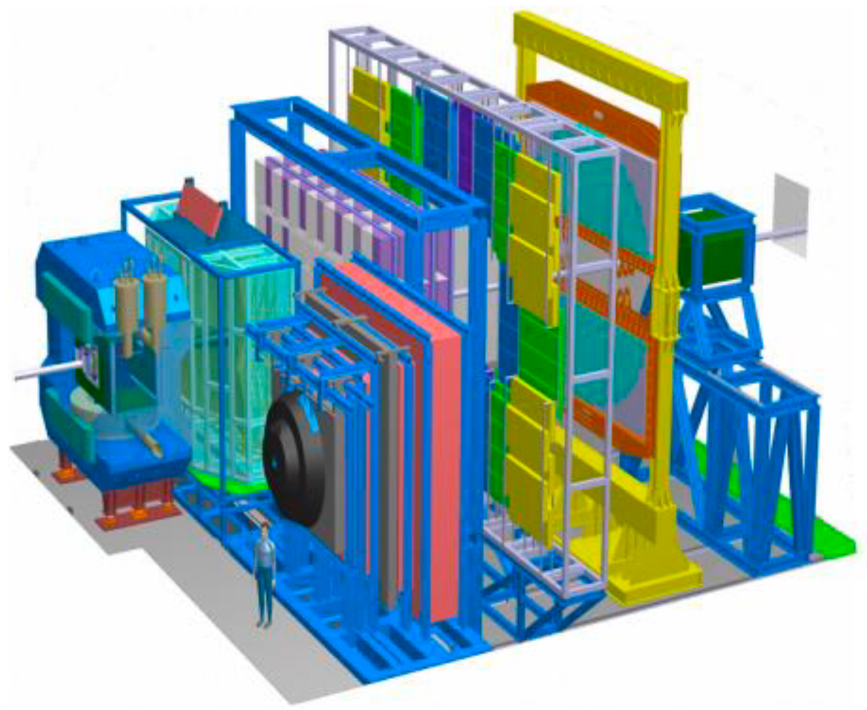


- Outer system
  - **3 layers** of flat staves and inclined rings.
  - **~7k planar quad modules** with 150µm thick sensor + 150µm thick ASIC, 50x50µm² pixel size.
- Inner system
  - **2 layers** of flat staves and rings.
  - L0: **~1.2k 3D single modules** (25x100µm² for flat, 50x50µm² for EC).
  - L1: **~1.2k planar quad modules** with 100µm thick sensor + 150µm thick ASIC, 50x50µm² pixel size.

CPPM, 20/09/2023 The new Inner Tracker of ATLAS F. Costanza 9



Another ongoing project: MVD @ CBM



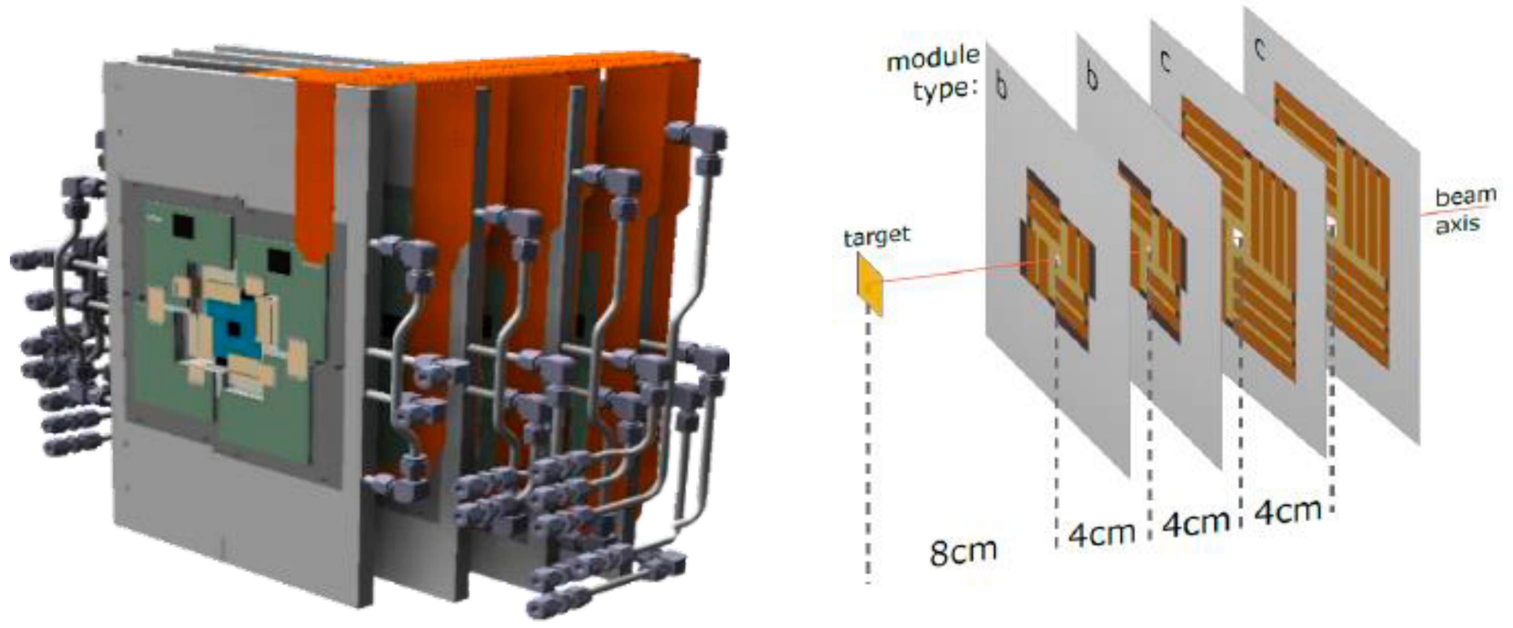
CBM – Experiment @ FAIR

MIMOSIS chip

- ✓ Based on ALPIDE architecture
- ✓ Discriminator on 27x30μm² pixel
- ✓ Multiple data concentration steps
- ✓ Elastic output buffer
- ✓ 8 x 320 Mbps links (switchable)
- ✓ Triple redundant electronics

Parameter	Value
Technology	TowerJazz 180 nm
Epi layer	$\sim$25 μm
Epi layer resistivity	$> 1 k\Omega cm$
Sensor thickness	60 μm
Pixel size	26.88 μm × 30.24 μm
Matrix size	1024 × 504 (516096 pix)
Matrix area	$\approx$ 4.2 cm^2
Matrix readout time	5 μs (event driven)
Power consumption	40-70 mW/cm^2

MIMOSIS = a milestone for Higgs factories (5 μm / ≤5 μs)



CBM Micro Vertex Detector (MVD)

MIMOSIS-1: 1st full size prototype

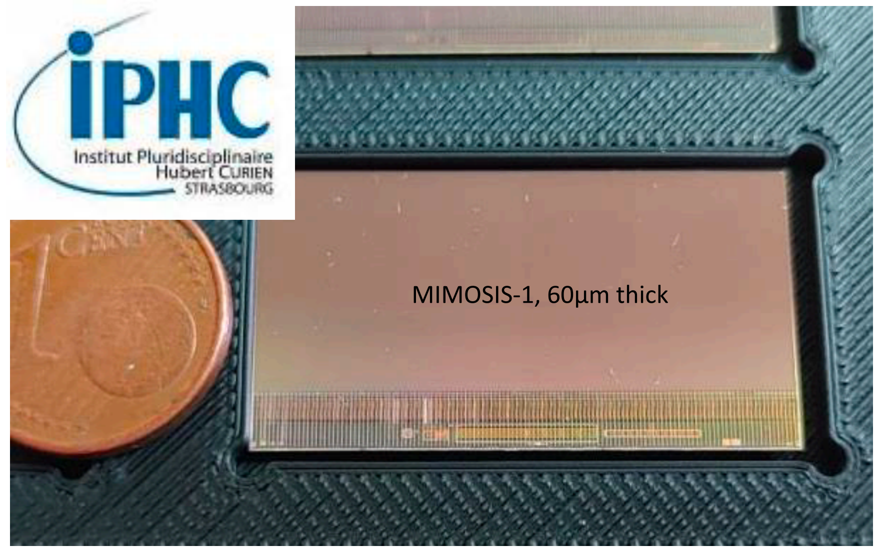
- ✓ Elastic buffer, SEE hardened
- ✓ Fabricated in 2020
- ✓ Intense test campaign in 2021-22
  - Lab and beam tests
  - Irradiations
  - Latchup tests

MIMOSIS-2:

- ✓ On-chip clustering
- ✓ Triplication added
- ✓ Back from foundry Q2 2023

MIMOSIS-3: final pre-production sensor

- ✓ ≥2025



CMOS Monolithic Active Pixel Sensor
MIMOSIS

Lessons learned up to now

Mimosis-1

Lab tests for all different versions (pixels, process)
~10 beam test campaigns over 2 years
Single Event Effect studies (not covered here)
3 irradiations campaigns
Large FTE effort

Very valuable experience shared during the workshop!

Follow-up and next step

- Very productive (although short) workshop.
  - Thanks to all the speakers to have consent to share their good and bad experiences.
- Problematics that emerged during the discussions:
  - From « retour d'expérience »:
    - Integrating the timing of the industry is key.
    - Extra-care should be given to propagate the engineer's expertise to new generations.
    - Sharing knowledges could save us time (and money).
  - Possible ideas for the futur:
    - Co-supervision of students.
    - Creation of a dedicated graduated school specific to pixel detectors.
    - Share common « building blocs » (firmware, software library…) for test bench (via a national platform ?).
- Common wish to have regular (annual ?) workshops on more specific topic:
  - Next workshop could be dedicated to integration.
- Thanks once again to the GDR for its help!