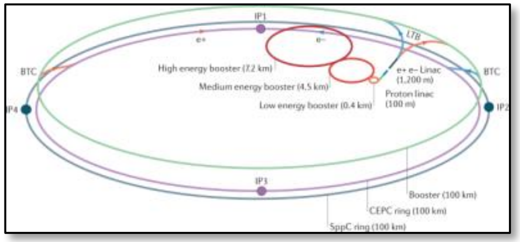
IPHC Scientific Council
2023, June 27th
CMOS MAPS projects

Future e^+e^- collider

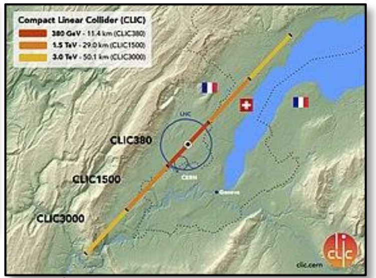
A. Scientific motivations
B. Building a strategy
C. Highlights on some activities (MIMOSIS, 65nm R&D, software)
D. Gantt plan & Resources

FCCee

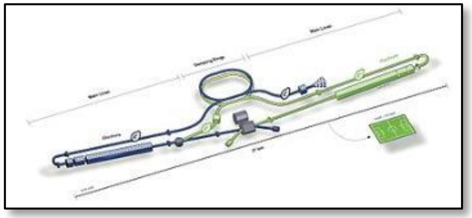
CEPC



CLIC



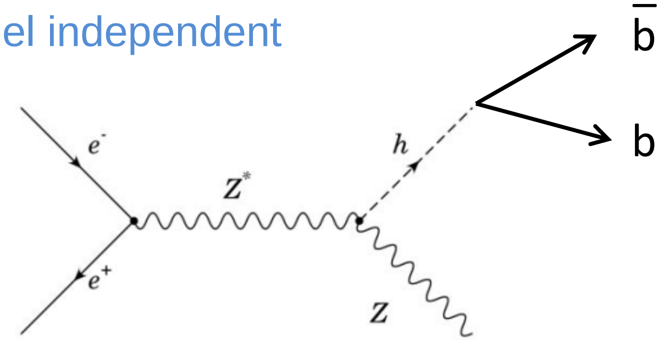
ILC



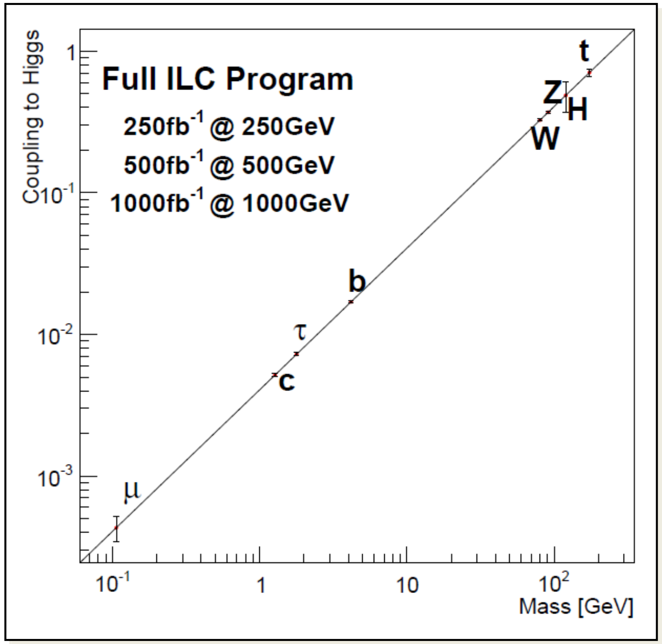
A. Scientific motivations

Motivations for a future e^+e^- collider

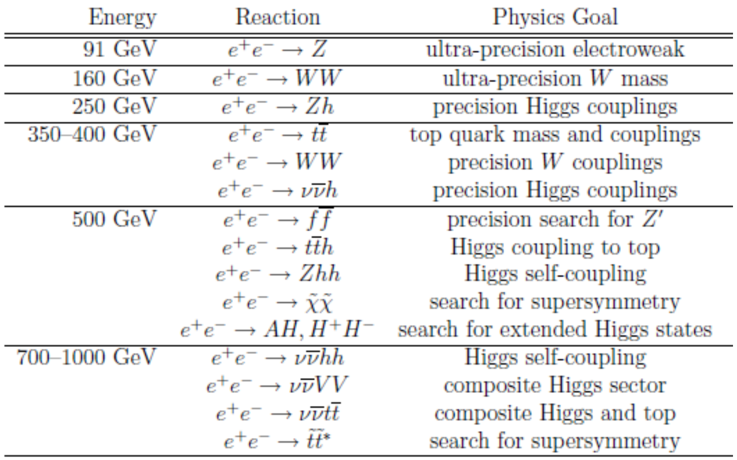
- Higgs Boson discovery by LHC (2012)
  - ✓ Not the end of the story. What is BSM ?
  - ✓ One approach consists in testing the SM in the Higgs sector
    - Model independent



    - ➢ Probe to new physics, model identification

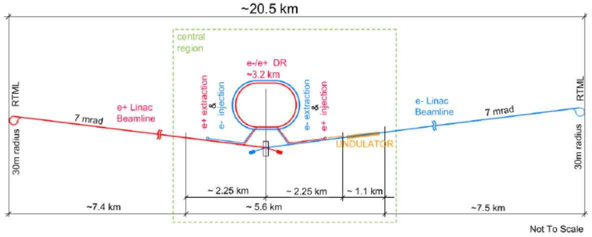


- A lot more than Higgs physics ! (EW, top, BSM, etc.)
  - ✓ No QCD background
  - ✓ Well defined initial state
  - ✓ Theoritical uncertainties under control
  - ✓ Tunable √s :
    - 91 GeV(Z), 160 GeV (WW), 250 GeV(Zh), 350 GeV (ttbar), up to 500 GeV (ILC) or even 3 Te (CLIC)
  - ✓ Beam polarization (ILC, CLIC)

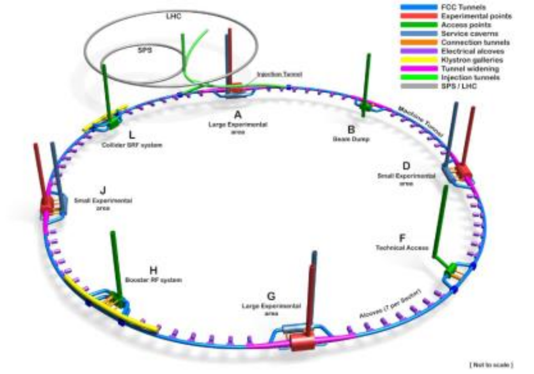


Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

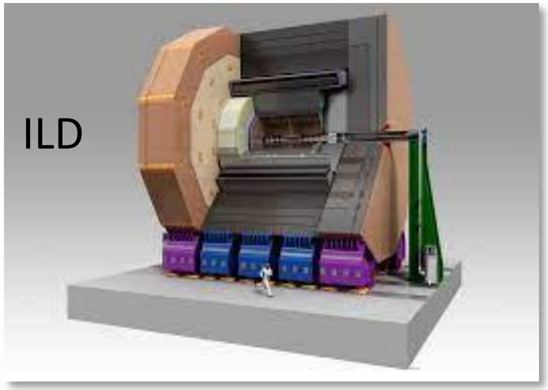
Future e^+e^- colliders (« Higgs factories »)



- 2 approaches
  - ✓ Circular (luminosity) : FCCee, CEPC
  - ✓ Linear (maximum Energy = Gradient$_{eff}$ × Length): ILC, CLIC



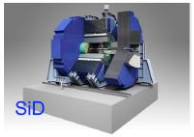
- All future e+e- collider physic programs demand
  - ✓ Impact parameter resolution: $\sigma_{ip} \lesssim 5\mu m \oplus \frac{10\ \mu m.\mathrm{GeV}}{p.sin^{3/2}\theta}$
    - CMS/4
  - ✓ Track momentum resolution: $\sigma_{p_T}/{p_T}^2 < 5 \times 10^{-5}\ GeV^{-1}$
    - CMS/40
  - ✓ Jet Energy resolution: $\sigma_E/E \sim 3 - 4\%$
    - ATLAS/2
  - ✓ **General particle flow approach**

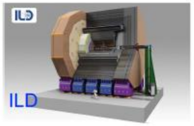


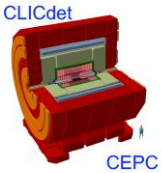
- Vertex/tracking detector role:
  - ✓ **b,c,τ tagging everywhere**
    - Standalone tracking capabilities
    - Low momentum tracking
    - Jet charge determination

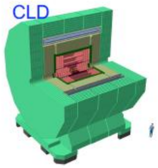
Tracking/vertexing detectors in future e^+e^- colliders

Collider	ILC		CLIC	FCCee			CEPC	
Bunch separation (ns)	330/550		0.5	20/990/3000			25/680	
Power Pulsing	yes		yes	no			no	
beamstrahlung	high		high	low			low	
Detector concept	SiD	ILC	CLICdet	CLD	IDEA	Lar	Baseline	IDEA
B Field (T)	5	3.5	4	2	2	2	3	2
Vertex	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel
Vertex Rmin (mm)	16	16	31	12	12	12	16	16
Tracker	Si-strips	TPC	Si-Pixel	Si-Pixel	DC/Si-strips	DC/Si-strips or Si-Pixels	TPC or Strips	DC/Si-strips
Tracker Rmax (m)	1.25	1.8	1.5	2.2	2.0	2.0	1.8	2.1
Disks layers	4 + 4	2 + 5	6 + 7	3 + 7	3 (150 mrad)		2+6	

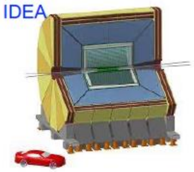


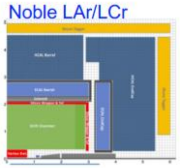


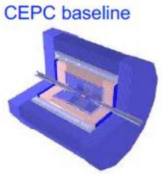


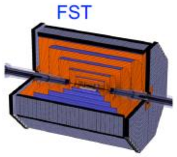


(From D. Dannheim)



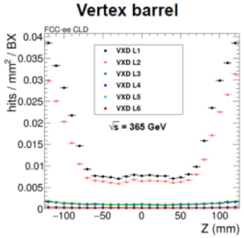


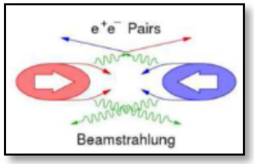




Large similarities between the concepts

Vertex detector requirements (ILC/FCCee)

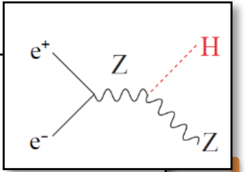




Physics O(Hz/cm^2)

Beam background O(10-50 MHz/cm^2)

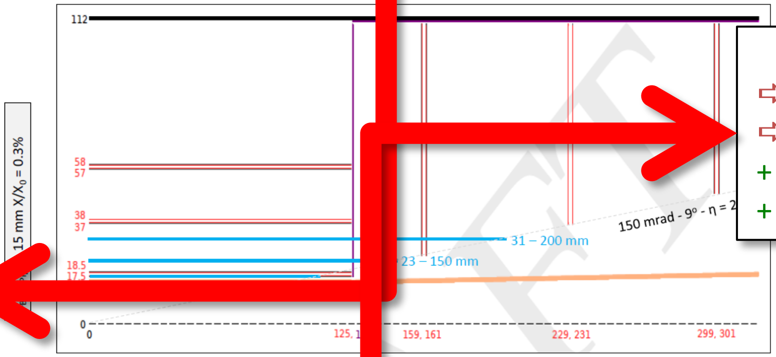
Physics
- ➪ Flavour tagging
- ➪ Low pT tracks
- ➪ Vertex/Jet charge determination



Vertex reconstruction
- ➪ granularity
- ➪ Pitch ~17-20 μm
- ➪ (σ_{sp} ~3-4 um)

CLD and IDEA Vertex Detectors designs (superimposed)

MAPS with $\sigma_{hit} \simeq 3$ μ and $X/X_0 \simeq 0.3\%$ / layer of Si
- CLD concept: double layers arrel/Endcap configuration
- IDEA concept: single closer ers in Long Barrel configuration



(Figure: D. Contardo)

Beam background

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Rad.Tol. devices

Time resolution
O(1 μs)

O(10ns)@CLIC

Power consumption
~< 50mW/cm^2

Fast read-out & low Power Architectures (~ 20-50 mW/cm^2)

No Power pulsing @FCCee

Cooling
Stiffness / Alignment

Material Budget
- ➪ ~ 0.15% X_0 / layer
- ➪ < 1% X_0 for the whole VTX
- + ~0.3 % X_0 for the beam pipe
- + 0.15% X_0 for 5 μm Gold coating

Low material detectors & supports structures

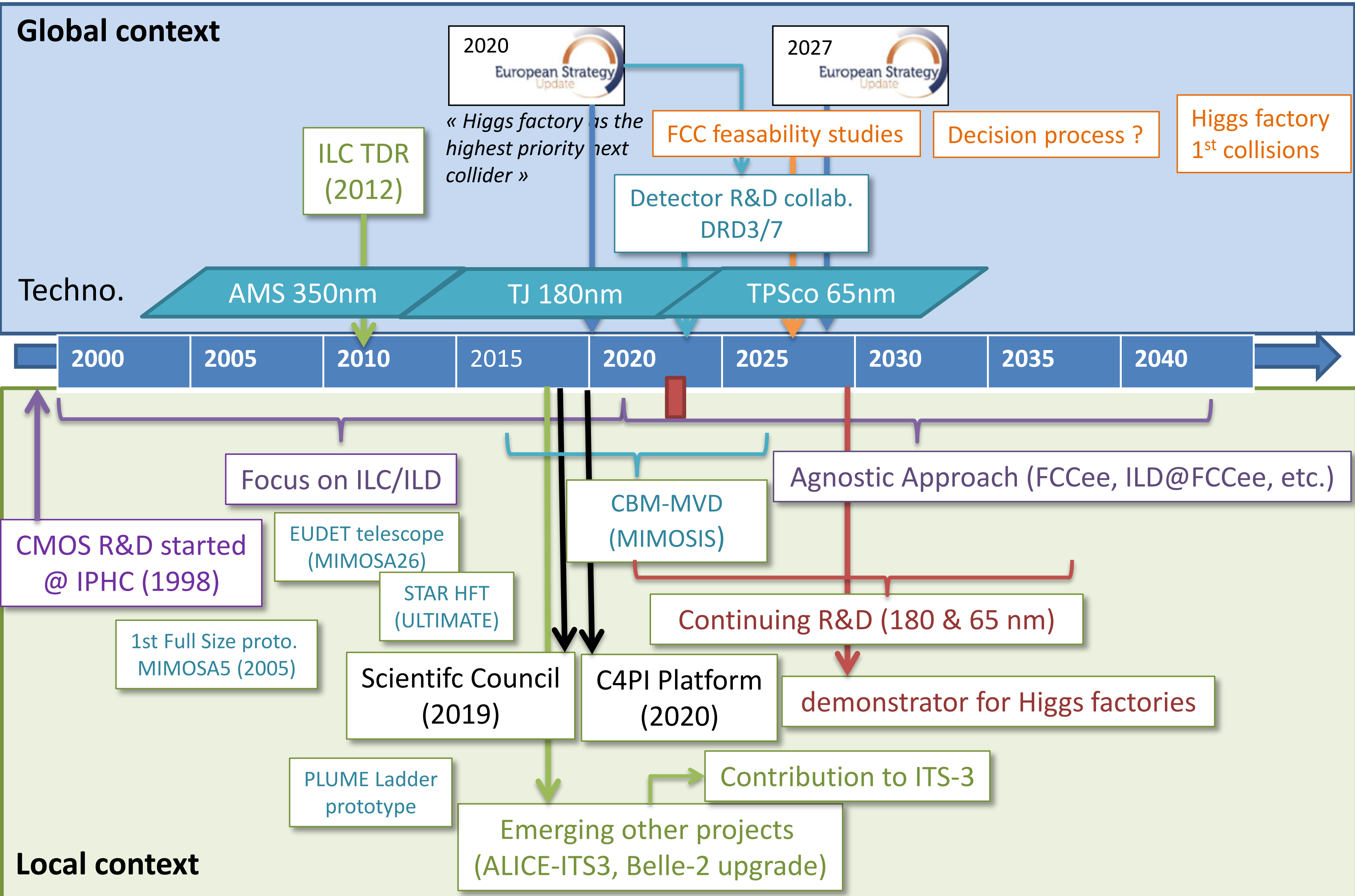
$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

$a \simeq 5\,\mu m$ $b \sim 10\ \mu m.GeV$

- Design: 5 single layers or 3 double layers ? Inner and outer radius ? Etc.
- R&D: ➪Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution (BX)

B. Building a strategy

Future e^+e^- collider: global and local context



Global context

2020 European Strategy Update

« Higgs factory as the highest priority next collider »

2027 European Strategy Update

ILC TDR (2012)

FCC feasability studies

Decision process ?

Higgs factory 1st collisions

Detector R&D collab. DRD3/7

Techno.

AMS 350nm

TJ 180nm

TPSco 65nm

Focus on ILC/ILD

CBM-MVD (MIMOSIS)

Agnostic Approach (FCCee, ILD@FCCee, etc.)

CMOS R&D started @ IPHC (1998)

EUDET telescope (MIMOSA26)

STAR HFT (ULTIMATE)

1st Full Size proto. MIMOSA5 (2005)

Continuing R&D (180 & 65 nm)

Scientifc Council (2019)

C4PI Platform (2020)

demonstrator for Higgs factories

PLUME Ladder prototype

Contribution to ITS-3

Emerging other projects (ALICE-ITS3, Belle-2 upgrade)

Local context

Building a strategy for CMOS R&D towards e^+e^- colliders

- Long History of CMOS R&D targeting e^+e^- colliders @ IPHC
  - ✓ Key features make them excellent candidate for VTX/TRK in a e^+e^- collider

- Strategy (~ up to 2019)
  - ✓ Focus on ILC
  - ✓ Step by step approach
    - Participation to mid-term projects to approach the final VTX for e^+e^- collider requirements

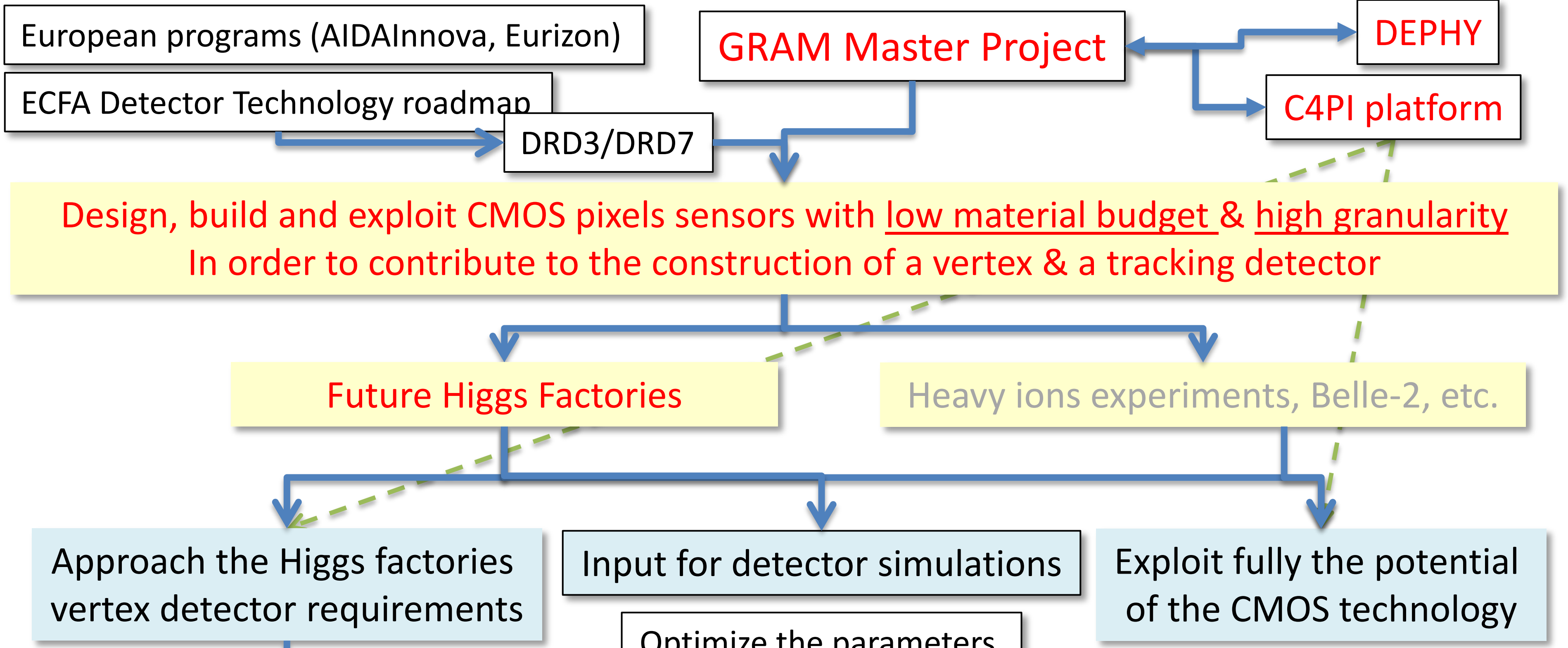
- Evolution of the strategy
  - ✓ Local changes
    - C4PI platform, IPHC teams developing their own projects (ALICE, Belle-2)
    - Generic R&D less specific but still favoring granularity w.r.t. high flux
  - ✓ International context concerning e^+e^-
    - More ecumenical approach (FCCee, ILC, CEPC, CLIC, etc.)
    - R&D for future e^+e^- collider must be integrated inside the ECFA Detector R&D framework (DRD3/DRD7)
  - ✓ Therefore
    - R&D can be more generic with different models:
      - sometimes fully endorsed by C4PI/other teams. Possible opportunities (Belle-2 ⇨ e.g. test beam in KEK)
      - Joined effort (65 nm : R&D with ALICE-ITS3)
    - The strong connection with C4PI remains absolutely crucial
    - The R&D for future e^+e^- collider, carried by the PICSEL team remains still essential for the CMOS R&D ecosystem @ IPHC

⇨ Mid-term projects are still the way to go (e.g. MIMOSIS program carried by PICSEL team)

⇨ Maintain/develop our international & national collaborations

⇨ Find synergies/collaborate with the mid-term projects carried by other teams whenever possible/adequate

⇨ Develop simulation & physics studies dedicated to FCCee



European programs (AIDAInnova, Eurizon)

ECFA Detector Technology roadmap

DRD3/DRD7

GRAM Master Project

DEPHY

C4PI platform

Design, build and exploit CMOS pixels sensors with low material budget & high granularity
In order to contribute to the construction of a vertex & a tracking detector

Future Higgs Factories

Heavy ions experiments, Belle-2, etc.

Approach the Higgs factories vertex detector requirements

Input for detector simulations

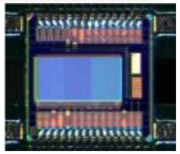
Exploit fully the potential of the CMOS technology

MIMOSIS chip family (180 nm)

Optimize the parameters
of the technology
(e.g. sensitive layer)

Maintain & develop the know how to build sensors to be installed in real experiments

R&D 65 nm



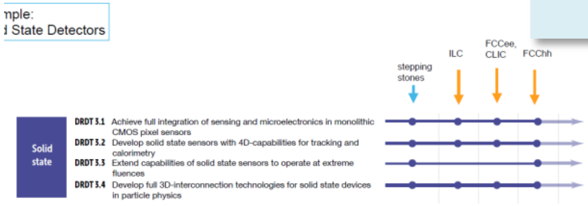
Large surfaces (stitching)

Bent sensors

Exploring new architectures

Integration

Emerging technologies
(e.g. double tier)



mple:
d State Detectors

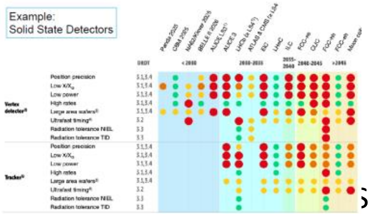
Solid state

DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors

DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry

DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences

DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics



Example:
Solid State Detectors

C. Highlights on some activities

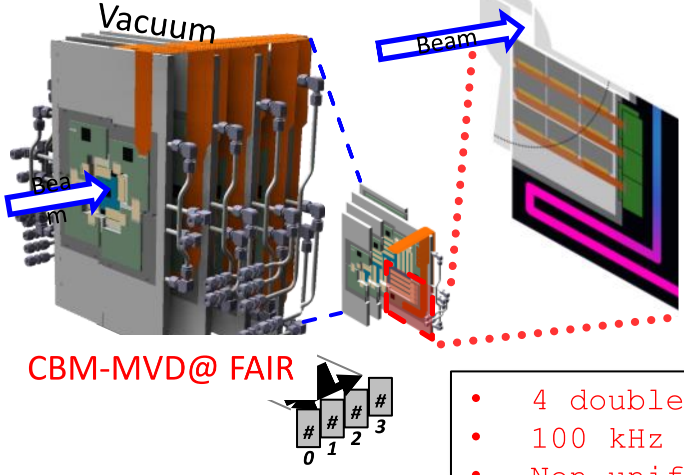
MIMOSIS

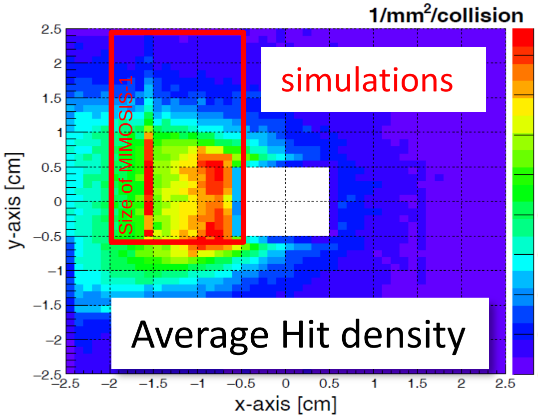
65nm R&D

Simulations & integration

MIMOSIS requirements

- Requirements

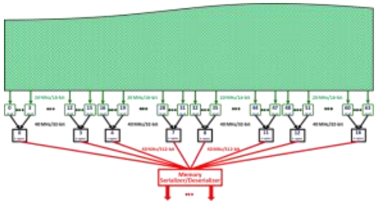




Physics parameter	Requirements
Spatial resolution	~ 5 um
Time resolution	~ 5 us
Material budget	0.05% X_0
Power consumption	< 100 – 200 mW/cm^2
Operation temperature	- 40 °C to 30 °C
Temp gradient on sensor	< 5K
Radiation tol* (non-ion)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation tol* (ionizing)	~ 5 MRad
Data flow (peak hit rate)	@ 7 x 10^5 / $(mm^2 s)$ > 2 Gbit/s

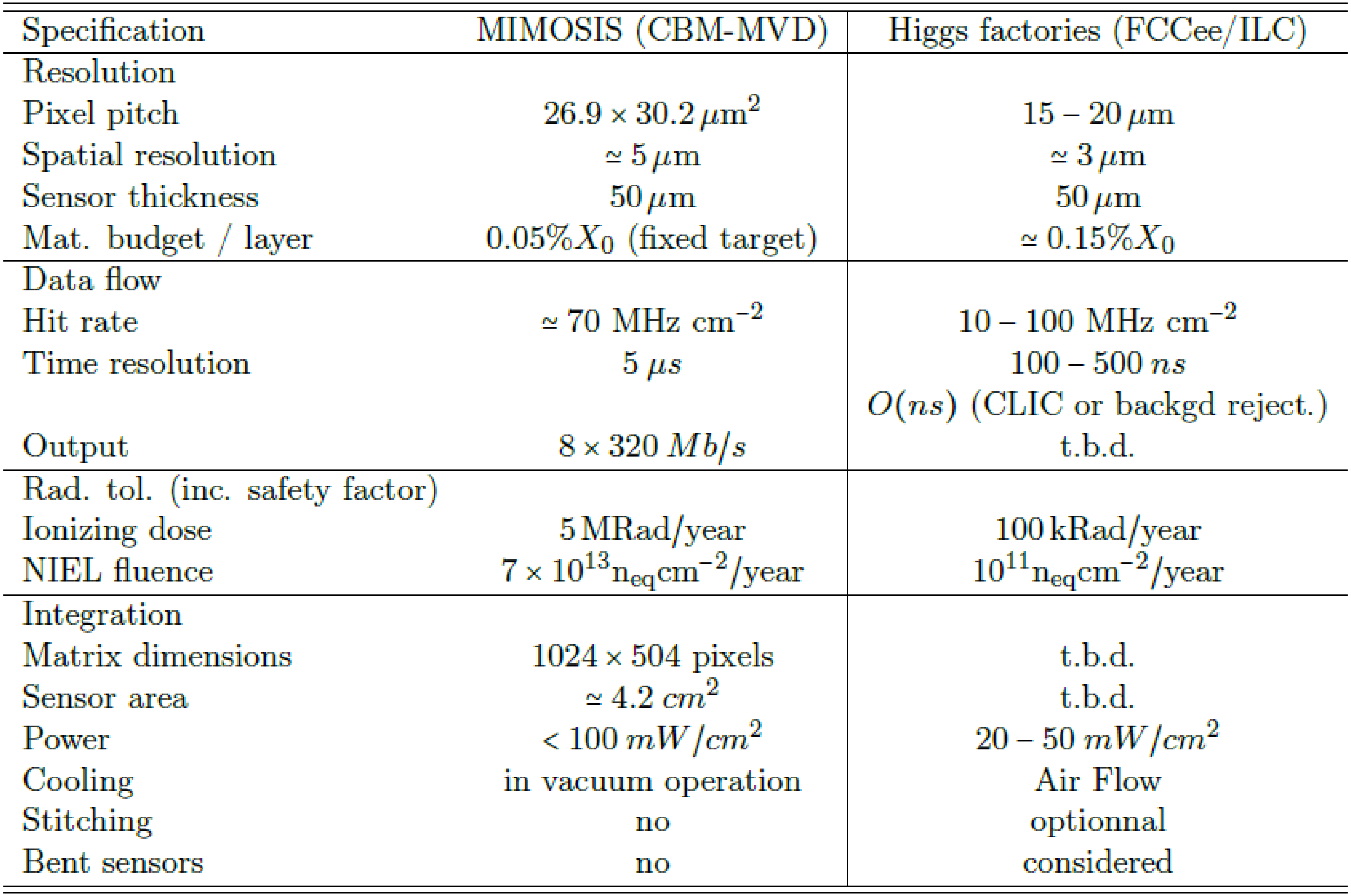
- 4 double-sided thin planar detector stations
- 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
- Non uniform hit density in time and space
- High radiation environment, operating in vacuum

- 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	$\sim 25\,\mu m$
Epi layer resistivity	$> 1k\Omega cm$
Sensor thickness	$60\,\mu m$
Pixel size	$26.88\,\mu m \times 30.24\,\mu m$
Matrix size	1024×504 (516096 pix)
Matrix area	$\approx 4.2\,cm^2$
Matrix readout time	$5\,\mu s$ (event driven)
Power consumption	40-70 mW/cm^2

The MIMOSIS program w.r.t. e^+e^- colliders requirements



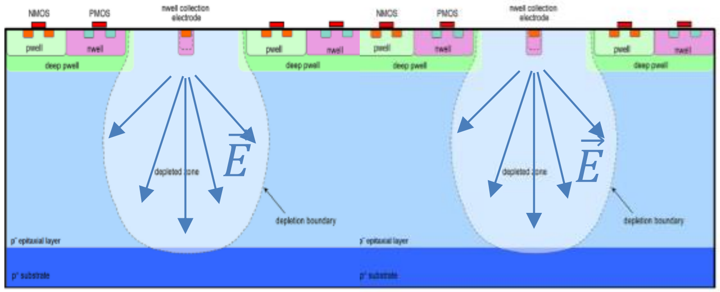
Specification	MIMOSIS (CBM-MVD)	Higgs factories (FCCee/ILC)
Resolution		
Pixel pitch	$26.9 \times 30.2\,\mu m^2$	$15 - 20\,\mu m$
Spatial resolution	$\simeq 5\,\mu m$	$\simeq 3\,\mu m$
Sensor thickness	$50\,\mu m$	$50\,\mu m$
Mat. budget / layer	$0.05\%X_0$ (fixed target)	$\simeq 0.15\%X_0$
Data flow		
Hit rate	$\simeq 70$ MHz cm^{-2}	$10 - 100$ MHz cm^{-2}
Time resolution	$5\ \mu s$	$100 - 500\ ns$
		$O(ns)$ (CLIC or backgd reject.)
Output	$8 \times 320\ Mb/s$	t.b.d.
Rad. tol. (inc. safety factor)		
Ionizing dose	5 MRad/year	100 kRad/year
NIEL fluence	$7 \times 10^{13} \mathrm{n_{eq}cm^{-2}}$/year	$10^{11} \mathrm{n_{eq}cm^{-2}}$/year
Integration		
Matrix dimensions	1024×504 pixels	t.b.d.
Sensor area	$\simeq 4.2\ cm^2$	t.b.d.
Power	$< 100\ mW/cm^2$	$20 - 50\ mW/cm^2$
Cooling	in vacuum operation	Air Flow
Stitching	no	optionnal
Bent sensors	no	considered

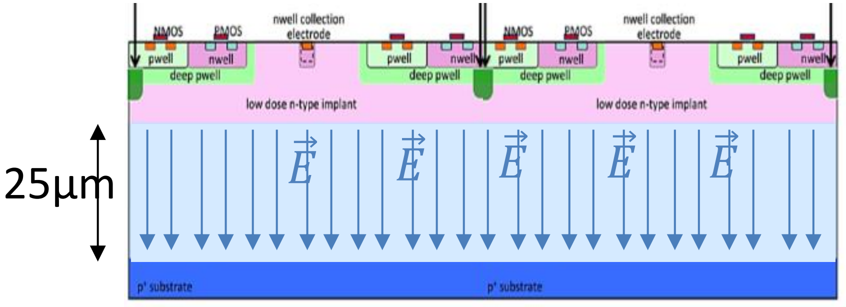
MIMOSIS = a milestone for Higgs factories (5 µm / ≤5 µs)

Example: MIMOSIS (CBM-MVD) & Decision on options for sensing elements

Process modification: Standard? P-stop? N-Gap?

25 or 50 µm epi?



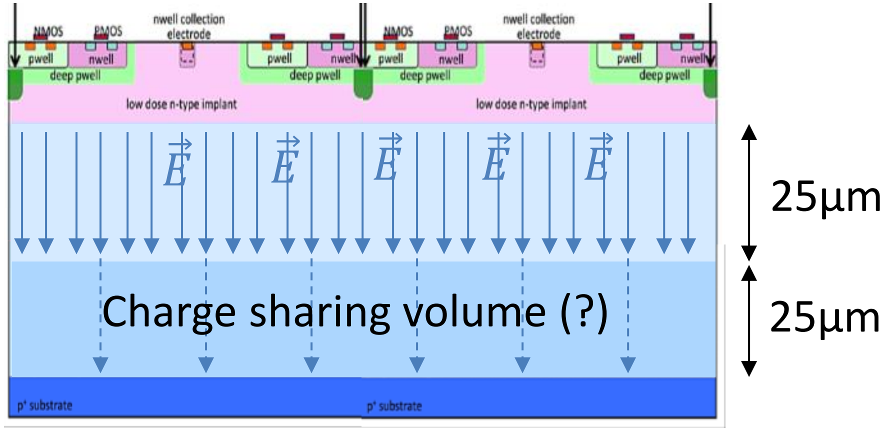


$\sigma = 4 - 5$ µm
> 3 x $10^{13} n_{eq}/cm^2$

Spatial resolution
Rad. hardness

$\sigma = 5 - 7$ µm
> 30 x $10^{13} n_{eq}/cm^2$

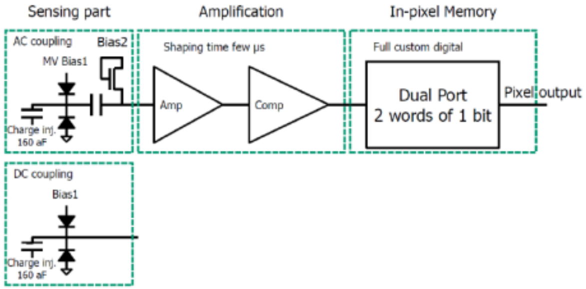
Process options inherited from ALPIDE



Charge sharing volume (?)

- Better spatial res. at given rad. tolerance?
- Higher S/N => Robustness to external noise?
- Nuclear fragment ID by dE/dx?

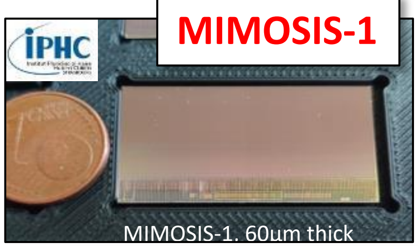
AC? DC? pixel



- DC pixel – limited rad. hardness.
- AC Pixel – more biasing lines.

W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

MIMOSIS program timeline


MIMOSIS-1

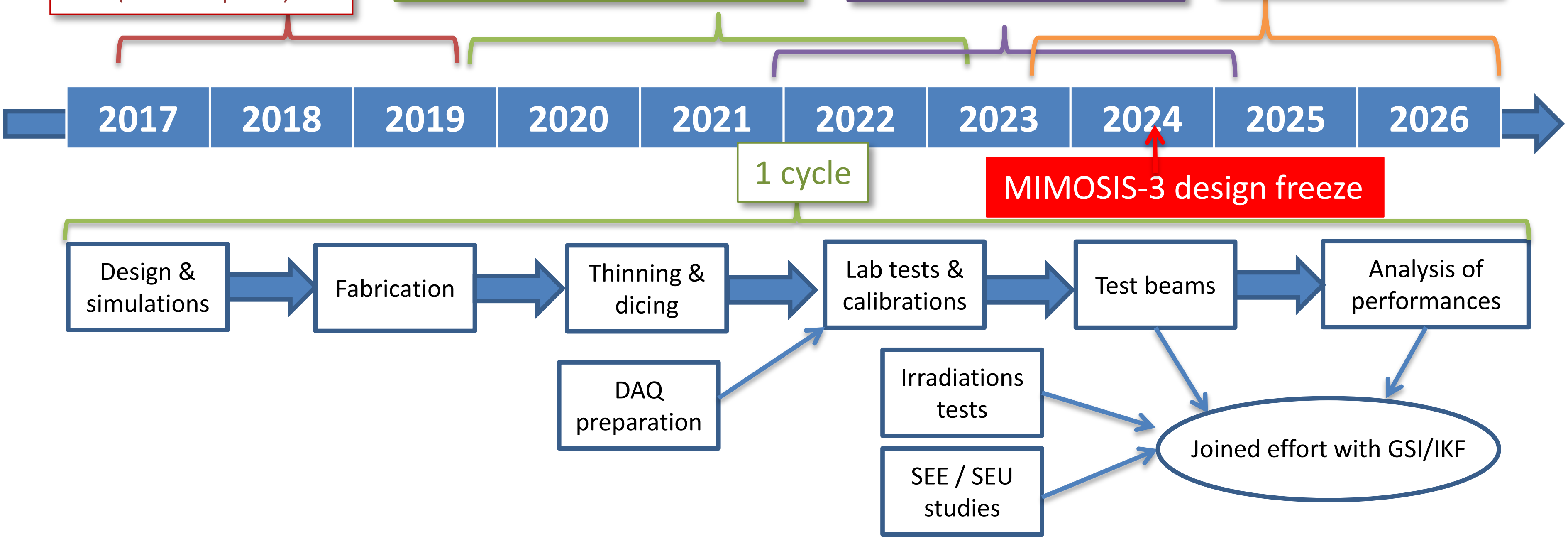
MIMOSIS-1, 60µm thick

MIMOSIS-0
- Small size prototype
- (32 x 504 pixels)

MIMOSIS-1
- 1st full size prototype
- AC / DC submatrices
- Full digital part (elastic buffer)
- SEE hardened
- (1024 x 504 pixels)

MIMOSIS-2
- On-chip clustering
- 25 / 50 µm epi layers
- Corrections &
- Improvments w.r.t. M-1
- (1024 x 504 pixels)

MIMOSIS-3
- Final sensor
- (1024 x 504 pixels)


2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

1 cycle

MIMOSIS-3 design freeze

Design & simulations → Fabrication → Thinning & dicing → Lab tests & calibrations → Test beams → Analysis of performances

DAQ preparation

Irradiations tests

SEE / SEU studies

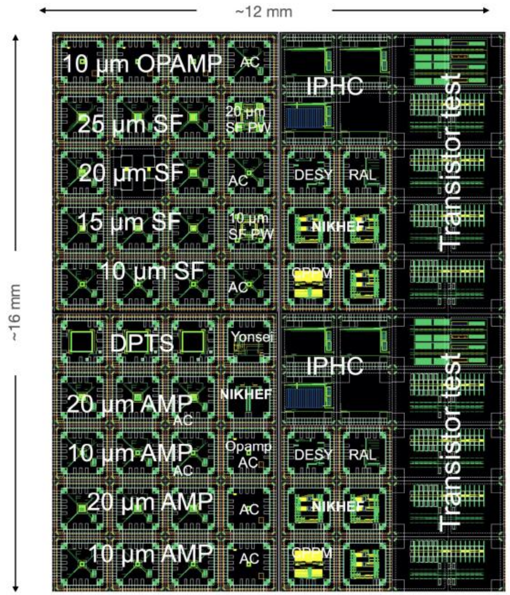
Joined effort with GSI/IKF

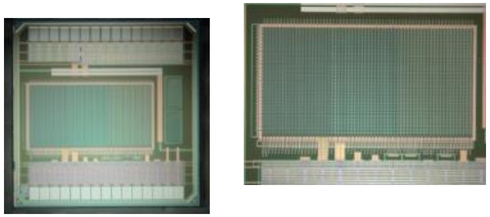
FTE needs estimate

TASK	2023				2024				2025				2026				2027			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MIMOSIS Program																				
MIMOSIS Physicists (PICSEL)	1,5	1,5	1,5	2	1	1	1	1	1	2	2	2	1,5	1						
MIMOSIS microtechnics (C4PI)			0,3	0,3	0,3				0,5	0,5	0,5	0,5								
MIMOSIS-1 Tests (C4PI)	1	1																		
MIMOSIS-2 Fabrication	///////	//////																		
MIMOSIS-2 Tests (C4PI)			3	3	2	2	2	2	1											
MIMOSIS-3 Designs (C4PI)			0,5	0,5	0,5	0,5														
MIMOSIS-3 Fabrication							///////	//////												
MIMOSIS-3 Tests (C4PI)									1	1	1	1	1							

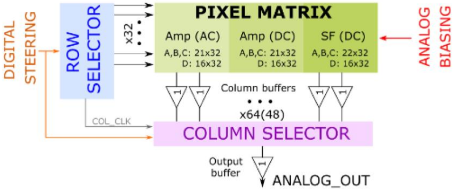
R&D in TPSCo 65nm technology

- 65 nm feature size technology
  - ✓ (ALPIDE & MIMOSIS fabricated in 180 nm)
  - ✓ Larger wafers (➩ 30 cm)
  - ✓ More functionalities inside the pixel
  - ✓ Keeps pixel dimensions small ➩ spatial res.
  - ✓ Potentially faster read-out
  - ✓ Lower Power consumption
  - ✓ Synergy with Higgs factories requirements
- 2020: TJ-65 nm 1st submission (MLR1)
  - ✓ Main driver: CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades
    - ▪ Privileged Relation between CERN with the foundry (access to options is a key factor)
  - ✓ Goal: **validate the process for charged particle detection**
  - ✓ Contributions to MOSS/MOST
  - ✓ MLR1 submission: CE_65v1 prototype designed@IPHC
  - ✓ Analog output, various designs (pitch, amplification)
- CE_65v2 (ER1 submission)
  - ✓ 18/22 μm pitch, hex design
  - ✓ Availaible in August 2023

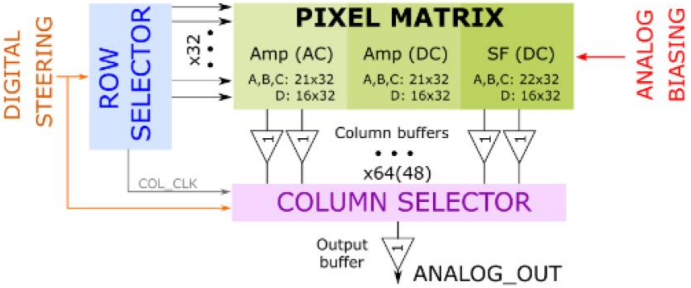




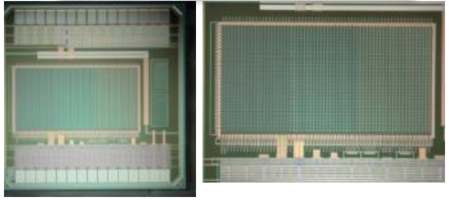
CE_65 prototypes

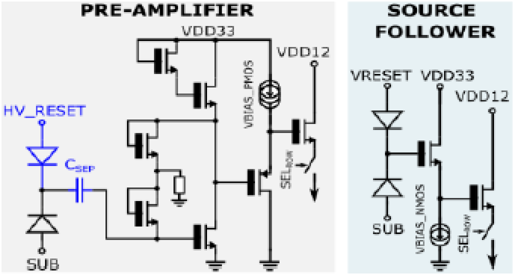


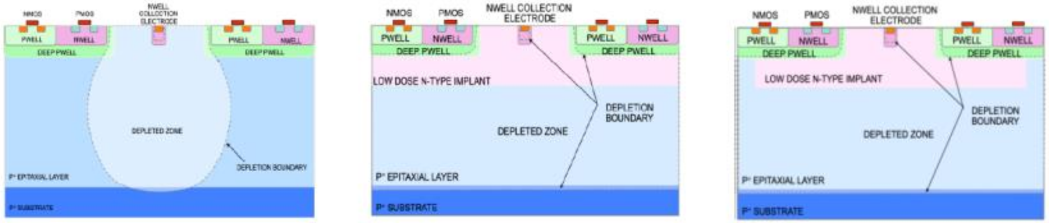
CE65_v1



CE_65 prototypes

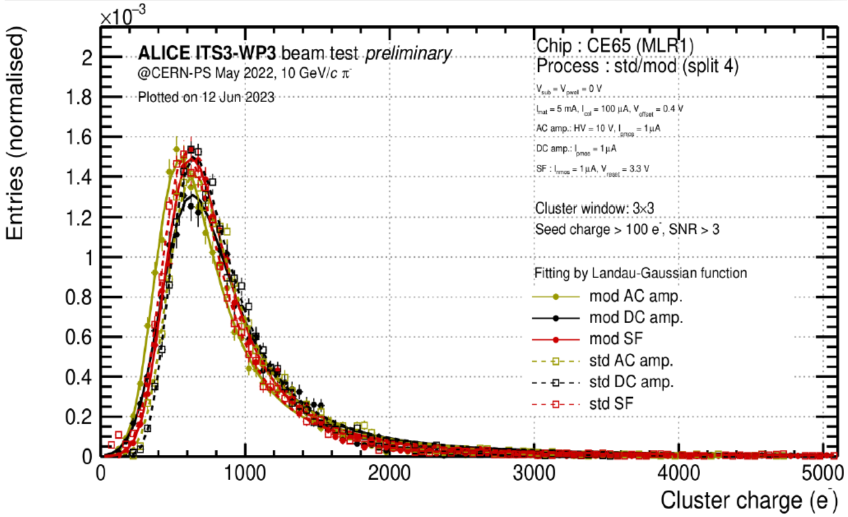


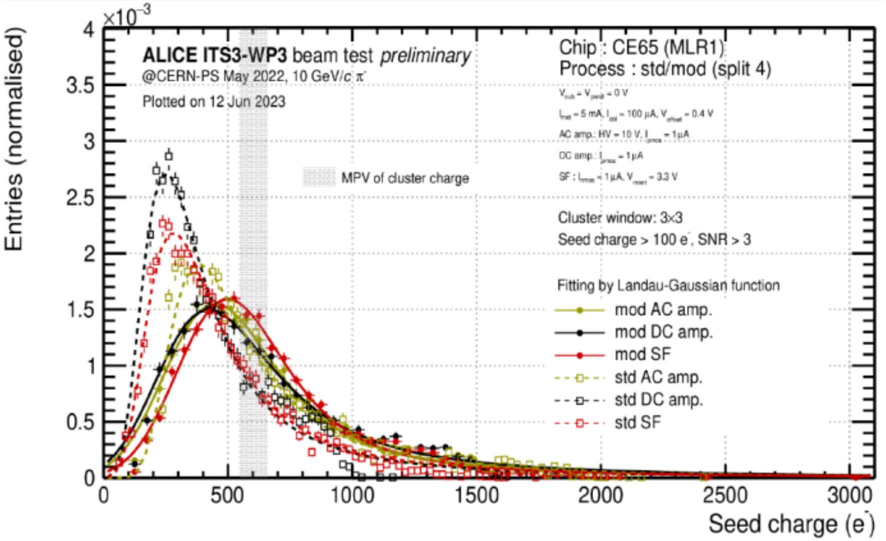




(a) Standard (b) Modified (c) Modified with gap

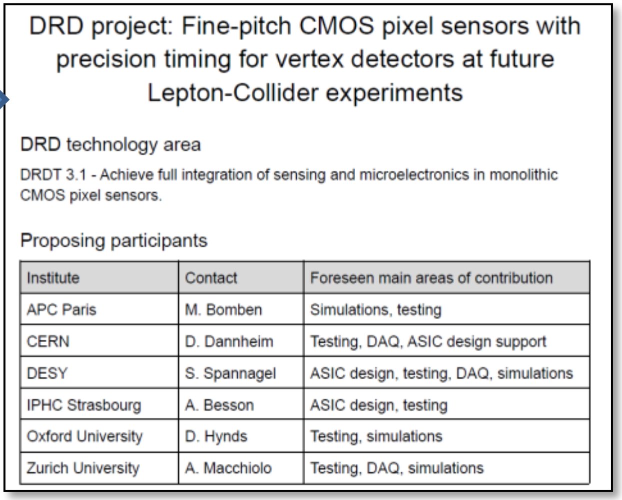
Variant	Process	Pitch	Matrix	Sub-matrix
CE65-A	std	15μm	64×32	AC/21, DC/21, SF/22
CE65-B	mod_gap	15μm	64×32	AC/21, DC/21, SF/22
CE65-C	mod	15μm	64×32	AC/21, DC/21, SF/22
CE65-D	std	25μm	48×32	AC/16, DC/16, SF/16





CMOS 65 nm submissions and connexion with DRD3/DRD7

- 2 lines of submissions
  - ✓ Submissions dedicated to ALICE ITS-3 (ER2 & ER3)
  - ✓ Submissions for generic R&D, supported by CERN EP R&D WP1.2 (« MLR2 » and beyond)
- Solid state detector R&D framework = DRD3/7
- Generic R&D possible contributions
  - ✓ One expression of interest submitted with future e+e- collider vertex detectors as the main driver
    - Goal: gather groups to reach a critical size
    - Targets 3 μm spatial resolution, improved time resolution (5-500 ns), controlled Power (< 50 mW/cm^2), data flow (10-100 MHz/cm^2) and low material budget (50 μm thickness)
    - Demonstrator to equip new generation beam telescope
    - Proposing Institutes: CERN, DESY, IPHC, APC, etc.
    - Open to other participations
  - ✓ Other projects in discussion (tracking, timing, calorimeters)



DRD project: Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments

DRD technology area

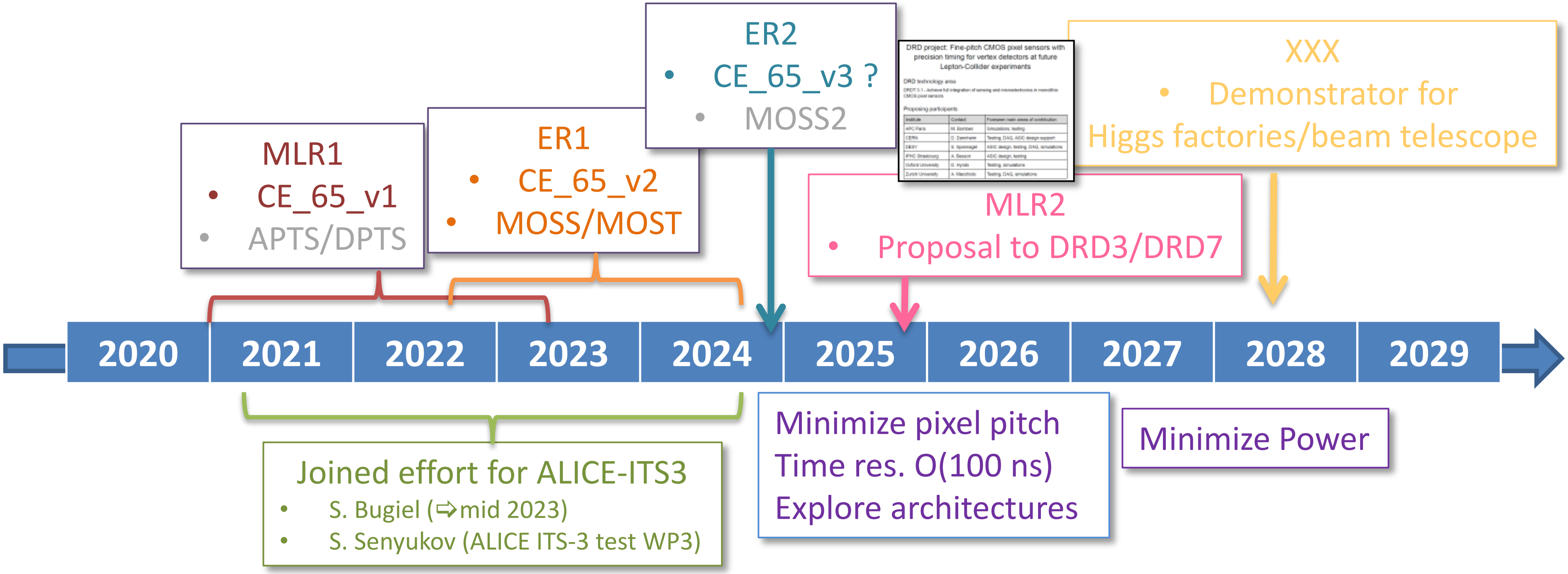
DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.

Proposing participants

Institute	Contact	Foreseen main areas of contribution
APC Paris	M. Bomben	Simulations, testing
CERN	D. Dannheim	Testing, DAQ, ASIC design support
DESY	S. Spannagel	ASIC design, testing, DAQ, simulations
IPHC Strasbourg	A. Besson	ASIC design, testing
Oxford University	D. Hynds	Testing, simulations
Zurich University	A. Macchiolo	Testing, DAQ, simulations

- MLR2 submission model ?
  - ✓ MLR2 submission: ~ end 2025 (another expected > 2027)
  - ✓ Cost to be shared between EP R&D WP 1.2 and participating projects
  - ✓ Multi-year plan needed to allow significant contributions to the targeted submissions

65 nm R&D timeline (e^+e^- point of view)



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Oxford University	D. Hynds	Testing, simulations
Zurich University	A. Macchiolo	Testing, DAQ, simulations

MLR1
- CE_65_v1
- APTS/DPTS

ER1
- CE_65_v2
- MOSS/MOST

ER2
- CE_65_v3 ?
- MOSS2

MLR2
- Proposal to DRD3/DRD7

XXX
- Demonstrator for Higgs factories/beam telescope

Joined effort for ALICE-ITS3
- S. Bugiel (⇨mid 2023)
- S. Senyukov (ALICE ITS-3 test WP3)

Minimize pixel pitch
Time res. O(100 ns)
Explore architectures

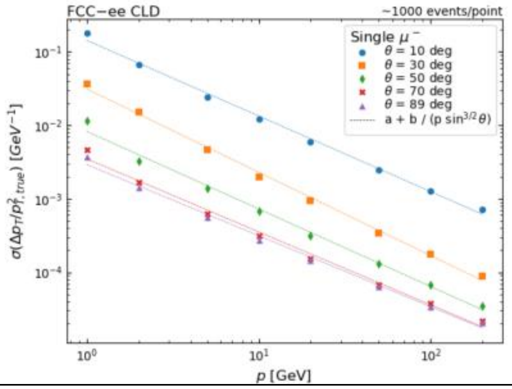
Minimize Power

FTE needs estimate

TASK	2023				2024				2025				2026				2027			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
R &D for e+ e- colliders																				
65 nm / 180 nm R & D (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	2	2,5	2,5	2,5	3	3	3	3
CE65 tests (C4PI)	1	1	1	1	1	1														
Microtechnics (C4PI)									0,1	0,1					0,5	0,5	0,5			
ER_2 test structure design (C4PI)	1	1	1	1,5	1,5	1,5	1,5													
ER_2 fabrication								//////	///////											
MLR2 design (C4PI)								2	3	4	4	4								
MLR2 Fabrication												//////	///////							
beam telescope demonstrator													tests	tests						
beyond MLR2 design (C4PI)													4	4	4	4	4	4	4	4
beyond MLR2 fabrication ?																			///////	///////
R & D Test (C4PI)													1,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5

Simulations & integration

- Master the full simulation chain (key4hep) for detector optimisation
  - ✓ Complete physics studies
- Master Tools for CMOS sensor characterization, charge transport and digitization studies, analytical tools for detector optimization, etc.
  - ✓ Local tools (TAF, Guariguanchi)
  - ✓ Tools developed by the commmunity (Allpix2, corryvreckan)



- Bent sensors
  - ✓ Adress questions specific to Higgs factories
  - ✓ Understand limitations
- Plans
  - ✓ Reproduce the procedure with MIMOSIS-1/2
  - ✓ Process, Epitaxial variants ?
  - ✓ Irradiations tests ?
  - ✓ R min ? Ring ?
  - ✓ Aging ?
  - ✓ Develop flex / mec. Support / Tools for bending
- Exploit MIMOSIS
  - ✓ Double sided telescope ?

FTE needs estimate

	2023				2024				2025				2026				2027			
TASK	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Integration																				
Integration (PICSEL)	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
microtechnics (C4PI)		0,2	0,2	0,2	0,2	0,2	0,2	0,2					0,2	0,2	0,2	0,2	0,2			
Simulations for e+ e- colliders																				
Physics Simulations (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
CMOS Simulation (PICSEL)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Simulation C4PI (TCAD, etc,)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

D. Gantt plan & resources

FTE per Project

FTE needs estimate

	2023				2024				2025				2026				2027			
TASK	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MIMOSIS Program																				
MIMOSIS Physicists (PICSEL)	1,5	1,5	1,5	2	1	1	1	1	1	2	2	2	1,5	1						
MIMOSIS microtechnics (C4PI)			0,3	0,3	0,3				0,5	0,5	0,5	0,5								
MIMOSIS-1 Tests (C4PI)	1	1																		
MIMOSIS-2 Fabrication	///////	//////																		
MIMOSIS-2 Tests (C4PI)			3	3	2	2	2	2	1											
MIMOSIS-3 Designs (C4PI)			0,5	0,5	0,5	0,5														
MIMOSIS-3 Fabrication							///////	//////												
MIMOSIS-3 Tests (C4PI)									1	1	1	1	1							
R &D for e+ e- colliders																				
65 nm / 180 nm R & D (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	2	2,5	2,5	2,5	3	3	3	3
CE65 tests (C4PI)	1	1	1	1	1	1														
Microtechnics (C4PI)									0,1	0,1					0,5	0,5	0,5			
ER_2 test structure design (C4PI)	1	1	1	1,5	1,5	1,5	1,5													
ER_2 fabrication								//////	///////											
MLR2 design (C4PI)								2	3	4	4	4								
MLR2 Fabrication												//////	///////							
beam telescope demonstrator													tests	tests						
beyond MLR2 design (C4PI)													4	4	4	4	4	4	4	4
beyond MLR2 fabrication ?																			///////	///////
R & D Test (C4PI)													1,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Integration																				
Integration (PICSEL)	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
microtechnics (C4PI)		0,2	0,2	0,2	0,2	0,2	0,2	0,2					0,2	0,2	0,2	0,2	0,2			
Simulations for e+ e- colliders																				
Physics Simulations (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
CMOS Simulation (PICSEL)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Simulation C4PI (TCAD, etc,)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
TOTAL Test (C4PI)	2	2	4	4	3	3	2	2	2	1	1	1	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
TOTAL Design (C4PI)	1	1	1,5	2	2	2	1,5	2	3	4	4	4	4	4	4	4	4	4	4	4
Total Microtechnics (C4PI)	0	0,2	0,5	0,5	0,5	0,2	0,2	0,2	0,6	0,6	0,5	0,5	0,2	0,2	0,7	0,7	0,7	0	0	0
TOTAL PICSEL	4,9	4,9	4,9	5,4	4,4	4,4	4,4	4,4	4,4	5,4	5,4	5,4	5,4	5,4	4,4	4,4	4,9	4,9	4,9	4,9

Local human resources

	FTE of the PICSEL team									
		2022	2023		2024		2025		2026	
		S2	S1	S2	S1	S2	S1	S2	S1	S2
Nom	fonction									
Baudot	Professor	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20
Besson	Associate Professor	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
El Bitar	Senior scientist	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Senyukov	scientist engineer	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Andrea	Senior scientist	0,05	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
Medernach	Computing engineer	0,50	0,50	0,50	0,20	0,20	0,20	0,20	0,20	0,20
Bugiel S.	post-doc	1,00	1,00	CERN						
Bugiel R.	post-doc	0.5	1,00	1,00						
ajit Kumar	post-doc AidaInnova (Belle-2-PICSEL)		0.5	0.5	0.5	0.5				
Ali Murteza	post-doc ANR		1,00	1,00	1,00	1,00				
X	post-doc CMS-FCC		0,00	0,00	1,00	1,00				
G.Sadowski	PhD Region-QMAT	1,00	1,00	1,00	1,00	1,00	1,00			
H. Darwish	co tutelle CBM	0,00	1,00	1,00	0,00					
Total FTE		5,25	8,30	7,30	6,00	6,00	4,00	3,00	3,00	3,00

Funding resources

- R & D supported mainly by the GRAM Master project.
  - ✓ Constant support from IN2P3 ⇨ support test equipment of C4PI
  - ✓ Supported MLR1/ER1 submissions
- MIMOSIS program
  - ✓ Submissions fully funded by CBM experiment
    - 3 engineering runs (M-1, M-2, M-3)
- Future contributions to funding for R&D
  - ✓ R&D will be driven inside the DRD framework
    - DRDs are not providing the funding
  - ✓ IN2P3 will define its priorities for the DRDs
    - contributors to CMOS R&D: IPHC-Strasbourg, CPPM-Marseille & emerging labs ⇨ IP2I-Lyon, APC-Paris
    - Starting discussions at the national level (head of IN2P3)
    - Target a national contribution for funding
  - ✓ Joined effort with international collaborators (CERN, DESY, Zurich, etc.)
- Project calls and external funding
  - ✓ Existing supports: Grand-Est region, QMAT, AIDAInnova, Eurizon, etc.
    - Prioritize manpower requests

Summary

- Despite uncertainties concerning the time line of the future e^+e^- collider
  - ✓ the physics case and the related R&D line is clearly defined

- With respect to the other projects, the timeline @IPHC is favorable
  - ✓ Safety margin for delays ?

- The strategy has to rely on mid-term projects and synergies
  - ✓ Keep the motivation
  - ✓ Maintain the know-how
  - ✓ Develop new skills
  - ✓ Allows new ideas, new concepts, technological breakthroughs.
- The main threat is clearly related to manpower
  - ✓ National and international network needed to find synergies
  - ✓ Focus on priorities:
    - Make the MIMOSIS program a success
    - Stay a key player in CMOS R&D
    - Physics studies

Questions from the experts

- The PICSEL team seems to have significant involvement in ALICE ITS3. This can provide the opportunity to profit from synergies between the projects. But there may also be a risk that this leads to lack of resources for the future e+e- collider developments by the PICSEL team, in case of delays / issues with the deliverables for ITS3. Is there enough contingency in the personnel resources, to accommodate possible delays / additional design iterations for the already approved / committed ALICE, Belle2 and CBM projects, without jeopardizing the start of these design activities in 2025? Is there any possibility to reinforce the PICSEL team by recruiting more PhD students? Are there plans to use MSc and PhD students for microtechnique integration?
  - ✓ Gap between senior scientists (occupied with management) > 45 years old and younger physicists
  - ✓ PhD students ⇨ management limit. Getting the funding is also a challenge
  - ✓ Permanent expertise in Detector R&D needed
- Can you elaborate on why the year 2025 is identified to be a “critical period” (section VI-D)?
  - ✓ Transition MIMOSIS – R&D program inside DRD3 ⇨ Tests FTE potential issue
  - ✓ Manpower in the team not consolidated yet (non permanent FTEs)
  - ✓ Rising needs in other projects
- What is the sharing of the 180 nm vs. 65 nm design experience within the C4Pi designer team? Are all current 180 nm designers in principle available to move towards 65 nm designs in the long term?
  - ✓ Question to C4PI ⇨ yes
- Simulations / detector optimization are discussed as activities (section VI-B.3). Should this include sensor design optimizations based on TCAD-simulations? This may be problematic, given the very restricted access to the TPSCo65 technology parameters.
  - ✓ TCAD expertise @ C4PI
  - ✓ Goals are towards detector response simulation for physics studies ⇨ Allpix2 and digitization model
  - ✓ Test beam data can help for an empiric approach (done in the past)
- How is the 65nm process and designs produced to be qualified for radiation hardness (FCChh)?
  - ✓ Not the goal of the team but interest from DEPHY MP
  - ✓ CE65 irradiation program ⇨ leakage current
- Beam telescopes could perhaps be added to the list of spin offs, given the leadership expertise of IPHC in this domain (e.g. Mimosa beam telescopes) and the fact that beam-telescope sensors are mentioned as an intermediate application for Higgs-factory sensor developments.
  - ✓ Agreed
  - ✓ MIMOSIS chips have also potential applications for telescopes.

Back up

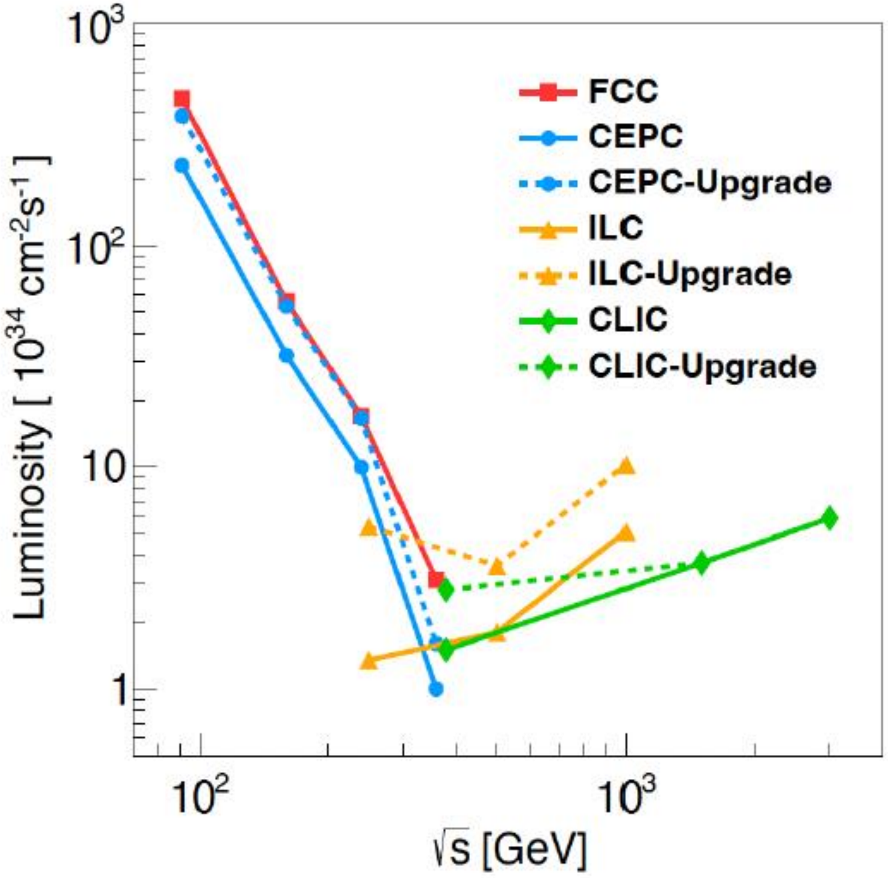
A. Future e^+e^- colliders
B. Software
C. Detector requirements
D. Detector performances
E. MIMOSIS program
F. 65 nm R&D; spin-off, bent sensors
G. Implementation of DRD3/DRD7
H. Submissions
I. Human resources
J. HCERES report & SWOT
K. History

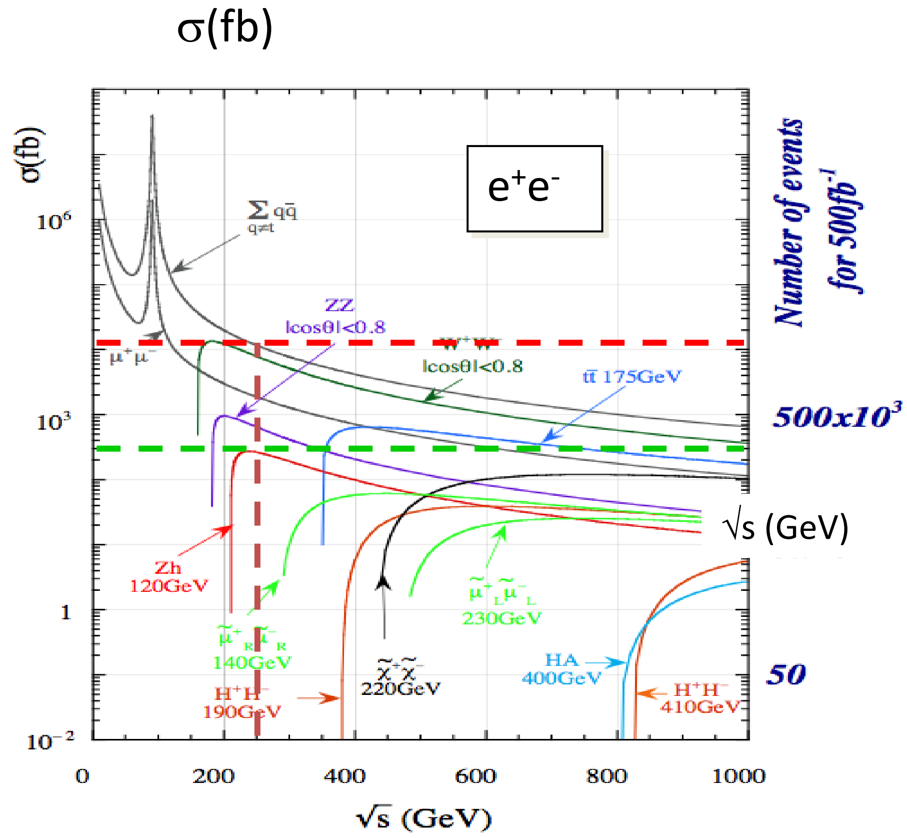
Questions to the scientific council

1. Evaluate the scientific and technical relevance of each of the proposed instrumental projects in the context of national and international collaborations, as well as in the framework of the In2p3 prospective and the European strategy for particle physics
2. Evaluate the degree of feasibility of each project with regard to current know-how, existing means and available resources, in particular human resources.
3. Evaluate the impact of these instrumental projects in maintaining and developing relevant technical skills for the future.
4. Assess the possible synergies and complementarities between the different projects.
5. Evaluate whether the commitment to this set of instrumental projects will leave sufficient room and flexibility for staff training, technological monitoring and the possibility of seizing future opportunities.

(A).Future e^+e^- colliders

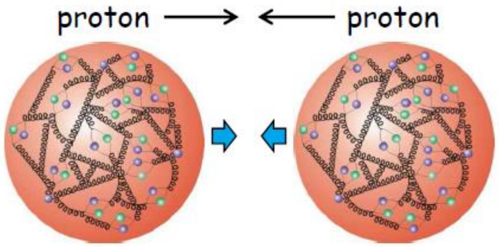
A. Luminosity & cross-sections



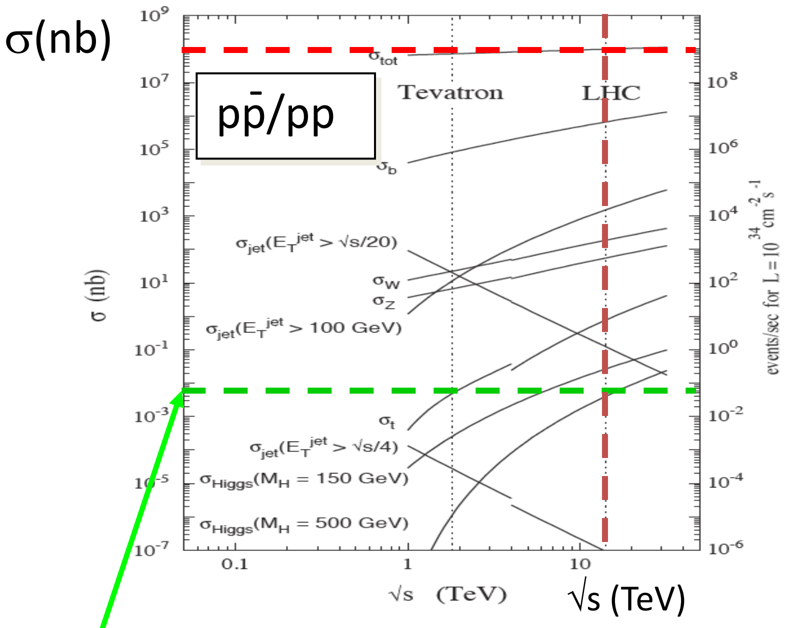


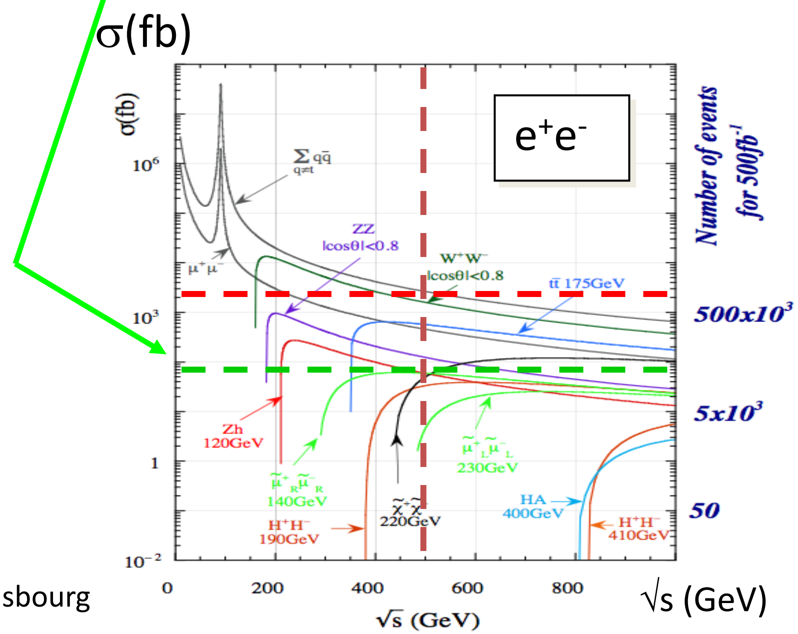
A. Key features of ILC for physics

- Key features of ILC (physics)
  - ✓ Clean environment



  - ✓ Precise theoretical predictions
  - ✓ Tunable √s
  - ✓ Beam polarization to enhance S/N
  - ✓ Democratic cross sections
    - Higgs production @ LHC: 1evt/10^{10}
    - Higgs production @ ILC: 1evt/10^{2}
    - Globally small (σ_{ZH} ~ 100 fb)
    - ⇨ Most measurements limited by statistics



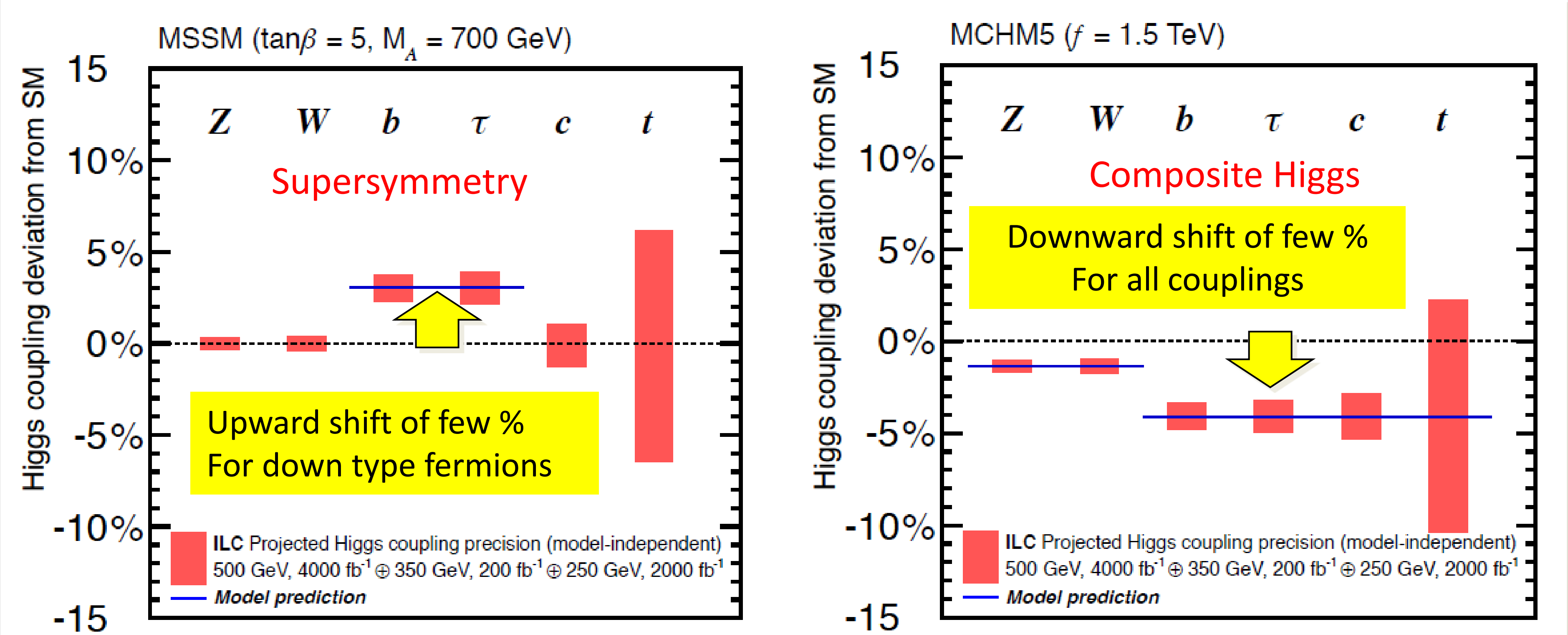


A. Higgs boson couplings shifts in BSM (examples)

- Is the % level on the coupling precision enough ?
  - ✓ Size of deviation depends on new physics scale

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

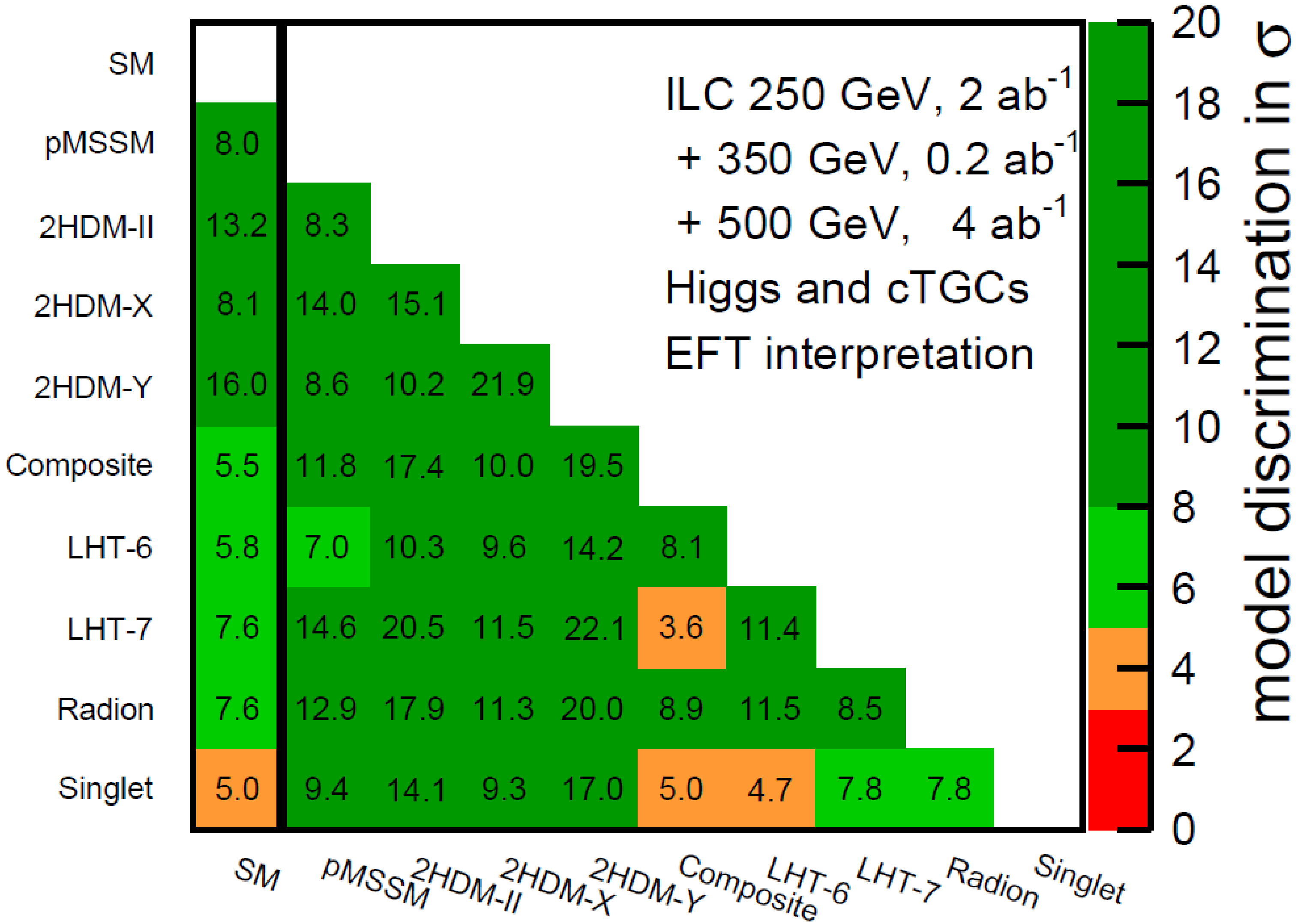
heavy Higgs mass



Physics Case for the International Linear Collider
K. Fuji et al. ILC-NOTE-2015-067

🟥 = 1 σ expected uncertainties from the full ILC data set (model-independent fit)

Model discrimination with ILC full data set



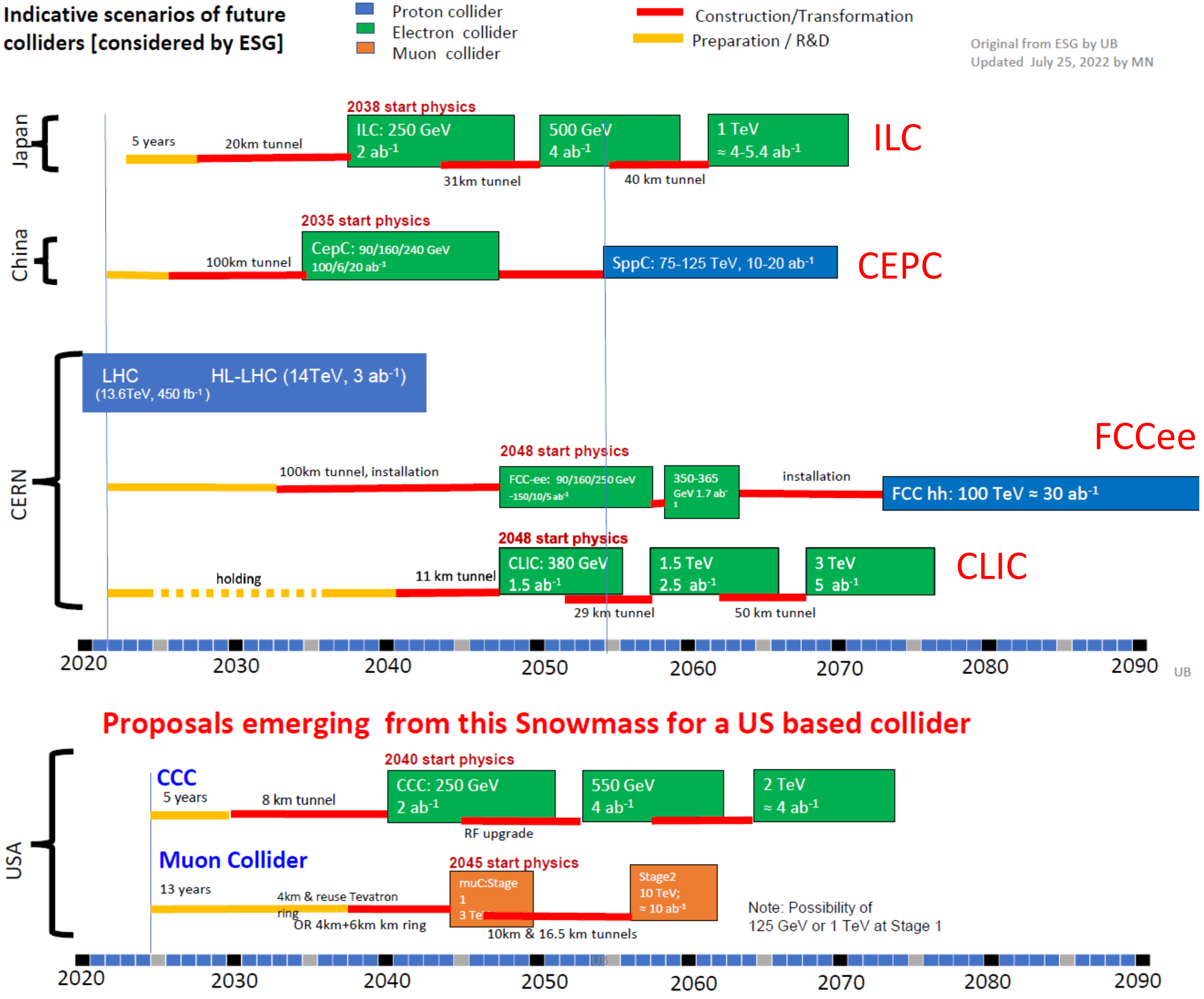
ILC 250 GeV, 2 ab^{-1}
+ 350 GeV, 0.2 ab^{-1}
+ 500 GeV, 4 ab^{-1}
Higgs and cTGCs
EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

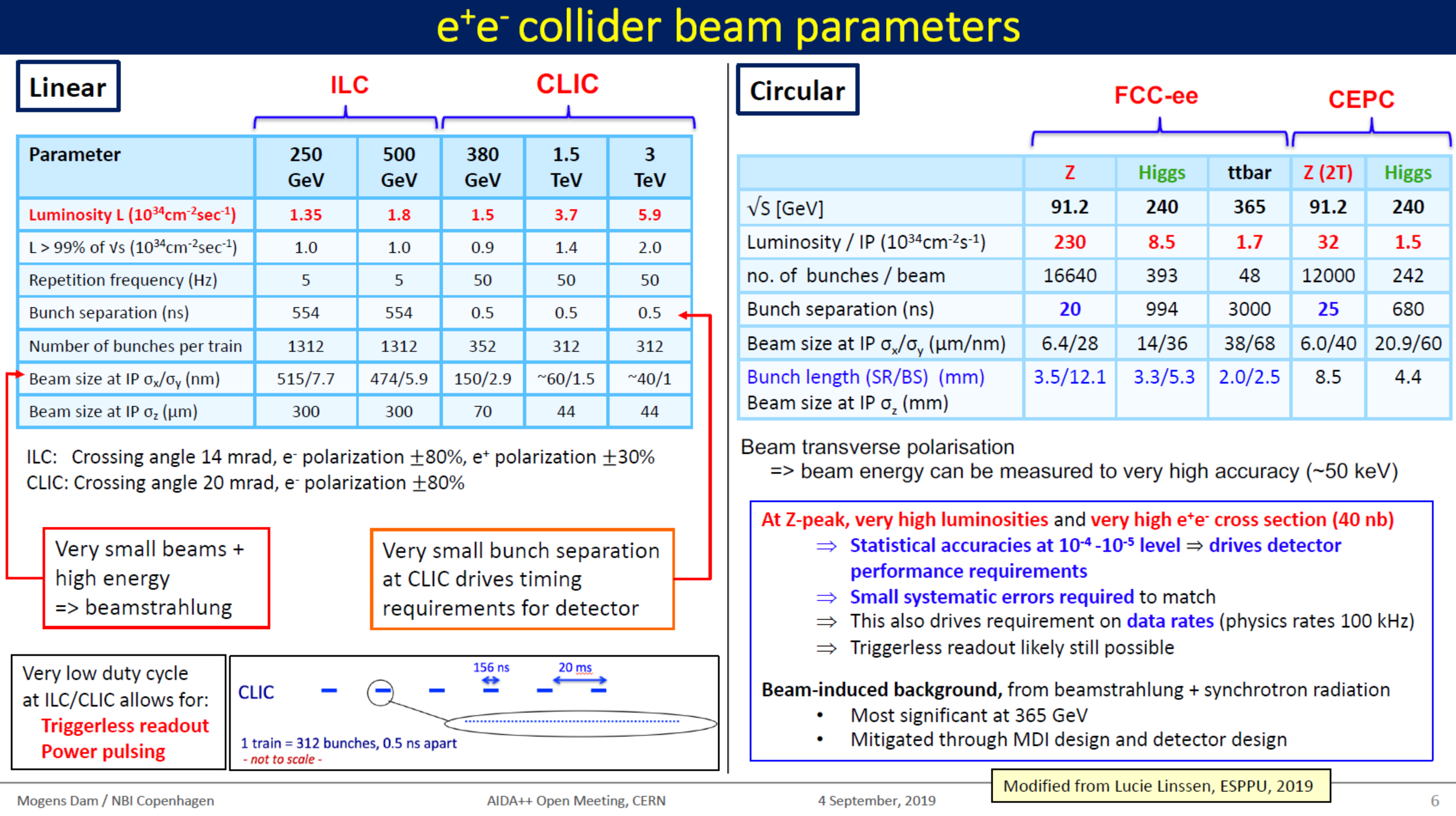
Graphical representation of the χ^2 separation of the Standard Model

A. Future e^+e^- colliders (« Higgs factories »)

Snowmass summary (summer 2022): https://snowmass21.org/energy/start



- Different levels of maturity for the different projects
  - ❑ ILC ready to go
  - ❑ FCCee/CEPC: feasability studies
- Hosting, International cost sharing, political decision ?
- Next Milestone: European Strategy Update for particle physics (~2026)
- Other proposals considered (e.g. new concepts, ILC hosted outside Japan, etc.)



e^+e^- collider beam parameters

Linear

Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity L (10^{34}cm^{-2}sec^{-1})	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
L > 99% of √s (10^{34}cm^{-2}sec^{-1})	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

ILC: Crossing angle 14 mrad, e^- polarization ±80%, e^+ polarization ±30%
CLIC: Crossing angle 20 mrad, e^- polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
Triggerless readout
Power pulsing

CLIC

156 ns

20 ms

1 train = 312 bunches, 0.5 ns apart
- not to scale -

Circular

	FCC-ee Z	FCC-ee Higgs	FCC-ee ttbar	CEPC Z (2T)	CEPC Higgs
√s [GeV]	**91.2**	**240**	**365**	**91.2**	**240**
Luminosity / IP (10^{34}cm^{-2}s^{-1})	**230**	**8.5**	**1.7**	**32**	**1.5**
no. of bunches / beam	16640	393	48	12000	242
Bunch separation (ns)	**20**	994	3000	**25**	680
Beam size at IP σ_x/σ_y (μm/nm)	6.4/28	14/36	38/68	6.0/40	20.9/60
Bunch length (SR/BS) (mm) Beam size at IP σ_z (mm)	3.5/12.1	3.3/5.3	2.0/2.5	8.5	4.4

Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV)

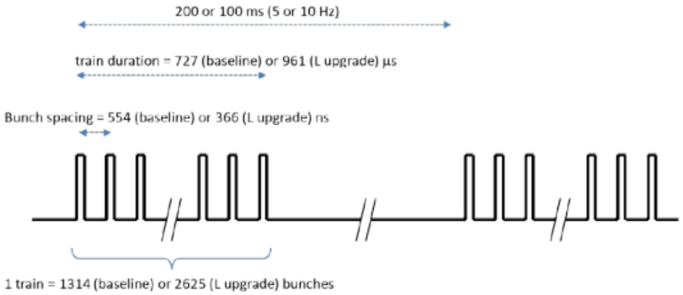
At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
⇒ **Statistical accuracies at 10^{-4} -10^{-5} level** ⇒ **drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
⇒ Triggerless readout likely still possible

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Mitigated through MDI design and detector design

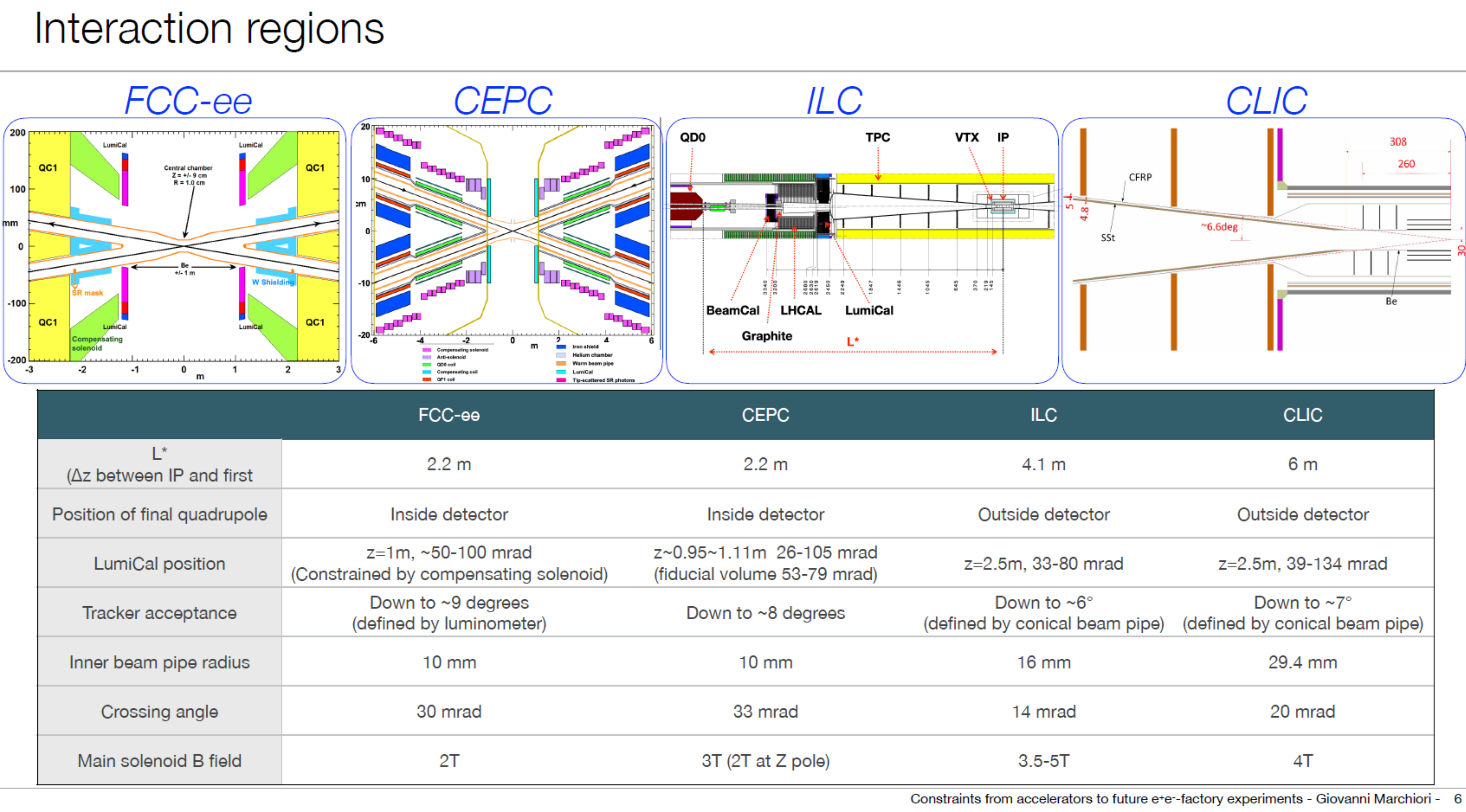
Mogens Dam / NBI Copenhagen AIDA++ Open Meeting, CERN 4 September, 2019 6

Modified from Lucie Linssen, ESPPU, 2019

(slide from Mogens Dam/Lucie Linssen)



A. Interaction region



Interaction regions

FCC-ee

CEPC

ILC

CLIC

	FCC-ee	CEPC	ILC	CLIC
L* (Δz between IP and first	2.2 m	2.2 m	4.1 m	6 m
Position of final quadrupole	Inside detector	Inside detector	Outside detector	Outside detector
LumiCal position	z=1m, ~50-100 mrad (Constrained by compensating solenoid)	z~0.95~1.11m 26-105 mrad (fiducial volume 53-79 mrad)	z=2.5m, 33-80 mrad	z=2.5m, 39-134 mrad
Tracker acceptance	Down to ~9 degrees (defined by luminometer)	Down to ~8 degrees	Down to ~6° (defined by conical beam pipe)	Down to ~7° (defined by conical beam pipe)
Inner beam pipe radius	10 mm	10 mm	16 mm	29.4 mm
Crossing angle	30 mrad	33 mrad	14 mrad	20 mrad
Main solenoid B field	2T	3T (2T at Z pole)	3.5-5T	4T

Constraints from accelerators to future e+e−-factory experiments - Giovanni Marchiori - 6

G. Marchiori, ECFA WG3: [Topical workshop on tracking and vertexing]

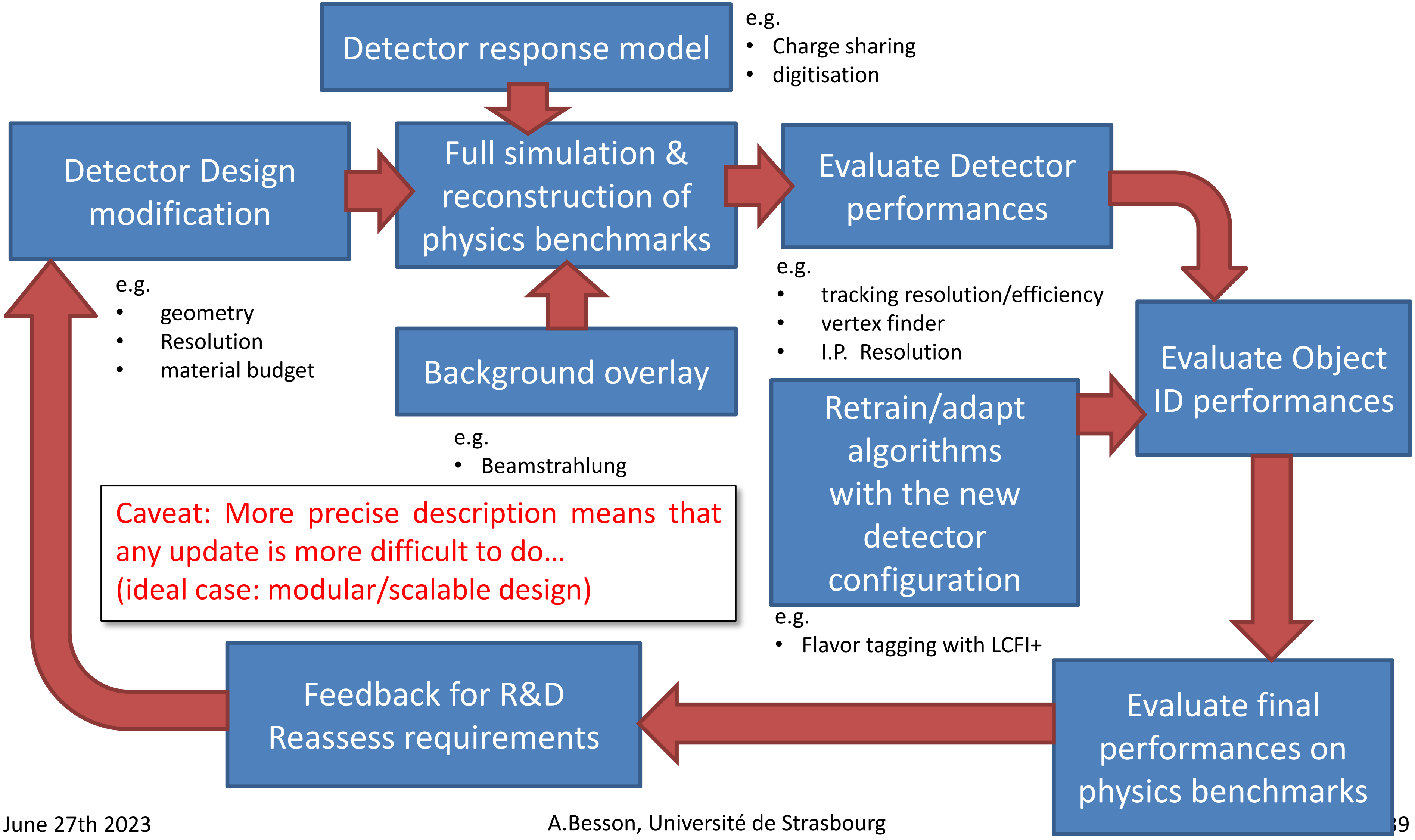
(B).Software

B. Motivations

- Master the full simulation chain (key4hep) for detector optimisation
- Master Tools for CMOS sensor characterization, charge transport and digitization studies, Analytical tools for detector optimization, etc.
  - ✓ Local tools (TAF, Guariguanchi)
  - ✓ Tools developed by the commmunity (Allpix2, corryvreckan)

B. Software challenge: optimization of the detector

- Example: Shall we target 18 or 22 μm pitch ?
- Caveat: One can not decouple detector optimization and algorithm optimization



Detector response model

e.g.
- Charge sharing
- digitisation

Detector Design modification

e.g.
- geometry
- Resolution
- material budget

Full simulation & reconstruction of physics benchmarks

Background overlay

e.g.
- Beamstrahlung

Evaluate Detector performances

e.g.
- tracking resolution/efficiency
- vertex finder
- I.P. Resolution

Retrain/adapt algorithms with the new detector configuration

e.g.
- Flavor tagging with LCFI+

Evaluate Object ID performances

Evaluate final performances on physics benchmarks

Feedback for R&D
Reassess requirements

Caveat: More precise description means that any update is more difficult to do…
(ideal case: modular/scalable design)

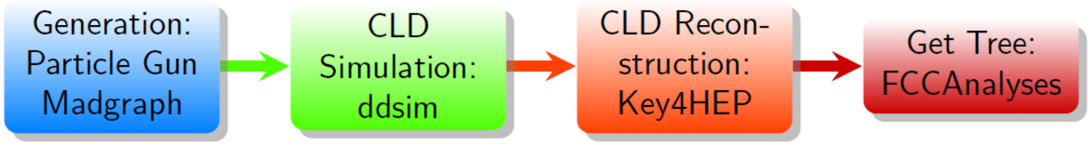
B. Higgs factories simulation studies

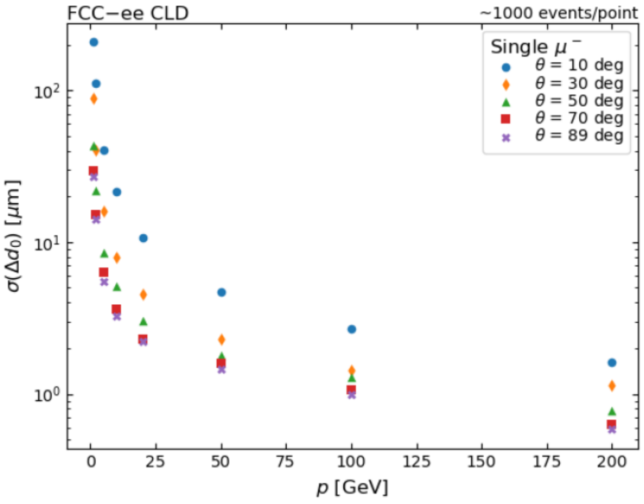
(PhD: G. Sadowski, El Bitar, Andrea, Besson)

Objectives:

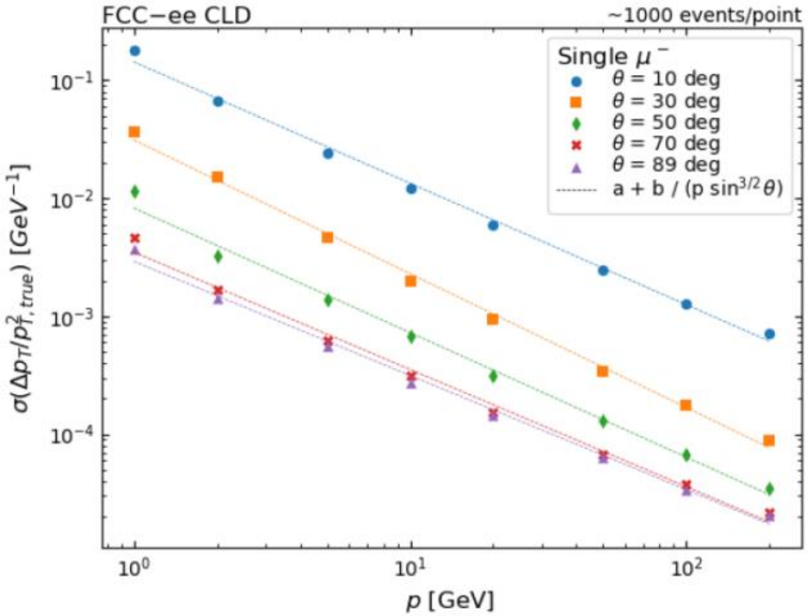
- Define different geometries and design options of Vertex Detector
- Candle for physics performance : increasing level of complexity (Tracking, Vertexing, flavour tagging, full analysis)
- Chosen approach: full simulation, for more precise results, use of CLD here. Starts with particle Reco and tracking
  - ▸ Determine Reco-MC matching
  - ▸ Implement estimations of performance plot : resolution, performances.

- What we have done:


Generation: Particle Gun Madgraph
CLD Simulation: ddsim
CLD Reconstruction: Key4HEP
Get Tree: FCCAnalyses



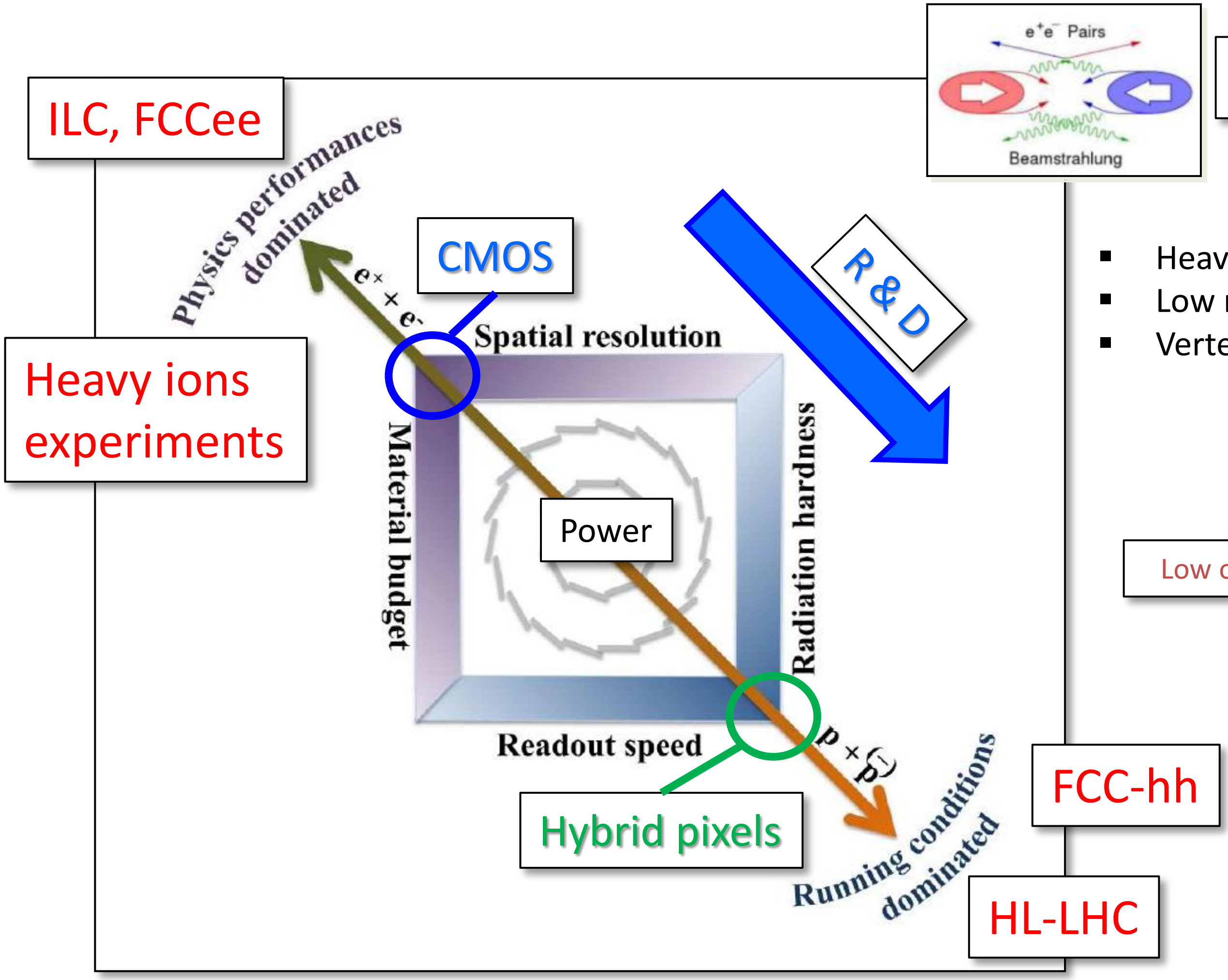
(a) d0



(C).Detector requirements

1. Spatial resolution
2. Machine related backgrounds
3. Time resolution
4. Material budget and integration
5. Power
6. ILC vs FCCee

C. Vertex detector technology figure of merit



ILC, FCCee

Heavy ions experiments

CMOS

Power

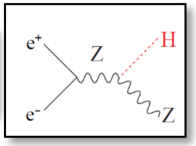
R & D

Hybrid pixels

FCC-hh

HL-LHC

e^+e^- requirements



- Heavy flavor tagging (b, c, τ)
- Low momentum tracking (pT ~ 100 MeV/c)
- Vertex/Jet charge determination

Spatial resolution
σ_{sp} ~3 μm (pitch ~ 17 μm)

Low occupancy

Material Budget
~ 0.15% X_0 / layer

Impact parameter

$$\sigma_b < 5 \oplus \frac{10}{p\beta \sin^{\frac{3}{2}}\theta}\ \mu m$$

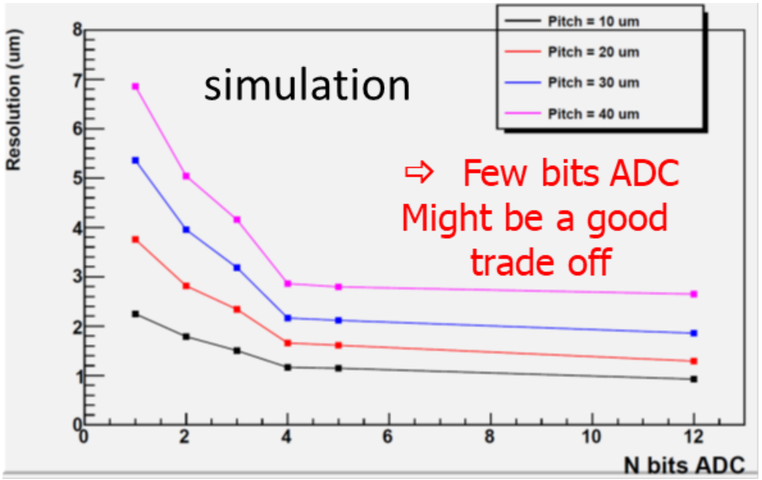
Time resolution
O(1-4 μs)

Challenge:

⇨Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution (BX)

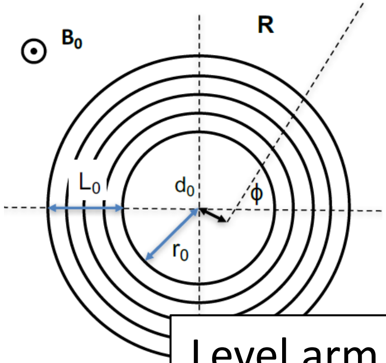
C1. Spatial resolution in Higgs factories

- Typical targets:
  - ✓ σ_{sp}~3 µm for the vertex layers
  - ✓ σ_{sp}~5-10 µm for the outer tracker layers
- Resolution in each layer depends on
  - ✓ Pitch
    - In conflict with the functionnalities inside the pixel
    - Favored by small feature size technology
  - ✓ Charge deposition
    - Sensitive layer thickness
  - ✓ Charge sharing (SNR vs resolution)
    - Depletion:
    - Staggered pixels
  - ✓ Charge encoding
    - Binary output / ADC / Tot / etc.



⇨ Few bits ADC Might be a good trade off

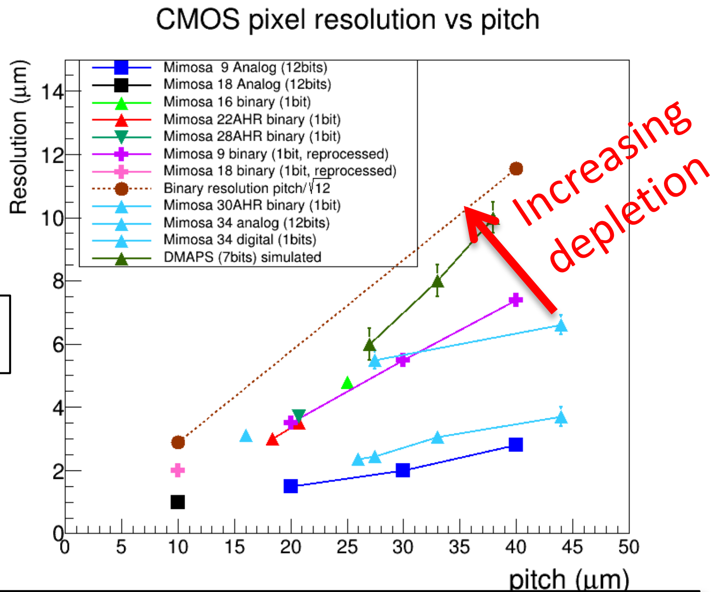
$$\boxed{{\sigma_{d0}}^2 = a^2 + \left(\frac{b}{p.\,sin^{3/2}\theta}\right)^2}$$



Level arm !

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$



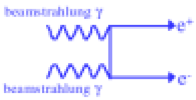
Increasing depletion

⇨ σ_{sp} ~ 3 µm ⇦⇨ pitch ~ 15-20 µm

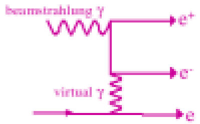
(assuming binary output, ~20 µm epi.thickness & large depletion in 180nm tech.)

C2. Understand beam related backgrounds

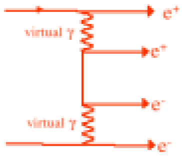
Breit-Wheeler



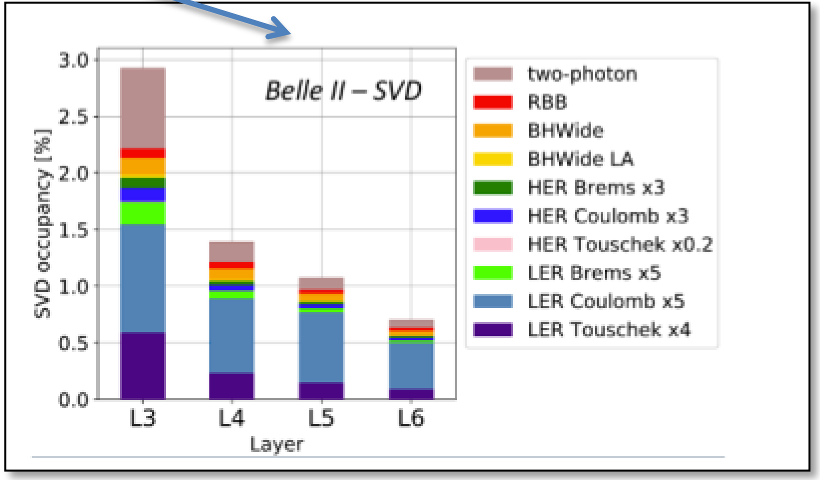
Bethe-Heitler



Landau-Lifshitz



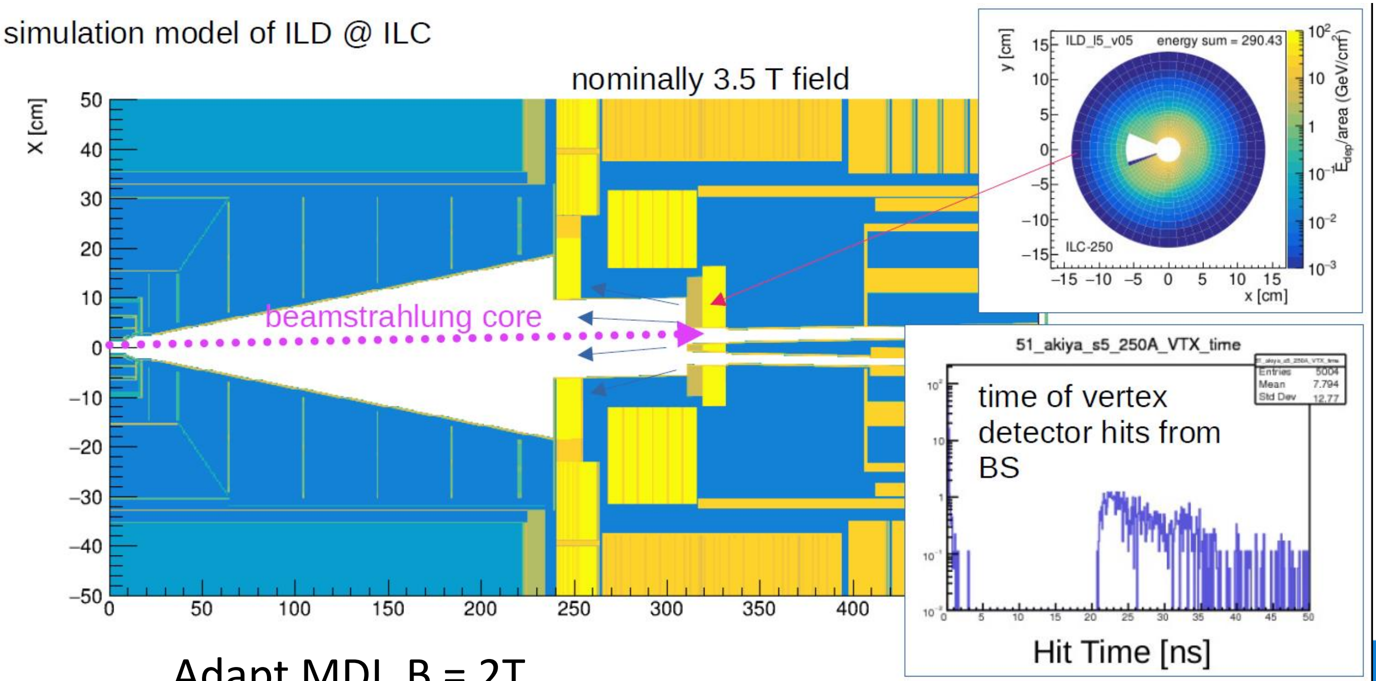
- Sources:
  - ✓ Incoherent pairs (« beamstrahlung »)
  - ✓ Synchrotron
  - ✓ Beam loss (circular machines)
  - ✓ Radiative bhabha
  - ✓ Beam gas, etc.
- Usually one considers that occupancy ~< 10^{-2}-10^{-3} is safe for tracking/vertexing purposes
- Experience from ILC studies over 20 years
  - ✓ Any modification in the Interaction region (beam scheme, beam pipe design, B field) might bring surprises
  - ✓ One should not consider that a 10^{-4} occupancy estimation means that there is no issue.
    - The robustness is questionnable
    - Large possible variations in some acceptance corners (asymmetries in φ or z)
    - Safety factor absolutely mandatory
    - 2 independant simulation tools would be welcome (GuineaPig, Fluka, etc.)
- Experience from Belle-2
  - ✓ Discrepancies observed between simulations and first collisions
- Direct beam background vs backscattered background
  - ✓ Generally the backscattered ones are more sensitive to any MDI change.
- What about timing information to reject background ?
  - ✓ Need ~ 5 ns to reject backscattered particles
  - ✓ Is it worth paying the price in terms of additionnal power ?
- What about cluster shape to reject background ?
  - ✓ Need very good sensitive thickness/pitch ratio (> 2).
  - ✓ Charge information helps.
  - ✓ (you actually reject very low pT particles)

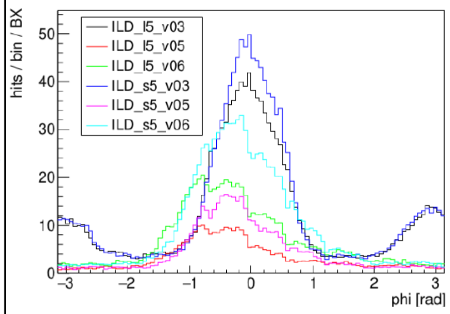


C2. Example of background study: ILD, from linear to circular

simulation model of ILD @ ILC

D. Jeans LCWS2023



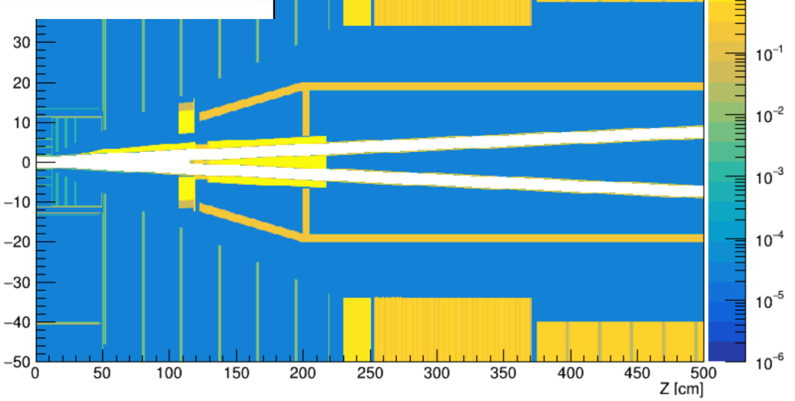


Adapt MDI, B = 2T,

Sensitive to precise B-field map

Adapt Beam structure

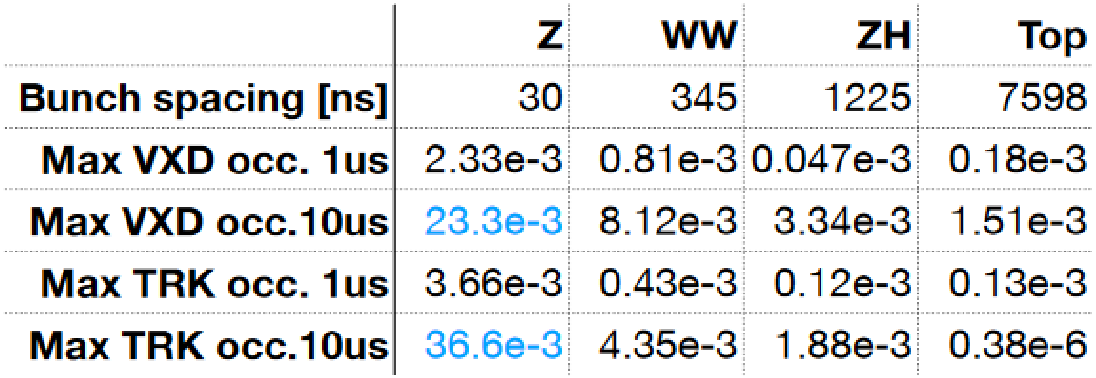
Effect in TPC also being studied



at FCCee,
quasi-continuous ion cloud from ~14M bunch crossings

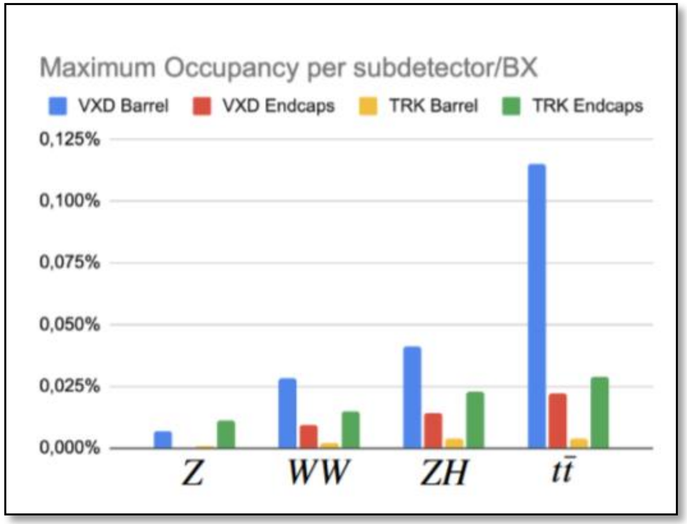
- at FCCee, MDI extends to ~1m from IP
  → 6 times more beamstrahlung background hits in TPC

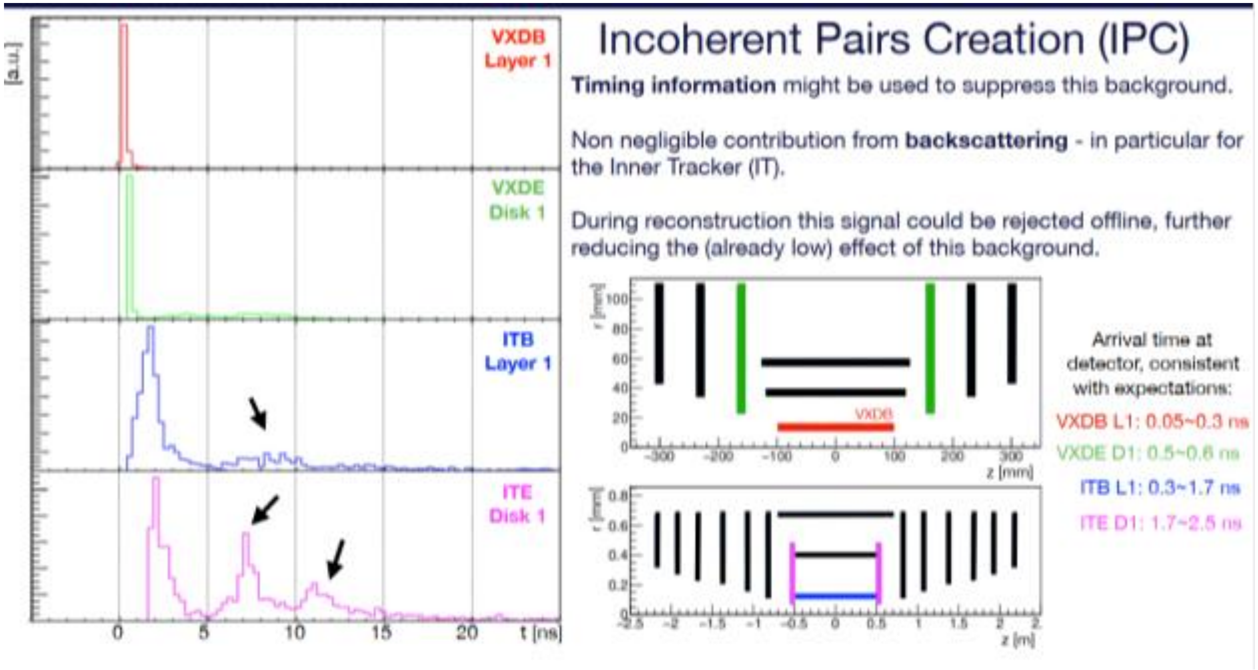
C2.Example of study in CLD



	Z	WW	ZH	Top
Bunch spacing [ns]	30	345	1225	7598
Max VXD occ. 1us	2.33e-3	0.81e-3	0.047e-3	0.18e-3
Max VXD occ.10us	23.3e-3	8.12e-3	3.34e-3	1.51e-3
Max TRK occ. 1us	3.66e-3	0.43e-3	0.12e-3	0.13e-3
Max TRK occ.10us	36.6e-3	4.35e-3	1.88e-3	0.38e-6

US FCC workshop 25/04/2023 Ciarma





Incoherent Pairs Creation (IPC)

Timing information might be used to suppress this background.

Non negligible contribution from **backscattering** - in particular for the Inner Tracker (IT).

During reconstruction this signal could be rejected offline, further reducing the (already low) effect of this background.

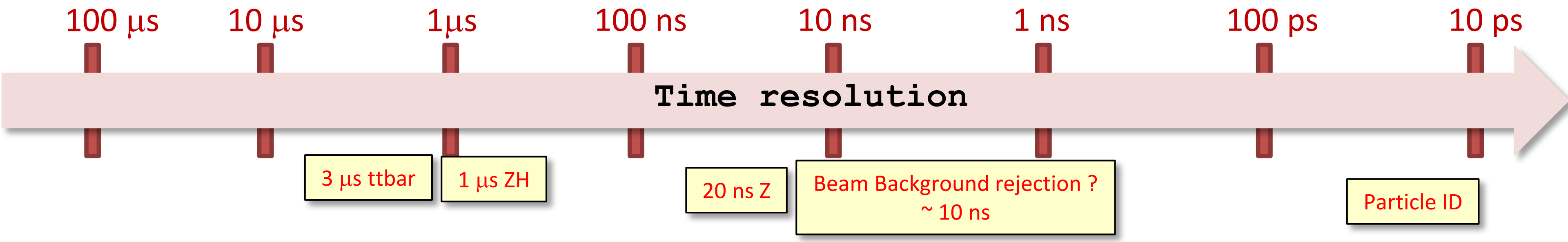
Arrival time at detector, consistent with expectations:

VXDB L1: 0.05~0.3 ns
VXDE D1: 0.5~0.6 ns
ITB L1: 0.3~1.7 ns
ITE D1: 1.7~2.5 ns

BX rate might be an issue at the Z-pole

Timing resolution range to reject background ~ 1 ns

C3.Timing & 4-D tracking



100 µs 10 µs 1µs 100 ns 10 ns 1 ns 100 ps 10 ps

Time resolution

3 µs ttbar

1 µs ZH

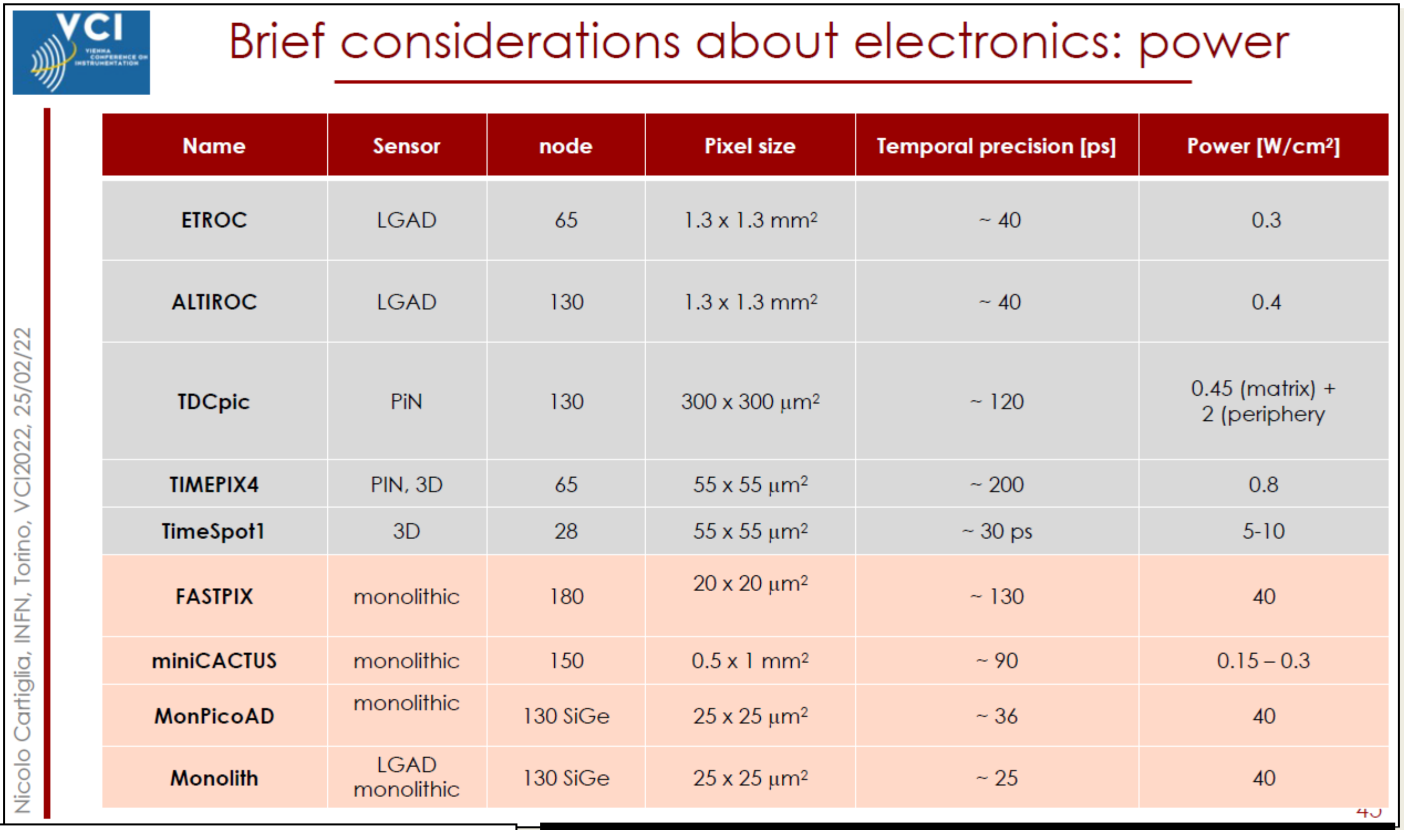
20 ns Z

Beam Background rejection ?
~ 10 ns

Particle ID

- Time resolution Δt
  - ✓ Bunch separation (3 µs / 1 µs / 20 ns @ FCCee)
  - ✓ Background rejection ? (1-10 ns range)
  - ✓ Particle ID (10-100 ps)
- Usual drawbacks to go faster
  - ✓ Power consumption
  - ✓ Active Cooling & geometrical acceptance due to services
  - ✓ In pixel circuitry ⇨ larger pixels (or multipixels)
  - ✓ Fill factor, dead time
  - ✓ PID Restricted to low momentum particles (~< few GeV/c)
- Still
  - ✓ Forward region not covered by a central gazeous detector
  - ✓ Added value for intermediate radii (e.g. LLPs ?)

C3. Power vs fast timing vs pixel size

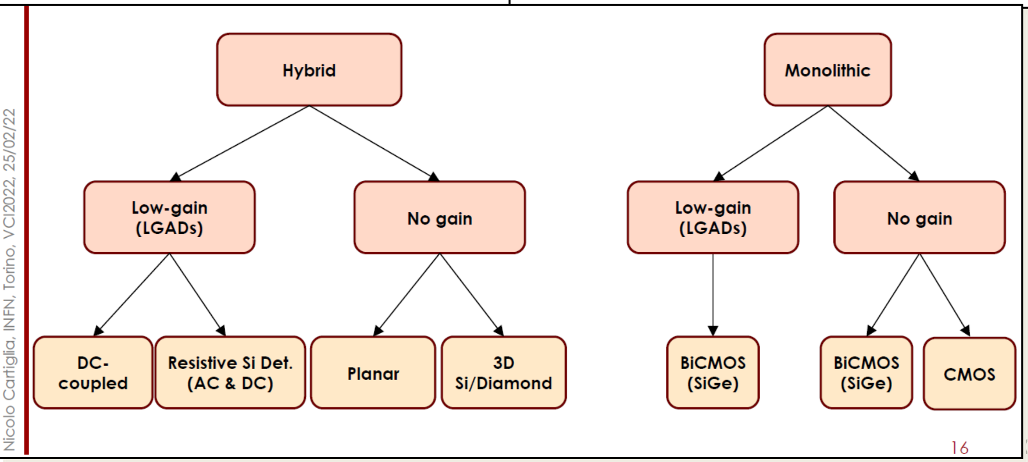


Brief considerations about electronics: power

Name	Sensor	node	Pixel size	Temporal precision [ps]	Power [W/cm²]
ETROC	LGAD	65	1.3 x 1.3 mm²	~ 40	0.3
ALTIROC	LGAD	130	1.3 x 1.3 mm²	~ 40	0.4
TDCpic	PiN	130	300 x 300 μm²	~ 120	0.45 (matrix) + 2 (periphery
TIMEPIX4	PIN, 3D	65	55 x 55 μm²	~ 200	0.8
TimeSpot1	3D	28	55 x 55 μm²	~ 30 ps	5-10
FASTPIX	monolithic	180	20 x 20 μm²	~ 130	40
miniCACTUS	monolithic	150	0.5 x 1 mm²	~ 90	0.15 – 0.3
MonPicoAD	monolithic	130 SiGe	25 x 25 μm²	~ 36	40
Monolith	LGAD monolithic	130 SiGe	25 x 25 μm²	~ 25	40

Nicolo Cartiglia, INFN, Torino, VCI2022, 25/02/22

Nicolo Cartiglia, INFN, Torino, VCI2022, 25/02/22



Hybrid

Low-gain (LGADs)

DC-coupled

Resistive Si Det. (AC & DC)

No gain

Planar

3D Si/Diamond

Monolithic

Low-gain (LGADs)

BiCMOS (SiGe)

No gain

BiCMOS (SiGe)

CMOS

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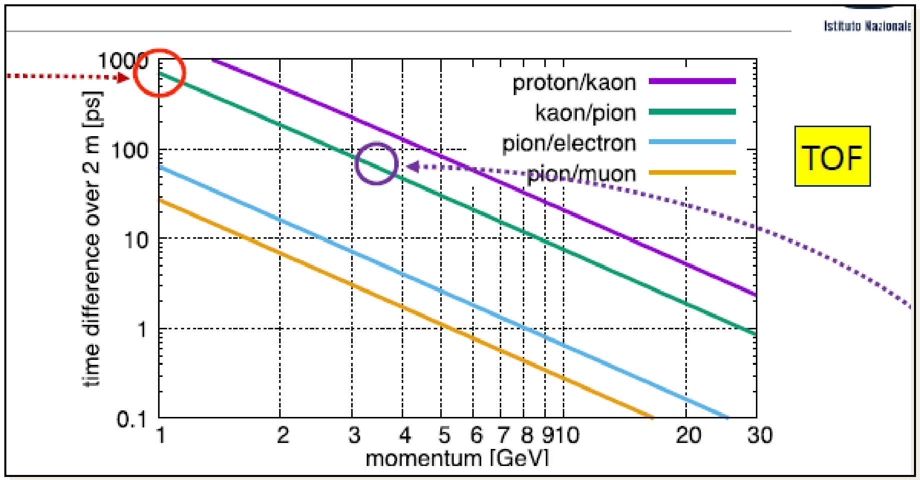
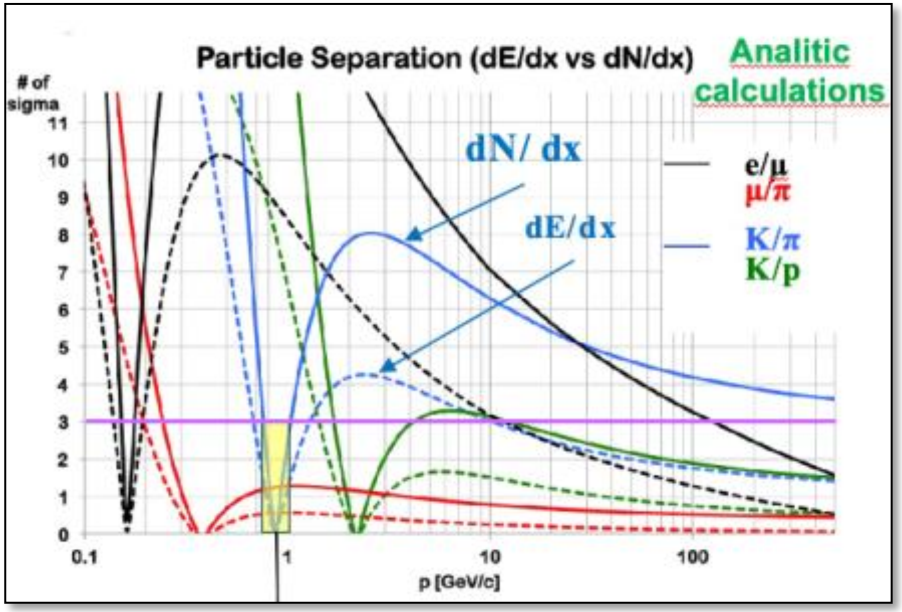
16

Price to pay: additionnal cooling system (addtionnal material)

C3. Fast timing

- Extremely active domain
  - ✓ Interest to push beyond 10 ps resolution
- PID not discussed here (covered by TF4)
  - ✓ dE/dX ; dN_{cl}/dx and timing for PID
  - ✓ Fast timing not proper to silicon (also scintillation, gazeous, Cerenkov)

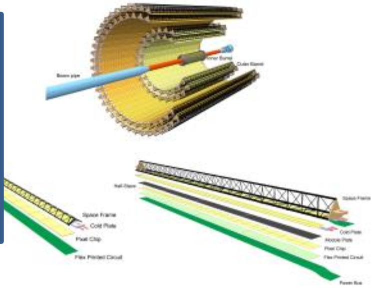




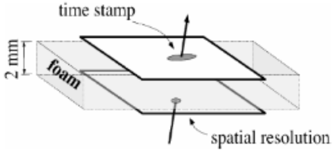
- Specialized layers
  - ✓ Doesn’t compromise the other requirements (material budget and granularity)
    - Probably not in the most inner layers
  - ✓ Dedicated studies needed for design optimization

C4. Material budget: starting from the layers

Classical single sided layers (e.g. ALICE ITS-2)



Double sided layers



PLUME

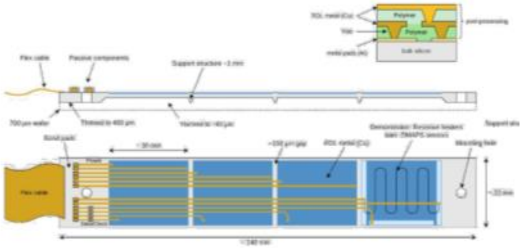
(Bristol, DESY, IPHC)

Double sided ladders with minimized material budget 0.35% X_0 reached ⇨ ~0.3 X_0 doable (with air flow cooling)

Self supported silicon (Belle-2 upgrade)

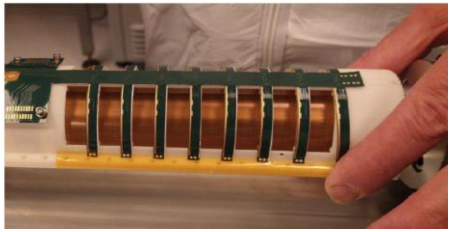
I. Peric

7.1x1.5 cm²
Thickness (edge/center) 430/90 µm
Planarity ~17 µm



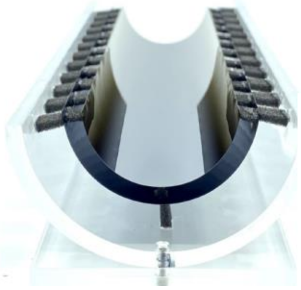
Pseudo stitching + bent sensors (superALPIDE)

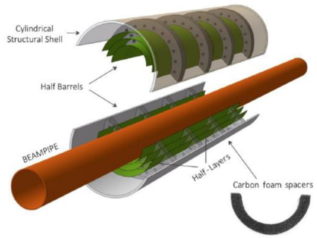
- 1 silicon piece cut from one ALPIDE wafer (9x2 dies, ~1/2 of layer 0)



Stitching + bent sensors ALICE-ITS3

Layers 2+1





Inputs for engineering studies

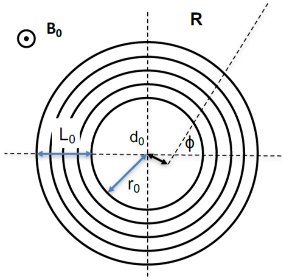
C4.Material budget in Higgs factories

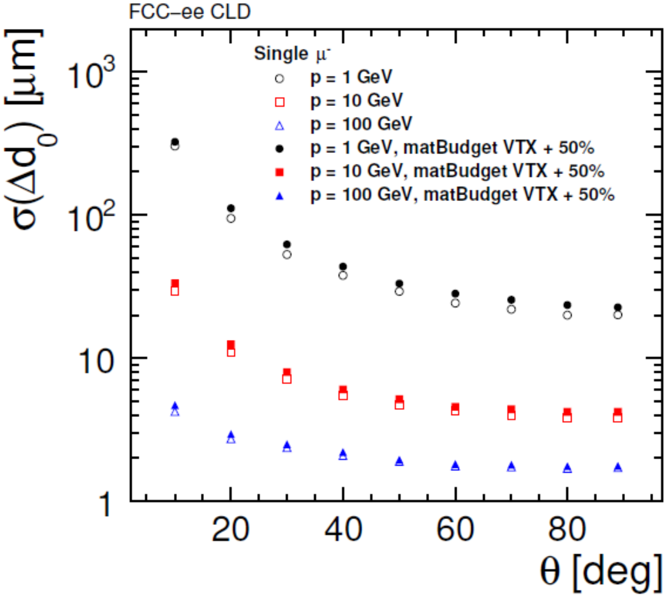
$$\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\sin^{3/2}\theta}\right)^2$$

- Driving parameter
  - ✓ Inner radius

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin\theta}} \sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

  - ✓ Beam pipe
    - Constant term ~ 0.15-0.3 % X_0
  - ✓ Material budget / layer
    - Requirement ~ ~0.15% X_0 /layer



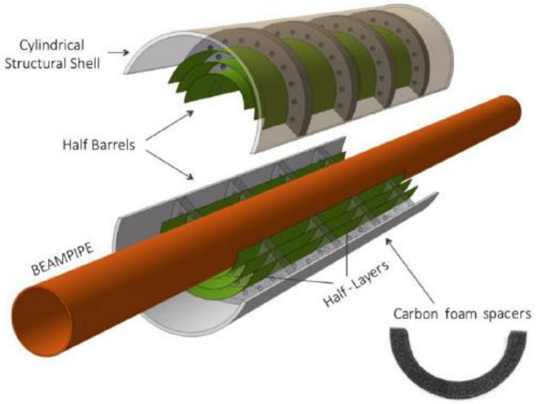


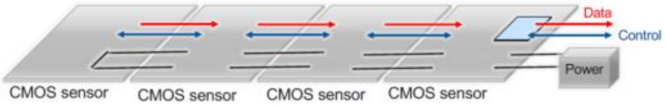
(a) d_0 resolution

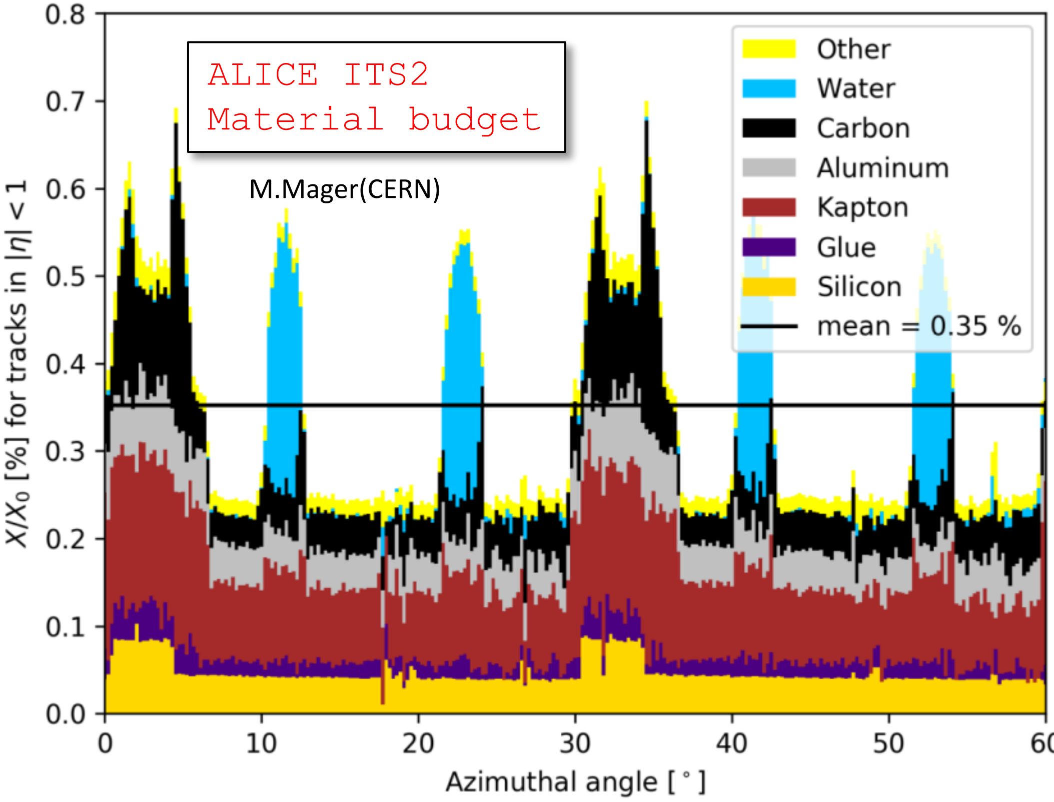
Sensitivity to impact parameter resolution

- Material budget optimization
  - ✓ Double sided approach
    - PLUME prototypes
  - ✓ Stitching (see later)
    - Larger surfaces (fill factor ?)
  - ✓ Bent sensors
    - Optimize inner layers
  - ✓ Integration
    - Cooling system, mech. Support, cabling, Powering scheme, etc.

C4. From ITS-3 to stitched and bent sensors for e^+e^- colliders

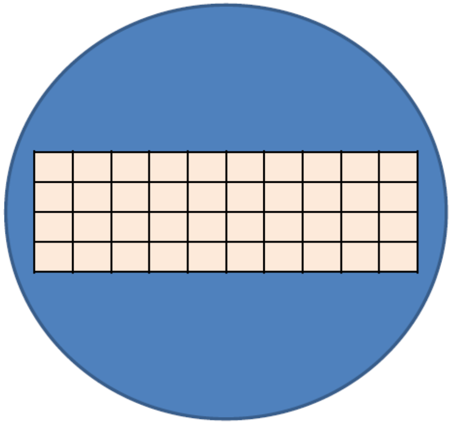




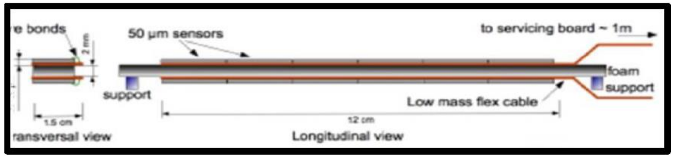


https://indico.cern.ch/event/1071914/

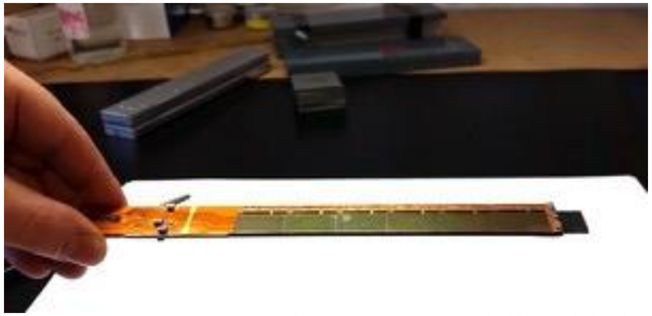
- ALICE-ITS3/CERN drives the R&D on Stitching + bent sensors:
  - ✓ Sensor part ~15% of total material budget
  - ✓ Sensors thinned down to 50 µm
  - ✓ Minimizing overlapping regions, minimizing minimal radius around the beam pipe
- Challenges and caveats (for e^+e^- colliders)
  - ✓ Mechanics ? Bonding ? Air cooling only ?
  - ✓ Design: Minimizing peripheral circuits (Fill factor ~90%)
  - ✓ Bent sensor performances ? Yield
  - ⇨ design rules constraints the minimal pitch (~22 µm)
  - ✓ ITS-3 do not have disk (chip periphery adds Z position constraint)
  - ✓ Approach validated in a limited radius range (R> 18mm)

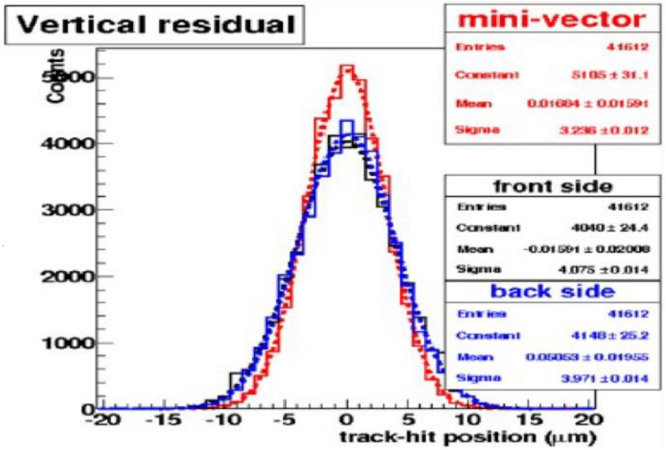


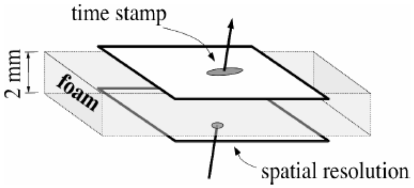
Integration
(example of PLUME collaboration)

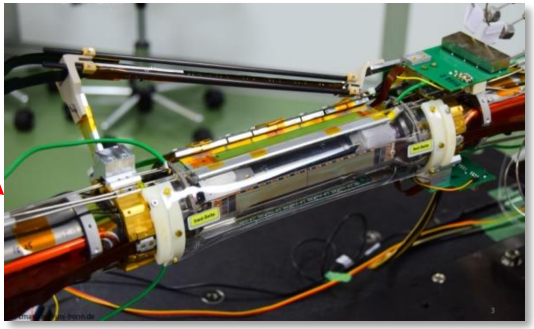


- Plume collaboration (Bristol, DESY, IPHC)
  - ✓ Double sided ladders with minimized material budget
- Plume-02 prototypes
  - ✓ Successfully validated in test beam
  - ✓ Cu/Al flex cable (0.42/0.35 % X_0)
  - ✓ 6 ladders fabricated
    - 2 installed in BEAST for Belle-2 commissioning
- Summary
  - ✓ No major issue
  - ✓ 0.3 % X_0 reachable
  - ✓ Possible next step:
    - ≠ chips on each side
    - Replace carbon foam by carbon fiber



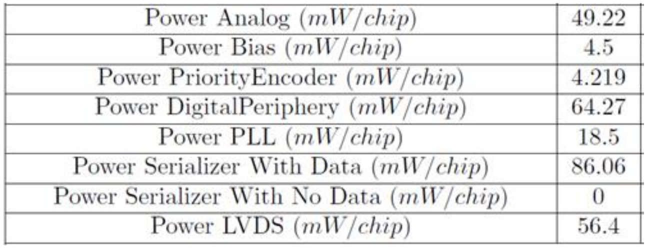






Know-how acquired ⇨ Ladders close to ILC mat. budget specifications

C5. Power challenges

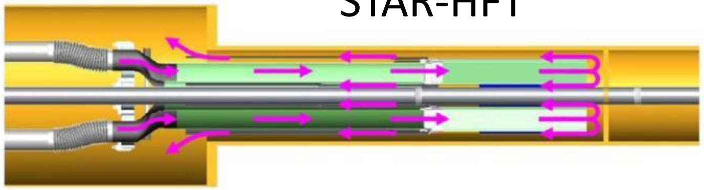


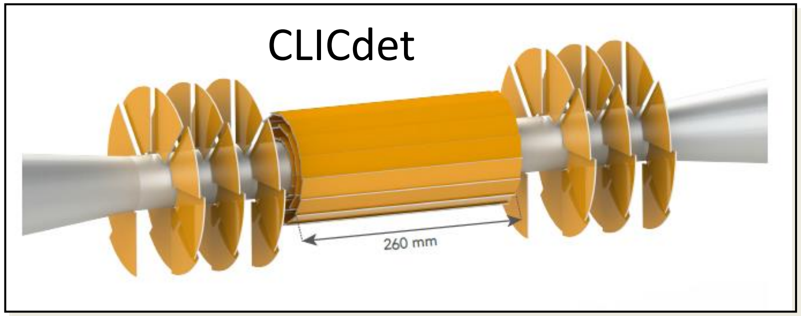
Power Analog $(mW/chip)$	49.22
Power Bias $(mW/chip)$	4.5
Power PriorityEncoder $(mW/chip)$	4.219
Power DigitalPeriphery $(mW/chip)$	64.27
Power PLL $(mW/chip)$	18.5
Power Serializer With Data $(mW/chip)$	86.06
Power Serializer With No Data $(mW/chip)$	0
Power LVDS $(mW/chip)$	56.4

MIMOSIS like architecture, 180 nm

- Power is in conflict with all other parameters
- Baseline:
  - ✓ Air flow cooling only to minimize material budget
  - ✓ Up to ~ 20 mW/cm^2
    - what is the limit ? ~50 mW/cm^2 or even more ?
- Driving parameters:
  - ✓ # channels, Time resolution / data flux
  - ✓ Surface (VXD ~ 3500 cm^2 ; tracker O(10 m^2)
  - ✓ Power Pulsing (ILC/CLIC) ⇨ Constraints more relaxed w.r.t. FCCee
- The « Power paradox »
  - ✓ Small radius ⇨ Higher hit density and Power/cm^2 but small fraction of total power
  - ✓ Higher radius ⇨ less hit density but higher total power/layer
- Power sharing
  - ✓ Analog part: O(25-50%) ⇨ density of pixels, charge collection speed
  - ✓ Digital part: O(25-50%) ⇨ data flux, freq.
  - ✓ Output→DAQ: maximum flux. (25%)
- Architecture optimization is important
  - ✓ Priority encoder (limited by flux)
  - ✓ Asynchronous might be adapted (tot, etc.)
  - ✓ Etc.
- Technology feature size
  - ✓ e.g. 180nm to 65 nm: ~50% Power reduction
- Air extraction:
  - ✓ In conflict with disks and forward acceptance
    - (≠ALICE ITS2/3, Belle-2, STAR-HFT)

STAR-HFT

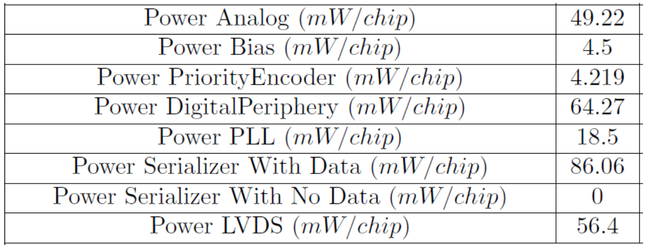




CLICdet

C5. Power & cooling in Higgs Factories

- Baseline:
  - ✓ air flow cooling only to minimize material budget
  - ✓ Up to ~ 20 mW/cm^2
- Driving parameters:
  - ✓ # channels, Time resolution / data flux
  - ✓ Surface (VXD ~ 3500 cm^2)
- Power Pulsing (ILC/CLIC)
  - ✓ Constraints more relaxed w.r.t. FCCee



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Power PLL ($mW/chip$)	18.5
Power Serializer With Data ($mW/chip$)	86.06
Power Serializer With No Data ($mW/chip$)	0
Power LVDS ($mW/chip$)	56.4

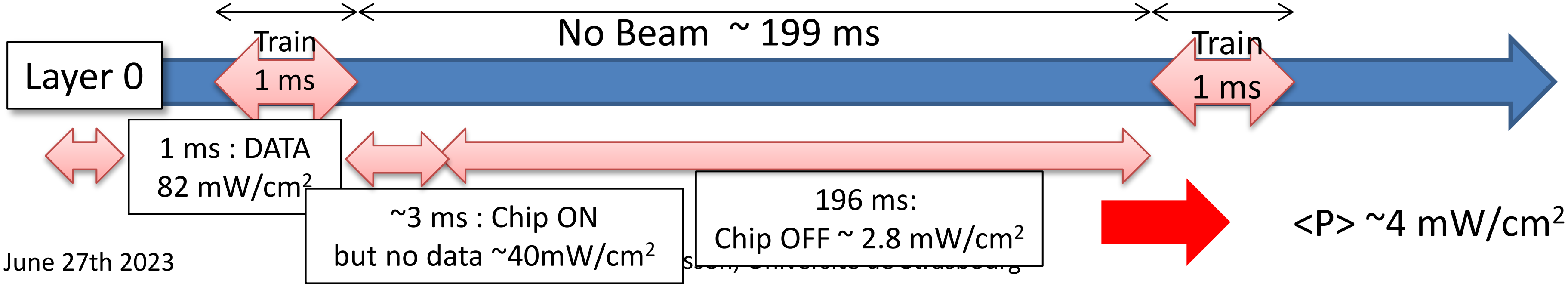
MIMOSIS like architecture, 180 nm

Period	Relative Energy
E during train	225 mJ ~ 4 %
E between train (Power ON)	380 mJ ~ 6 %
E between train (Power OFF)	5740 mJ ~ 90 %

Beam background rate	Read-out speed	<Power (NO P.P.)	<Power> (P.P.)	
	(μs)	(W)	Conservative	Ambitious
DBD	4 μs	102 W (~30mW/cm^2)	~31 W (~10 mW/cm^2)	~12 W
DBD	2 μs	122 W (~33mW/cm^2)		
DBD x 2	4 μs	107 W		
DBD x 2	2 μs	127 W		

Layers	Relative Power
Layers 0/1	~ 10 %
Layers 2/3	~ 35%
Layers 4/5	~ 55 %

Challenge: Air flow cooling only



Layer 0

Train 1 ms

No Beam ~ 199 ms

Train 1 ms

1 ms : DATA 82 mW/cm^2

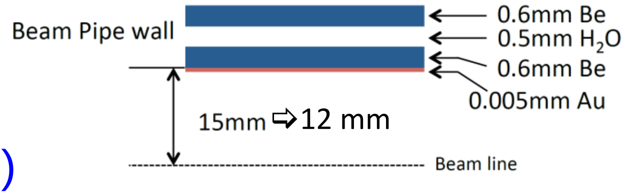
~3 ms : Chip ON but no data ~40mW/cm^2

196 ms: Chip OFF ~ 2.8 mW/cm^2

<P> ~4 mW/cm^2

C6. Being generic: ILC & FCCee differences

- Beam structure: « continuous » vs trains
  - ✓ Power Pulsing: allows a factor O(10) reduction in average power
  - ✓ ILC: However, avoiding PP is desirable (alignment)
- Beam pipe shape and material
  - ✓ ILC: ~0.14% X_0 for the beam pipe (500 μm)
  - ✓ FCCee: Sync. Radiations ⇨ Cooling of the beam pipe ⇨ higher Mat.Budget
  - ⇨ 800 (2 pipes) + 400 (water) ~ 0.34% X_0
  - ⇨ + 5 μm Au = 0.15% X_0
  - ⇨ Smaller inner radius @ FCCee (12 mm)



- MDI:
  - ✓ CLD: Forward acceptance limited to 150 mradian (8.6°)
  - ✓ ILD: Froward acceptance (disks) ~ 5°
- TeraZ vs Giga Z
  - ✓ Specific timing and impact parameter resolution ?
    - e.g. lower radius ?
- Magnetic field:
  - ✓ ILC: 3.5/4 T (R_{max} ~1.8m)
  - ✓ CLIC: R_{max}(CLIC): 1.5m
  - ✓ FCC: 2 T max ⇨ compensate by larger level arm (R_{max} ~ 2.15m)

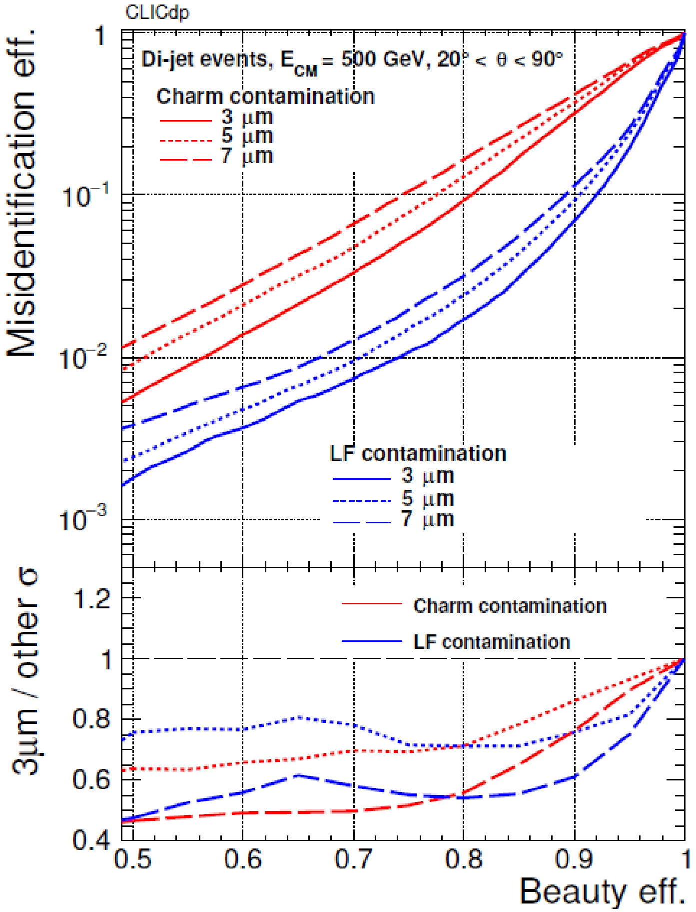
⇨ Overall most of the R&D can be fruitfully made common

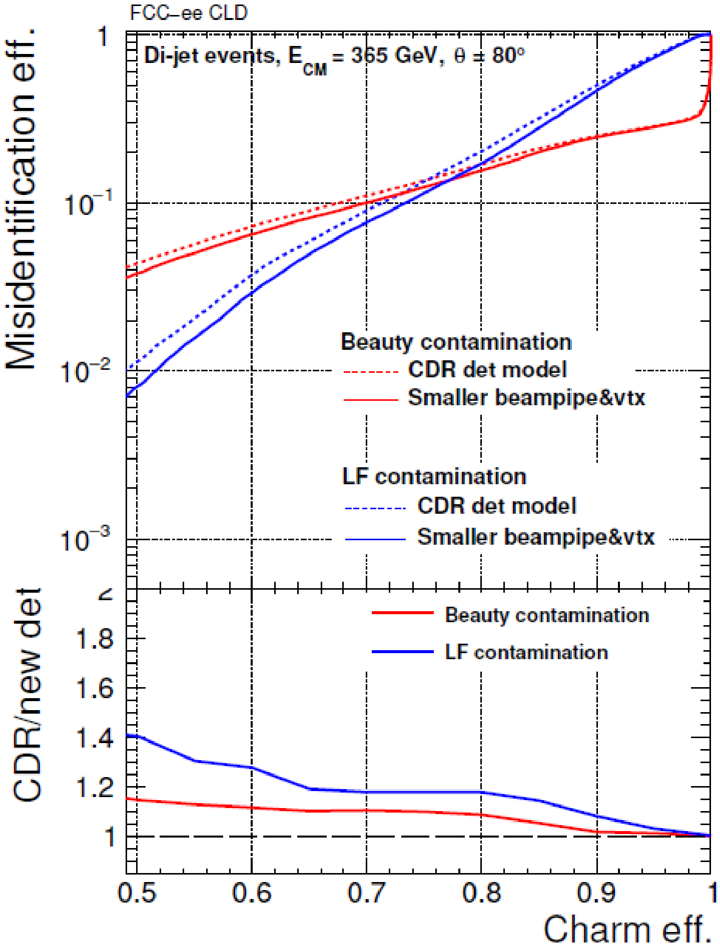
(D). Detector performances

D. b/c tagging sensitivity (CLIC example)

Sensitivity to b/c-tagging performances

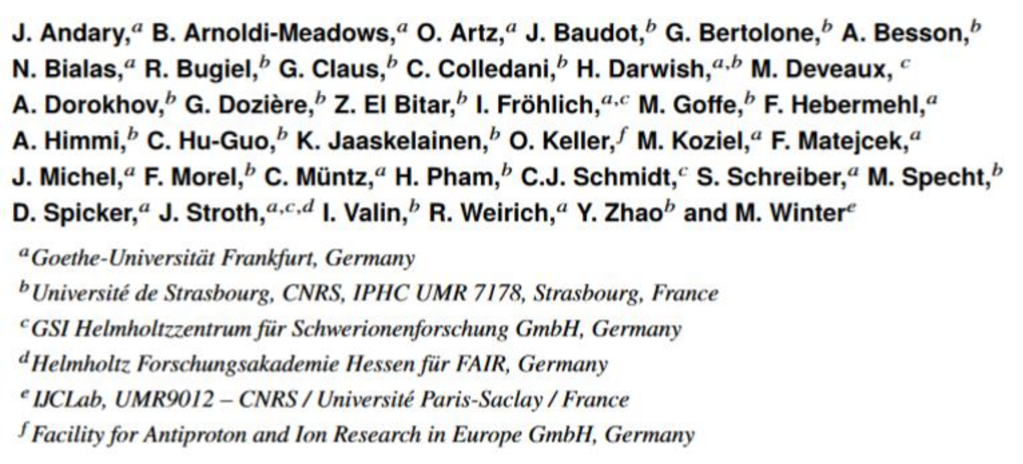
CLICdp-Note-2018-005
17 December 2018





(E). MIMOSIS Program

CBM-MVD collaboration



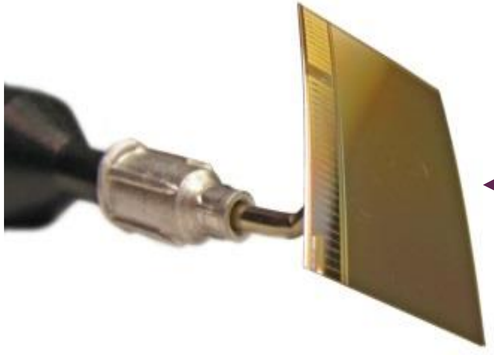
J. Andary,[a] B. Arnoldi-Meadows,[a] O. Artz,[a] J. Baudot,[b] G. Bertolone,[b] A. Besson,[b] N. Bialas,[a] R. Bugiel,[b] G. Claus,[b] C. Colledani,[b] H. Darwish,[a,b] M. Deveaux, [c] A. Dorokhov,[b] G. Dozière,[b] Z. El Bitar,[b] I. Fröhlich,[a,c] M. Goffe,[b] F. Hebermehl,[a] A. Himmi,[b] C. Hu-Guo,[b] K. Jaaskelainen,[b] O. Keller,[f] M. Koziel,[a] F. Matejcek,[a] J. Michel,[a] F. Morel,[b] C. Müntz,[a] H. Pham,[b] C.J. Schmidt,[c] S. Schreiber,[a] M. Specht,[b] D. Spicker,[a] J. Stroth,[a,c,d] I. Valin,[b] R. Weirich,[a] Y. Zhao[b] and M. Winter[e]

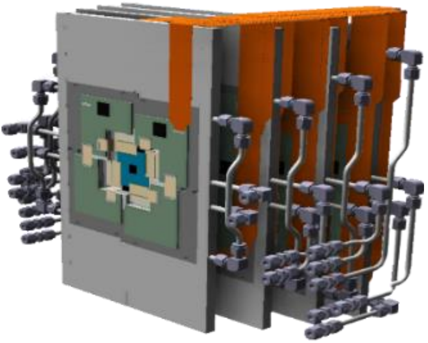
[a] *Goethe-Universität Frankfurt, Germany*
[b] *Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
[c] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany*
[d] *Helmholtz Forschungsakademie Hessen für FAIR, Germany*
[e] *IJCLab, UMR9012 – CNRS / Université Paris-Saclay / France*
[f] *Facility for Antiproton and Ion Research in Europe GmbH, Germany*

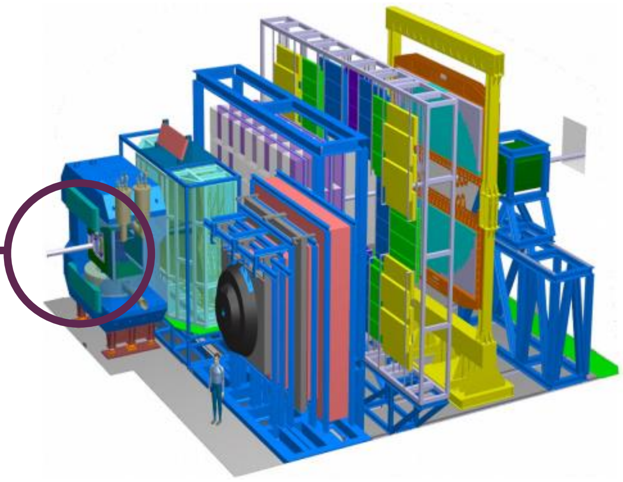
E. CBM experiment @ FAIR (GSI)

- The Compressed Baryonic Matter (CBM)
  - ✓ Fixed target experiment @ FAIR (GSI)
  - ✓ Explore QCD phase diagram @ high baryon densities
- The Micro-Vertex-Detector (MVD)

- 4 double-sided thin planar detector stations
- 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
- Non uniform hit density in time and space
- High radiation environment, operating in vacuum

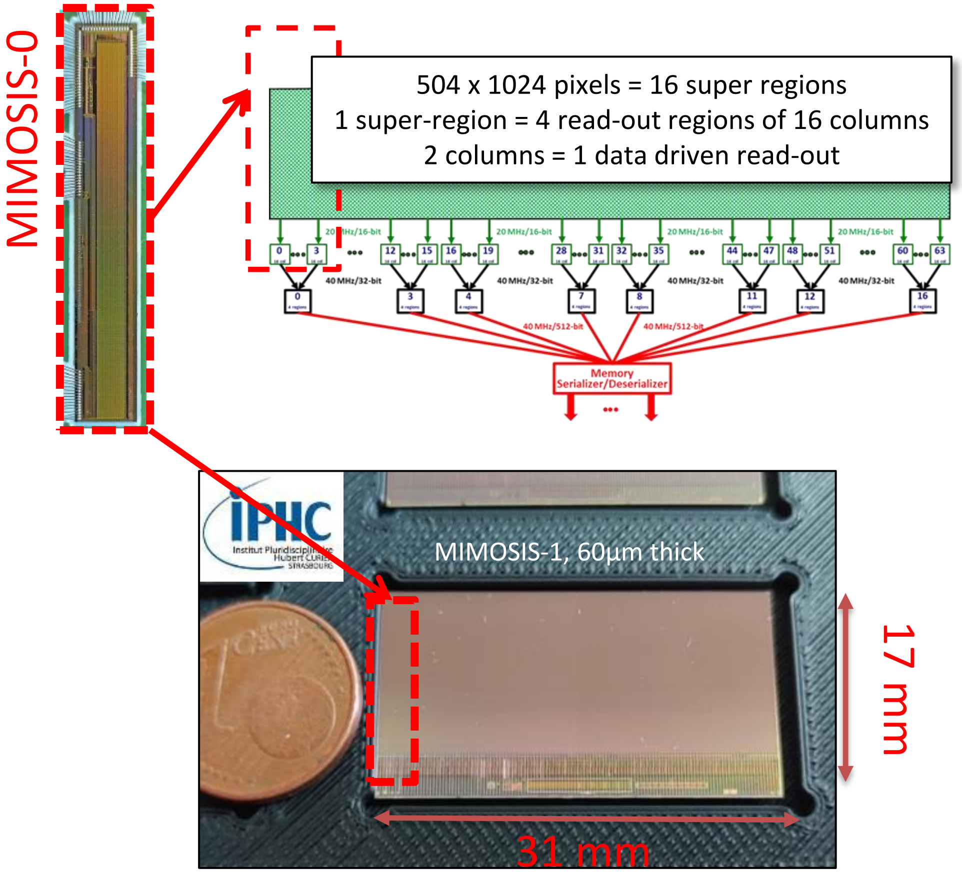

CMOS Monolithic
Active Pixel Sensor*


CBM Micro Vertex Detector
(MVD)


CBM – Experiment @ FAIR

E. MIMOSIS roadmap

- 4 prototypes:
- MIMOSIS-0: = 2 regions
  - ✓ Tests (2018-2019)
    - Testability
- MIMOSIS-1: 1st full size prototype
  - ✓ Elastic buffer, SEE hardened
  - ✓ Fabricated in 2020
  - ✓ Lab/beam test campaign in 2021-22
- MIMOSIS-2:
  - ✓ On-chip clustering
  - ✓ Back from foundry Q2 2023 ⇨ tests Q3 2023
- MIMOSIS-3: final pre-production sensor
  - ✓ ≥2024

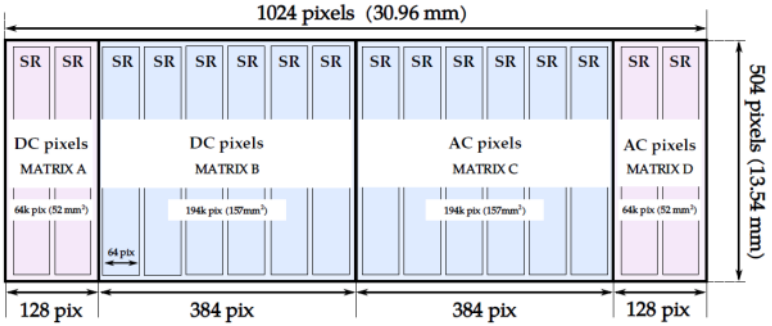


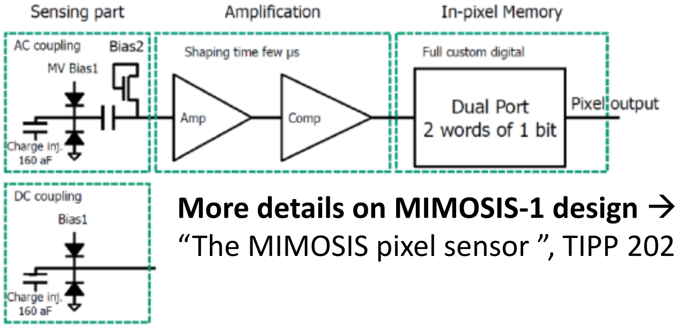
504 x 1024 pixels = 16 super regions
1 super-region = 4 read-out regions of 16 columns
2 columns = 1 data driven read-out

⇨ architecture adaptable to a fast sensor for an ILC vertex detector
⇨ Opportunity to study different designs/options

E. MIMOSIS-1

- MIMOSIS tests
  - ✓ Submatrices: DC/AC pixels
    - DC pixels: ALPIDE-derived
    - **AC pixels: top bias up to > 20V**
  - ✓ 6 epitaxial variants (18 wafers)
    - Thinned down to 60 µm
    - Study **Yield**
    - Study **charge collection / spatial res.**
    - Explore performances after **irradiation**

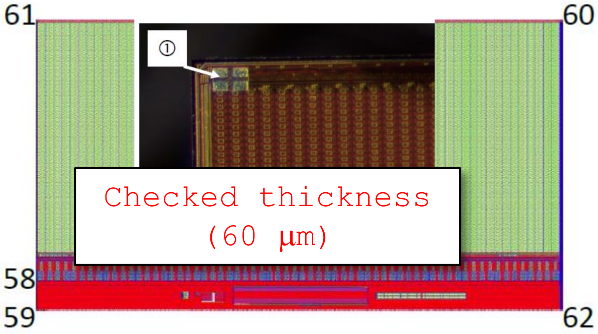




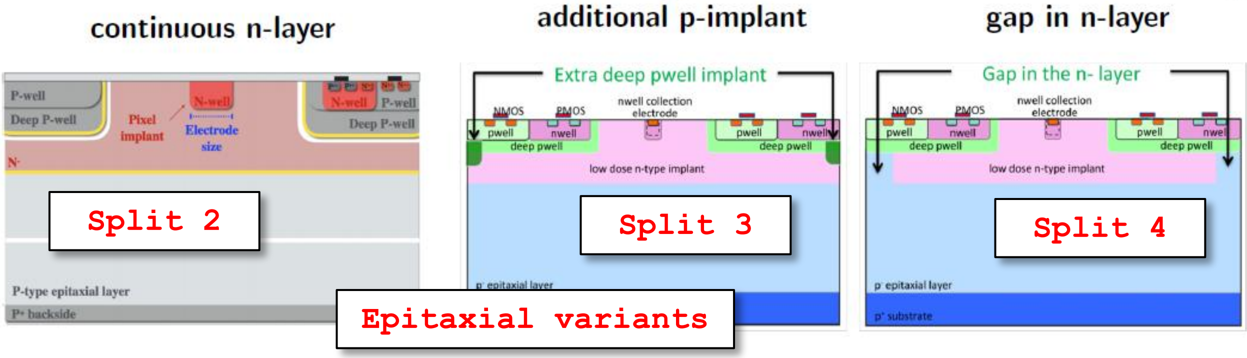
More details on MIMOSIS-1 design → F. Morel, “The MIMOSIS pixel sensor ”, TIPP 2021

- Intense test program in 2021/22:
  - ✓ Laboratory tests
  - ✓ Irradiation tests
  - ✓ Beam tests @ DESY/CERN (3 campaigns)
  - ✓ Latchup / SEE tests at GSI

Ljubjana (TRIGA)	**~1 MeV reactor neutrons**
Karlsruhe (KIT)	~10 keV X-rays



Checked thickness (60 µm)



Split 2

Split 3

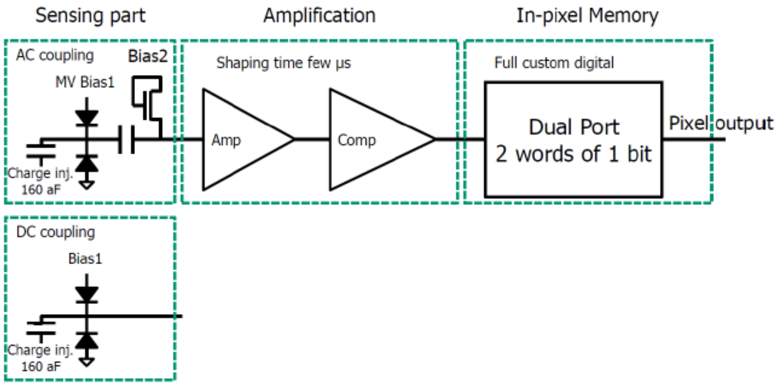
Split 4

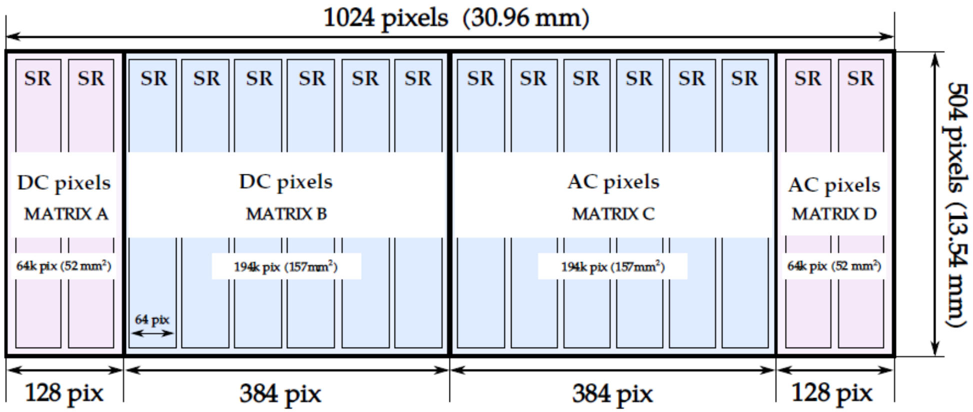
Epitaxial variants

- standard process (3 available wafers)
- continuous n-layer (blanket) (3 wafers)
- additional p-implant (3 wafers)
- gap in n-layer (3 wafers)

Pic from: Munker, Vertex 2018, Status of silicon detector R&D at CLIC
Carlos, TREDI 2019, Results of the Malta CMOS pixel detector prototype for the ATLAS Pixel ITK

E. AC / DC pixels

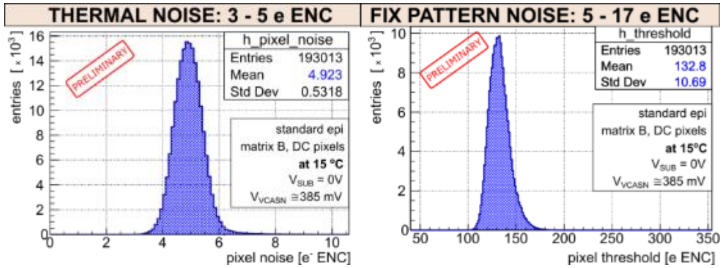


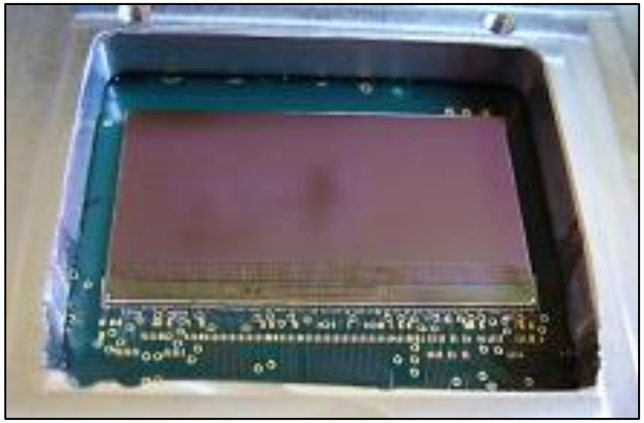


- DC Pixels (~ALPIDE) & AC pixels (top bias up to > 20V)
  - ✓ Amplifier / shaper / discriminator chain similar to ALPIDE in both scheme
  - ✓ Data driven readout
  - ✓ Pulse injection for calibration
  - ✓ Pixel masking options

MIMOSIS beam test results

- Noise
  - ✓ DC pixels, no back bias applied)
  - @ room T^{o}C
  - ✓ Pixel Noise ~ 3-5 e$^-$ ENC
  - ✓ FPN ~5-17 e$^-$ ENC
- Efficiency
  - ✓ ≥ 99.5 %
  - ✓ Time walk correction
- Cluster multiplicity
  - ✓ Typically in the 1-2 range
- Resolution as expected
- Fake rate very low
  - ✓ < 10^{-6}





Pixel dimensions

~26.9 µm x 30.2 µm

Binary resolution

~ 7.8 (U) x 8.3 (V) µm

Depletion - Cluster size - resolution dependencies observed

E. Noise

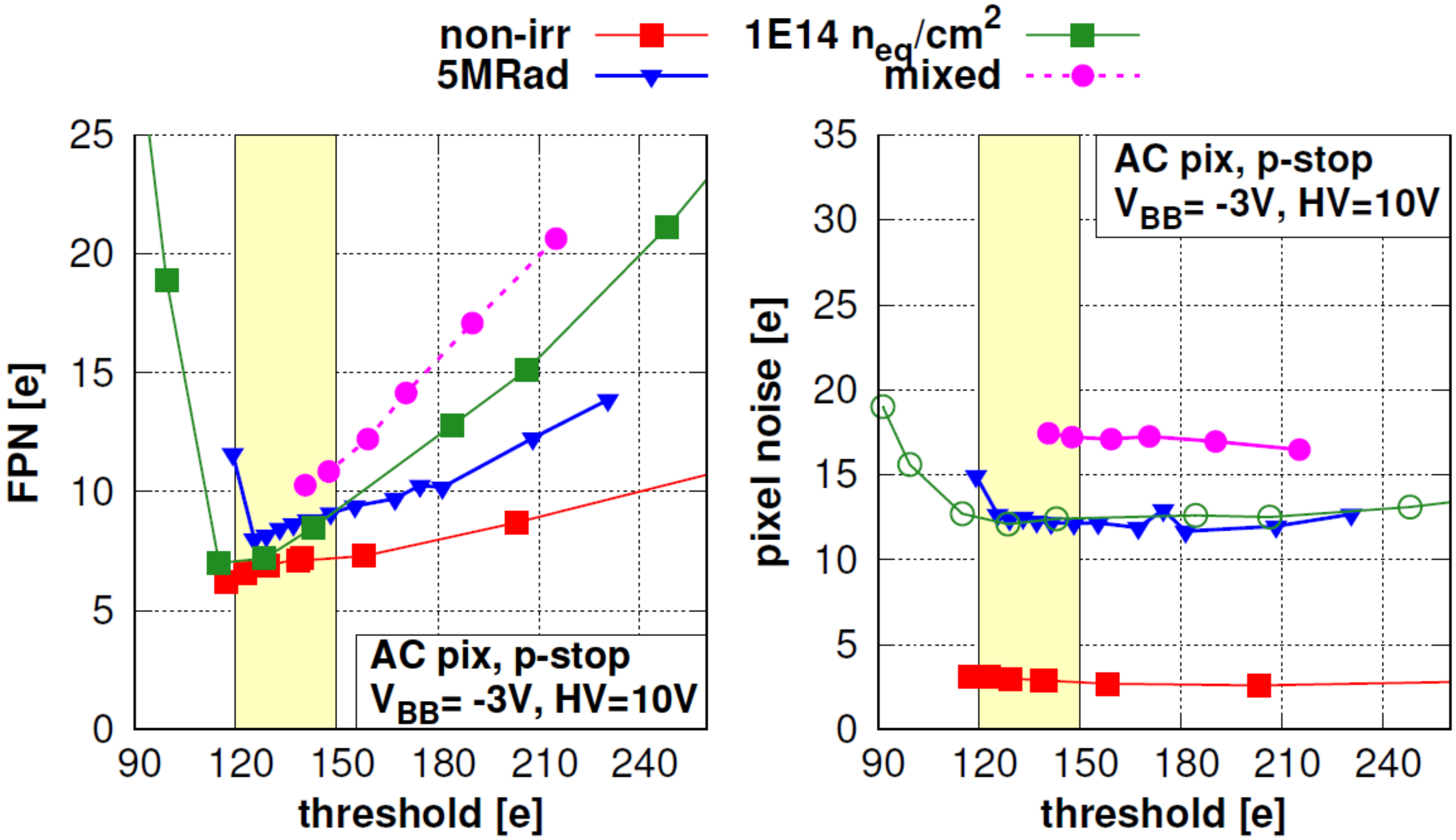
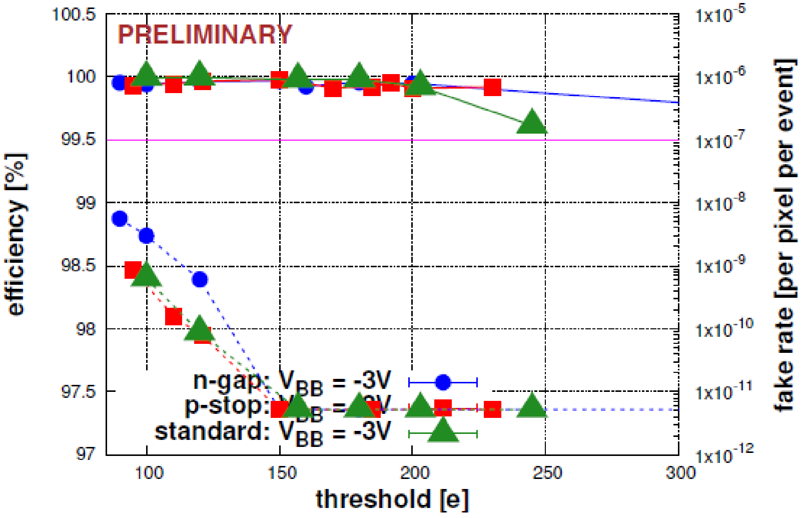
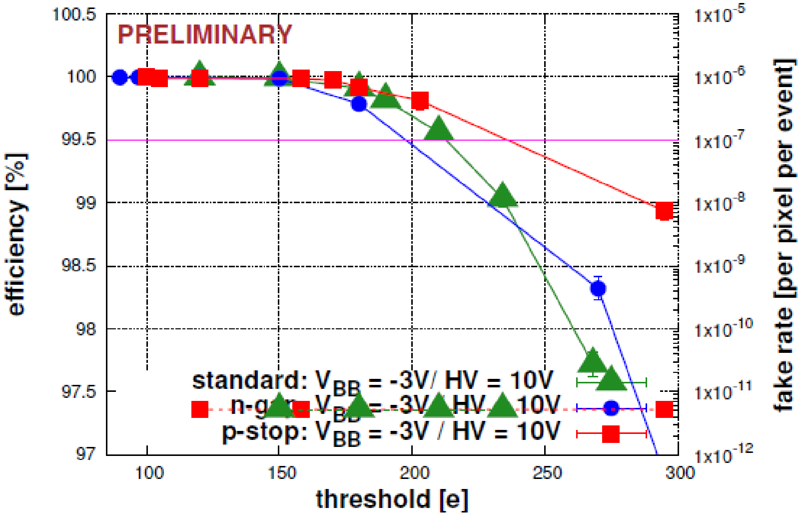


Figure 7: FPN and pixel noise after ionizing, non-ionizing and combined irradiation. The extracted uncertainties are of order 0.01 e⁻ and are not shown for clarity.

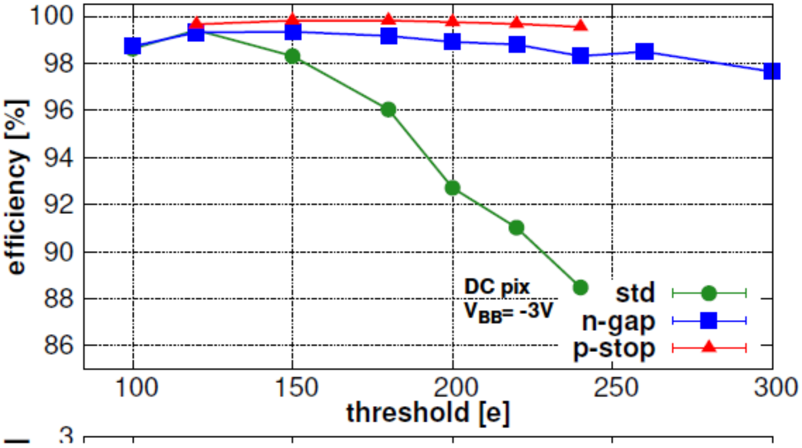
E. Process comparison



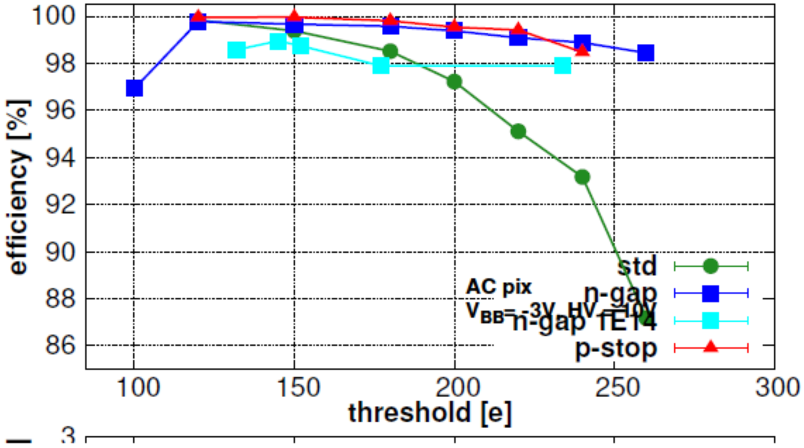
(a) DC pixels



(b) AC pixels

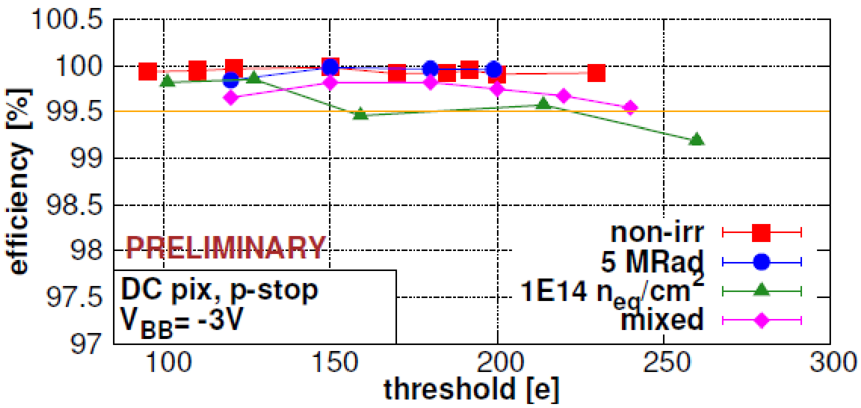


(a) DC pixels

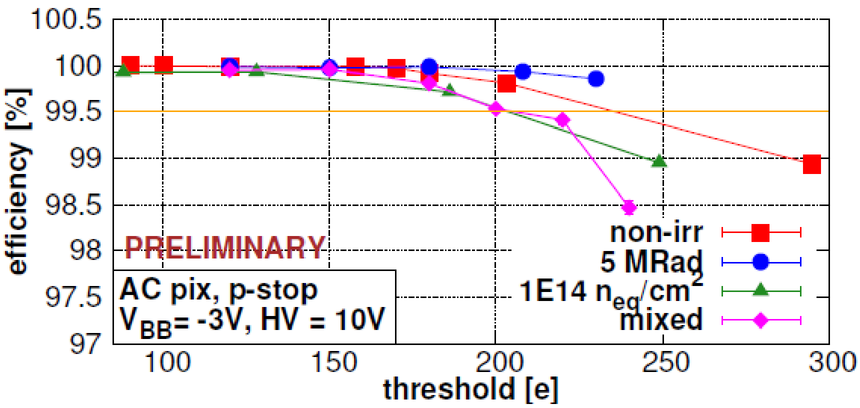


(b) AC pixels

E. Irradiations

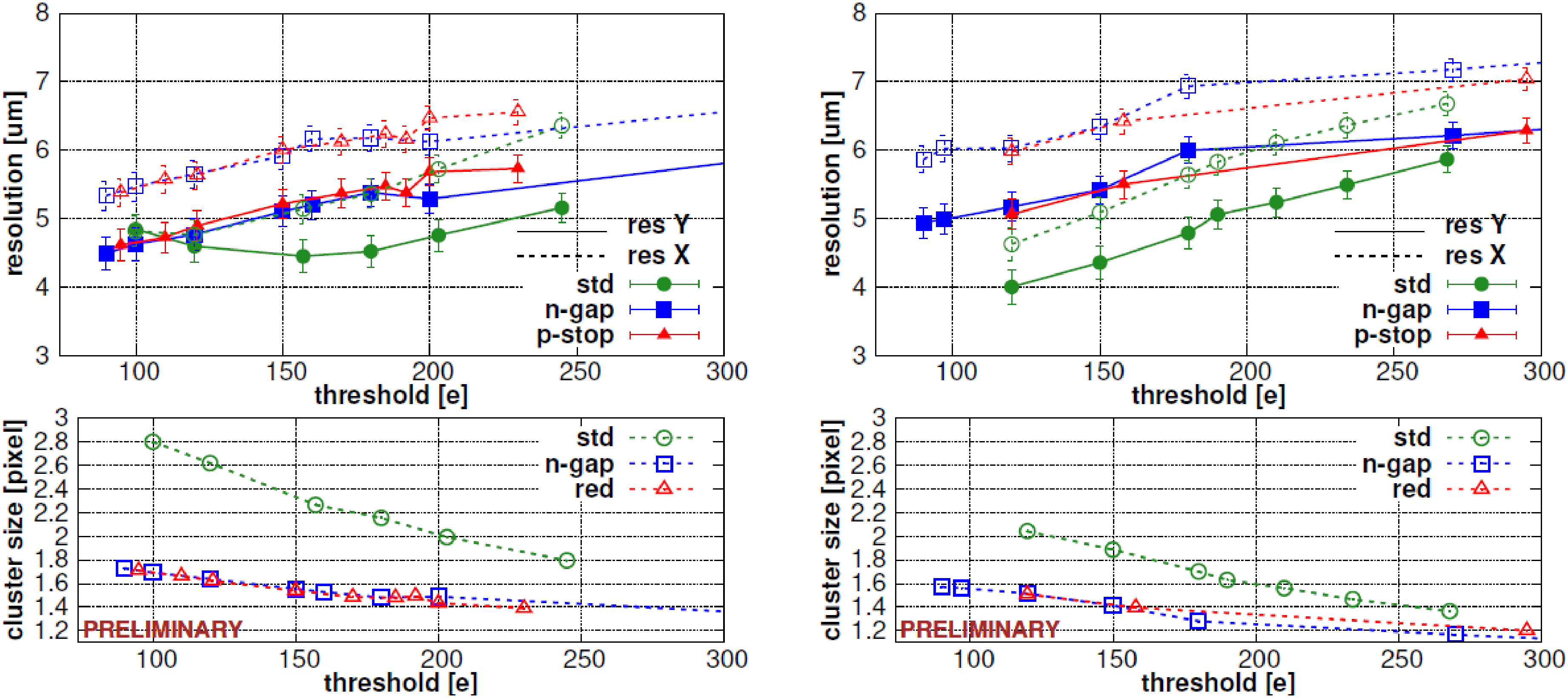


(a) DC pixels



(b) AC pixels

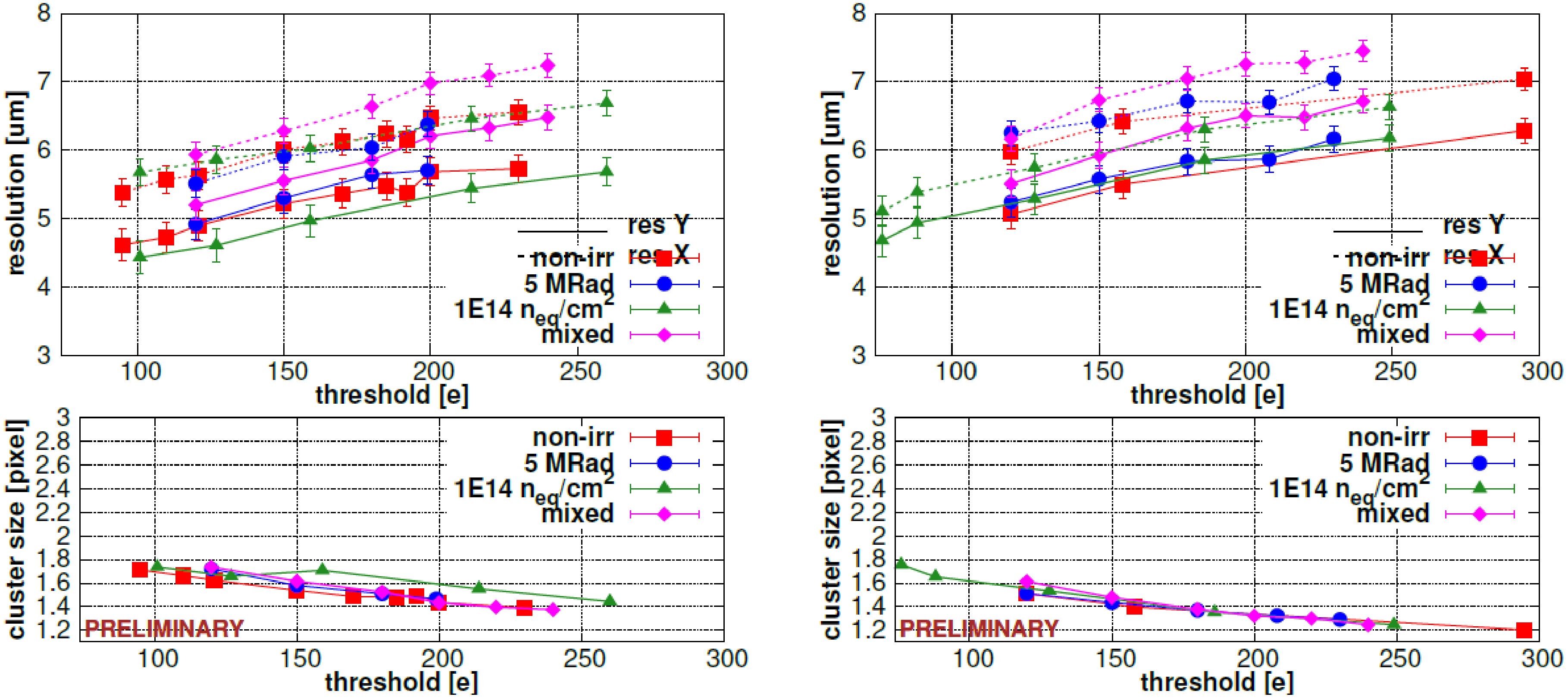
E. Resolution vs process



(a) DC pixels

(b) AC pixels

E. Resolution vs irradiation



(a) DC pixels (b) AC pixels

Figure 15: Comparison of resolution and cluster size for various irradiation types - p-stop.

E. Tests of MIMOSIS-2 (in 2023)

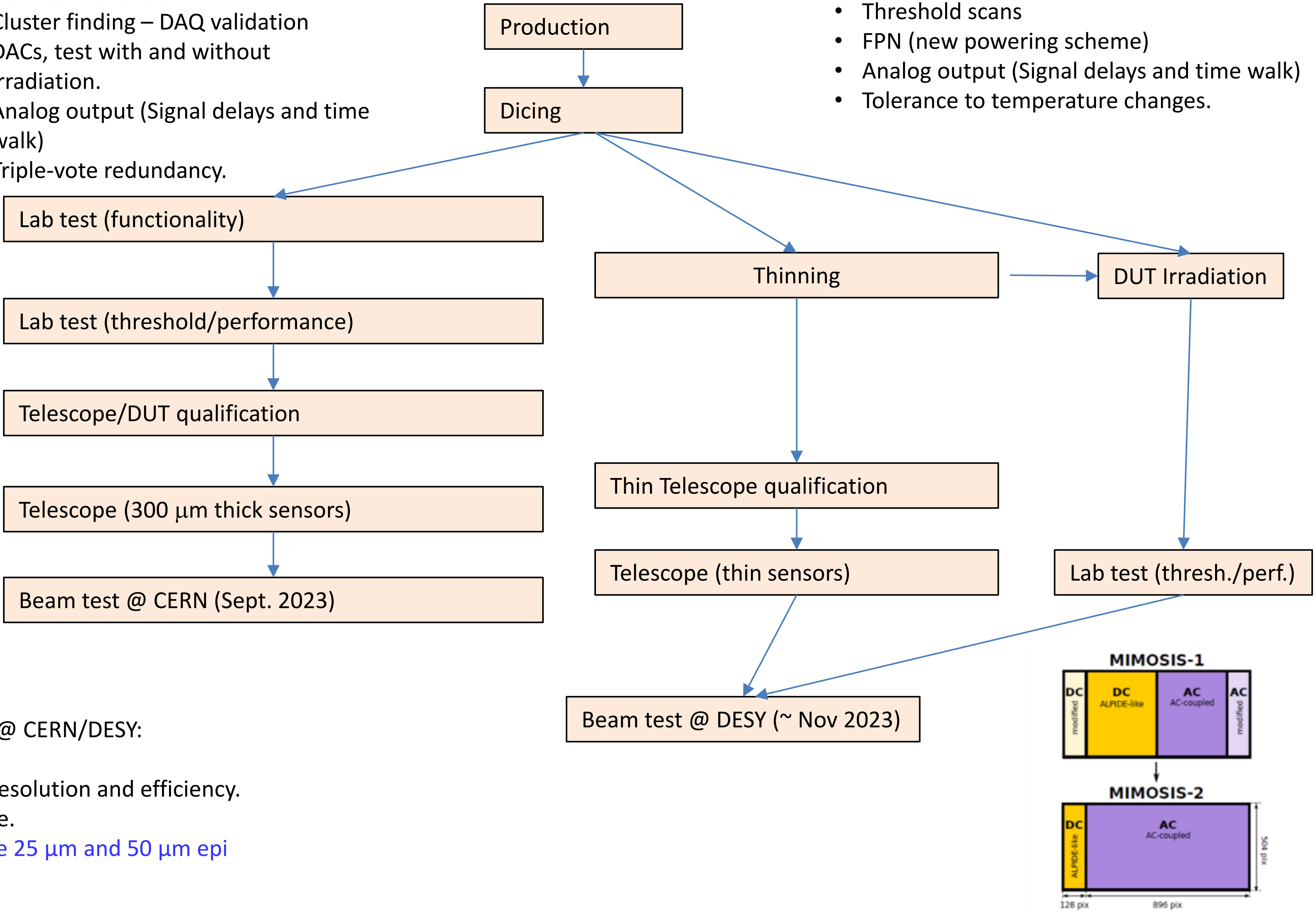
Debug/commissioning phase for DAQ (in lab):

Do new/reworked features work?

- PLL validation (dispersion)
- Slow control check
- Cluster finding – DAQ validation
- DACs, test with and without irradiation.
- Analog output (Signal delays and time walk)
- Triple-vote redundancy.

Lab characterization: ➪ Chip qualification

- Threshold uniformity check (voltage drop)
- Threshold scans
- FPN (new powering scheme)
- Analog output (Signal delays and time walk)
- Tolerance to temperature changes.



Production

Dicing

Lab test (functionality)

Lab test (threshold/performance)

Telescope/DUT qualification

Telescope (300 µm thick sensors)

Beam test @ CERN (Sept. 2023)

Thinning

Thin Telescope qualification

Telescope (thin sensors)

DUT Irradiation

Lab test (thresh./perf.)

Beam test @ DESY (~ Nov 2023)

Beam test @ CERN/DESY:

- Spatial resolution and efficiency.
- Dark rate.
- Compare 25 µm and 50 µm epi

E. Wafer types

Wafer nb	Type	thickness µm	Goal µm	Epi	company
1	Process Standard CIS 	**700**	**200-300**	**25µm**	**Tower (Simple dicing)**
2		700	50	25µm	Optim (Simple dicing)
3		700		25µm	
4		700	200-300	50µm	Tower (Simple dicing)
~~5~~		~~700~~	~~70 ?~~	~~50µm~~	~~Optim (Simple dicing)~~
6		700		50µm	
7	**Non Uniform N- Layer with gap (N-Gap)** 	700	200-300	25µm	Tower (Simple dicing)
8		700	50	25µm	Aptek (Simple dicing)
9		700		25µm	
10		**700**	**200-300**	**50µm**	**Tower (Simple dicing)**
11		700	70 ?	50µm	Aptek (Simple dicing)
12		700		50µm	
13	**Uniform N- Layer + extra Deep P (P-Stop)** 	**700**	**200-300**	**25µm**	**Tower (Simple dicing)**
14		700	50	25µm	Aptek (Simple dicing)
15		700	50	25µm	Optim (Simple dicing)
16		**700**	**200-300**	**50µm**	**Tower (Simple dicing)**
17		700	70 ?	50µm	Aptek (Simple dicing)
18		700		50µm	

One wafer lost in the fabrication process

\+ 6 Pads Wafer

3 x 6 wafers ⇨ Wafer Intact = 36 Mimosis_2 per wafer

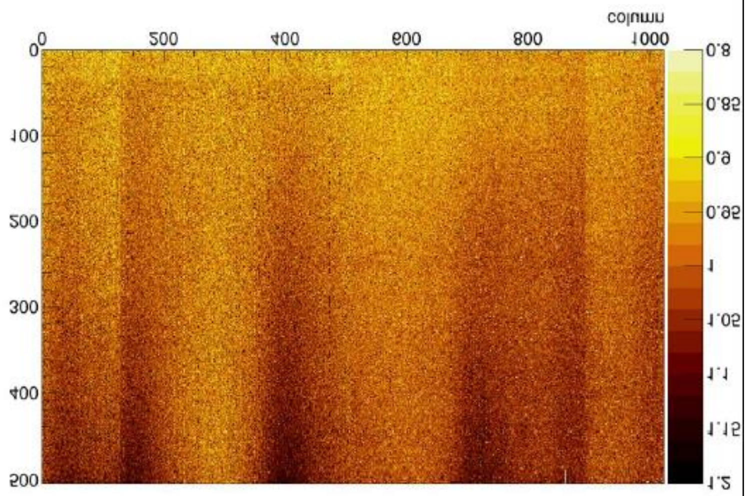
To be tested with priority

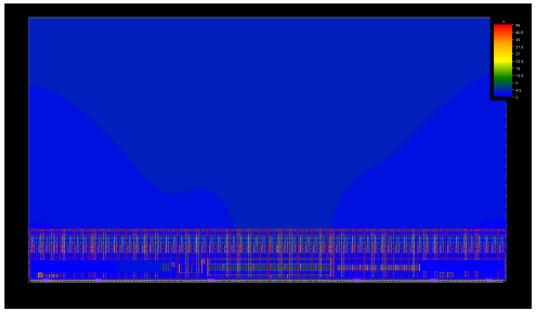
E. Mimosis-1 Verification tools example

- Large and complex designs need
  - ✓ A hierarchy in the work flow to keep submission on schedule
  - ✓ Verification tools that can be run in a reasonnable time
  - ✓ Knowledge of these tools is crucial
- Example Power-grid problem observed in MIMOSIS-1
  - ✓ Threshold shifts
  - ✓ Problem fixed quickly

F. Morel DRD7 kick-off meeting

Threshold shift of MIMOSIS-1 (measurements)

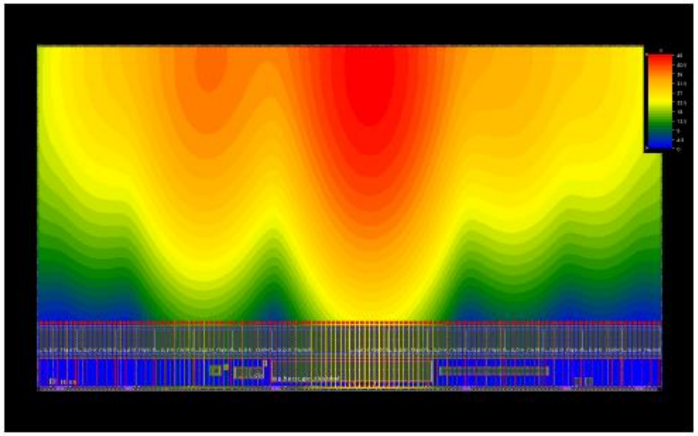




IR drop on AVDD (simulations)
0-45 mV scale

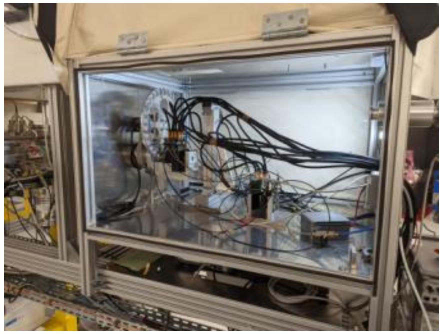
MIMOSIS-1
Mean= 26 mV

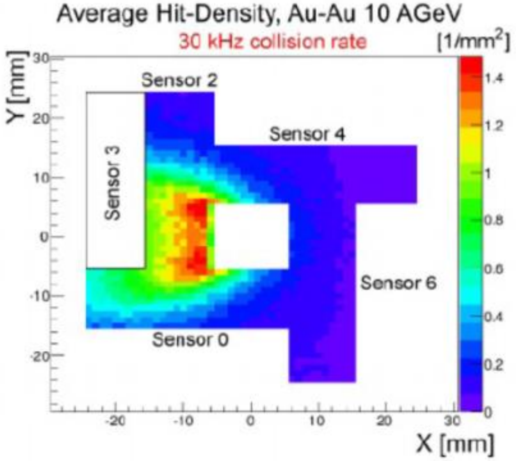
MIMOSIS-2
Mean = 3 mV

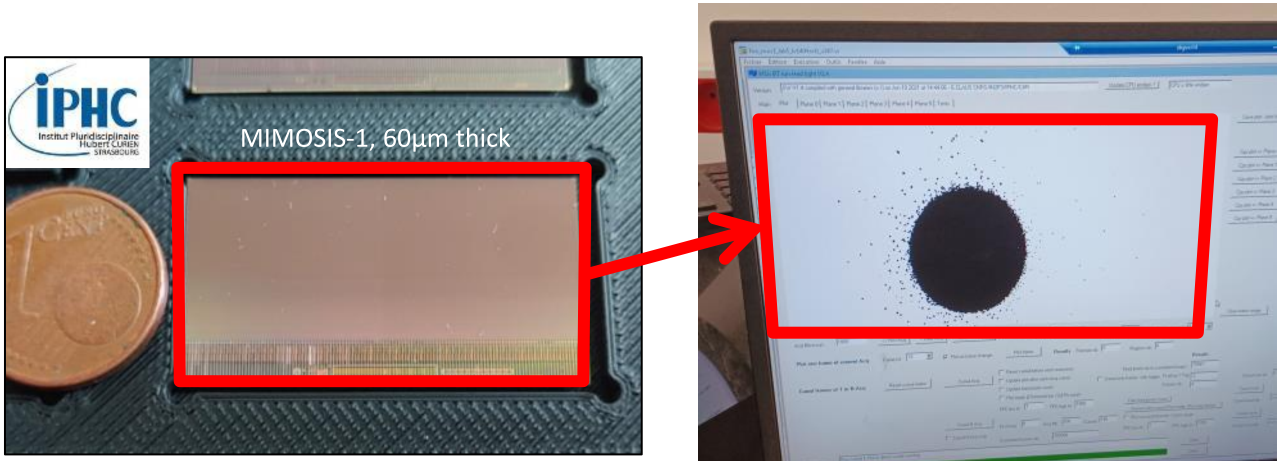


E. Localized irradiations

- CYRCE platform @IPHC
  - ✓ https://cyrce.fr/
  - ✓ Delivers 25 MeV proton beams
    - Niel factor ~1.8
  - ✓ Can control precisely the dose
    - CYRCE beam characterization
    - High rate tests
    - Localized irradiations
    - Check performances uniformity with non uniform irradiations to mimic the expected MVD irradiation non uniformity
    - First tests performed with MIMOSIS-1 in Q2 2023



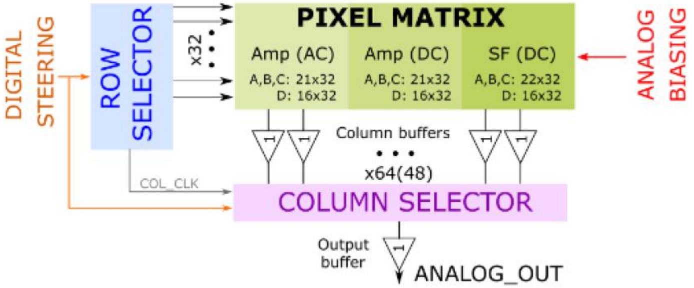




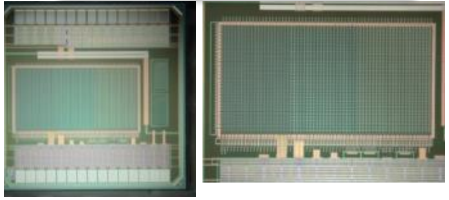
Example of MIMOSIS-1 illuminated with a 8 mm diameter collimation

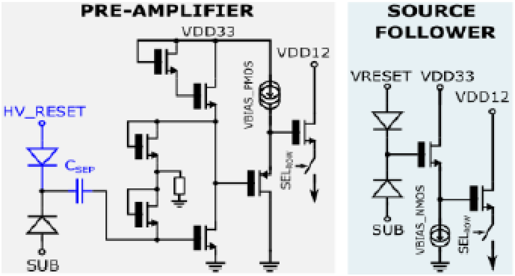
F. CE65 performances

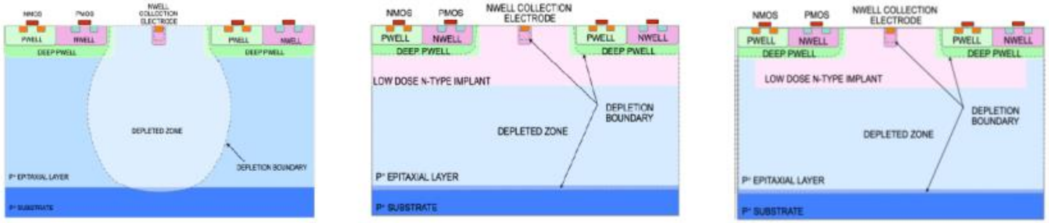
F. CE65_v1



CE_65 prototypes

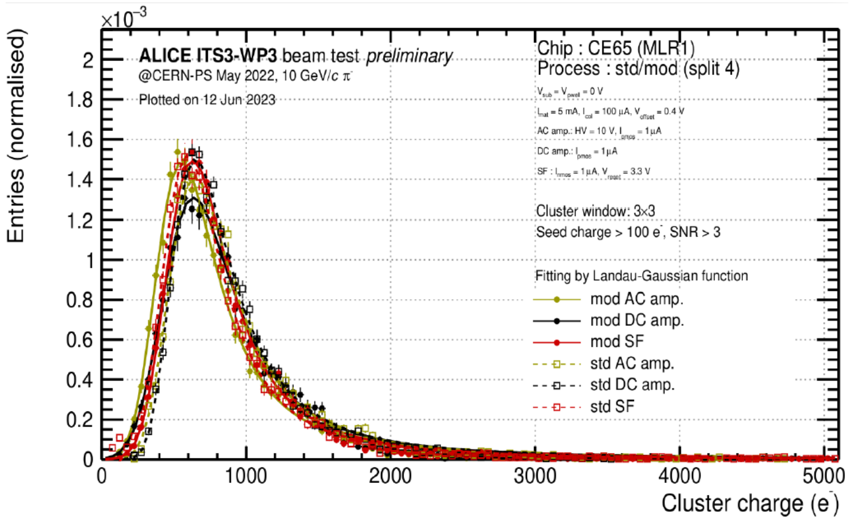


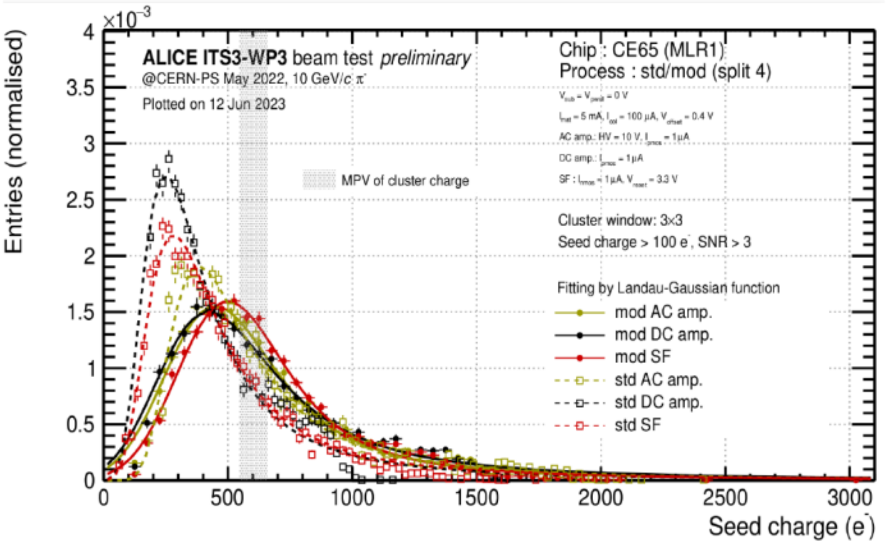




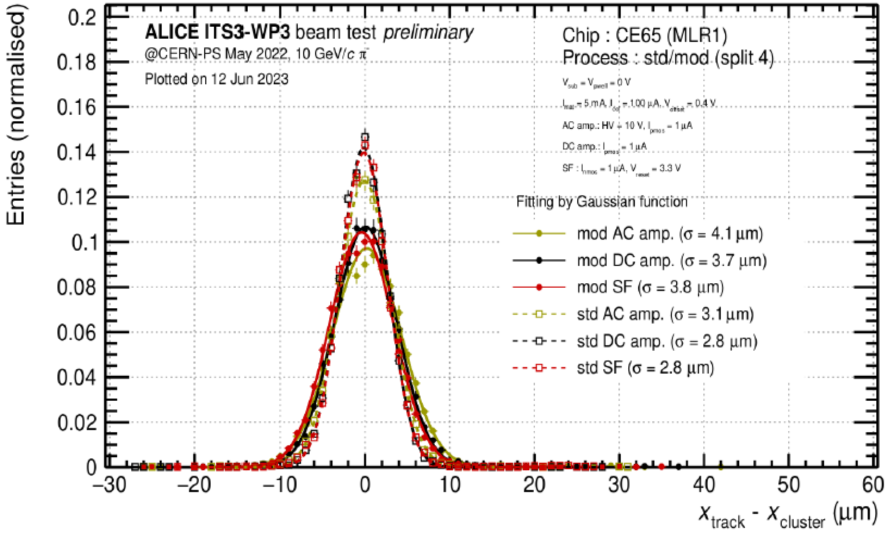
(a) Standard (b) Modified (c) Modified with gap

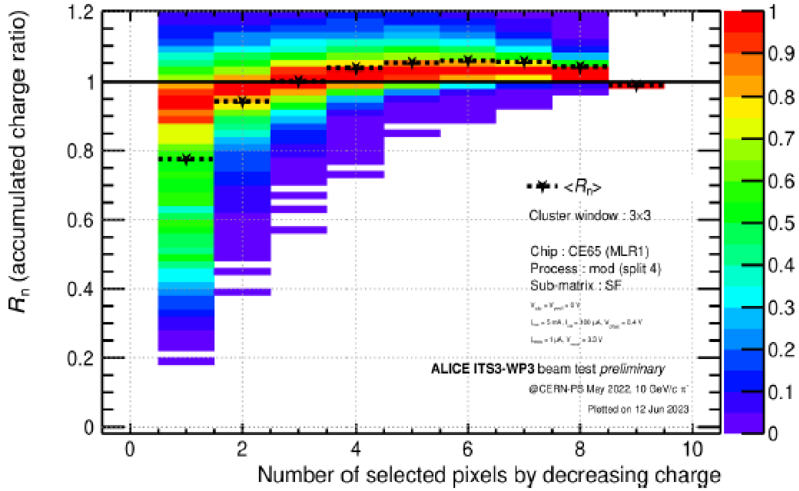
Variant	Process	Pitch	Matrix	Sub-matrix
CE65-A	std	15μm	64×32	AC/21, DC/21, SF/22
CE65-B	mod_gap	15μm	64×32	AC/21, DC/21, SF/22
CE65-C	mod	15μm	64×32	AC/21, DC/21, SF/22
CE65-D	std	25μm	48×32	AC/16, DC/16, SF/16



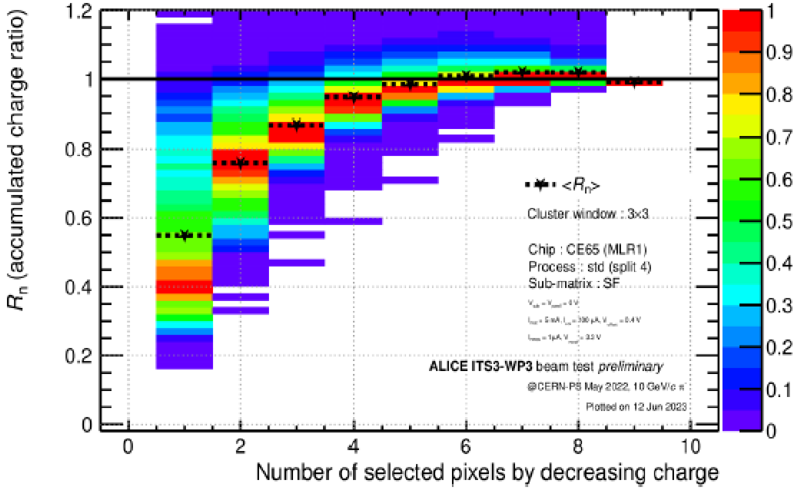


F. CE65_v1 charge sharing and residuals





(a) C4 chip



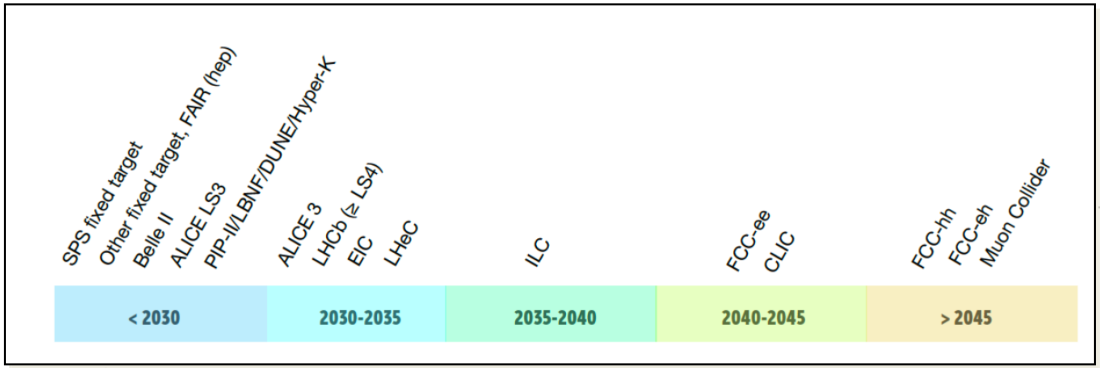
(b) A4 chip

G. Implementation of the ECFA Detector R&D Roadmap

&

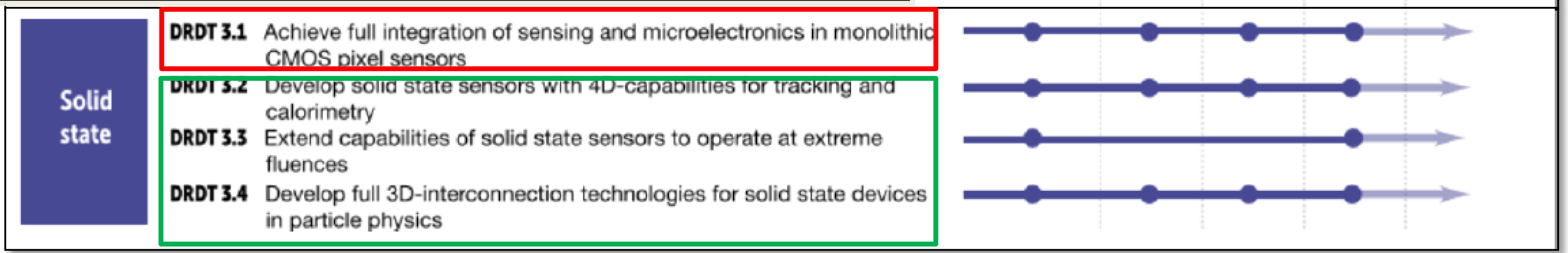
DRD3/DRD7

G. Detector R&D Roadmap: themes (DRDTs)



References: ECFA/RC/21/510
CERN-ESU-017
DOI: 10.17181/CERN.XDPL.W2EX

		< 2030	2030-2035	2035-2040	2040-2045	> 2045



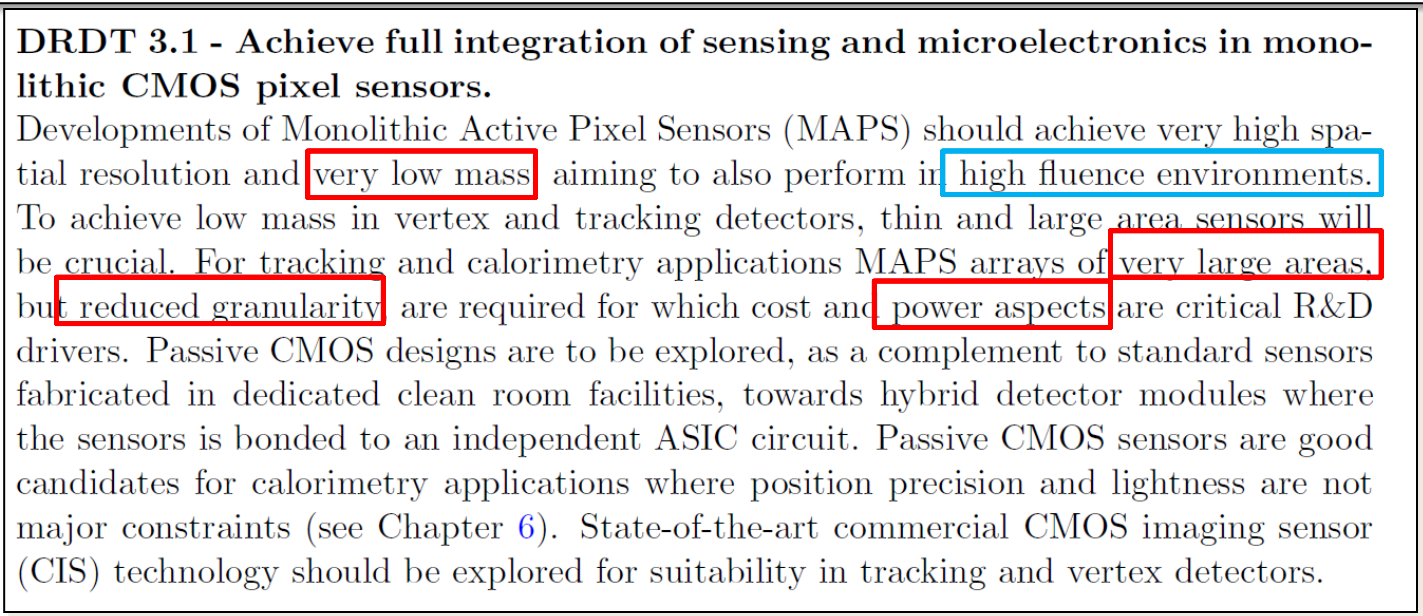
Solid state

DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors

DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry

DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences

DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics



DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.

Developments of Monolithic Active Pixel Sensors (MAPS) should achieve very high spatial resolution and very low mass aiming to also perform in high fluence environments. To achieve low mass in vertex and tracking detectors, thin and large area sensors will be crucial. For tracking and calorimetry applications MAPS arrays of very large areas, but reduced granularity are required for which cost and power aspects are critical R&D drivers. Passive CMOS designs are to be explored, as a complement to standard sensors fabricated in dedicated clean room facilities, towards hybrid detector modules where the sensors is bonded to an independent ASIC circuit. Passive CMOS sensors are good candidates for calorimetry applications where position precision and lightness are not major constraints (see Chapter 6). State-of-the-art commercial CMOS imaging sensor (CIS) technology should be explored for suitability in tracking and vertex detectors.

G. Synergies

ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather. ***ECFA supports a series of workshops*** *with the aim to* ***share challenges and expertise, to explore synergies in their efforts*** *and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).*

Goal: bring the entire e^+e^- Higgs factory effort together, foster cooperation across various projects; collaborative research programmes are to emerge

K. Jakobs, FCC Physics Workshop, Feb 2022

		DRDT	Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3[1]	ALICE 3	LHCb (≥ LS4[1])	ATLAS & CMS (≥ LS4[1])	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030					2030-2035					2035-2040	2040-2045		>2045		
Vertex detector[2]	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low X/X_0	3.1,3.4	🟠	🟢	🟡	🟠	🔴	🔴	🟠	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low power	3.1,3.4		🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	High rates	3.1,3.4		🟢	🔴	🟢		🟢	🟢		🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢
	Large area wafers[3]	3.1,3.4	🟡	🟡	🟡	🟡	🔴	🔴			🔴	🟡	🟠	🔴	🟠	🟡	🟡	🔴
	Ultrafast timing[4]	3.2			🔴				🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢	🟡						🔴		
	Radiation tolerance TID	3.3							🟢	🟡						🔴		
Tracker[5]	Position precision	3.1,3.4						🔴	🟡		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low X/X_0	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low power	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	High rates	3.1,3.4							🟢			🟢				🔴	🟢	
	Large area wafers[3]	3.1,3.4						🟡	🟡		🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
	Ultrafast timing[4]	3.2							🟡		🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢							🟢		
	Radiation tolerance TID	3.3							🟢							🟢		

🔴 **Must happen or main physics goals cannot be met** 🟠 **Important to meet several physics goals** 🟡 **Desirable to enhance physics reach** 🟢 **R&D needs being met**

+ integration know-how (e.g. ALICE, Belle-2)

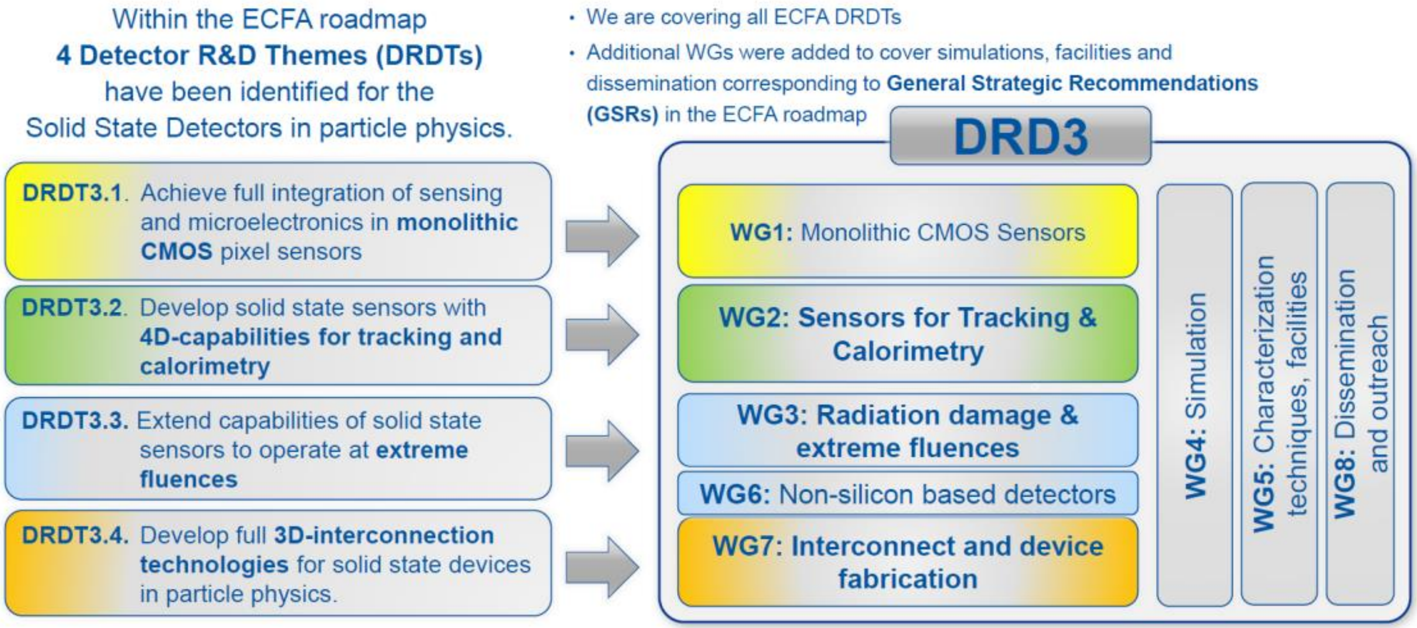
"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				**< 2030**					**2030-2035**					**2035 - 2040**	**2040-2045**		**> 2045**		
				Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 1)	ALICE 3	LHCb (≳LS4) 1)	ATLAS/CMS (≳ LS4) 1)	EIC	LHeC	ILC 2)	FCC-ee	CLIC 2)	FCC-hh	FCC-eh	Muon Collider
Vertex Detector 3)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≃ 5		≲ 5	≃ 3	≲ 3	≲ 10	≲ 15	≲ 3	≃ 5	≲ 3	≲ 3	≲ 3	≃ 7	≃ 5	≲ 5
			X/X_0 (%/layer)	≲ 0.1	≃ 0.5	≃ 0.5	≲ 0.1	≃ 0.05	≃ 0.05	≃ 1		≃ 0.05	≲ 0.1	≃ 0.05	≃ 0.05	≲ 0.2	≃ 1	≲ 0.1	≲ 0.2
			Power (mW/cm^2)		≃ 60			≃ 20	≃ 20			≃ 20		≃ 20	≃ 20	≃ 50			
			Rates (GHz/cm^2)		≃ 0.1	≃ 1	≲ 0.1		≲ 0.1	≃ 6		≲ 0.1	≃ 0.1	≃ 0.05	≃ 0.05	≃ 5	≃ 30	≃ 0.1	
			Wafers area (") 4)					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns) 5)	10		≲ 0.05	100		25	≲ 0.05	≲ 0.05	25	25	500	25	≃ 5	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							≃ 6	≃ 2						≃ 10^2		
			Radiation tolerance TID (Grad)							≃ 1	≃ 0.5						≃ 30		
Tracker 6)	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)						≃ 6	≃ 5		≃ 6	≃ 6	≃ 6	≃ 6	≃ 7	≃ 10	≃ 6	
			X/X_0 (%/layer)						≃ 1	≃ 1		≃ 1	≃ 1	≃ 1	≃ 1	≃ 1	≲ 2	≃ 1	
			Power (mW/cm^2)						≲ 100	≃ 100		≲ 100		≲ 100	≲ 100	≲ 150			
			Rates (GHz/cm^2)							≃ 0.16									
			Wafers area (") 4)						12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t (ns) 5)						25	≲ 25		25	25	≲ 0.1	≲ 0.1	≲ 0.1	≲ 0.02	25	≲ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							≃ 0.3							≲ 1		
			Radiation tolerance TID (Grad)							≃ 0.25							≲ 1		

CERN/SPC/1190
CERN/3679

**European Strategy for Particle Physics
Implementation of the
Detector Research and Development Roadmap**

→ TF3 Solid State Detectors →

DRD3 organisation



Within the ECFA roadmap
4 Detector R&D Themes (DRDTs)
have been identified for the
Solid State Detectors in particle physics.

- We are covering all ECFA DRDTs
- Additional WGs were added to cover simulations, facilities and dissemination corresponding to **General Strategic Recommendations (GSRs)** in the ECFA roadmap

DRDT3.1. Achieve full integration of sensing and microelectronics in **monolithic CMOS** pixel sensors

DRDT3.2. Develop solid state sensors with **4D-capabilities for tracking and calorimetry**

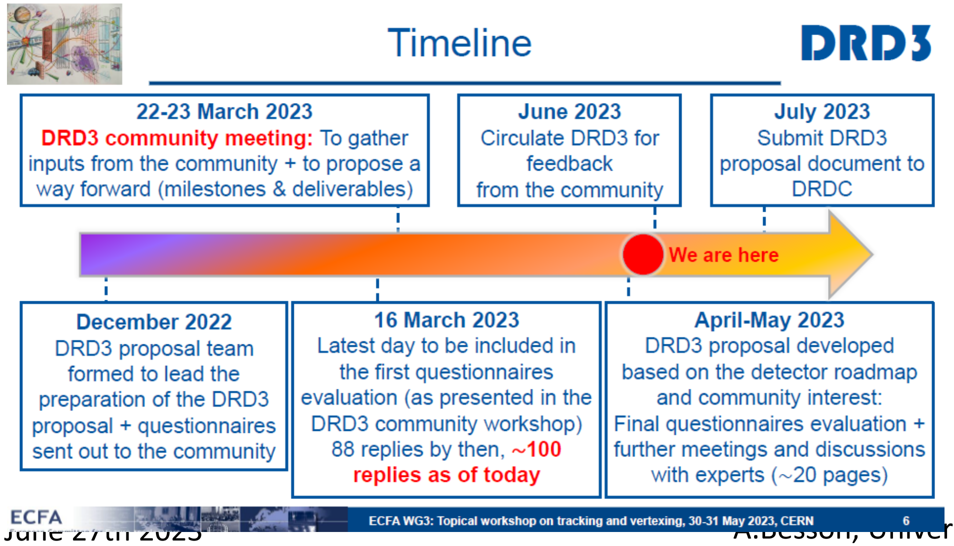
DRDT3.3. Extend capabilities of solid state sensors to operate at **extreme fluences**

DRDT3.4. Develop full **3D-interconnection technologies** for solid state devices in particle physics.

DRD3

- **WG1:** Monolithic CMOS Sensors
- **WG2: Sensors for Tracking & Calorimetry**
- **WG3: Radiation damage & extreme fluences**
- **WG6:** Non-silicon based detectors
- **WG7: Interconnect and device fabrication**
- **WG4:** Simulation
- **WG5:** Characterization techniques, facilities
- **WG8:** Dissemination and outreach

(WG2 includes LGADS & hybrids)



Timeline

DRD3

22-23 March 2023
DRD3 community meeting: To gather inputs from the community + to propose a way forward (milestones & deliverables)

June 2023
Circulate DRD3 for feedback from the community

July 2023
Submit DRD3 proposal document to DRDC

We are here

December 2022
DRD3 proposal team formed to lead the preparation of the DRD3 proposal + questionnaires sent out to the community

16 March 2023
Latest day to be included in the first questionnaires evaluation (as presented in the DRD3 community workshop)
88 replies by then, **~100 replies as of today**

April-May 2023
DRD3 proposal developed based on the detector roadmap and community interest:
Final questionnaires evaluation + further meetings and discussions with experts (~20 pages)

ECFA
ECFA WG3: Topical workshop on tracking and vertexing, 30-31 May 2023, CERN 6

Lab	Main WGs	Secondary WGs
IPHC	WG3.1	WG3.5, 3.7, 3.8

- WG 3.1: Monolithic CMOS sensors
  - ✓ Spatial resolution of 3 µm
  - ✓ Timing precision of 20 ps
  - ✓ Readout architectures for 100 MHz/cm^2
  - ✓ Radiation tolerance of 10^{16} n_{eq}/cm^{2}NIEL and 500 MRad

- WG 3.2: Sensors for tracking and calorimetry
  - ✓ Spatial and temporal resolutions at extreme radiation levels
  - ✓ Reduction of pixel cell size for 3D sensors
  - ✓ 3D sensors with a temporal resolution of about 50 ps
  - ✓ Spatial and temporal resolutions at low radiation levels and low material and power budgets
  - ✓ LGAD sensors with very high fill factor and an excellent spatial and temporal resolution
  - ✓ LGAD sensors for Time of Flight applications

- WG 3.3: Radiation damage and extreme fluence operation
  - ✓ Build up data sets on radiation induced defect formation in WBG materials
  - ✓ Develop silicon radiation damage models based on measured point and cluster defects
  - ✓ Provide measurements and detector radiation damage models for radiation levels faced in HL-LHC operation
  - ✓ Measure and model the properties of silicon and WBG sensors in the fluence range 10^{16} to 10^{18} n_{eq}/cm^2

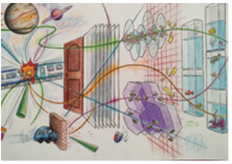
- **WG 3.4: Simulation**
  - ✓ Flexible CMOS simulation of 65 nm to test design variations
  - ✓ Implementation of newly measured semiconductor properties into TCAD and MC simulation tools
  - ✓ Definition of benchmark for the validation of the radiation damage models with measurements and benchmark different models
  - ✓ Developing of bulk and surface model for 10^{16} n_{eq}/cm^2 to 10^{17} n_{eq}/cm^2 NIEL
  - ✓ Collate solutions from different MC tools and develop algorithms to include adaptive electric and weighting fields

- **WG 3.5: Measurement and characterization techniques**
  - ✓ Development of new semiconductor characterization techniques is a priority for future detector developments
  - ✓ These techniques should enable high-resolution imaging and defect spectroscopy of semiconductor materials, as well as advanced characterization of charge transport properties
  - ✓ The Two Photon Absorption –TCT setup, Caribou DAQ system and the Ion Beam testing and irradiation facility at RBI have been identified as good examples and further improvements are being proposed

- WG 3.6: Wide bandgap and innovative sensor materials
  - ✓ 3D diamond detectors, cages/interconnects, base length 25 µm, impact ionisation
  - ✓ Fabrication of large area SiC and GaN detectors, improve material quality and reduce defect levels
  - ✓ Improve tracking capabilities of WBG materials
  - ✓ Apply graphene and/or other 2D materials in radiation detectors, understand signal formation

- WG 3.7: Sensor interconnection techniques
  - ✓ Yield consolidation for fast interconnections
  - ✓ Demonstration of small pitch (< 30 µm) pixel interconnections
  - ✓ Demonstration of radiation hardness and thermomechanical constraints
  - ✓ Development of maskless post-processing for commonly-used interconnection technologies
  - ✓ Bring part of the commonly-used interconnection technologies to specialised academic groups
  - ✓ Develop device-to-wafer interconnection technologies
  - ✓ Develop wafer-to-wafer in presently advanced interconnection technologies
  - ✓ Develop VIAS in multi-tier sensor/front-end assemblies
  - ✓ Develop connection techniques for post-processed devices

- **WG 3.8: Outreach and dissemination**
  - ✓ Disseminating knowledge on solid-state detectors to people working in high energy physics
  - ✓ Disseminating knowledge on solid-state detectors to high-school students and the general public
  - ✓ Design and set-up of the DRD3 website
  - ✓ Collection of the outreach material
  - ✓ Set-up and organize schools and exchange programs
  - ✓ Set-up of the DRD3 conference committee



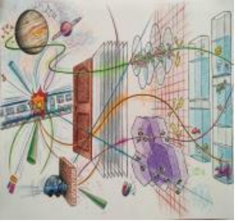
Ball park performance targets MCMOS

Three main time scales/phases to define program up to: 2027-28, 2029-2035, >2035

Ball park generic performance targets*
mandatory/desireable

	Tracking VD/CT	Timing Layer + Calorimeter
Heavy Ion	ultralight low power tracker pitch 10 - 30 μm @ O(100) MHz/cm^2, O(1) μs	O(20) ps (TL)
Flavour collider	ultralight low power tracker pitch 10 - 30 μm @ O(100) MHz/cm^2, O(1) ns	O(20) ps in (TL)
Lepton collider	e-e : ultralight low power tracker pitch down to $\lesssim$10 μm, @ O(100) MHz/cm^2 timing driven by power timing driven by power dissipation μ-μ : O(20) ps rates and irradiation tbc	O(10) ps in TL O(< 50) ps in calorimeter driven by power power dissipation
pp collider	HL-LHC: 25-50 μm @ O(5) GHz/cm^2 5x10^{15} to 5x10^{16} neq/cm^2, 250 - 500 MRad timing O(<50) ps timing O(<50) ps	HL-LHC: pitch O(<1) mm O(20) ps in TL, NIEL 5x10^{15}
	FCC-hh: < 10 - 20 μm @ 30 GHz/cm^2 4D tracking 4D tracking O(<10)ps up to O(10^{18}) to O(10^{18}) neq/cm^2, up to O(50) GRad	FCC-hh: 5D calorimeter O(<10)ps up to O(10^{18}) neq/cm^2, up to O(50) GRad O(50) GRad

[*] ranges representative, ex. for VD and CT with more stringent constraints to be achieved in VD

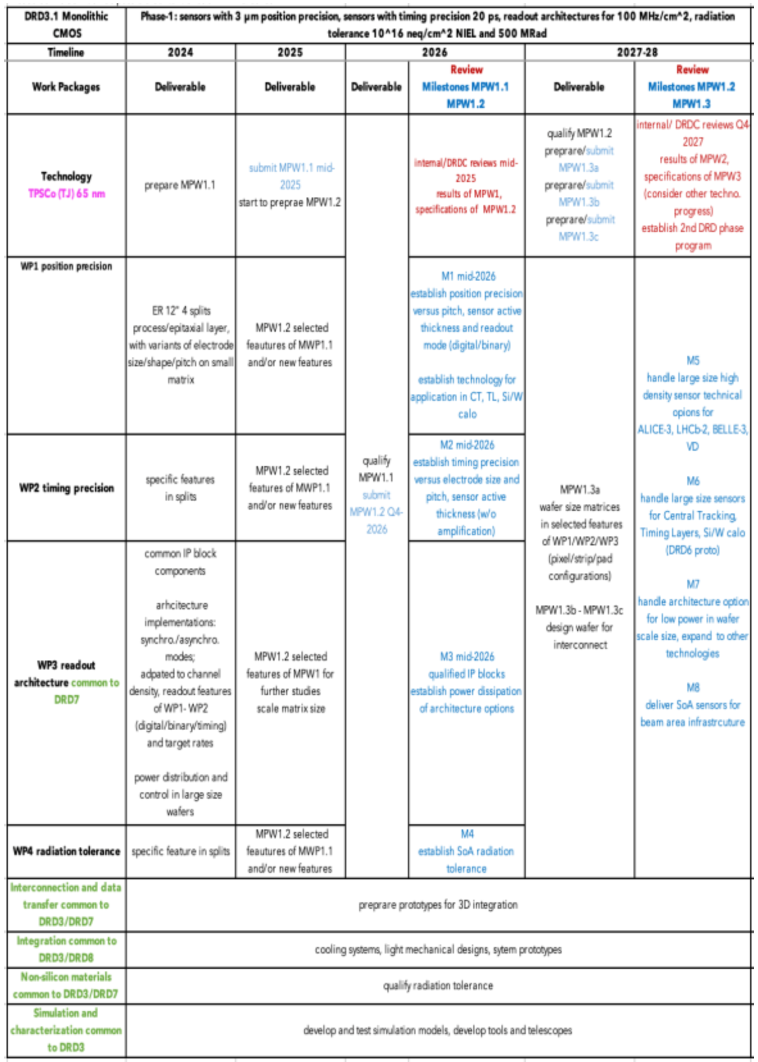


MCMOS 1st R&D phase up to 2027-2028

DRD3

Deliverables: MPW submissions/reviews/milestones (ex. MCMOS TPSC 65 nm)

Work Packages

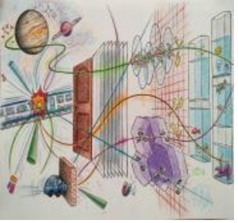


DRD3.1 Monolithic CMOS	Phase-1: sensors with 3 µm position precision, sensors with timing precision 20 ps, readout architectures for 100 MHz/cm^2, radiation tolerance 10^16 neq/cm^2 NIEL and 500 MRad					
Timeline	2024	2025	2026		2027-28	
Work Packages	Deliverable	Deliverable	Deliverable	Review Milestones MPW1.1 MPW1.2	Deliverable	Review Milestones MPW1.2 MPW1.3
Technology TPSCo (TJ) 65 nm	prepare MPW1.1	submit MPW1.1 mid-2025 start to preprae MPW1.2	qualify MPW1.1 submit MPW1.2 Q4-2026	internal/DRDC reviews mid-2025 results of MPW1, specifications of MPW1.2	qualify MPW1.2 preprare/submit MPW1.3a preprare/submit MPW1.3b preprare/submit MPW1.3c	internal/ DRDC reviews Q4-2027 results of MPW2, specifications of MPW3 (consider other techno. progress) establish 2nd DRD phase program
WP1 position precision	ER 12" 4 splits process/epitaxial layer, with variants of electrode size/shape/pitch on small matrix	MPW1.2 selected feautures of MWP1.1 and/or new features		M1 mid-2026 establish position precision versus pitch, sensor active thickness and readout mode (digital/binary) establish technology for application in CT, TL, Si/W calo	MPW1.3a wafer size matrices in selected features of WP1/WP2/WP3 (pixel/strip/pad configurations) MPW1.3b - MPW1.3c design wafer for interconnect	M5 handle large size high density sensor technical opions for ALICE-3, LHCb-2, BELLE-3, VD M6 handle large size sensors for Central Tracking, Timing Layers, Si/W calo (DRD6 proto) M7 handle architecture option for low power in wafer scale size, expand to other technologies M8 deliver SoA sensors for beam area infrastrcuture
WP2 timing precision	specific features in splits	MPW1.2 selected features of MWP1.1 and/or new features		M2 mid-2026 establish timing precision versus electrode size and pitch, sensor active thickness (w/o amplification)		
WP3 readout architecture common to DRD7	common IP block components arhcitecture implementations: synchro./asynchro. modes; adpated to channel density, readout features of WP1- WP2 (digital/binary/timing) and target rates power distribution and control in large size wafers	MPW1.2 selected features of MPW1 for further studies scale matrix size		M3 mid-2026 qualified IP blocks establish power dissipation of architecture options		
WP4 radiation tolerance	specific feature in splits	MPW1.2 selected feautures of MWP1.1 and/or new features		M4 establish SoA radiation tolerance		
Interconnection and data transfer common to DRD3/DRD7	preprare prototypes for 3D integration					
Integration common to DRD3/DRD8	cooling systems, light mechanical designs, sytem prototypes					
Non-silicon materials common to DRD3/DRD7	qualify radiation tolerance					
Simulation and characterization common to DRD3	develop and test simulation models, develop tools and telescopes					

Ball park goals

- explore all performance aspects in several technologies against design/process parameters
- develop few architectures with low power consumption for different work packages
- prepare (start?) 3D integration
- Review achievements, narrow down technology options
- Handle :
  - technical solutions for initial strategic programs: ALICE-3, LHCB-2, Belle-3, ATLAS/CMS…
  - sensors for DRD6 High Granularity Calorimetry prototypes
  - telescope for beam-test infrastructure

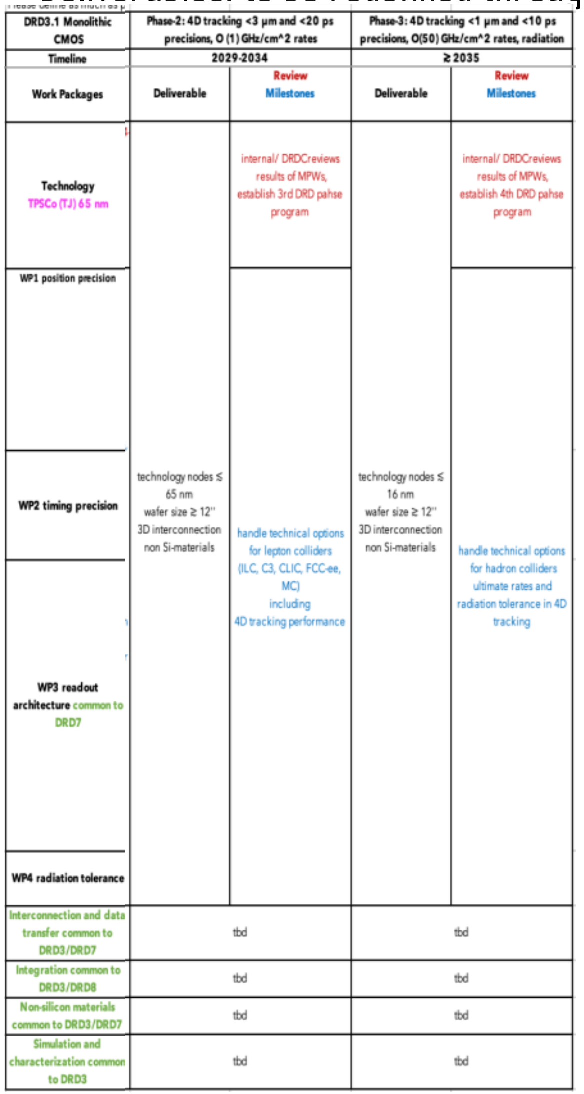
common areas within DRD3 and with DRD7



MCMOS 2nd and 3rd R&D phases

Deliverables: to be redefined through reviewing of Phase 1 progress and achievements

Work Packages



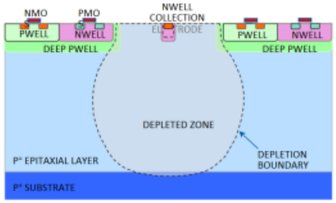
DRD3.1 Monolithic CMOS	Phase-2: 4D tracking <3 µm and <20 ps precisions, O (1) GHz/cm^2 rates		Phase-3: 4D tracking <1 µm and <10 ps precisions, O(50) GHz/cm^2 rates, radiation	
Timeline	2029-2034		≥ 2035	
Work Packages	Deliverable	Review Milestones	Deliverable	Review Milestones
Technology TPSCo (TJ) 65 nm	technology nodes ≲ 65 nm wafer size ≥ 12'' 3D interconnection non Si-materials	internal/ DRDCreviews results of MPWs, establish 3rd DRD pahse program	technology nodes ≲ 16 nm wafer size ≥ 12'' 3D interconnection non Si-materials	internal/ DRDCreviews results of MPWs, establish 4th DRD pahse program
WP1 position precision		handle technical options for lepton colliders (ILC, C3, CLIC, FCC-ee, MC) including 4D tracking performance		handle technical options for hadron colliders ultimate rates and radiation tolerance in 4D tracking
WP2 timing precision				
WP3 readout architecture common to DRD7				
WP4 radiation tolerance				
Interconnection and data transfer common to DRD3/DRD7	tbd		tbd	
Integration common to DRD3/DRD8	tbd		tbd	
Non-silicon materials common to DRD3/DRD7	tbd		tbd	
Simulation and characterization common to DRD3	tbd		tbd	

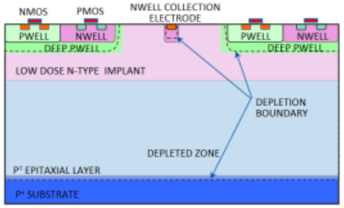
Ball park goals

- Integrate WP features in same sensors at low power consumption
- Evolve to further technologies/lower nodes toward full 4D tracking
- Implement 3D integration
- Reach ultimate timing precision, rates and rad. tol. for in 3rd phase

common areas within DRD3 and with DRD7

WG 3.1: CMOS @ IN2P3

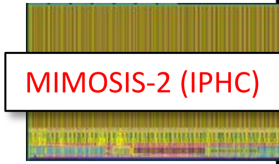




- IN2P3: MP GRAM & DEPHY (since end 2022)
  - ✓ DEPHY: high fluences, high flux for CMOS & hybrid pixels
  - ✓ GRAM: granularity, material budget, low power
- IPHC (C4PI, PICSEL, Belle-2, ALICE)
  - ✓ 20 years: STAR HFT, EUDET telescopes, ALICE ITS-2, AidaInnova, etc.)
  - ✓ 3 teams in HEP are pursuing a CMOS R&D activity:
    - PICSEL: MIMOSIS for CBM-MVD ⇨e^+e^- colliders (TJ180 nm & TPSco 65nm)
    - Belle-2 upgrades (TJ180 nm and beyond)
    - ALICE ITS3 (TPSco 65nm)
  - ✓ DRD3: focus on TPSco 65nm
  - ✓ IPHC Scientific council June 27th
- CPPM
  - ✓ > 10 years: (ITK ATLAS, Belle-2, RD50, RD53, AidaInnova)
    - Depleted CMOS
    - LF150nm, TSI180nm, TJ 180 nm, TPSco 65nm, etc.
    - high fluences, high flux
- IP2I
  - ✓ Interest for fast timing (< 100 ps)
  - ✓ Growing activity in digital micro-electronics with C4PI (TJ 180 nm)
    - Contribution to DRD3.1 (TPSCo TJ 65 nm)
    - Digital on Top methodology for read-out (with DRD7)
    - Low power architecture with ToF measurement
    - interconnection 3D (wafer stacking) (with DRD7)
- APC
  - ✓ Tests for the TPSco 65nm prototypes
  - ✓ Possible contributions to design (TPSco 65nm)
  - ✓ Expertise in simulations (TCAD, Allpix2) and radiation damages

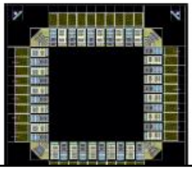
STAR-HFT (IPHC)

EUDET telescope

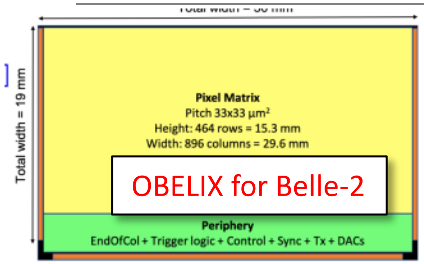


MIMOSIS-2 (IPHC)

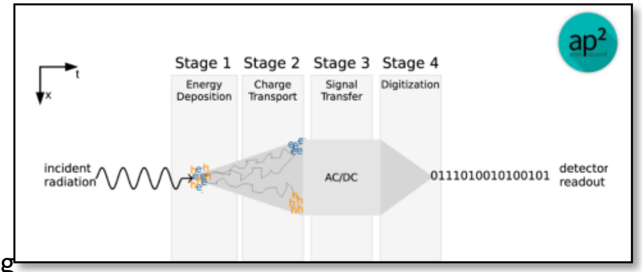
ER1 for ALICE ITS-3



Ring Oscillator (CPPM)

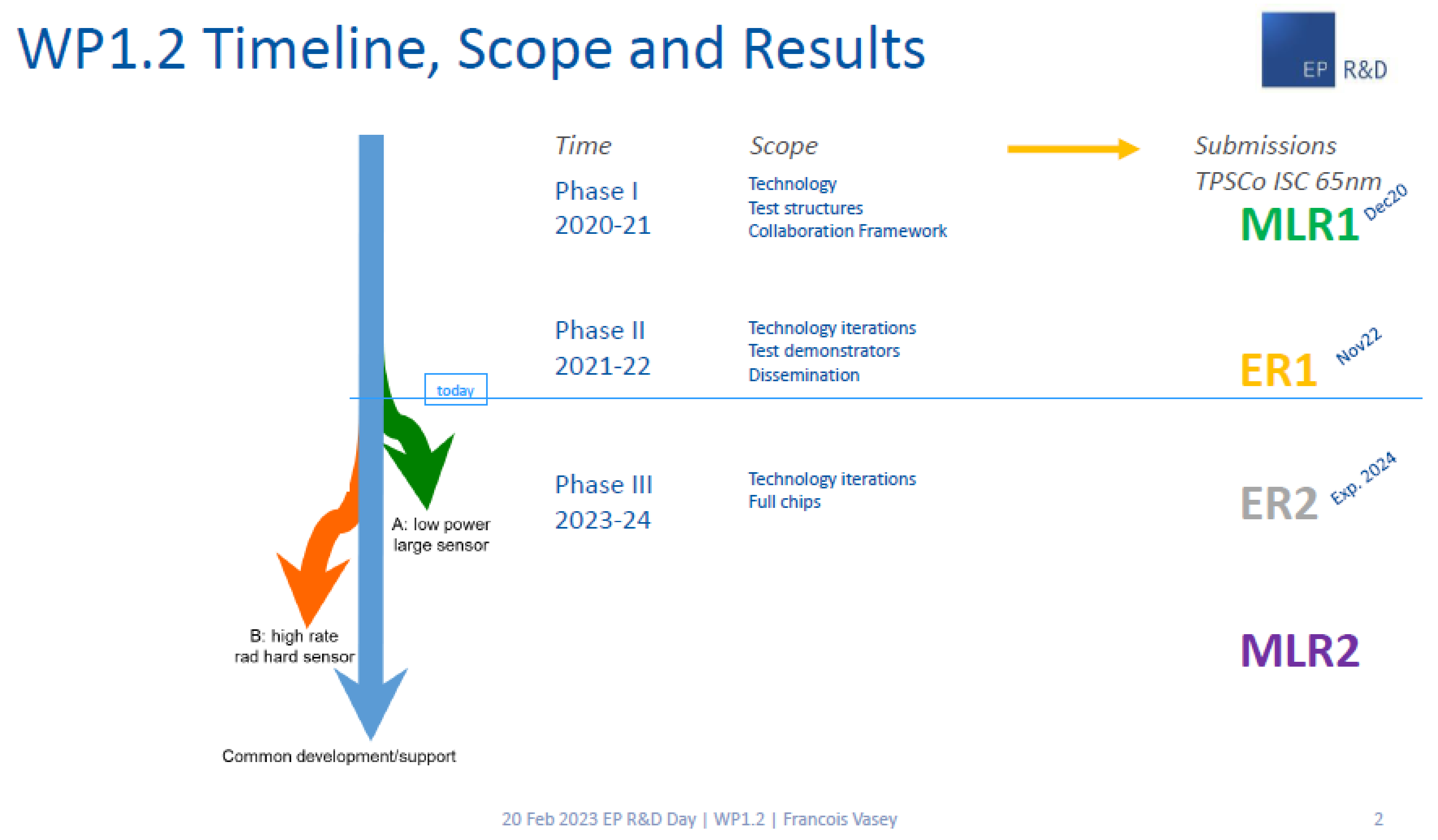


OBELIX for Belle-2



H. Submissions plans

TPSCo 65 nm timeline (from CERN EP R&D WP 1.2)



WP1.2 Timeline, Scope and Results

EP R&D

Time	*Scope*	*Submissions* *TPSCo ISC 65nm*
Phase I 2020-21	Technology Test structures Collaboration Framework	**MLR1** Dec20
Phase II 2021-22	Technology iterations Test demonstrators Dissemination	**ER1** Nov22
Phase III 2023-24	Technology iterations Full chips	**ER2** Exp. 2024
		MLR2

20 Feb 2023 EP R&D Day | WP1.2 | Francois Vasey 2

I. Human resources

FTE per Project

FTE needs estimate

TASK	2023				2024				2025				2026				2027			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MIMOSIS Program																				
MIMOSIS Physicists (PICSEL)	1,5	1,5	1,5	2	1	1	1	1	1	2	2	2	1,5	1						
MIMOSIS microtechnics (C4PI)			0,3	0,3	0,3				0,5	0,5	0,5	0,5								
MIMOSIS-1 Tests (C4PI)	1	1																		
MIMOSIS-2 Fabrication	///////	//////																		
MIMOSIS-2 Tests (C4PI)			3	3	2	2	2	2	1											
MIMOSIS-3 Designs (C4PI)			0,5	0,5	0,5	0,5														
MIMOSIS-3 Fabrication							///////	//////												
MIMOSIS-3 Tests (C4PI)									1	1	1	1	1							
R &D for e+ e- colliders																				
65 nm / 180 nm R & D (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	2	2,5	2,5	2,5	3	3	3	3
CE65 tests (C4PI)	1	1	1	1	1	1														
Microtechnics (C4PI)									0,1	0,1					0,5	0,5	0,5			
ER_2 test structure design (C4PI)	1	1	1	1,5	1,5	1,5	1,5													
ER_2 fabrication								//////	///////											
MLR2 design (C4PI)								2	3	4	4	4								
MLR2 Fabrication												//////	///////							
beam telescope demonstrator													tests	tests						
beyond MLR2 design (C4PI)													4	4	4	4	4	4	4	4
beyond MLR2 fabrication ?																			///////	///////
R & D Test (C4PI)													1,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Integration																				
Integration (PICSEL)	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
microtechnics (C4PI)		0,2	0,2	0,2	0,2	0,2	0,2	0,2					0,2	0,2	0,2	0,2	0,2			
Simulations for e+ e- colliders																				
Physics Simulations (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
CMOS Simulation (PICSEL)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Simulation C4PI (TCAD, etc,)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
TOTAL Test (C4PI)	2	2	4	4	3	3	2	2	2	1	1	1	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
TOTAL Design (C4PI)	1	1	1,5	2	2	2	1,5	2	3	4	4	4	4	4	4	4	4	4	4	4
Total Microtechnics (C4PI)	0	0,2	0,5	0,5	0,5	0,2	0,2	0,2	0,6	0,6	0,5	0,5	0,2	0,2	0,7	0,7	0,7	0	0	0
TOTAL PICSEL	4,9	4,9	4,9	5,4	4,4	4,4	4,4	4,4	4,4	5,4	5,4	5,4	5,4	5,4	4,4	4,4	4,9	4,9	4,9	4,9

Local human resources

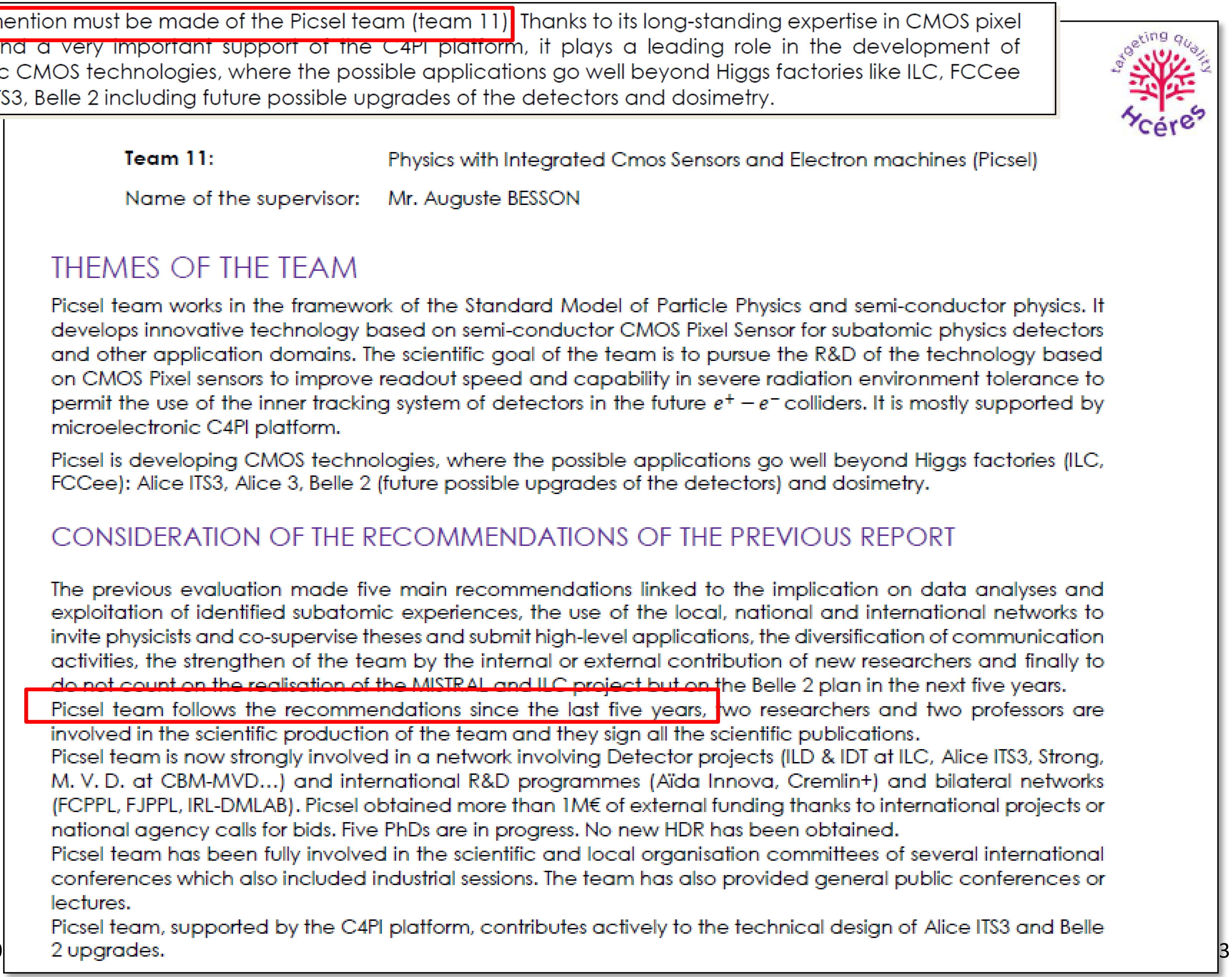
	FTE of the PICSEL team									
		2022	2023		2024		2025		2026	
		S2	S1	S2	S1	S2	S1	S2	S1	S2
Nom	fonction									
Baudot	Professor	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20
Besson	Associate Professor	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
El Bitar	Senior scientist	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Senyukov	scientist engineer	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Andrea	Senior scientist	0,05	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
Medernach	Computing engineer	0,50	0,50	0,50	0,20	0,20	0,20	0,20	0,20	0,20
Bugiel S.	post-doc	1,00	1,00	CERN						
Bugiel R.	post-doc	0.5	1,00	1,00						
ajit Kumar	post-doc AidaInnova (Belle-2-PICSEL)		0.5	0.5	0.5	0.5				
Ali Murteza	post-doc ANR		1,00	1,00	1,00	1,00				
X	post-doc CMS-FCC		0,00	0,00	1,00	1,00				
G.Sadowski	PhD Region-QMAT	1,00	1,00	1,00	1,00	1,00	1,00			
H. Darwish	co tutelle CBM	0,00	1,00	1,00	0,00					
Total FTE		5,25	8,30	7,30	6,00	6,00	4,00	3,00	3,00	3,00

J. HCERES report

(Haut Conseil de l'évaluation de la recherche et de l'enseignement supérieur)

HCERES

Special mention must be made of the Picsel team (team 11) Thanks to its long-standing expertise in CMOS pixel sensors and a very important support of the C4PI platform, it plays a leading role in the development of monolithic CMOS technologies, where the possible applications go well beyond Higgs factories like ILC, FCCee or Alice ITS3, Belle 2 including future possible upgrades of the detectors and dosimetry.



Team 11: Physics with Integrated Cmos Sensors and Electron machines (Picsel)

Name of the supervisor: Mr. Auguste BESSON

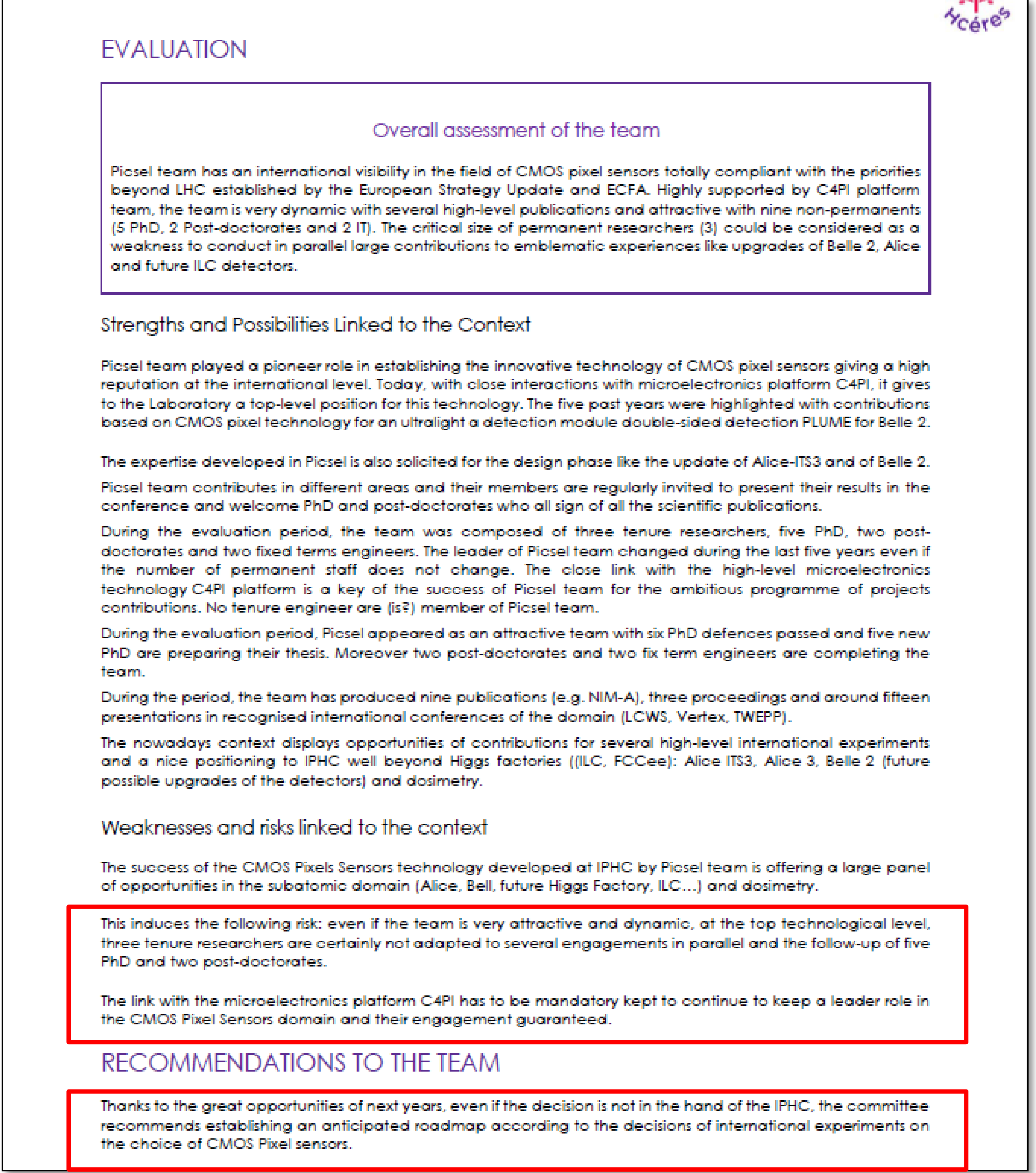
THEMES OF THE TEAM

Picsel team works in the framework of the Standard Model of Particle Physics and semi-conductor physics. It develops innovative technology based on semi-conductor CMOS Pixel Sensor for subatomic physics detectors and other application domains. The scientific goal of the team is to pursue the R&D of the technology based on CMOS Pixel sensors to improve readout speed and capability in severe radiation environment tolerance to permit the use of the inner tracking system of detectors in the future $e^+ - e^-$ colliders. It is mostly supported by microelectronic C4PI platform.

Picsel is developing CMOS technologies, where the possible applications go well beyond Higgs factories (ILC, FCCee): Alice ITS3, Alice 3, Belle 2 (future possible upgrades of the detectors) and dosimetry.

CONSIDERATION OF THE RECOMMENDATIONS OF THE PREVIOUS REPORT

The previous evaluation made five main recommendations linked to the implication on data analyses and exploitation of identified subatomic experiences, the use of the local, national and international networks to invite physicists and co-supervise theses and submit high-level applications, the diversification of communication activities, the strengthen of the team by the internal or external contribution of new researchers and finally to do not count on the realisation of the MISTRAL and ILC project but on the Belle 2 plan in the next five years.
Picsel team follows the recommendations since the last five years, two researchers and two professors are involved in the scientific production of the team and they sign all the scientific publications.
Picsel team is now strongly involved in a network involving Detector projects (ILD & IDT at ILC, Alice ITS3, Strong, M. V. D. at CBM-MVD…) and international R&D programmes (Aïda Innova, Cremlin+) and bilateral networks (FCPPL, FJPPL, IRL-DMLAB). Picsel obtained more than 1M€ of external funding thanks to international projects or national agency calls for bids. Five PhDs are in progress. No new HDR has been obtained.
Picsel team has been fully involved in the scientific and local organisation committees of several international conferences which also included industrial sessions. The team has also provided general public conferences or lectures.
Picsel team, supported by the C4PI platform, contributes actively to the technical design of Alice ITS3 and Belle 2 upgrades.



EVALUATION

Overall assessment of the team

Picsel team has an international visibility in the field of CMOS pixel sensors totally compliant with the priorities beyond LHC established by the European Strategy Update and ECFA. Highly supported by C4PI platform team, the team is very dynamic with several high-level publications and attractive with nine non-permanents (5 PhD, 2 Post-doctorates and 2 IT). The critical size of permanent researchers (3) could be considered as a weakness to conduct in parallel large contributions to emblematic experiences like upgrades of Belle 2, Alice and future ILC detectors.

Strengths and Possibilities Linked to the Context

Picsel team played a pioneer role in establishing the innovative technology of CMOS pixel sensors giving a high reputation at the international level. Today, with close interactions with microelectronics platform C4PI, it gives to the Laboratory a top-level position for this technology. The five past years were highlighted with contributions based on CMOS pixel technology for an ultralight a detection module double-sided detection PLUME for Belle 2.

The expertise developed in Picsel is also solicited for the design phase like the update of Alice-ITS3 and of Belle 2.

Picsel team contributes in different areas and their members are regularly invited to present their results in the conference and welcome PhD and post-doctorates who all sign of all the scientific publications.

During the evaluation period, the team was composed of three tenure researchers, five PhD, two post-doctorates and two fixed terms engineers. The leader of Picsel team changed during the last five years even if the number of permanent staff does not change. The close link with the high-level microelectronics technology C4PI platform is a key of the success of Picsel team for the ambitious programme of projects contributions. No tenure engineer are (is?) member of Picsel team.

During the evaluation period, Picsel appeared as an attractive team with six PhD defences passed and five new PhD are preparing their thesis. Moreover two post-doctorates and two fix term engineers are completing the team.

During the period, the team has produced nine publications (e.g. NIM-A), three proceedings and around fifteen presentations in recognised international conferences of the domain (LCWS, Vertex, TWEPP).

The nowadays context displays opportunities of contributions for several high-level international experiments and a nice positioning to IPHC well beyond Higgs factories ((ILC, FCCee): Alice ITS3, Alice 3, Belle 2 (future possible upgrades of the detectors) and dosimetry.

Weaknesses and risks linked to the context

The success of the CMOS Pixels Sensors technology developed at IPHC by Picsel team is offering a large panel of opportunities in the subatomic domain (Alice, Bell, future Higgs Factory, ILC…) and dosimetry.

This induces the following risk: even if the team is very attractive and dynamic, at the top technological level, three tenure researchers are certainly not adapted to several engagements in parallel and the follow-up of five PhD and two post-doctorates.

The link with the microelectronics platform C4PI has to be mandatory kept to continue to keep a leader role in the CMOS Pixel Sensors domain and their engagement guaranteed.

RECOMMENDATIONS TO THE TEAM

Thanks to the great opportunities of next years, even if the decision is not in the hand of the IPHC, the committee recommends establishing an anticipated roadmap according to the decisions of international experiments on the choice of CMOS Pixel sensors.

SWOT

STRENGTHS

Scientific activities inline with European particle physics roadmap
Recognized expertise in vertex detectors and trackers
Recognized expertise in MAPS R&D through connection with C4Pi

WEAKNESSES

Uncertainty on the timescale for future ee colliders
Somewhat low attractivity for PhD students and grants

OPPORTUNITIES

Strong and vivid partnerships worldwide
Structuration of the Higgs factory community
DRD3/DRD7 collaboration
Synergy with mid-term projects of other IPHC groups

THREATS

Limited person power, highly dependent on temporary staff
Uncertainties at the technological level: Si costs & competitors

K. History

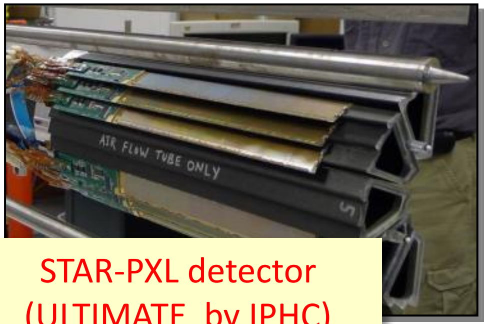
Some dates

- 1998: CMOS-MAPS R&D started @Strasbourg (IReS and LEPSI)
- MIMOSA-1
- 2002: 1st large scale prototype (MIMOSA-5)
- MIMOSA-6: binary output encoding
- MIMOSA-26 (large scale & column // read-out)
- 2009: EUDET telescopes
- 2010-2016: ULTIMATE (M-28) running in STAR-HFT
- MISTRAL/ASTRAL concepts. ALPIDE for ITS-2
- 2019: C4PI platform creation
- 2020: MIMOSIS-1 protototype

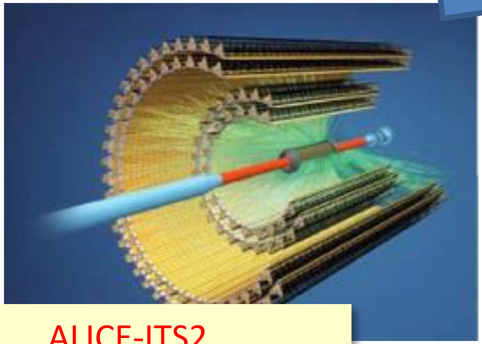
CMOS pixel sensors in particle physics

EUDET beam telescope
(Mimosa 26 by IPHC)
~ 15 copies since 2009

O(100 µs)

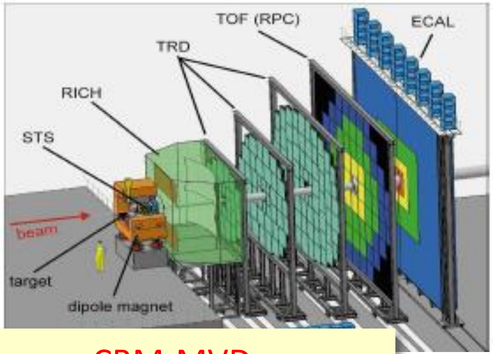


STAR-PXL detector
(ULTIMATE by IPHC)
2014-16



ALICE-ITS2
(ALPIDE by CERN & IPHC)
In construction

O(10 µs)



CBM-MVD
(MIMOSIS by IPHC & IKF)
Under development

O(1 µs)

ILC VXD & inner tracker
R & D

STAR-HFT half barrel