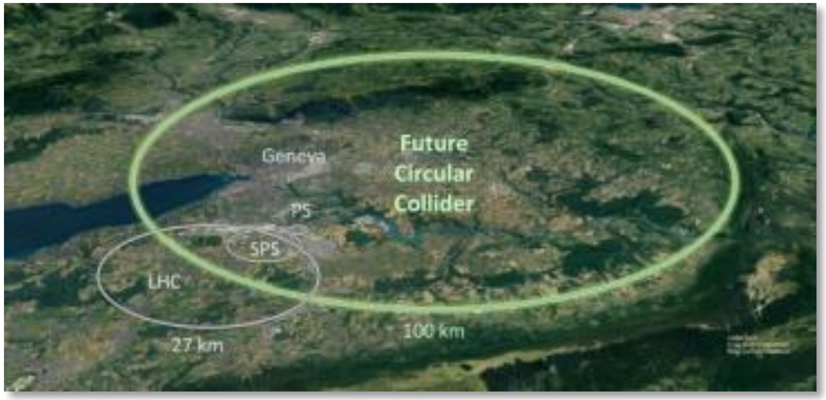
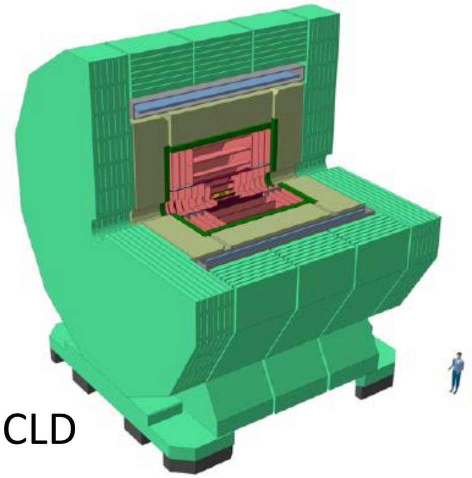
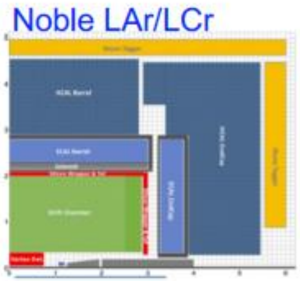
Détecteurs à pixel : retour d'expérience et futures projets

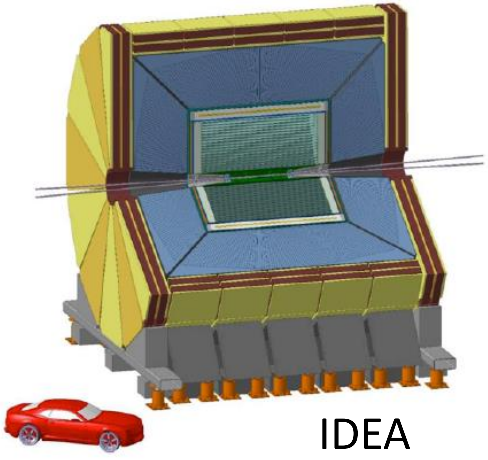
19–20 sept. 2023
Fuseau horaire Europe/Paris

Pixel detectors for FCCee



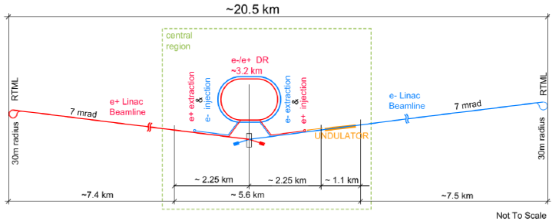


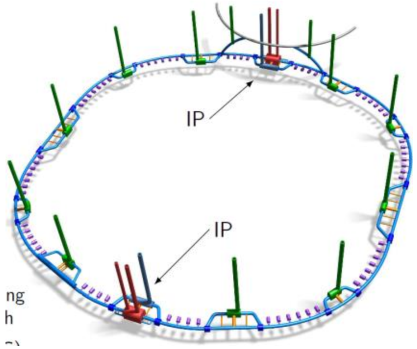


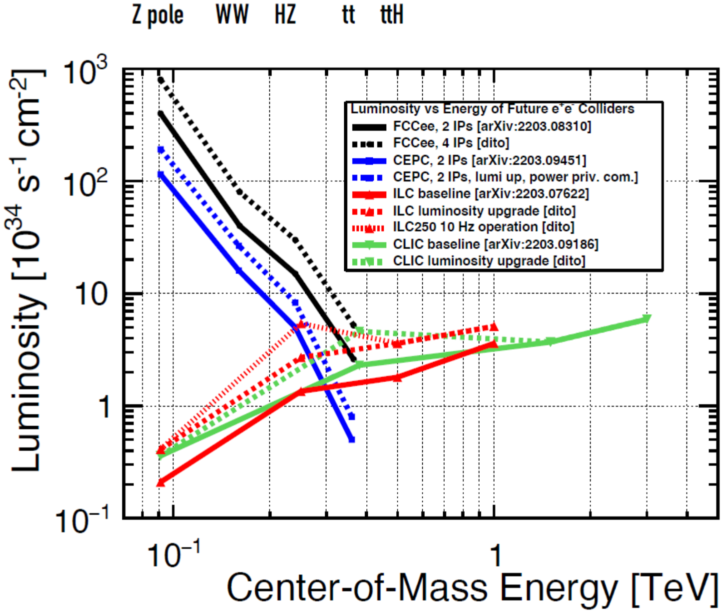


Future e^+e^- colliders (« Higgs factories »)

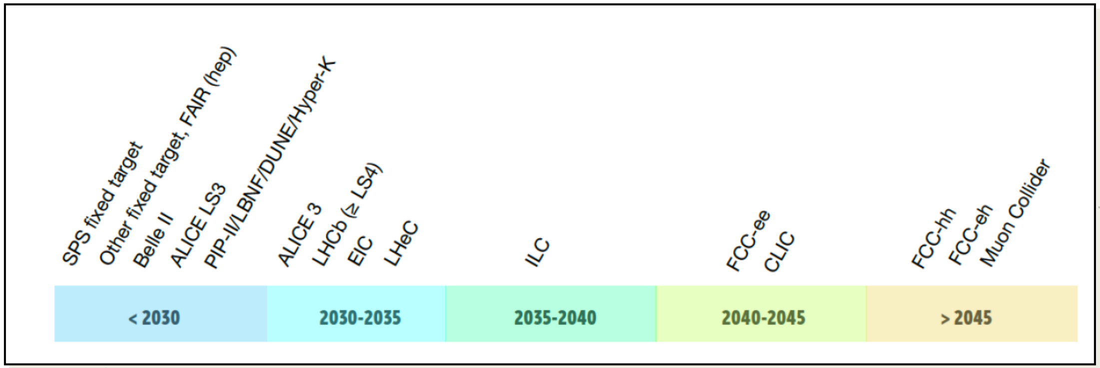
- 2 approaches
  - ✓ Circular (luminosity, 2-4 interaction points) : **FCCee**, CEPC
  - ✓ Linear (maximum Energy = $\text{Gradient}_{\text{eff}} \times$ Length): ILC, CLIC
- A lot more than Higgs physics ! (EW, top, BSM, etc.)
  - ✓ No QCD background, negligible pile-up
  - ✓ Triggerless operation possible
  - ✓ Well defined initial state, small theoretical uncertainties
  - ✓ Tunable √s
    - (91 GeV(Z), 160 GeV, 250 GeV(Zh), 350 GeV (ttbar), up to 500 GeV (ILC) or even 3 TeV (CLIC))
  - ✓ Beam polarization (ILC, CLIC)
- Future e^+e^- collider physics program demands
  - ✓ Minimizing experimental systematic uncertainties
  - ✓ High acceptance/Hermiticity
  - ✓ Track momentum resolution: $\sigma_{p_T}/p_T^2 < 5 \times 10^{-5}\ GeV^{-1}$
    - CMS/40
  - ✓ Impact parameter resolution: $\sigma_{ip} \lesssim 5\mu m \oplus \frac{10\ \mu m.\text{GeV}}{p.sin^{3/2}\theta}$
    - CMS/4
  - ✓ Jet Energy resolution: $\sigma_E/E \sim 3 - 4\%$
    - ATLAS/2
  - ✓ General particle flow approach
- Next Milestones:
  - ✓ European Strategy Update for particle physics (~2026-27)
  - ✓ Coming decade: Detector R&D programs through DRDs



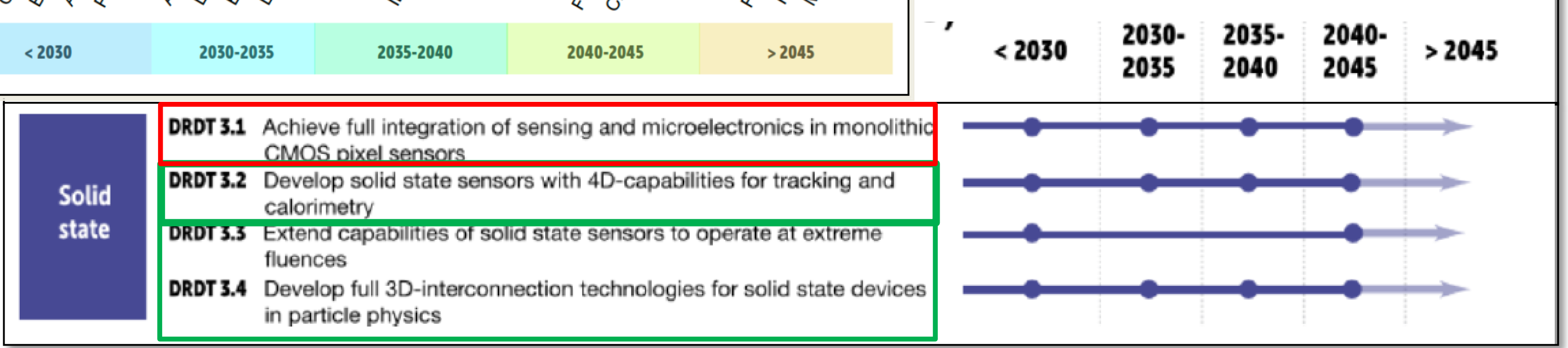




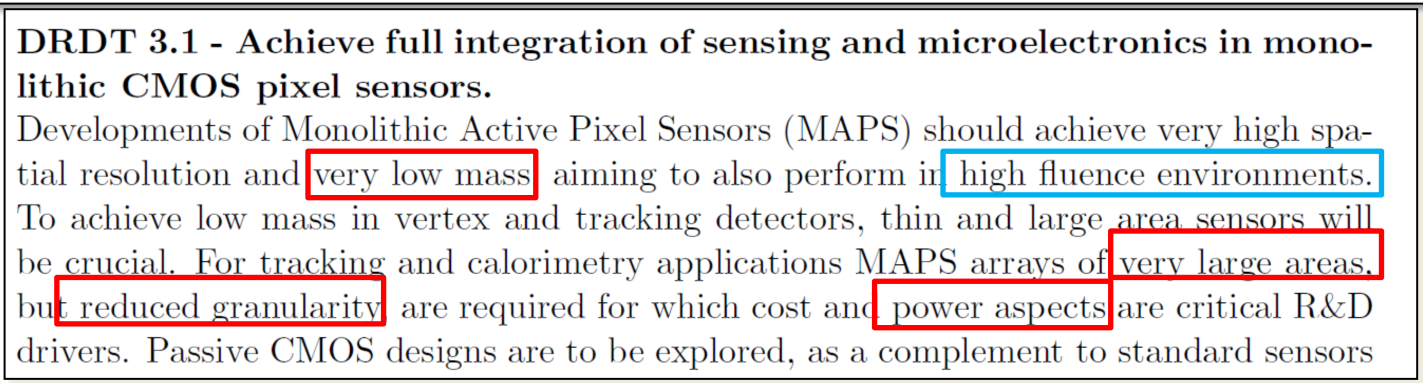
Detector R&D Roadmap: themes (DRDTs)



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

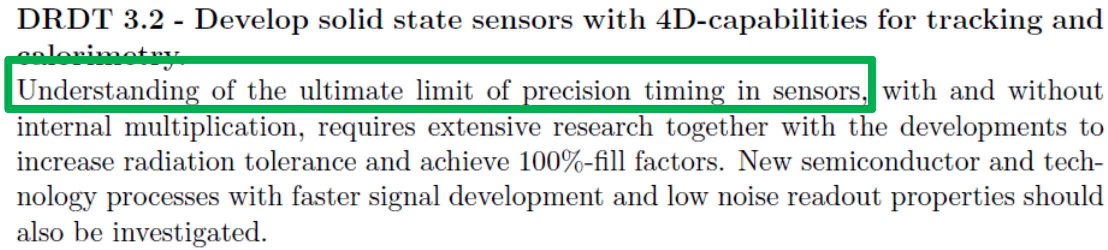


			< 2030	2030-2035	2035-2040	2040-2045	> 2045
Solid state	**DRDT 3.1**	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors	●	●	●	●	→
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry	●	●	●	●	→
	DRDT 3.3	Extend capabilities of solid 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



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

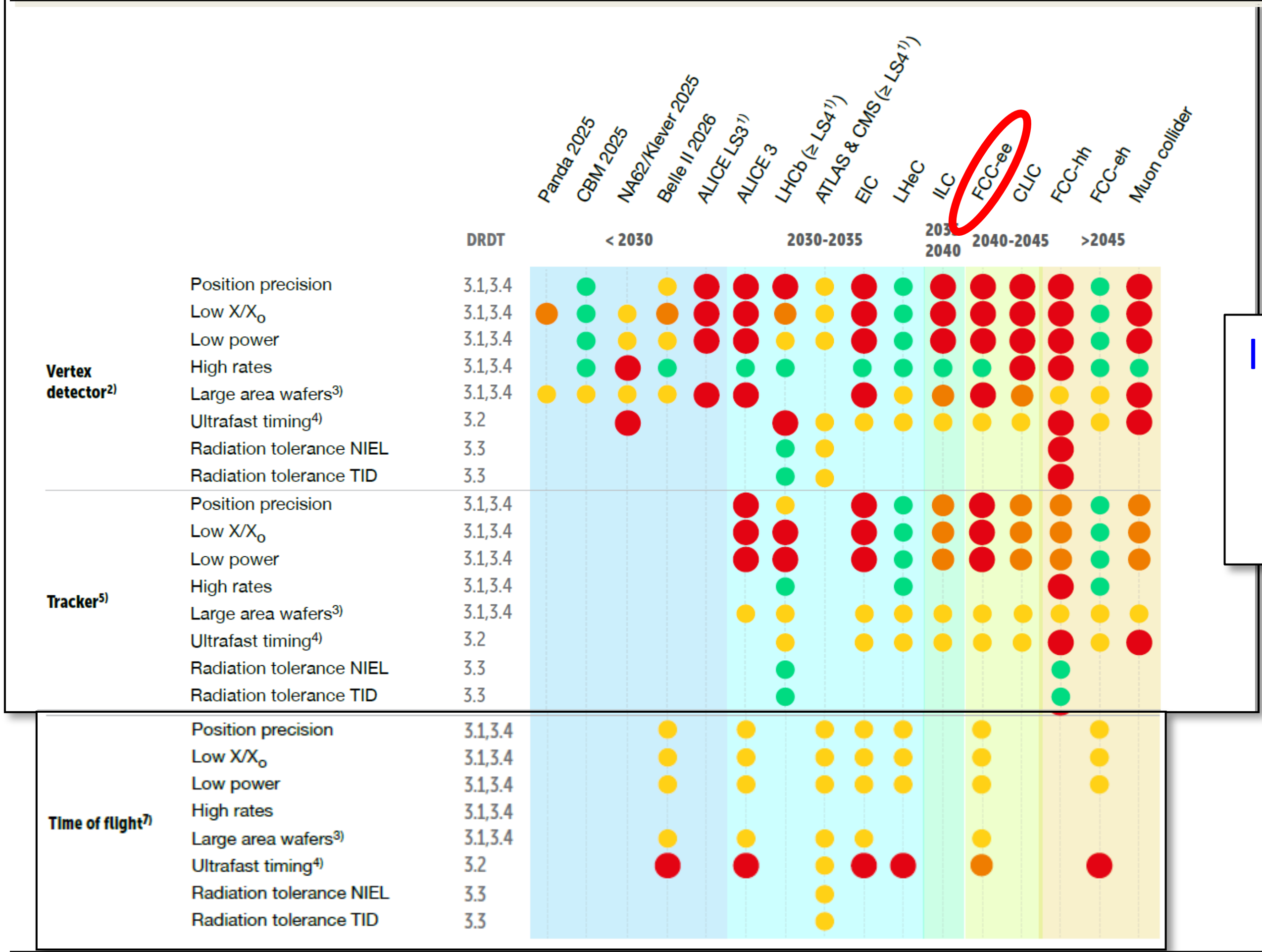
Understanding of the ultimate limit of precision timing in sensors, with and without internal multiplication, requires extensive research together with the developments to increase radiation tolerance and achieve 100%-fill factors. New semiconductor and technology processes with faster signal development and low noise readout properties should also be investigated.

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



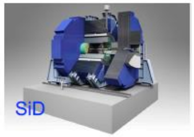
		DRDT	Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 1)	ALICE 3	LHCb (≥ LS4 1))	ATLAS & CMS (≥ LS4 1))	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030					2030-2035					2035-2040	2040-2045		>2045		
Vertex detector 2)	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	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							🟢							🟢		
Time of flight 7)	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								🟡								

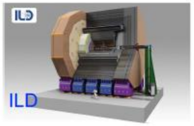
Important similarities between FCCee requirements & Heavy ions experiments (ALICE ITS3, ALICE3, EIC, etc.)

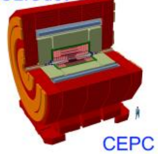
🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

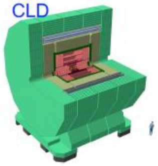
Tracking/vertexing detectors in future e^+e^- colliders

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	ILD	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 (+RICH ?)	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	

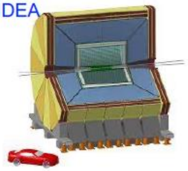

SiD


ILD

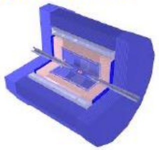
CLICdet


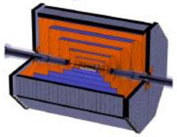
CLD


(From D. Dannheim)

IDEA


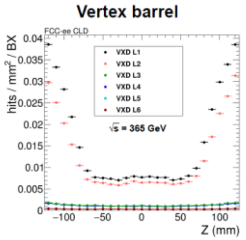
Noble LAr/LCr

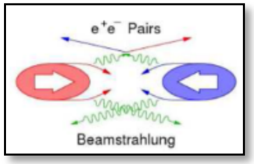

CEPC baseline


FST


Large similarities between the concepts but also significant differences

Vertex detector requirements (ILC/FCCee)



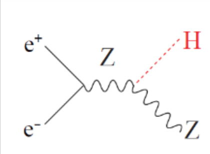


Physics O(Hz/cm^2)

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

Physics

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



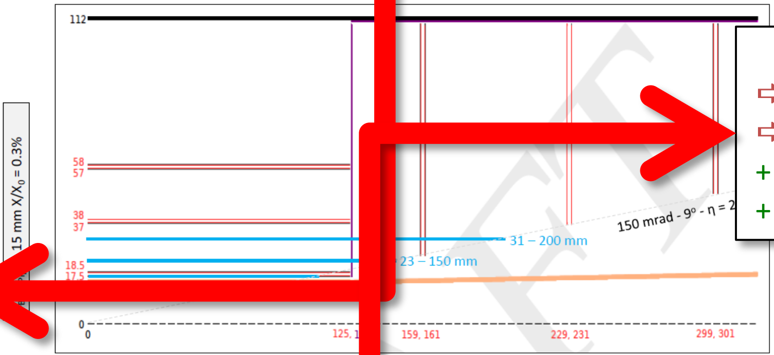
Vertex reconstruction

- ➪ 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$_0$ ≃ 0.3% / layer of Si

- CLD concept: double layers Barrel/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(100ns-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

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

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

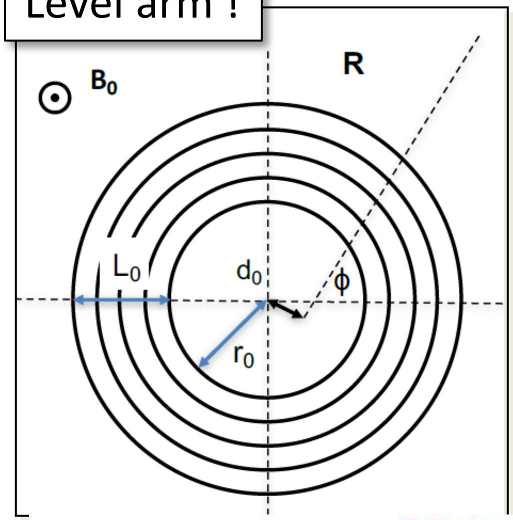
- Design: 5 single layers or 3 double layers ? Inner and outer radius ? Etc.
- R&D: ➪Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution (BX)

Tracker requirements

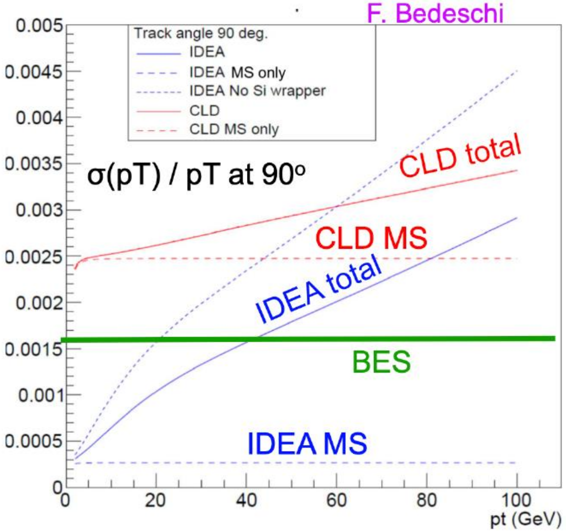
Expected performances

$$\frac{\sigma_{p_T}}{{p_T}^2} \sim 2 \times 10^{-5} GeV^{-1}$$

Level arm !



F. Bedeschi



Physics

- ➪ Momentum resolution
- ➪ Tracking efficiency
- ➪ Track separation, low fake tracks
- ➪ Etc.

- Material budget vs intrinsic resolution
  - ✓ Typically σ_{sp} ~5-10 μm/layer ; material ~1-2% X_0/layer ; Power ~< 100 mW/cm^2
  - ✓ Low momentum vs high momentum
- 2 main options:
  - ✓ All silicon (CLD, CLICdet, SiD)
    - Few high resolution layers
    - Possibly timing capabilities
  - ✓ Silicon + Gazeous detector
    - TPC (ILD) / Drift Chamber (IDEA)
    - dEdx/dNdx capabilities,
    - More hits, overall less materials
    - TPC: Ion back flow issue for circular colliders
- PID Strategy to be included (RICH, timing, dEdx, etc.)

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

$$d_{tot}/X_0 = (N+1)d/X_0.$$

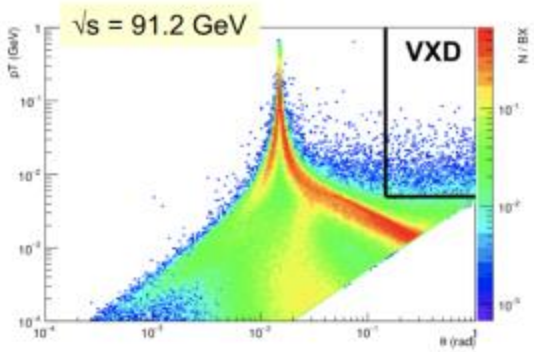
d = layer thickness, N = # layers

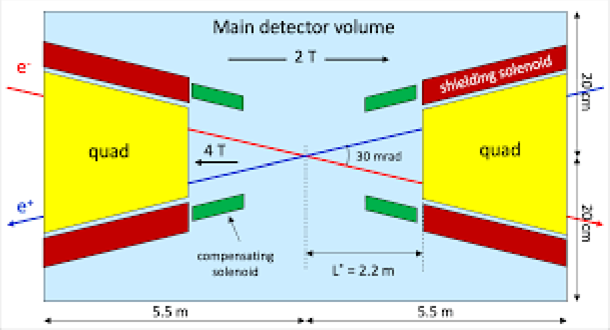
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}} \qquad \frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

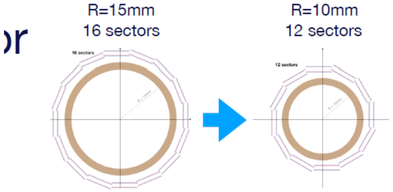
m.s. term dominates for pT ~< 100 GeV/c

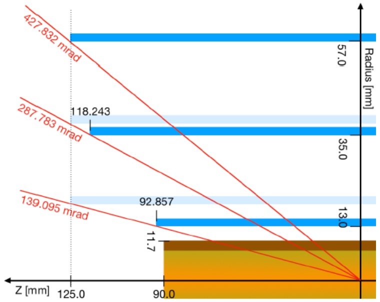
Vertex/tracking detector comments

- Particle ID has to be included in the tracker concept
  - dEdx and/or dNdx and/or fast timing
- Inner and outer radius are key factors
- Forward acceptance (e.g. asymmetry measurements)
  - Limited by MDI constraints, beam pipe, luminosity measurements, etc.
    - 30 mrad acceptance (FCCee)
- B-field
  - Limited to 2 T in circular machine (@ Z-pole)
- Beam time structure
  - Power pulsing only for linears
- Beam related Background
  - Beamstrahlung (incoherent e$^+$e$^-$ pairs)
    - Occupancy driver for linears
    - Less severe for circular (⇨Rmin reduction ~10mm))
  - Synchrotron radiation (mainly circulars)
    - Possible shielding (increase beampipe material budget)
- VTX Geometry
  - Probably 5-6 layers VTX (R < 60 mm)
    - Robustness (standalone tracking)
    - low momentum tracking
    - Track seeding @ different radii
    - e.g. FIPs, highly ionizing particles, LLPs, etc.
  - « long barrel » (sticking the first measurement point to the beam pipe)





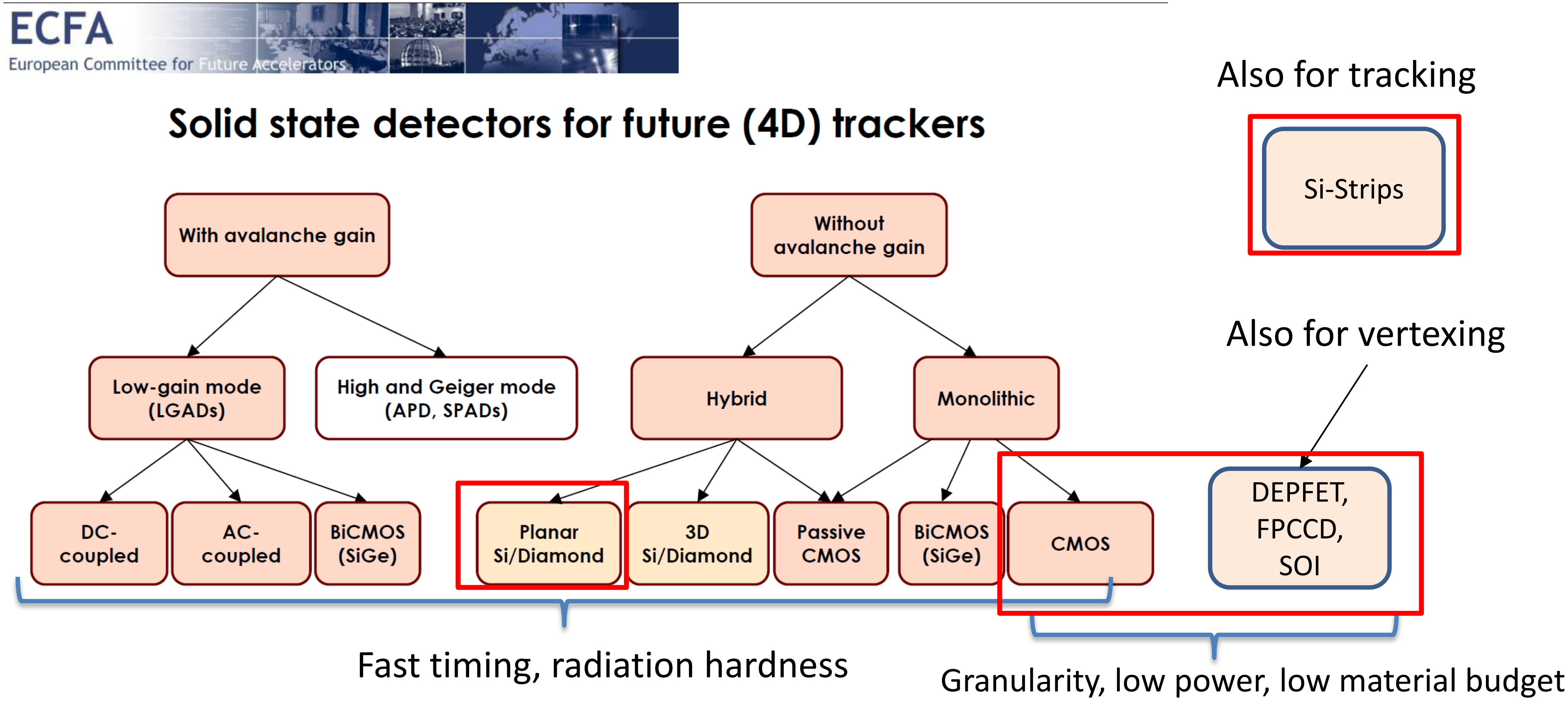




VTX/Tracking detector is highly connected to the MDI and the whole detector concept

Technologies

Pixel detectors landscape for FCCee detectors



ECFA
European Committee for Future Accelerators

Solid state detectors for future (4D) trackers

With avalanche gain
Low-gain mode (LGADs)
High and Geiger mode (APD, SPADs)
DC-coupled
AC-coupled
BiCMOS (SiGe)

Without avalanche gain
Hybrid
Monolithic
Planar Si/Diamond
3D Si/Diamond
Passive CMOS
BiCMOS (SiGe)
CMOS

Also for tracking
Si-Strips

Also for vertexing
DEPFET, FPCCD, SOI

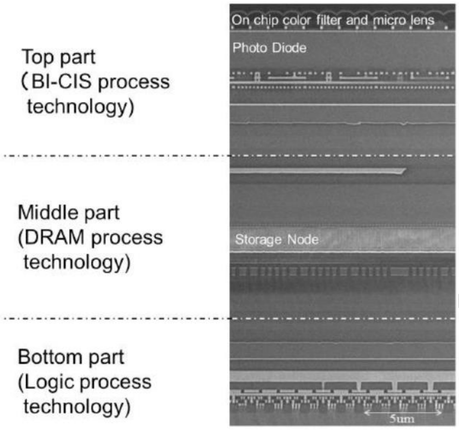
Fast timing, radiation hardness

Granularity, low power, low material budget

- VTX hierarchy of the driving parameters
  - ✓ Granularity & material budget > Power > time resolution > Radiation hardness
- Outer tracker
  - ✓ Material budget still a must. Relaxed granularity ⇨ possible focus on Power, time resolution
- Specialized timing layers
  - ✓ Timing layer ⇨ Price to pay: granularity and/or Power
- R&D needed to improve the parameter space

Plenty of R&Ds to follow carefully…

Wafer stacking in CMOS (quoted by W. Snoeys)



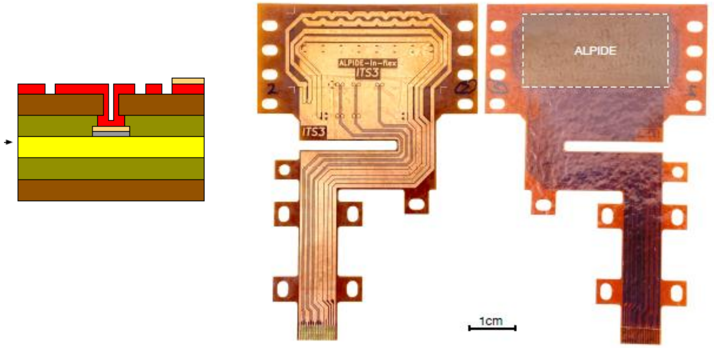
Example: SONY

Several wafers stacked with different technologies to make a full sensor

⇨ Starts to be available in imaging tech.

MAPS Foil: Embedded MAPS inside polymide flexible printed circuits

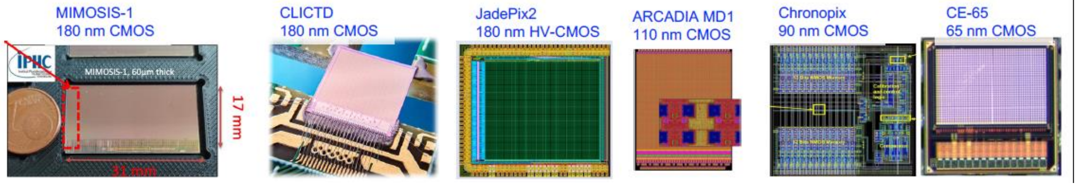
⇨ Provides electrical connection, protection, bending, 0.1%X_0



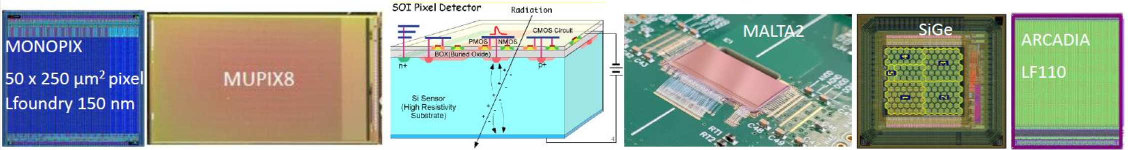
arXiv:2205.12669v1 [physics.ins-det] 2022

Huge panel of R&D and projects in CMOS

✓ Different technologies (TJ180 nm, TPSCo 65nm, LF 110 nm, etc.)

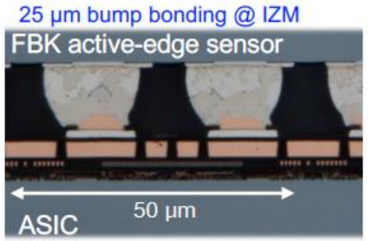


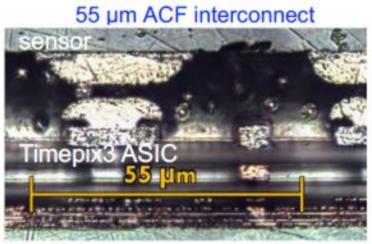
Many others: LF150, LF110, SOI, XFAB, SiGe BiCMOS, with and without gain layer, TJ180 …



Hybrid R&D

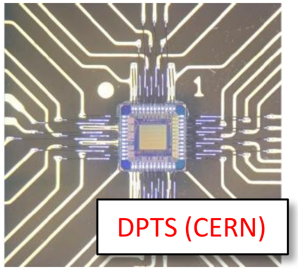
- 25 um bump bonding
- Anisotropic Conductive Film

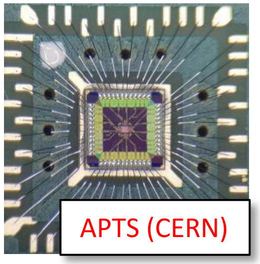


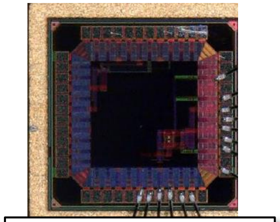


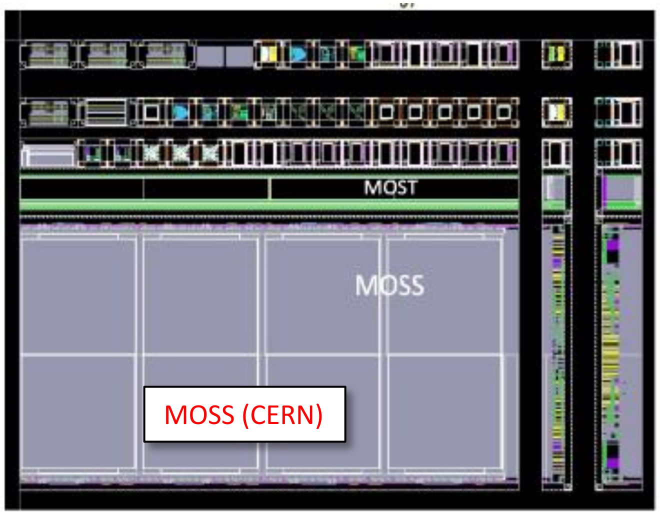
An example of R&D: TPSCo 65 nm CMOS technology

- 65 nm feature size technology
  - ✓ Main driver: CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades
    - ▪ Privileged relation between CERN with the foundry
- Added values
  - ✓ 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
- First submission: MLR1 (2020)
  - ✓ Validated the technology for HEP
- 2nd Submission ER1 (2022-23)
  - ✓ Dedicated to ITS3 (MOSS/MOST; stitching)

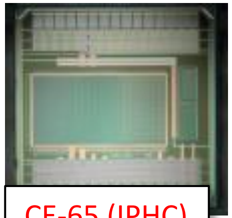

DPTS (CERN)


APTS (CERN)


TANGERINE (DESY)



MOSS (CERN)


CE-65 (IPHC)

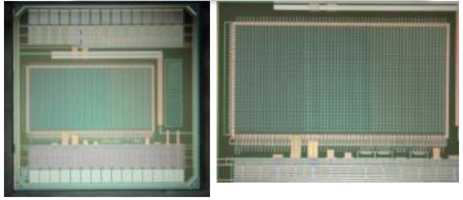

PICSEL

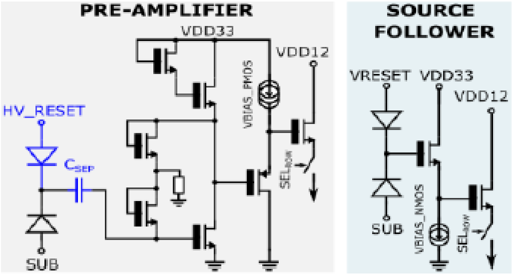
C4PI-Platform

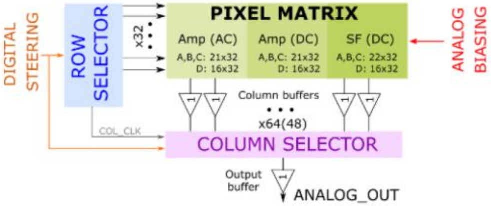
CE65_v1

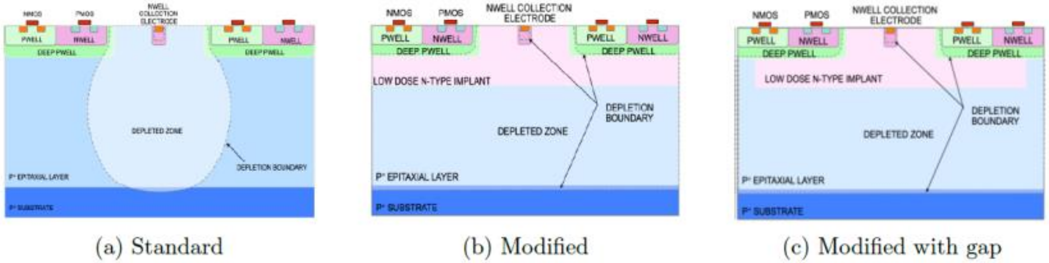
- CE_65v2 (MLR1 submission)
  - ✓ prototype designed @IPHC
  - ✓ Analog output, various designs (pitch, amplification)
- CE_65v2 (ER1 submission)
  - ✓ 18/22 μm pitch, hex design
  - ✓ Available in August 2023
- ✓ More results: PSD13, Oxford, El Bitar

CE_65 prototypes



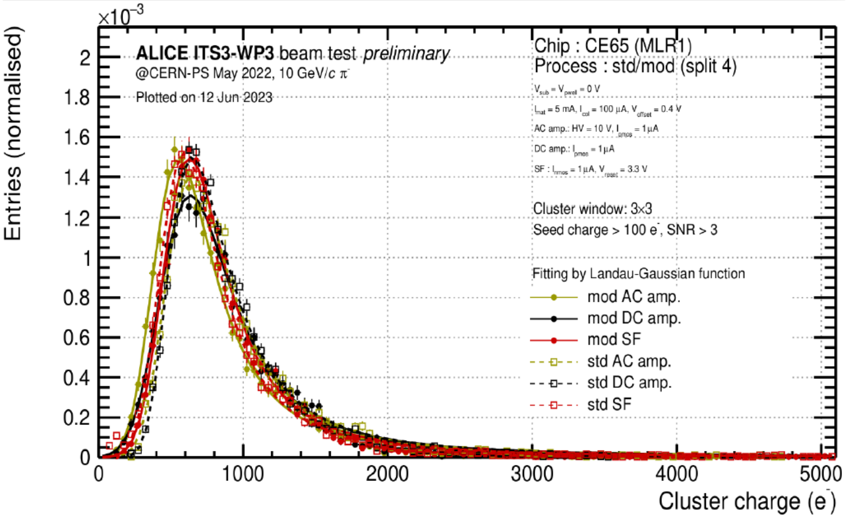


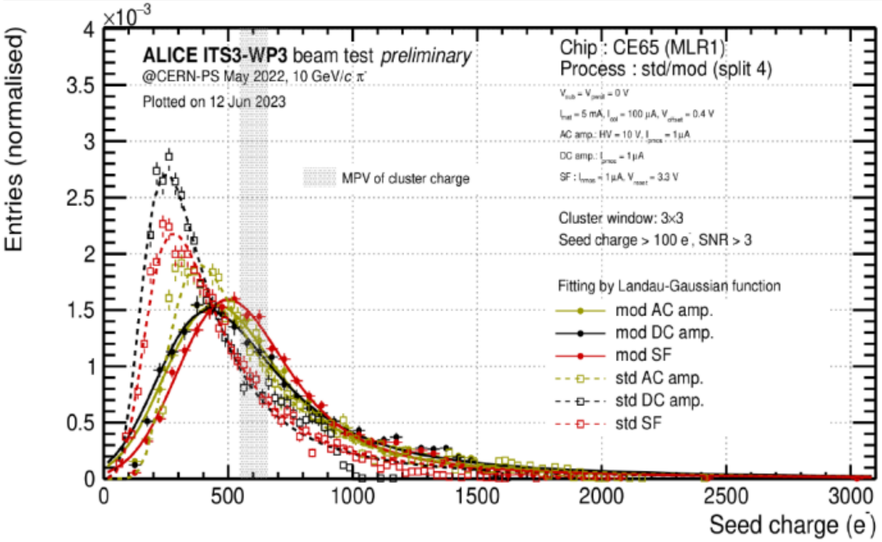




(a) Standard (b) Modified (c) Modified with gap

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





Total charge not affected by process/pixel

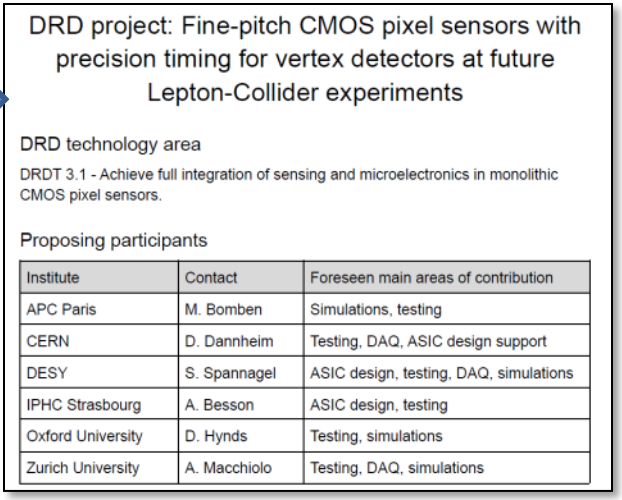
Charge sharing affected by process/pixel

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

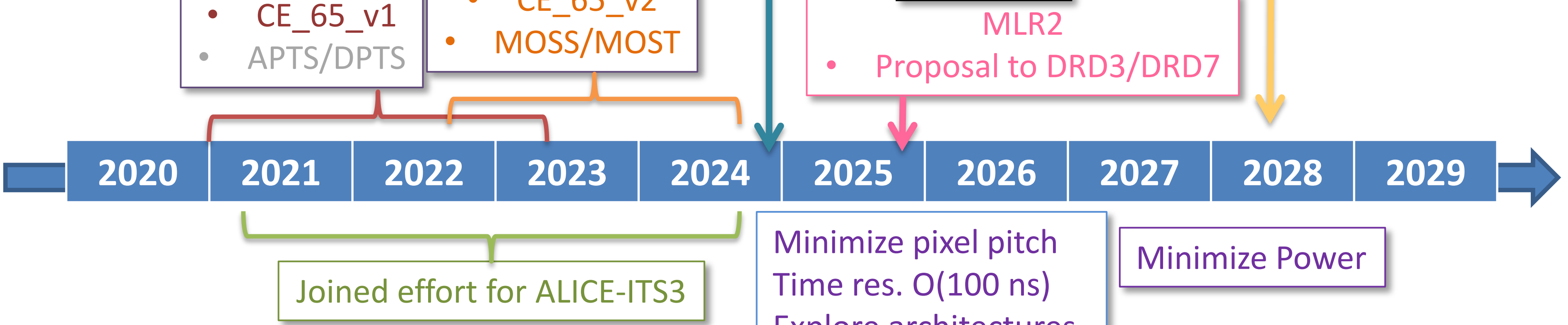
DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.

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) & strategy for FCCee



MLR1
- CE_65_v1
- APTS/DPTS

ER1
- CE_65_v2
- MOSS/MOST

ER2
- CE_65_v3 ?
- MOSS2

MLR2
- Proposal to DRD3/DRD7

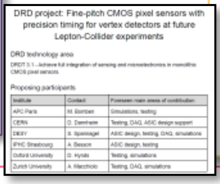
XXX
- Demonstrator for Higgs factories/beam telescope

Joined effort for ALICE-ITS3

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

Minimize Power

Fast timing prototypes ?



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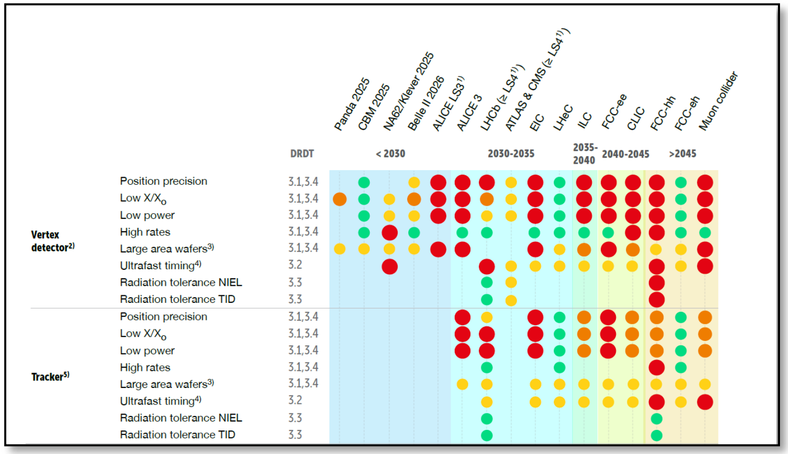
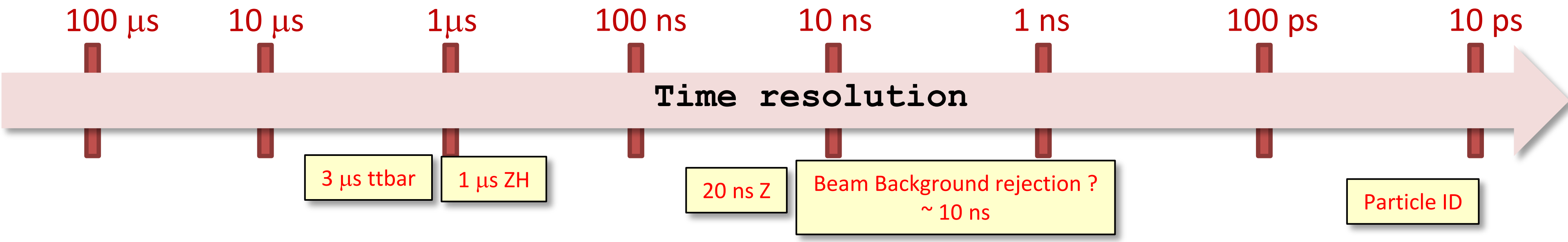
- Synergies: Mid-term projects are still the way to go
  - ✓ CBM (Mimosis), ALICE ITS-3, Belle-2 upgrade (Obelix), LHCb, EIC, etc.
  - ✓ provides invaluable milestones
- National effort:
  - ✓ Continue to strengthen the community targeting FCCee applications ⇨ ANR ?
  - ✓ Find the right balance between generic R&D and specific requirements
  - ✓ Develop simulations & physics studies dedicated to FCCee
- International effort
  - ✓ DRD3/DRD7



		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							🟢							🟢		

Particle ID & Timing

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 (TPC)
  - ✓ Added value for intermediate radii (e.g. LLPs ?)
- Specialized layers
  - ✓ Doesn't compromise the other requirements (material budget and granularity)
    - ▪ Probably not in the most inner layers

Particle ID and time resolution DRD4 & 1/3

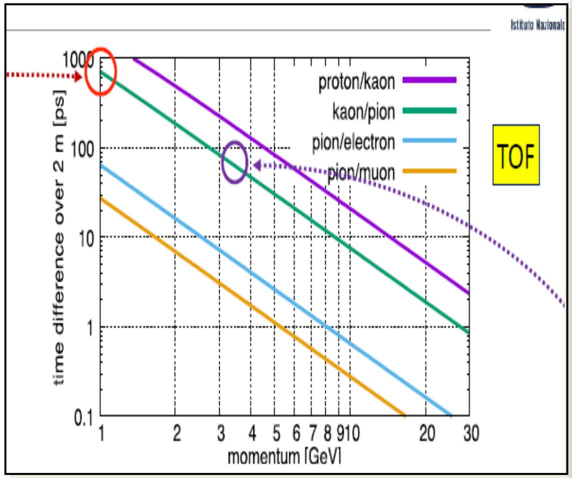
More details here: https://indico.cern.ch/event/1202105/contributions/5402790/attachments/2662086/4612032/FCC-DRD4.pdf

- Goal:
  - ✓ K/π, π/e⁻ separation, etc. ⇨ Interest to push beyond 10 ps resolution
  - ✓ Even more important for the physics program @ Z peak

Fast timing (<100 ps)
Solid state (pixelated) detector (DRD3)

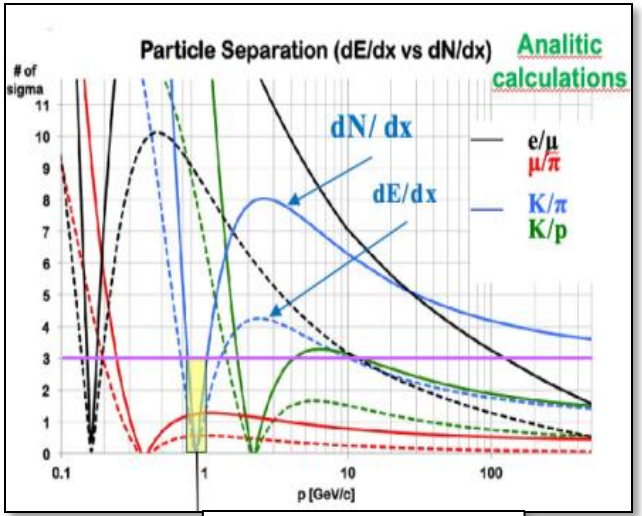
dE/dx + dN/dx
Mainly gazeous detector, e.g. TPC, RICH (DRD1)

Time difference (ps)



Time of Flight

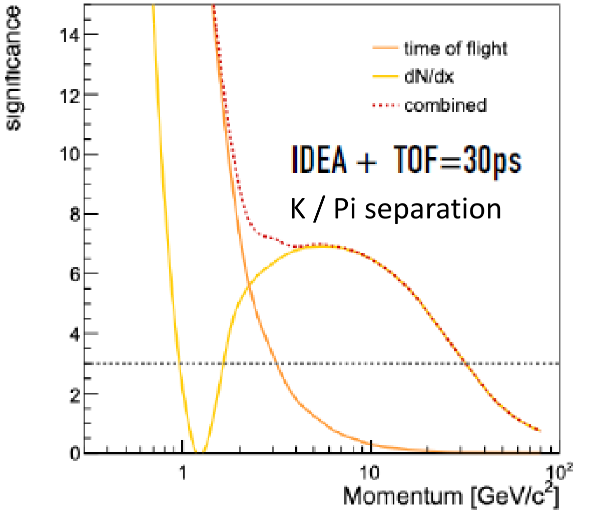
Separation Power (significance)



dE/dx – dN/dx

Separation Power

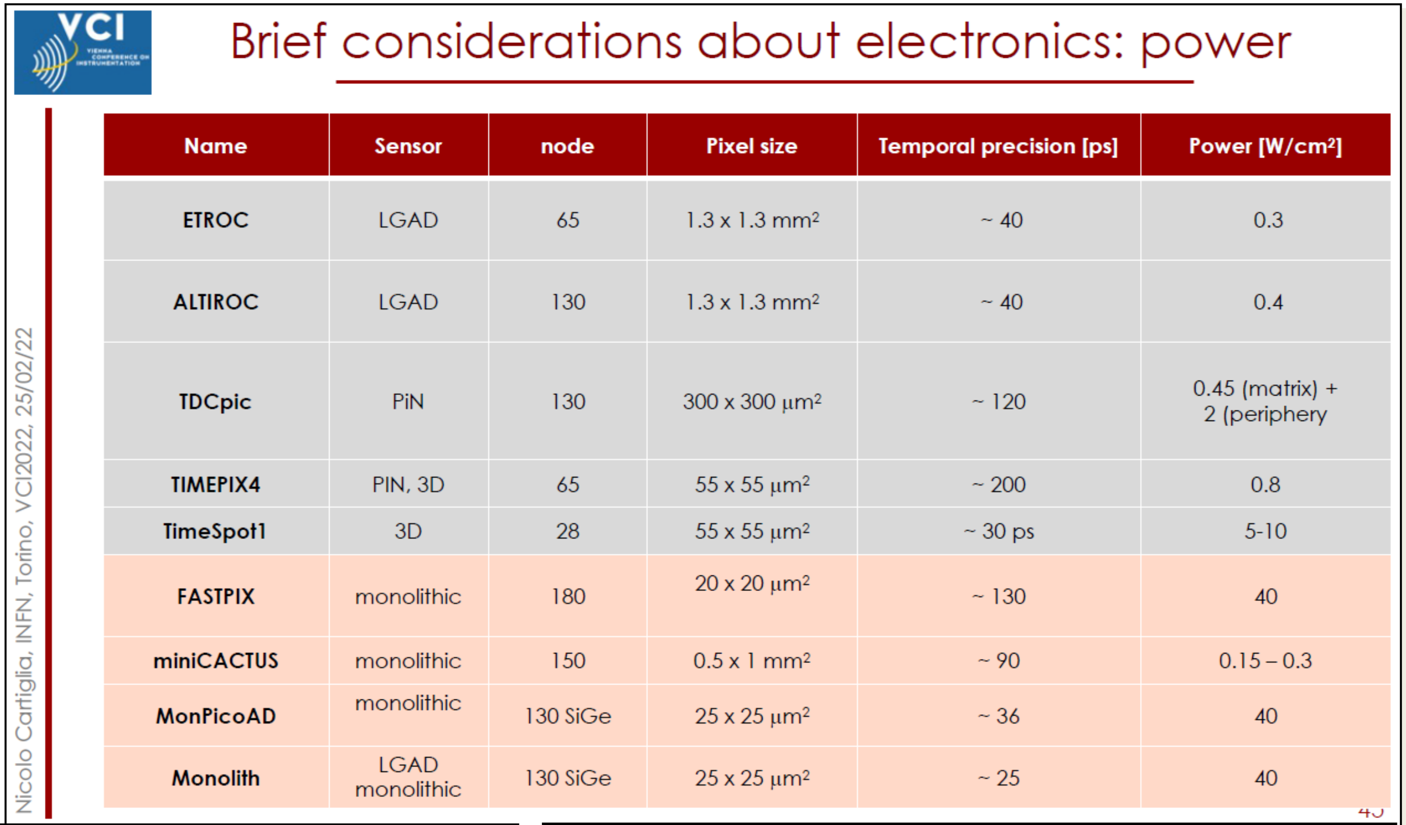
Bedeschi et al Eur. Phys. J. C 82, 646



Combined measurement

Momentum (GeV/c)

Power vs fast timing vs pixel size

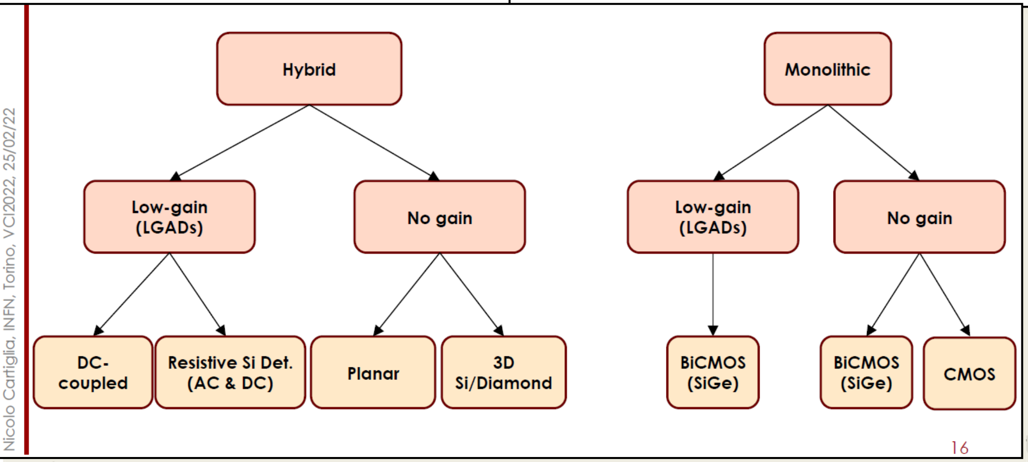


Brief considerations about electronics: power

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)
No gain
DC-coupled
Resistive Si Det. (AC & DC)
Planar
3D Si/Diamond

Monolithic
Low-gain (LGADs)
No gain
BiCMOS (SiGe)
BiCMOS (SiGe)
CMOS

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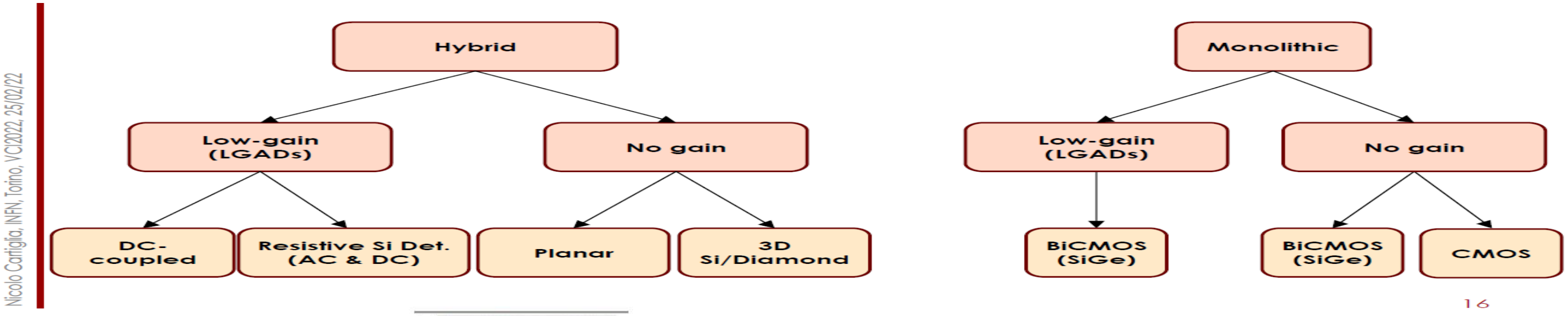
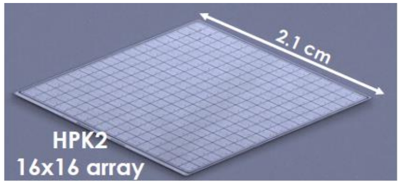
16

Price to pay: additionnal cooling system (addtionnal material)

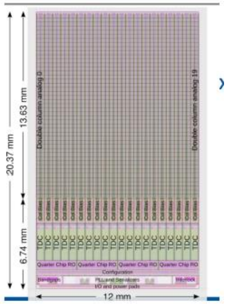
Timing Landscape in semi-conductor technologies



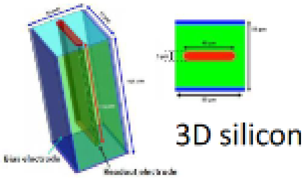
Low gain to minimize jitter

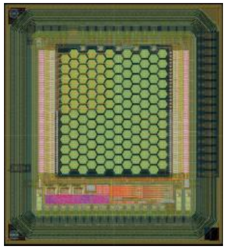


CMS & ATLAS
(LGAD DC coupled)

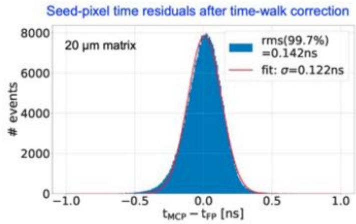


NA62 Gigatracker
(planar)

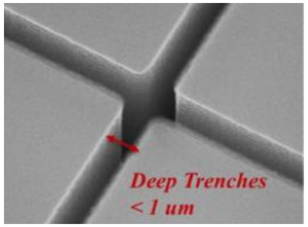




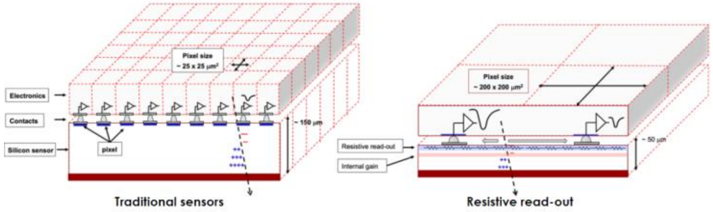
MonPicoAd
(BiCMOS)



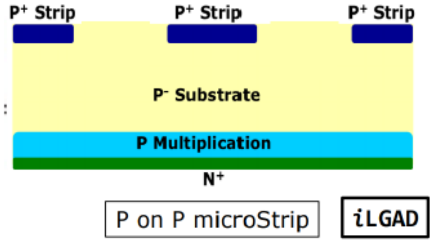
FastPix
(CMOS)



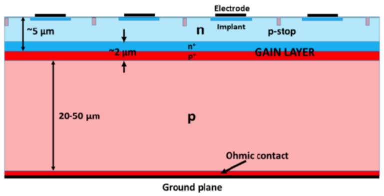
Trench Isolated-LGAD
(reduces no gain region)



Resistive read-out
AC-LGADS
(signal sharing)



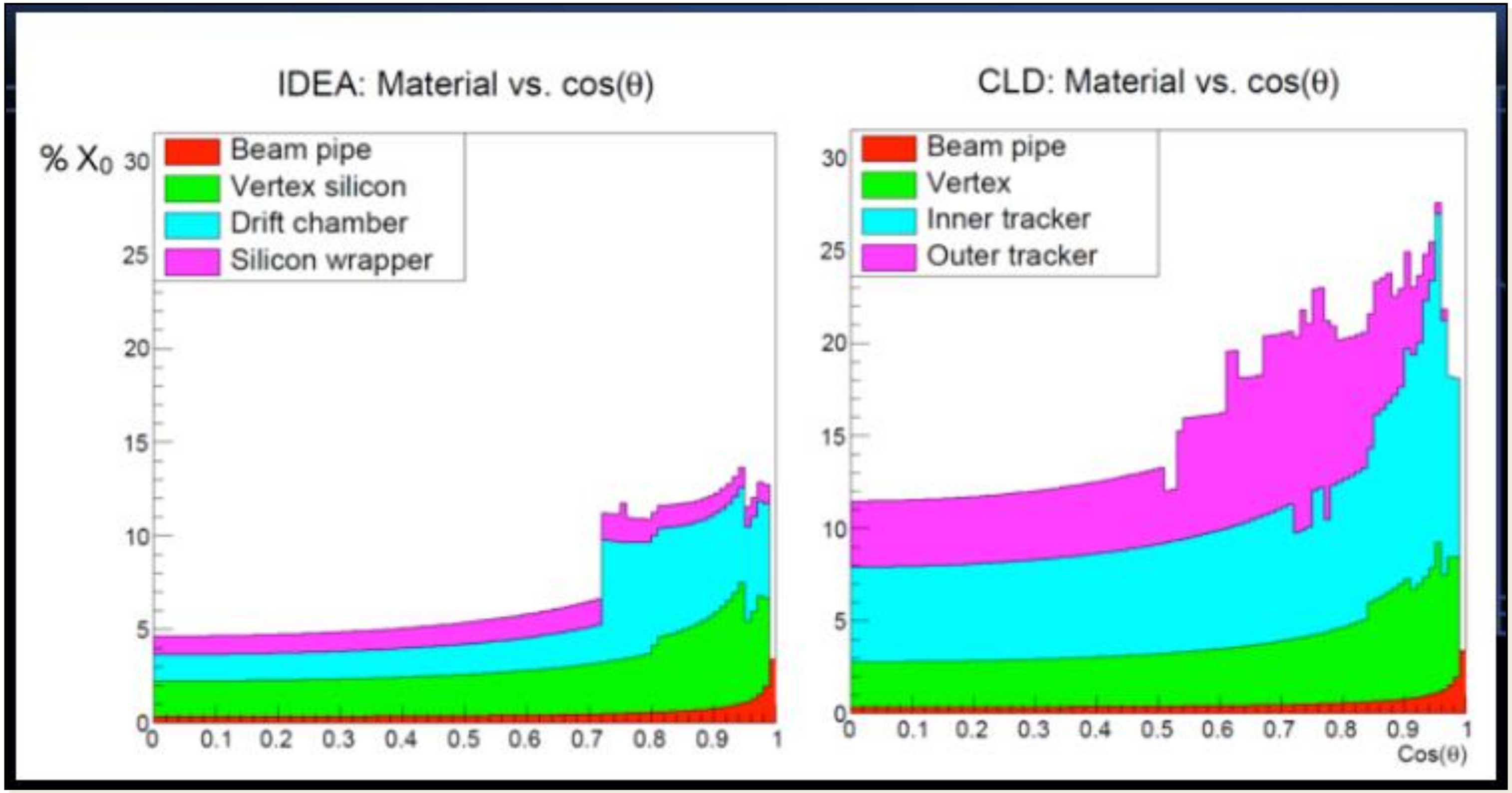
Inverse ILGAD



Deep Junction
DJ-LGAD

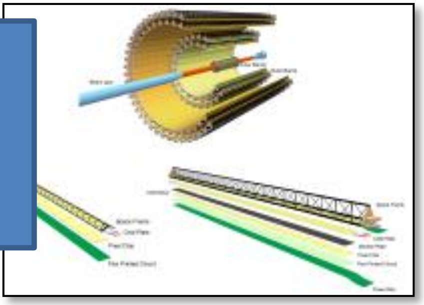
See e.g. ECFA-TF4 Time of flight technologies (R. Forty)

Material budget

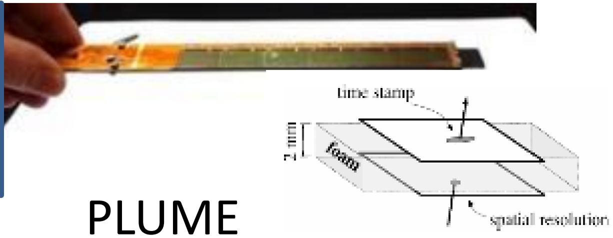


Material budget: starting from the layers

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



Double sided layers

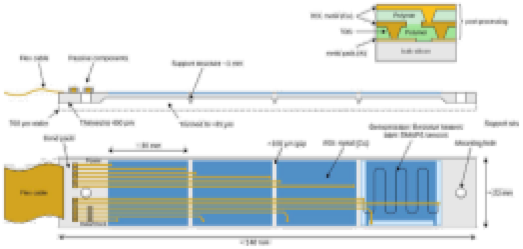


PLUME
(Bristol, DESY, IPHC)

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

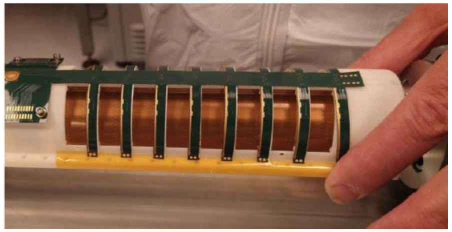
Self supported silicon
(Belle-2 upgrade)

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



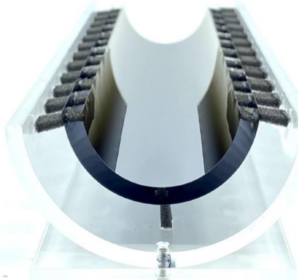
Pseudo stitching
+ bent sensors
(superALPIDE)

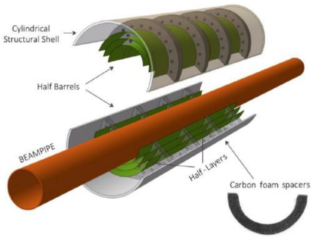
- 1 silicon piece cut from one ALPIDE wafer
(9x2 dies, ~1/2 of layer 0)



Stitching
+ bent sensors
ALICE-ITS3

Layers 2+1

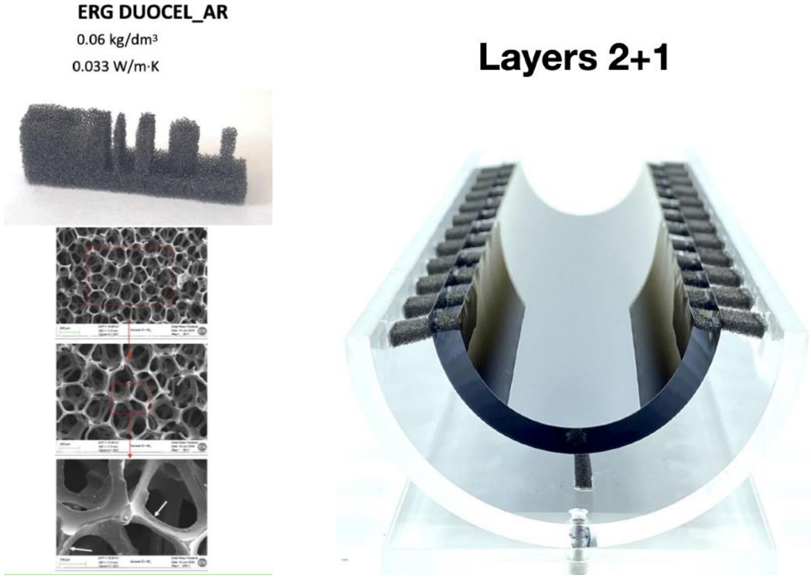




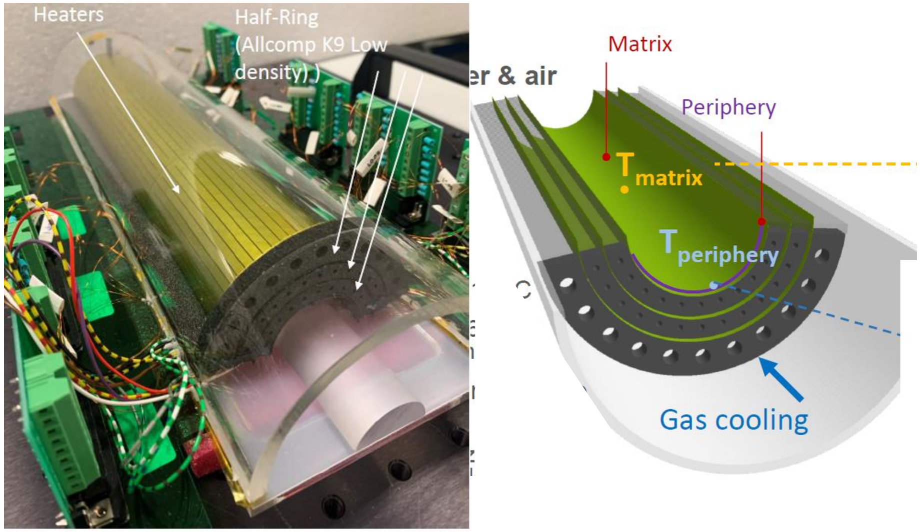
Inputs for engineering studies

ALICE ITS3 tests

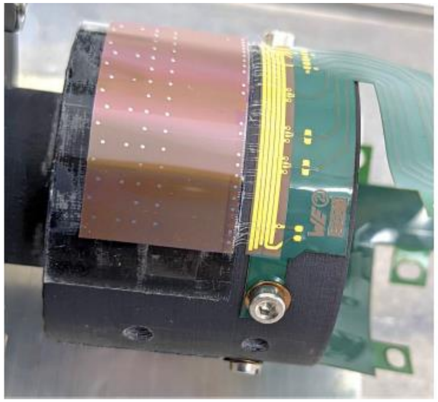
A. Kluge
on behalf of the ALICE collaboration
22 February, 2022
VCI



Carbon fiber foam spacer



Integration and cooling studies



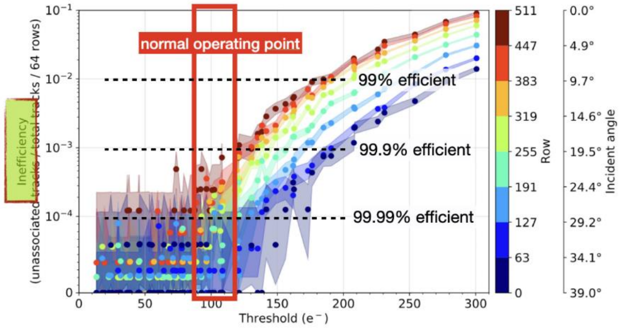
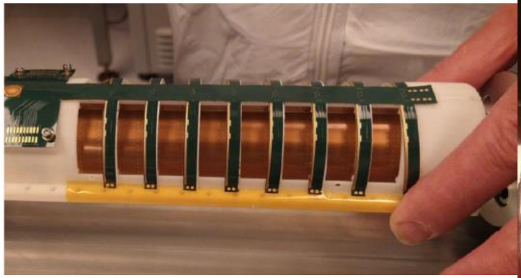


Fig. 10: Inefficiency as a function of threshold for different rows and incident angles with partially logarithmic scale (10^{-1} to 10^{-5}) to show fully efficient rows. Each data point corresponds to at least 8k tracks.

Bent sensors in test beam

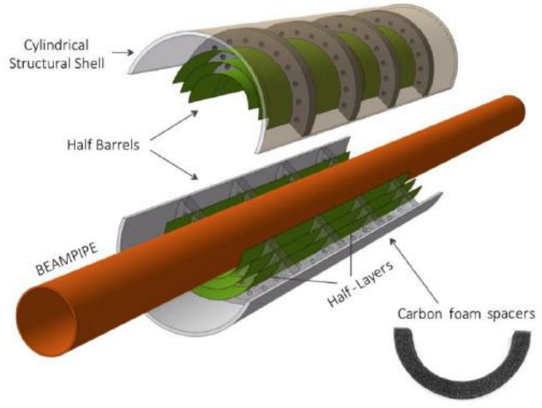
- 1 silicon piece cut from one ALPIDE wafer (9x2 dies, ~1/2 of layer 0)

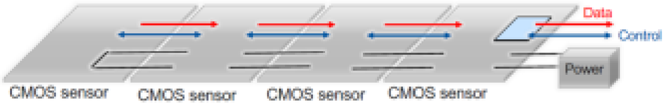


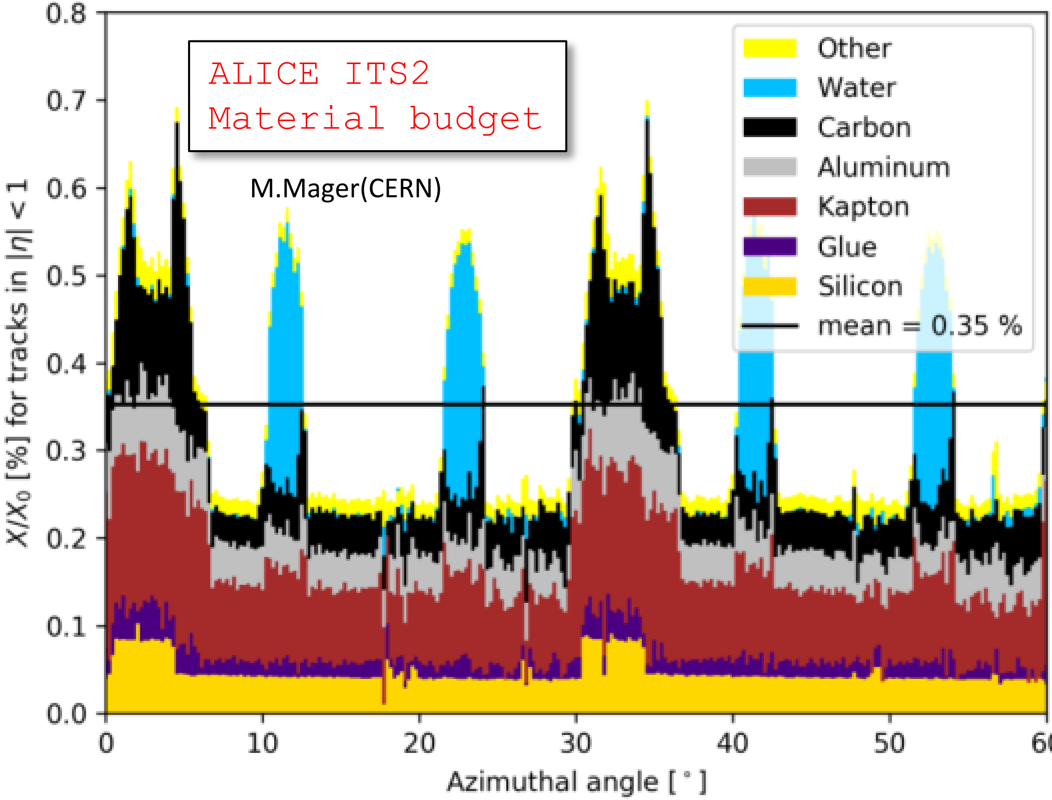
Inteconnexion tests (superALPIDE)

On going experiments pave the road for Higgs factory detectors (many other examples)

ALICE ITS3: Bent sensors & stitching

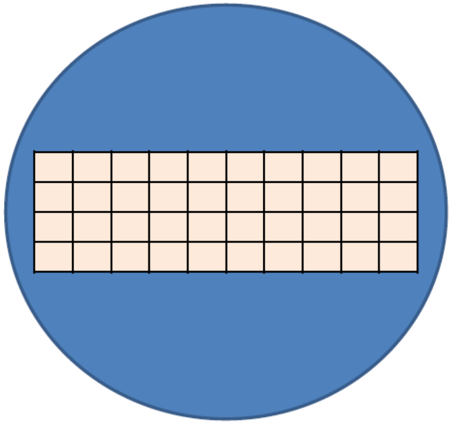






https://indico.cern.ch/event/1071914/

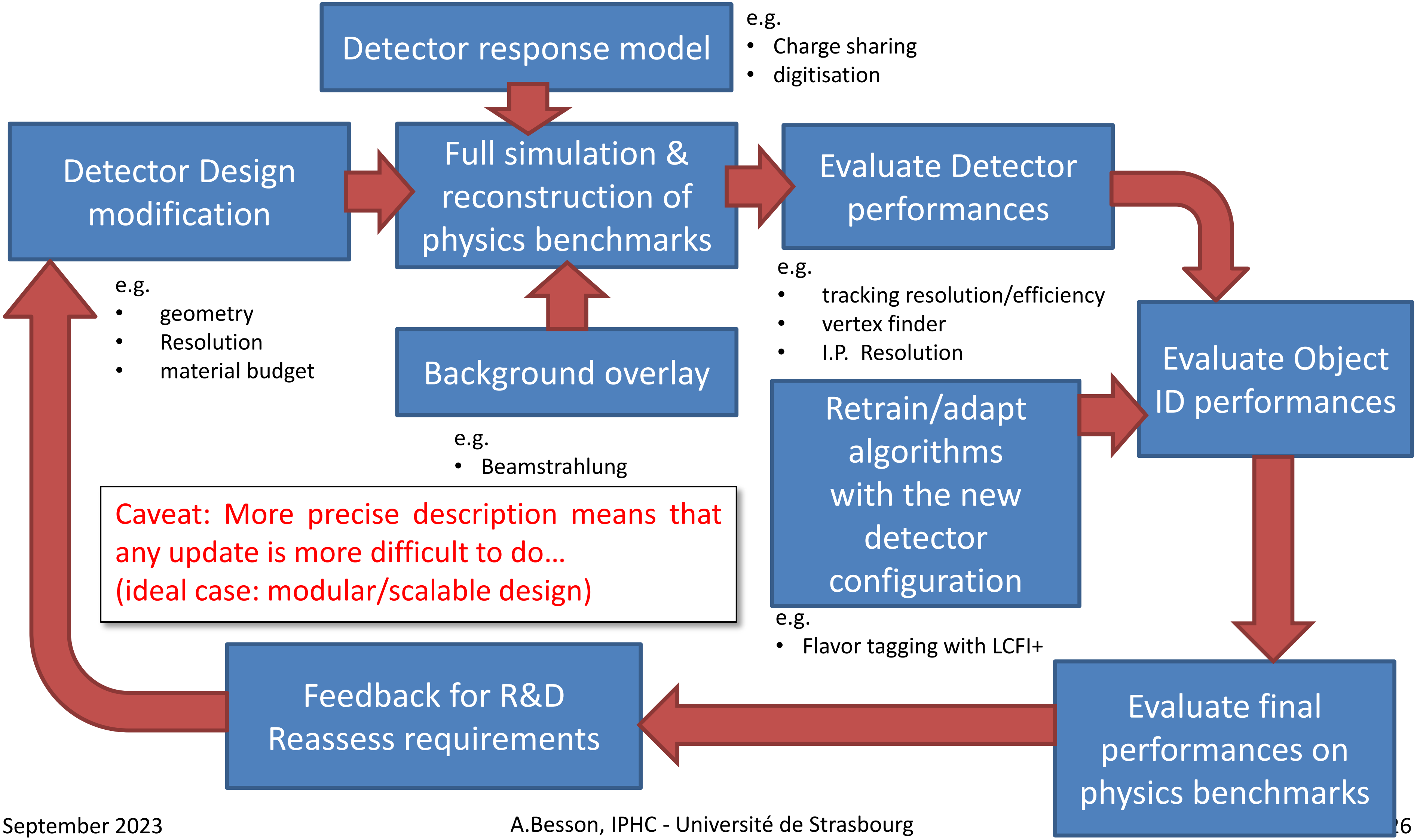
- ALICE-ITS3/CERN drives the R&D on Stitching + bent sensors:
  - ✓ Sensor part ~15% of total material budget
  - ✓ Sensors thinned down to 50 µm
  - ✓ Minimizing overlapping regions, minimizing minimal radius around the beam pipe
- Challenges and caveats (for e$^+$e$^-$ colliders)
  - ✓ Mechanics ? 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)



Detector optimization and simulations

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

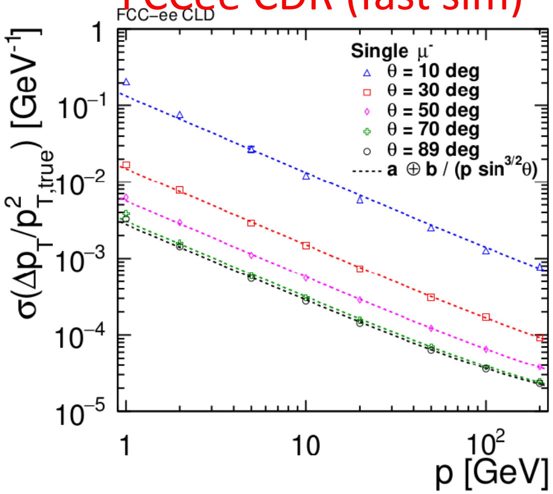
Caveat: More precise description means that any update is more difficult to do…
(ideal case: modular/scalable design)

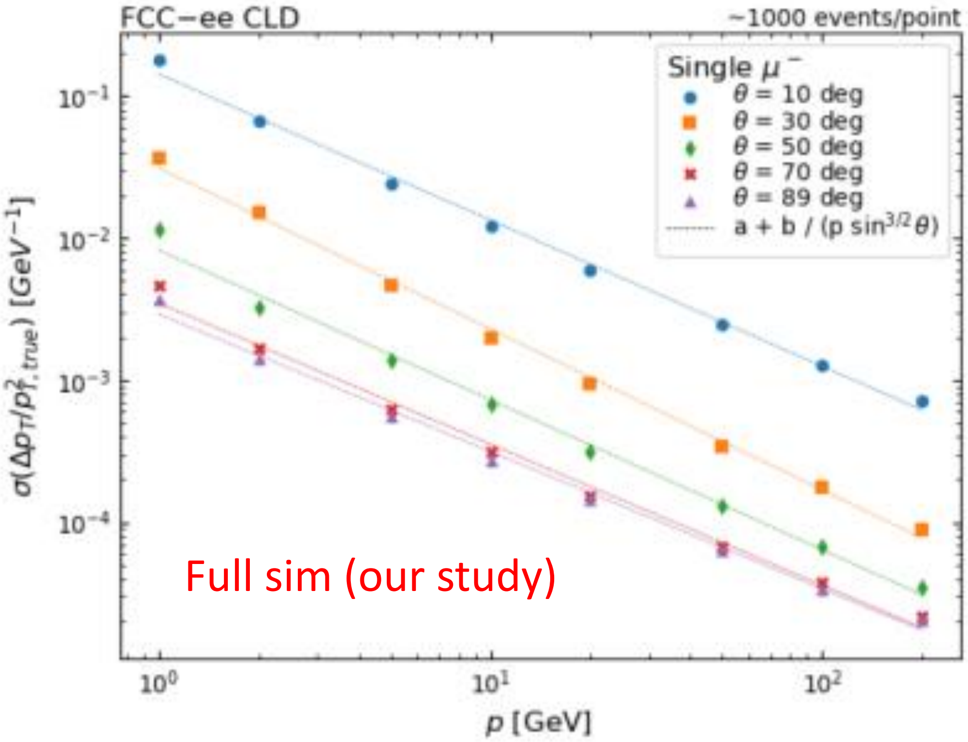
Example of detector optimization: CLD vertex/tracker

Jeremy Andrea, Auguste Besson, Ziad El Bitar, Gaelle Sadowski (PhD) (IPHC, CNRS, Strasbourg)

- Master the full simulation chain (key4hep) for detector optimisation
  - ✓ Goal: Optimisation of the Design
    - Complete physics studies (Long lived particle: HNL, etc.)
    - Object performances: Tracking, vertexing, Flavour tagging
  - ✓ Test new ideas
  - ✓ Guidelines for future R&D

FCCee CDR (fast sim)





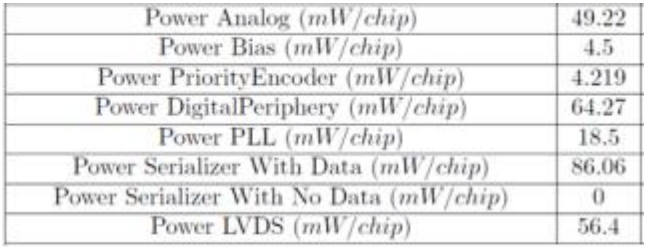
Full sim (our study)

Full simulation chain validated

Power, Architecture & designs

Power challenges

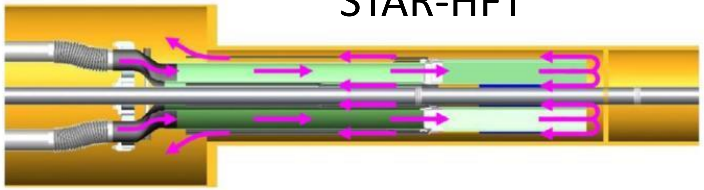
- Power is in conflict with all other parameters
- Baseline:
  - ✓ Air flow cooling only to minimize material budget
  - ✓ Up to ~ 20 mW/cm^2
    - ▪ what is the limit ? ~50 mW/cm^2 or even more ?
- Driving parameters:
  - ✓ # channels, Time resolution / data flux
  - ✓ Surface (VXD ~ 3500 cm^2 ; tracker 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)



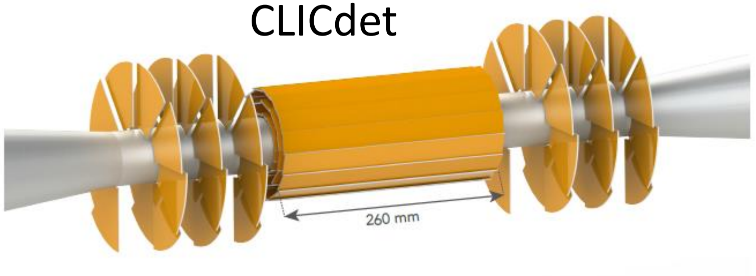
Power Analog ($mW/chip$)	49.22
Power Bias ($mW/chip$)	4.5
Power PriorityEncoder ($mW/chip$)	4.219
Power DigitalPeriphery ($mW/chip$)	64.27
Power PLL ($mW/chip$)	18.5
Power Serializer With Data ($mW/chip$)	86.06
Power Serializer With No Data ($mW/chip$)	0
Power LVDS ($mW/chip$)	56.4

MIMOSIS like architecture, 180 nm

STAR-HFT



CLICdet



Design challenges: From new ideas to real chips

- How to really make it ?
  - ✓ R&D prototypes ≠ final production chip installed in real experiment
  - ✓ Submission cost issue for R&D
    - Trade-off between new (expensive) technologies and older (cheaper) technologies
- The complexity is growing
  - ✓ New read-out architecture, etc.
  - ✓ Work flow inspired from successfull chips installed in experiments (e.g. ALPIDE for ALICE-ITS2)
    - ⇨ push to concentrate on few technologies
  - ✓ Verification tools are absolutely crucial
    - « Digital on top »
    - Global support on tools DRD3/ DRD7 connexion !
- Connexion with foundries absolutely crucial
  - ✓ Contracts, confidentiality, etc.
  - ✓ Long term plans to maintain interest from fourndries (HEP is a small player)
  - ✓ Access to technology options to optimize it for HEP applications

Pixel detector @FCCee: Summary

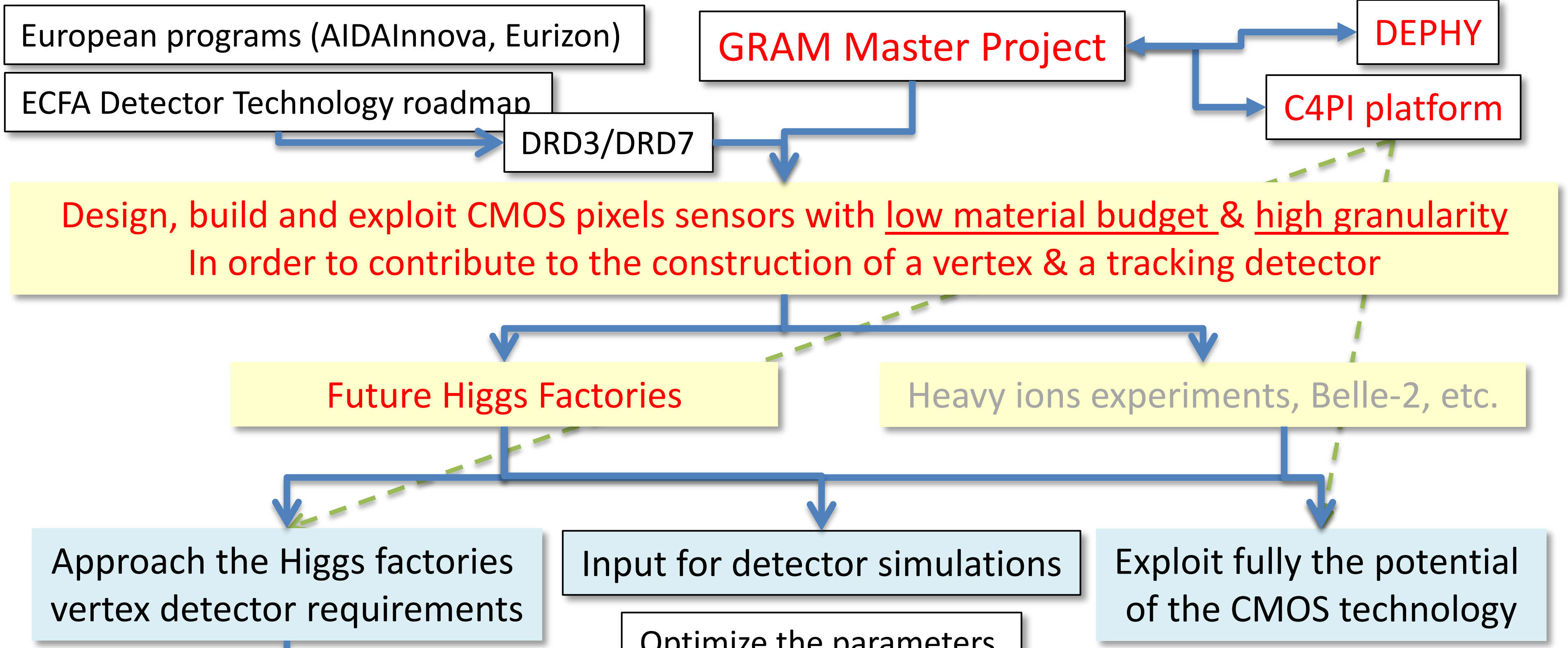
- Apologies for not covering
  - ✓ Many technologies and on going R&D
    - (FPCCD, SOI, DEPFET, BiCMOS (SiGe), etc.
  - ✓ Integration
    - Cooling R&D (MCC, etc.), Read-out
  - ✓ Operation and monitoring (Built-in Self Test (BIST) approach ?)
  - ✓ Alignment

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

- Integration R&D is a final performances driver !
  - ✓ Fill the gap between nice ideas and real detectors
    - e.g. Stitching & bent sensors developed in ALICE-ITS3 context

- Strategy
  - ✓ The right balance has to be found inside DRDs between defining priorities and allowing new ideas to emerge
  - ✓ Given the complex parameter space of R&D and detector design, a pragmatic approach should be privileged
    - Although the R&D is generic, studies on VTX/TRK should be don inside a while detector concept
    - French community strategy ?
    - Increasing complexity step by step, demonstrators, mock-ups, experience from mid-term experiments, etc.

backup



European programs (AIDAInnova, Eurizon)

ECFA Detector Technology roadmap

DRD3/DRD7

GRAM Master Project

DEPHY

C4PI platform

Design, build and exploit CMOS pixels sensors with <u>low material budget</u> & <u>high granularity</u>
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

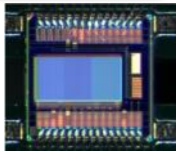
Exploit fully the potential of the CMOS technology

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



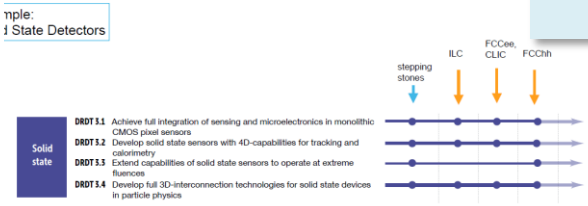
Large surfaces (stitching)

Bent sensors

Exploring new architectures

Integration

Emerging technologies
(e.g. double tier)



nple:
d State Detectors

stepping stones

ILC

FCCee, CLIC

FCChh

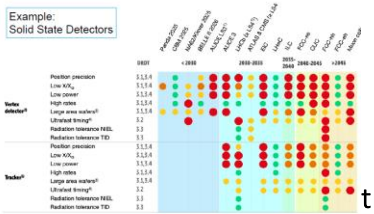
Solid state

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

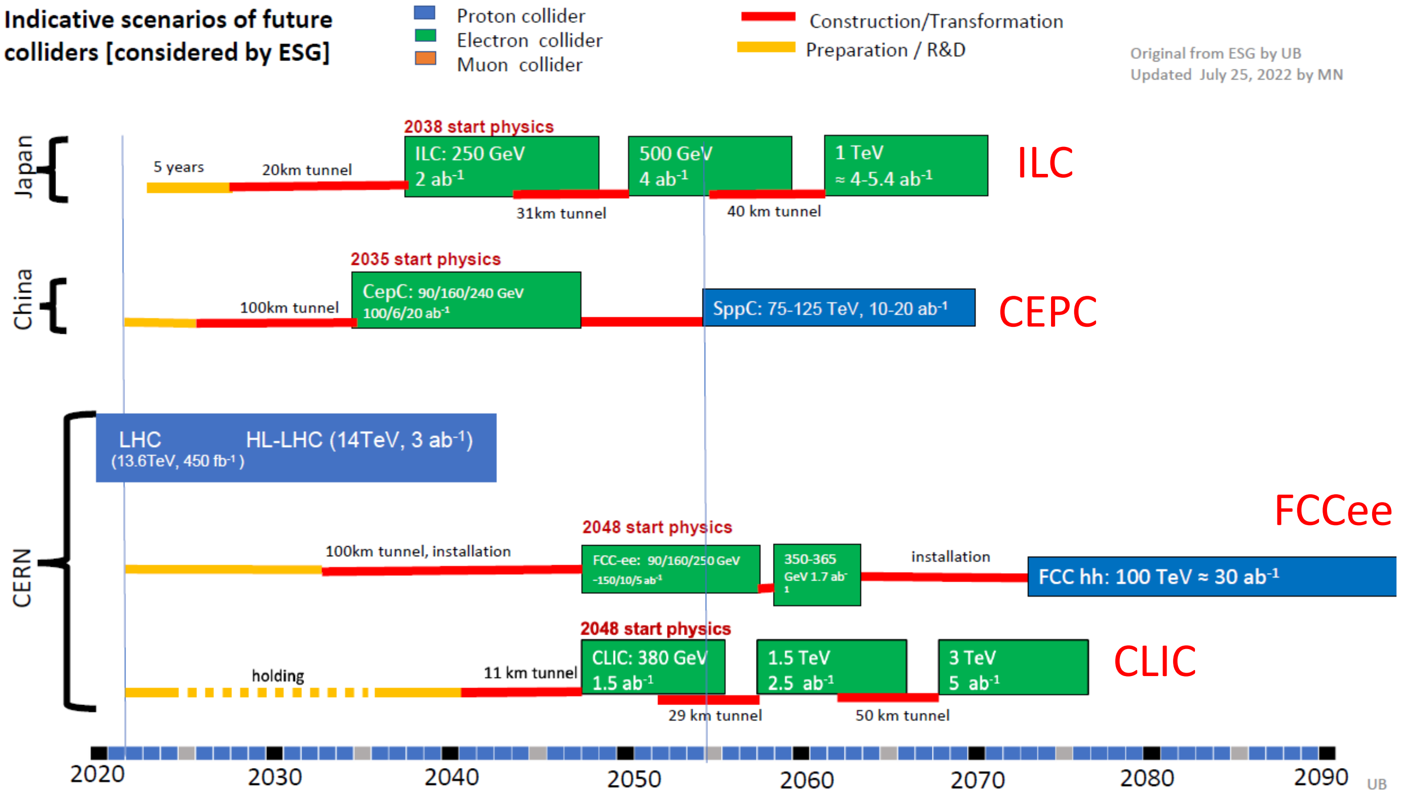
DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics



Example:
Solid State Detectors

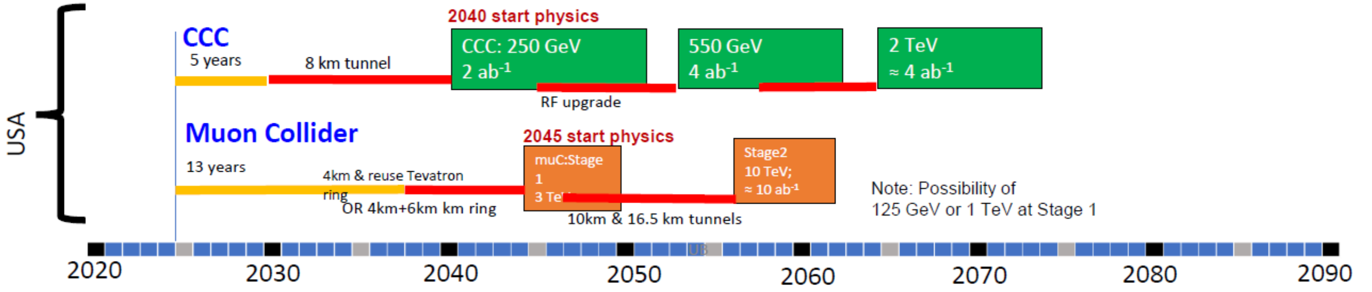
Future e^+e^- colliders (« Higgs factories »)

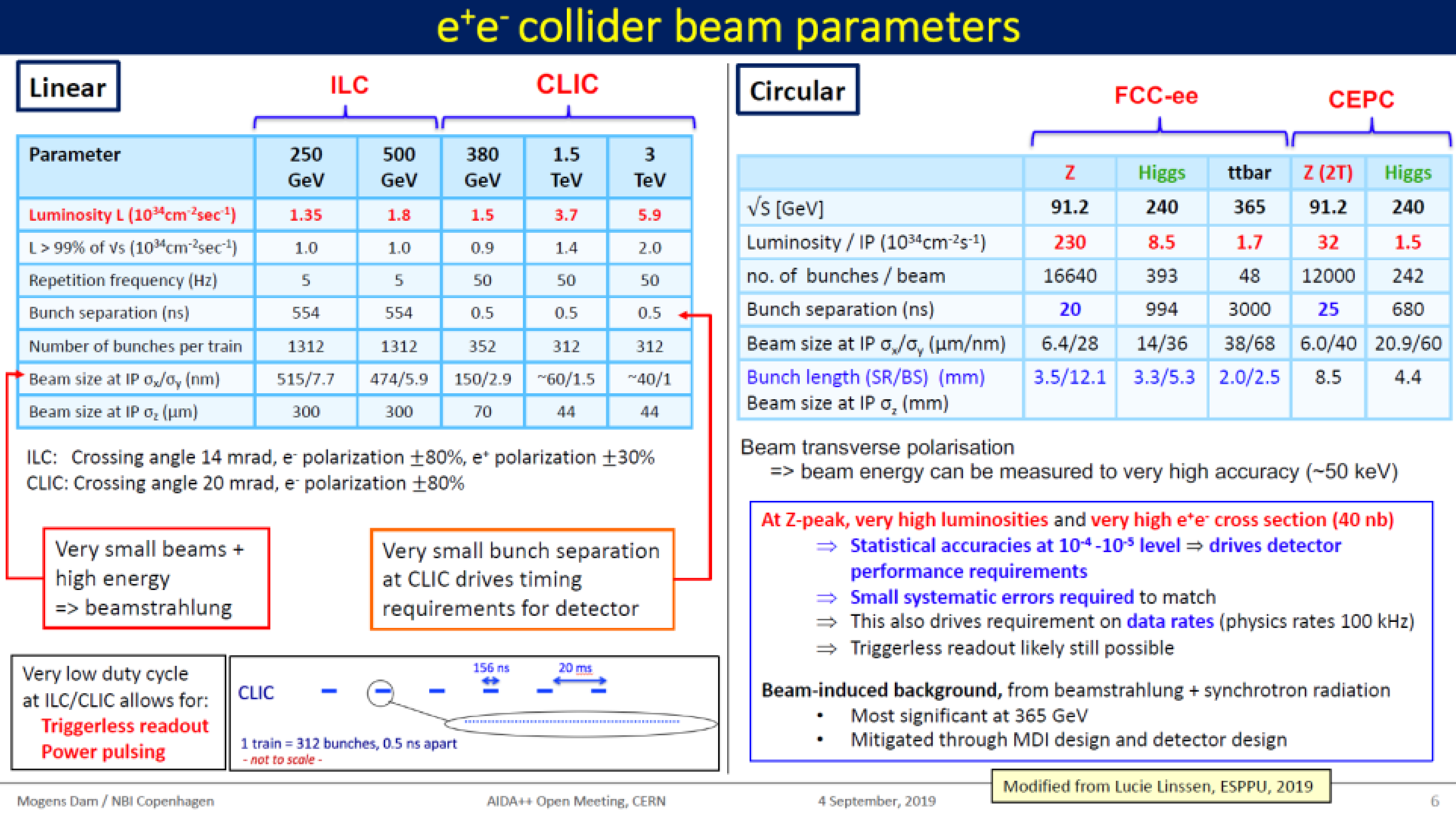
Snowmass summary (summer 2022): https://snowmass21.org/energy/start



- Next Milestone: European Strategy Update for particle physics (~2026-27)
- Coming decade: Detector R&D programs through DRDs
- Other proposals considered (e.g. new concepts, ILC hosted outside Japan, etc.)

Proposals emerging from this Snowmass for a US based collider





e^+e^- collider beam parameters

Linear

	ILC		CLIC		
Parameter	**250 GeV**	**500 GeV**	**380 GeV**	**1.5 TeV**	**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			CEPC	
	Z	**Higgs**	**ttbar**	**Z (2T)**	**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)

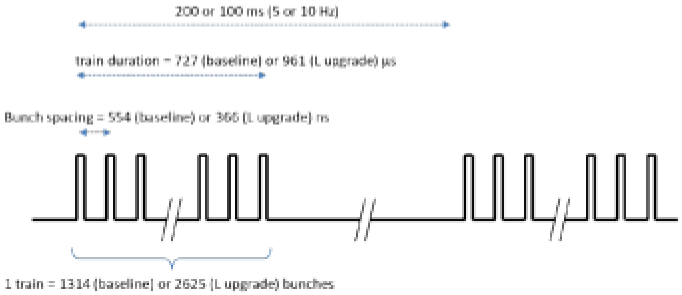
At Z-peak, very high luminosities and **very high e$^+$e$^-$ cross section (40 nb)**
⇒ **Statistical accuracies at 10^{-4} -10^{-5} level ⇒ drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)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

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

Modified from Lucie Linssen, ESPPU, 2019

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

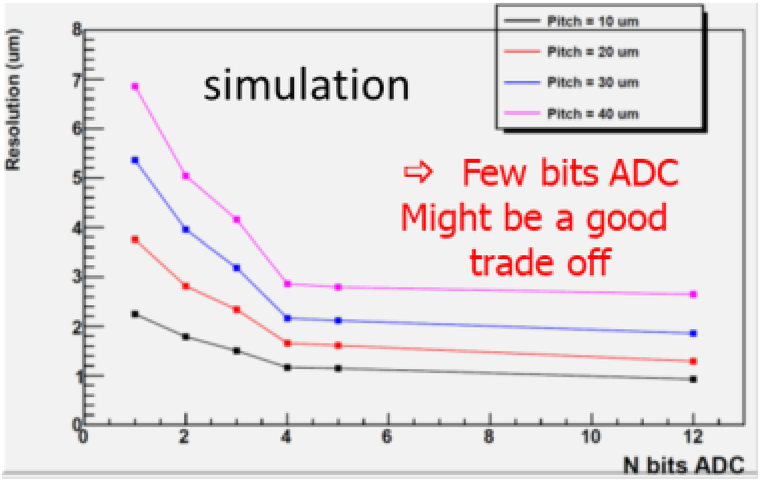
(slide from Mogens Dam/Lucie Linssen)



Challenge 1: the spatial resolution

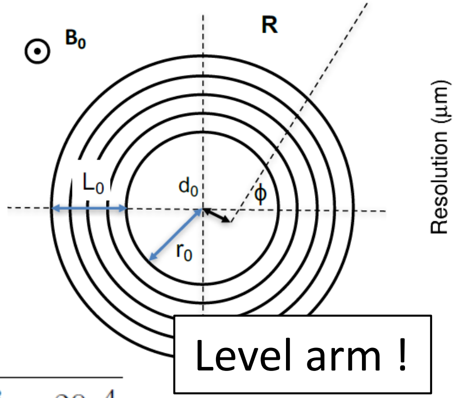
Spatial resolution in Higgs factories

- 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

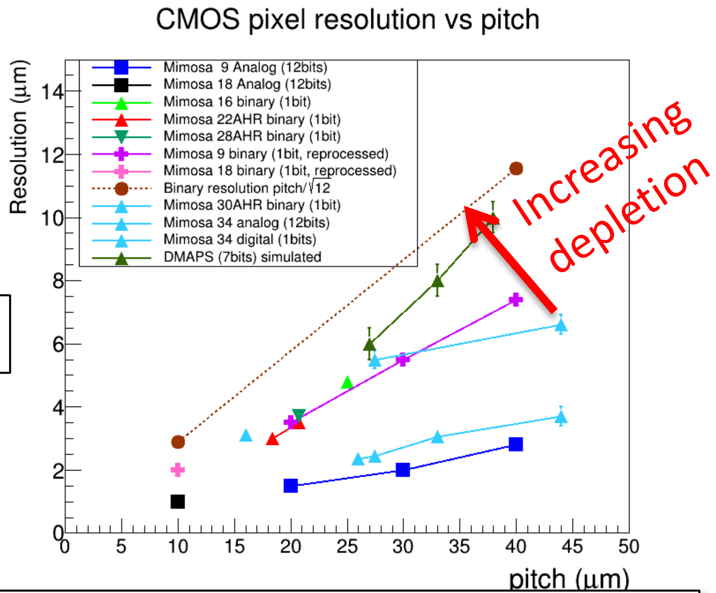
$$\boxed{\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\sin^{3/2}\theta}\right)^2}$$



Level arm !

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

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

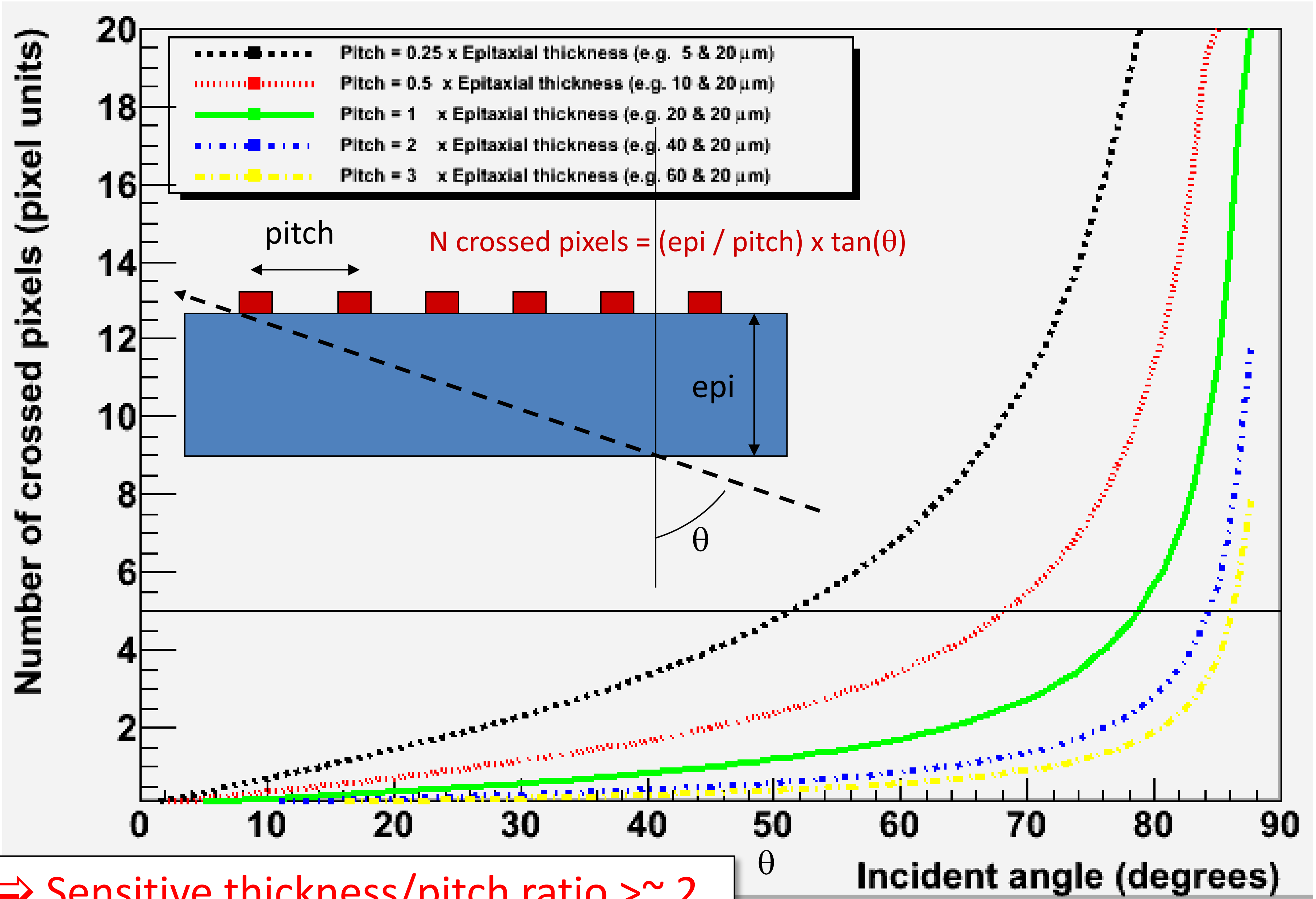


Increasing depletion

⇨ σ_{sp} ~ 3 μm ⇦⇨ pitch ~ 15-20 μm

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

Elongated clusters: low pT tagging



N crossed pixels = (epi / pitch) x tan(θ)

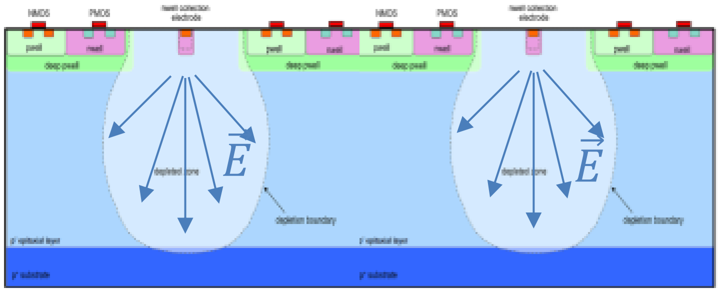
⇨ Sensitive thickness/pitch ratio >~ 2

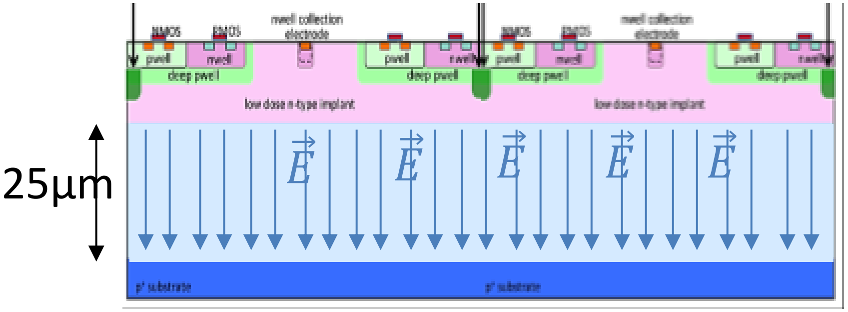
MIMOSIS

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

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

25 or 50 µm epi?



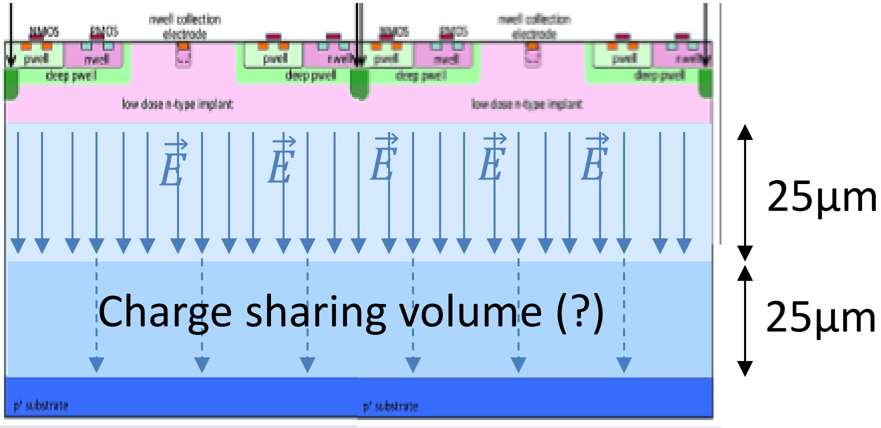


$\sigma = 4 - 5$ µm
> 3 x $10^{13} n_{eq}/cm^2$

Spatial resolution
Rad. hardness

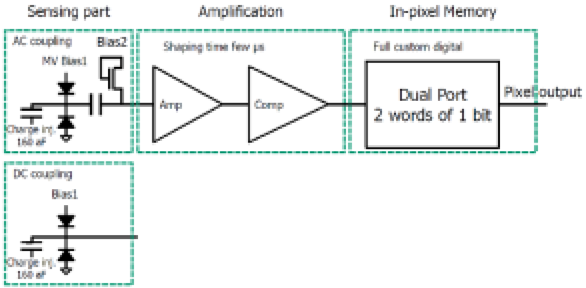
$\sigma = 5 - 7$ µm
> 30 x $10^{13} n_{eq}/cm^2$

Process options inherited from ALPIDE



- 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.

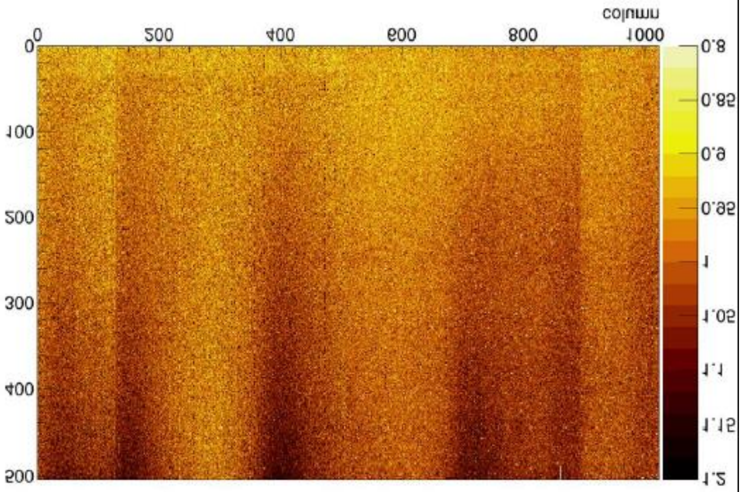
W. Snoeys et al., NIM-A Vol.871 (2017) 90–96.
Munker, Vertex 2018, Status of silicon detector R&D at CLIC

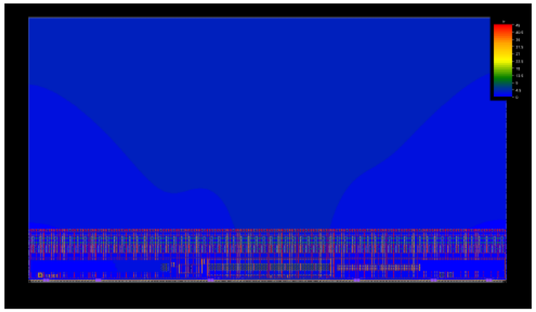
Mimosis-1 Verification tools example

- 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)

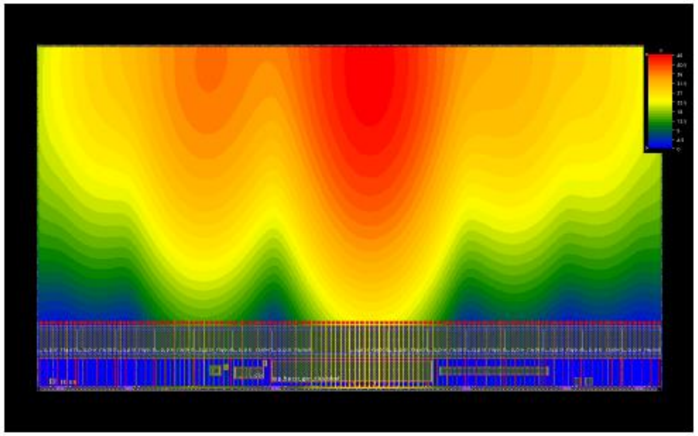




IR drop on AVDD (simulations)
0-45 mV scale

MIMOSIS-1
Mean= 26 mV

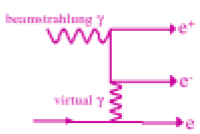
MIMOSIS-2
Mean = 3 mV



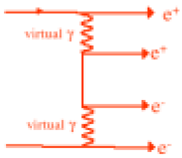
Challenge 6: understanding beam related background

Challenge: understand beam related backgrounds

Breit-Wheeler

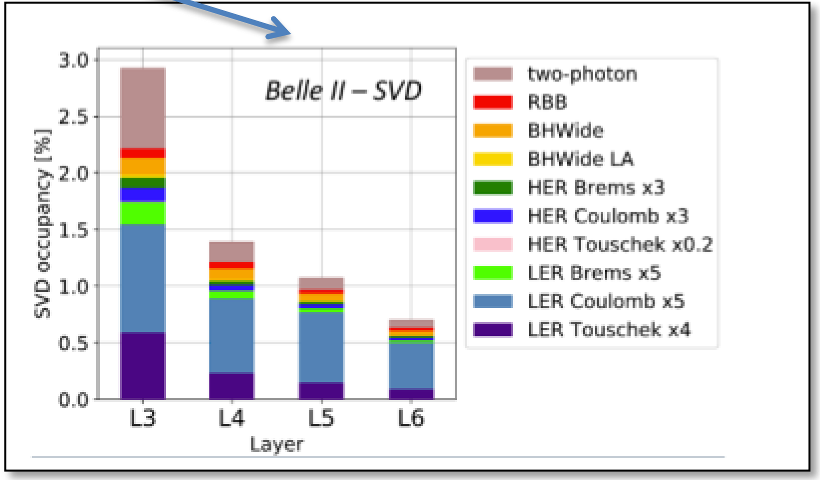


Bethe-Heitler

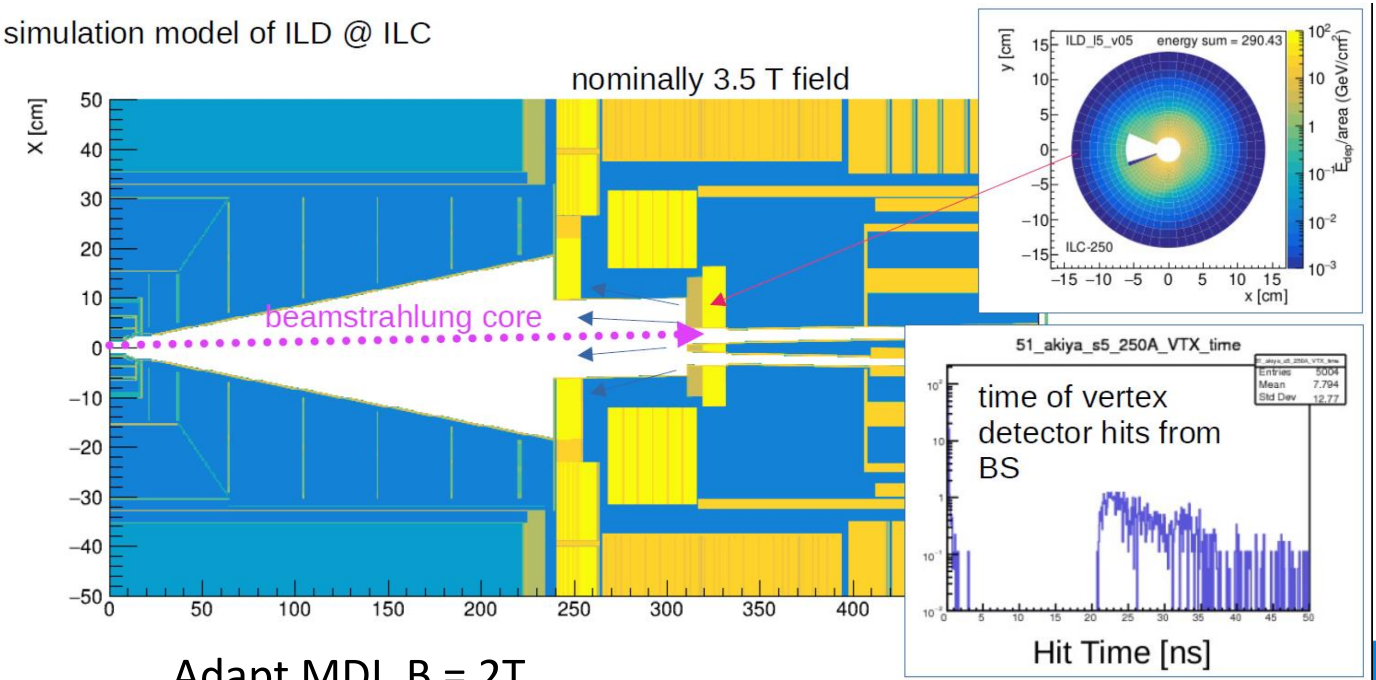


Landau-Lifshitz

- 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)



Example of background study: ILD, from linear to circular

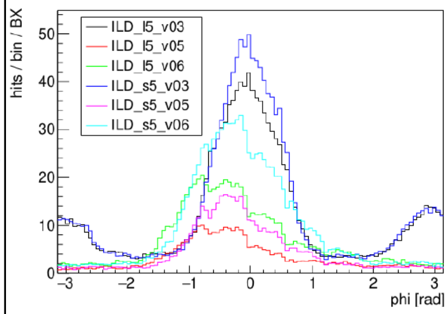

simulation model of ILD @ ILC

nominally 3.5 T field

beamstrahlung core

time of vertex detector hits from BS

D. Jeans LCWS2023

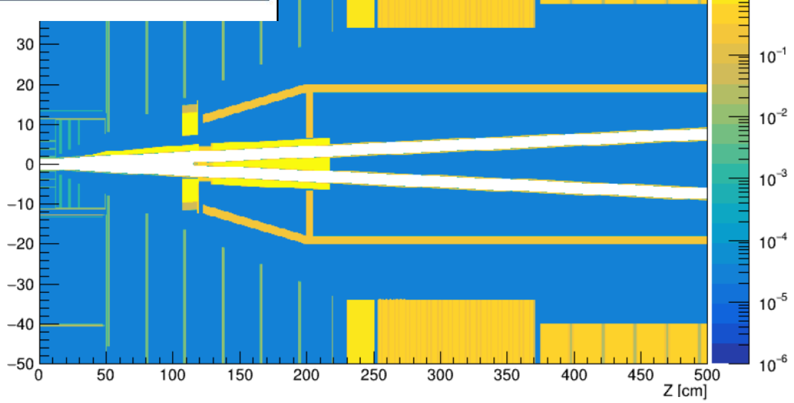


Adapt MDI, B = 2T,

Sensitive to precise B-field map

Adapt Beam structure

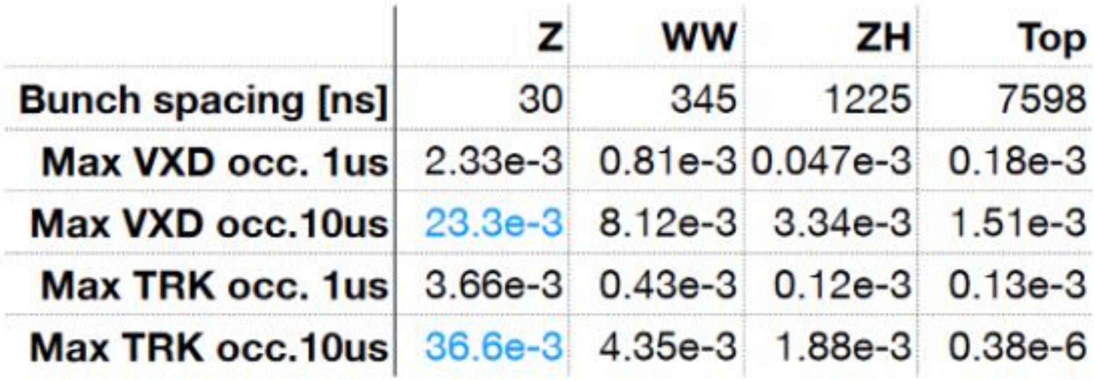
Effect in TPC also being studied



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

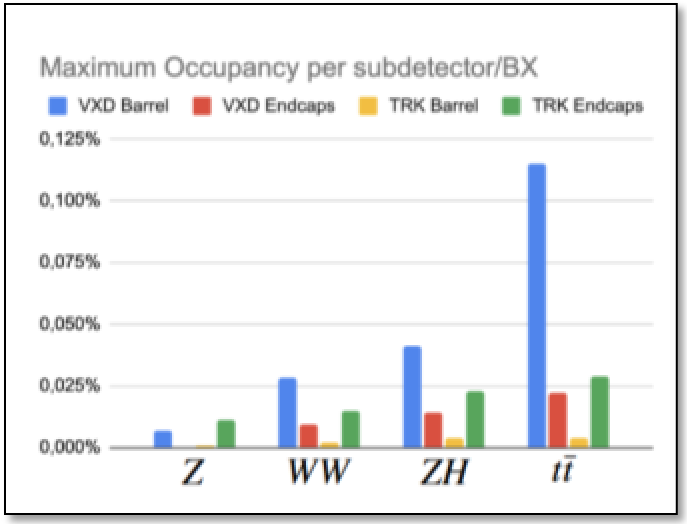
- at FCCee, MDI extends to ~1m from IP
  → 6 times more beamstrahlung background hits in TPC

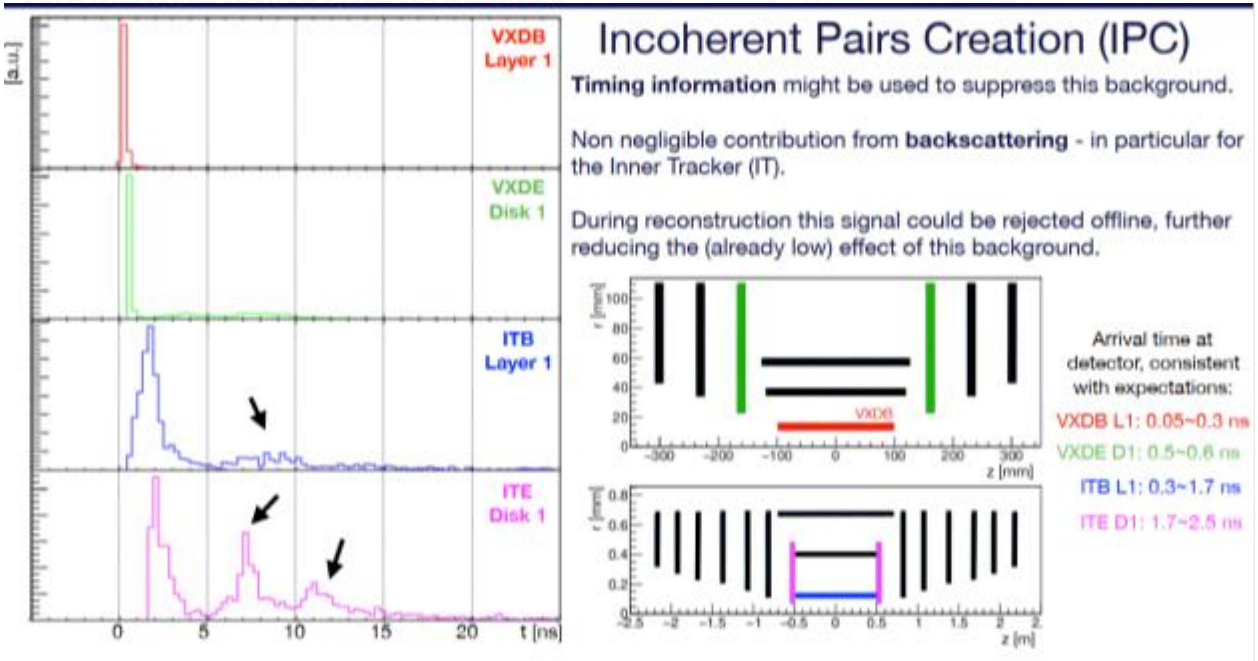
Example of study in CLD



	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

A pragmatic approach: mechanical/simulation studies for the IDEA vertex detector

- Starts from a detector concept and chip modules
  - ✓ Based on ARCADIA design

Fabrizio Palla[1]

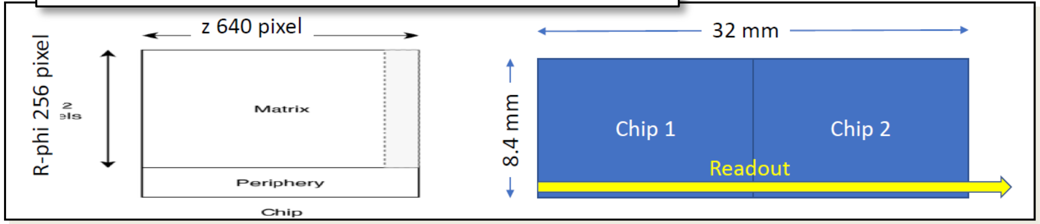
Manuela Boscolo [2], Filippo Bosi [1], Francesco Fransesini [2], Stefano Lauciani [2]

[1]INFN Sezione di Pisa, Italy

[2]INFN Laboratori Nazionali di Frascati (RM), Italy

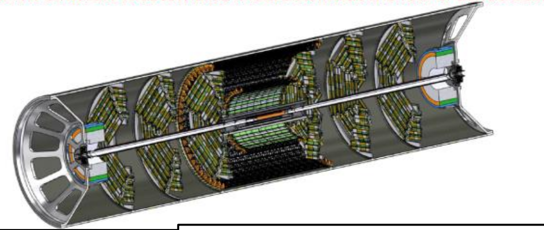
First Annual U.S. Future Circular Collider Workshop
BNL, April 24-26, 2023

Chip model based on ARCADIA

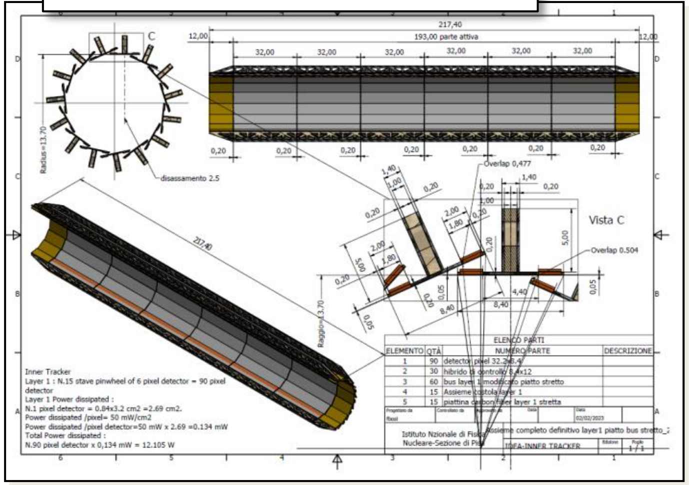


Mechanical support

- All elements in the interaction region (Vertex, Tracker and LumiCal) are mounted rigidly on a support cylinder that guarantees mechanical stability and alignment
  - Once the structure is assembled it is slided inside the rest of the detector



Single layer description



ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
1	90	detector pixel 32.2x8.4	
2	30	hibrido di controllo 8.4x12	
3	60	bus layer 1 modificato piatto stretto	
4	15	Assieme costola layer 1	
5	15	piattina carbon fiber layer 1 stretta	

Progettato da fbosi

Data 02/02/2023

Istituto Nzionale di Fisica Nucleare-Sezione di Pisa

Assieme completo definitivo layer1 piatto bus stretto_2

IDEA-INNER TRACKER

Foglio 1 / 1

Inner Tracker
Layer 1 : N.15 stave pinwheel of 6 pixel detector = 90 pixel detector
Layer 1 Power dissipated :
N.1 pixel detector = 0.84x3.2 cm2 =2.69 cm2.
Power dissipated /pixel= 50 mW/cm2
Power dissipated /pixel detector=50 mW x 2.69 =0.134 mW
Total Power dissipated :
N.90 pixel detector x 0,134 mW = 12.105 W

Layer 1

15 overlapping staves of 6 modules each

Pinwheel geometry: all modules at the same (smallest) radius

Power budget ~12 W

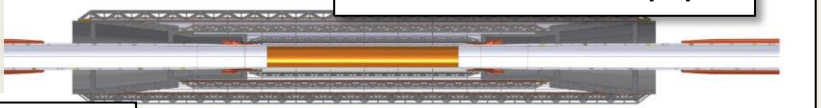
Total weight ~22 grams

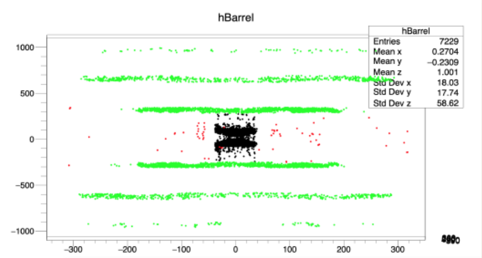
Total thickness 0.25% X_0

Silicon: 0.053% X_0

Power and readout bus: 0.056% X_0

Vertex + beam pipe

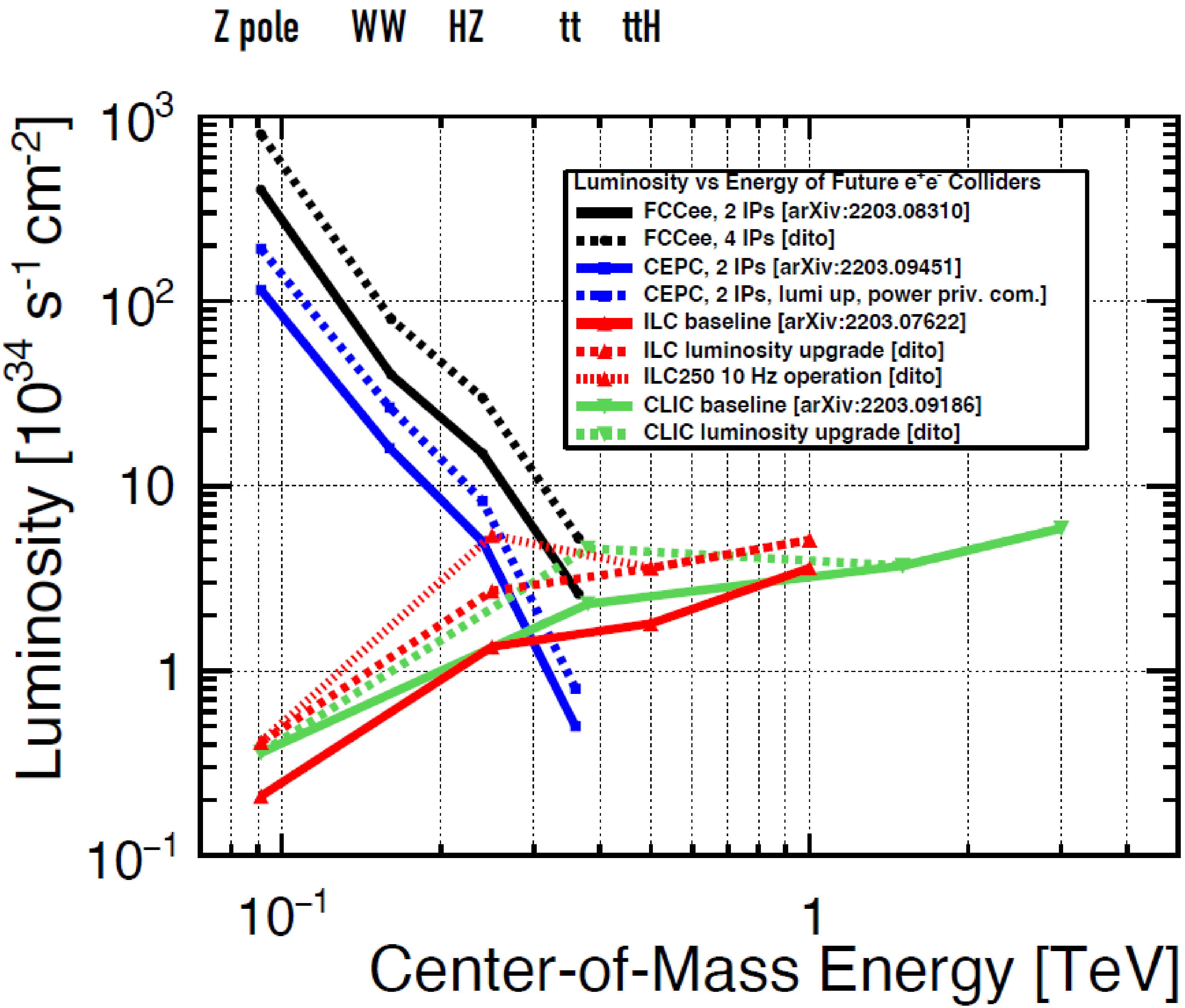




hBarrel	
Entries	7229
Mean x	0.2704
Mean y	−0.2309
Mean z	1.001
Std Dev x	18.03
Std Dev y	17.74
Std Dev z	58.62

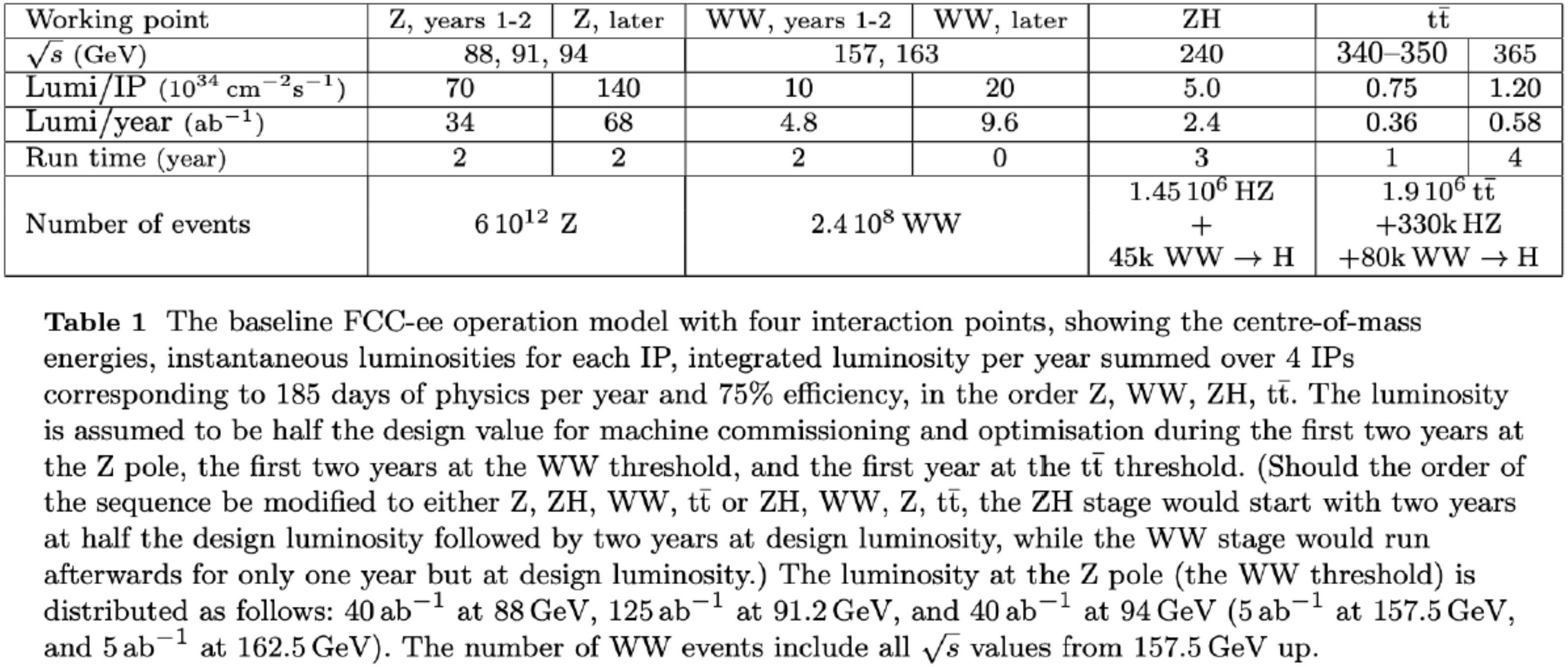
Figur
$Z \to$
Green
vertex

Model implemented in Key4hep
A. Ilg FCCee MDI Meeting 15.05.2023


Z pole
WW
HZ
tt
ttH
Luminosity [10^{34} s^{-1} cm^{-2}]
10^3
10^2
10
1
10^{-1}
10^{-1}
1
Center-of-Mass Energy [TeV]
Luminosity vs Energy of Future e$^+$e$^-$ Colliders
FCCee, 2 IPs [arXiv:2203.08310]
FCCee, 4 IPs [dito]
CEPC, 2 IPs [arXiv:2203.09451]
CEPC, 2 IPs, lumi up, power priv. com.]
ILC baseline [arXiv:2203.07622]
ILC luminosity upgrade [dito]
ILC250 10 Hz operation [dito]
CLIC baseline [arXiv:2203.09186]
CLIC luminosity upgrade [dito]

FCCee Collider parameters

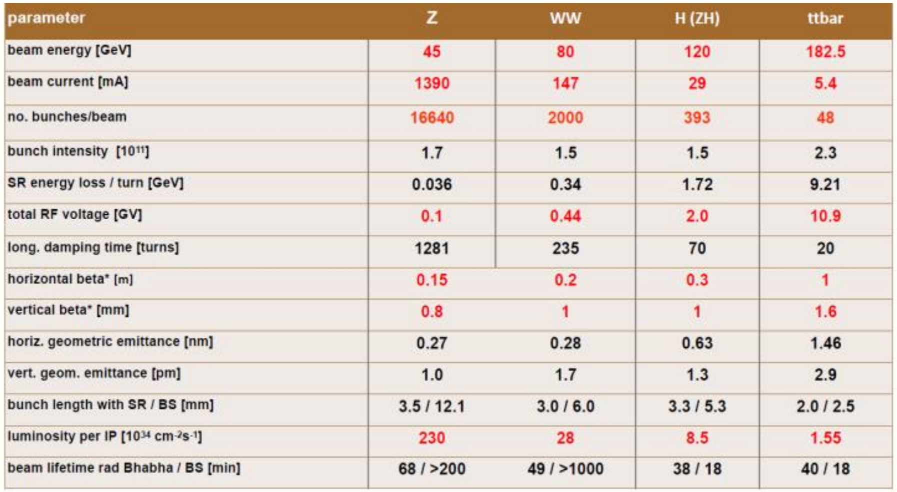
Updated luminosity parameters (2023):



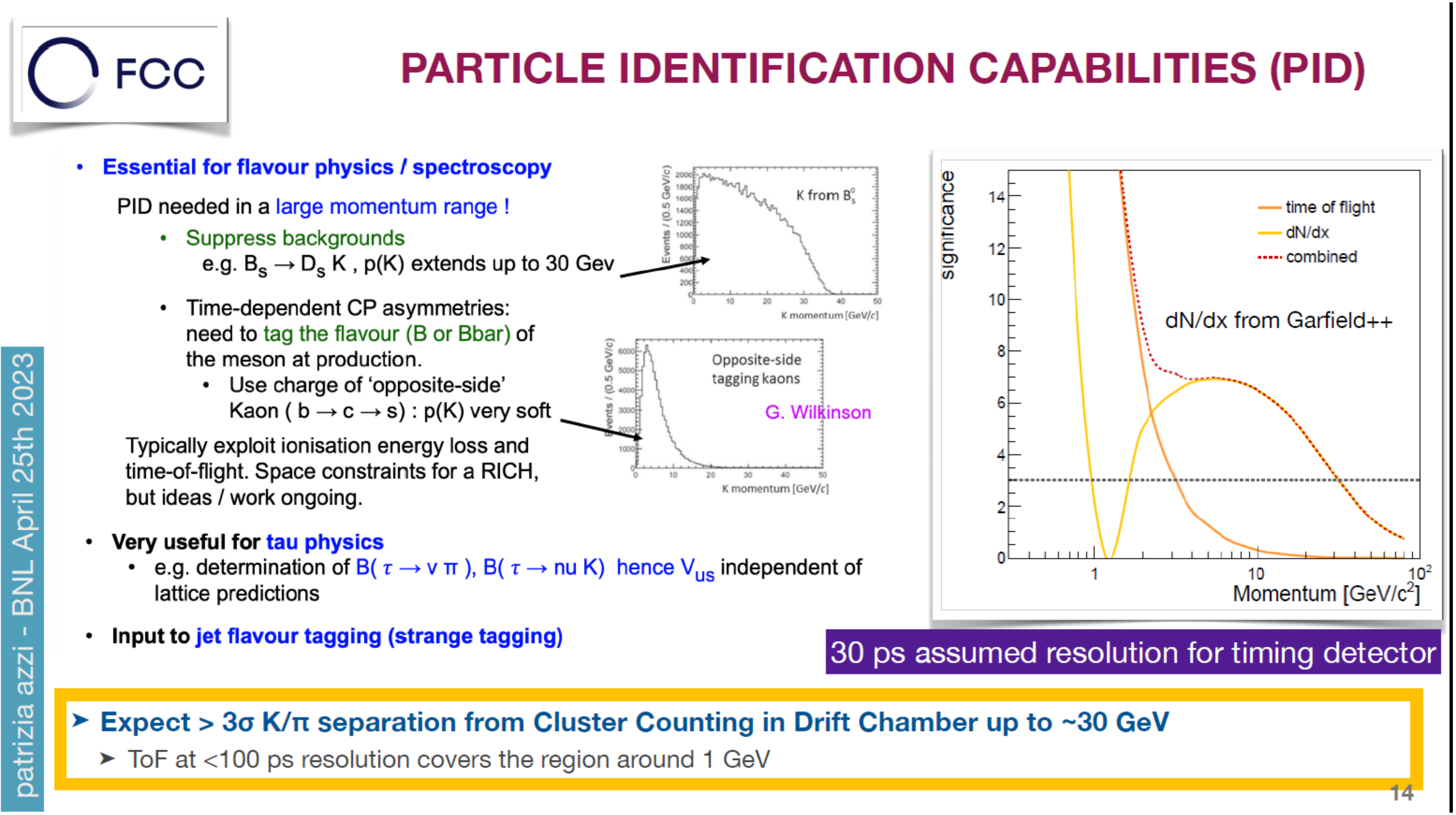
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW → H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW → H	

Table 1 The baseline FCC-ee operation model with four interaction points, showing the centre-of-mass energies, instantaneous luminosities for each IP, integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency, in the order Z, WW, ZH, $t\bar{t}$. The luminosity is assumed to be half the design value for machine commissioning and optimisation during the first two years at the Z pole, the first two years at the WW threshold, and the first year at the $t\bar{t}$ threshold. (Should the order of the sequence be modified to either Z, ZH, WW, $t\bar{t}$ or ZH, WW, Z, $t\bar{t}$, the ZH stage would start with two years at half the design luminosity followed by two years at design luminosity, while the WW stage would run afterwards for only one year but at design luminosity.) The luminosity at the Z pole (the WW threshold) is distributed as follows: 40 ab^{-1} at 88 GeV, 125 ab^{-1} at 91.2 GeV, and 40 ab^{-1} at 94 GeV (5 ab^{-1} at 157.5 GeV, and 5 ab^{-1} at 162.5 GeV). The number of WW events include all $\sqrt{s}$ values from 157.5 GeV up.

2021



parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18



PARTICLE IDENTIFICATION CAPABILITIES (PID)

- **Essential for flavour physics / spectroscopy**

  PID needed in a large momentum range !
  - Suppress backgrounds
    e.g. $B_s \to D_s$ K , p(K) extends up to 30 Gev
  - Time-dependent CP asymmetries: need to tag the flavour (B or Bbar) of the meson at production.
    - Use charge of 'opposite-side' Kaon (b → c → s) : p(K) very soft

  Typically exploit ionisation energy loss and time-of-flight. Space constraints for a RICH, but ideas / work ongoing.

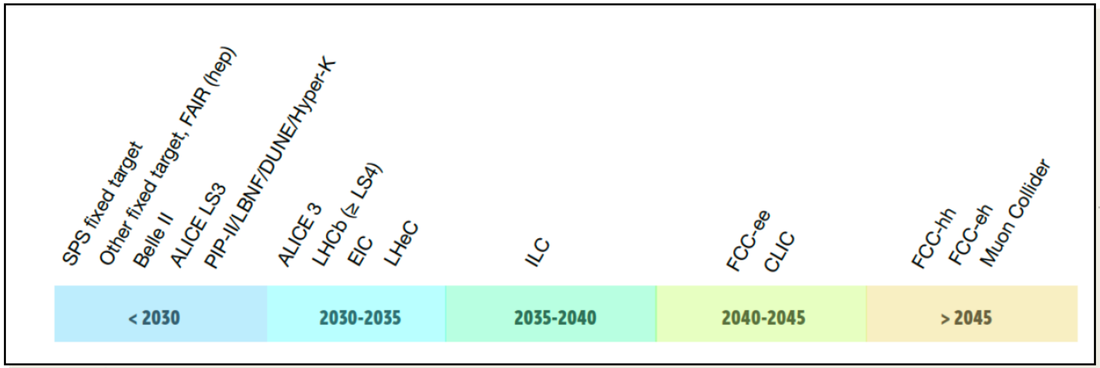
- **Very useful for tau physics**
  - e.g. determination of B($\tau \to \nu \pi$), B($\tau \to$ nu K) hence V_{us} independent of lattice predictions
- **Input to jet flavour tagging (strange tagging)**

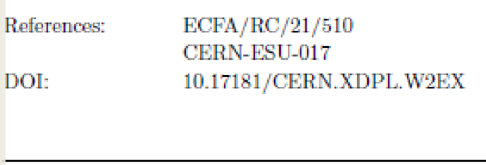
G. Wilkinson

30 ps assumed resolution for timing detector

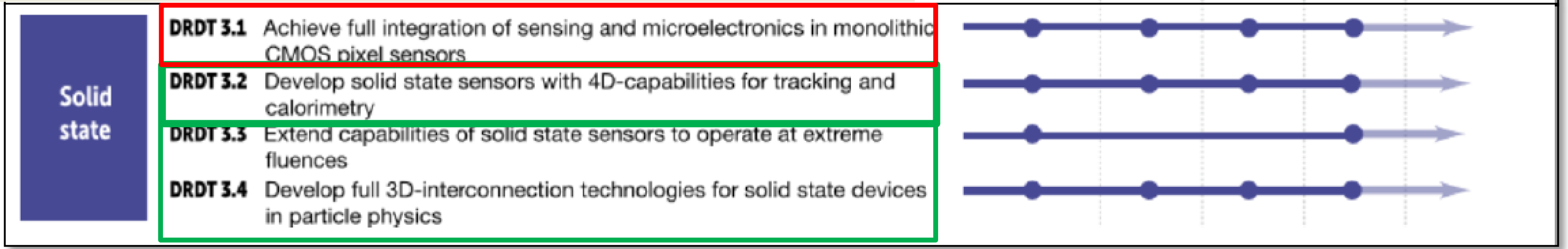
- **Expect > 3σ K/π separation from Cluster Counting in Drift Chamber up to ~30 GeV**
  - ToF at <100 ps resolution covers the region around 1 GeV

Detector R&D Roadmap: themes (DRDTs)

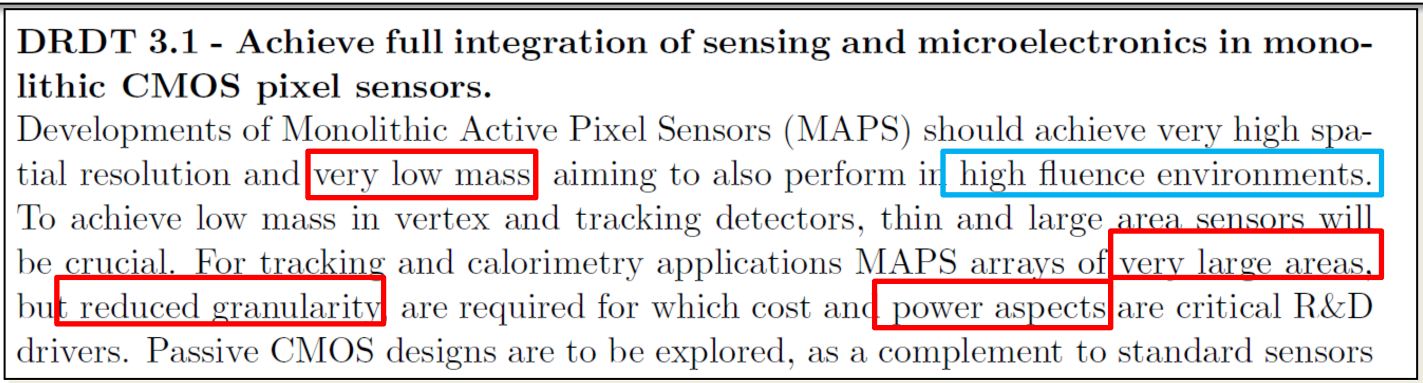




References: ECFA/RC/21/510
CERN-ESU-017
DOI: 10.17181/CERN.XDPL.W2EX

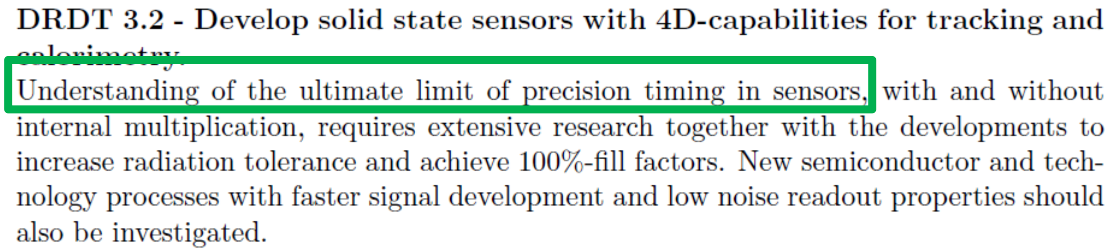


			< 2030	2030-2035	2035-2040	2040-2045	> 2045
Solid state	**DRDT 3.1**	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors	●	●	●	●	→
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry	●	●	●	●	→
	DRDT 3.3	Extend capabilities of solid 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



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

Understanding of the ultimate limit of precision timing in sensors, with and without internal multiplication, requires extensive research together with the developments to increase radiation tolerance and achieve 100%-fill factors. New semiconductor and technology processes with faster signal development and low noise readout properties should also be investigated.

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

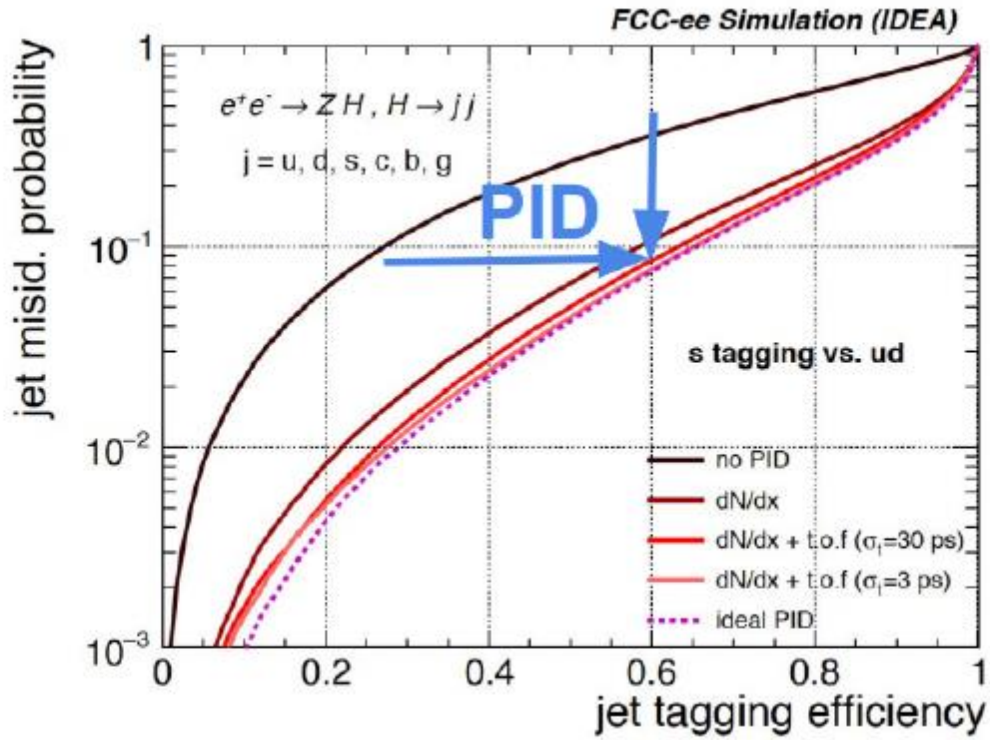
K. Jakobs, FCC Physics Workshop, Feb 2022

		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					203 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							🟢							🟢		
Time of flight$^{7)}$	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**

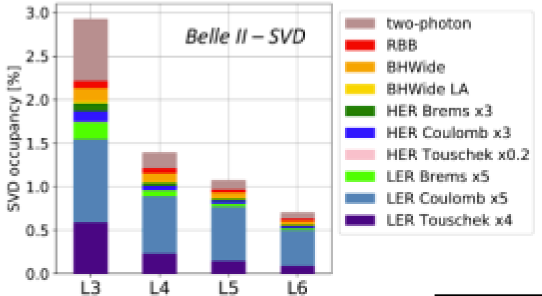
Important similarities between FCCee requirements & Heavy ions experiments (ALICE ITS3, ALICE3, EIC, etc.)

s-tagging


FCC-ee Simulation (IDEA)
$e^+e^- \to ZH,\ H \to jj$
j = u, d, s, c, b, g
PID
s tagging vs. ud
no PID
dN/dx
dN/dx + t.o.f (σ_t=30 ps)
dN/dx + t.o.f (σ_t=3 ps)
ideal PID
jet misid. probability
jet tagging efficiency
1
10^{-1}
10^{-2}
10^{-3}
0
0.2
0.4
0.6
0.8
1

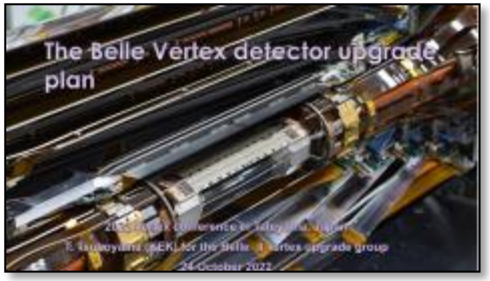
The Silicon Vertex Detector of the Belle II Experiment

Kookhyun Kang - Kavli IPMU
on behalf of the Belle II SVD Collaboration
VERTEX 2022 Oct 24, 2022

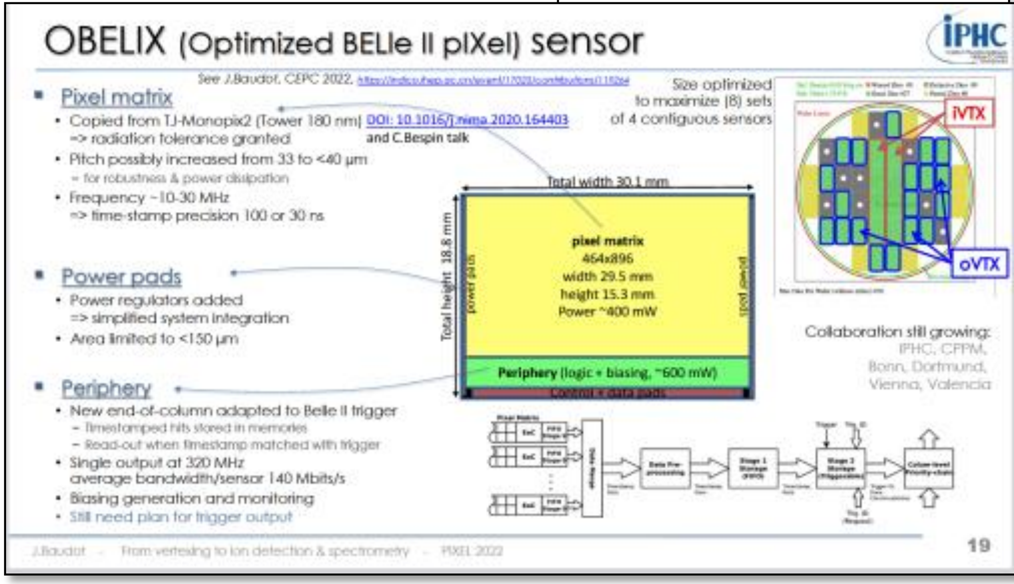


L3 L4 L5 L6

Layer



The Belle Vertex detector upgrade plan



OBELIX (Optimized BELle II pIXel) sensor

See J.Baudot, CEPC 2022, https://indico.ihep.ac.cn/event/17020/contributions/118264

- Pixel matrix
  - Copied from TJ-Monopix2 (Tower 180 nm) DOI: 10.1016/j.nima.2020.164403 and C.Bespin talk
    => radiation tolerance granted
  - Pitch possibly increased from 33 to <40 µm
    - for robustness & power dissipation
  - Frequency ~10-30 MHz
    => time-stamp precision 100 or 30 ns
- Power pads
  - Power regulators added
    => simplified system integration
  - Area limited to <150 µm
- Periphery
  - New end-of-column adapted to Belle II trigger
    - Timestamped hits stored in memories
    - Read-out when timestamp matched with trigger
  - Single output at 320 MHz
    average bandwidth/sensor 140 Mbits/s
  - Biasing generation and monitoring
  - Still need plan for trigger output

Size optimized to maximize (8) sets of 4 contiguous sensors

Collaboration still growing:
IPHC, CPPM,
Bonn, Dortmund,
Vienna, Valencia

J.Baudot – From vertexing to ion detection & spectrometry – PIXEL 2022

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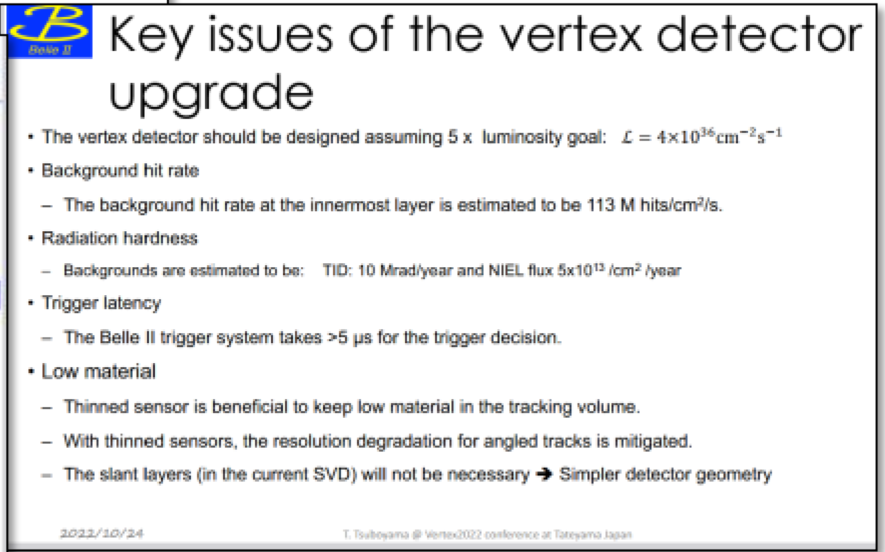


Key issues of the vertex detector upgrade

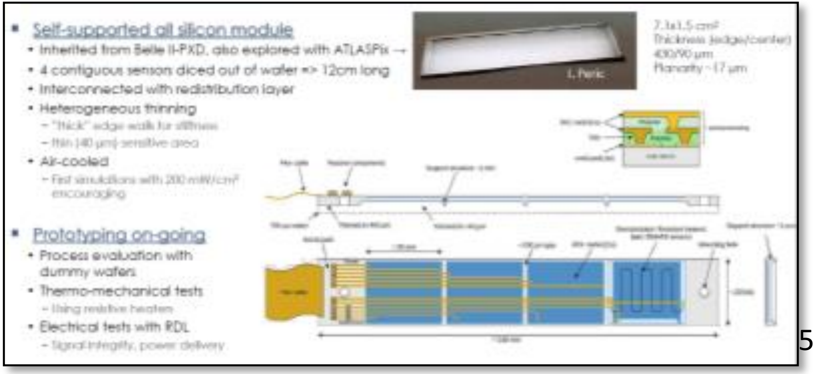
- The vertex detector should be designed assuming 5 x luminosity goal: $\mathcal{L} = 4\times10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Background hit rate
  - The background hit rate at the innermost layer is estimated to be 113 M hits/cm²/s.
- Radiation hardness
  - Backgrounds are estimated to be: TID: 10 Mrad/year and NIEL flux 5×10^{13} /cm² /year
- Trigger latency
  - The Belle II trigger system takes >5 µs for the trigger decision.
- Low material
  - Thinned sensor is beneficial to keep low material in the tracking volume.
  - With thinned sensors, the resolution degradation for angled tracks is mitigated.
  - The slant layers (in the current SVD) will not be necessary ➔ Simpler detector geometry

2022/10/24 T. Tsuboyama @ Vertex2022 conference at Tateyama Japan

https://indico.cern.ch/event/1140707/contributions/5036352/attachments/2533480/4359729/tsuboyama-Belle2-vertex-upgrade-S3.pdf

https://indico.cern.ch/event/1140707/contributions/4988213/attachments/2533474/4359608/Vertex2022_khkang_v3.pdf

https://indico.cern.ch/event/829863/contributions/5062886/attachments/2568342/4428391/baudot-pixel2022.pdf



- Self-supported all silicon module
  - Inherited from Belle II-PXD, also explored with ATLASPix →
  - 4 contiguous sensors diced out of wafer => 12cm long
  - Interconnected with redistribution layer
  - Heterogeneous thinning
    - "thick" edge walls for stiffness
    - thin (40 µm) sensitive area
  - Air-cooled
    - First simulations with 200 mW/cm² encouraging
- Prototyping on-going
  - Process evaluation with dummy wafers
  - Thermo-mechanical tests
    - Using resistive heaters
  - Electrical tests with RDL
    - Signal integrity, power delivery

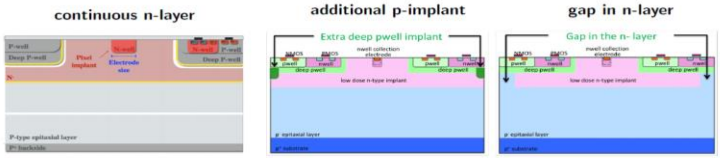
7.3x1.5 cm²
Thickness (edge/center) 430/90 µm
Planarity ~17 µm

Example of trade off: MIMOSIS

- MIMOSIS-1 chip for CBM-MVD @ FAIR

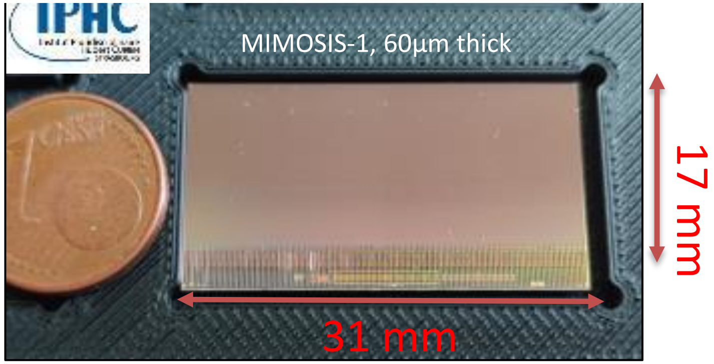
Parameter	Value
Technology	TowerJazz 180 nm
Epi layer	$\sim 25\,\mu m$
Epi layer resistivity	$> 1k\Omega cm$
Sensor thickness	$60\,\mu m$
Pixel size	$26.88\,\mu m \times 30.24\,\mu m$
Matrix size	1024×504 (516096 pix)
Matrix area	$\approx 4.2\,cm^2$
Matrix readout time	$5\,\mu s$ (event driven)
Power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

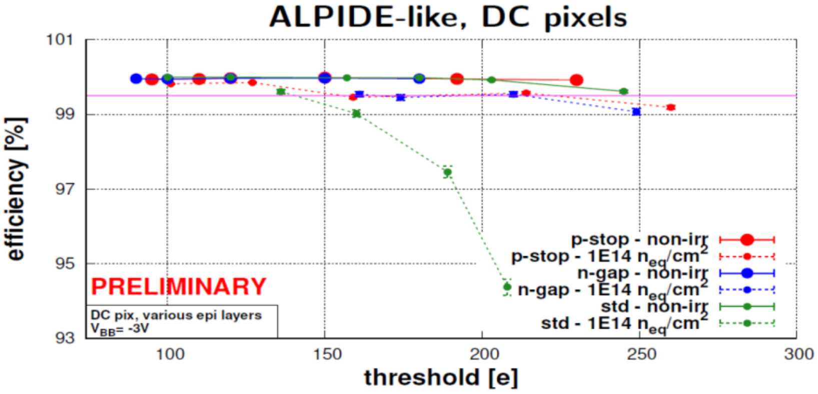
  - ✓ Based on ALPIDE architecture
    - Multiple data concentration steps
    - Elastic output buffer
    - 8 x 320 Mbps links (switchable)
    - Triple redundant electronics
  - ✓ Pixel variants: DC/AC (top bias up to >20V)
  - ✓ Different epitaxial variants tested

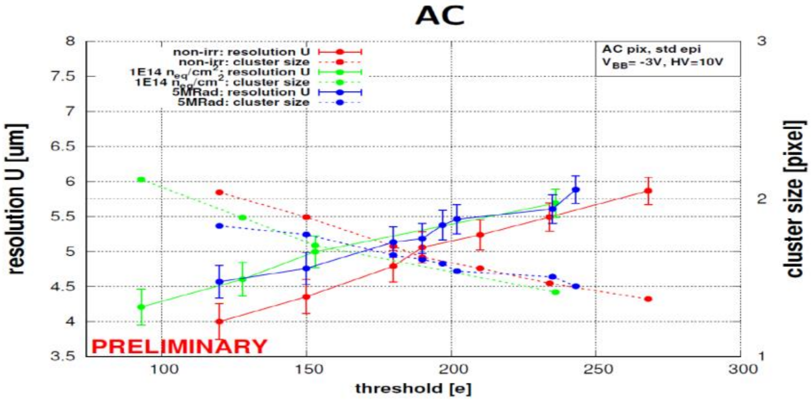


Pic from: Munker, Vertex 2018, Status of silicon detector R&D at CLIC
Carlos, TREDI 2019, Results of the Malta CMOS pixel detector prototype for the ATLAS Pixel ITK

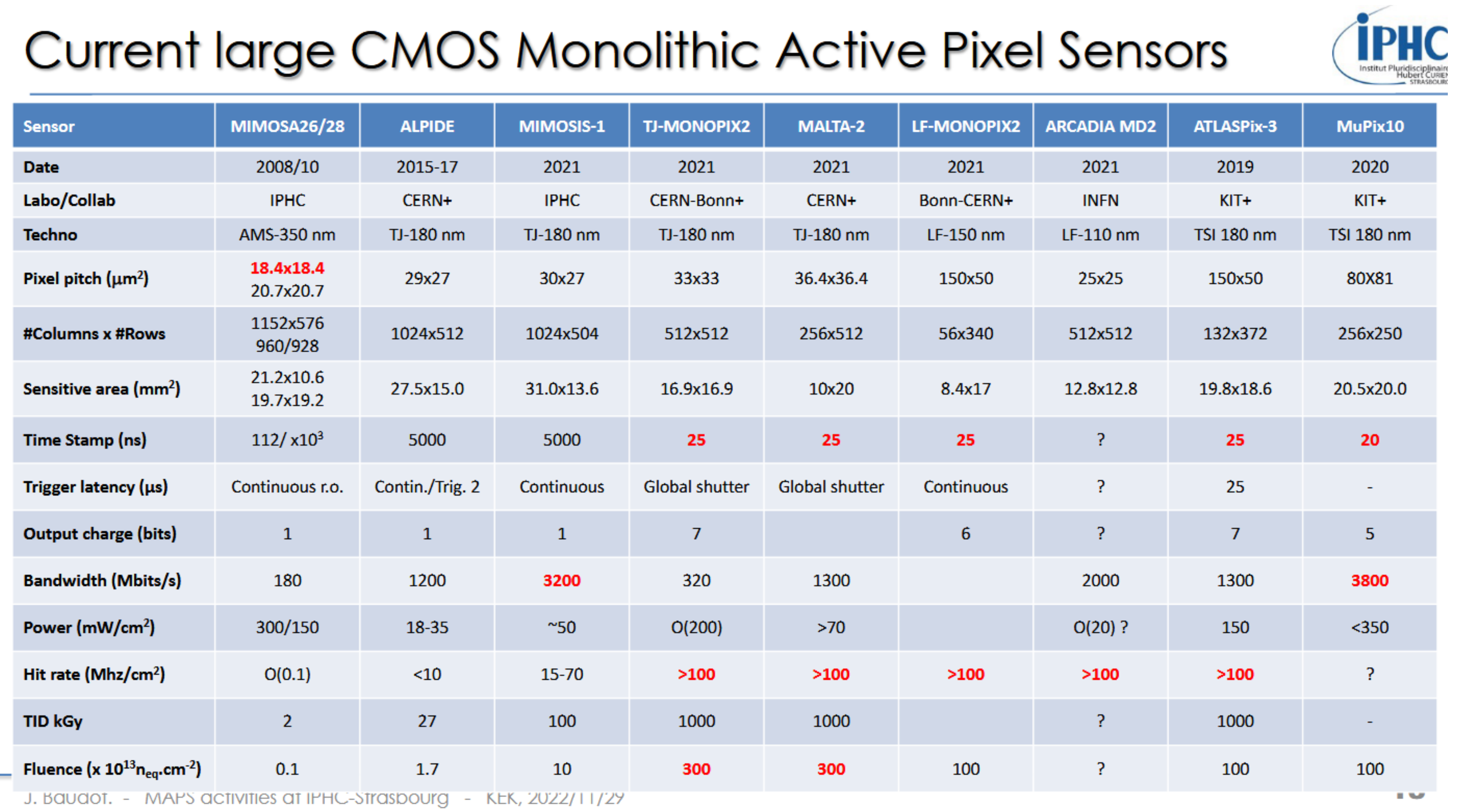
- Intense test beam campaign(2021-22)
  - ✓ Mimosis-2 submission these weeks
    - Thicker epi layer tests
    - Test prototype for 1 μs readout time







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



Current large CMOS Monolithic Active Pixel Sensors

Sensor	MIMOSA26/28	ALPIDE	MIMOSIS-1	TJ-MONOPIX2	MALTA-2	LF-MONOPIX2	ARCADIA MD2	ATLASPix-3	MuPix10
Date	2008/10	2015-17	2021	2021	2021	2021	2021	2019	2020
Labo/Collab	IPHC	CERN+	IPHC	CERN-Bonn+	CERN+	Bonn-CERN+	INFN	KIT+	KIT+
Techno	AMS-350 nm	TJ-180 nm	TJ-180 nm	TJ-180 nm	TJ-180 nm	LF-150 nm	LF-110 nm	TSI 180 nm	TSI 180 nm
Pixel pitch (μm^2)	**18.4x18.4** 20.7x20.7	29x27	30x27	33x33	36.4x36.4	150x50	25x25	150x50	80X81
#Columns x #Rows	1152x576 960/928	1024x512	1024x504	512x512	256x512	56x340	512x512	132x372	256x250
Sensitive area (mm^2)	21.2x10.6 19.7x19.2	27.5x15.0	31.0x13.6	16.9x16.9	10x20	8.4x17	12.8x12.8	19.8x18.6	20.5x20.0
Time Stamp (ns)	112/ $x10^3$	5000	5000	**25**	**25**	**25**	?	**25**	**20**
Trigger latency (µs)	Continuous r.o.	Contin./Trig. 2	Continuous	Global shutter	Global shutter	Continuous	?	25	-
Output charge (bits)	1	1	1	7		6	?	7	5
Bandwidth (Mbits/s)	180	1200	**3200**	320	1300		2000	1300	**3800**
Power (mW/cm^2)	300/150	18-35	~50	O(200)	>70		O(20) ?	150	<350
Hit rate (Mhz/cm^2)	O(0.1)	<10	15-70	**>100**	**>100**	**>100**	**>100**	**>100**	?
TID kGy	2	27	100	1000	1000		?	1000	-
Fluence (x $10^{13} n_{eq}.cm^{-2}$)	0.1	1.7	10	**300**	**300**	100	?	100	100

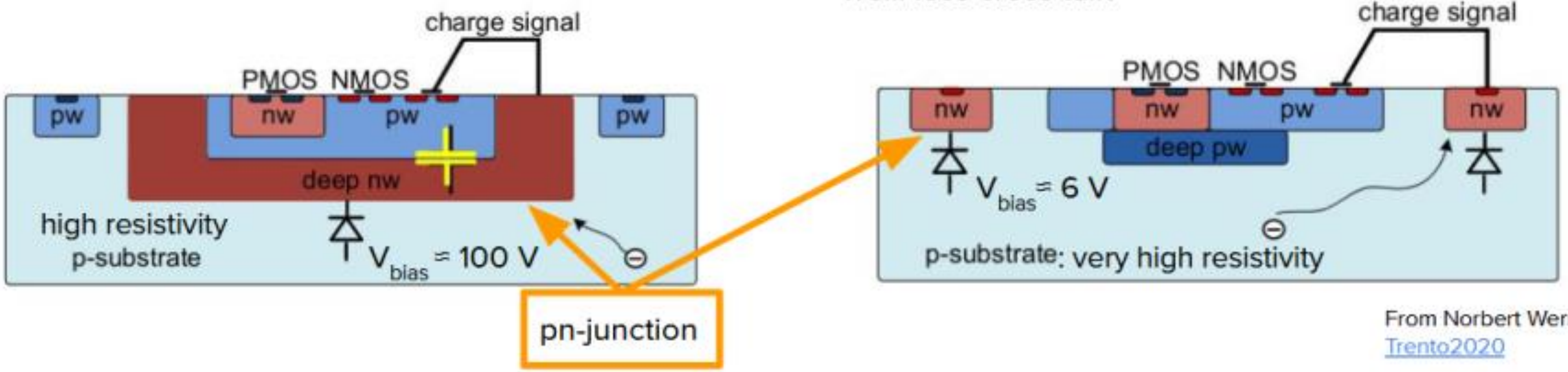
J. Baudot. - MAPS activities at IPHC-Strasbourg - KEK, 2022/11/29

Depleted MAPS: small and large collection electrodes

- ✅ High field almost everywhere
- ✅ Short drift distances
- ✅ Higher radiation tolerance

- ✅ Very small sensor capacitance ~5 fF
- ✅ Reduced noise & power
- ✅ Readout outside charge collection

well: less cross talk



From Norbert Wermes, Trento2020

- Stronger electric field results in less trapping and higher radiation tolerance
- Larger electric field comes at a cost: more capacitance, power and more noise

From E. Vilella, Vertex2018