Detector challenges for future colliders

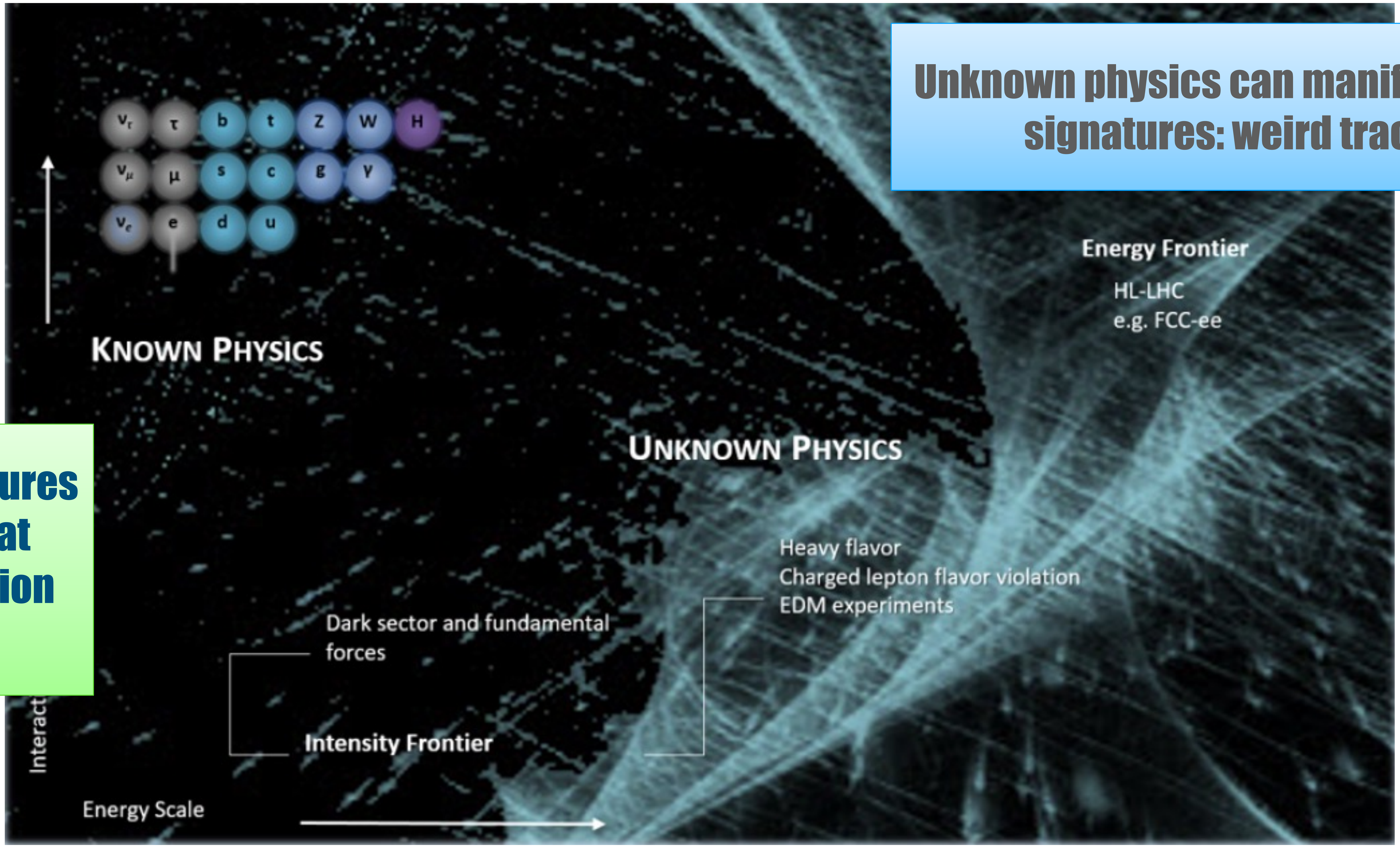
Basic research instrumentation needs and R&D goals

- ☐ Some themes for discussion and identification of broad synergies with other fields in experimental particle-physics, nuclear physics, and broader applied physics fields
- ☐ Illustrations of approaches to address these challenges (not comprehensive) - apologies if details are not included of your favorite solution; much more information in the parallel sessions

Marina Artuso CPAD workshop November 7th 2023 @ SLAC

The physics landscape

High luminosity colliders span the precision frontier (Higgs, flavor, EW) and the unknown



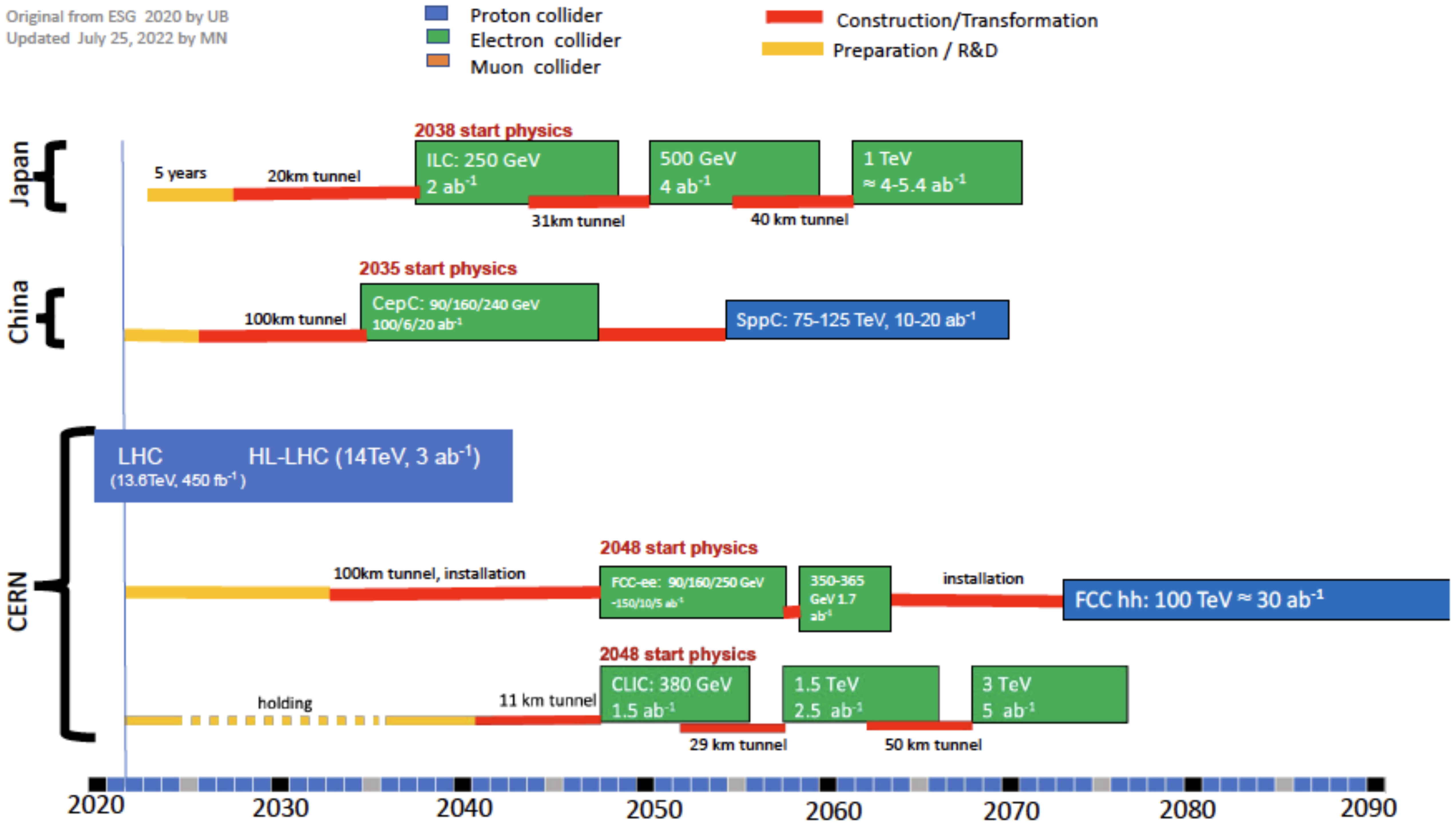
Unknown physics can manifest itself through unexpected signatures: weird tracks, long-lived particles

Studies of Standard Model features allow for a more in-depth view at the micro-word through precision measurements

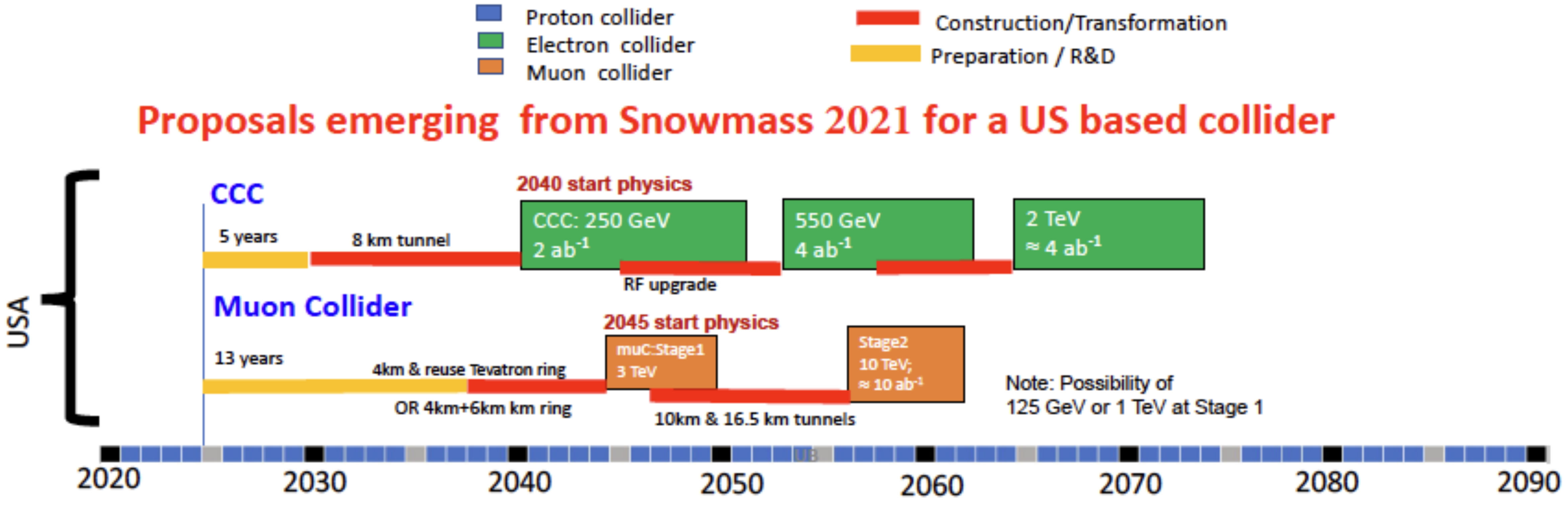
key goals of the energy frontier detectors

- ☐ Precision Standard Model tests:
  - Higgs physics:
    - Sub-percent precision measurement on the Higgs coupling to SM particles
    - 5% measurement of Higgs self-coupling
  - Flavor physics (b,c,τ) at the Z pole: new physics that is flavor-specific
  - Precision electroweak physics
- ☐ Direct searches for new particles:
  - Validation of specific top-down models (leptoquark, Z′…)
  - Dark sector, long lived particles (direct evidence of feebly interacting particles)

The facilities currently being considered



https://arxiv.org/pdf/2211.11084.pdf



To achieve the physics goals:

All these R&D streams can happen only with a concerted effort to train and retain skilled work force & share design tools and basic designs

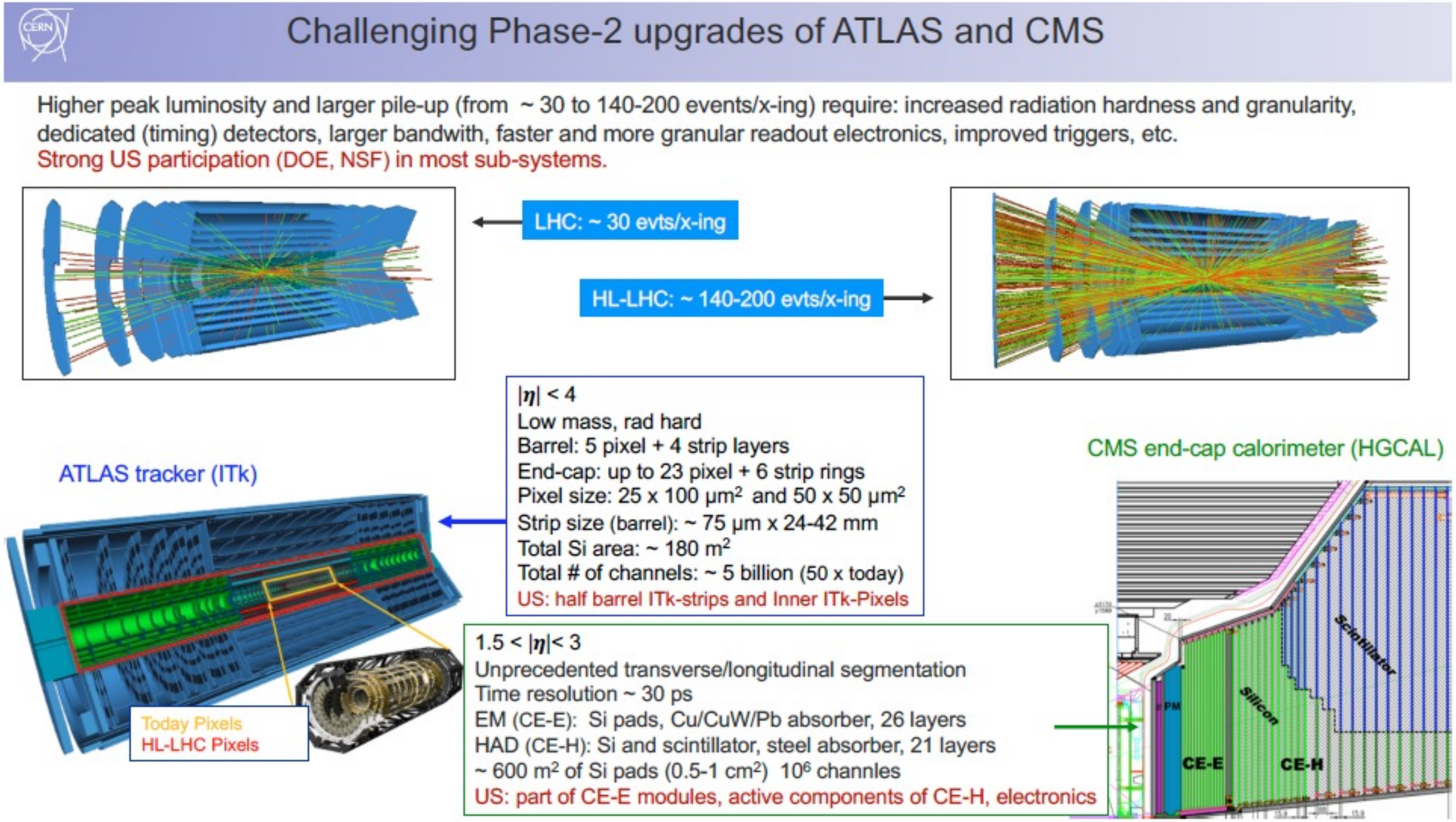
ASIC R&D needed for all

Detector subsystem	e+e- colliders	Hadron colliders
Tracking	Precise vertex topology High pT resolution: $\frac{\sigma_{p_T}}{p_T}$=0.2% for central tracks with p_T<100 GeV, $\frac{\sigma_{p_T}}{p_T^2} = \frac{2^{-5}}{\mathrm{GeV}}$ for central tracks with p_T>100GeV Impact parameter resolution $\sigma_{r\phi} = (5 \oplus 15(p[GeV]\, sin^{\frac{3}{2}}\theta)^{-1}$ Granularity 25x50 μm^2 5 μm single hit resolution	e+e- requirements+ 5 ps per track timing except pT resolution: $\frac{\sigma_{p_T}}{p_T}$=0.5% for central tracks with p_T<100 GeV Rad tolerant to 300 MGy and 8×10^{17} n_{eq}/cm^2
Calorimeters	High jet energy resolution (4%): Improve jet energy resolution using spectral separation of scintillation and Cherenkov signals and timing, and provide segmentation to match with incident tracks High EM energy resolution PID: hadron ID (TOF, Cherenkov, dN/dx in gaseous detectors)	5d reconstruction High radiation 4(5000)MGy $3 \times 10^{16}(5 \times 10^{18}) n_{eq}/cm^2$ Per shower time resolution of 5 ps
Trigger DAQ	Data volumes intelligent tracking	High data volume – Real-time trigger algorithms Throughput of 1 exabyte/s Logic and transmitters wit rad tol 300 MGy 8×10^{17} n_{eq}/cm^2

BRN Report

State of the art at the HL-LHC phase

Fabiola Gianotti – Snowmass CSS
July 2023



Challenging Phase-2 upgrades of ATLAS and CMS

Higher peak luminosity and larger pile-up (from ~ 30 to 140-200 events/x-ing) require: increased radiation hardness and granularity, dedicated (timing) detectors, larger bandwith, faster and more granular readout electronics, improved triggers, etc.
Strong US participation (DOE, NSF) in most sub-systems.

LHC: ~ 30 evts/x-ing

HL-LHC: ~ 140-200 evts/x-ing

ATLAS tracker (ITk)

$|\eta| < 4$
Low mass, rad hard
Barrel: 5 pixel + 4 strip layers
End-cap: up to 23 pixel + 6 strip rings
Pixel size: 25 x 100 μm^2 and 50 x 50 μm^2
Strip size (barrel): ~ 75 μm x 24-42 mm
Total Si area: ~ 180 m^2
Total # of channels: ~ 5 billion (50 x today)
US: half barrel ITk-strips and Inner ITk-Pixels

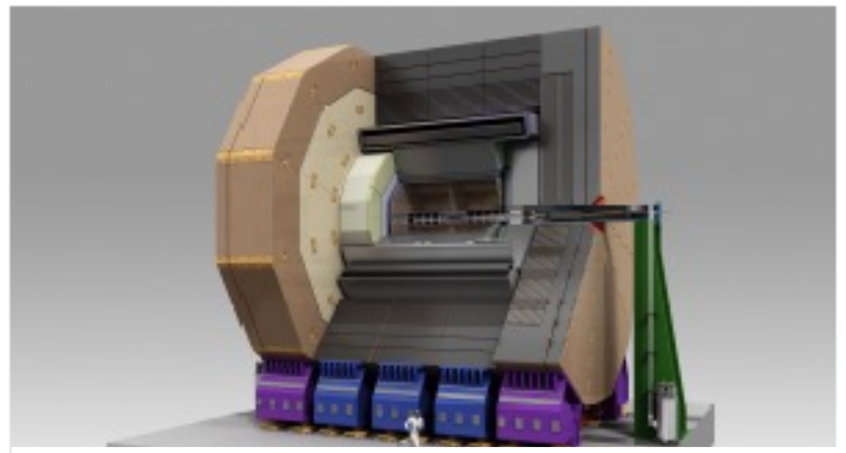
Today Pixels
HL-LHC Pixels

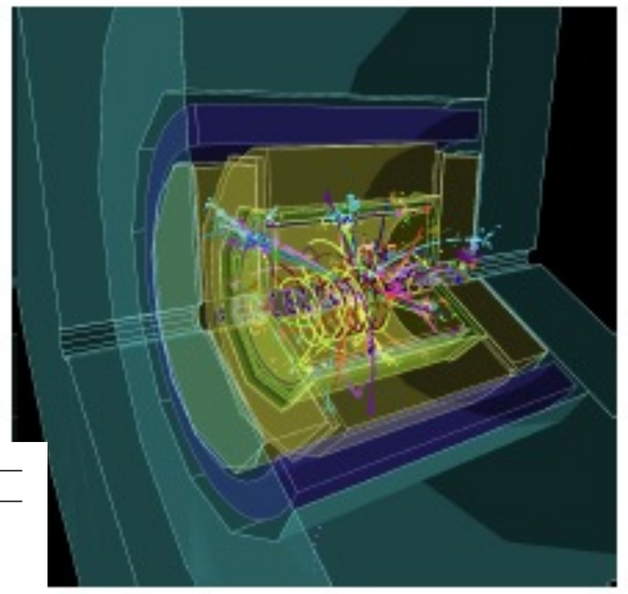
CMS end-cap calorimeter (HGCAL)

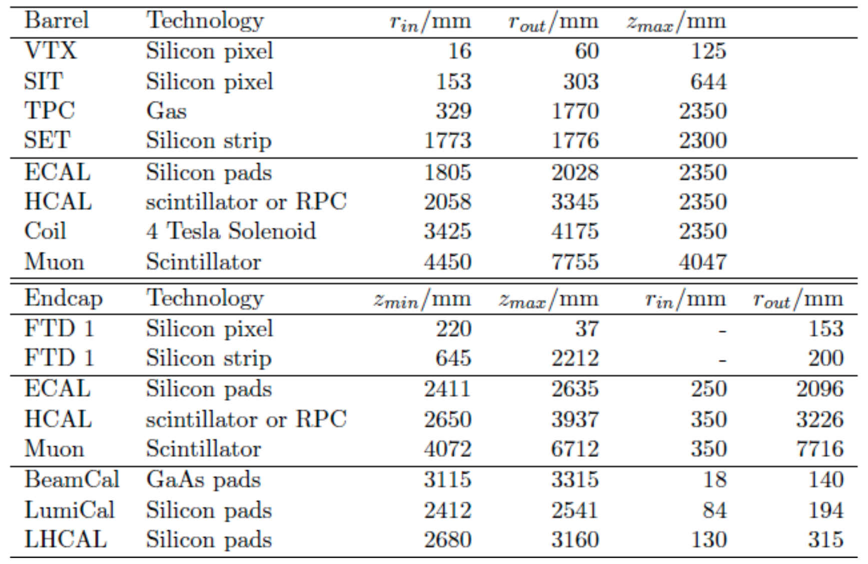
$1.5 < |\eta| < 3$
Unprecedented transverse/longitudinal segmentation
Time resolution ~ 30 ps
EM (CE-E): Si pads, Cu/CuW/Pb absorber, 26 layers
HAD (CE-H): Si and scintillator, steel absorber, 21 layers
~ 600 m^2 of Si pads (0.5-1 cm^2) 10^6 channles
US: part of CE-E modules, active components of CE-H, electronics

Different detector concepts

The ILD detector





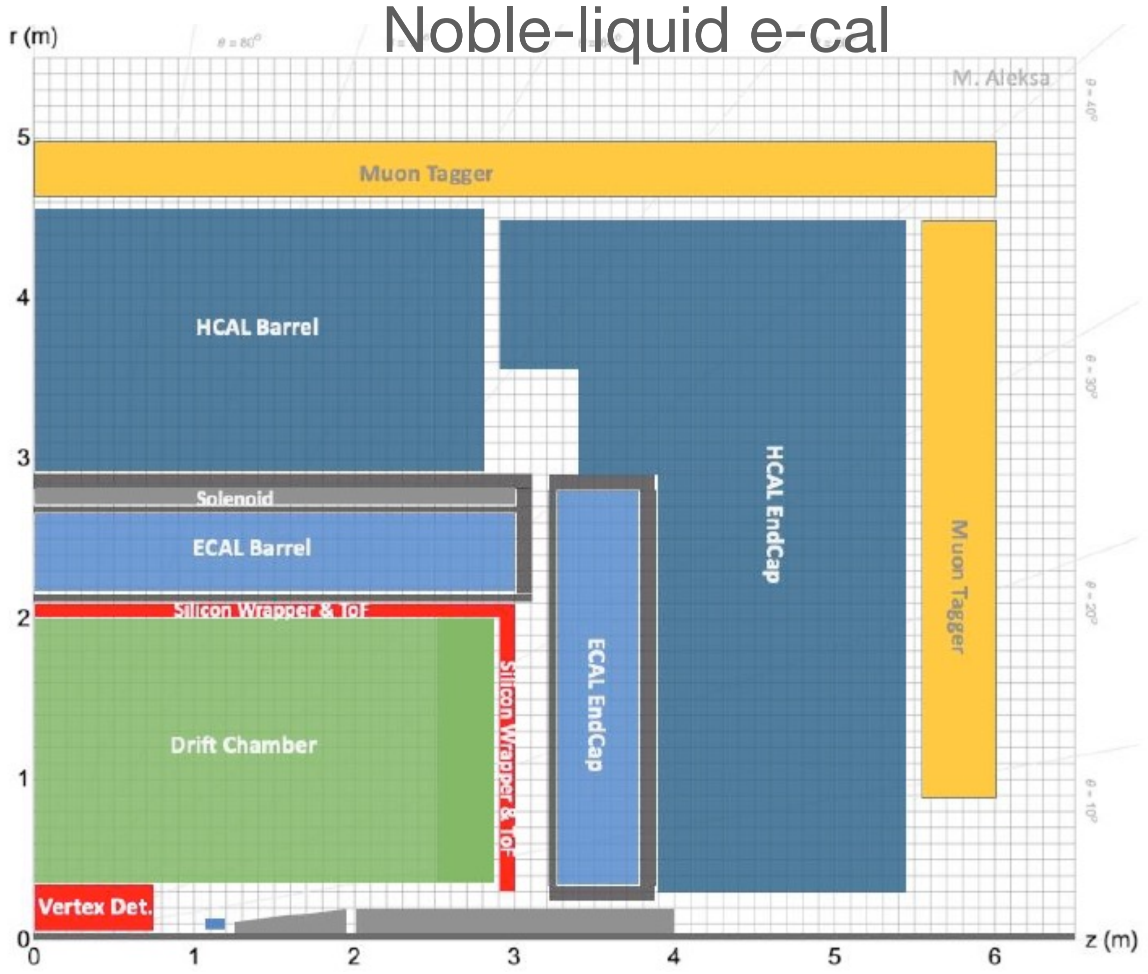


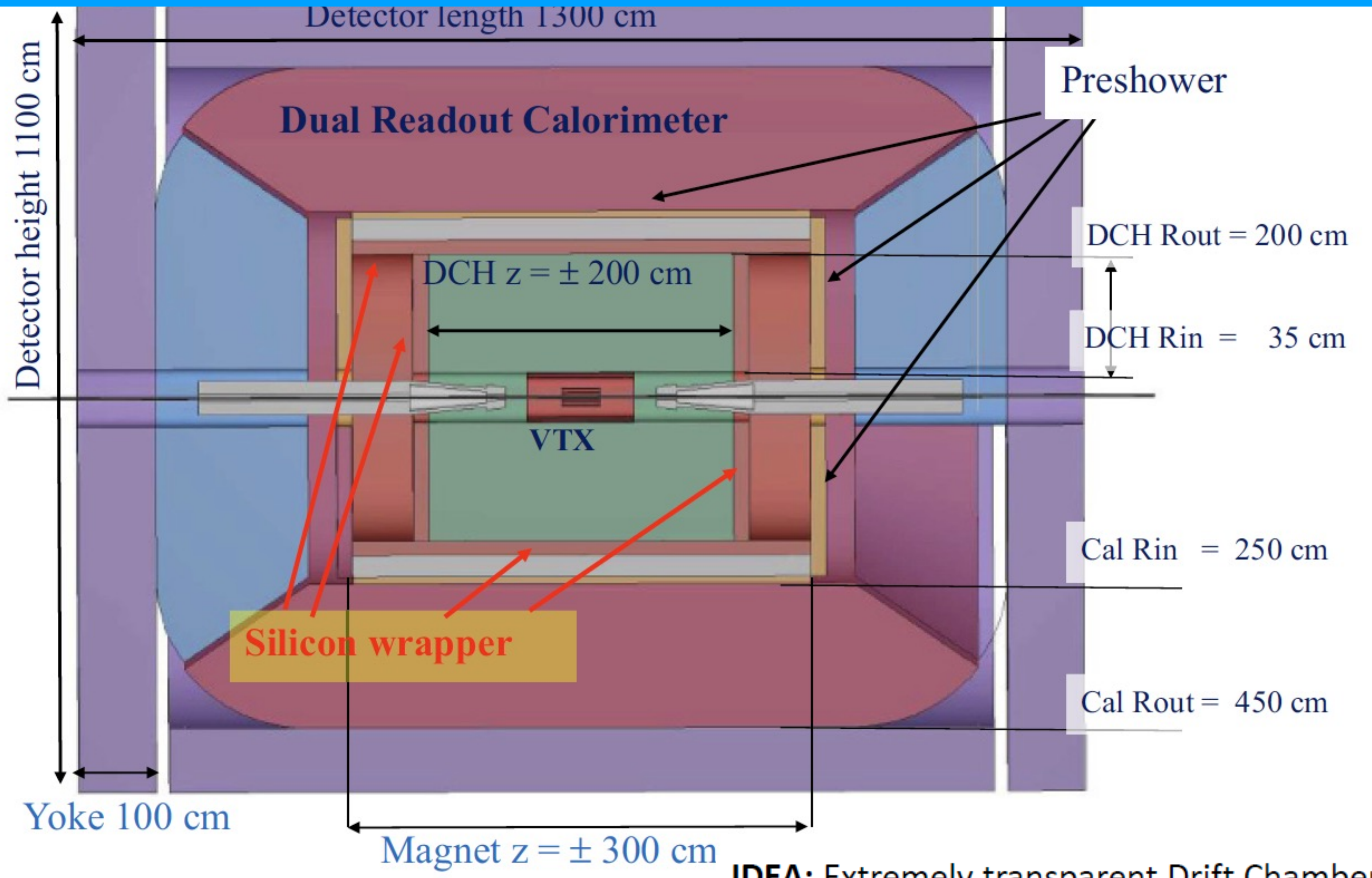
Barrel	Technology	r_{in}/mm	r_{out}/mm	z_{max}/mm
VTX	Silicon pixel	16	60	125
SIT	Silicon pixel	153	303	644
TPC	Gas	329	1770	2350
SET	Silicon strip	1773	1776	2300
ECAL	Silicon pads	1805	2028	2350
HCAL	scintillator or RPC	2058	3345	2350
Coil	4 Tesla Solenoid	3425	4175	2350
Muon	Scintillator	4450	7755	4047

Endcap	Technology	z_{min}/mm	z_{max}/mm	r_{in}/mm	r_{out}/mm
FTD 1	Silicon pixel	220	37	-	153
FTD 1	Silicon strip	645	2212	-	200
ECAL	Silicon pads	2411	2635	250	2096
HCAL	scintillator or RPC	2650	3937	350	3226
Muon	Scintillator	4072	6712	350	7716
BeamCal	GaAs pads	3115	3315	18	140
LumiCal	Silicon pads	2412	2541	84	194
LHCAL	Silicon pads	2680	3160	130	315

Large high-granularity high-hermeticity system featuring excellent spatial and energy resolution

Noble-liquid e-cal





IDEA: Extremely transparent Drift Chamber

- GAS: 90% He – 10% iC_4H_{10}
- Radius 0.35 – 2.00 m
- Total thickness: 1.6% of X_0 at 90°
  - Tungsten wires dominant contribution
- Full system includes Si VTX and Si "wrapper"

Muon collider detector concept

hadronic calorimeter

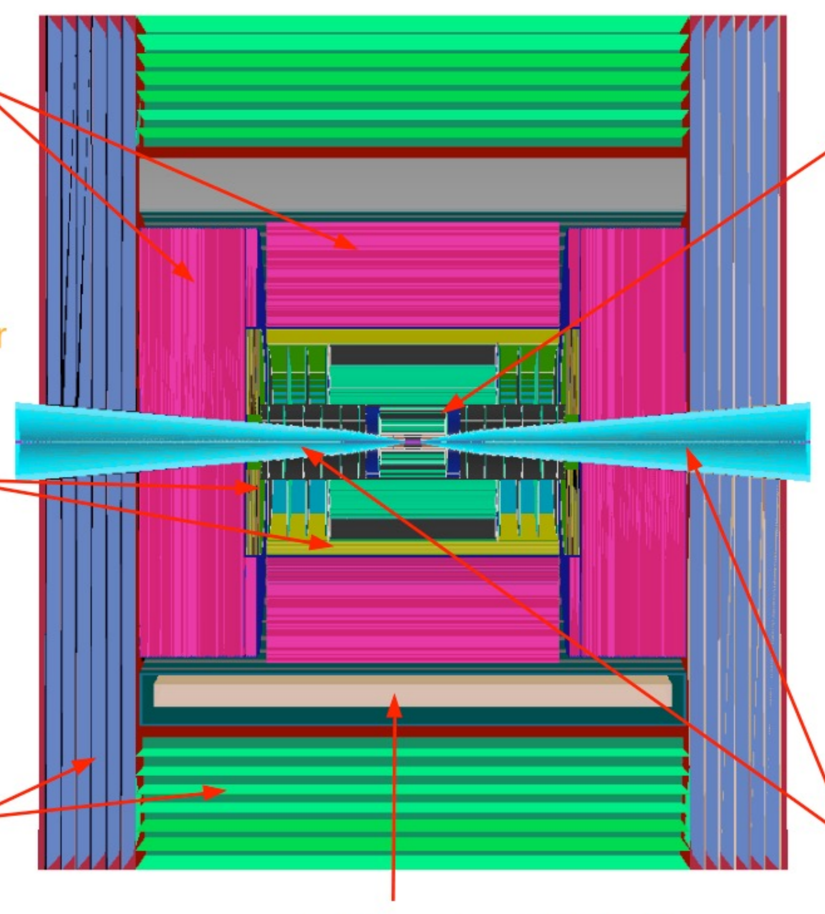
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 µm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

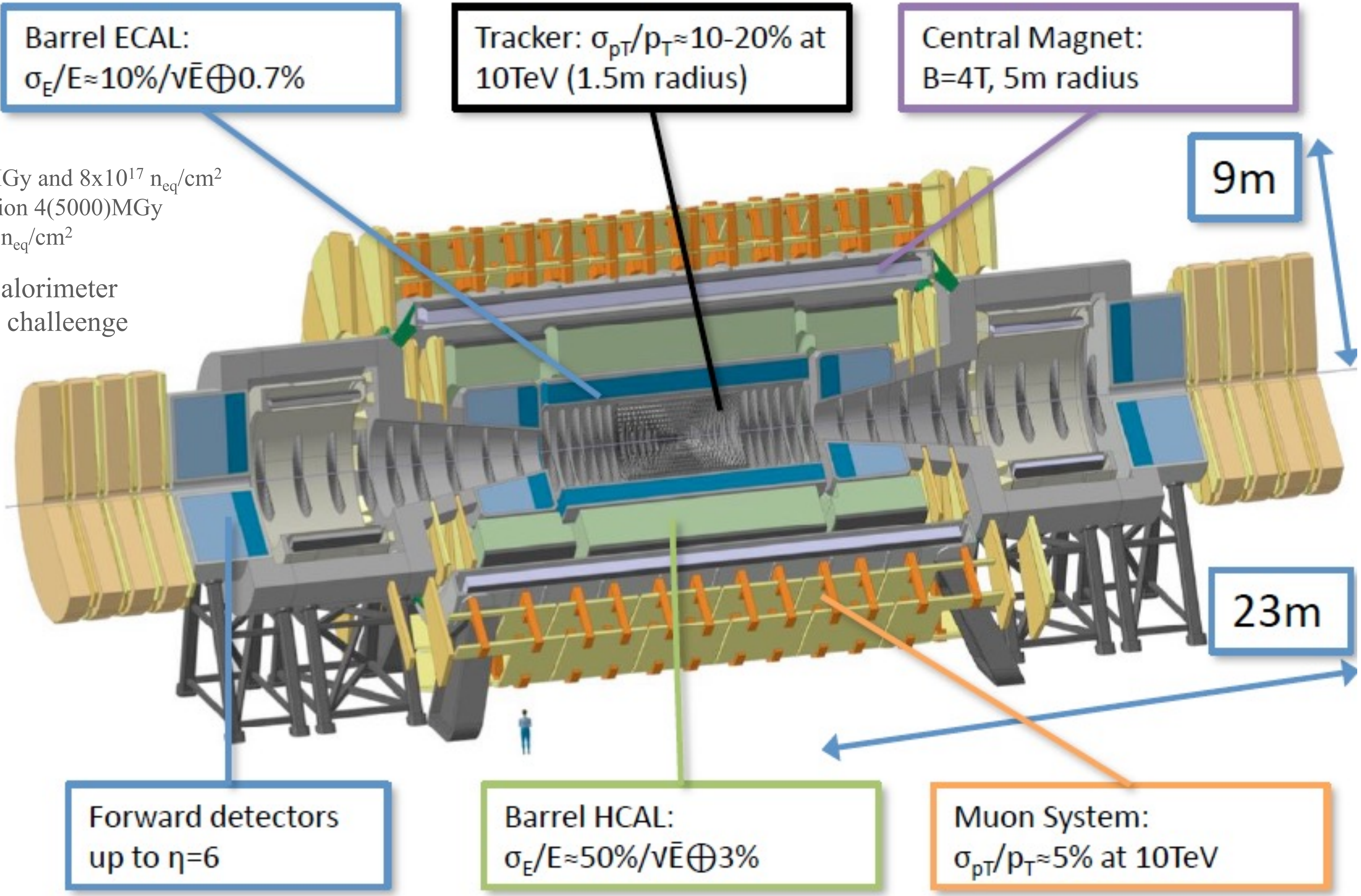
- Tungsten cones + borated polyethylene cladding.

High-energy hadron colliders (e.g. FCChh) have the additional requirement of precise time-stamp to reduce pile-up and unprecedented levels of integrated doses

FCC-hh: the ultimate challenge

Tracker Rad tolerant to 300 MGy and $8\times10^{17}\ n_{eq}/cm^2$
Calorimeter High radiation 4(5000)MGy
$3\times10^{16}(5\times10^{18})n_{eq}/cm^2$

4d tracking, 5d calorimeter
Trigger aad DAQ challeenge



Barrel ECAL:
$\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Tracker: $\sigma_{pT}/p_T \approx$ 10-20% at 10TeV (1.5m radius)

Central Magnet:
B=4T, 5m radius

Forward detectors
up to $\eta=6$

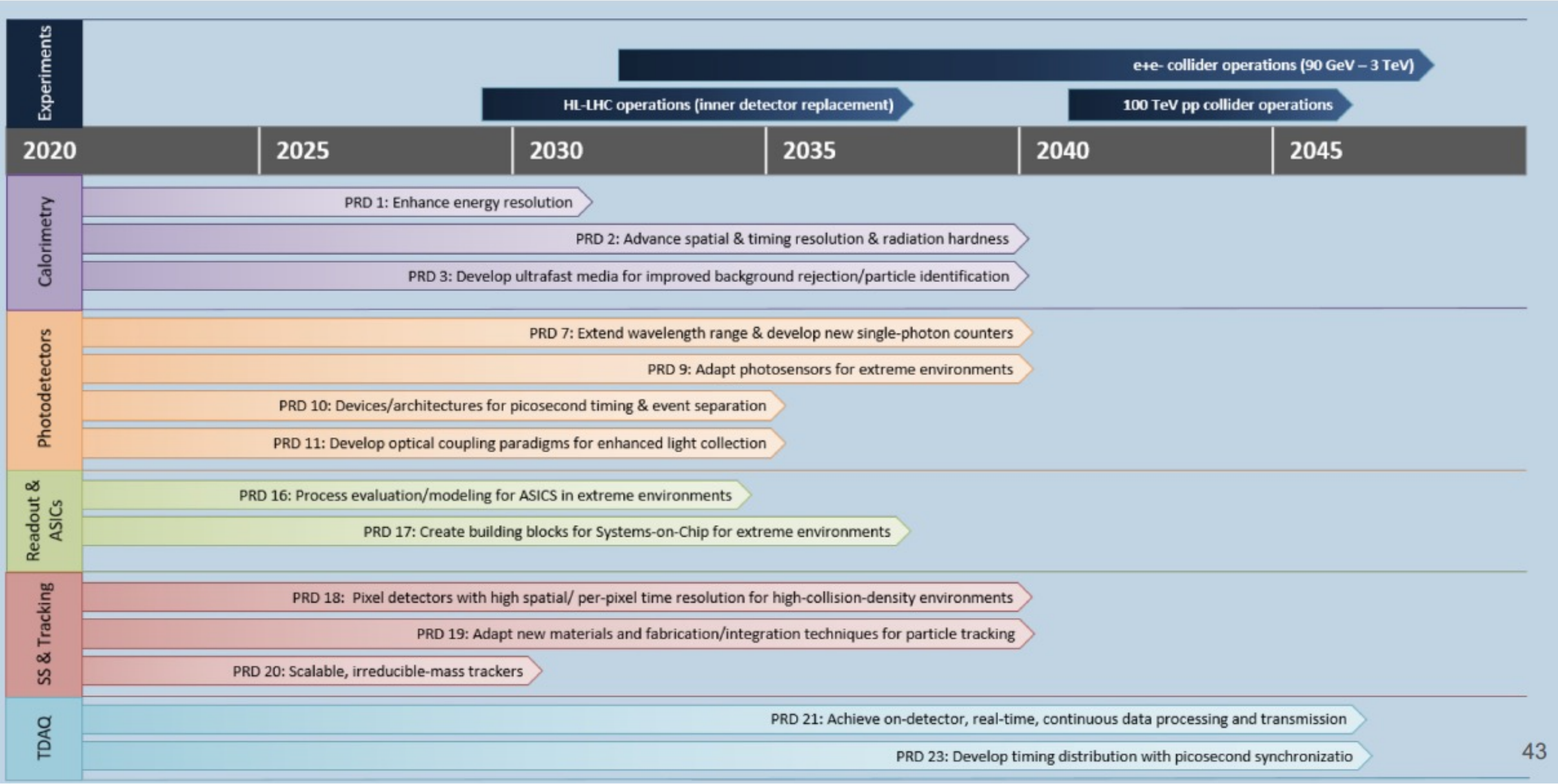
Barrel HCAL:
$\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

Muon System:
$\sigma_{pT}/p_T \approx 5\%$ at 10TeV

Key technical requirements

- Challenges for e^+e^- high-luminosity colliders: position & energy measurements with excellent resolution for all basic signatures (electrons, photons, muon and tau leptons, hadronic jets and missing energy) in a broad range of energies and in very large detectors. "Particle flow method" needed → information from calorimeter and charged particle tracking needs to be combined.
  - Charged particle reconstruction:
    - excellent resolution at low p_T over a large momentum range → low mass, large radius detectors with excellent single-hit resolution.
  - Calorimetry:
    - Excellent energy resolution for electromagnetic particles
  - Hadron identification:
    - If time of flight is used, excellent time resolution is needed
  - Detector trigger and readout:
    - high-granularity → high-data rates
    - Broad range for new physics searches → distributed intelligence for data reduction, with efficacious use of machine-learning techniques
- Hadron colliders add high radiation tolerance, fast time stamp for pileup mitigation, and unprecedented data rate and trigger requirements.

A detector R&D timeline



Experiments
- e+e- collider operations (90 GeV – 3 TeV)
- HL-LHC operations (inner detector replacement)
- 100 TeV pp collider operations

2020 | 2025 | 2030 | 2035 | 2040 | 2045

Calorimetry
- PRD 1: Enhance energy resolution
- PRD 2: Advance spatial & timing resolution & radiation hardness
- PRD 3: Develop ultrafast media for improved background rejection/particle identification

Photodetectors
- PRD 7: Extend wavelength range & develop new single-photon counters
- PRD 9: Adapt photosensors for extreme environments
- PRD 10: Devices/architectures for picosecond timing & event separation
- PRD 11: Develop optical coupling paradigms for enhanced light collection

Readout & ASICs
- PRD 16: Process evaluation/modeling for ASICS in extreme environments
- PRD 17: Create building blocks for Systems-on-Chip for extreme environments

SS & Tracking
- PRD 18: Pixel detectors with high spatial/ per-pixel time resolution for high-collision-density environments
- PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking
- PRD 20: Scalable, irreducible-mass trackers

TDAQ
- PRD 21: Achieve on-detector, real-time, continuous data processing and transmission
- PRD 23: Develop timing distribution with picosecond synchronizatio

Tracking detectors – solid state

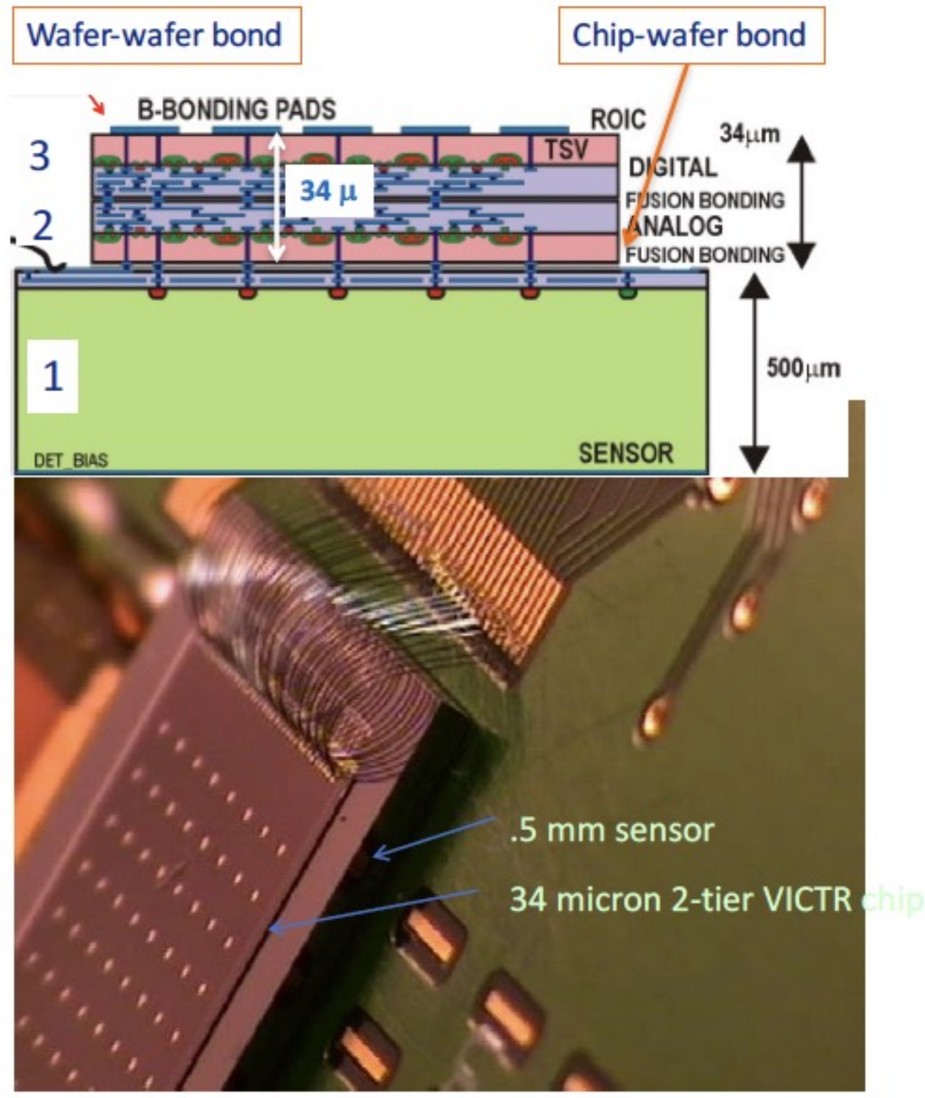
❑High granularity is needed to achieve high spatial resolution & high radiation resistance. Lepton colliders require high granularity and small pixel size in the innermost region, and a broader area covered with pixel devices.

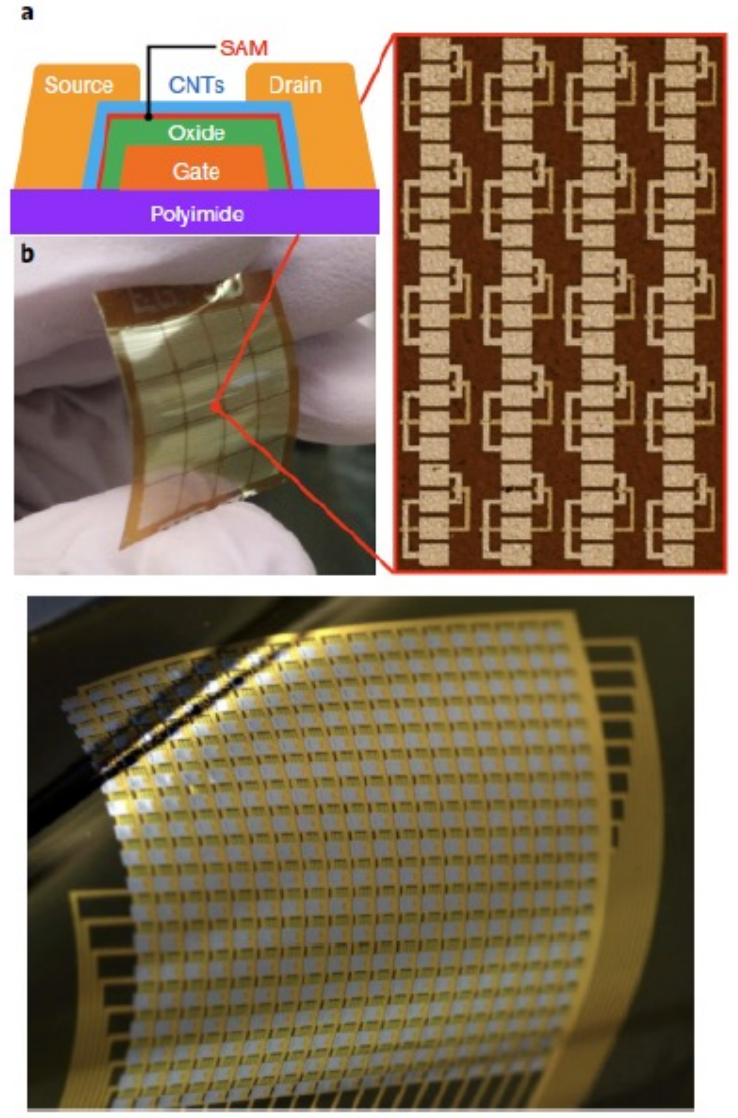
- Pixel size ~10 μm
- Large distributed system:
  - Low noise, low power electronics
  - Low mass integration (mechanics and cooling)
  - Large volume of data transmission (interconnection, data processing →intelligent tracker)

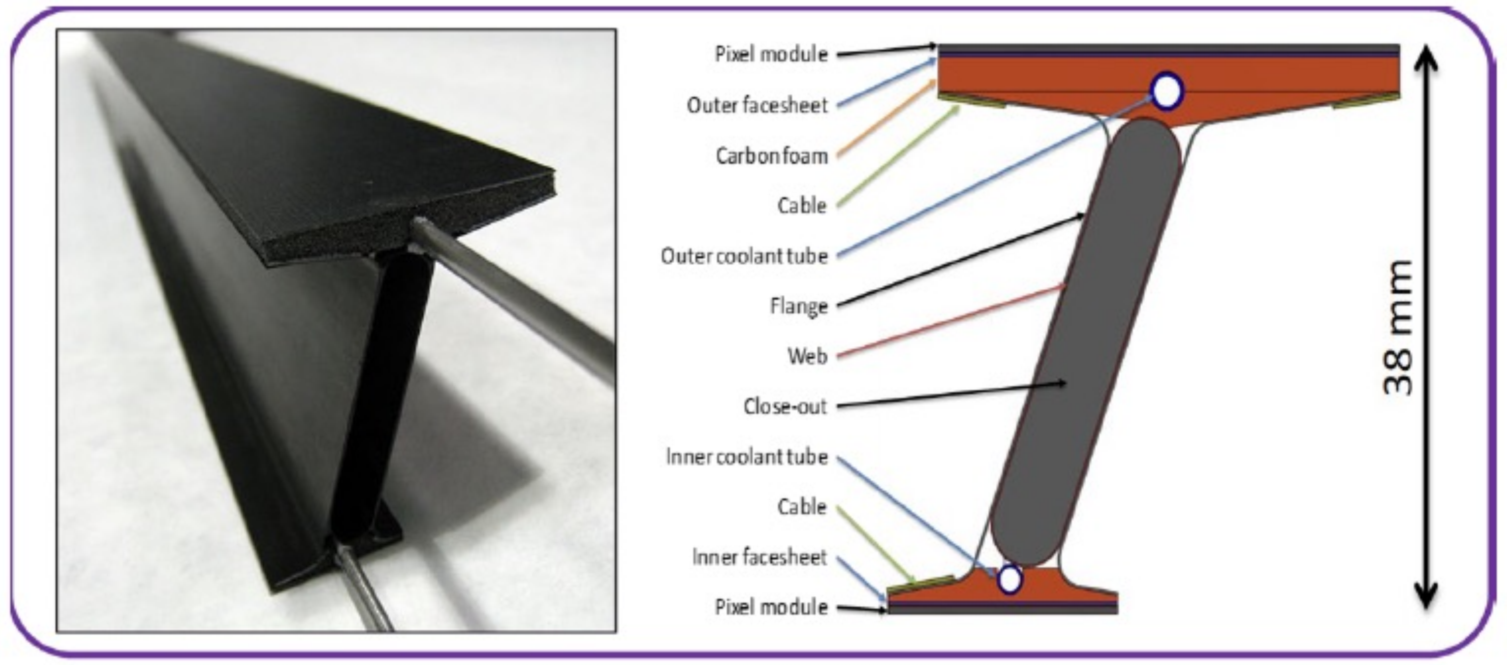
❑Hadron colliders: all of the above + O(1ps timing) and radiation resistance up to fluences of the order of $10^{18} n_{eq}/cm^2$

Priority research directions

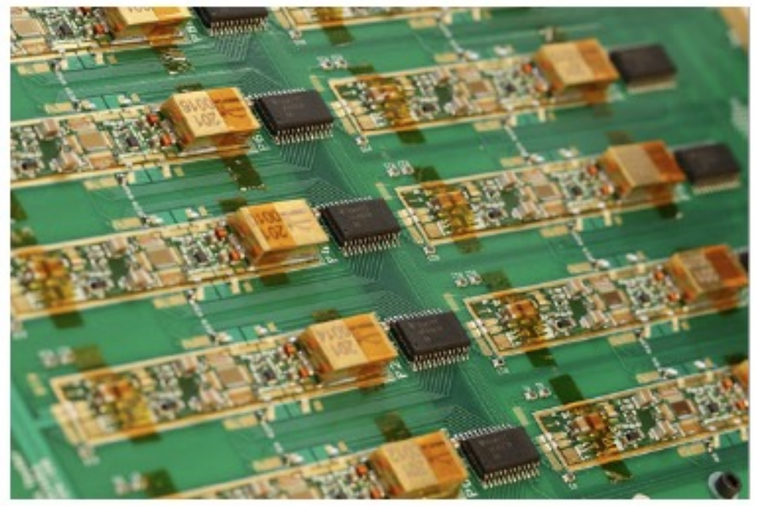
- ❑ Adapt new materials and fabrication/integration techniques for particle tracking:
  - New materials (diamond, large-bandgap semiconductors, thin film materials…) essential to develop new industrial partners
  - Sensor-detector integration with novel hybridization techniques [e.g. wafer bonding, vertical 3D integration]
- ❑ Development of scalable, irreducible mass trackers:
  - Low mass trackers with small pixel sizes covering large areas:
    - Thinned monolithic sensors
    - System aspects (pulsed power, gas cooling)

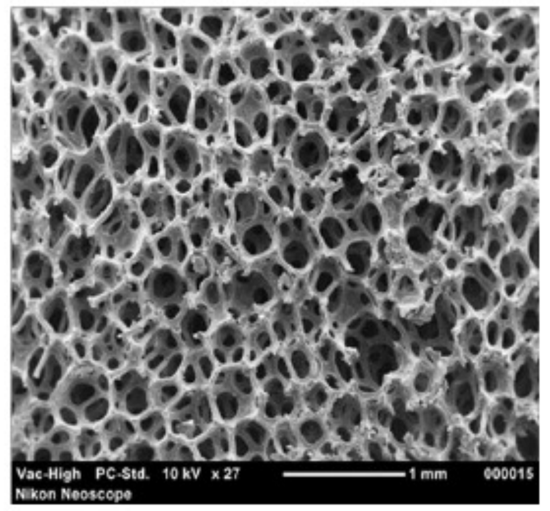






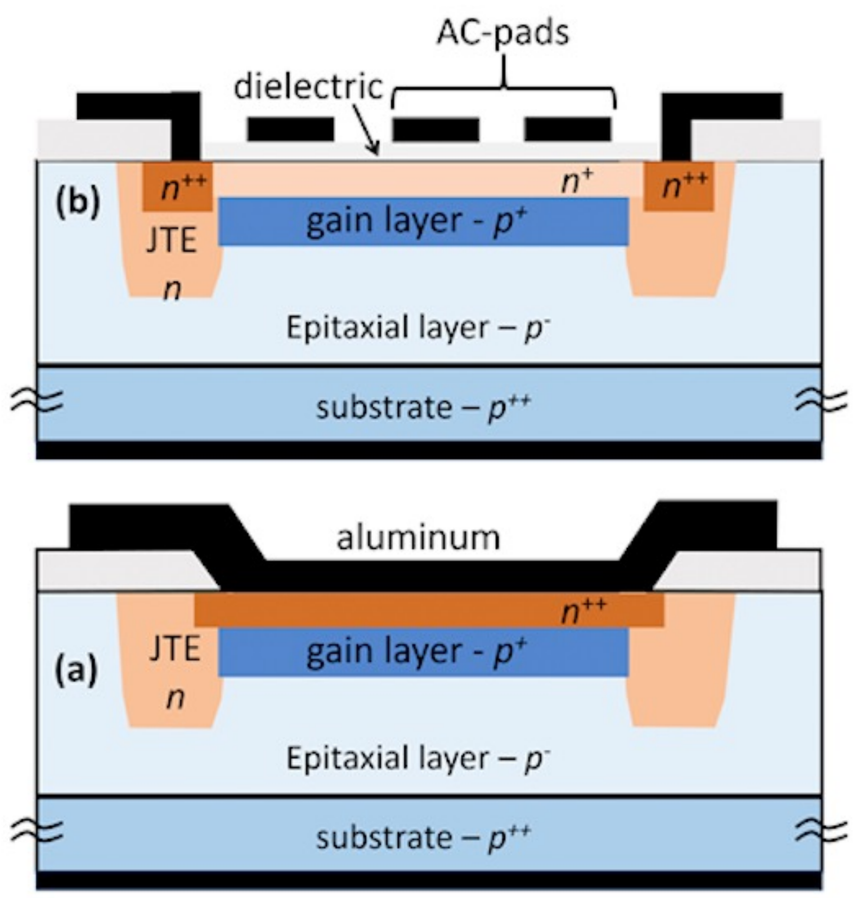
Synergy with EIC, LHCb upgrade II



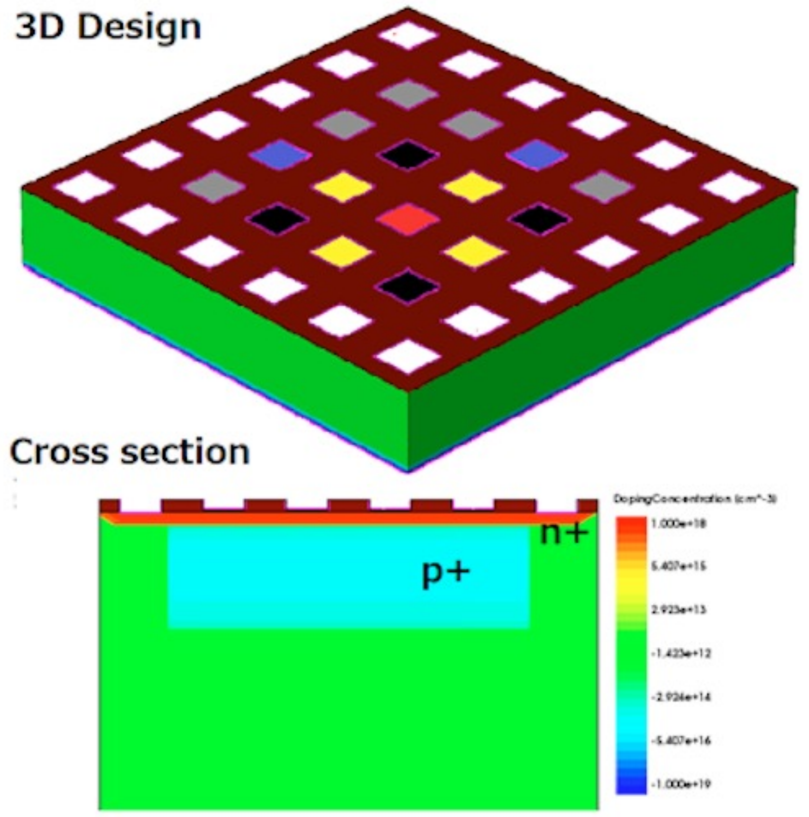


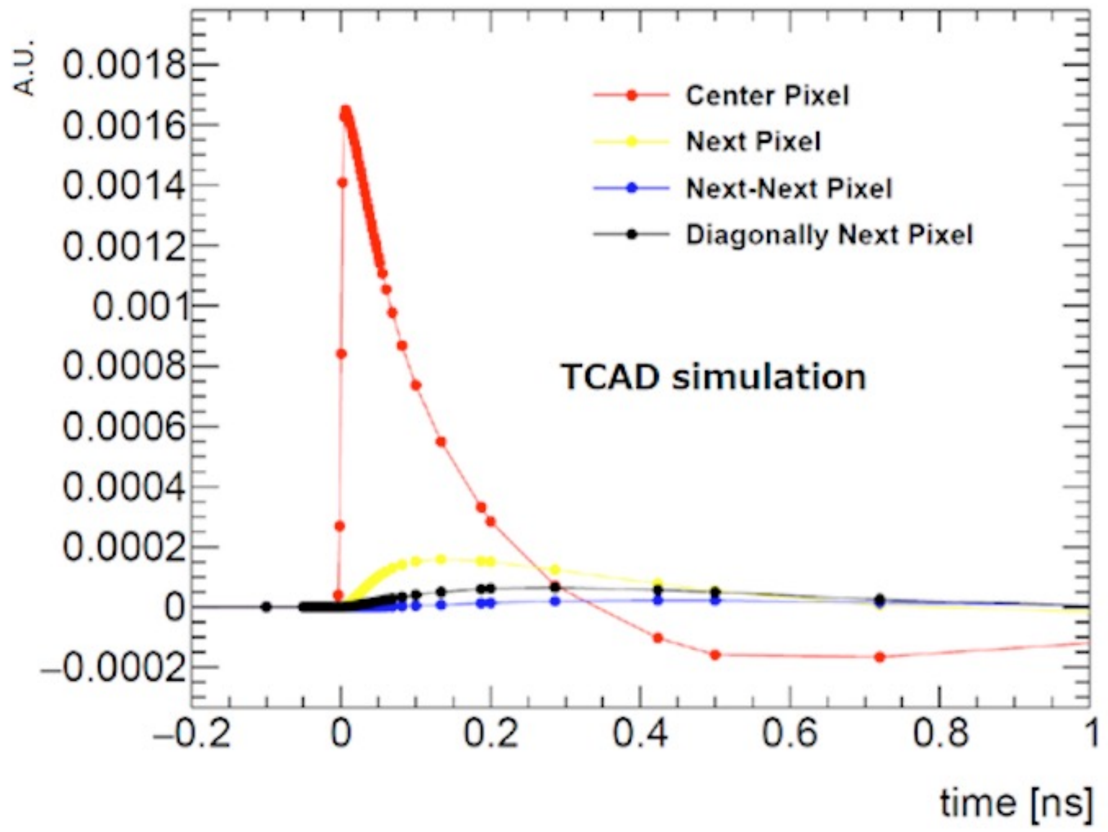
Ultrafast Si detectors

- ❑ High spatial resolution [O(10 μm)] with precision time stamp (O(1ps)) to resolve individual interactions in a high-collision-density environments, with new level of rad-hard technologies
- ❑ A time stamp of O(10ps) is suitable for TOF applications



From BRN report





3D silicon detectors

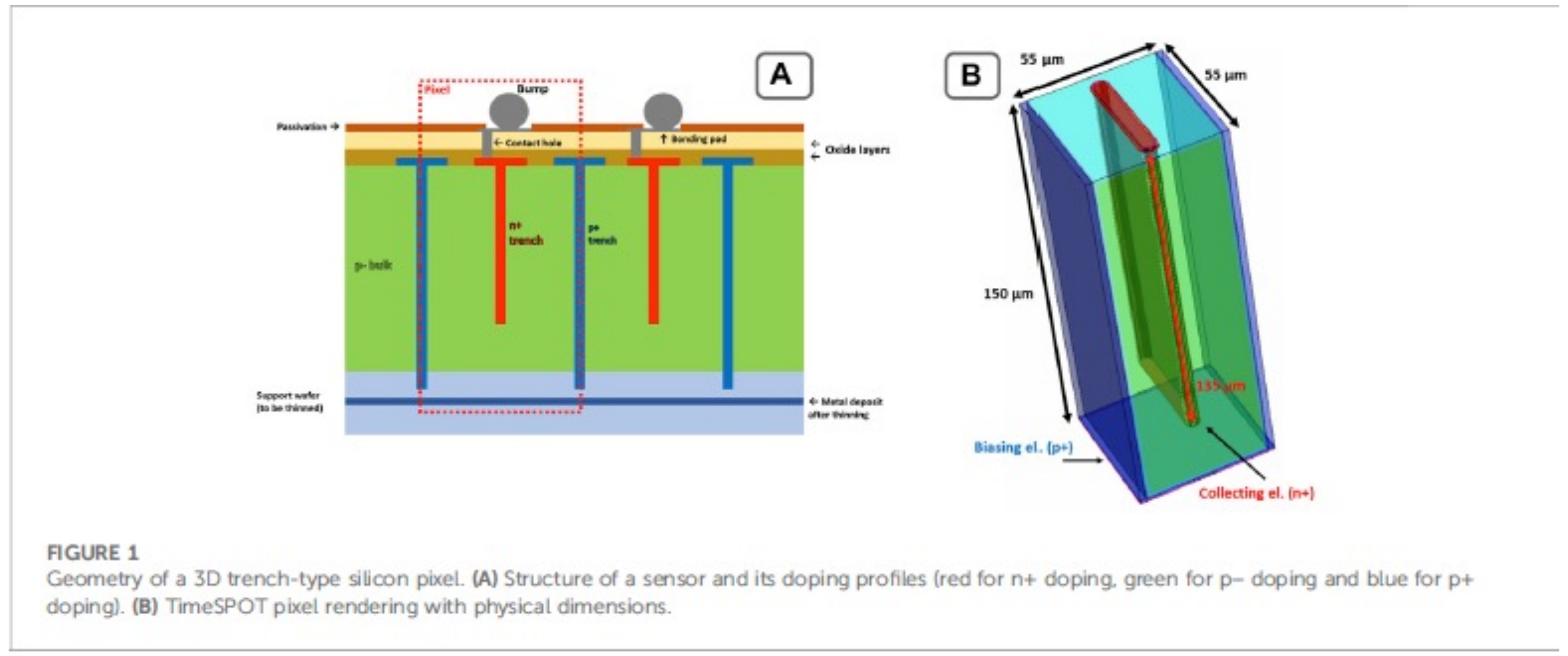
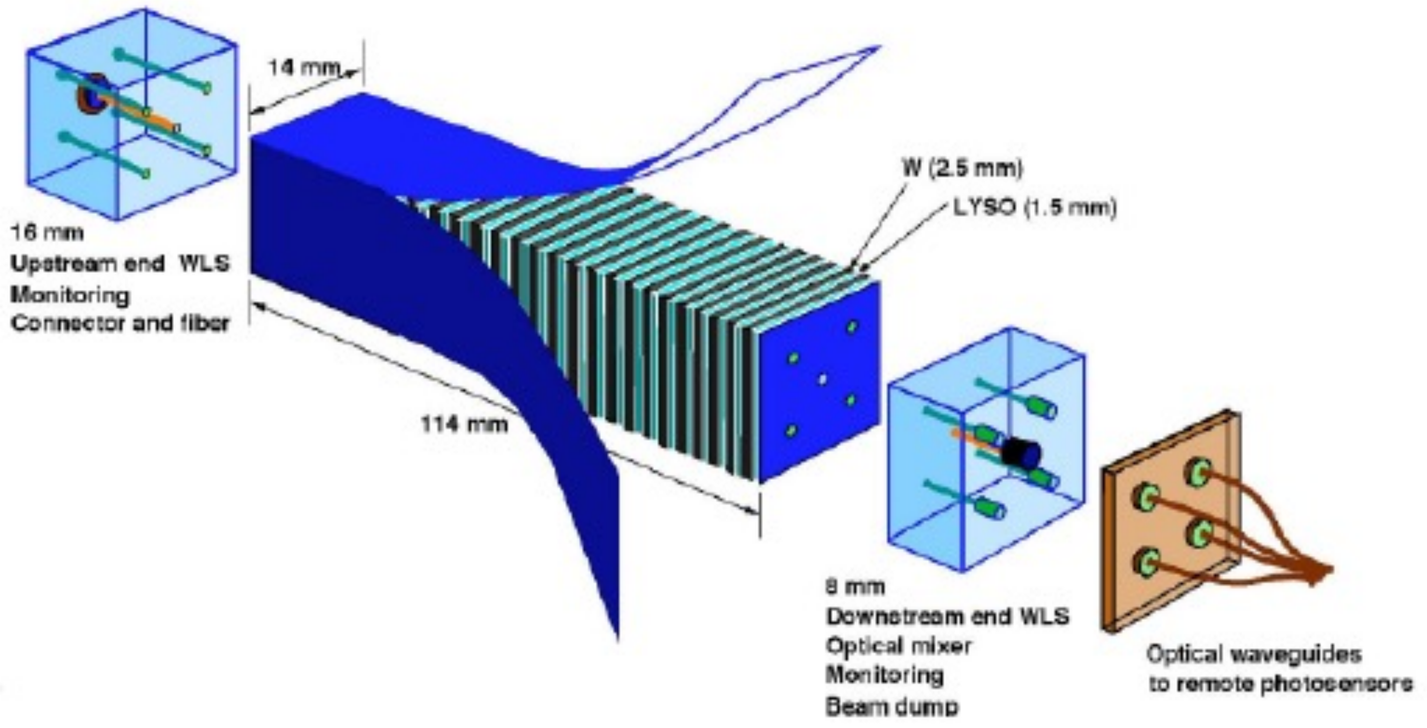


FIGURE 1
Geometry of a 3D trench-type silicon pixel. (A) Structure of a sensor and its doping profiles (red for n+ doping, green for p− doping and blue for p+ doping). (B) TimeSPOT pixel rendering with physical dimensions.

Calorimetry

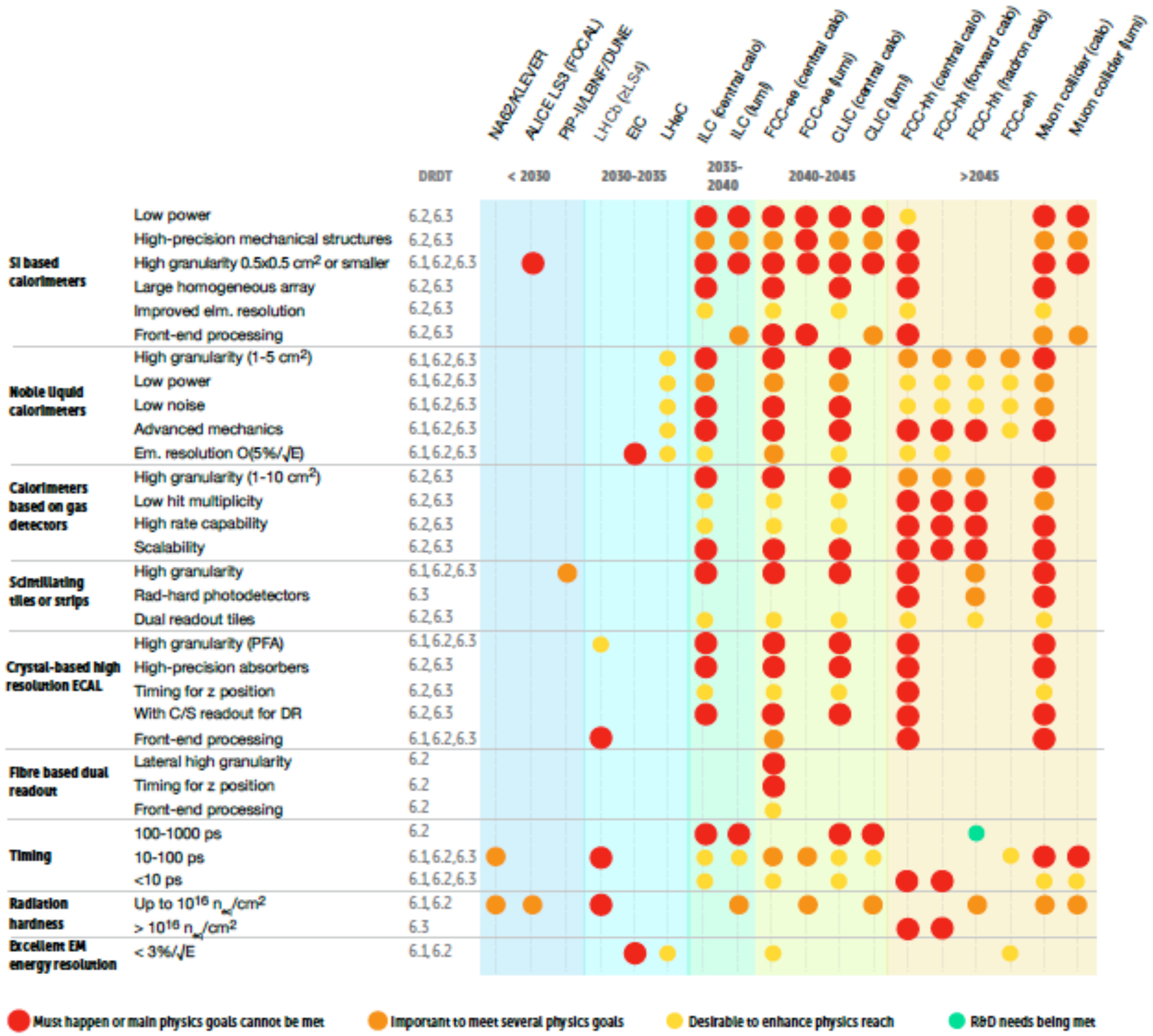
- ❑A paradigm shift, already occurred in the world of calorimetry, is the way in which information from the tracker and calorimeters are combined in a "particle flow" processing
- ❑Key design drivers:
  - High-fidelity high-resolution particle-flow reconstruction for precise jet reconstruction
  - Lateral and depth segmentation
  - Timing information (moderate ~ 1ns can distinguish E&M and hadronic showers)
  - High resolution reconstruction of photons, π^0 and electrons
- ❑Approaches to achieve these goals:
  - using spectral separation of scintillation and Cherenkov signals (dual-readout calorimeters)
  - Improvement of E&M energy resolution using either multi-anode liquid noble elements (Ar, Kr, or Xe) [stochastic resolution of $6\%/\sqrt{E}$ obtained with LKr]
  - Imaging calorimeters [get Si to fulfill its potential for imaging calorimeters]
- ❑For pp machines: time stamp to mitigate pileup & radiation hard materials
- ❑Important thrust: new materials, especially for ultrafast applications

RaDiCAL



A variety of approaches

THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP



		DRDT	NA62/KLEVER	ALICE LS3 (FOCAL)	PIP-II/LBNF/DUNE	LHCb (≥LS4)	EIC	LHeC	ILC (central calo)	ILC (lumi)	FCC-ee (central calo)	FCC-ee (lumi)	CLIC (central calo)	CLIC (lumi)	FCC-hh (central calo)	FCC-hh (forward calo)	FCC-hh (hadron calo)	FCC-eh	Muon collider (calo)	Muon collider (lumi)
			< 2030			2030-2035			2035-2040		2040-2045				>2045					
Si based calorimeters	Low power	6.2,6.3							🔴	🔴	🔴	🔴	🔴	🔴	🟡				🔴	🔴
	High-precision mechanical structures	6.2,6.3							🟠	🟠	🟠	🔴	🟠	🟠	🔴				🟠	🟠
	High granularity 0.5x0.5 cm² or smaller	6.1,6.2,6.3		🔴					🔴	🔴	🔴	🔴	🔴	🔴	🔴				🔴	🔴
	Large homogeneous array	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Improved elm. resolution	6.2,6.3							🟡		🟡		🟡		🟡				🟡	
	Front-end processing	6.2,6.3								🟠	🔴	🔴		🟠	🔴				🟠	🟠
Noble liquid calorimeters	High granularity (1-5 cm²)	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟠	🟠	🟠	🟠	🔴	
	Low power	6.1,6.2,6.3						🟡	🟠		🟠		🟠		🟡	🟡	🟡	🟡	🟠	
	Low noise	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🟡	🟡	🟡	🟡	🟠	
	Advanced mechanics	6.1,6.2,6.3						🟡	🔴		🔴		🔴		🔴	🔴	🔴	🟡	🔴	
	Em. resolution O(5%/√E)	6.1,6.2,6.3					🔴	🟡	🟡		🟠		🟡		🟡	🟡				
Calorimeters based on gas detectors	High granularity (1-10 cm²)	6.2,6.3							🔴		🔴		🔴		🟠	🟠	🟠		🔴	
	Low hit multiplicity	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🟠	
	High rate capability	6.2,6.3							🟡		🟡		🟡		🔴	🔴	🔴		🔴	
	Scalability	6.2,6.3							🔴		🔴		🔴		🔴	🔴	🔴		🔴	
Scintillating tiles or strips	High granularity	6.1,6.2,6.3			🟠				🔴		🔴		🔴		🔴		🟠		🔴	
	Rad-hard photodetectors	6.3													🔴		🟠		🔴	
	Dual readout tiles	6.2,6.3							🟡		🟡		🟡		🟡		🟡		🟡	
Crystal-based high resolution ECAL	High granularity (PFA)	6.1,6.2,6.3				🟡			🔴		🔴		🔴		🔴				🔴	
	High-precision absorbers	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Timing for z position	6.2,6.3							🟡		🟡		🟡		🔴				🟡	
	With C/S readout for DR	6.2,6.3							🔴		🔴		🔴		🔴				🔴	
	Front-end processing	6.1,6.2,6.3				🔴					🟠				🔴				🔴	
Fibre based dual readout	Lateral high granularity	6.2									🔴									
	Timing for z position	6.2									🔴									
	Front-end processing	6.2									🟡									
Timing	100-1000 ps	6.2							🔴	🔴			🔴	🔴			🟢			
	10-100 ps	6.1,6.2,6.3	🟠			🔴			🟡	🟡	🟠	🟠	🟡	🟡				🟡	🔴	🔴
	<10 ps	6.1,6.2,6.3							🟡		🟡		🟡		🔴	🔴			🟡	🟡
Radiation hardness	Up to 10^{16} n_{eq}/cm^2	6.1,6.2	🟠	🟠		🔴				🟠		🟠		🟠			🟠		🟠	🟠
	> 10^{16} n_{eq}/cm^2	6.3													🔴	🔴				
Excellent EM energy resolution	< 3%/√E	6.1,6.2					🔴	🟡			🟡							🟡		

🔴 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

❑ For particle-flow algorithms:

- Silicon for imaging calorimeters (e.g. digital calorimeters with MAPS)
- Dual readout calorimeters to track fluctuations in hadronic showers and achieve better jet energy reconstruction
- Ultrafast calorimeter media for background rejection, may be useful for particle identification

❑ For electromagnetic energy resolution:

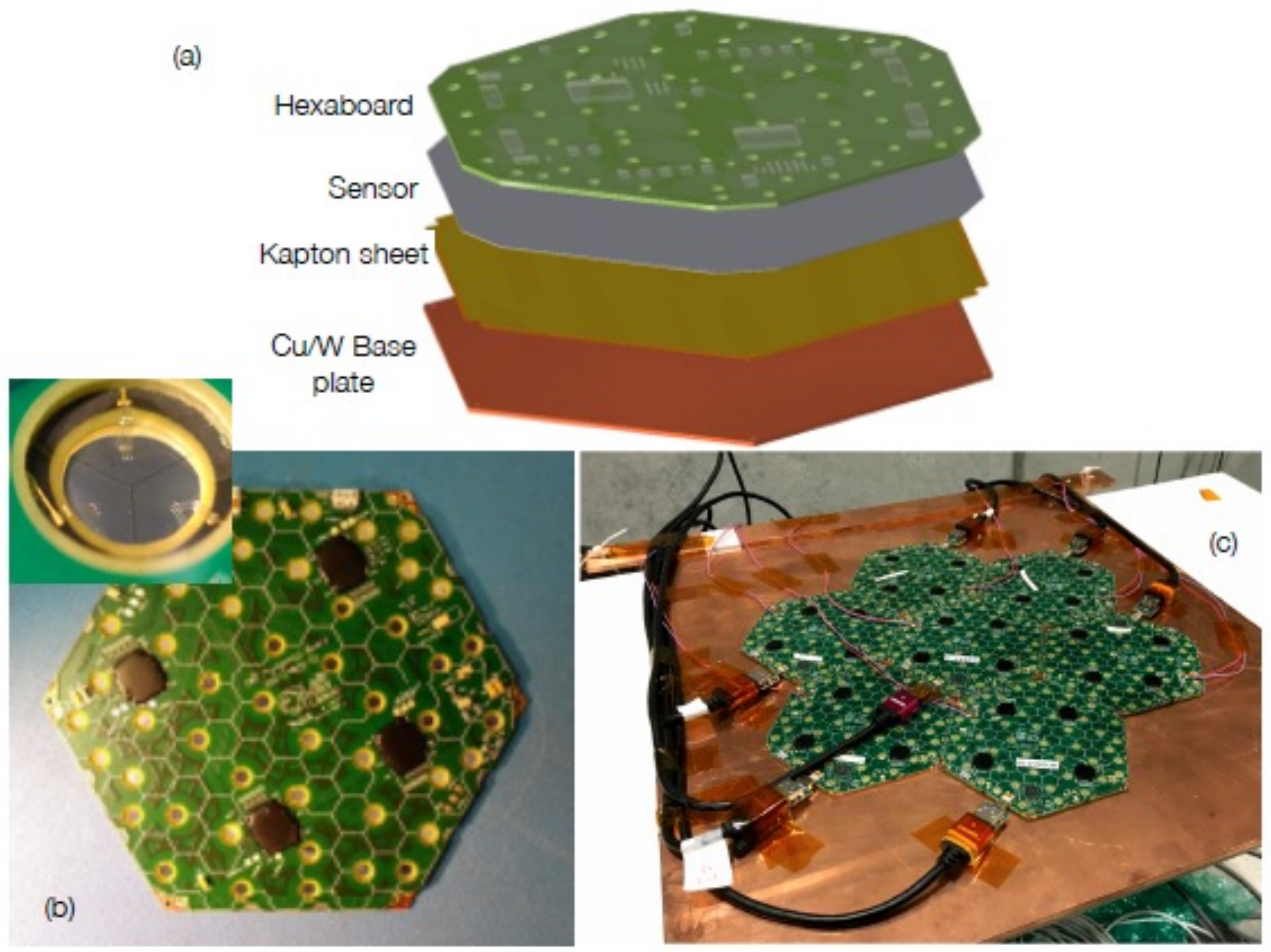
- noble-liquid calorimeters with higher segmentation (x12 wrt x4 ATLAS), SNR increased by a factor of 5 wrt ATLAS using cold electronics

❑ Structural material/system aspects:

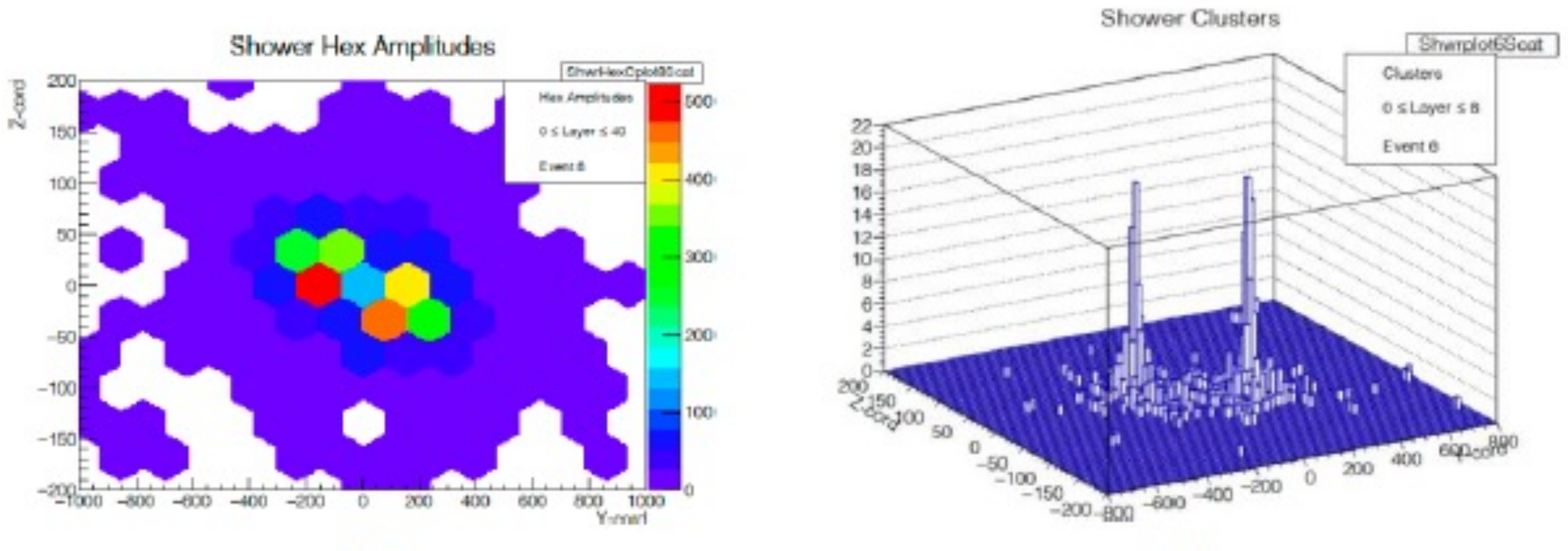
- Integrated design with higher segmentation: data transmission, power distribution, cooling

Si-based calorimeters

- From Si pads to Si MAPs



CMS HGCAL made of approximately 27,000 silicon detector modules: (a) shows a model (b) 6” module on a carrier plate (c) seven modules mounted on the copper support for test beam studies, cell size 0.5-1.2 cm^2



(a) (b)

Figure 4: Transverse distribution of two 10 GeV showers separated by one cm. LEFT: Pixel amplitudes in the ILC 13 mm^2 TDR design. RIGHT: Clusters in the first 5.4 radiation lengths in the new SiD digital MAPS 2.5 x 10^{-3} mm^2 design based on a GEANT4 simulation

Challenges: Large systems with fully embedded electronics with high dynamic range, low noise, low power and maximum compactness, with suitable interconnect technologies between Sensor, electronics and carrier boards + signal transmission to the periphery

Dual readout calorimeter

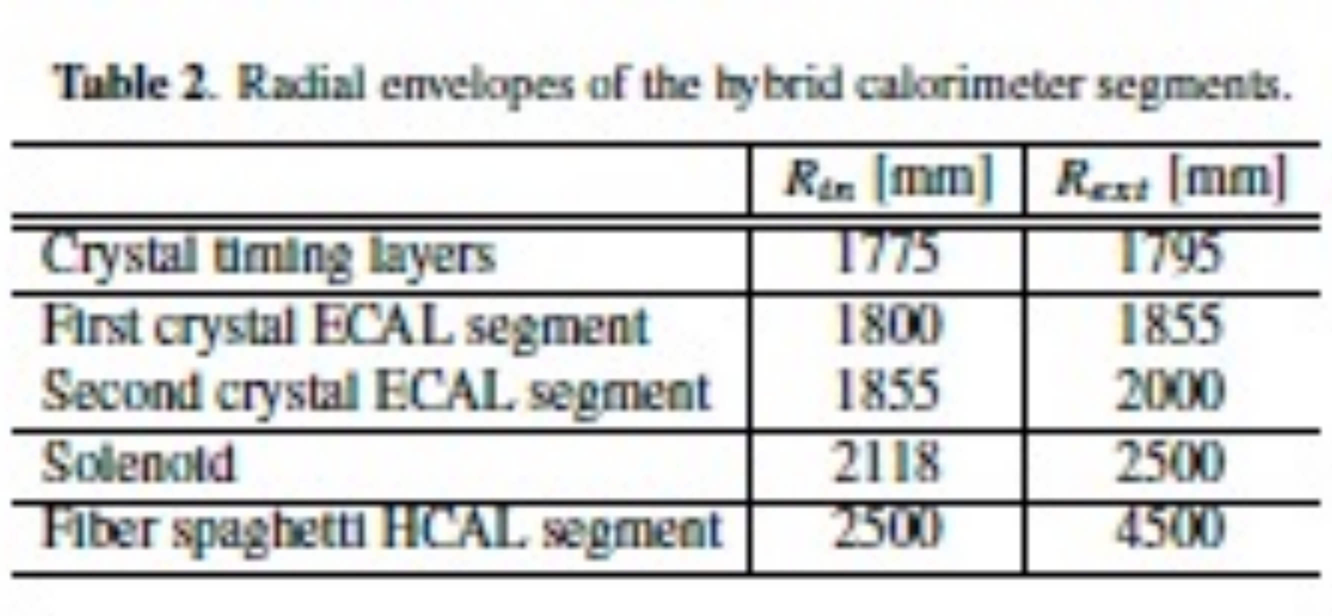


Table 2. Radial envelopes of the hybrid calorimeter segments.

	R_{in} [mm]	R_{ext} [mm]
Crystal timing layers	1775	1795
First crystal ECAL segment	1800	1855
Second crystal ECAL segment	1855	2000
Solenoid	2118	2500
Fiber spaghetti HCAL segment	2500	4500

Scintillating and Cherenkov fibers

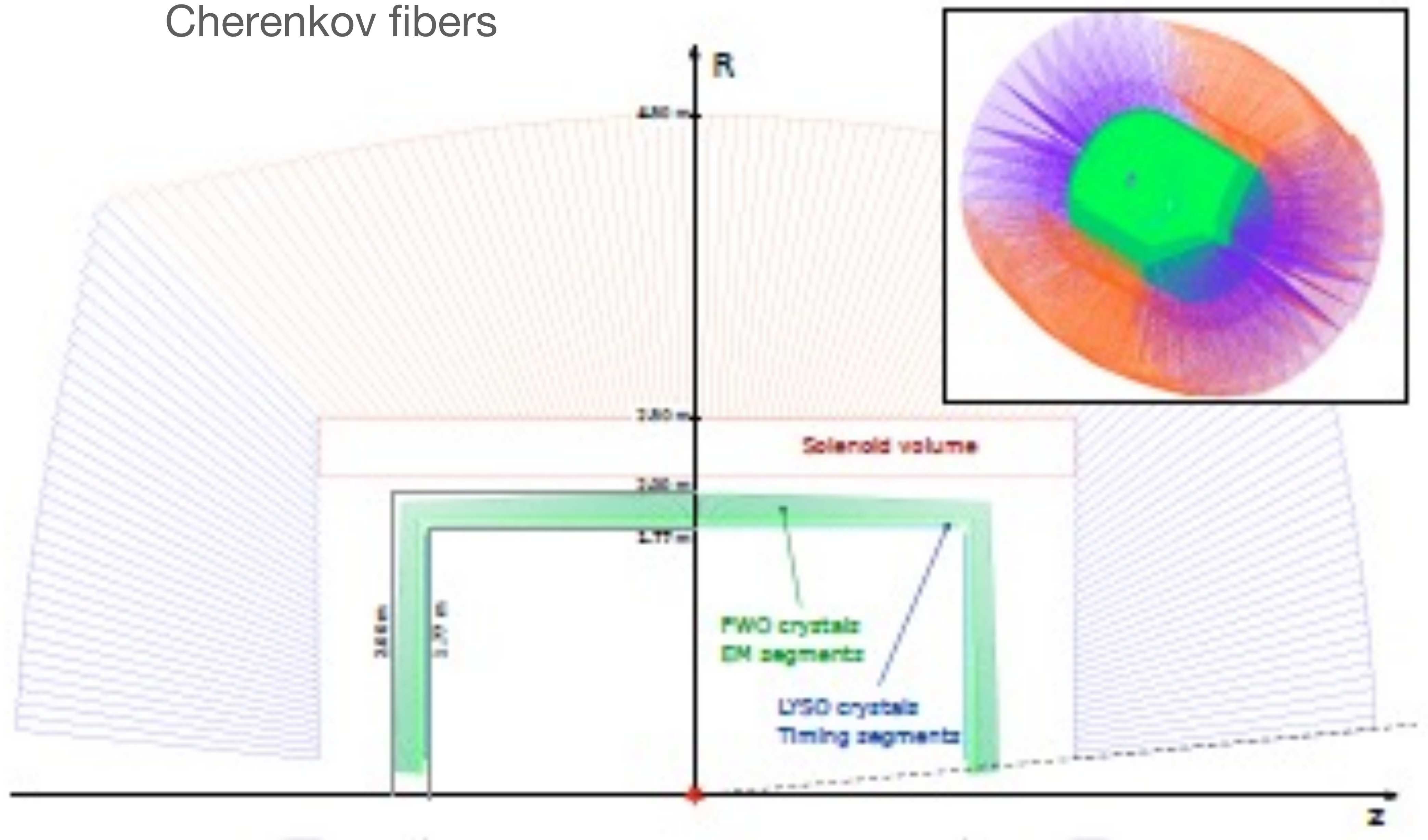


Figure 1. Side view of a single slice of the segmented dual-readout crystal calorimeter inside the IDEA solenoid (red) and fiber calorimeter (blue and orange towers).

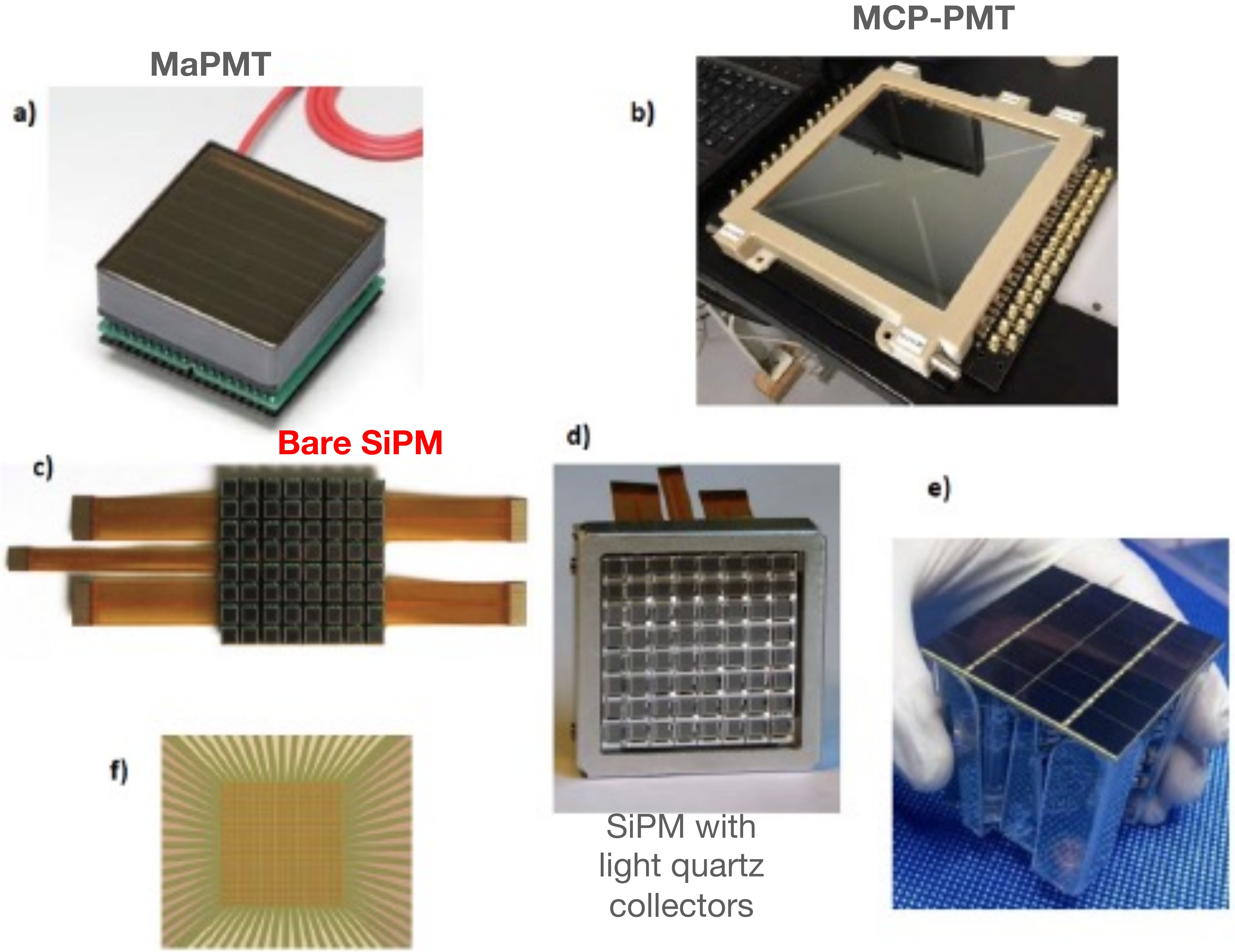
Reduced segmentation with respect to SiW calorimeter compensated by higher energy resolution

Photon detectors

☐ Goals:

- Extend wavelength range
- Adapt photodetectors for extreme environments
- Allow picosecond timing
- New optical coupling paradigms for enhanced light detection

☐ Needed for calorimetry & PID



MCP-PMT

MaPMT

Bare SiPM

SiPM with light quartz collectors

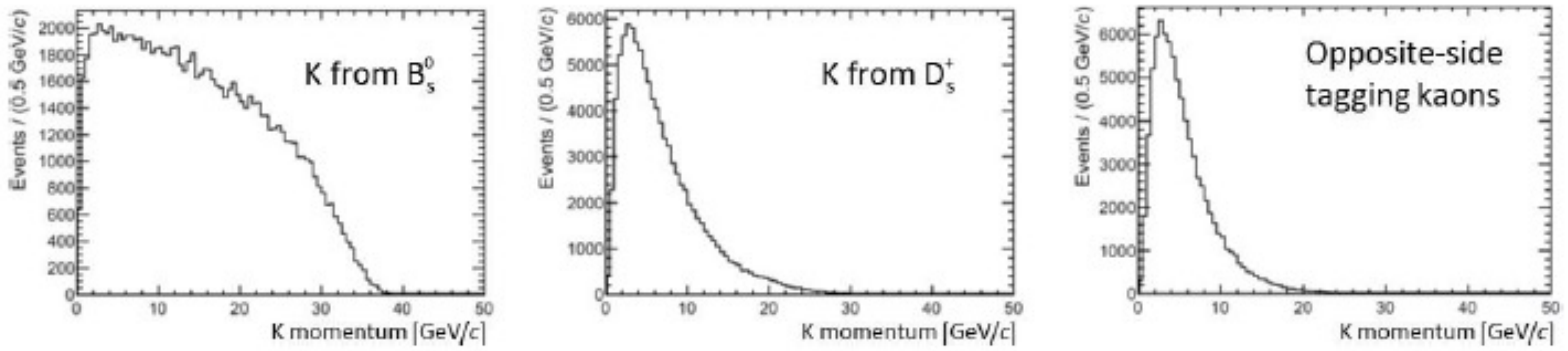
Superconducting nanowires single photon collectors

Materials for calorimetry

Material type	Material properties	Application
Inorganic scintillators	Bright and fast crystals (e.g. Cerium doped LYSO) Break the sub-ns time barrier, useful also for ps TOF systems & ultrafast total absorption ECAL	Radiation tolerance up to 10^{16} n_{eq}/cm^2
	dense, UV-transparent, and cost-effective inorganic scintillators for homogeneous hadron calorimeter (HHCAL) detector concept	Barrel hadronic calorimeters
Organic scintillators	Suited for doses limited to 10 kGy and $3x10^{14}$ ne_q/cm^2.	Barrel hadronic calorimeters
Cherenkov radiators	clear and high refractive-index Cherenkov radiators will be needed to support advances in calorimetry	As the radiation levels increase by factors of ten or hundred at future hadron colliders
Structural material	Electrical transmission components and mechanical support	Validate radiation performance at hadron machines

Hadron identification

Example: momentum range relevant to an iconic hadronic B decay

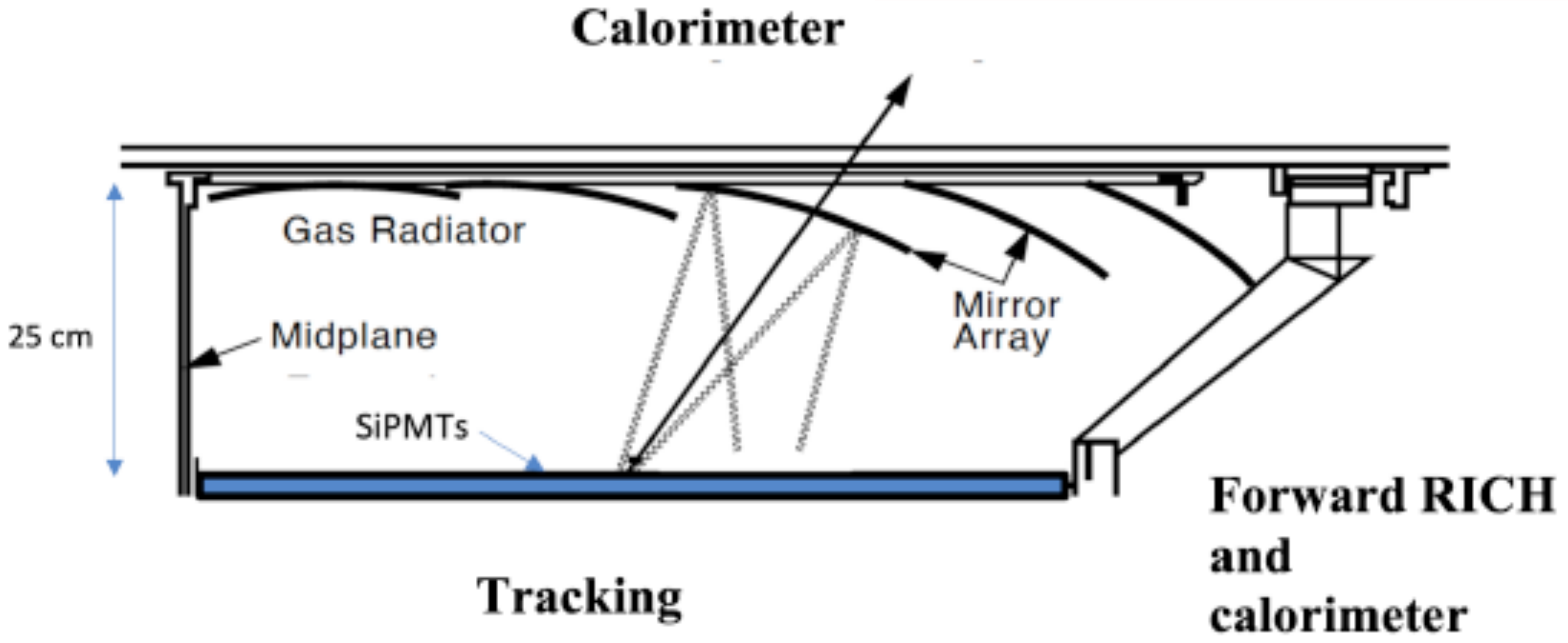


,compact RICH or novel approaches based on gaseous detectors

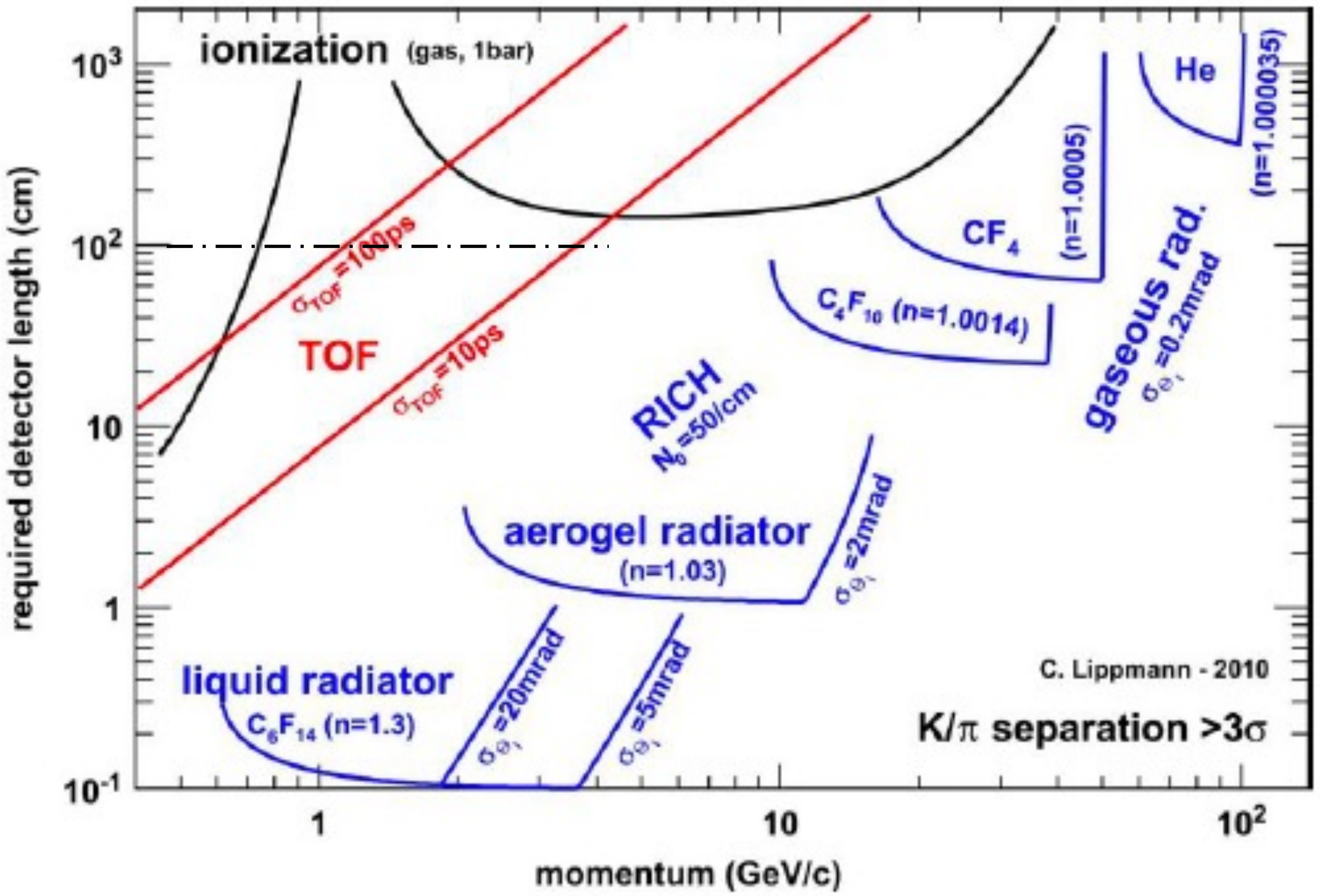
allow full momentum coverage

Compact through the use of SiPM to use time difference between track and Cherenkov photons to reduce SiPM nois

Basso et al Gaseous RICH



- ❑Time resolution of 10 ps allows 3s separation of p-K up to 5 GeV for 1 m TOF



Gas Detectors

- ❑ Gaseous detectors as components of the tracking system (e.g. IDEA detector), novel ideas on cluster-counting algorithms for hadron-identification

- ❑ Muon detectors:
  - Fast timing and high spatial resolution + time resolution <1ns
  - High-rate capability (10KHz/cm^2)
  - Large area + low cost

THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

		DRDT	< 2030						2030-2035						2035-2040	2040-2045			>2045		
			SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase¹⁾	Light dark matter...²⁾	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments³⁾	R&D ton scale 0νbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 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

1) Large ton dual-phase (PandaX-4T, LZ, DarkSide -20k, Argo 200k, ARIADNE, ...)
2) Light dark matter, solar axion, 0nbb, rare nucleii8ions and astro-particle reactions, Ba tagging)
3) R&D for 100-ton scale dual-phase DM/neutrino experiments

Readout and ASICs

❑High-granularity detectors covering large areas need front-end ASICs that must fulfill challenging requirements:

- Environmental and operating conditions (low power requirements, cryogenic operation, radiation exposure)
- Performance (low noise, high-dynamic range operating at low bias-voltage, high occupancy, requirement of extensive on-chip processing, precision timing with distributed clocks, deep analog pipelines
- Ever-evolving technologies (moving towards lower and lower feature size, each time increasing development cost)
- Adopt Artificial Intelligence and Machine Learning techniques

Technology evolution and development cost

FEI4 chip 65 nm

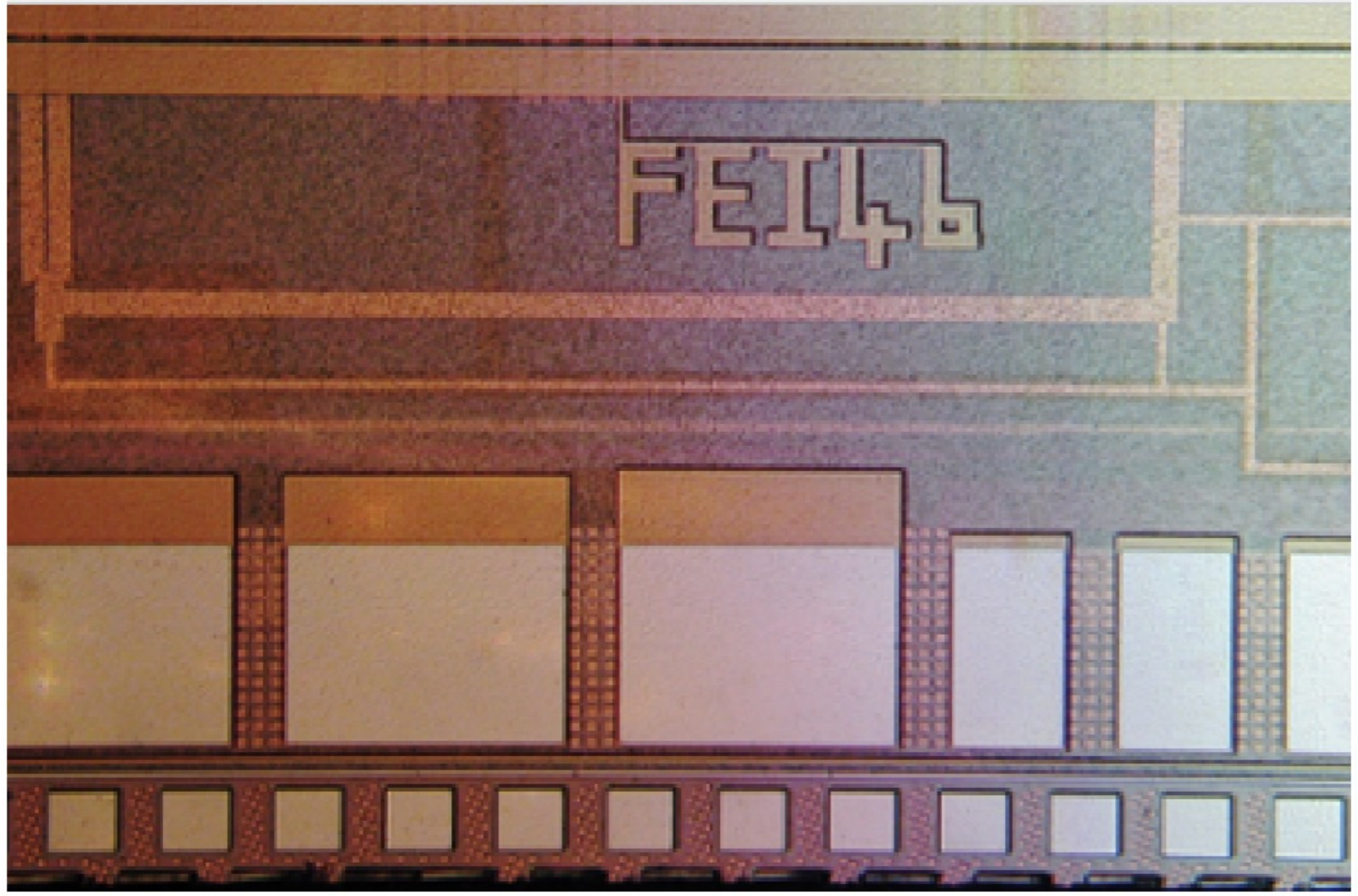
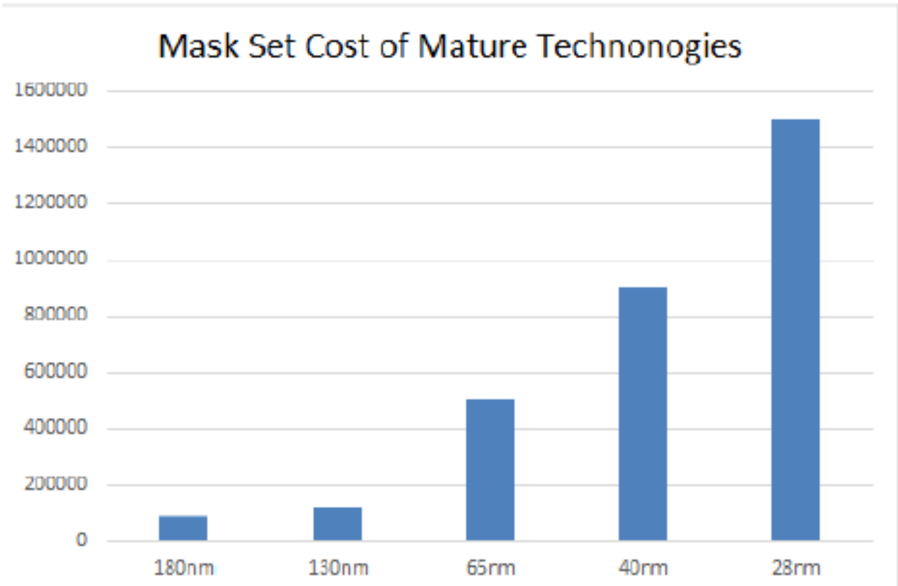


Figure 39: The FE-I4 chip designed in a 65 nm CMOS process represents a 2nd generation significant advance for silicon pixel detector readout. This ASIC contains 100M transistors and requires 800 mW power to readout 26,880 pixels bump bonded to its underside. It is optimized to be directly mounted on a pixel detector with a 50×250 μm^2 pitch. The time-of-threshold crossing is accurate to 25 ns (one beam crossing) for each pixel channel and has an ENC of 400 e^-. A 4-bit charge resolution is recorded and used to correct for time walk. An important design issue has been the requirement to have as high as possible ionizing radiation tolerance. FEI4 reliably achieves 3 MGy which is about 1/3 of the expected 10 MGy exposure expected for the inner pixel layers of the two upgraded LHC detectors.

NRE: Non-recurrent engineering

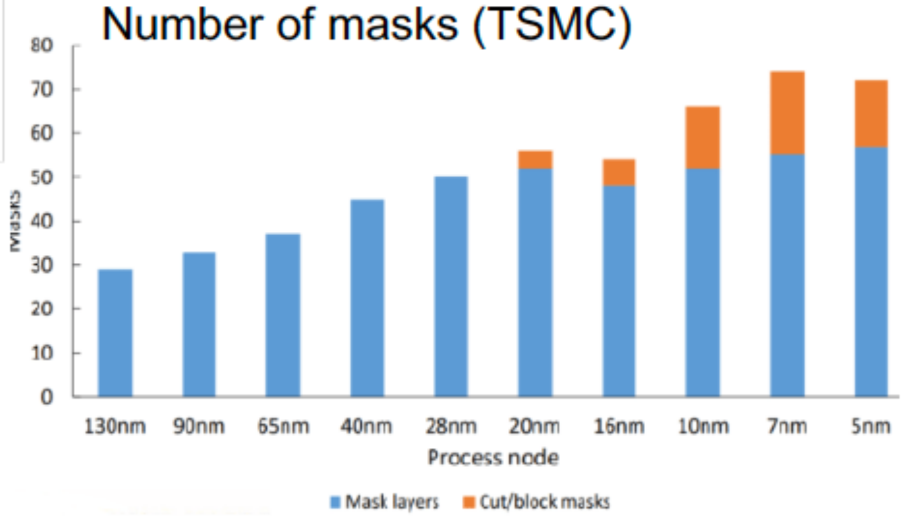
- Dominated by mask costs



source: friends of AnySilicon

Design rules and manuals scale in a similar way

Number of masks (TSMC)



Need to optimize the development process with shared design tools and IPs

Trigger and DAQ

The challenge: large amount data to be processed in real-time, data compression, real-time trigger (especially challenging for FCC-hh)

Goal	Implementation
Achieve on detector real-time continuous data processing to reach the exa-scale (FCC-hh) / muon collider to suppress beam induced background	1. High-bandwidth, rad-hard low-power data links 2. Real-time processing hardware 3. On-line data processing on heterogenous hardware 4. Advanced feature extraction for trigger 5. Triggerless readout
Develop technologies for autonomous detector systems	Autonomous operations; self-calibration and alignment
Develop timing distribution with picosecond synchronization	Clock distribution, stable DAQ control system

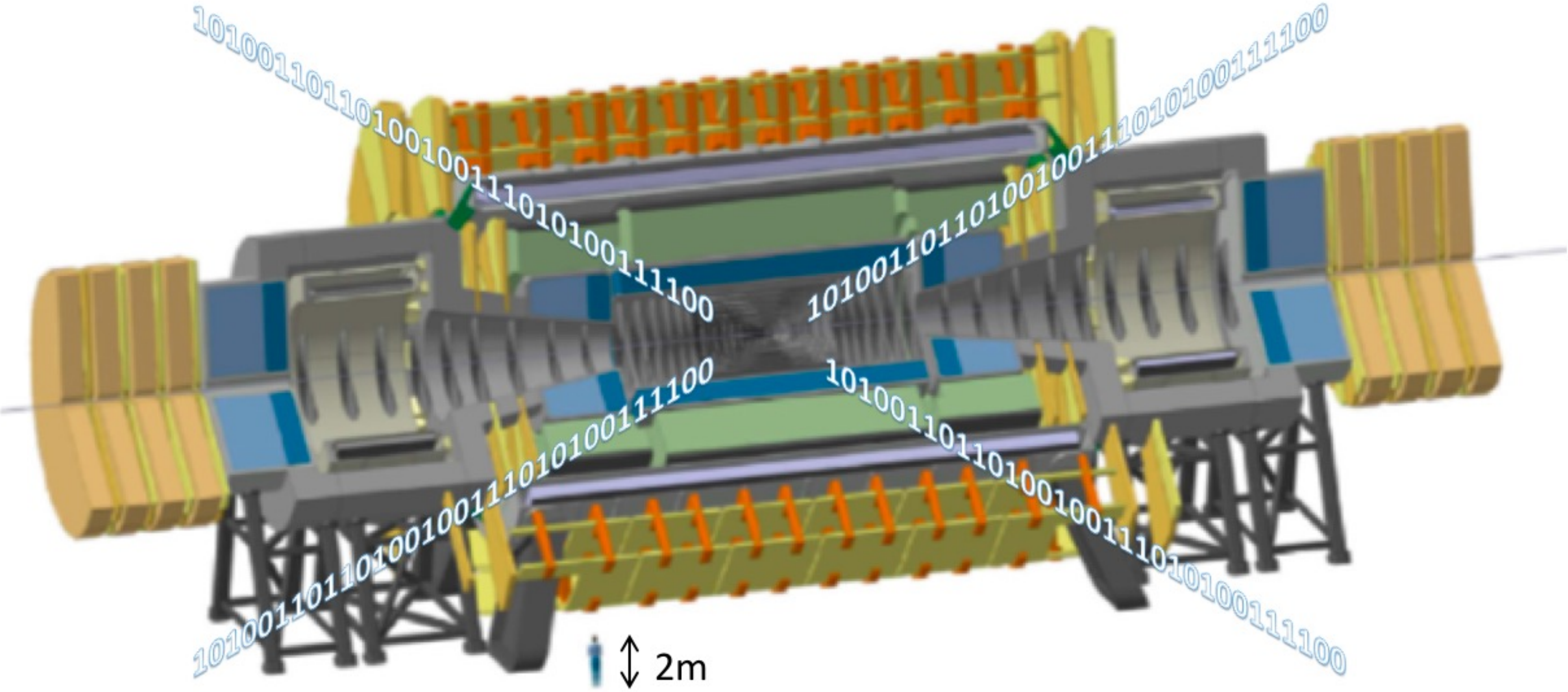
Optimization of processing with distributed intelligence and heterogeneous computing resources

- ❑Data reduction with ”smart-detectors” [system-on-chip ASICs, FPGAs..]
- ❑Deployment of machine learning at the first processing stages

Advances in heterogeneous computing driven by machine learning

An even more challenging world – the FCC-hh environment

☐ data at a rate of 1 exabyte/s

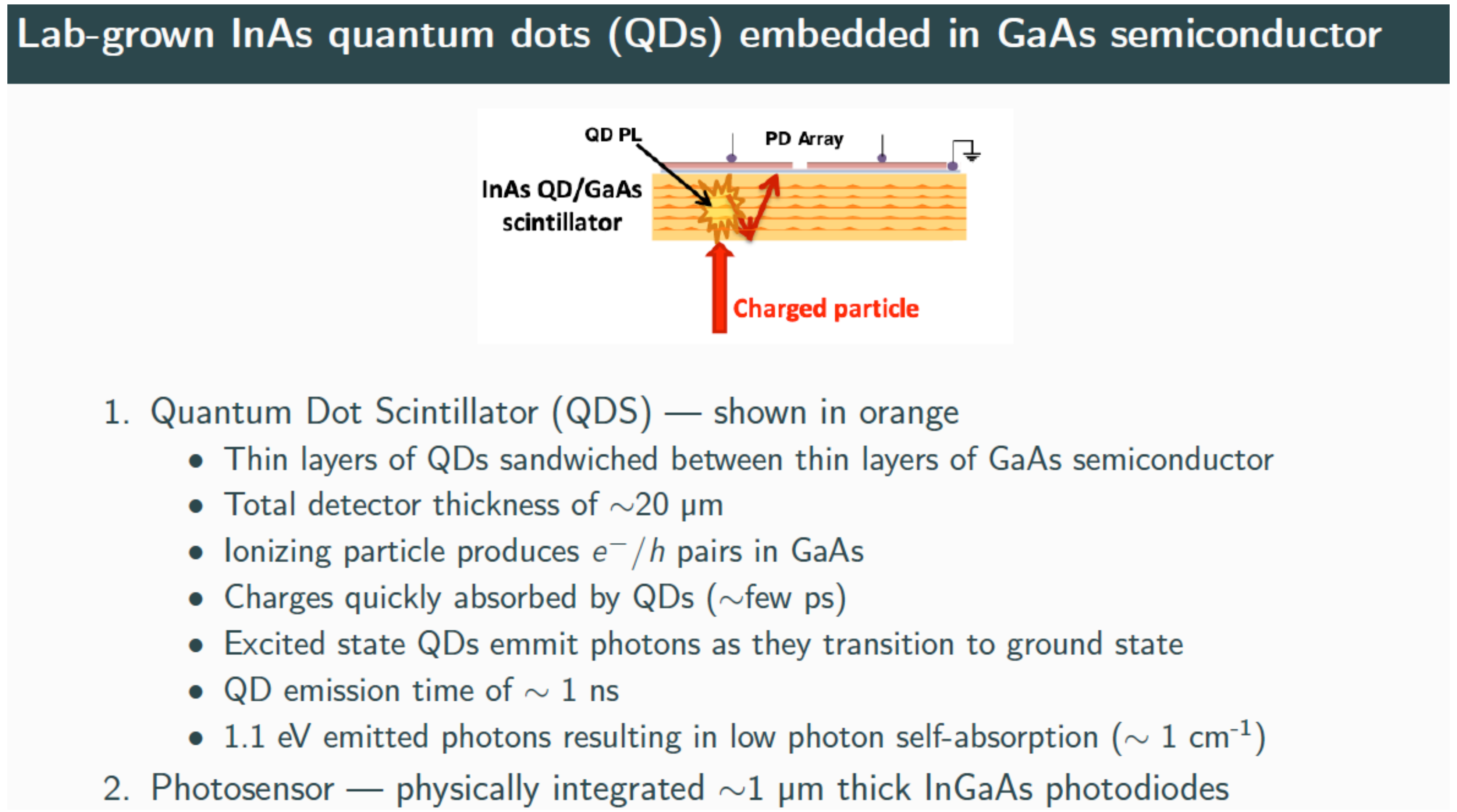


- Challenges to the data link technologies & data synchronization in a radiation hard environment
- Huge data movement challenge, is wireless transmission a viable option?

Opportunities in novel approaches

☐ Quantum dots to manipulate the properties of materials:

- Low-dimensional materials [for tracking and calorimetry]
- [tunable Cherenkov radiation]
- Low-mass fast timing & tracking [Michael Edges CPAD 2021]



Lab-grown InAs quantum dots (QDs) embedded in GaAs semiconductor

1. Quantum Dot Scintillator (QDS) — shown in orange
    - Thin layers of QDs sandwiched between thin layers of GaAs semiconductor
    - Total detector thickness of ∼20 μm
    - Ionizing particle produces e^-/h pairs in GaAs
    - Charges quickly absorbed by QDs (∼few ps)
    - Excited state QDs emmit photons as they transition to ground state
    - QD emission time of ∼ 1 ns
    - 1.1 eV emitted photons resulting in low photon self-absorption (∼ 1 cm^{-1})
2. Photosensor — physically integrated ∼1 μm thick InGaAs photodiodes

Themes connecting all the detector elements

- Novel materials for sensors, electronics, mechanics and cooling infrastructure
- Towards “irreducible mass detectors”
- Novel cooling approaches
- Power distribution
- Large-volume data transmission
- distributed intelligence & heterogeneous computing methodologies

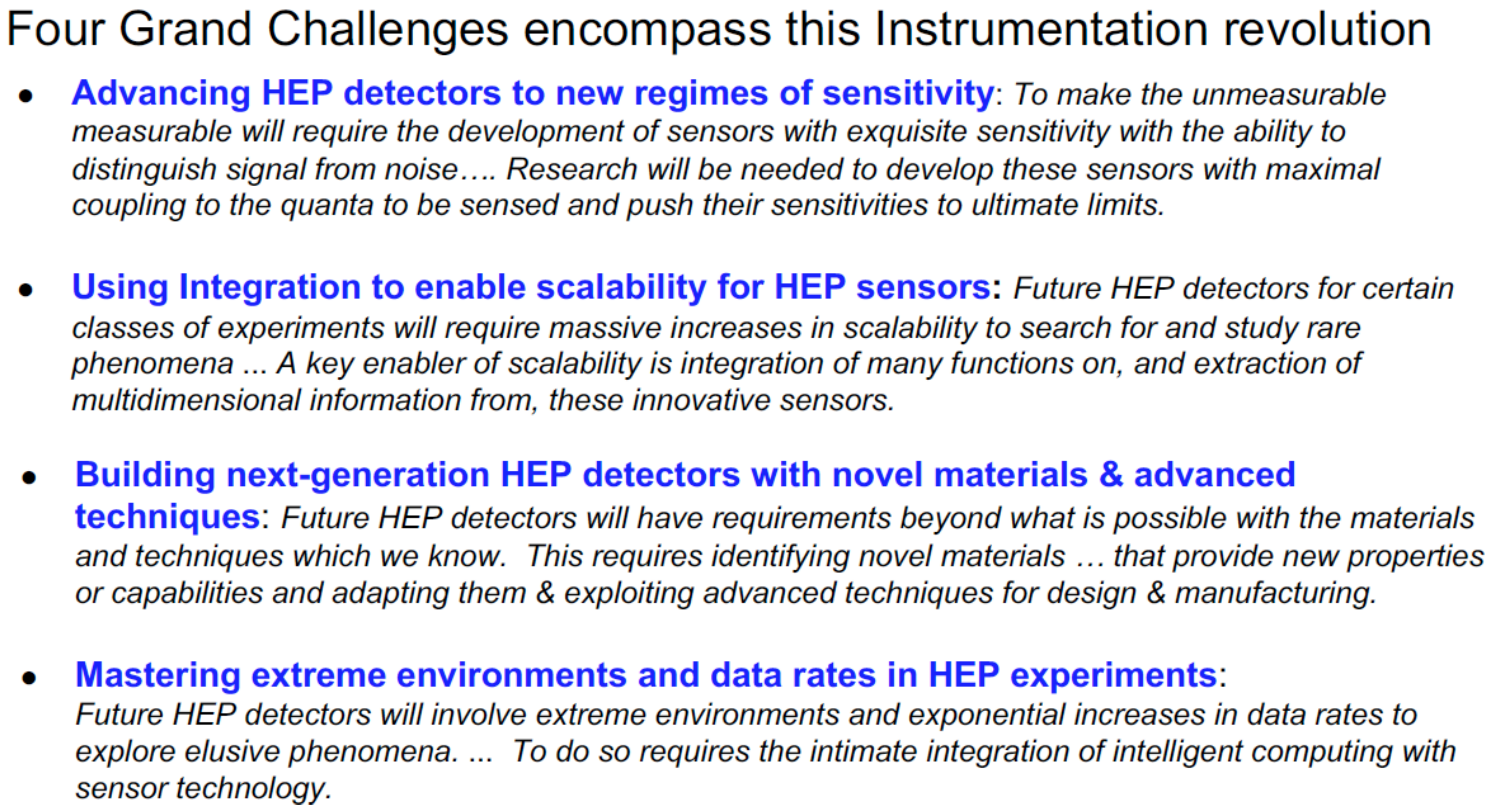
Conclusions

- ☐ Future colliders support our quest for a deeper understanding of fundamental particles and their interactions

- ☐ Our physics goals demand a vibrant R&D on several different detector technologies

- ☐ Broad targeted R&D programs have been proposed. It is important to investigate connections with other HEP fields, applicability to non-HEP development & examine blue-sky initiatives that are paradigm-transforming.

Ian Shipsey, CPAD Workshop 2021



Four Grand Challenges encompass this Instrumentation revolution

- **Advancing HEP detectors to new regimes of sensitivity**: *To make the unmeasurable measurable will require the development of sensors with exquisite sensitivity with the ability to distinguish signal from noise…. Research will be needed to develop these sensors with maximal coupling to the quanta to be sensed and push their sensitivities to ultimate limits.*
- **Using Integration to enable scalability for HEP sensors:** *Future HEP detectors for certain classes of experiments will require massive increases in scalability to search for and study rare phenomena ... A key enabler of scalability is integration of many functions on, and extraction of multidimensional information from, these innovative sensors.*
- **Building next-generation HEP detectors with novel materials & advanced techniques**: *Future HEP detectors will have requirements beyond what is possible with the materials and techniques which we know. This requires identifying novel materials … that provide new properties or capabilities and adapting them & exploiting advanced techniques for design & manufacturing.*
- **Mastering extreme environments and data rates in HEP experiments**: *Future HEP detectors will involve extreme environments and exponential increases in data rates to explore elusive phenomena. ... To do so requires the intimate integration of intelligent computing with sensor technology.*

The end

[expected performance of calorimeter approaches for FCCee]

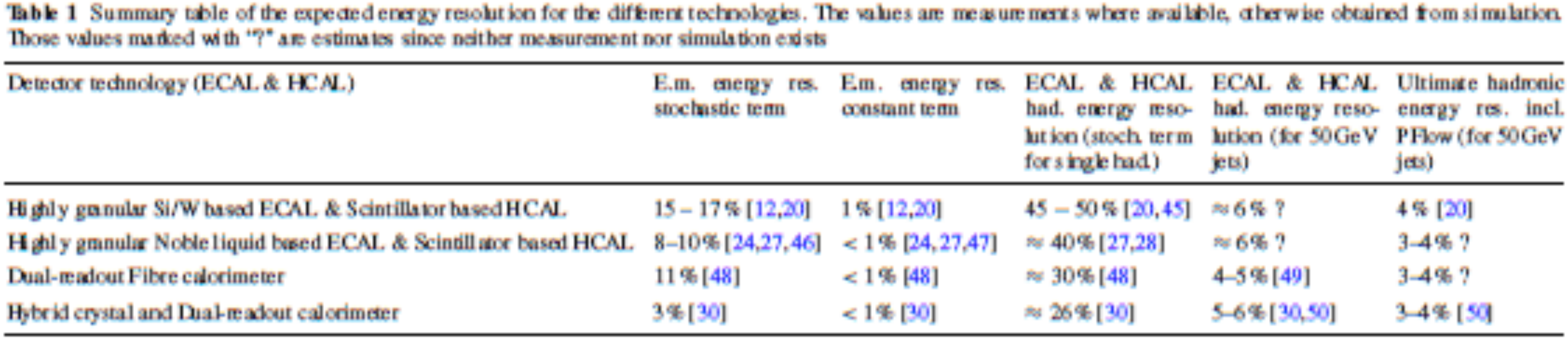


Table 1 Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [20,45]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8–10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3–4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4–5 % [49]	3–4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5–6 % [30,50]	3–4 % [50]