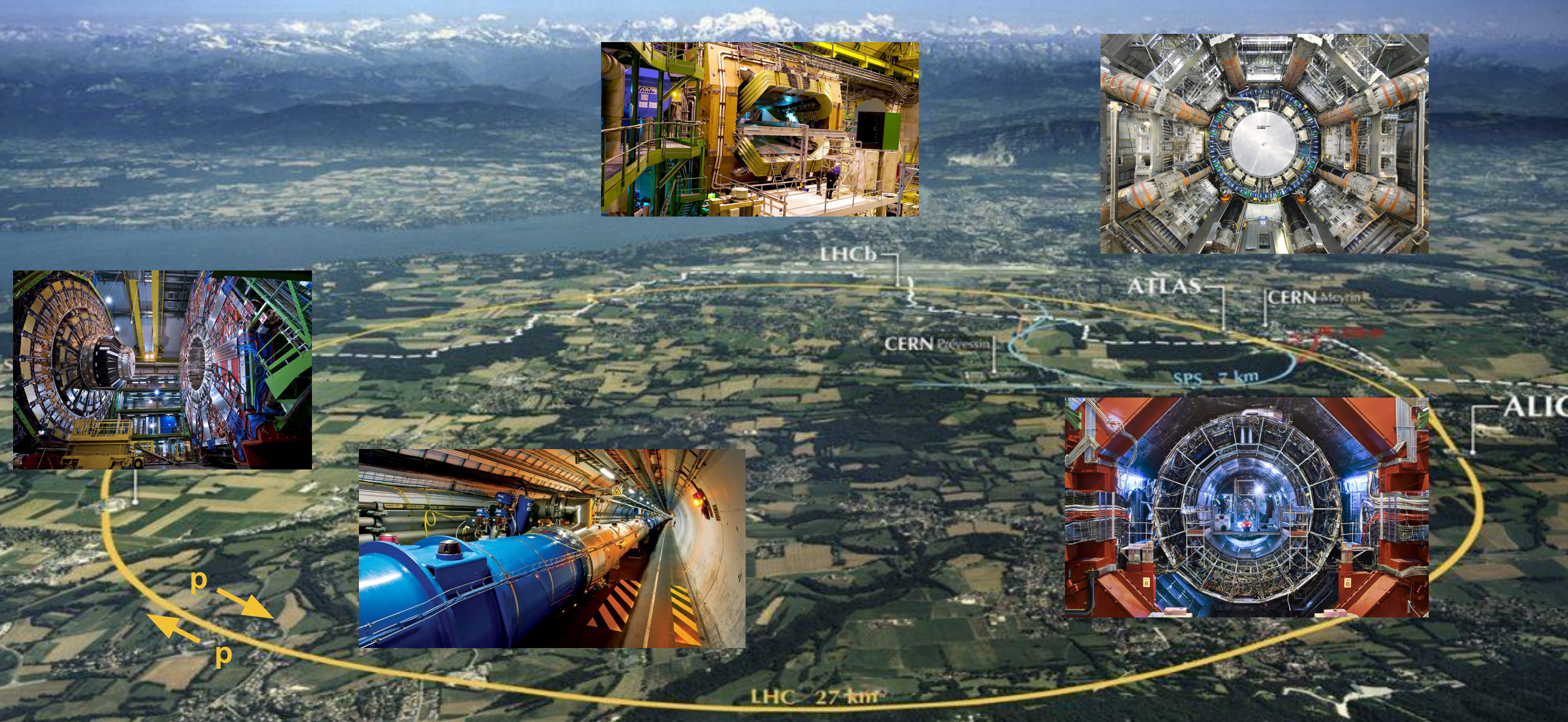
Detector developments for future colliders

Jory Sonneveld

Nikhef topical lectures 2024-03-20

The Large Hadron Collider at CERN



jory.sonneveld@nikhef.nl

https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg

H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg

https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG

https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

https://www.youtube.com/watch?v=NhXMXjXOWAA

High Luminosity LHC: very fast detectors needed

jory.sonneveld@nikhef.nl

https://cdn.zmescience.com/wp-content/uploads/2015/05/cern-lhc-aerial.jpg

H t tp://s ites.uci.edu/energyobserver/files/2012/11/lhc-aerial.jpg

https://home.cern/sites/home.web.cern.ch/files/image/inline-images/old/lhc_long_1.jpg

https://upload.wikimedia.org/wikipedia/commons/6/62/CERN_LHC_Proton_Source.JPG

https://www.youtube.com/watch?v=NhXMXiXOWAA

ATLAS
EXPERIMENT

ALICE

CMS

Compact Muon Solenoid

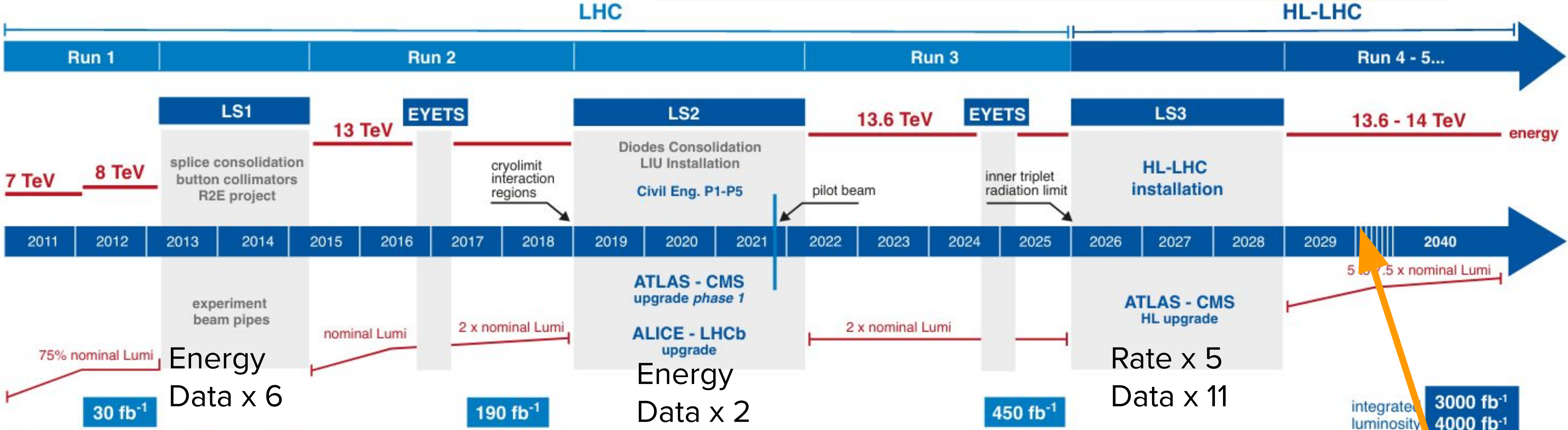
LHCb

So we have collisions now?

LHC timeline: collect more and more data

From the high lumi LHC project

LS = long shutdown: major upgrades!

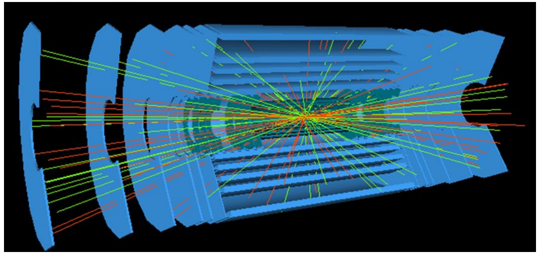


Energy
Data x 6

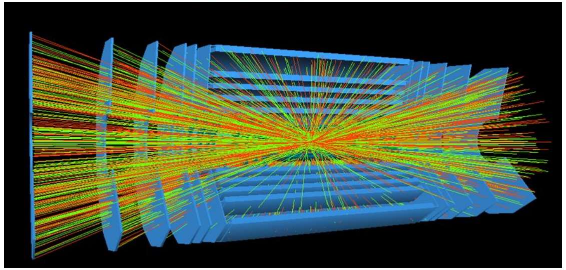
Energy
Data x 2

Rate x 5
Data x 11

2032: LS4
Rate x 50
for LHCb



Pileup x 10



In operation now

Voorjaar 2019

DIMENSIES

Nikhef

Nationaal
instituut voor
subatomaire fysica

UPGRADES
Van CERN tot Gran Sasso:
overal wordt nu gesleuteld
aan de experimenten

ASTRODEELTJES
Vele vensters
op het universum

12 / In Beeld

Nog
dichte
bij de
oerk

Deeltjeslab CERN, Genève. Als een geheimzinnige gouden halfpipe ligt een van de nieuwe onderdelen van deeltjesdetector ALICE in het assemblage-atelier. Dit is ITS, het Inner Tracking System dat het vederlichte hart van de detector gaat vormen. Een meterslange halve buis van ultralichte koolstofvezel vakwerkbalkjes met daarop gelijmd lange koelplaten en speciale siliciumchips. Staves noemen de technici het: de duigen van een high-tech ton.

Het goud is overigens geen goud, maar polyimide-folie met ragdunne [illegible] weg te zitten.

Het Inner Tracking System wordt een stelsel van zeven van dit soort lichtge-

Binnenin ITS ligt dan alleen nog de bundelpijp van de LHC-versneller, die middenin ALICE zware atoomkernen met de lichtsnelheid op elkaar laat versmelten tot een ziedende druppel quarks en gluonen. Het is miljarden graden heet, precies zoals vlak na de oerknal waarin het heelal zelf moet zijn ontstaan. ITS moet de deeltjes betrappen die uit d[illegible] oersoep [illegible] kernen is een verbijsterende warboel van rondvliegende deeltjes te zien. Veel eigenschappen van de druppel quarks en

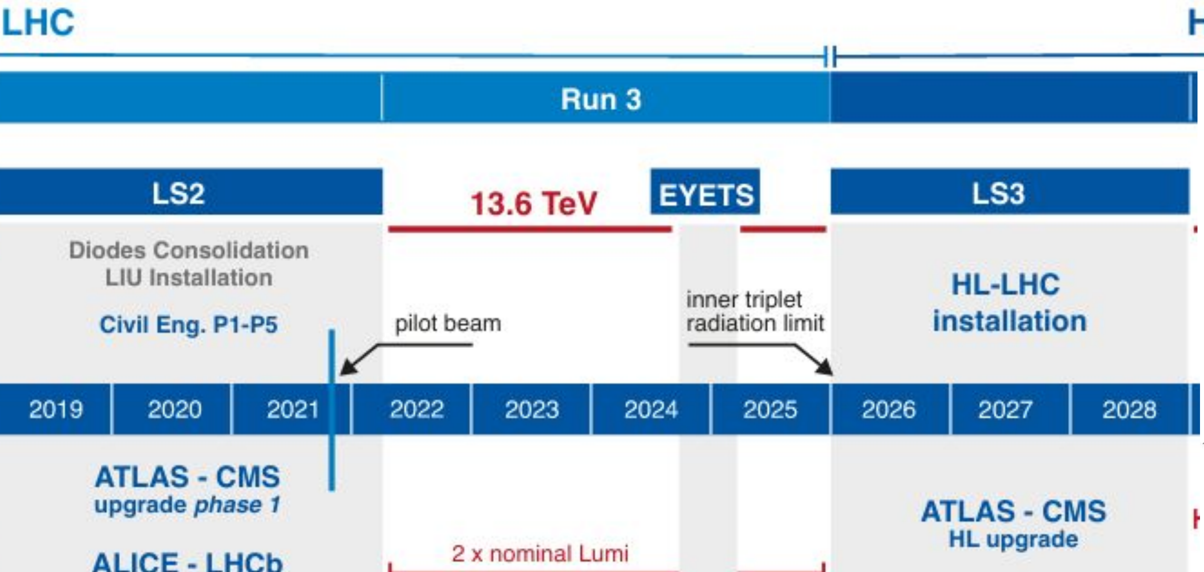
geven, is de verwachting. De nieuwe inner tracker doet dat van nog dichterbij dan de eerdere versie. Daardoor kunnen de kern-[illegible]

Hond[illegible]

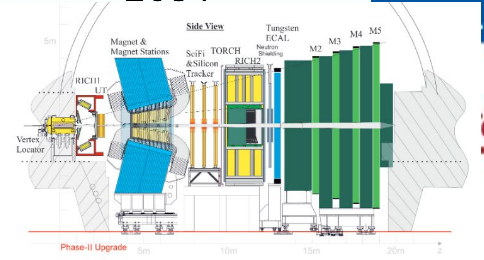
ITS is te zien als een van de grootste digitale camera's ter wereld. Het oppervlak is in totaal tien vierkante meter. Er zijn ruim

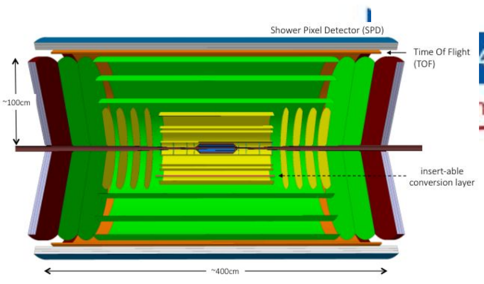
So Nikhef detector R&D builds detectors?

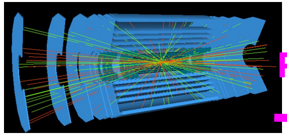
Nikhef R&D group works with LHC experiments and Nikhef electronics group on pixel detectors for future upgrades of experiments



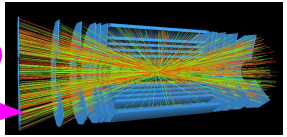
2034







Pileup x 10



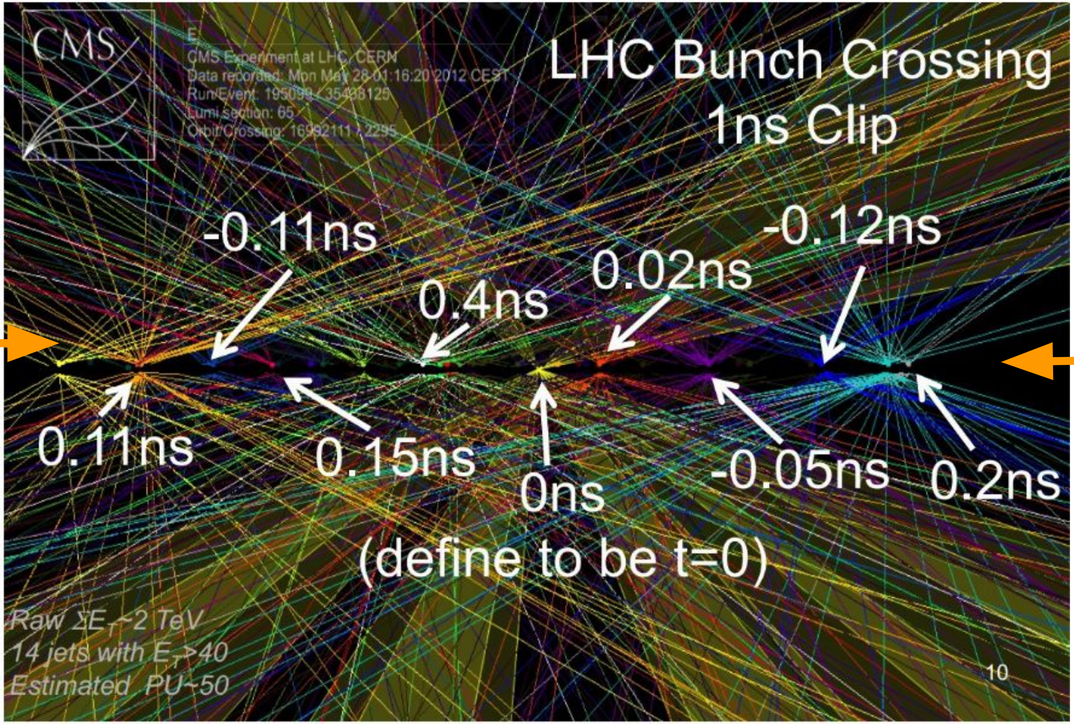
Pileup x 3

Fast timing needed!

FCC-ee: pileup 1000

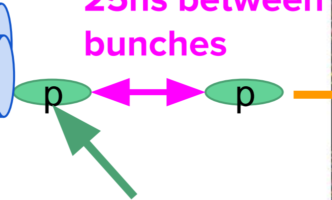
How to distinguish between these collisions?

Multiple **primary vertices** per bunch crossing!
Color indicates point in time within bunch crossing



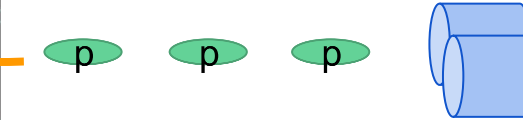
Example: inside the CMS detector

ATLAS and LHCb will face similar problems



25ns between bunches

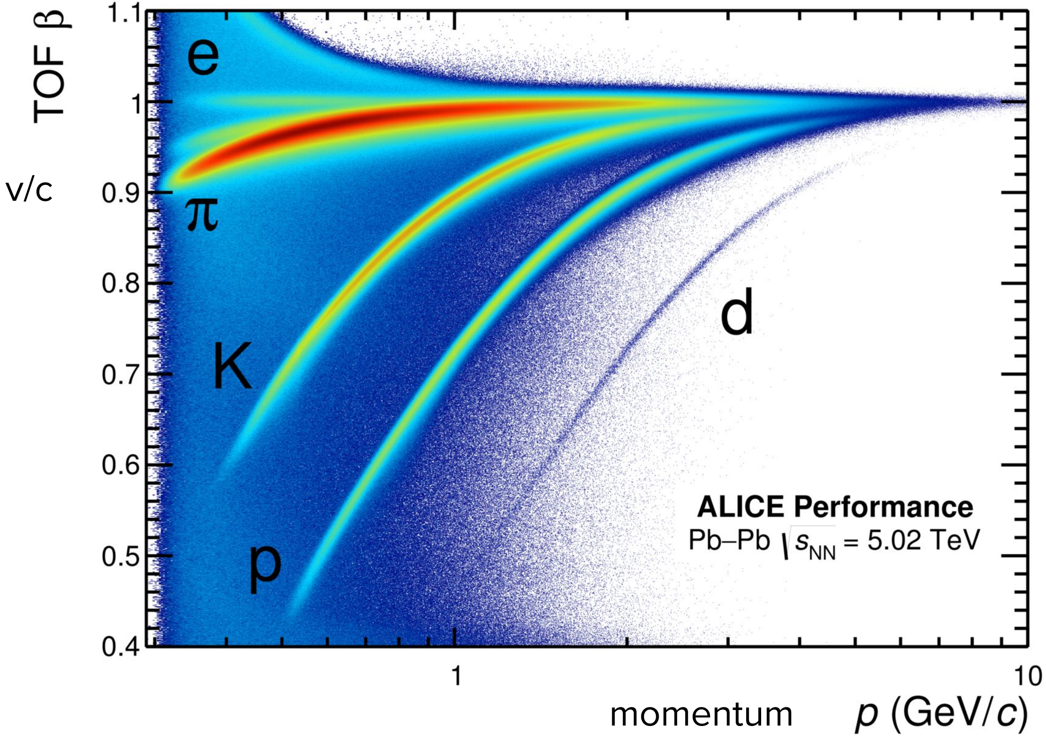
One bunch has $2 \cdot 10^{11}$ protons



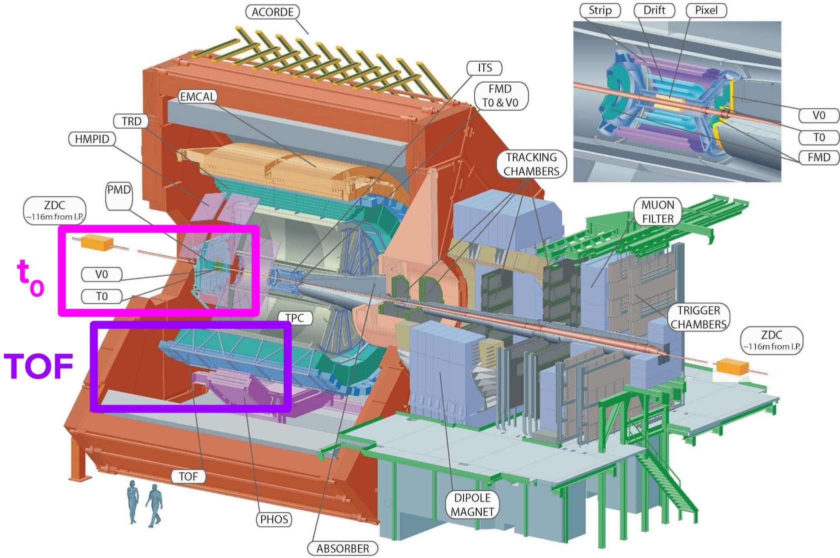
Does every proton collide?

From Nicolo Cartiglia (Nikhef colloquium on 2020-10-30)

How to identify particles with time of flight?



ALI-PERF-106336



Measure time at t_0 and **TOF**

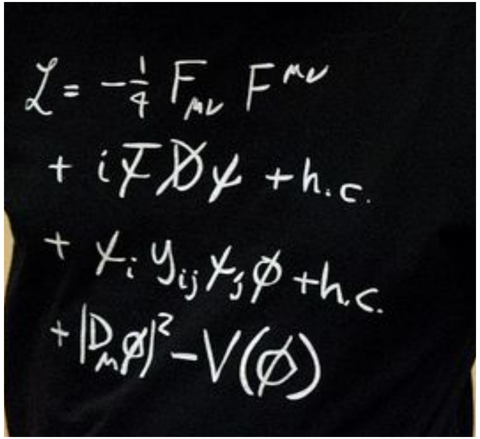
Future colliders and their challenges

Why future colliders?

More in the next lecture!

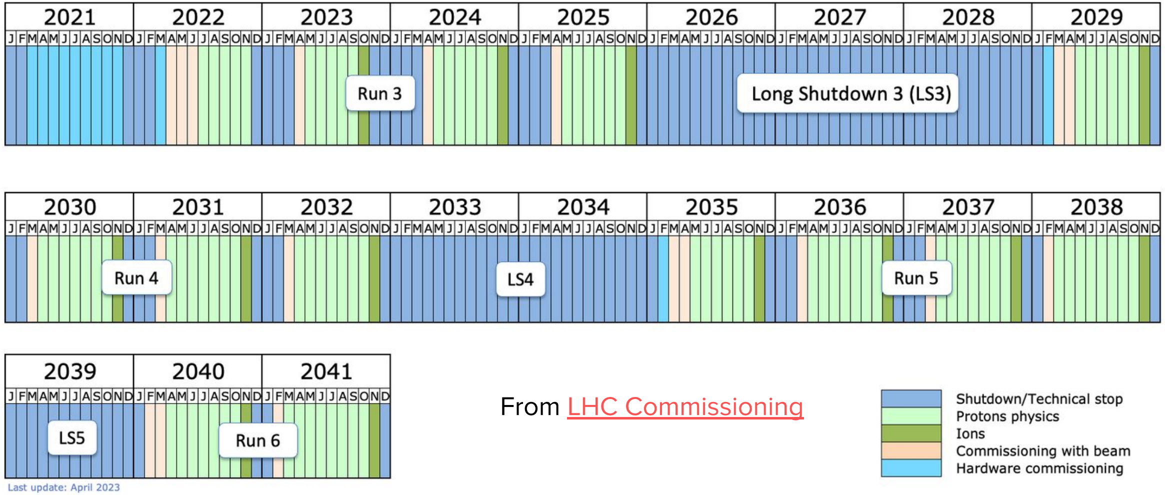
From Werner Riegler and 2023 CPAD workshop

- Explore physics of electroweak symmetry breaking: precision tests of the Standard Model of Particle Physics (SM)
  - Higgs coupling to SM particles: sub-percent precision
  - Higgs self-coupling: 5% precision
  - Flavor phenomena
  - Higgs properties
  - Nature of the hierarchy problem
- Explore origin of known deviations from SM: dark matter, neutrino masses, baryon asymmetry of the universe
  - Direct searches for new particles such as dark sector, long lived particles, leqptoquark, Z'...



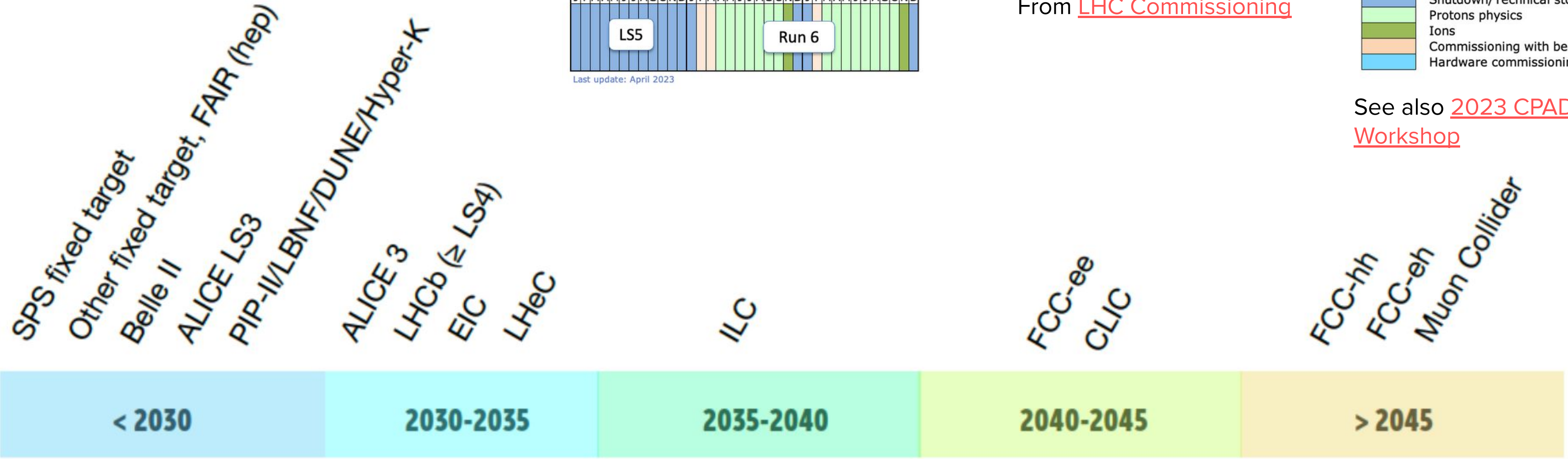
Future colliders

Five time periods in agreement with HL-LHC schedule



From LHC Commissioning

See also 2023 CPAD Workshop



LHC LS3

LHC LS4

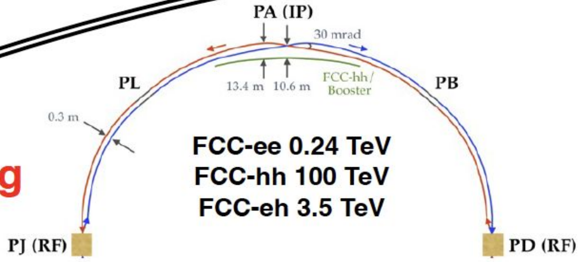
From the ECFA Detector Research and Development Roadmap

Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, …

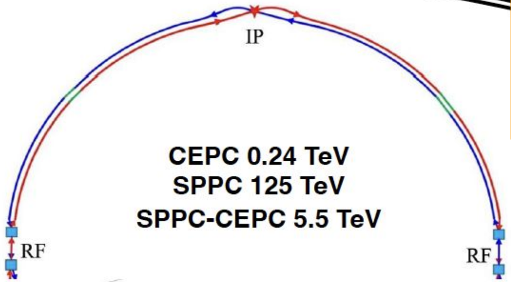
More details tomorrow

Collider-in-the-sea 500 TeV

- **Storage ring colliders**

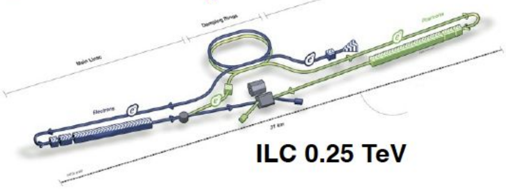


FCC-ee 0.24 TeV
FCC-hh 100 TeV
FCC-eh 3.5 TeV

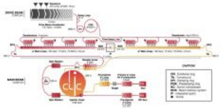


CEPC 0.24 TeV
SPPC 125 TeV
SPPC-CEPC 5.5 TeV

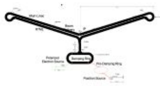
- **Linear colliders**



ILC 0.25 TeV

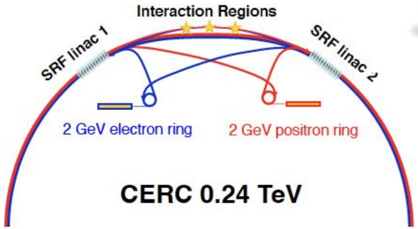


CLIC 0.24 TeV

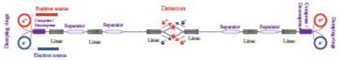


CCC 0.25 TeV

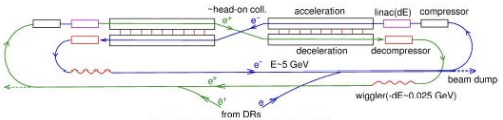
- **ERL colliders**



CERC 0.24 TeV

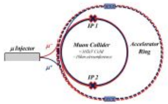


ReLiC 0.24 TeV



ERLC 0.24 TeV

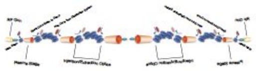
- **Muon collider**



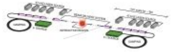
MC 10 TeV

10 km

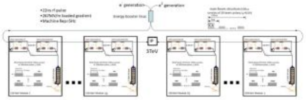
- **Wakefield colliders**



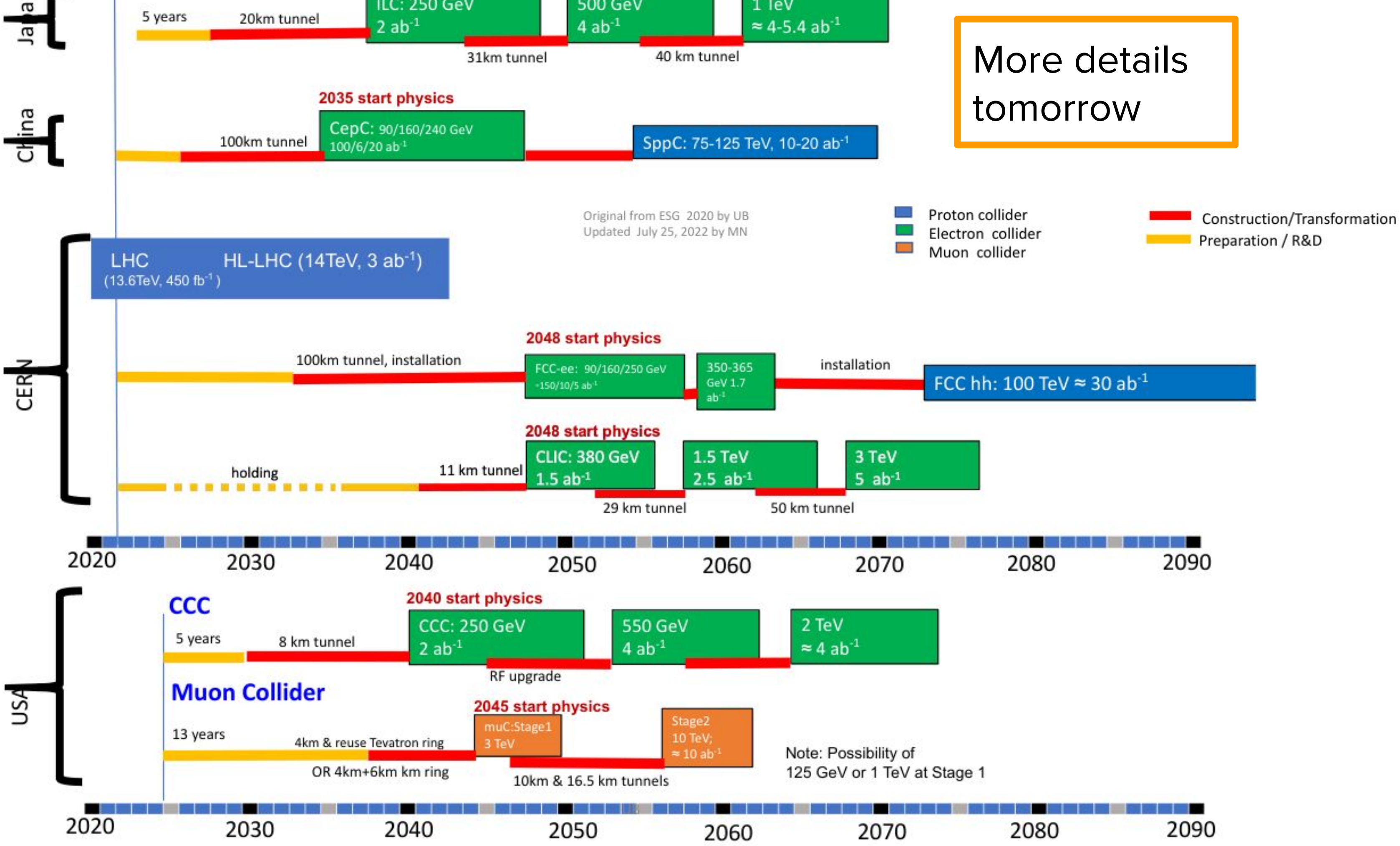
PWFA 15 TeV



LWFA 15 TeV



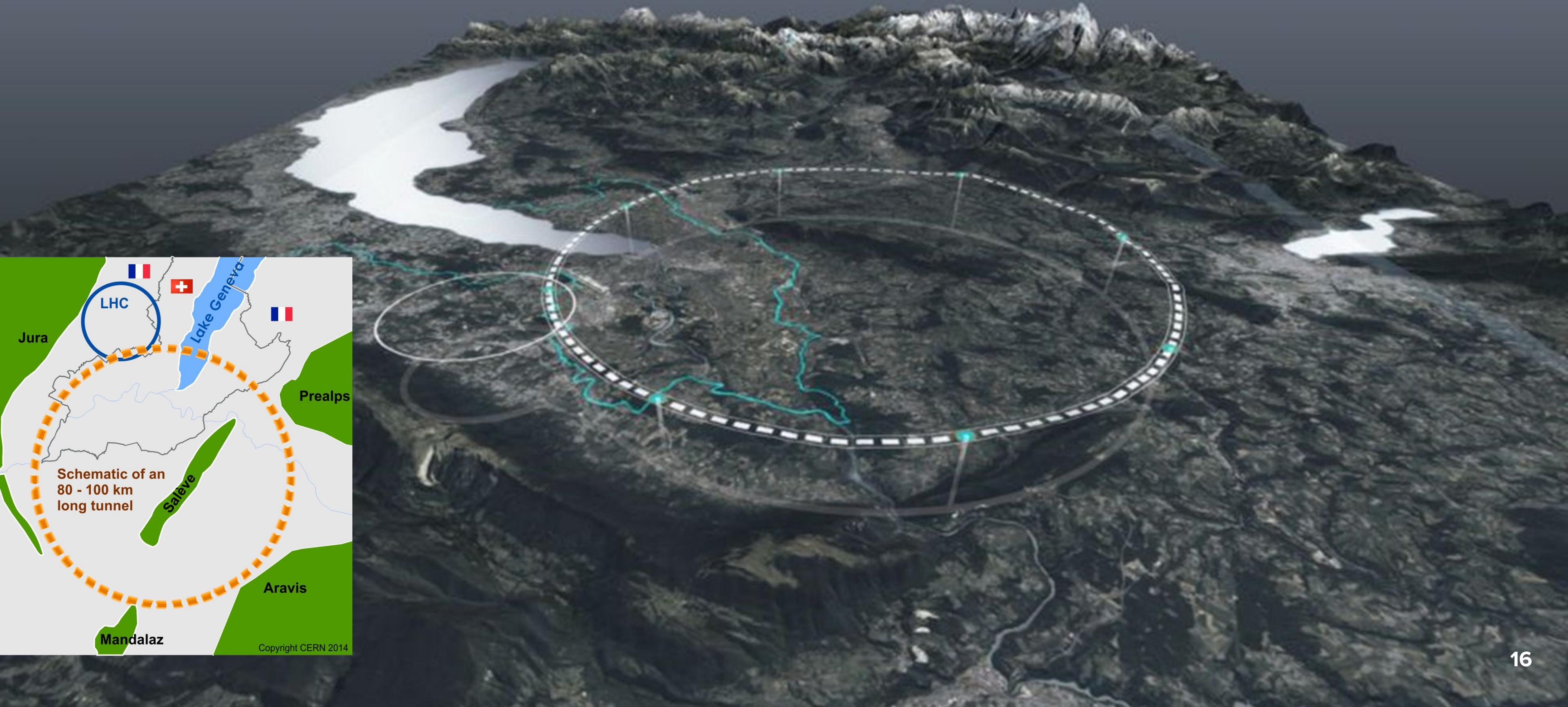
SWFA 3 TeV



More details tomorrow

LHC and FCC

From The International Accelerator School



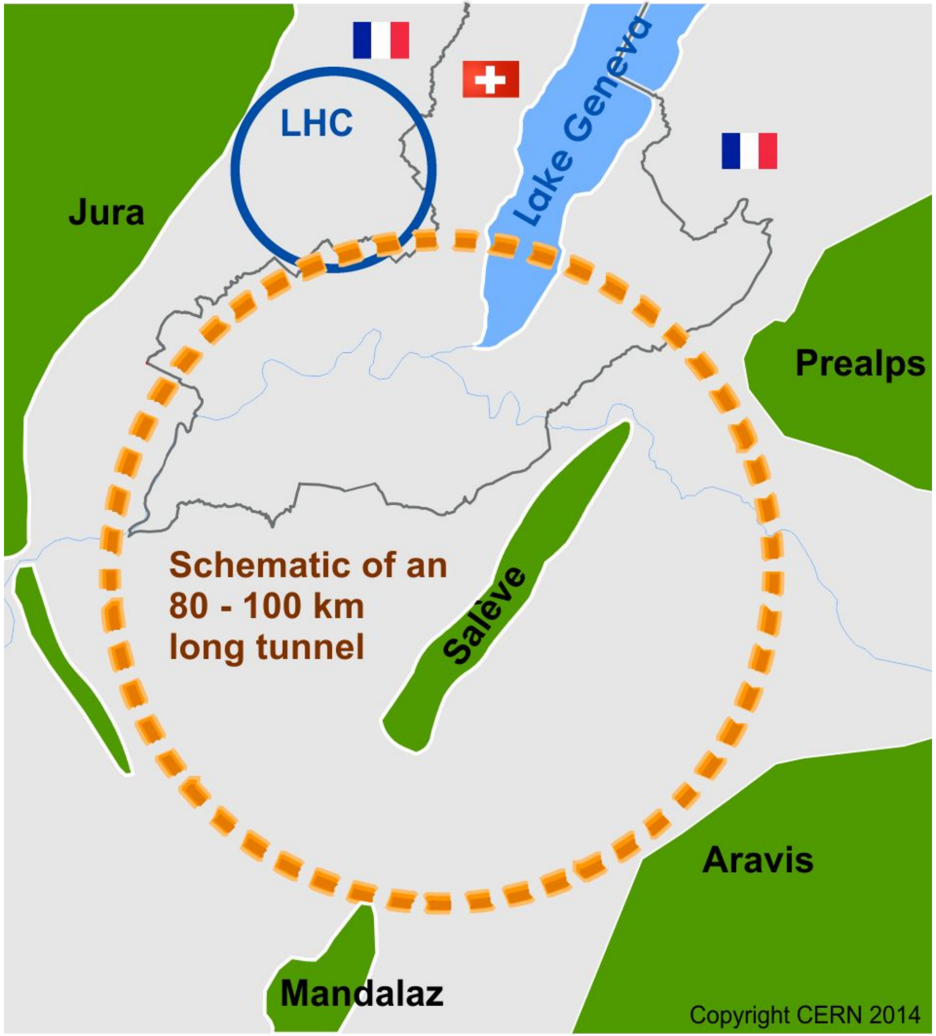
Future Circular Collider

From 7th FCC physics workshop

More details tomorrow

- 90.7 km ring
- 8 surface points
- 4 possible experiment sites
- Very large circular hadron collider only way to reach 100 TeV c.m. collision energy
- Direct production of few-TeV to 30 TeV particles far beyond LHC reach
- Much-increased rates for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC

From Michael Benedikt



Hadron collider energy reach

From Michael Benedikt

$$\boxed{E \propto B_{dipole} \times \rho_{bending}}$$

FCC-hh:

- Factor 4 radius of LHC
- Factor 2 magnetic field of LHC

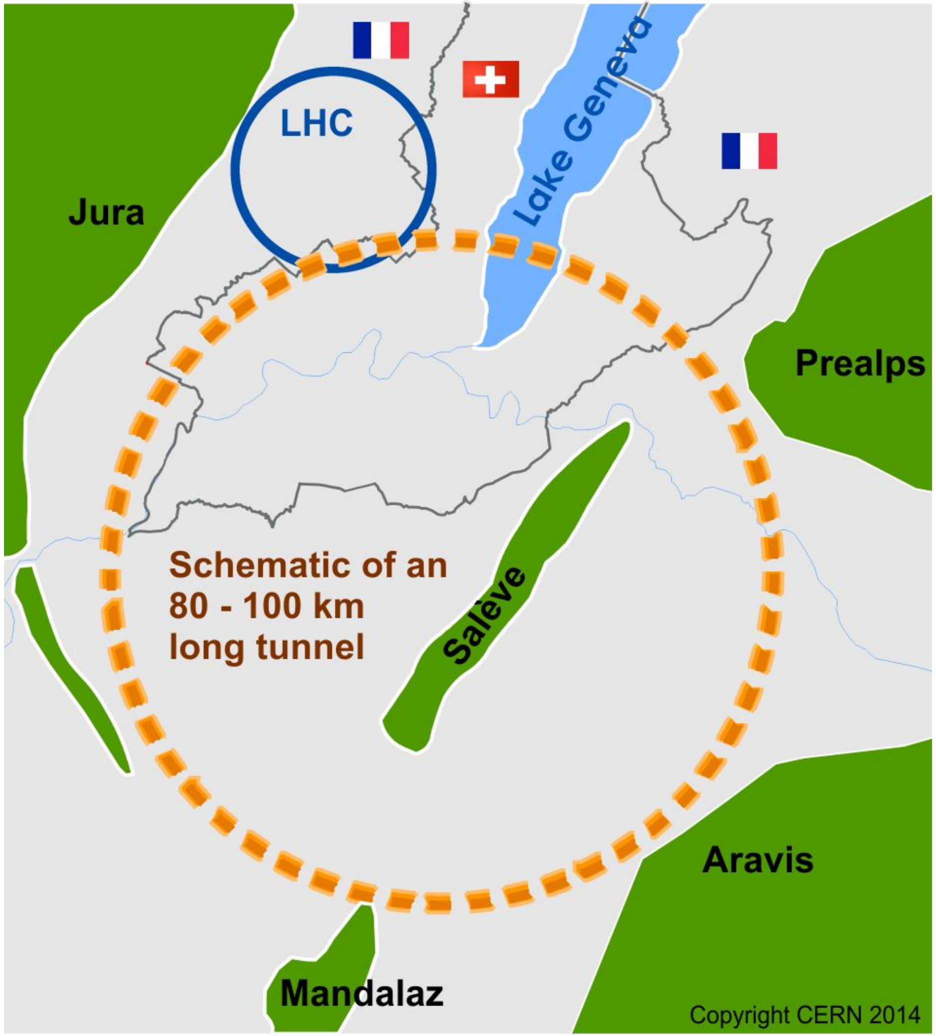
O(10) higher performance in E_{cms}

Future Circular Collider

From 7th FCC physics workshop

- 90.7 km ring
- 8 surface points
- 4 possible experiment sites
- Very large circular hadron collider only way to reach 100 TeV c.m. collision energy
- Direct production of few-TeV to 30 TeV particles far beyond LHC reach
- **Much-increased rates** for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC

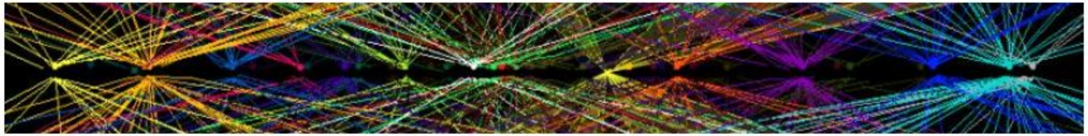
From Michael Benedikt



Copyright CERN 2014

From Werner Riegler

Pileup in 25 ns bunch crossing

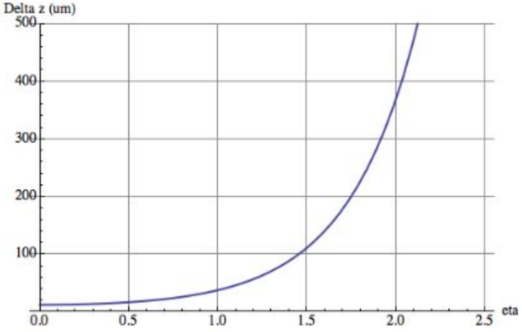


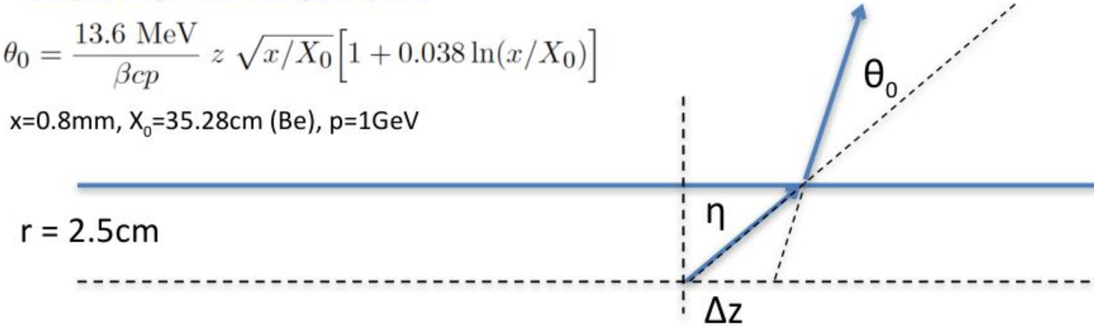
HL-LHC average distance between vertices at z=0 is
≈ 1mm in space and 3ps in time.

For 6 times higher luminosity at FCC-hh (an HE-LHC) this would become
≈ 170µm in space and 0.5ps in time.

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p} z \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

x=0.8mm, X_0=35.28cm (Be), p=1GeV



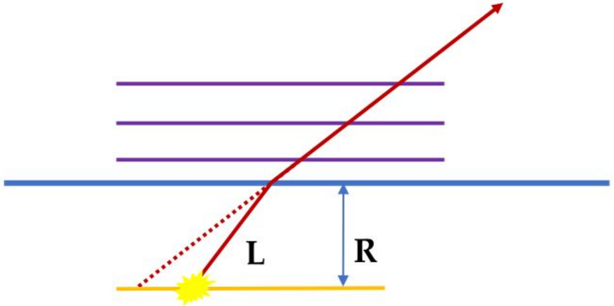


Even having a perfect tracking detector, the error due to multiple scattering in the beampipe for η > 1.7 is already larger than the average vertex distance !

Timing, very clever new ideas needed …

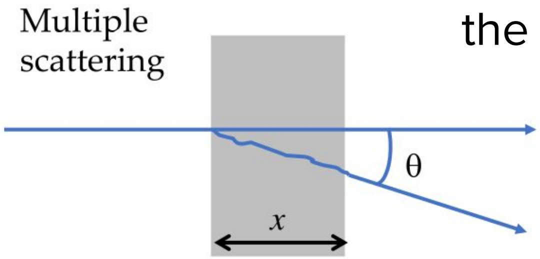
Multiple scattering

X_0: radiation length ~ energy loss: mean length at which the energy of an electron is reduced by the factor 1/e



- At a collider, the vertex detector is extrapolating the tracks back to the interaction region – usually through the intermediate material of the beam pipe

$$\sigma_{ip} \propto \mathrm{L}\frac{\sqrt{\mathrm{X}_0}}{\mathrm{p}} \propto \frac{\mathrm{R}}{\mathrm{p_T}}\sqrt{\mathrm{X}_0}$$



$$\sigma_{d_0} = \frac{r}{p}13.6\,MeV\sqrt{\frac{x}{X_0}}\left[1 + 0.038\log\left(\frac{x}{X_0}\right)\right]$$

For the best impact parameter precision:

Keep $\sqrt{x/\mathrm{X}_0}$ (the material) as small as possible

R (the innermost radius) as small as possible

From Werner Riegler

Data rates: trigger and data acquisition

Example: ATLAS Phase2 calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.

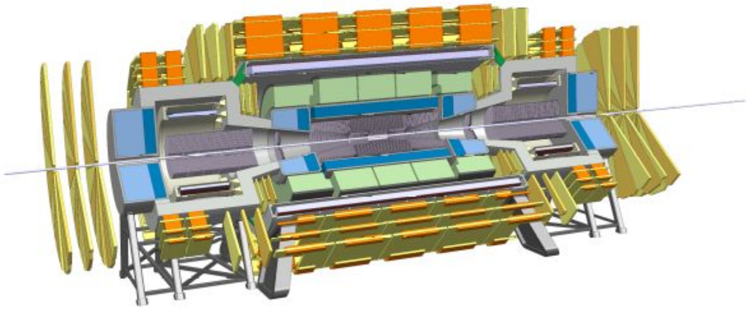
Muon system will also be read out at 40MHz to produce a L1 Trigger.

Reading out the FCC detector calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.

40MHz readout of the tracker would produce about 800TByte/s.

We need:

- Fast trigger
- Fast readout



Question:

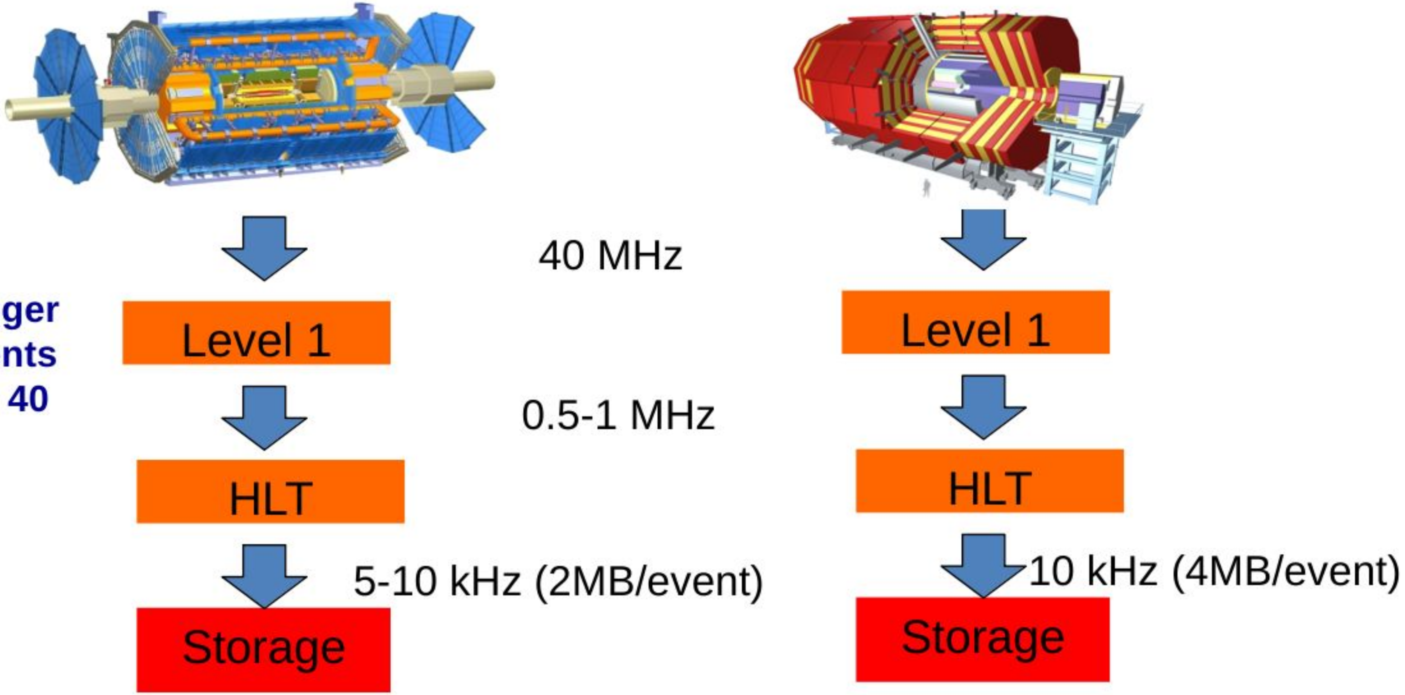
Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz ?

Un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.

From Werner Riegler

High Luminosity LHC: ATLAS and CMS

Hardware trigger to reduce events rate by factor 40



40 MHz

Level 1

0.5-1 MHz

HLT

5-10 kHz (2MB/event)

10 kHz (4MB/event)

Storage

10-20 GB/s

⚡ PEAK OUTPUT

40 GB/s

Requirements for detectors

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

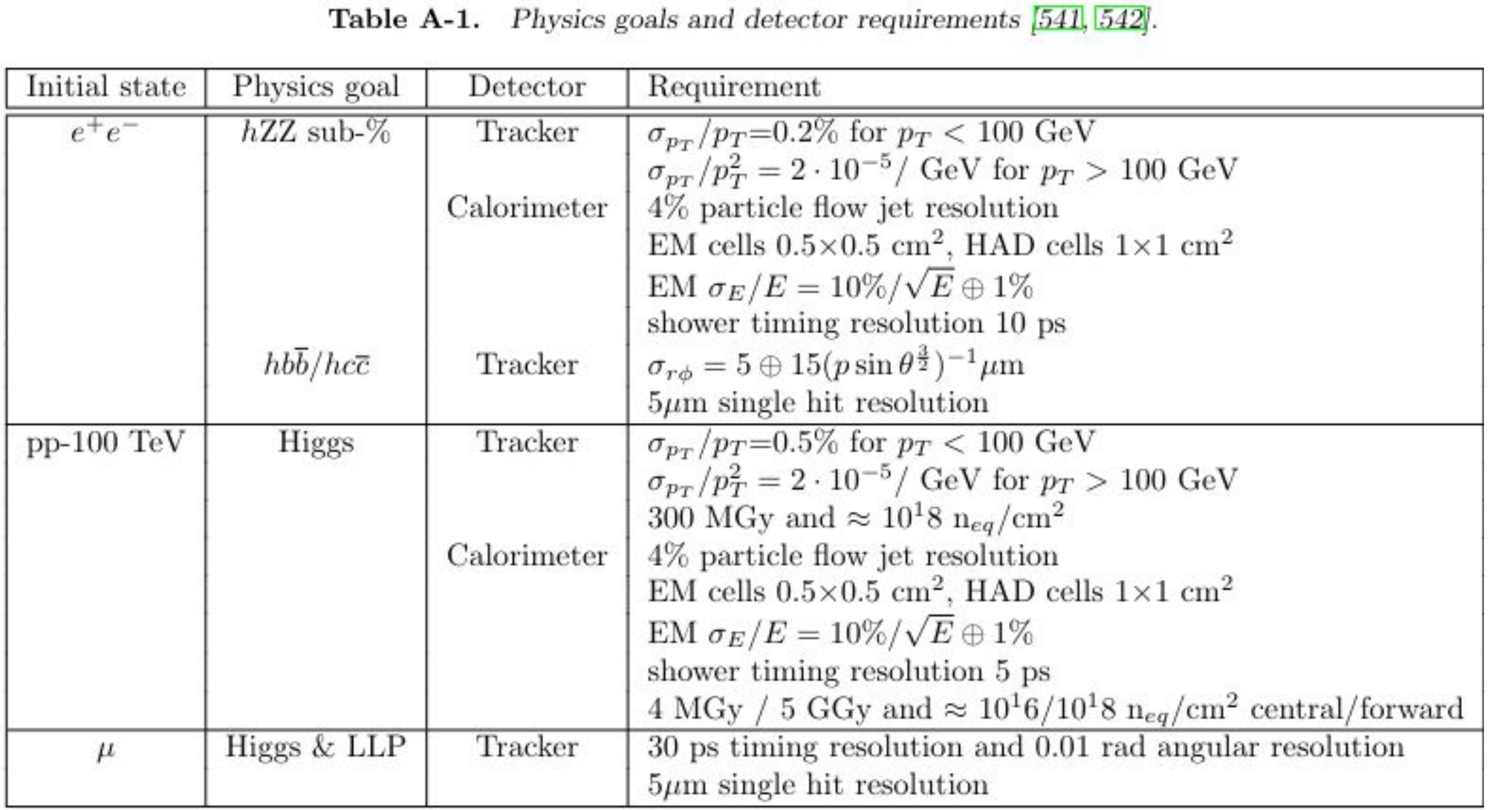


Table A-1. *Physics goals and detector requirements [541, 542].*

Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 10 ps
	$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin \theta^{\frac{3}{2}})^{-1} \mu$m
			5μm single hit resolution
pp-100 TeV	Higgs	Tracker	σ_{p_T}/p_T=0.5% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
			300 MGy and $\approx 10^18$ n$_{eq}$/cm^2
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 5 ps
			4 MGy / 5 GGy and $\approx 10^16/10^18$ n$_{eq}$/cm^2 central/forward
μ	Higgs & LLP	Tracker	30 ps timing resolution and 0.01 rad angular resolution
			5μm single hit resolution

Requirements for detectors

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

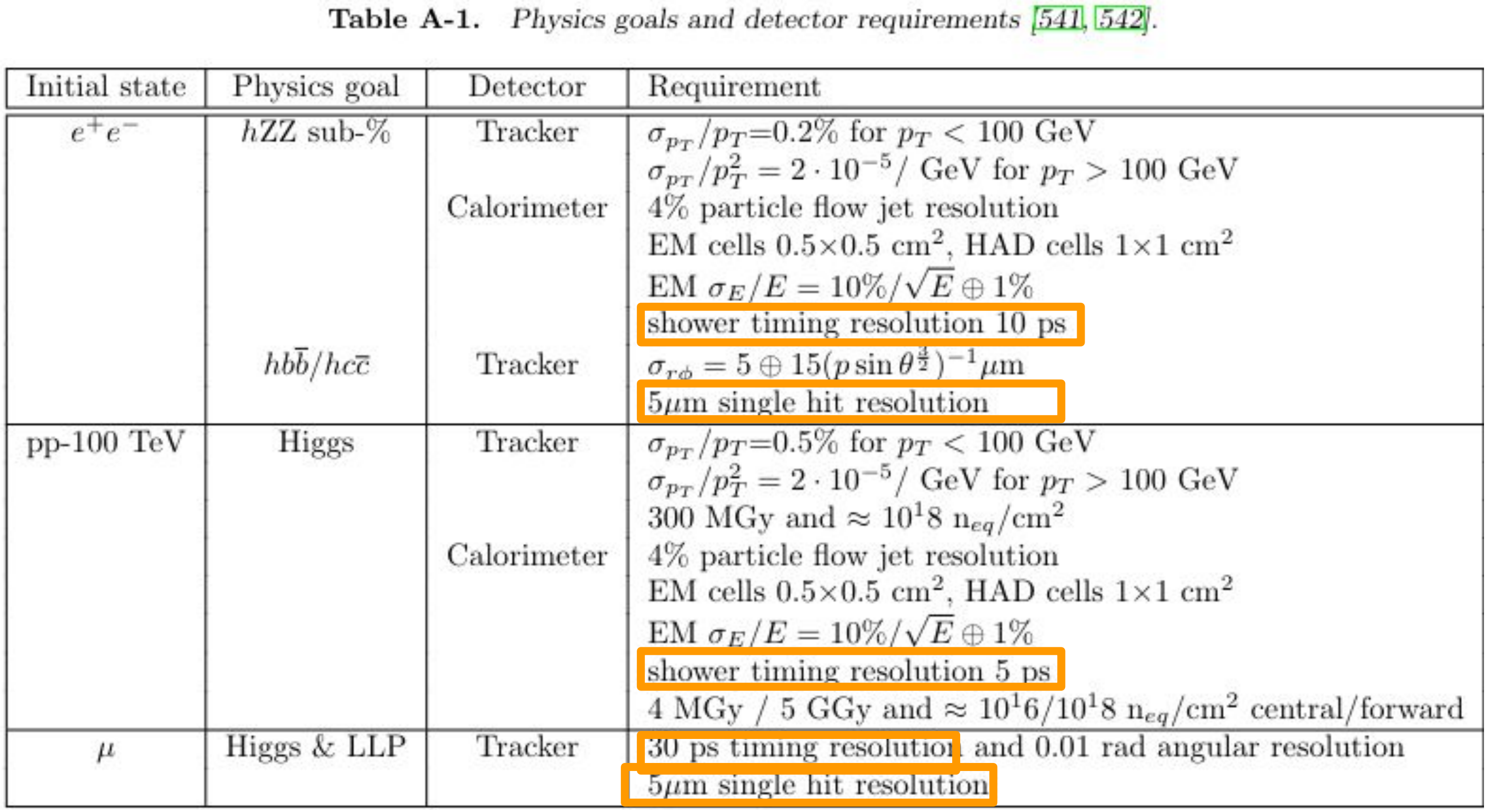


Table A-1. *Physics goals and detector requirements* [541, 542].

Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 10 ps
	$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu$m
			5μm single hit resolution
pp-100 TeV	Higgs	Tracker	σ_{p_T}/p_T=0.5% for $p_T < 100$ GeV
			$\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}/$ GeV for $p_T > 100$ GeV
			300 MGy and $\approx 10^18$ n$_{eq}$/cm^2
		Calorimeter	4% particle flow jet resolution
			EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2
			EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$
			shower timing resolution 5 ps
			4 MGy / 5 GGy and $\approx 10^16/10^18$ n$_{eq}$/cm^2 central/forward
μ	Higgs & LLP	Tracker	30 ps timing resolution and 0.01 rad angular resolution
			5μm single hit resolution

Computational challenges

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

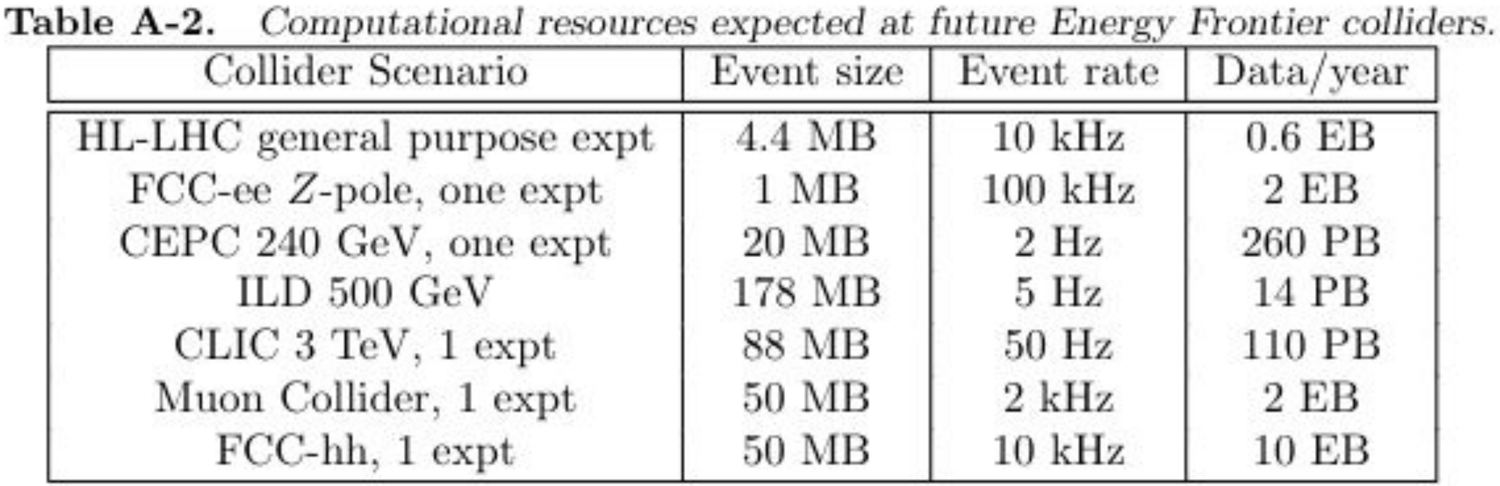


Table A-2. *Computational resources expected at future Energy Frontier colliders.*

Collider Scenario	Event size	Event rate	Data/year
HL-LHC general purpose expt	4.4 MB	10 kHz	0.6 EB
FCC-ee Z-pole, one expt	1 MB	100 kHz	2 EB
CEPC 240 GeV, one expt	20 MB	2 Hz	260 PB
ILD 500 GeV	178 MB	5 Hz	14 PB
CLIC 3 TeV, 1 expt	88 MB	50 Hz	110 PB
Muon Collider, 1 expt	50 MB	2 kHz	2 EB
FCC-hh, 1 expt	50 MB	10 kHz	10 EB

Computational challenges

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

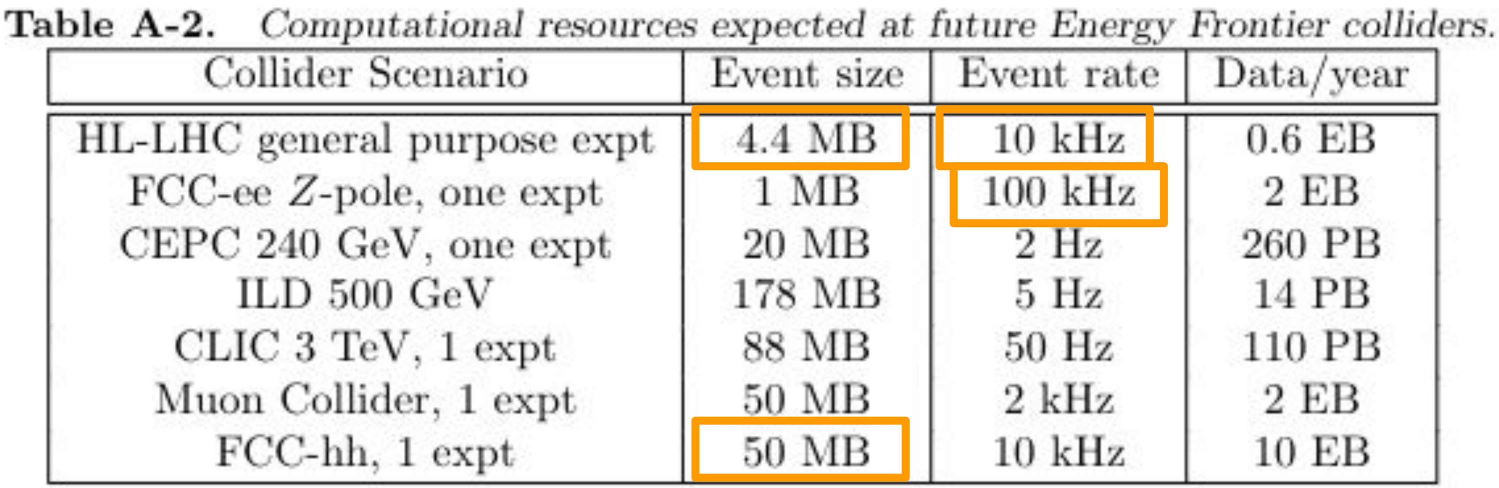
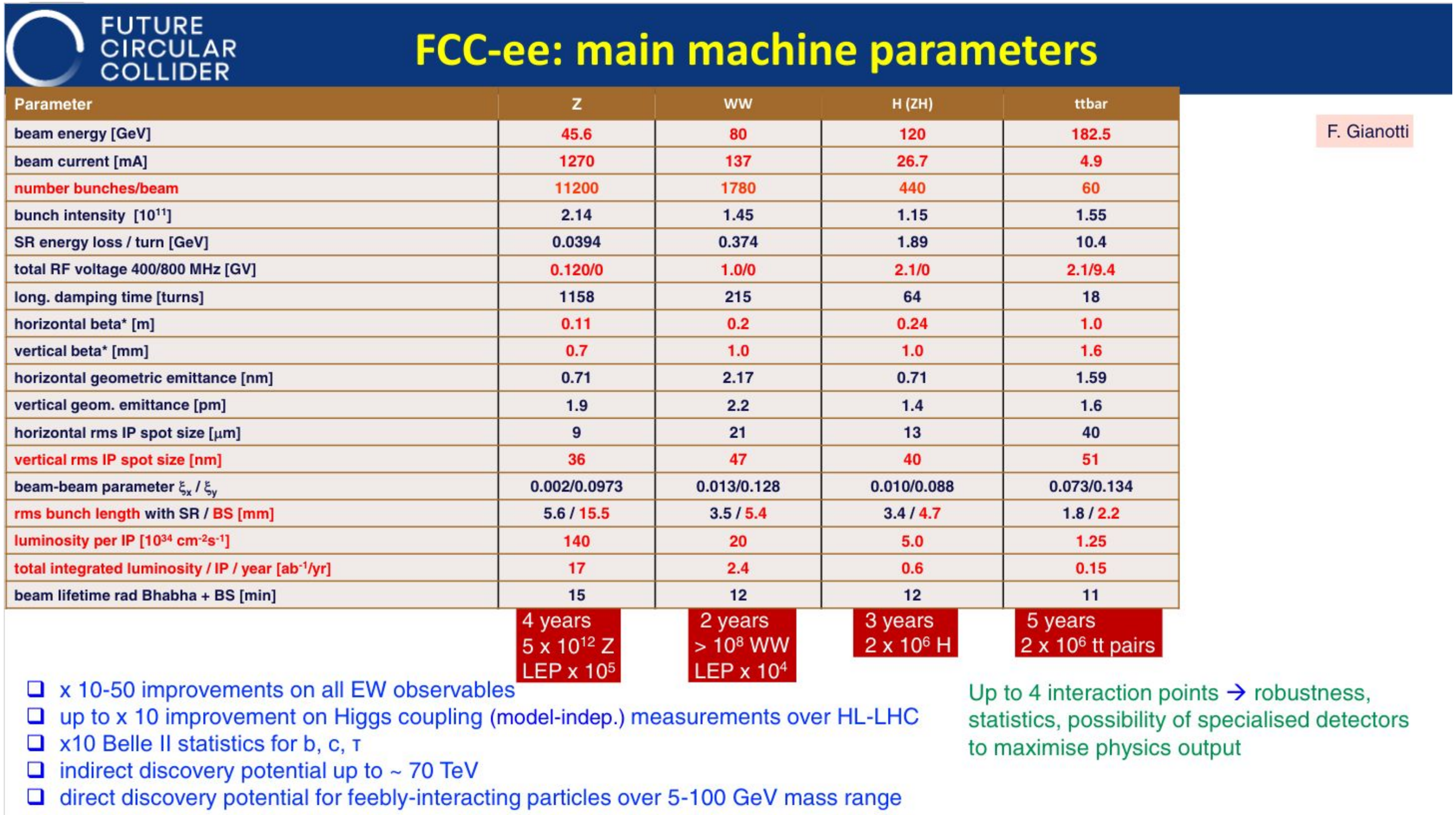


Table A-2. *Computational resources expected at future Energy Frontier colliders.*

Collider Scenario	Event size	Event rate	Data/year
HL-LHC general purpose expt	4.4 MB	10 kHz	0.6 EB
FCC-ee Z-pole, one expt	1 MB	100 kHz	2 EB
CEPC 240 GeV, one expt	20 MB	2 Hz	260 PB
ILD 500 GeV	178 MB	5 Hz	14 PB
CLIC 3 TeV, 1 expt	88 MB	50 Hz	110 PB
Muon Collider, 1 expt	50 MB	2 kHz	2 EB
FCC-hh, 1 expt	50 MB	10 kHz	10 EB

FCC parameters

From 7th FCC physics workshop



FUTURE CIRCULAR COLLIDER

FCC-ee: main machine parameters

F. Gianotti

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity $[10^{11}]$	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP $[10^{34}\ cm^{-2}s^{-1}]$	140	20	5.0	1.25
total integrated luminosity / IP / year $[ab^{-1}/yr]$	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

- ☐ x 10-50 improvements on all EW observables
- ☐ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ☐ x10 Belle II statistics for b, c, τ
- ☐ indirect discovery potential up to ~ 70 TeV
- ☐ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

Muon collider

More details tomorrow

From https://doi.org/10.1140/epjc/s10052-023-11889-x

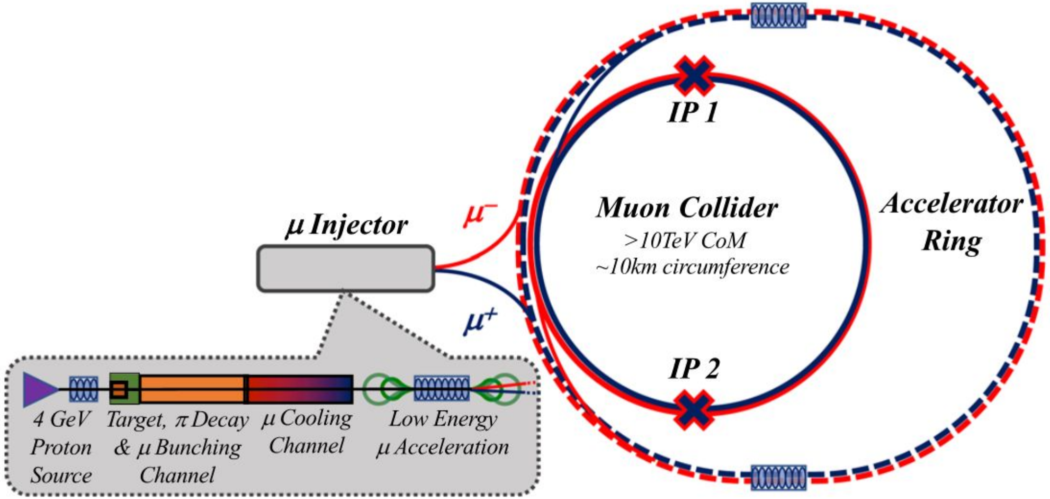


Fig. 1 A conceptual scheme of the muon collider

From the CERN accelerator school

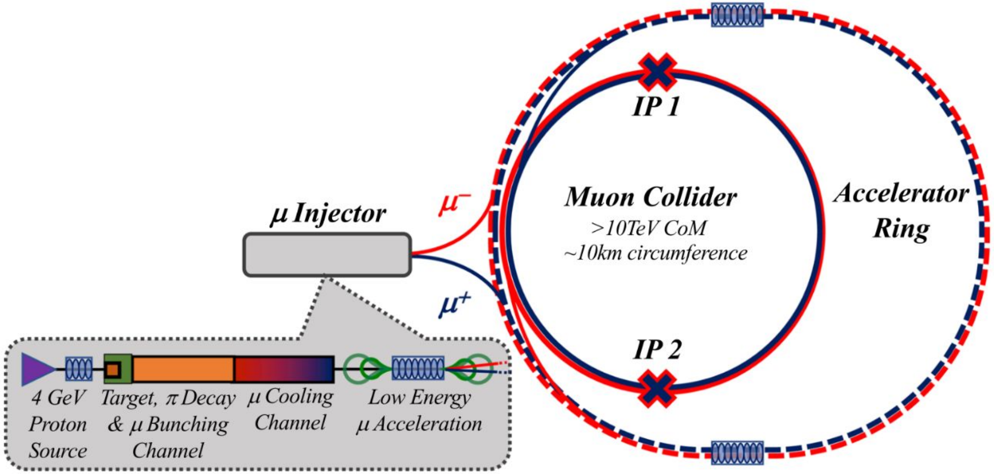
Synchrotron radiation ∝ E^4/m^4, m(μ) = 207 x m(e)
high energy muon collider ring possible!

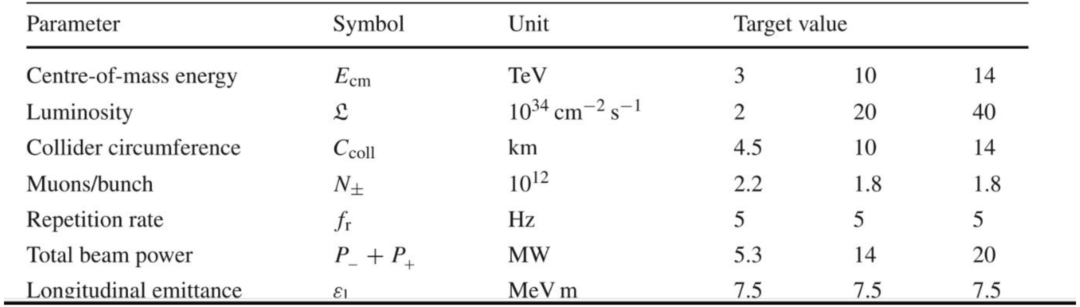
Muon collider

More details tomorrow

From https://doi.org/10.1140/epjc/s10052-023-11889-x

- Short high intensity proton pulse
- Hits target to produce pions
- Muons collected from pion decay into bunches
- Cooling reduces emittance
- Accelerated before going into collider ring





Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Total beam power	$P_{-} + P_{+}$	MW	5.3	14	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5

Muon collider major challenges

From https://doi.org/10.1140/epjc/s10052-023-11889-x

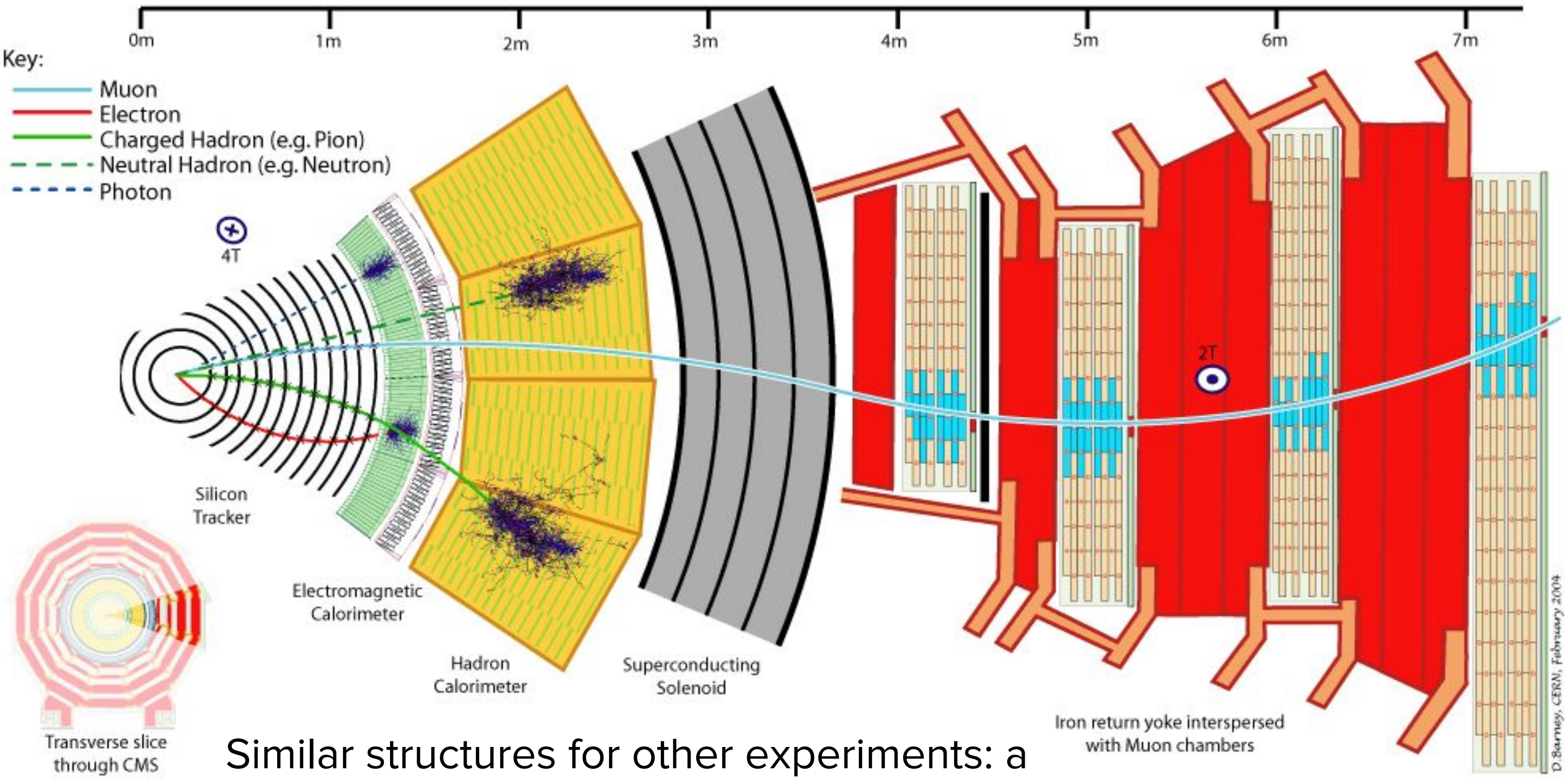
- Neutrino flux leading to neutron showering far from collider
- **Beam-induced background (BIB) from inpurities like muon decay products striking detector**
- Collider ring and acceleration system after muon cooling can limit energy reach. Not studied for 10 TeV, can impact machine-detector interface
- High quality muon beam to reach desired luminosity

Impact on detectors and event reconstruction

BIB: Low energy particles with a broad arrival time in the detector

Detectors for future colliders

A general purpose detector: CMS



Similar structures for other experiments: a tracker, calorimeters, and a muon system

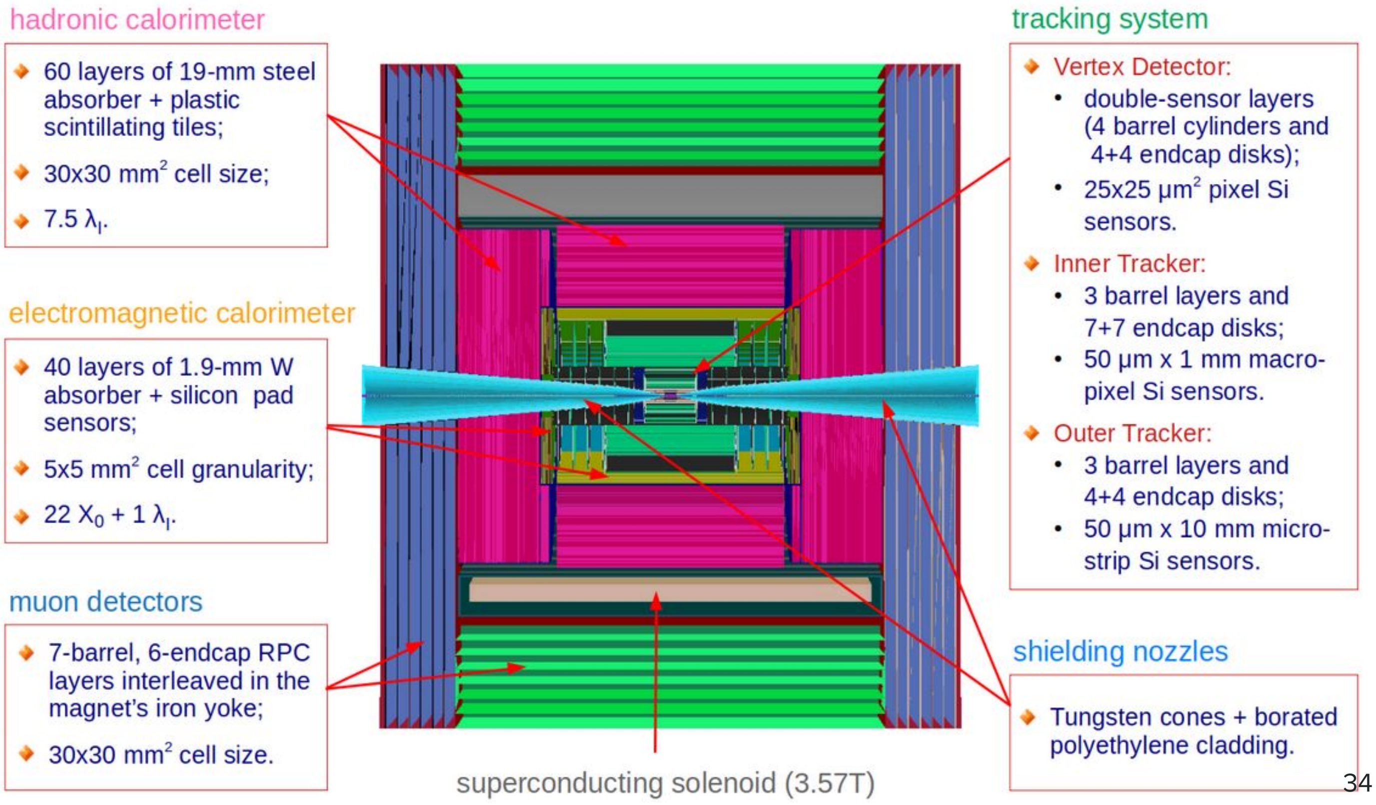
From https://muoncollider.web.cern.ch

Example: A muon collider experiment

Challenges:

- 30 ps time measurement on tracking
- Energy measurement
- High granularity
- Radiation hardness

What is the main cause of challenges in detecting and reconstructing collisions?



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)

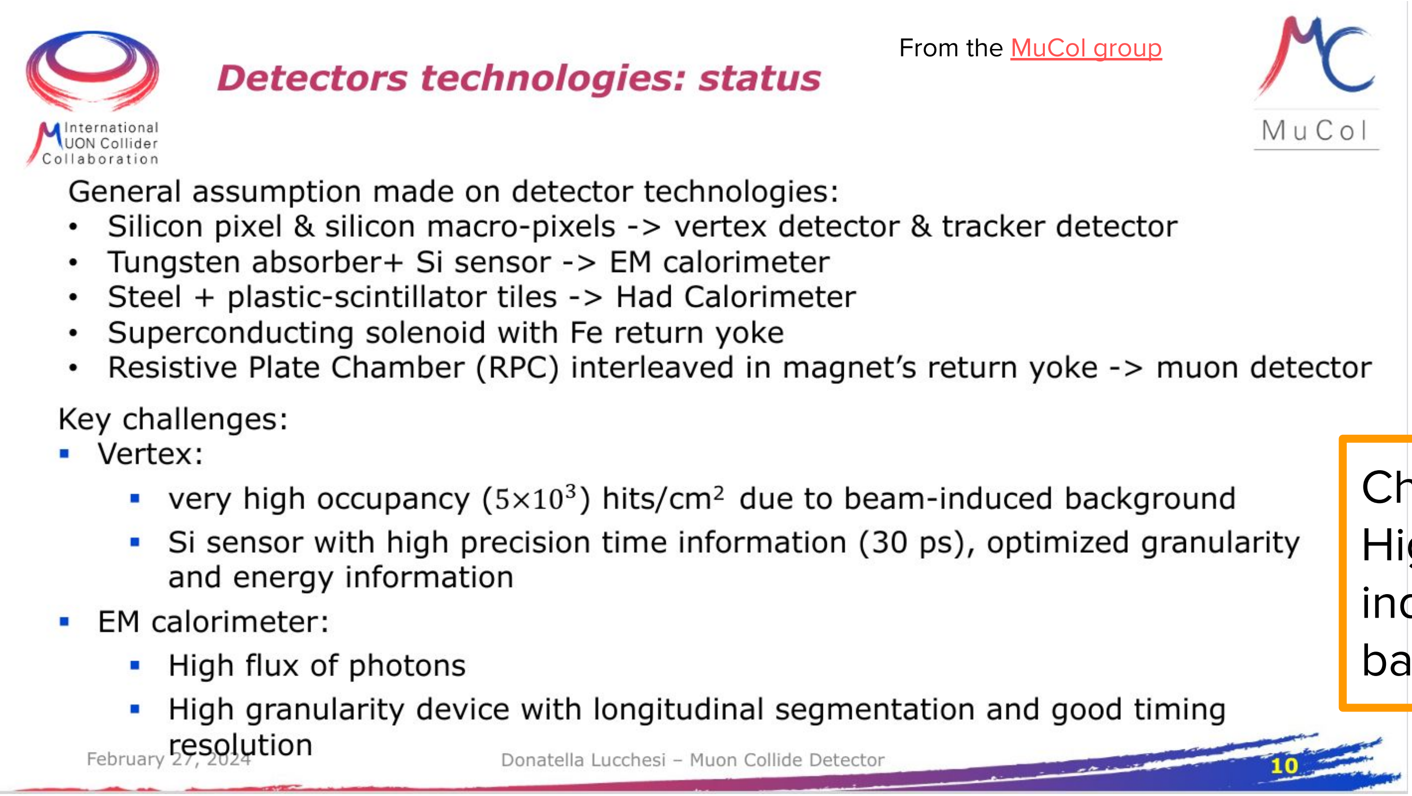
tracking system

- 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.

Muon collider detector technologies



From the MuCol group

Detectors technologies: status

General assumption made on detector technologies:
- Silicon pixel & silicon macro-pixels -> vertex detector & tracker detector
- Tungsten absorber+ Si sensor -> EM calorimeter
- Steel + plastic-scintillator tiles -> Had Calorimeter
- Superconducting solenoid with Fe return yoke
- Resistive Plate Chamber (RPC) interleaved in magnet’s return yoke -> muon detector

Key challenges:
- Vertex:
  - very high occupancy (5×10^3) hits/cm^2 due to beam-induced background
  - Si sensor with high precision time information (30 ps), optimized granularity and energy information
- EM calorimeter:
  - High flux of photons
  - High granularity device with longitudinal segmentation and good timing resolution

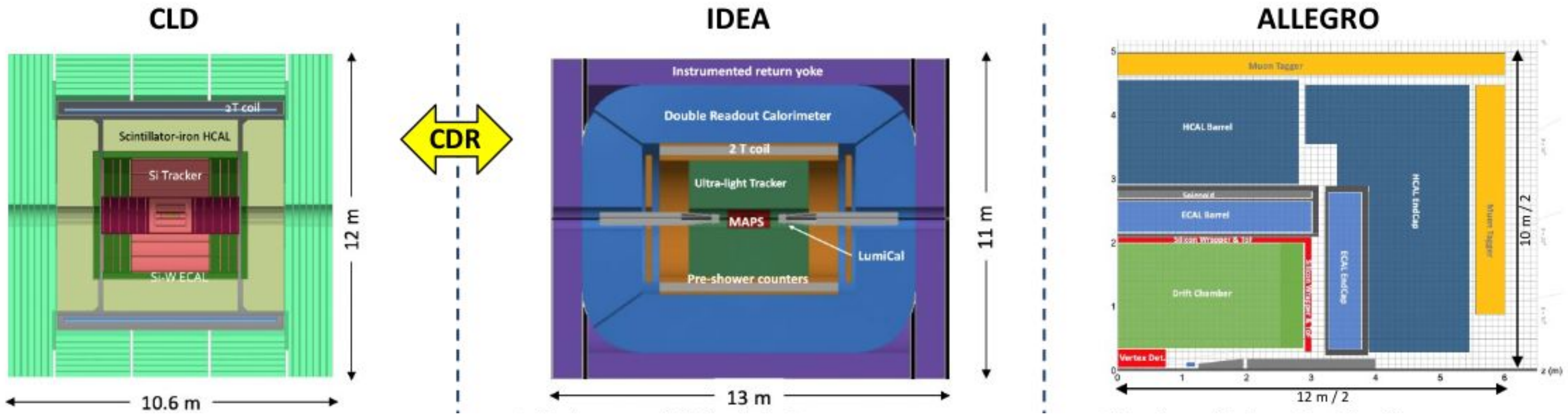
February 27, 2024 Donatella Lucchesi – Muon Collide Detector 10

Challenge:
High beam induced background

From FCC Physics Workshop

FCC-ee detector concepts

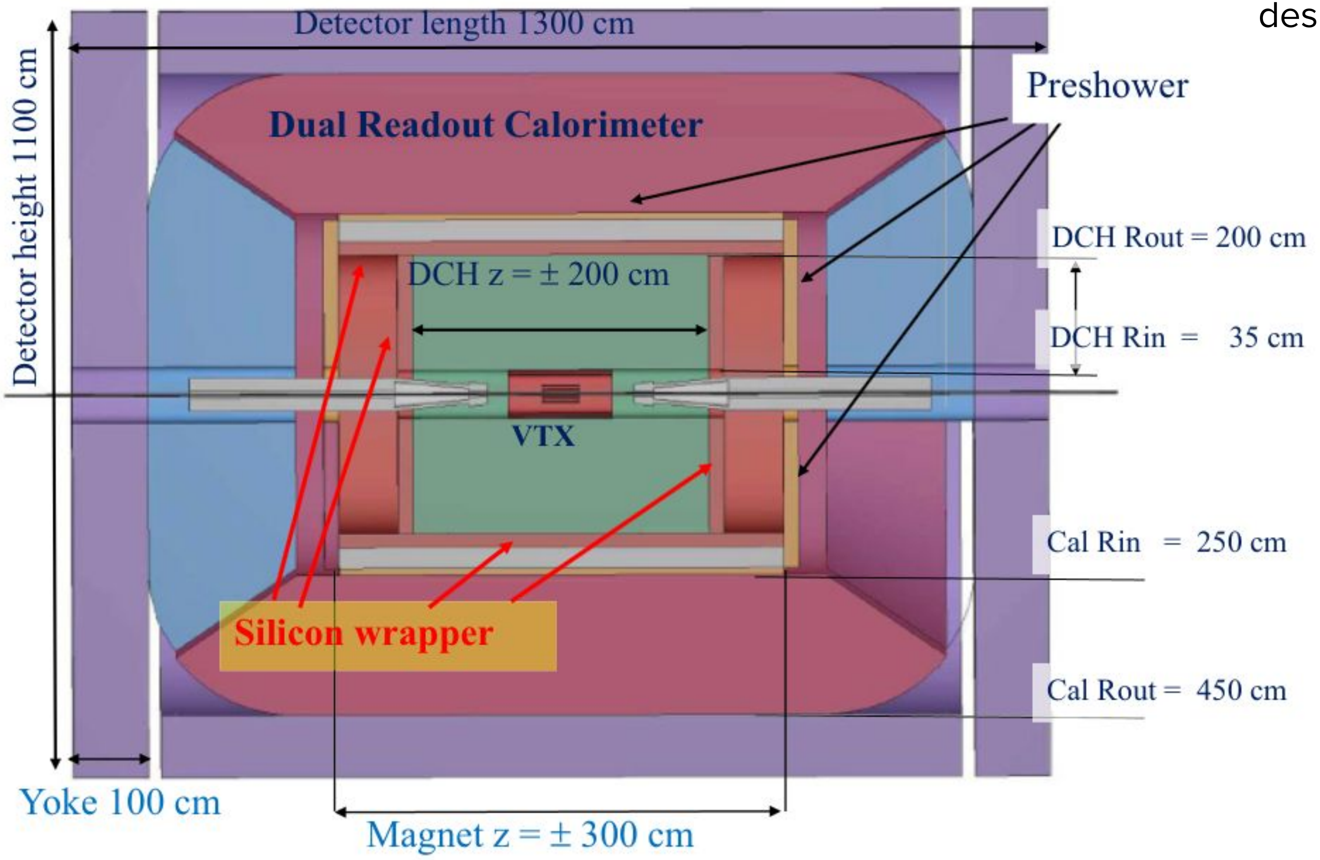
Many detector concepts, and possible technologies



MAPS: monolithic active pixel sensors

Example: the IDEA detector

From the [FCC-ee CDR](#) or conceptual design report as opposed to technical design report (TDR)



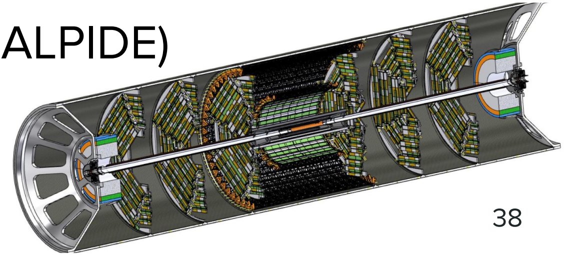
Vertex detector based on: **ALICE ITS upgrade detectors** based on the ALICE PIxel DEtector (ALPIDE): 0.3 (1.0)% X_0 per innermost (outermost) layer and 5 µm resolution

From the FCC-ee CDR
and the 7th FCC workshop

Build on current R&D and existing detectors

“International Detector for Electron-positron Accelerators” (IDEA):

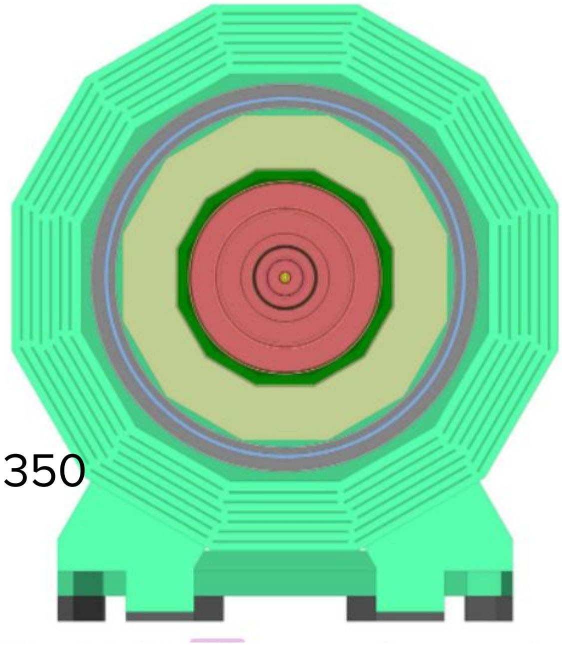
- Dual readout calorimeter
    - Cherenkov and scintillation light
    - Based on R&D by the RD52/DREAM collaboration
- Drift chamber for muons
    - with 1.6% X_0 in radial and 5% X_0 in forward direction
    - Based on existing KLOE (K^0_LLOng) experiment drift chamber
    - Microstrip surrounding detector for another space point measurement
- Vertex detector based on Monolithic Active Pixel Sensor (MAPS)
    - Based on ALICE ITS upgrade detectors
    - That is in turn based on the ALICE PIxel DEtector (ALPIDE)
    - 0.3 (1.0)% X_0 per innermost (outermost) layer
    - ~5 µm resolution

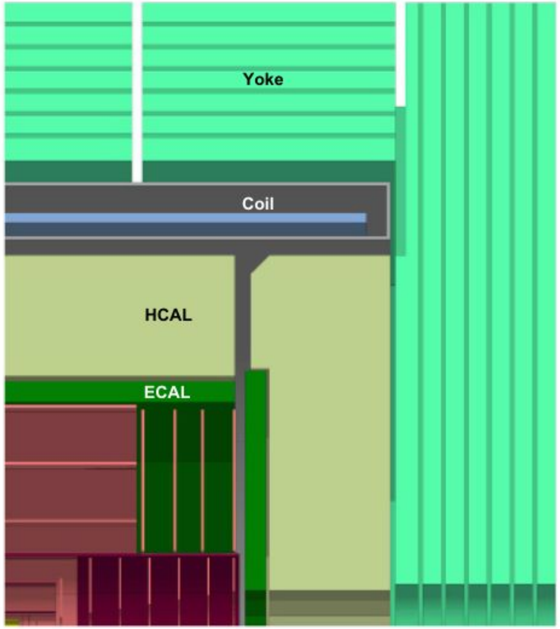


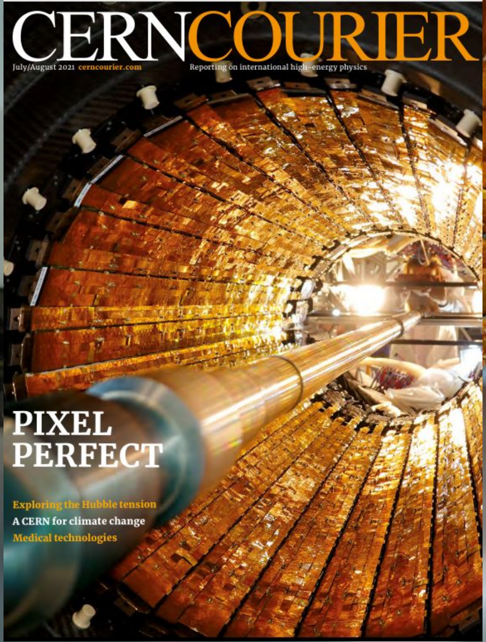
Build on existing detectors and current R&D

“CLIC-Like Detector” (CLD):

- Based on well-established design for CLIC detector
- All-silicon tracker
- Based on ALICE inner tracking system upgrade increased factor 1.5 material per layer compared to CLD
- Synchrotron radiation only 350 hits per bunch crossing (BX): max occupancy 10^{-4}







CERNCOURIER

July/August 2021 cerncourier.com

Reporting on international high-energy physics

PIXEL PERFECT

Exploring the Hubble tension

A CERN for climate change

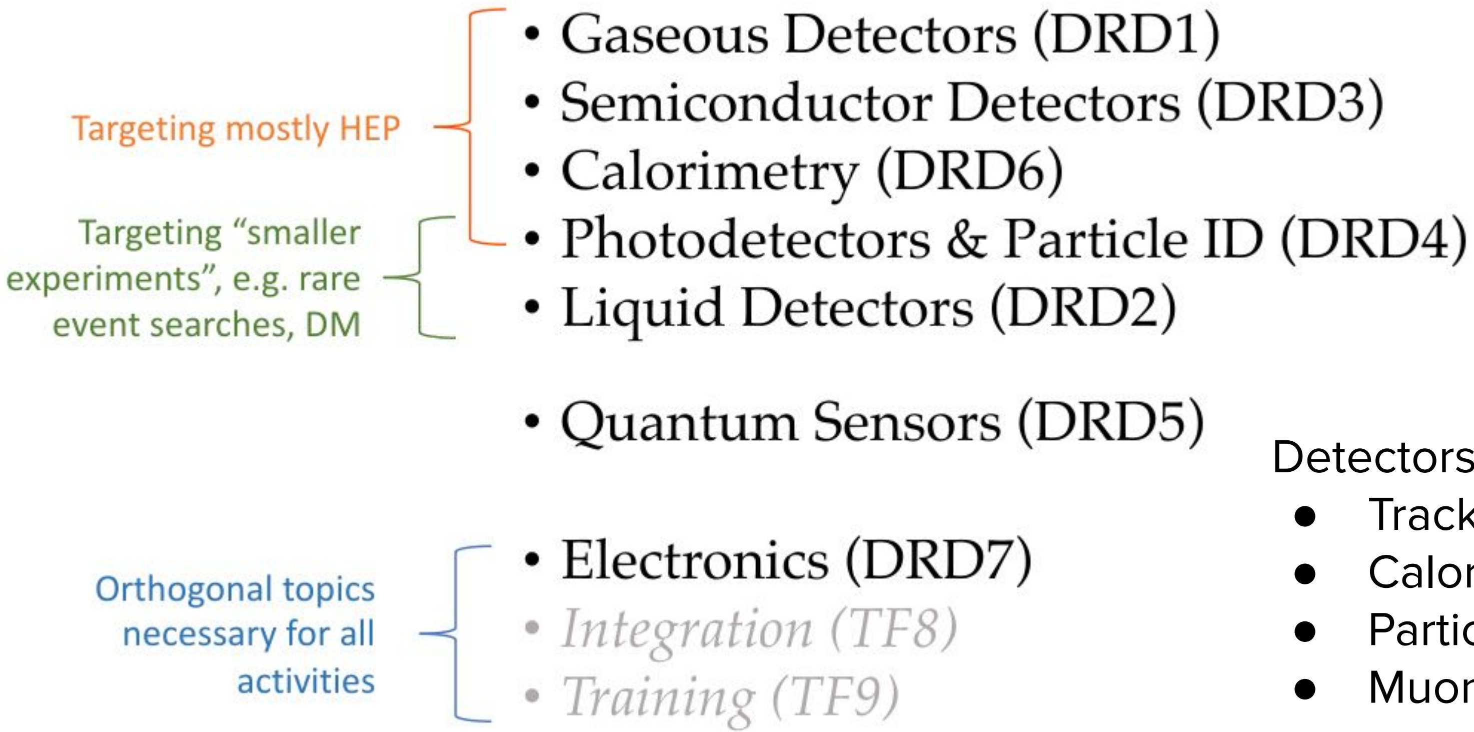
Medical technologies

ALICE silicon pixel detector

Detector development: European strategy

From 2023 CPAD Workshop

Detector development: various technologies and aspects



Targeting mostly HEP

- Gaseous Detectors (DRD1)
- Semiconductor Detectors (DRD3)
- Calorimetry (DRD6)
- Photodetectors & Particle ID (DRD4)

Targeting “smaller experiments”, e.g. rare event searches, DM

- Liquid Detectors (DRD2)

- Quantum Sensors (DRD5)

Orthogonal topics necessary for all activities

- Electronics (DRD7)
- *Integration (TF8)*
- *Training (TF9)*

Different detector Research & Development working groups

Detectors for:

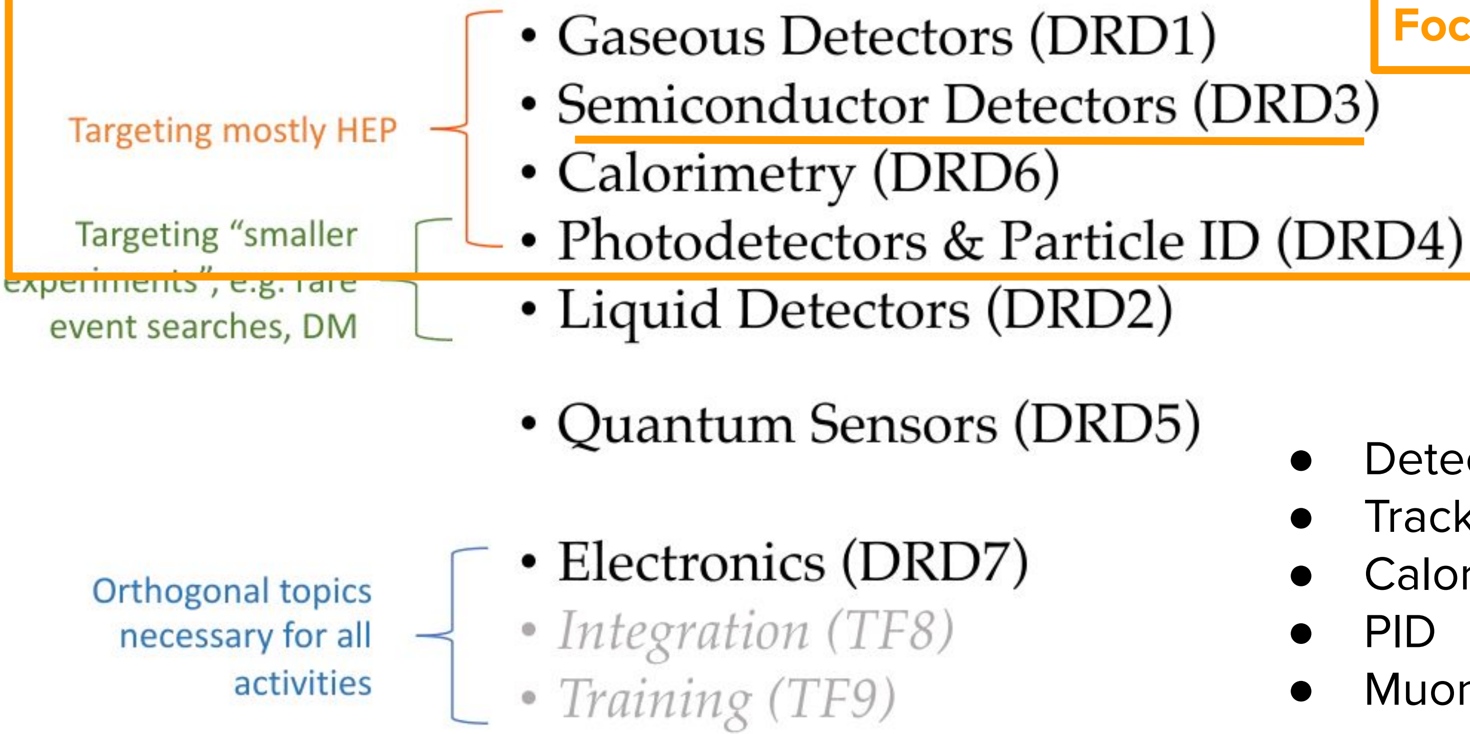
- Tracking
- Calorimetry
- Particle identification
- Muon systems

ECFA Detector R&D Roadmap

From 2023 CPAD Workshop

Detector development: various technologies and aspects

Focus of this lectur



Targeting mostly HEP
- Gaseous Detectors (DRD1)
- Semiconductor Detectors (DRD3)
- Calorimetry (DRD6)
- Photodetectors & Particle ID (DRD4)

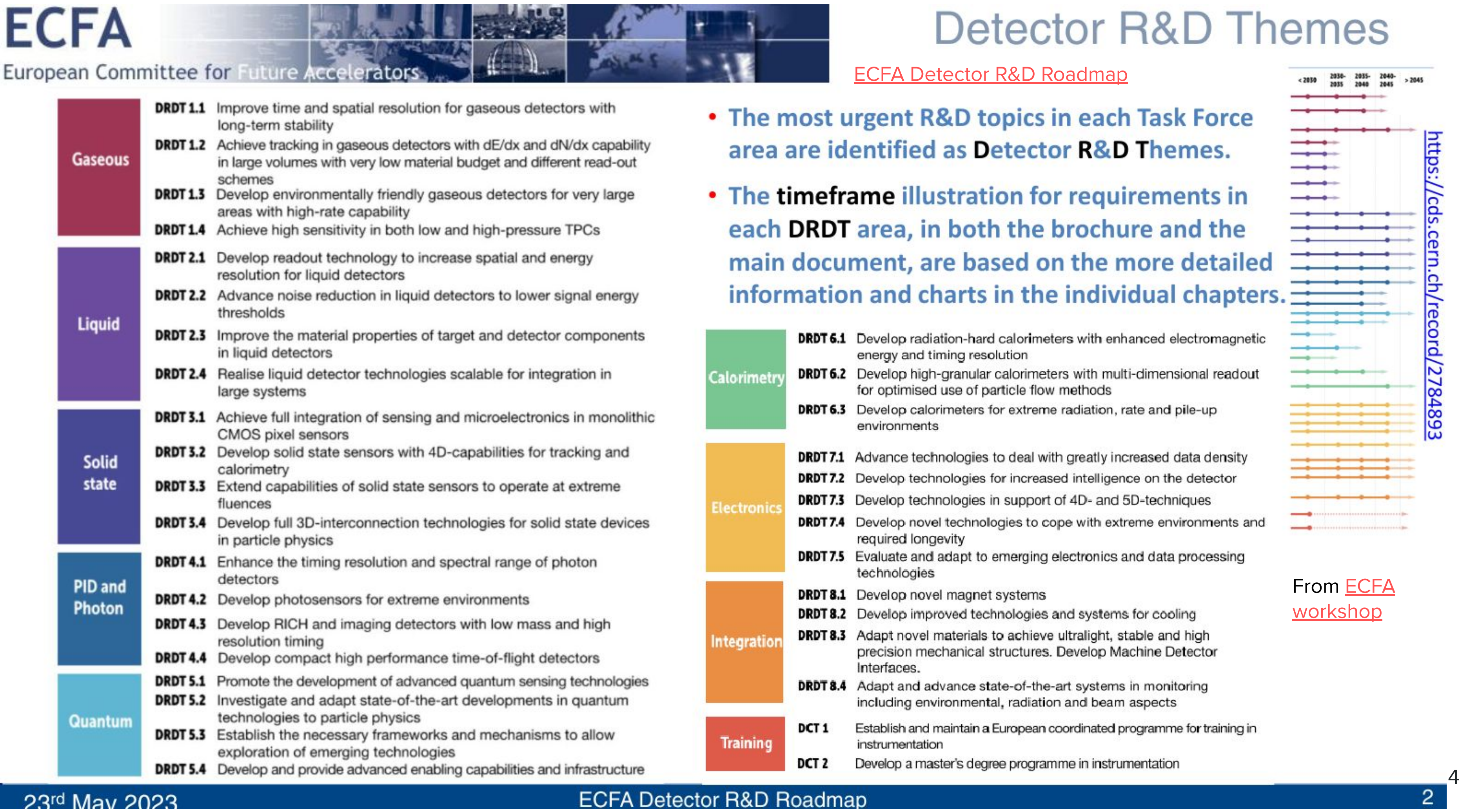
Targeting "smaller experiments", e.g. rare event searches, DM
- Liquid Detectors (DRD2)

- Quantum Sensors (DRD5)

Orthogonal topics necessary for all activities
- Electronics (DRD7)
- *Integration (TF8)*
- *Training (TF9)*

- Detectors for:
- Tracking
- Calorimetry
- PID
- Muon systems

ECFA Detector R&D Roadmap



Detector R&D Themes

ECFA Detector R&D Roadmap

- The most urgent R&D topics in each Task Force area are identified as **D**etector **R**&**D** **T**hemes.
- The **timeframe** illustration for requirements in each **DRDT** area, in both the brochure and the main document, are based on the more detailed information and charts in the individual chapters.

Gaseous	**DRDT 1.1**	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs
Liquid	**DRDT 2.1**	Develop readout technology to increase spatial and energy resolution for liquid detectors
	DRDT 2.2	Advance noise reduction in liquid detectors to lower signal energy thresholds
	DRDT 2.3	Improve the material properties of target and detector components in liquid detectors
	DRDT 2.4	Realise liquid detector technologies scalable for integration in large systems
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
PID and Photon	**DRDT 4.1**	Enhance the timing resolution and spectral range of photon detectors
	DRDT 4.2	Develop photosensors for extreme environments
	DRDT 4.3	Develop RICH and imaging detectors with low mass and high resolution timing
	DRDT 4.4	Develop compact high performance time-of-flight detectors
Quantum	**DRDT 5.1**	Promote the development of advanced quantum sensing technologies
	DRDT 5.2	Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
	DRDT 5.3	Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
	DRDT 5.4	Develop and provide advanced enabling capabilities and infrastructure
Calorimetry	**DRDT 6.1**	Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
	DRDT 6.2	Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
	DRDT 6.3	Develop calorimeters for extreme radiation, rate and pile-up environments
Electronics	**DRDT 7.1**	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	**DRDT 8.1**	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
Training	**DCT 1**	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation

https://cds.cern.ch/record/2784893

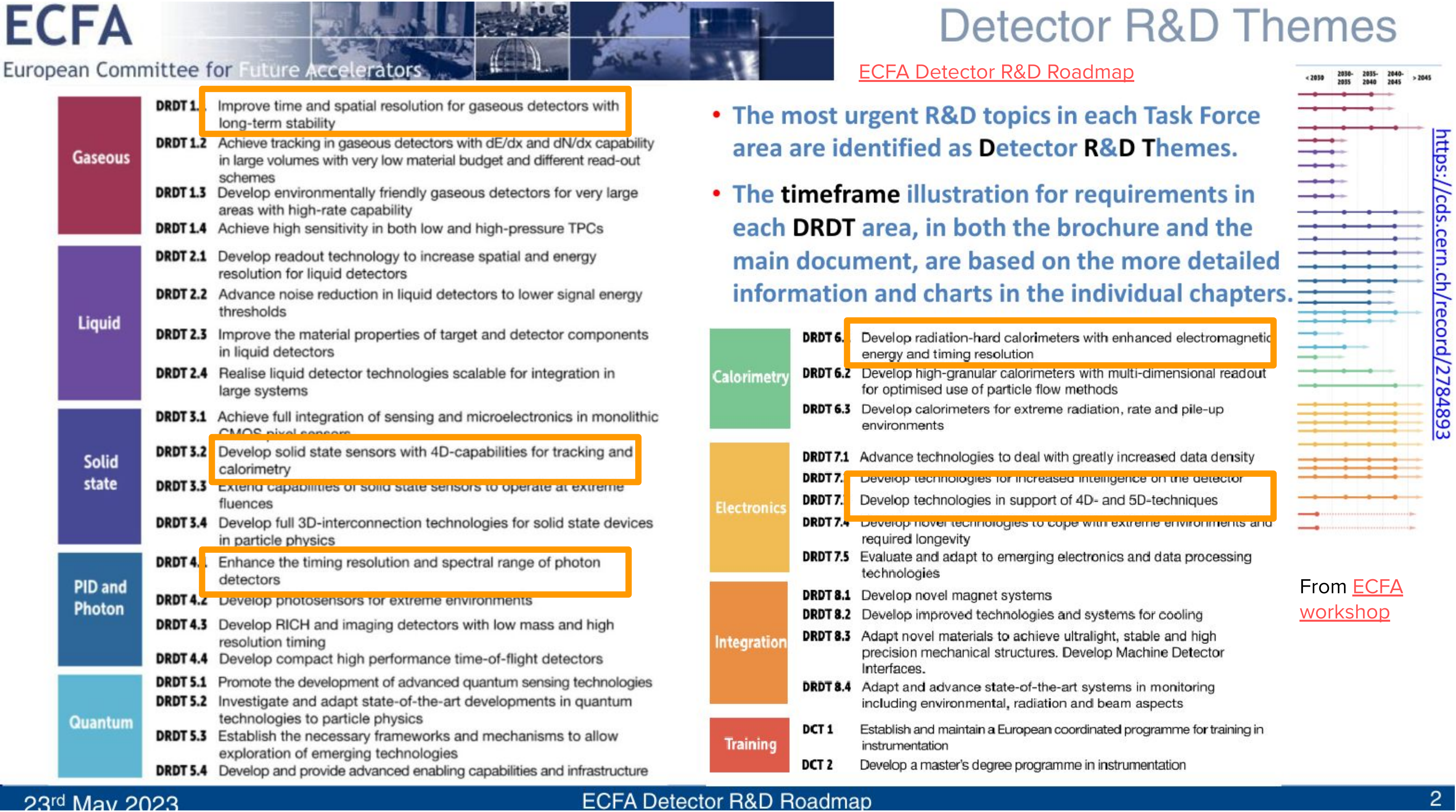
23rd May 2023 ECFA Detector R&D Roadmap 2

From ECFA workshop

Detector R&D Themes

ECFA Detector R&D Roadmap

- The most urgent R&D topics in each Task Force area are identified as **D**etector **R&D T**hemes.
- The **timeframe** illustration for requirements in each **DRDT** area, in both the brochure and the main document, are based on the more detailed information and charts in the individual chapters.



ECFA
European Committee for Future Accelerators

Gaseous
DRDT 1. Improve time and spatial resolution for gaseous detectors with long-term stability
DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs

Liquid
DRDT 2.1 Develop readout technology to increase spatial and energy resolution for liquid detectors
DRDT 2.2 Advance noise reduction in liquid detectors to lower signal energy thresholds
DRDT 2.3 Improve the material properties of target and detector components in liquid detectors
DRDT 2.4 Realise liquid detector technologies scalable for integration in large systems

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

PID and Photon
DRDT 4. Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2 Develop photosensors for extreme environments
DRDT 4.3 Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4 Develop compact high performance time-of-flight detectors

Quantum
DRDT 5.1 Promote the development of advanced quantum sensing technologies
DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure

Calorimetry
DRDT 6. Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments

Electronics
DRDT 7.1 Advance technologies to deal with greatly increased data density
DRDT 7. Develop technologies for increased intelligence on the detector
DRDT 7. Develop technologies in support of 4D- and 5D-techniques
DRDT 7.4 Develop novel technologies to cope with extreme environments and required longevity
DRDT 7.5 Evaluate and adapt to emerging electronics and data processing technologies

Integration
DRDT 8.1 Develop novel magnet systems
DRDT 8.2 Develop improved technologies and systems for cooling
DRDT 8.3 Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
DRDT 8.4 Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects

Training
DCT 1 Establish and maintain a European coordinated programme for training in instrumentation
DCT 2 Develop a master's degree programme in instrumentation

23rd May 2023
ECFA Detector R&D Roadmap
2

From ECFA workshop

https://cds.cern.ch/record/2784893

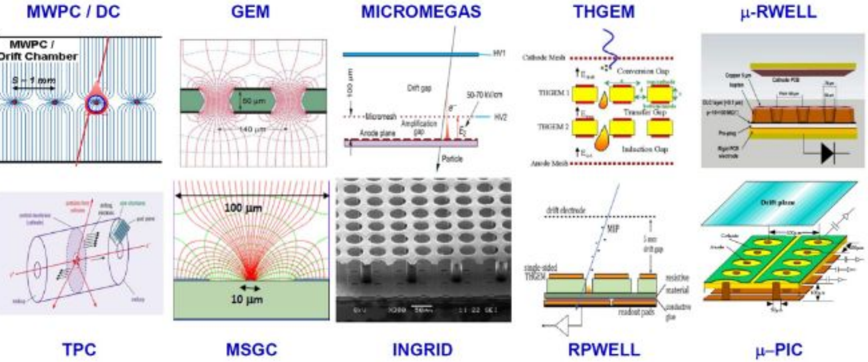
Gaseous detector development

Gaseous detectors

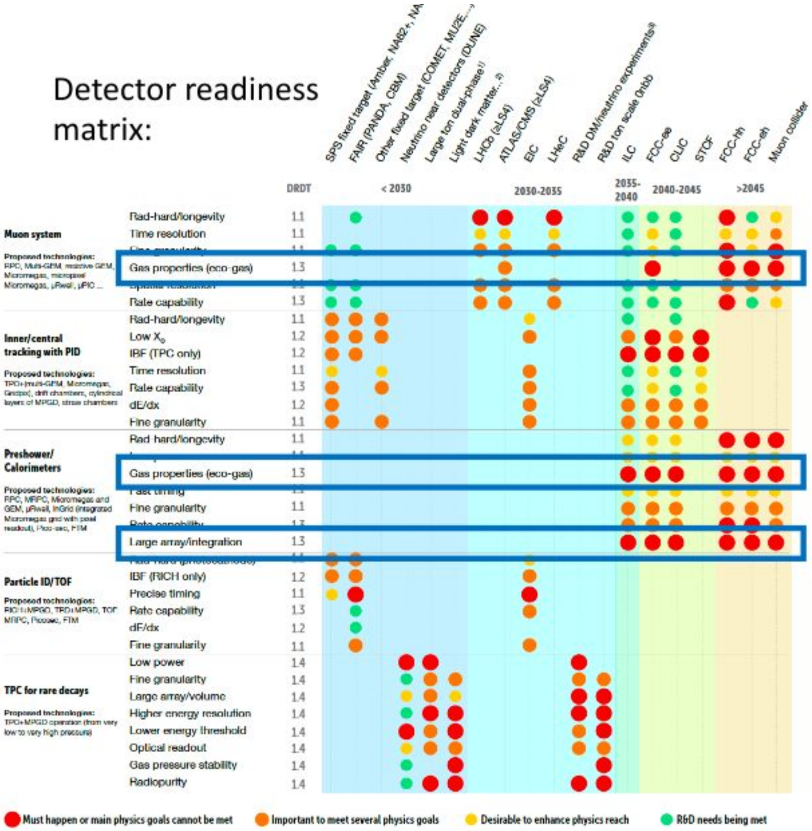
From 2023 CPAD Workshop

ECFA Detector R&D Roadmap

- from MWPC → Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors
- Primary choice for large-area coverage with low material budget & dE/dx measurement (TPC, Drift chamber) & ToF functionality (MRPC, PICOSEC)



Detector readiness matrix:



			< 2030						2030-2035						2035-2040	2040-2045			>2045		
		DRDT	SPS fixed target (Amber, NA62+, NA	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E...)	Neutrino near detectors (DUNE)	Large ton dual-phase $^{1)}$	Light dark matter... $^{2)}$	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments $^{3)}$	R&D ton scale 0nbb	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													🟡	🟡	🟡		🔴	🔴	🔴
	[illegible]	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

From 2023 CPAD Workshop

ECFA Detector R&D Roadmap

R&D for gaseous detectors

Large Areas:

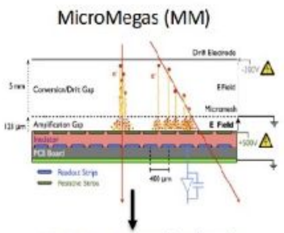
- Systems developed for LHC experiments led to unprecedented large systems, mostly based on MPGDs

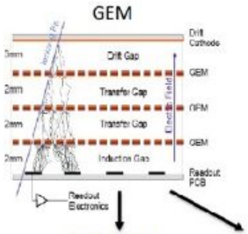
Fast Timing:

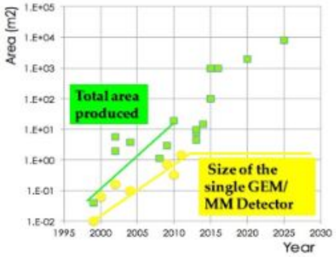
- Fast timing with Multi-Gap RPCs: achieved ~60ps time resolution (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396)
- Micromegas with timing (PICOSEC concept): 25ps

Eco-friendly gas mixtures

- 92% of emissions at CERN are related to LHC experiments
- Gas re-circulation: GHG emission reduced by >90%
- Alternatives to $C_2H_2F_4$ for TPCs with lower Global Warming Potential (GWP)



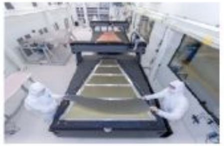


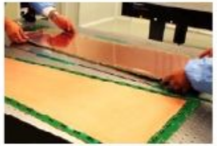


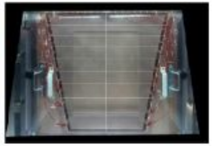
ATLAS new small wheels

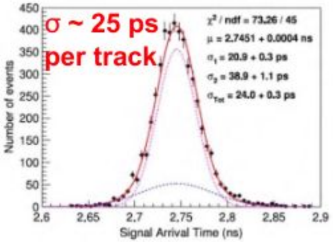
CMS GEM

ALICE TPC upgrade

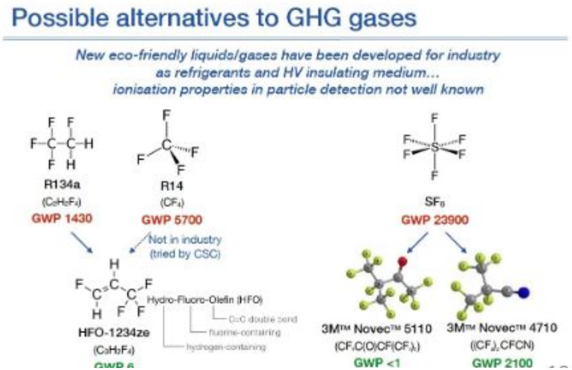








PICOSEC: NIMA903 (2018) 317



Possible alternatives to GHG gases

New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium… ionisation properties in particle detection not well known

Micromesh Gaseous Structure: Micromegas

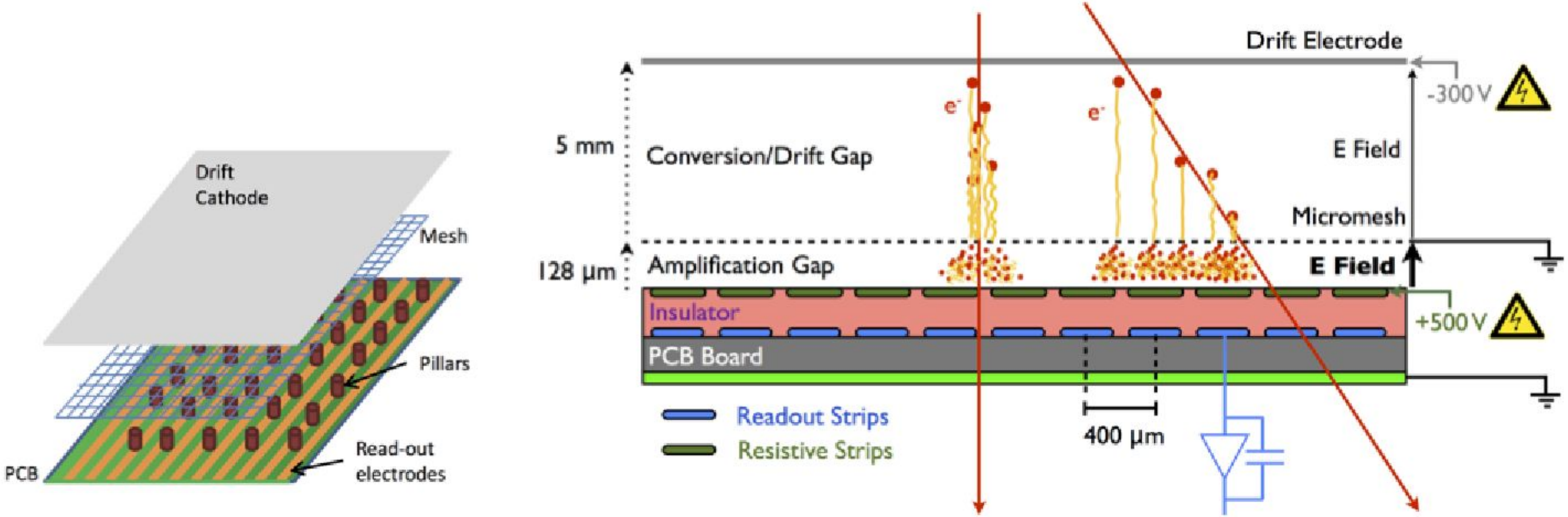
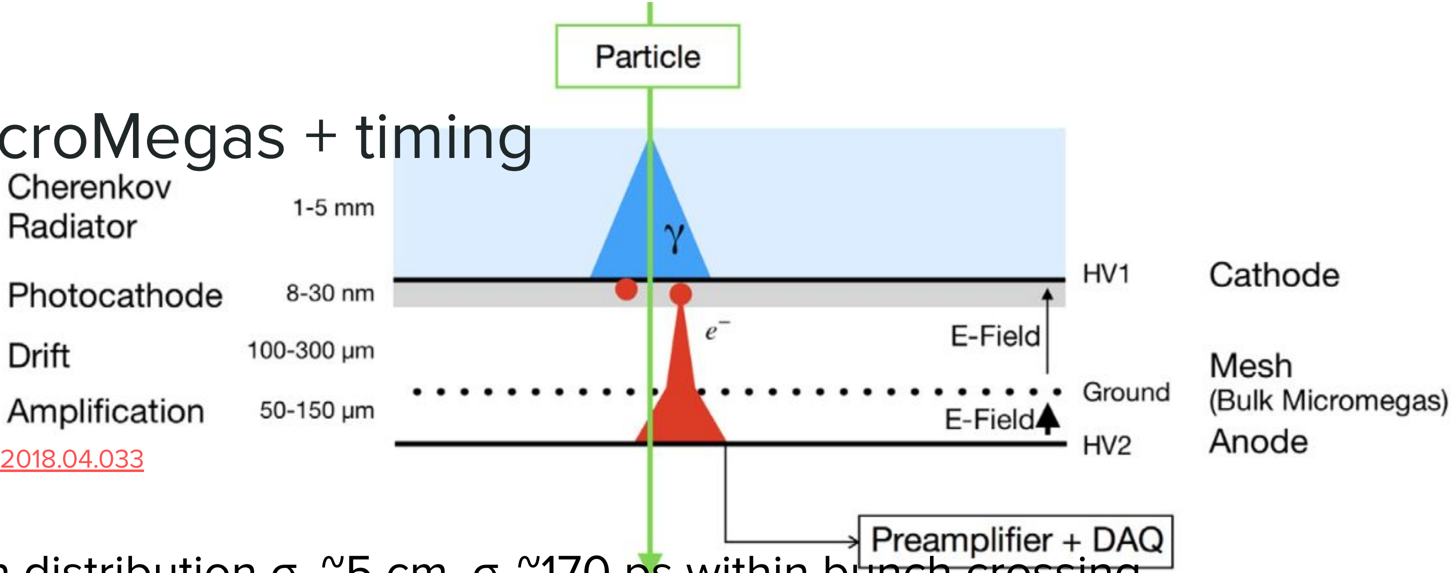


Figure from M. Iodice

- Type of micropattern gas detector (also: Gas Electron Multipliers)
- High gain of 10^4
- Intense electric field ~40kV/cm in amplification gap
- Ionization → drift → pass through mesh → avalanche → readout electrode

PICOSEC: MicroMegas + timing



From https://doi.org/10.1016/j.nima.2018.04.033

- HL-LHC interaction distribution σ_z ~5 cm, σ_t ~170 ps within bunch crossing
- Time resolution 20–30 ps significantly reduces backgrounds
- Two stage Micromegas detector with Cherenkov Radiator with photocathode
- Higher gain, reduced ion-backflow, better electron-peak and ion-tail separation
- Charged particle through Cherenkov radiator produces UV photons
- Photons are absorbed at the photocathode and partially converted into electrons
- Electrons are preamplified and then amplified in high-field drift stages
- Signal induced that is measured between anode and mesh
- Resolution of 24 ps for 150 GeV muons, and 76 ps for single photoelectrons

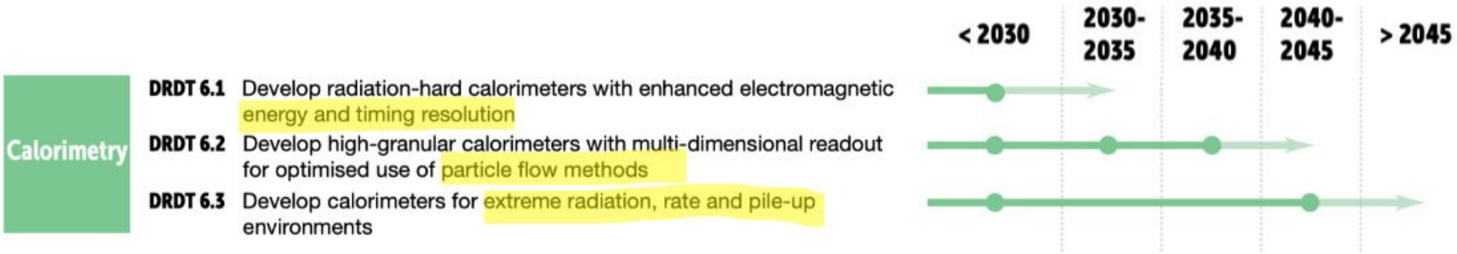
Calorimetry

From 2023 CPAD Workshop

ECFA Detector R&D Roadmap

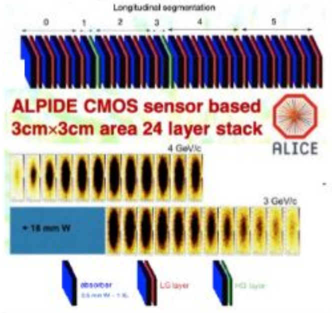
Calorimetry

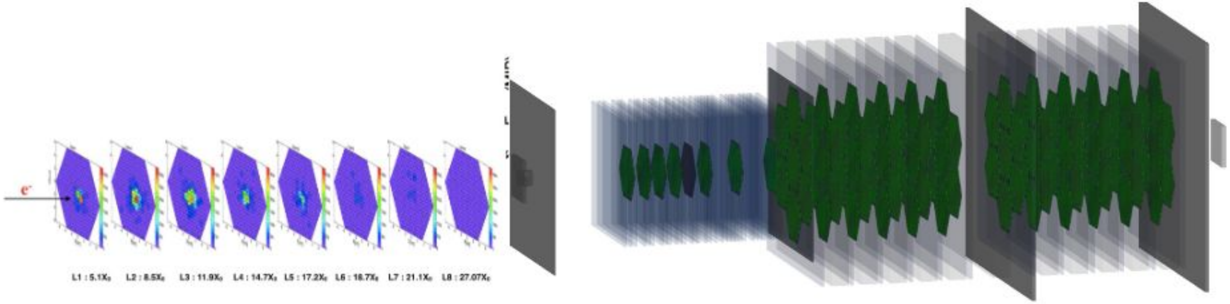
- R&D in calorimetry has a particularly long lead-time due
  - Many technology developments (gas, scintillator or Silicon-based readout)
  - Large and challenging prototype setups even in early stages



		< 2030	2030-2035	2035-2040	2040-2045	> 2045
Calorimetry	**DRDT 6.1** Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution					
	DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods					
	DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments					

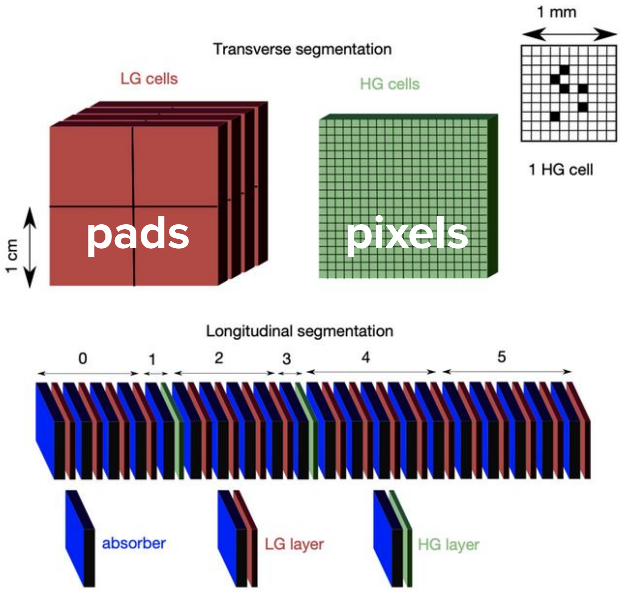
ALICE FoCAL





Forward electromagnetic and hadronic calorimeter (FOCAL)

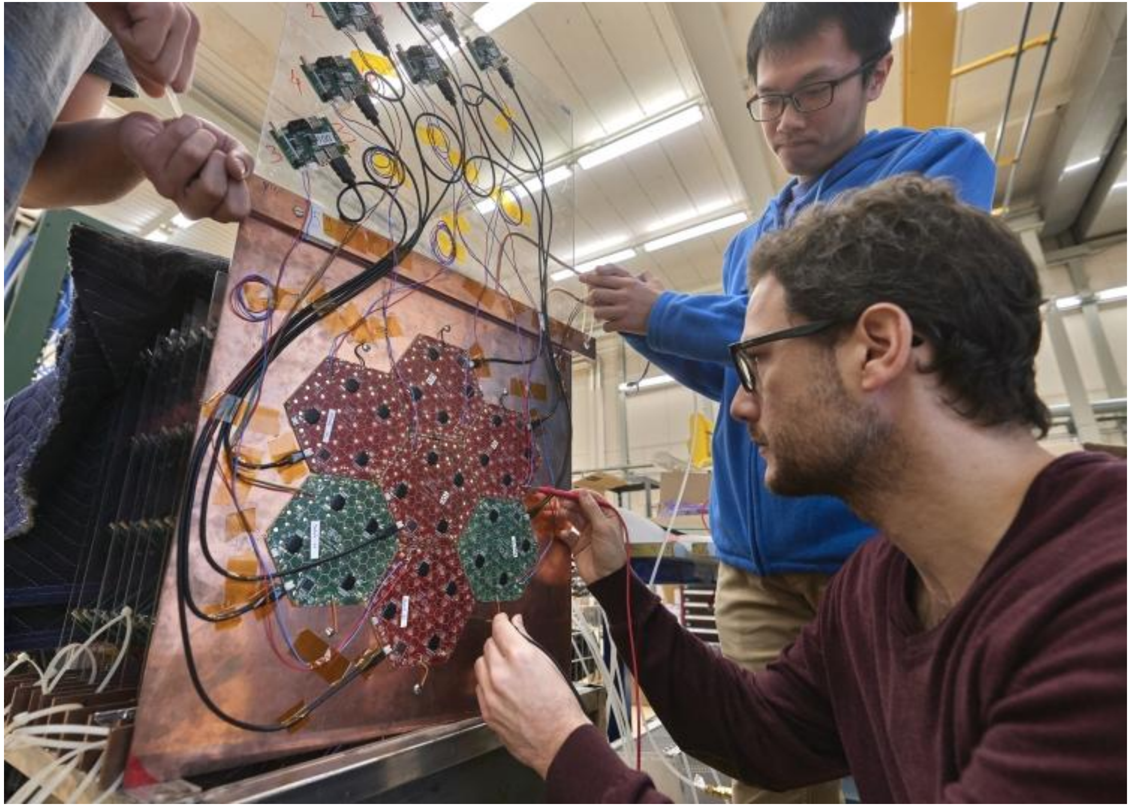
- To be installed in ALICE during LS3
- Highly granular silicon and tungsten ECAL
- Conventional sampling HCAL
- Covers pseudorapidities of 3.4 < η < 5.8
- Readout:
  - 18 pad layers, with transverse cell sizes of ≂ 1cm^(2)
  - 2 pixel layers (L5, L10) with digital readout and a cell size of ≂ 30×30μm2.



From the ALICE Collaboration

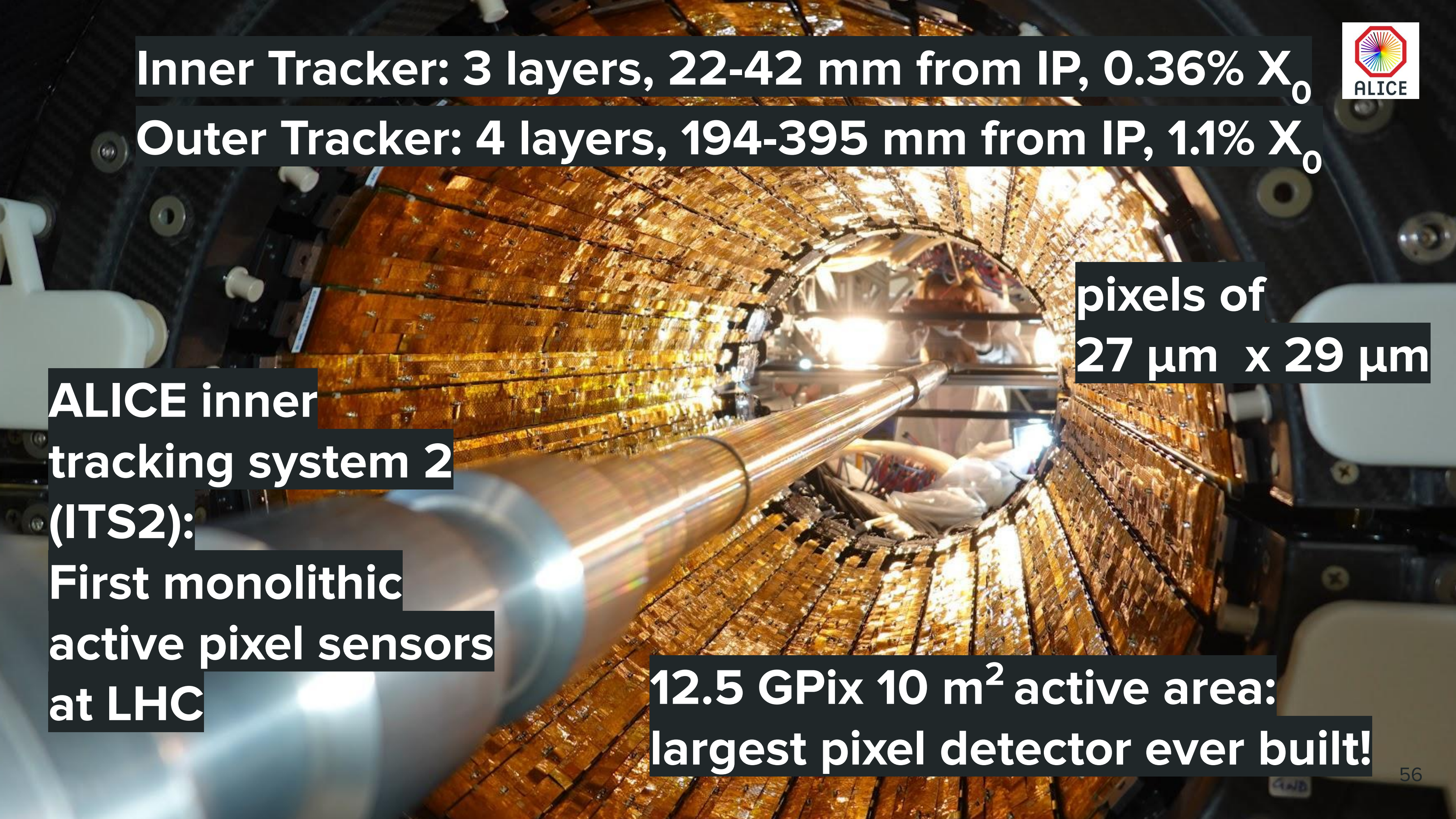
CMS High Granularity Calorimeter (HGCAL)

From CERN



- Silicon in high radiation region, elsewhere plastic scintillators
- Silicon cooled to ~ –32°C
- 6.5 million channels
- 50 layers, first 28 layers electromagnetic section
- hexagonal silicon sensors (maximising the useable surface of 8" circular silicon wafers) sandwiched between high-density copper-tungsten alloy baseplates and printed circuit boards

Solid state detectors



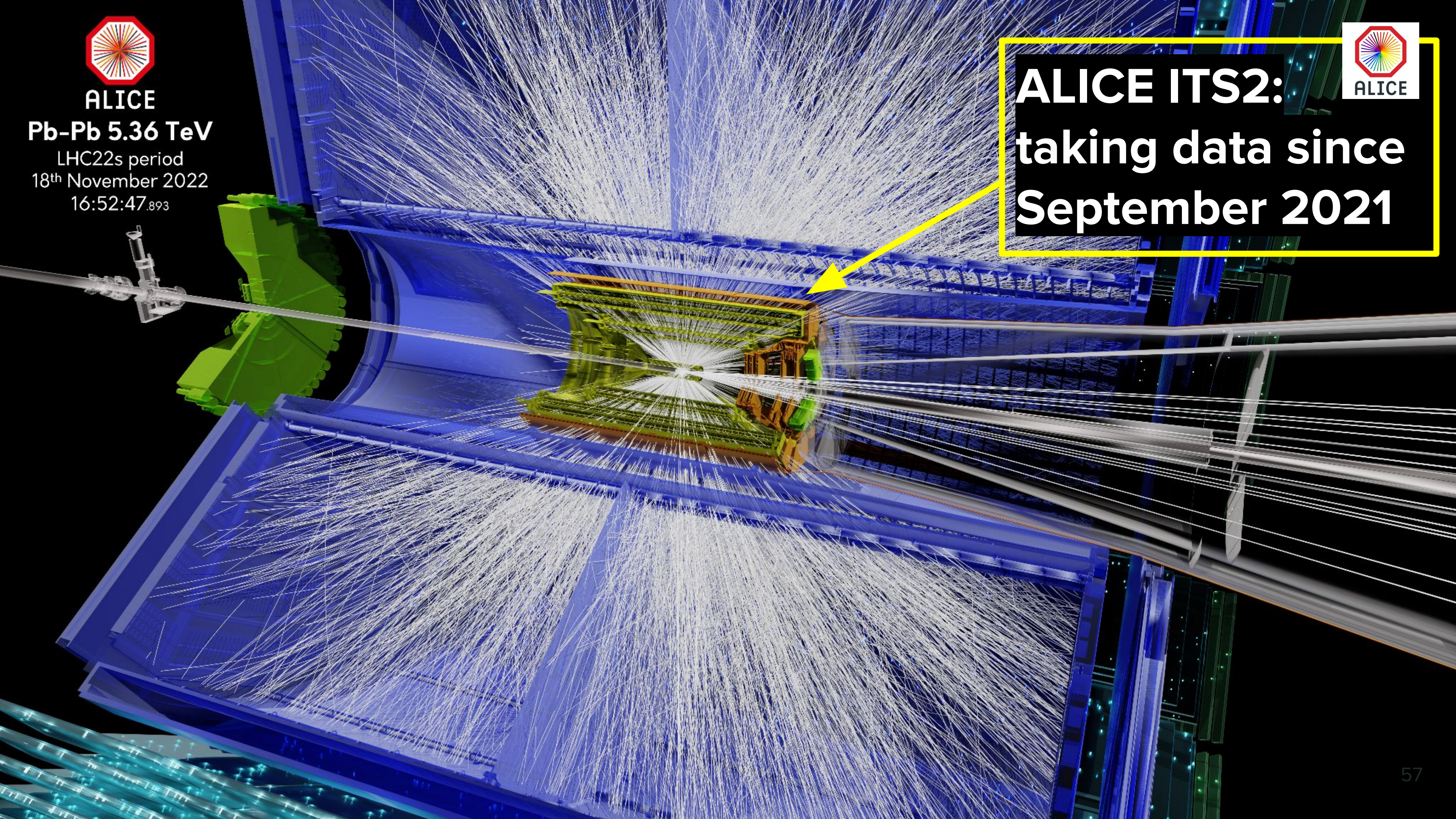
Inner Tracker: 3 layers, 22-42 mm from IP, 0.36% X_0

Outer Tracker: 4 layers, 194-395 mm from IP, 1.1% X_0

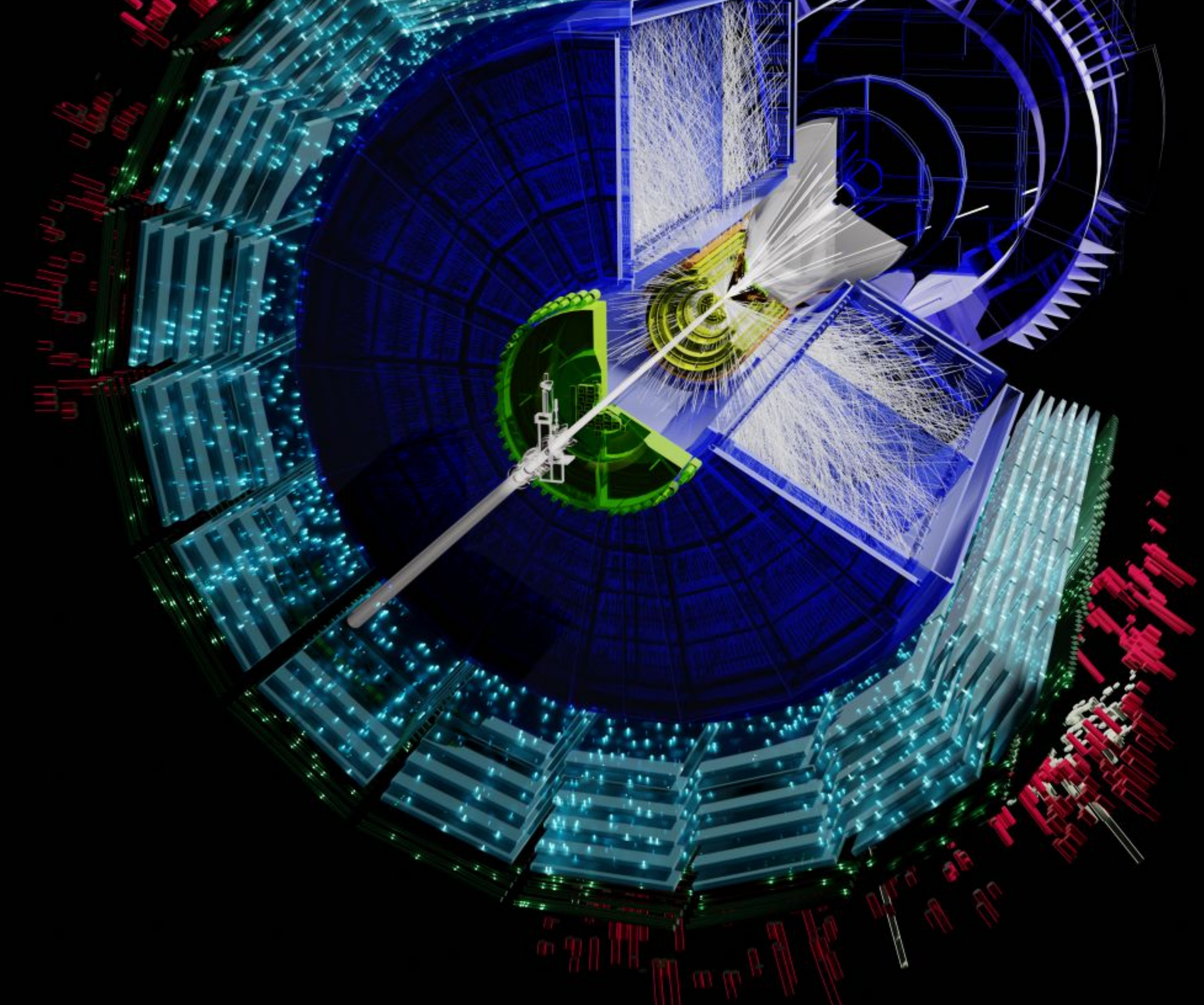
pixels of
27 μm x 29 μm

ALICE inner tracking system 2 (ITS2):
First monolithic active pixel sensors at LHC

12.5 GPix 10 m^2 active area:
largest pixel detector ever built!



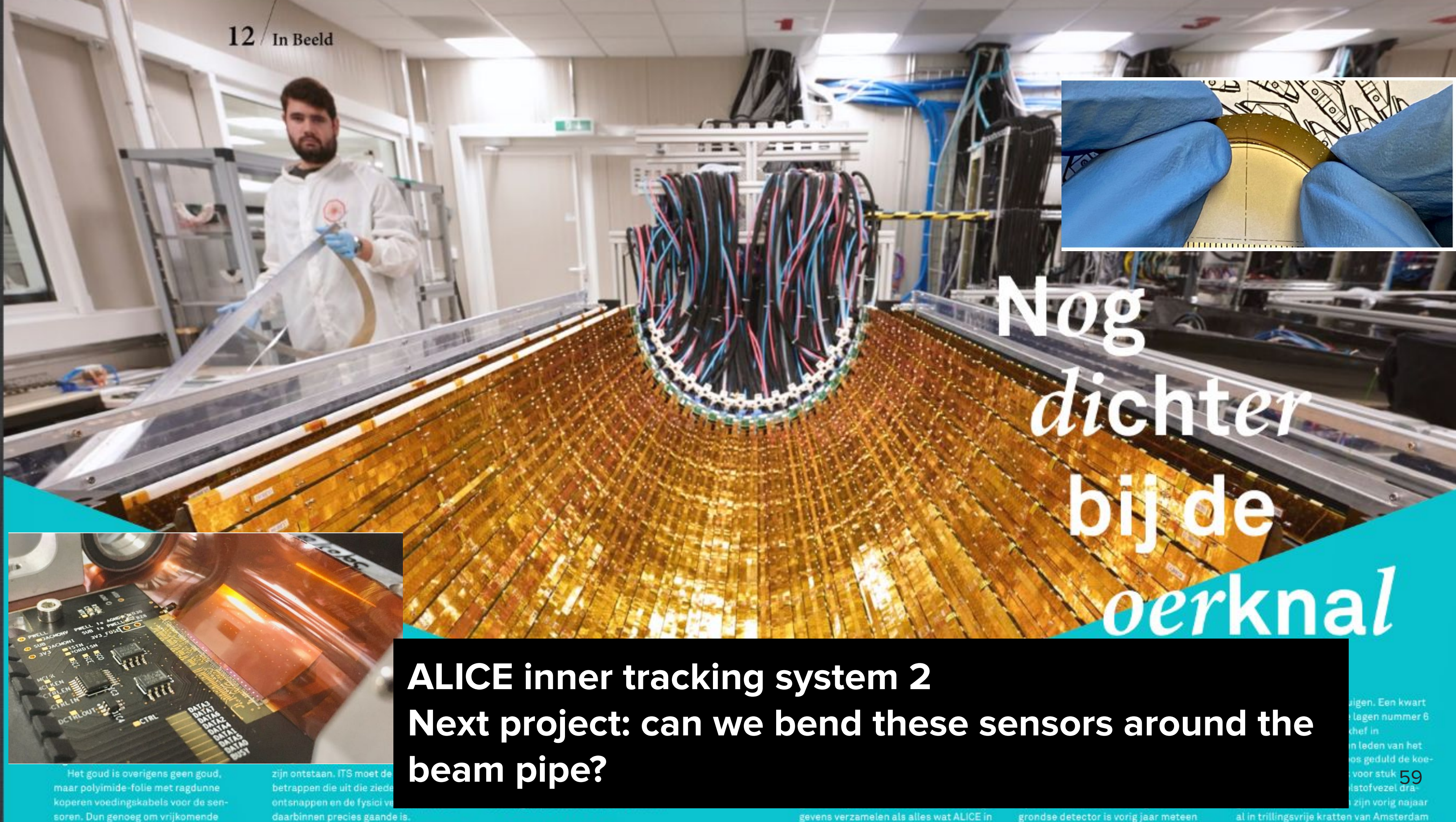
ALICE ITS2: taking data since September 2021



ALICE

Pb-Pb 5.36 TeV

LHC22s period
18th November 2022
16:52:47.893



12 / In Beeld

Nog *dichter* bij de *oerknal*

Het goud is overigens geen goud, maar polyimide-folie met ragdunne koperen voedingskabels voor de sensoren. Dun genoeg om vrijkomende

zijn ontstaan. ITS moet de
betrappen die uit die ziede
ontsnappen en de fysici ve
daarbinnen precies gaande is.

gevens verzamelen als alles wat ALICE in

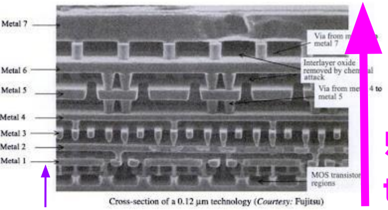
grondse detector is vorig jaar meteen

uigen. Een kwart
e lagen nummer 6
khef in
n leden van het
os geduld de koe-
voor stuk
istofvezel dra-
zijn vorig najaar
al in trillingsvrije kratten van Amsterdam

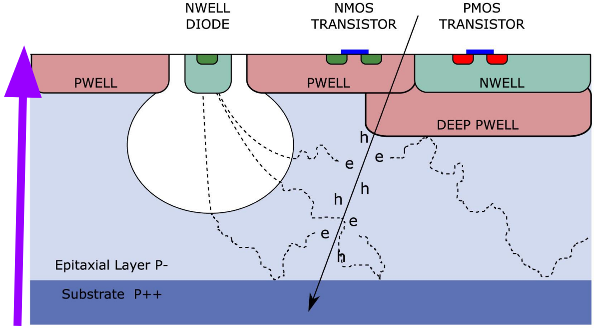
ALICE inner tracking system 2

Next project: can we bend these sensors around the beam pipe?

You will find these at Nikhef

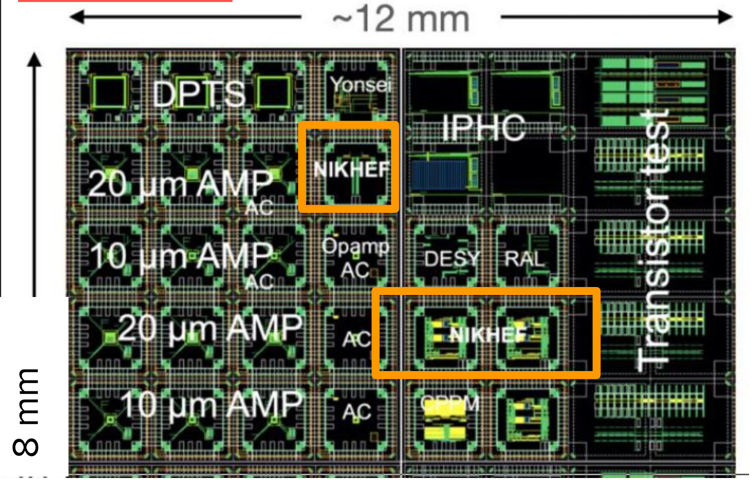


50 µm thick sensor

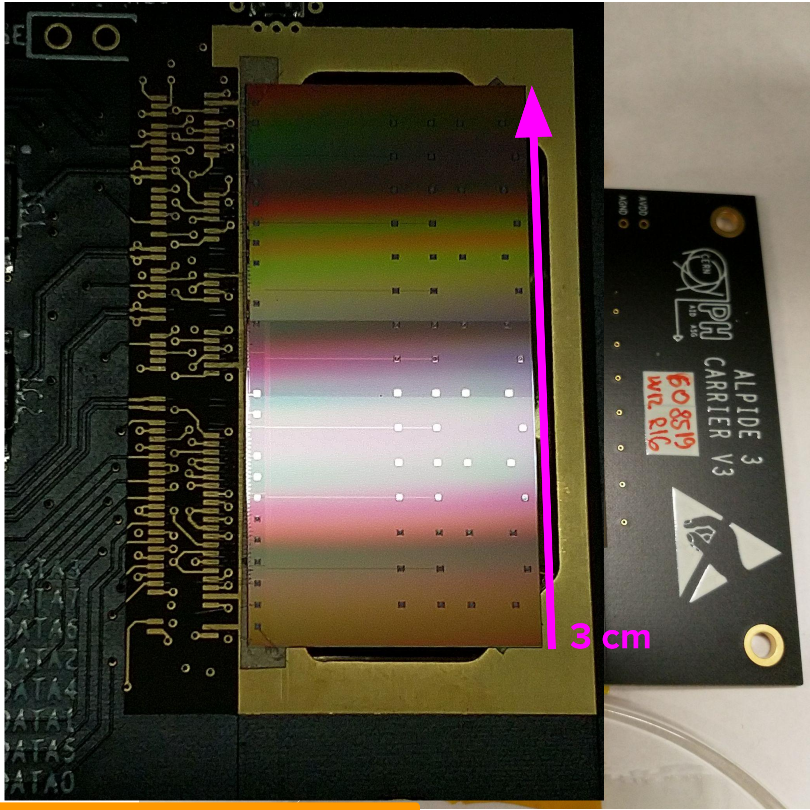


1 pixel: 28 µm x 28 µm

Talk at Vertex2021



ALICE PIxel DEtector: ALPIDE
TowerJazz 180nm



The Nikhef electronics technology (ET) group designs these chips for the ALICE inner tracking system!

Solid state detector development

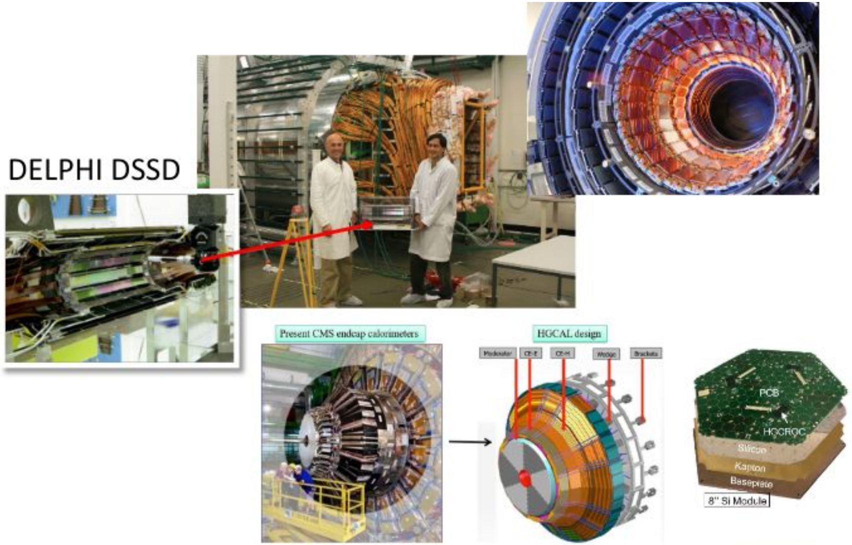
ECFA Detector R&D Roadmap

Remarkable success in HEP enabled by significant advancements in chip industries:

- **Detector area** increased by one order of magnitude each decade (1 m² → 10 m² → 200 m² → 600m²)
- **Radiation hardness** at levels not imagined decades ago
- **Endcap Timing detectors** for ATLAS and CMS (4D tracking)

New Challenges:

- FCC-ee: Vertex detectors with low mass, high resolution:
    - spatial resolution of $\leq 3\ \mu m$
    - Material budget $x/x0 \leq 0.05\%$
- FCC-hh: low power and high radiation hardness (up to $8{\cdot}10^{17}\ n_{eq}cm^{-2}$)
- Pile-up mitigation by ultra-fast timing in O(10-100ps)
- Fully integrated with electronics, mechanics, services
- Large area sensors at low cost (for calorimetry, eg. CMS HGCal)



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

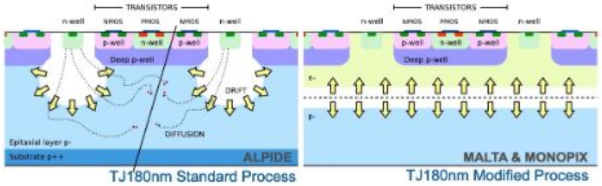
DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics

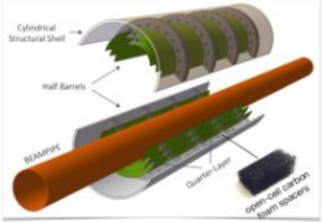
From 2023 CPAD Workshop

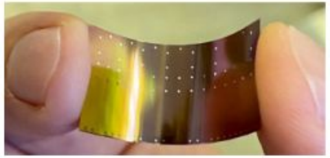
Material, timing, and radiation hardness

ECFA Detector R&D Roadmap

- CMOS Monolithic sensors: combining sensing and readout elements
    - Sensor development becomes chip development, but typically with modifications to standard process, e.g. Towerjazz 180 nm
    - overlap with DRD7 electronics
- 4D Tracking / ToF: Timing using LGAD sensors
    - Suppression of pile-ups
    - Foundries CNM, FBK, HPK
    - Timing performance (~ 25 ps for 50 μm sensors)
    - Radiation hardness limited by loss of gain
- Radiation hardness
    - Wide bandgap material (SiC, GaN)

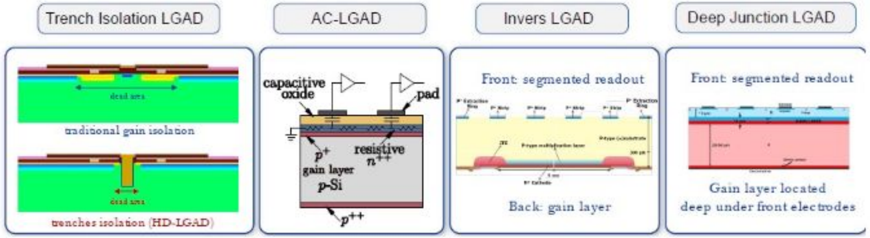




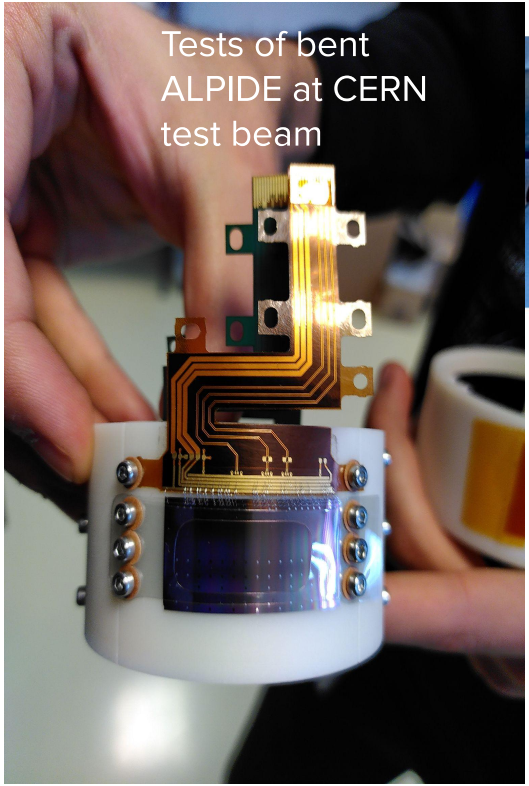


CMOS MAPS for ALICE ITS3 (Run 4

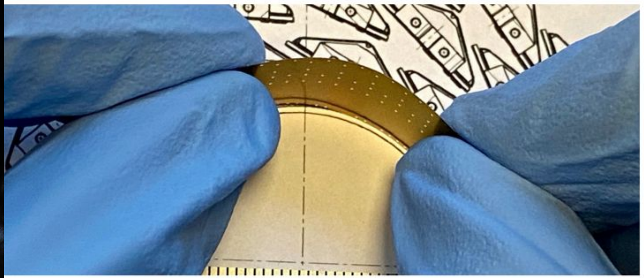
(LOI: CERN-LHCC-2019-018, M. Mager)



Next ALICE program: Bend the detector

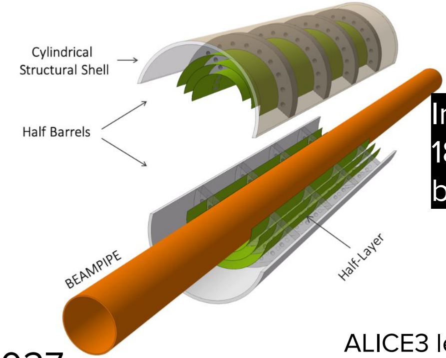


Tests of bent ALPIDE at CERN test beam



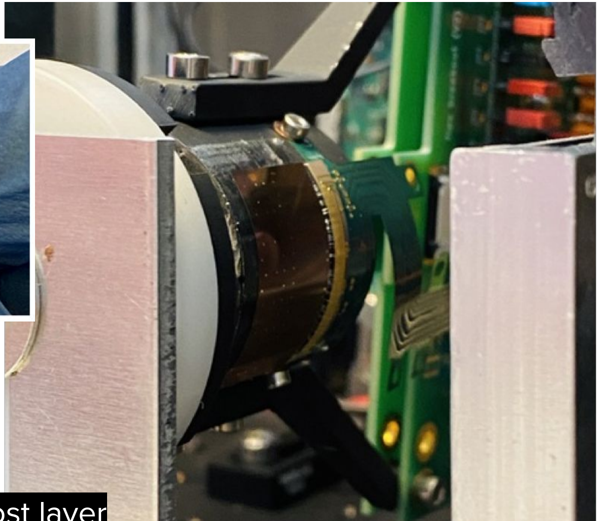
50 µm thick sensor

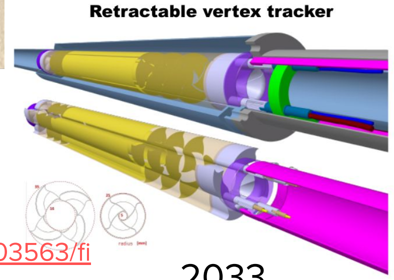
[ALICE ITS3 letter of intent]()



2027

Innermost layer 18 mm from beam line

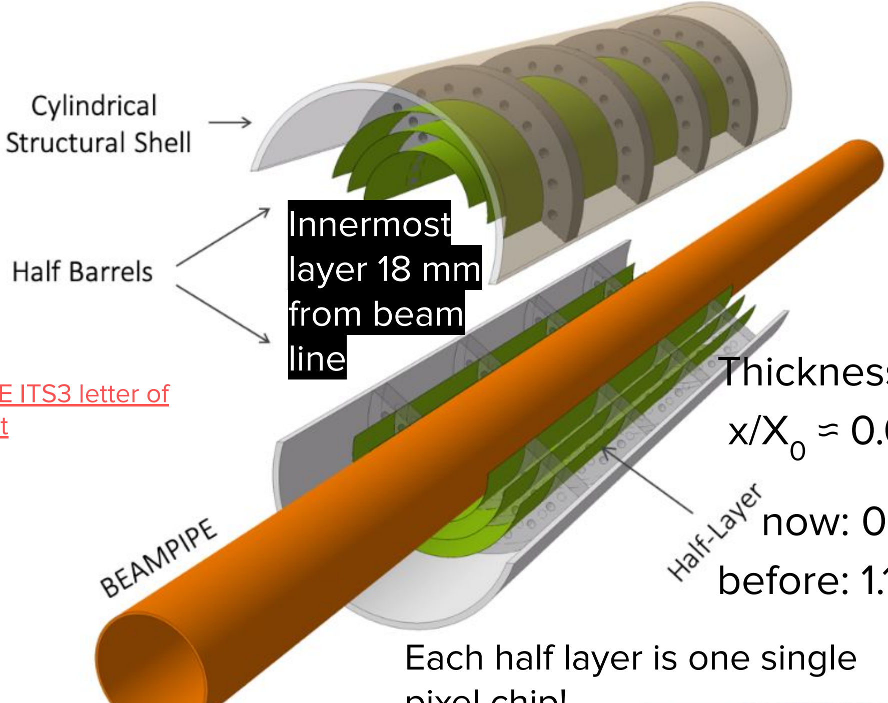




ALICE3 letter of intent: https://cds.cern.ch/record/2803563/files/2211.02491.pdf

2033

ALICE ITS3: 2027



Innermost layer 18 mm from beam line

ALICE ITS3 letter of intent

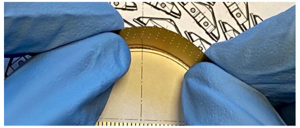
Thickness:

$x/X_0 \simeq 0.05\%$

now: 0.35%

before: 1.14%

Each half layer is one single pixel chip! **Stitching** and **bending**

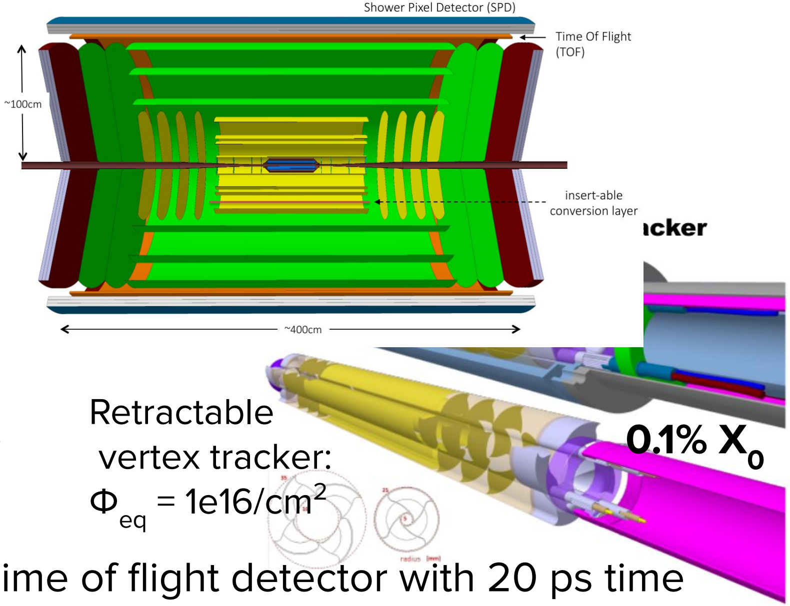


Φ_{eq} = 1e13 cm^{-2}, 10 kGy

Much less than ATLAS!

ALICE3: 2033

ALICE3 letter of intent: https://cds.cern.ch/record/2803563/files/2211.02491.pdf



0.1% X_0

Retractable vertex tracker:

Φ_{eq} = 1e16/cm^2

Time of flight detector with 20 ps time resolution -- possibly depleted MAPS:

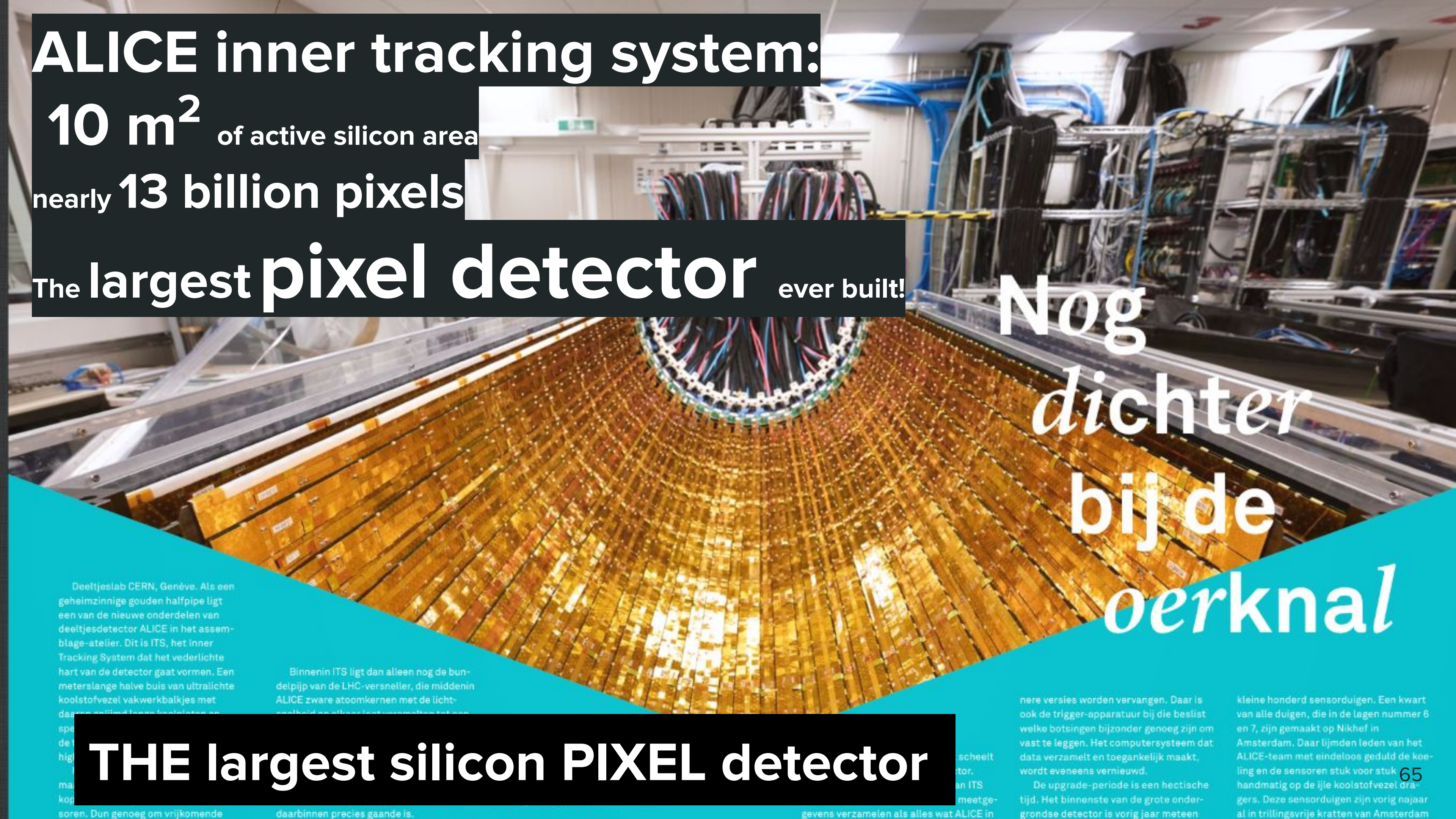
Φ_{eq} = 1e12 cm^{-2} **1% X_0**

ALICE inner tracking system:

10 m^2 of active silicon area

nearly 13 billion pixels

The largest pixel detector ever built!



Deeltjeslab CERN, Genève. Als een geheimzinnige gouden halfpipe ligt een van de nieuwe onderdelen van deeltjesdetector ALICE in het assemblage-atelier. Dit is ITS, het Inner Tracking System dat het vederlichte hart van de detector gaat vormen. Een meterslange halve buis van ultralichte koolstofvezel vakwerkbalkjes met

soren. Dun genoeg om vrijkomende

Binnenin ITS ligt dan alleen nog de bundelpijp van de LHC-versneller, die middenin ALICE zware atoomkernen met de lichtsnelheid op elkaar laat versmelten tot een

daarbinnen precies gaande is.

scheelt

tor.

an ITS

meetgegevens verzamelen als alles wat ALICE in

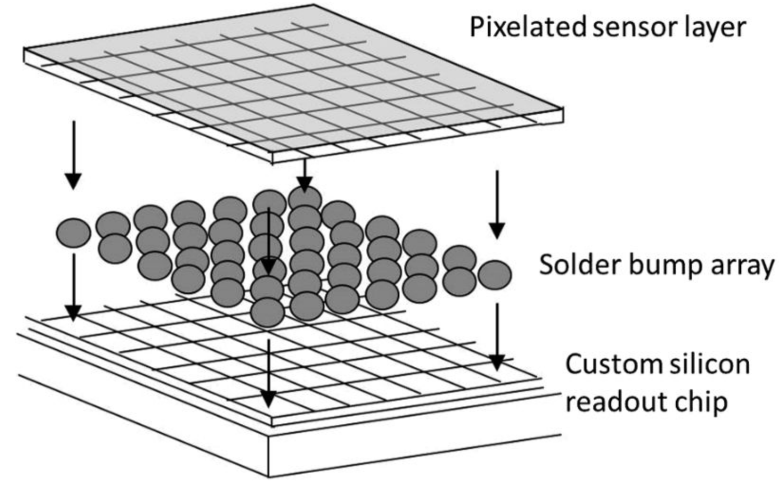
nere versies worden vervangen. Daar is ook de trigger-apparatuur bij die beslist welke botsingen bijzonder genoeg zijn om vast te leggen. Het computersysteem dat data verzamelt en toegankelijk maakt, wordt eveneens vernieuwd.

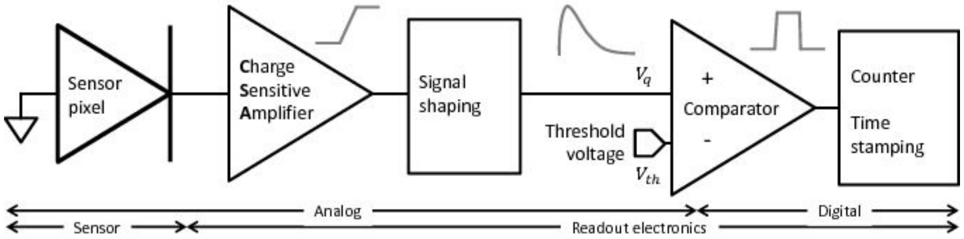
De upgrade-periode is een hectische tijd. Het binnenste van de grote ondergrondse detector is vorig jaar meteen

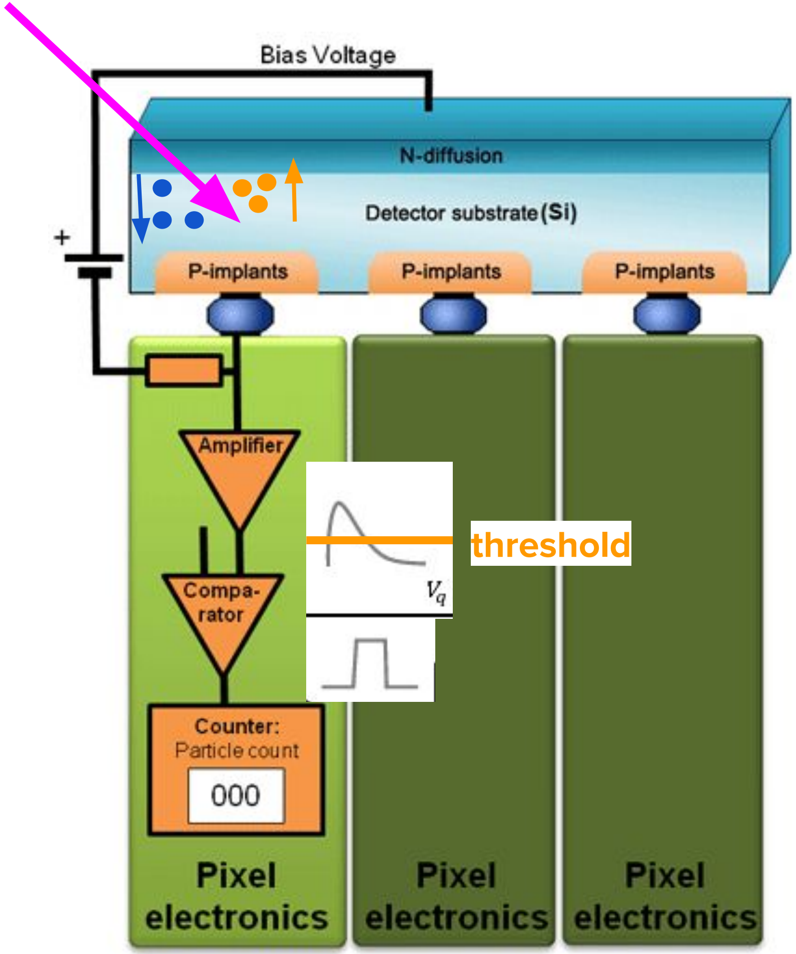
kleine honderd sensorduigen. Een kwart van alle duigen, die in de lagen nummer 6 en 7, zijn gemaakt op Nikhef in Amsterdam. Daar lijmden leden van het ALICE-team met eindeloos geduld de koeling en de sensoren stuk voor stuk handmatig op de ijle koolstofvezel dragers. Deze sensorduigen zijn vorig najaar al in trillingsvrije kratten van Amsterdam

THE largest silicon PIXEL detector

A hybrid pixel detector

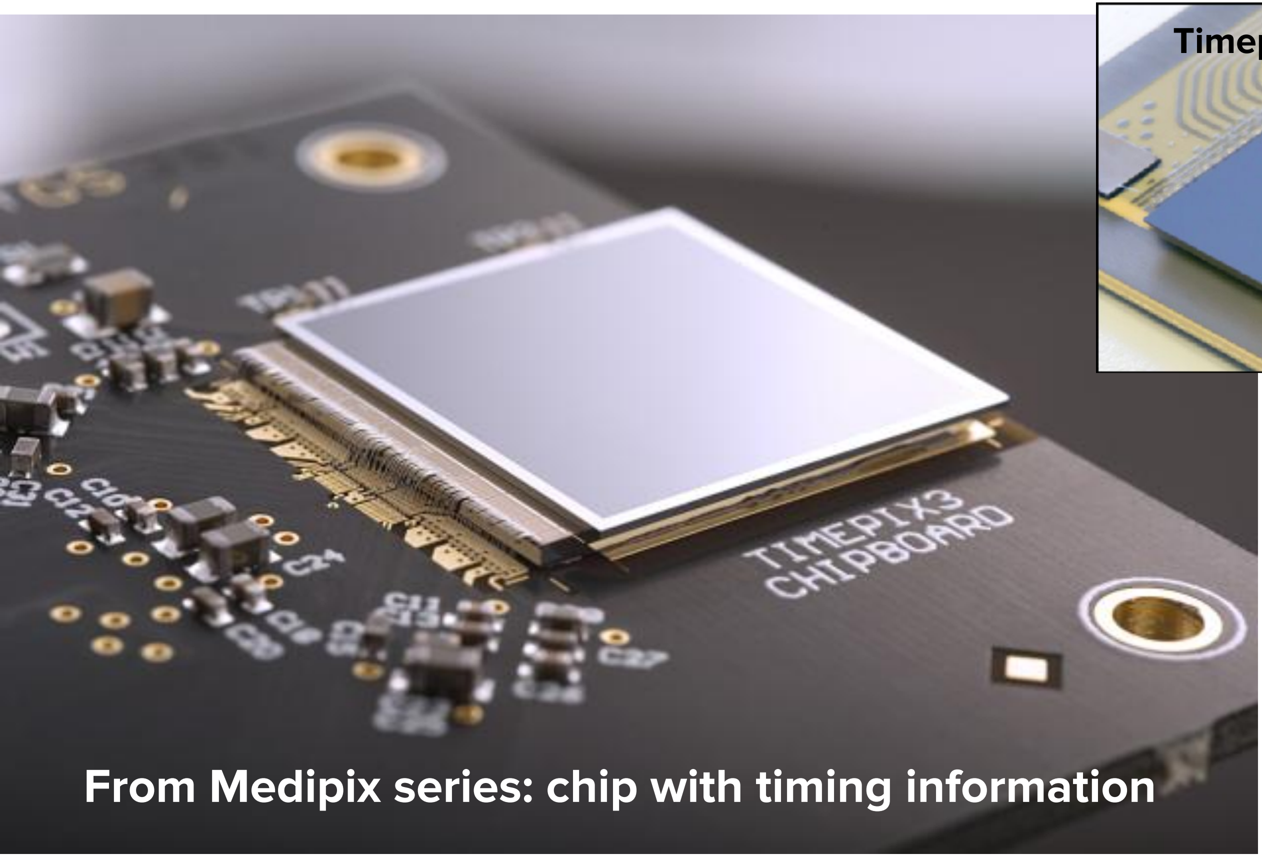




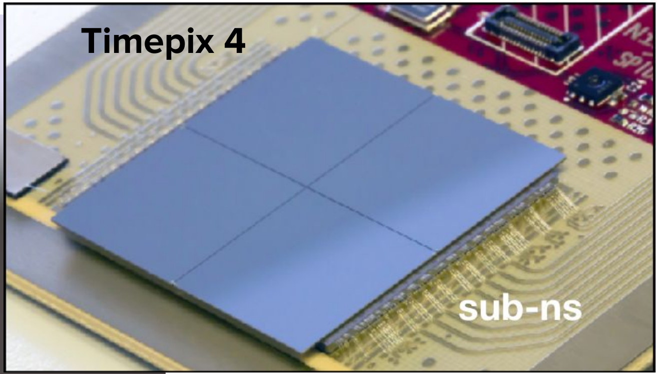


Timepix: an ASIC for hybrid pixel detectors

Here at Nikhef!

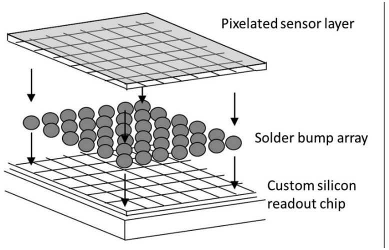


From Medipix series: chip with timing information



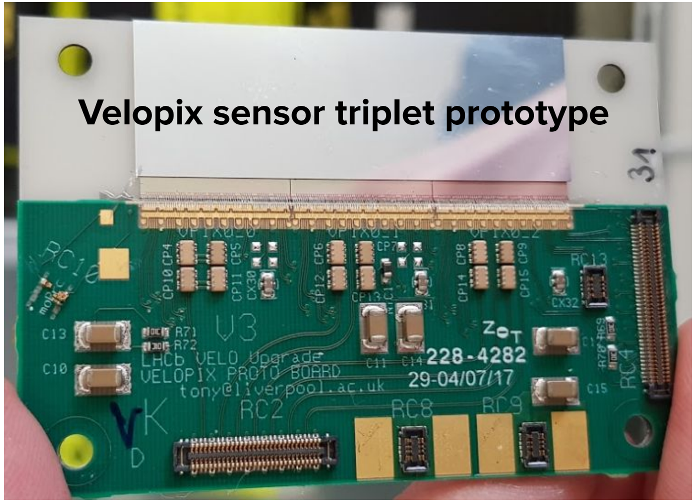
Timepix4 with 200 ps bin size, 77 ps time resolution

K. Heijhoff *et al* 2022 *JINST* **17** P07006

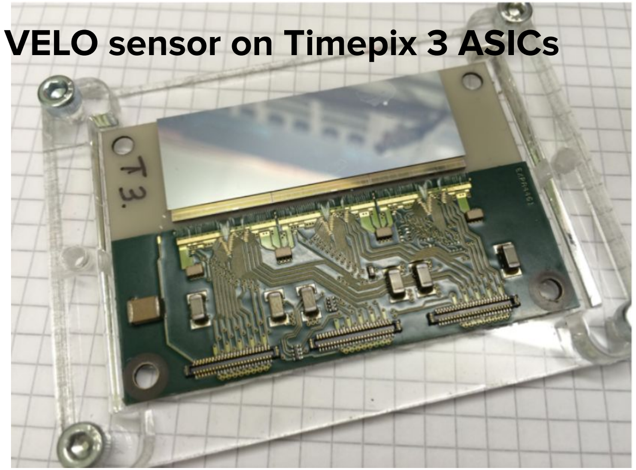


LHCb Vertex Locator (VeLo) upgrade

The Velopix ASIC: based on Timepix, 130nm TSMC, 55x55 µm^2 pixels

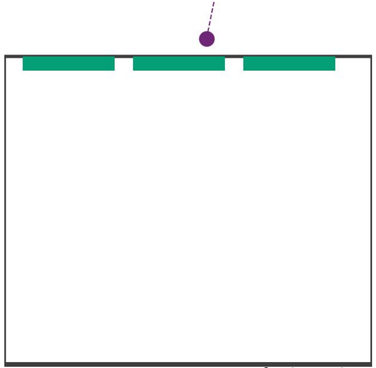


Velopix sensor triplet prototype

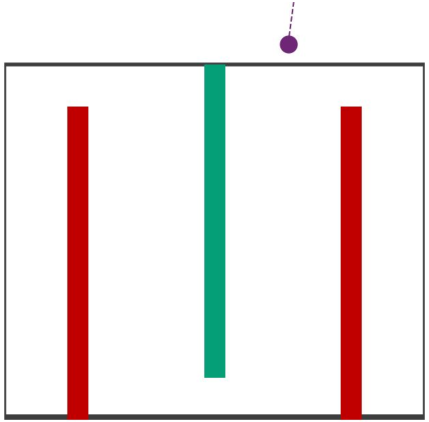


VELO sensor on Timepix 3 ASICs

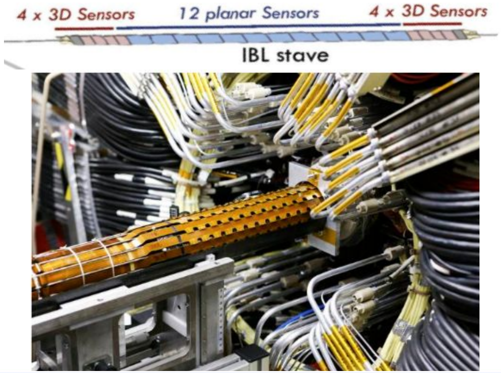
Planar sensors



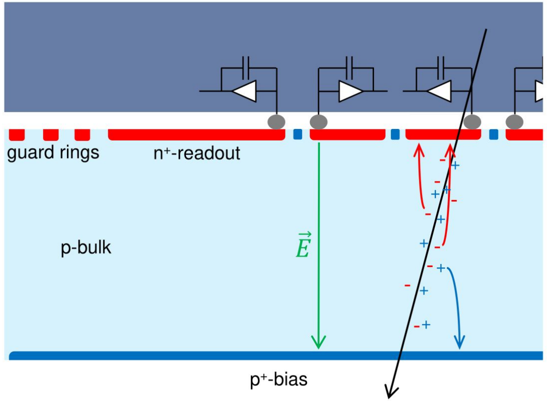
3D sensors



Already in ATLAS innermost layer:



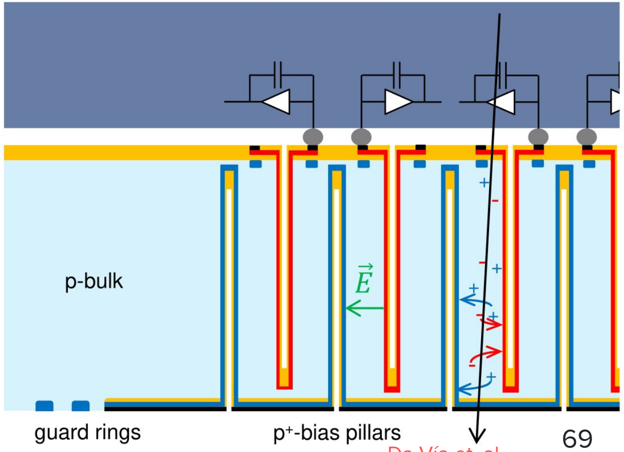
Animations courtesy of Robbert Geertsema



- Fast charge collection: short path!
- Large charge generated
- Radiation hard: in ATLAS at 30mm since 2015

10 ps time resolution

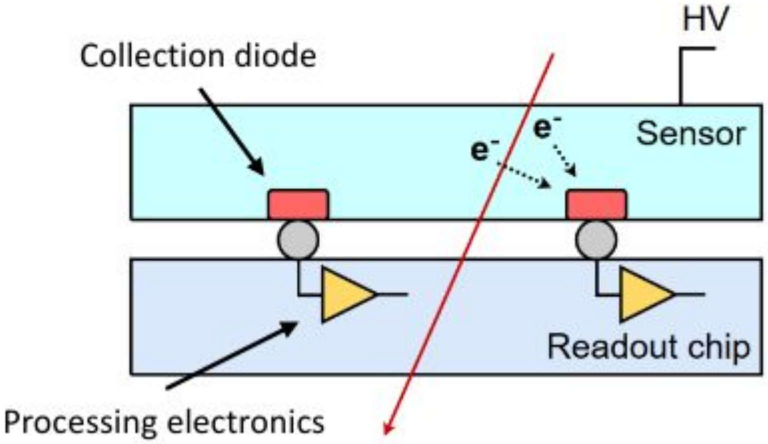
DOI:10.1088/1748-0221/18/01/C01051



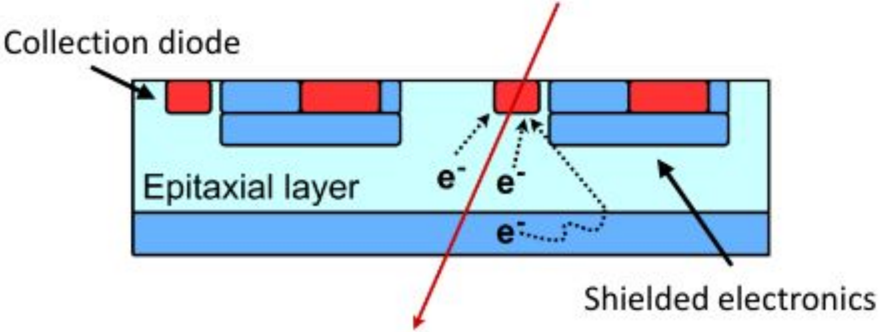
Da Vía et. al.

Integrated sensors

CMOS MAPS: in your phone!



Hybrid pixel detector



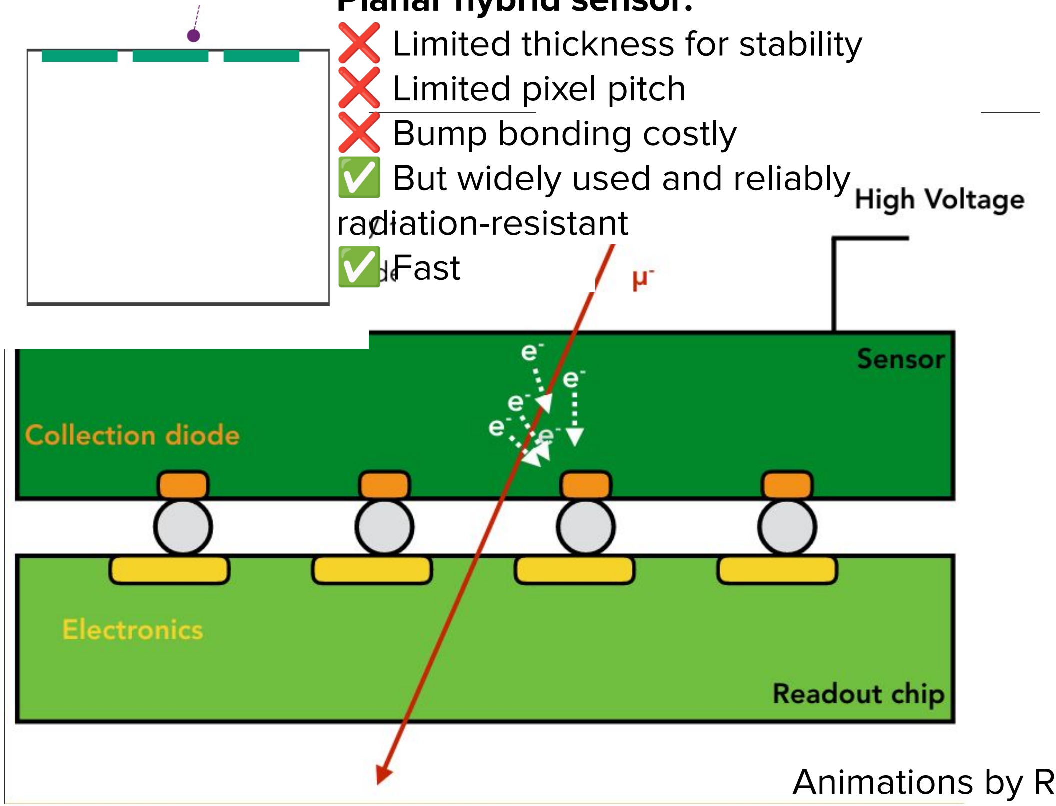
Monolithic Active Pixel Sensors: MAPS

Why would you use one or the other?

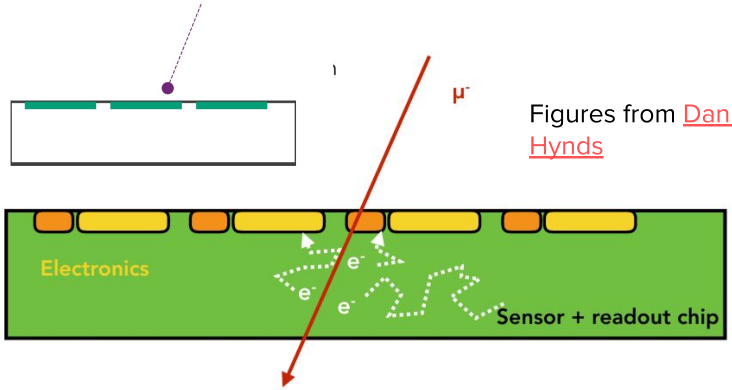
From I. Kremastiotis

Two types of silicon sensors: hybrid vs monolithic

Planar hybrid sensor:
❌ Limited thickness for stability
❌ Limited pixel pitch
❌ Bump bonding costly
✅ But widely used and reliably radiation-resistant
✅ Fast



Monolithic sensor:
✅ Very little material
✅ Low noise
❌ Limited depletion region: slow charge collection by diffusion **but this is improving**
❌ Not very radiation-hard **but this is improving**

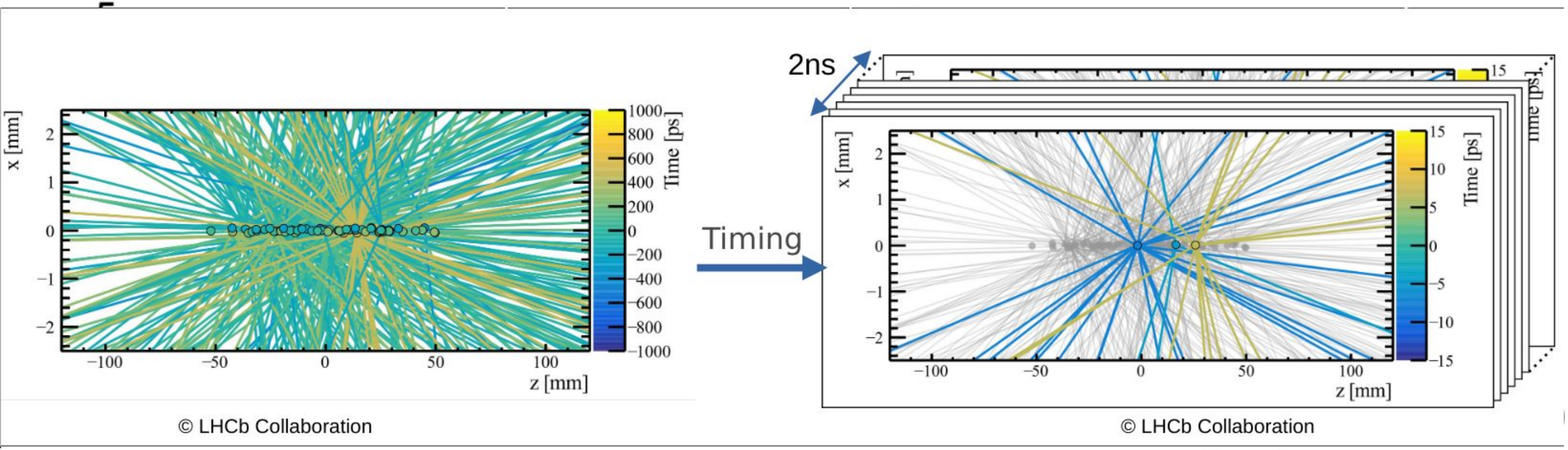


Figures from Daniel Hynds

Animations by Robbert Geertsema

4D tracking

Distinguish vertices based on precise timing information



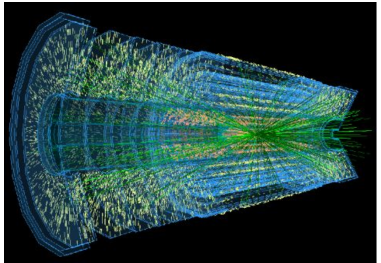
© LHCb Collaboration

© LHCb Collaboration

z [mm]

z [mm]

2 nanoseconds window: 2000 picoseconds

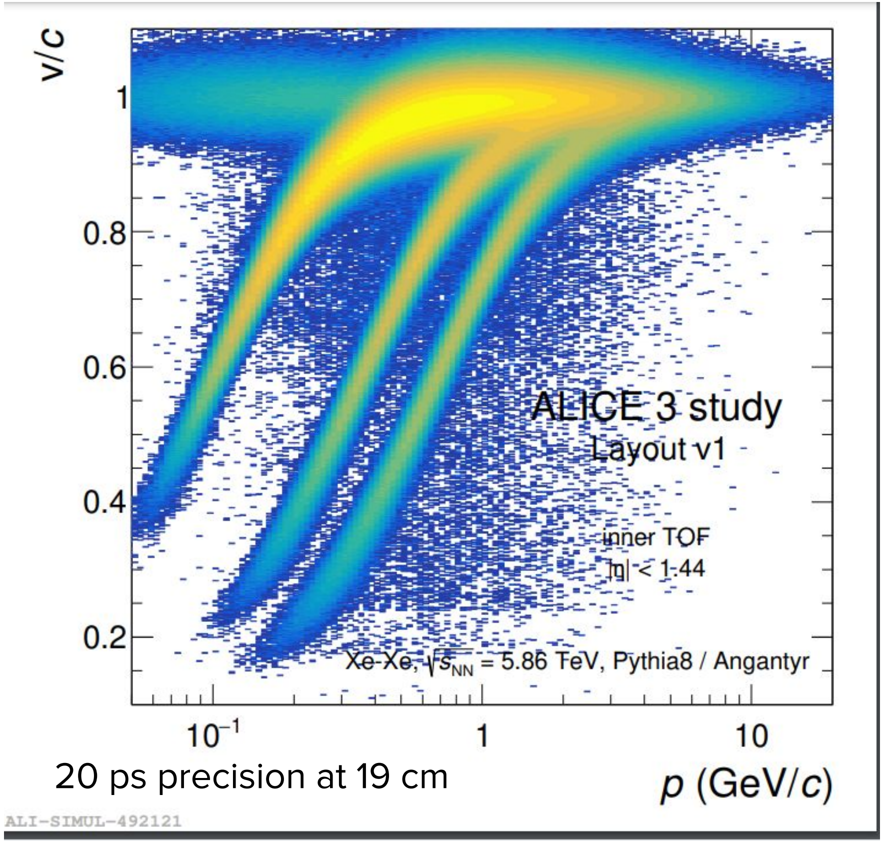


15 picoseconds

Figures courtesy of Robbert Geertsema

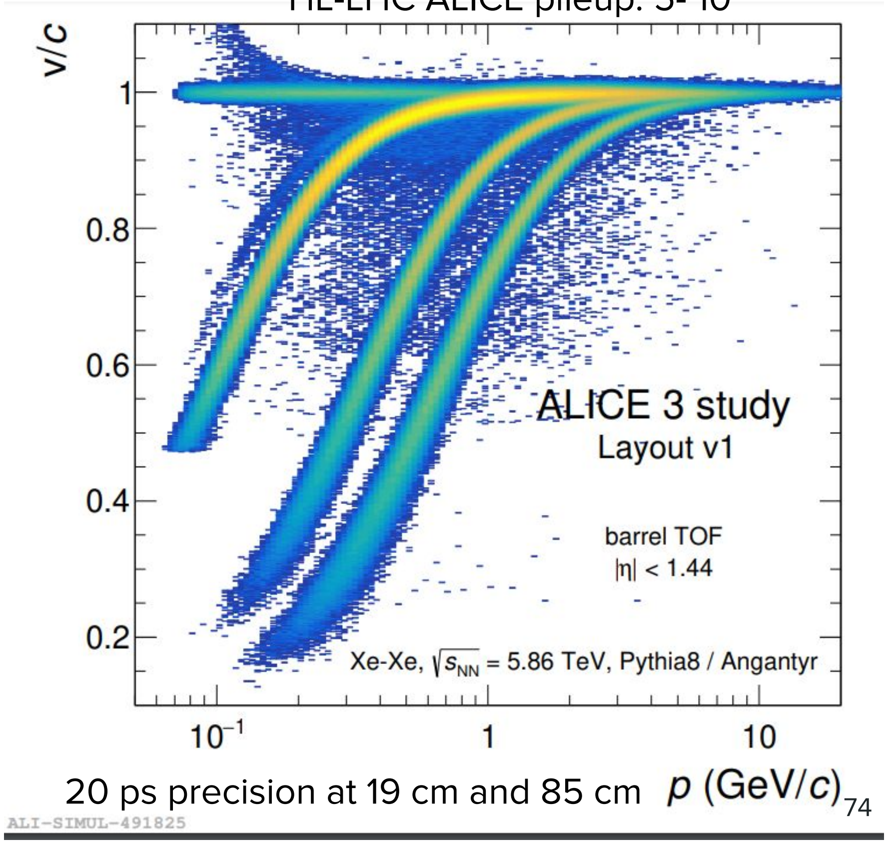
Particle identification improves with precise timing

HL-LHC ALICE pileup: 5- 10



20 ps precision at 19 cm

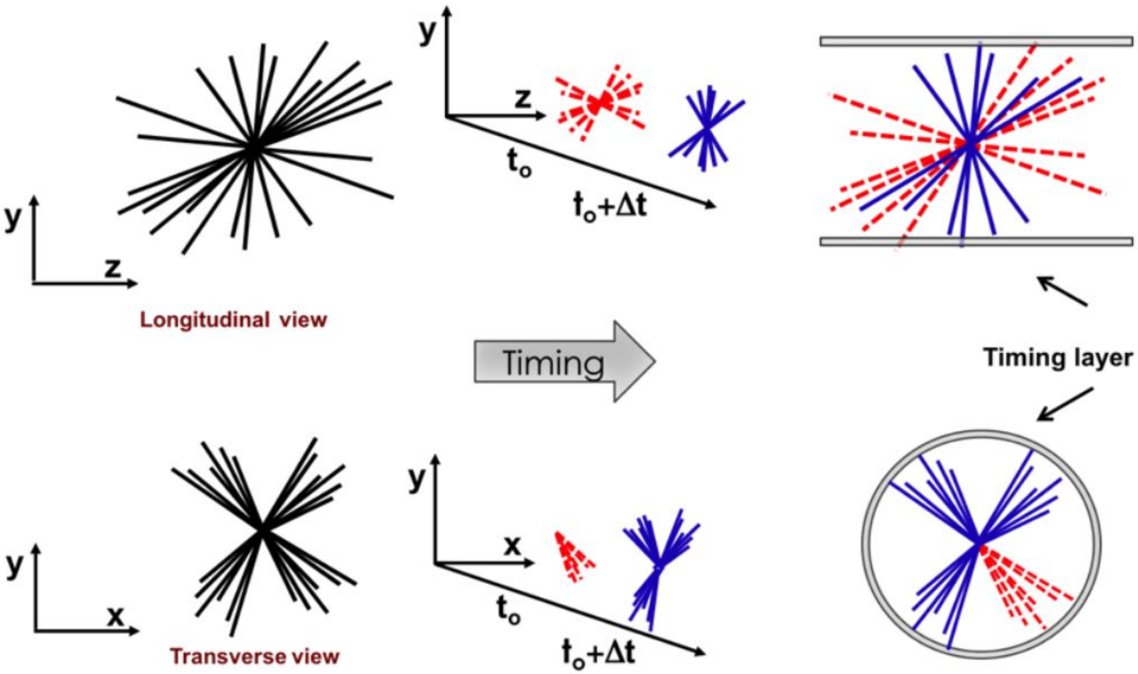
ALI-SIMUL-492121



20 ps precision at 19 cm and 85 cm

ALI-SIMUL-491825

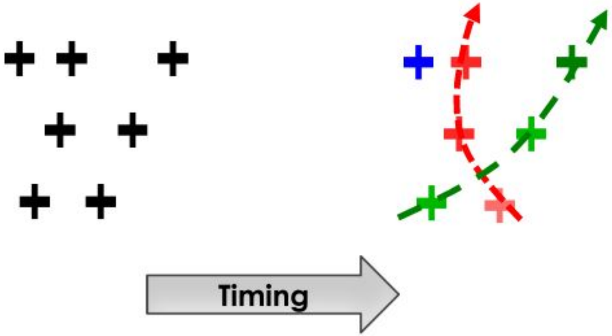
Timing information from a timing layer

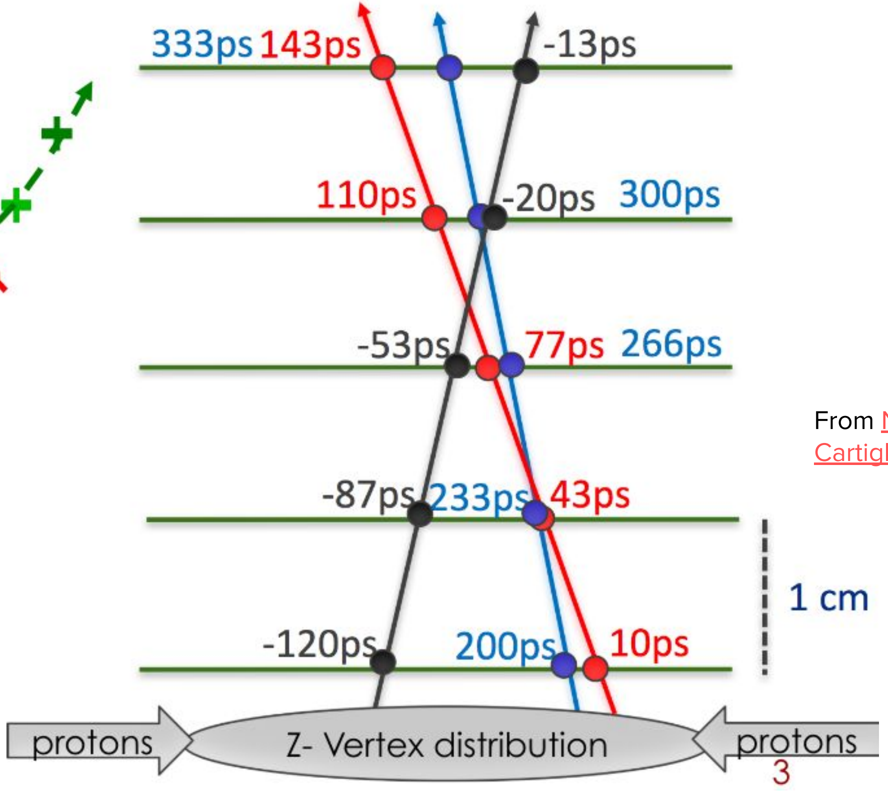


Primary vertex: Original collision location
LHCb also has many secondary vertices!

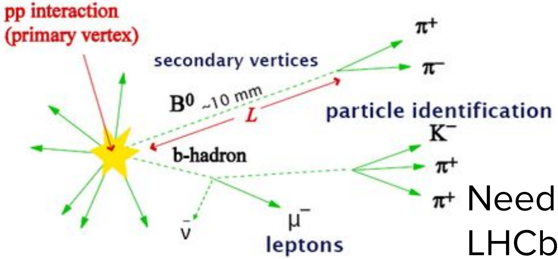
From Nicolo Cartiglia

Timing at points along the track





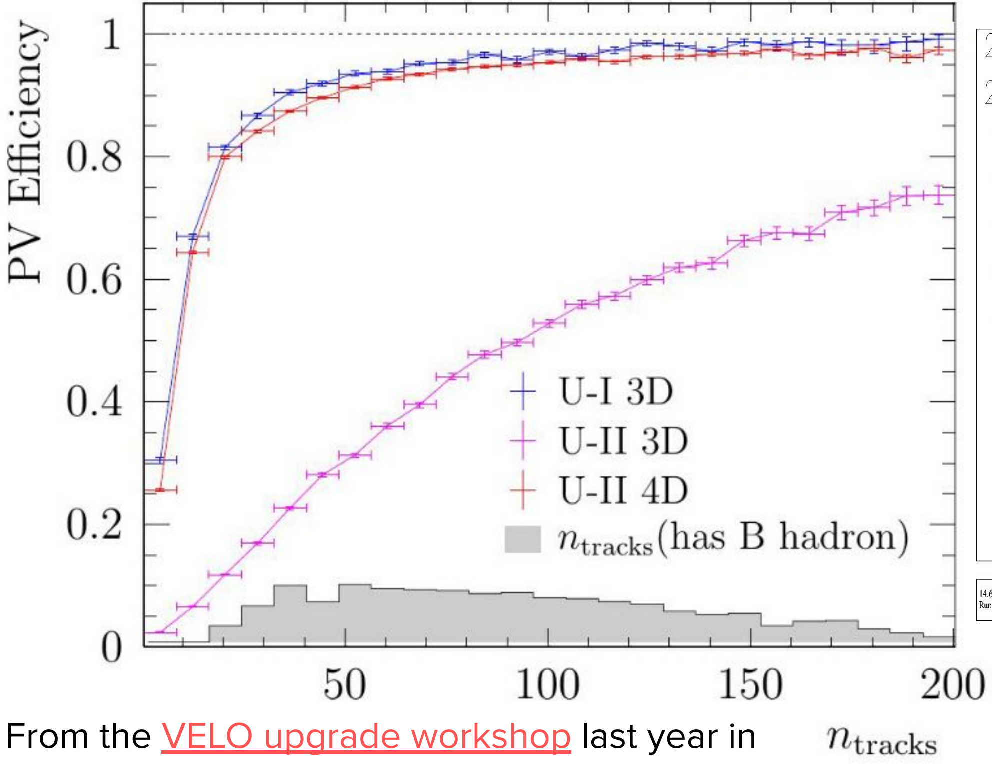
From Nicolo Cartiglia

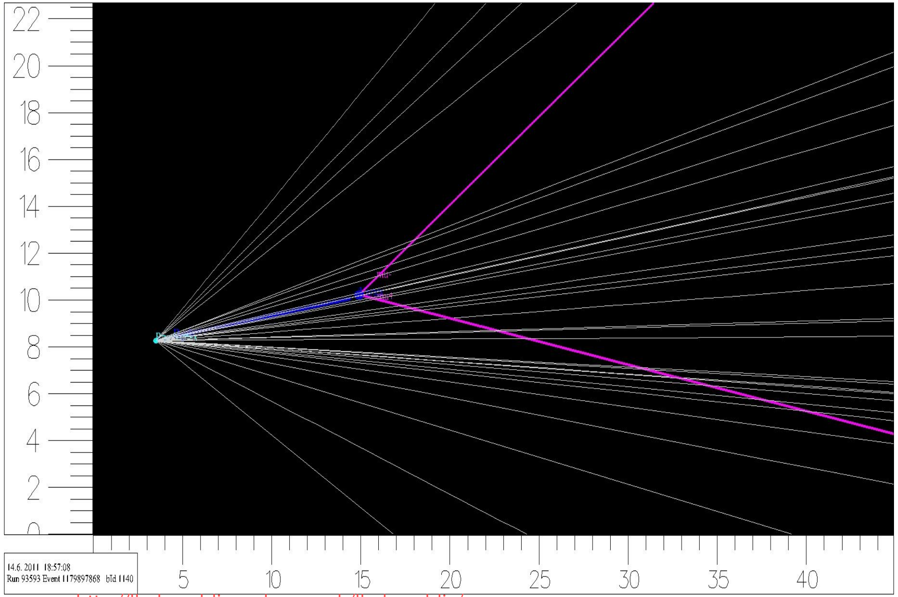


Needed for LHCb: primary and secondary vertices!

LHCb needs 4D tracking

Incorrect Primary Vertex (PV) assigned to tracks:
➡ poorly measured lifetime



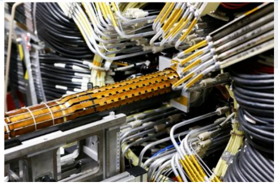


http://lhcb-public.web.cern.ch/lhcb-public/

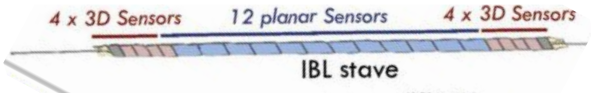
From the VELO upgrade workshop last year in Amsterdam and LHCb-PUB-2022-001

Other timing pixel detectors

From the high lumi LHC project

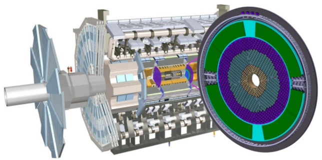


From Kerstin Lantsch

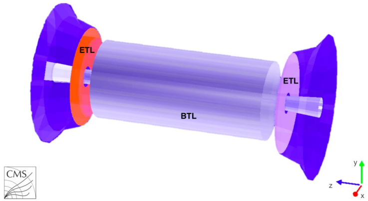


3D sensors now in ATLAS pixel detector

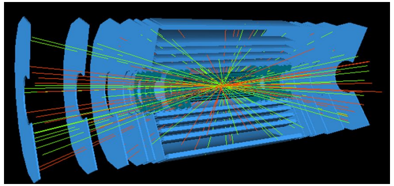
2027: LGADs in ATLAS high granularity timing detector



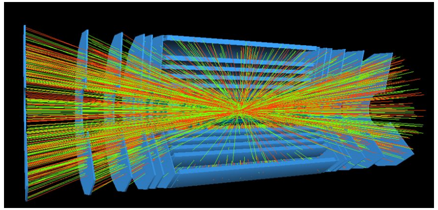
ATLAS EXPERIMENT



2027: LGADs and SiPMs in CMS timing detectors



Pileup x 10



Why so many collisions per second?

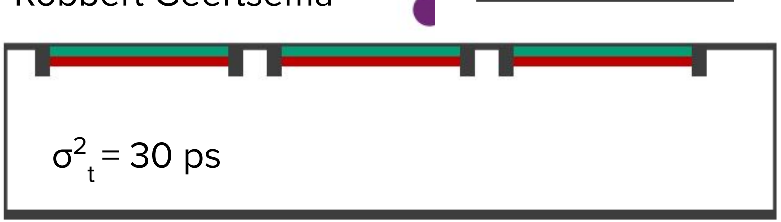
ATLAS High Granularity Timing Detector: a timing layer

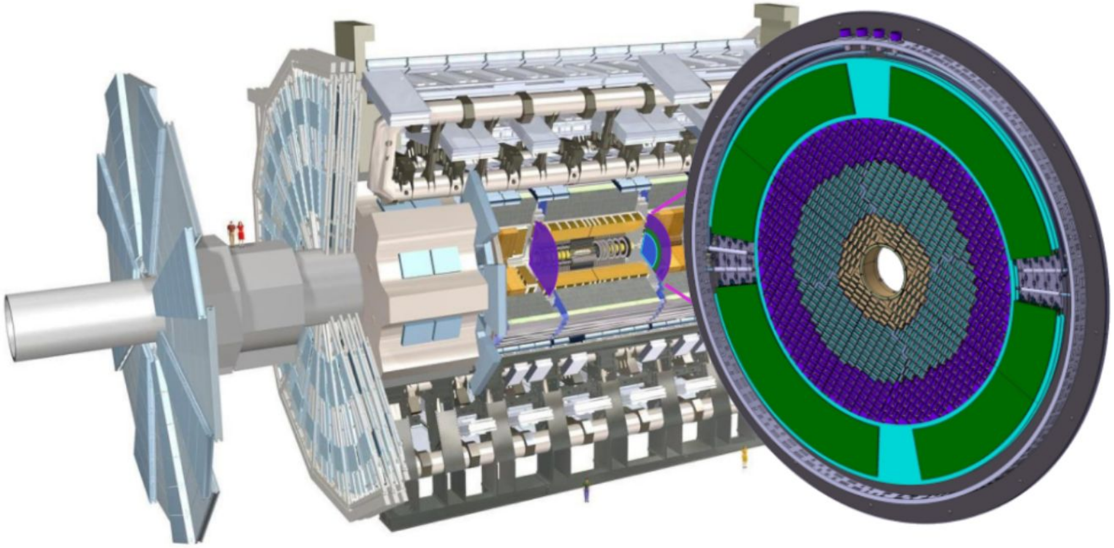
TDR

- **LGADs** with time resolution per track (per hit) 25 ps (35 ps) for r = 120 mm
- **Half will be replaced after 1000 fb^{-1}**: timing degrades with radiation damage

Low Gain Avalanche Diode signal: charge is multiplied in gain layer! Animation by Robbert Geertsema

Planar sensor signal:





Animations courtesy of Robbert Geertsema

Photodetectors & Particle IDentification

From 2023 CPAD Workshop

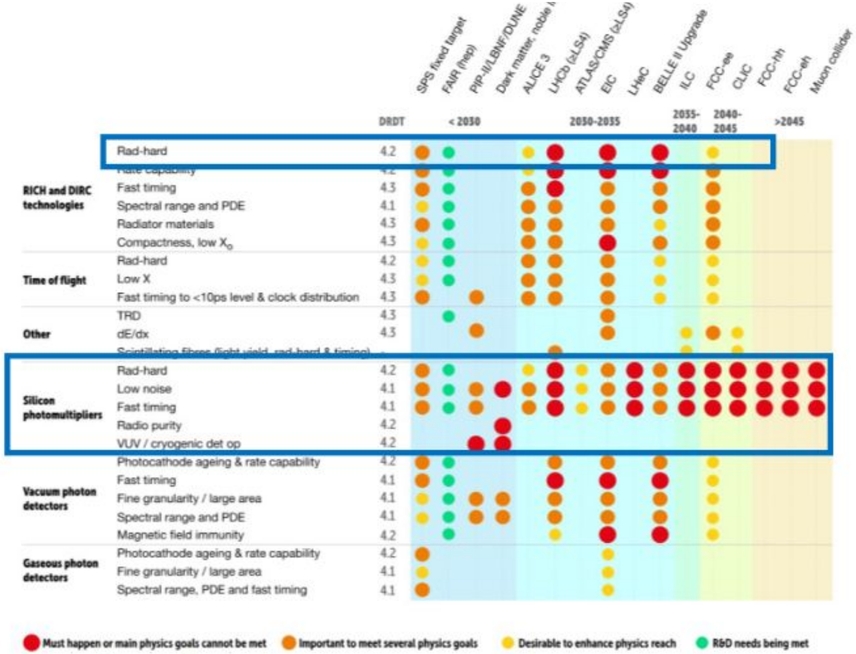
Photodetectors and particle identification (PID)

- Particle Identification (PID) essential to identify decays when heavy flavor are present

- **Developments** on MCP-PMTs, SiPMs, Vacuum and gaseous photon detectors
- **Applications** in Ring Imaging Cherenkov Detectors (RICH), Time-of-Flight (ToF), TRD

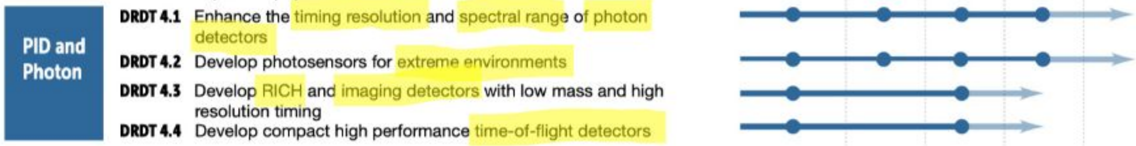
- Challenges for example for SiPMs: the high dark count rate and moderate radiation hardness prevented their use in RICH detectors where single photon detector required at low noise, but also new ideas emerge (e.g. backside illumination)

ECFA Detector R&D Roadmap



		DRDT
RICH and DIRC technologies	Rad-hard	4.2
	Rate capability	4.2
	Fast timing	4.3
	Spectral range and PDE	4.1
	Radiator materials	4.3
	Compactness, low X_0	4.3
Time of flight	Rad-hard	4.2
	Low X	4.3
	Fast timing to <10ps level & clock distribution	4.3
Other	TRD	4.3
	dE/dx	4.3
	Scintillating fibres (light yield, rad-hard & timing)	-
Silicon photomultipliers	Rad-hard	4.2
	Low noise	4.1
	Fast timing	4.1
	Radio purity	4.2
	VUV / cryogenic det op	4.2
Vacuum photon detectors	Photocathode ageing & rate capability	4.2
	Fast timing	4.1
	Fine granularity / large area	4.1
	Spectral range and PDE	4.1
	Magnetic field immunity	4.2
Gaseous photon detectors	Photocathode ageing & rate capability	4.2
	Fine granularity / large area	4.1
	Spectral range, PDE and fast timing	4.1

🔴 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



PID and Photon

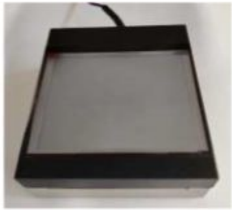
DRDT 4.1 Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2 Develop photosensors for extreme environments
DRDT 4.3 Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4 Develop compact high performance time-of-flight detectors

From 2023 CPAD Workshop

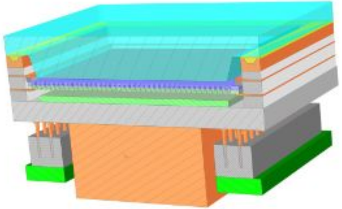
ECFA Detector R&D Roadmap

Photodetectors

- MCP-PMTs: Under evaluation for LHCb RICH, TORCH, PANDA, HIKE, etc.
  - Extremly good time resolution <70ps, custom pixelisation possible
  - R&D on lifetime improvements and rate capabilities



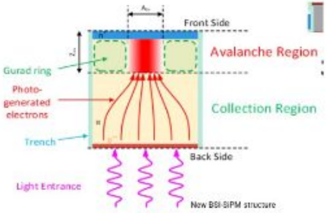
MCP with 64 x 64 anode pads (Photek)



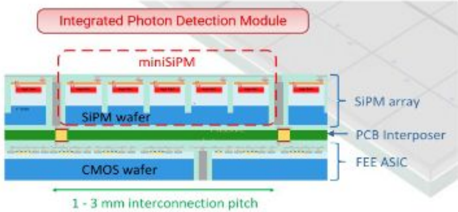
R&D to develop an MCP with integrated Timepix4 chip (55 x 55 μm^2 pixels)

Massimiliano Fiorini

- SiPMs:
  - Pros: High detection efficiency, low cost
  - Cons: High noise (DCR), neutron damage
  - Many R&D lines being followed: back-side illuminiation, sensor+electronics integration



FBK



FBK

From 2023 CPAD Workshop

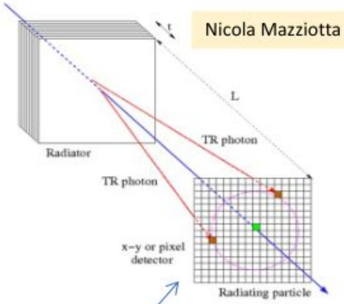
ECFA Detector R&D Roadmap

Particle identification

- **RICH** detectors
  - Proximity focusing aerogel development
  - Possible combination with TOF measurement
  - Environmentally friendly RICH radiator gases (replacement for fluorocarbons)
  - Compact RICH with dual aerogel + gas radiators
- **TOF** detectors
  - SiPMs detecting Cherenkov light from their entrance window
  - DIRC-style: TORCH (10 ps resolution per track over large areas)

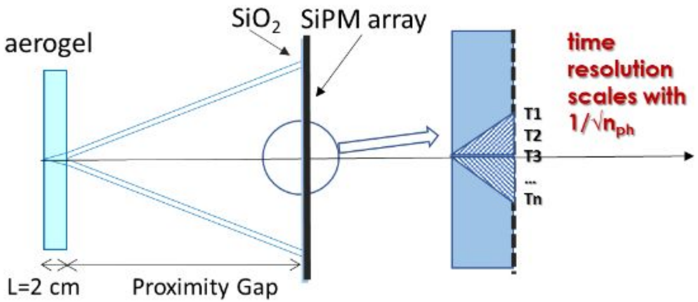
LHCb-TDR-023

- **TR** detectors
  - Solid-state detection of Transition Radiation



Nicola Mazziotta

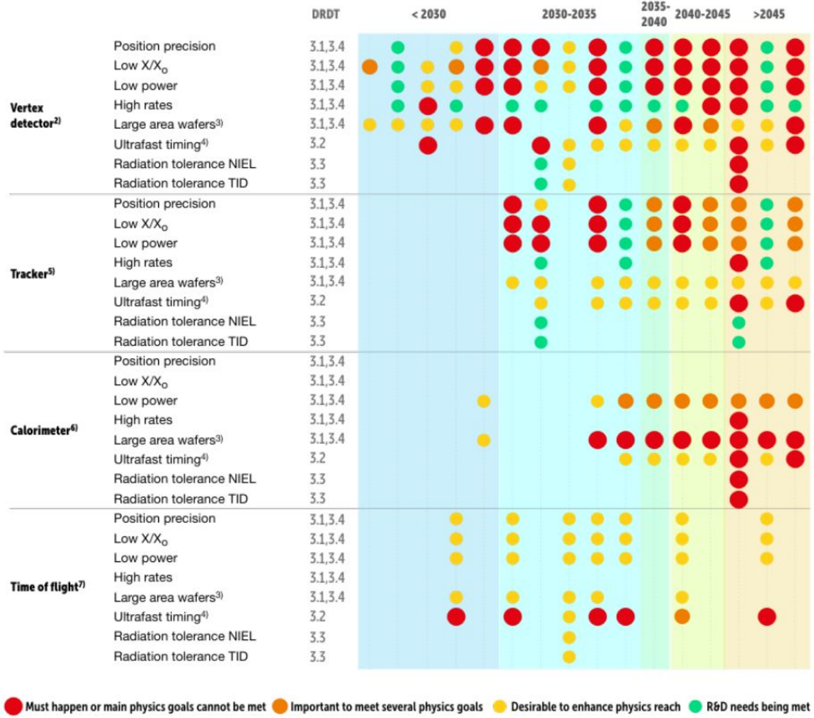
GaAs sensor + Timepix3 readout chip



time resolution scales with $1/\sqrt{n_{ph}}$

Summary

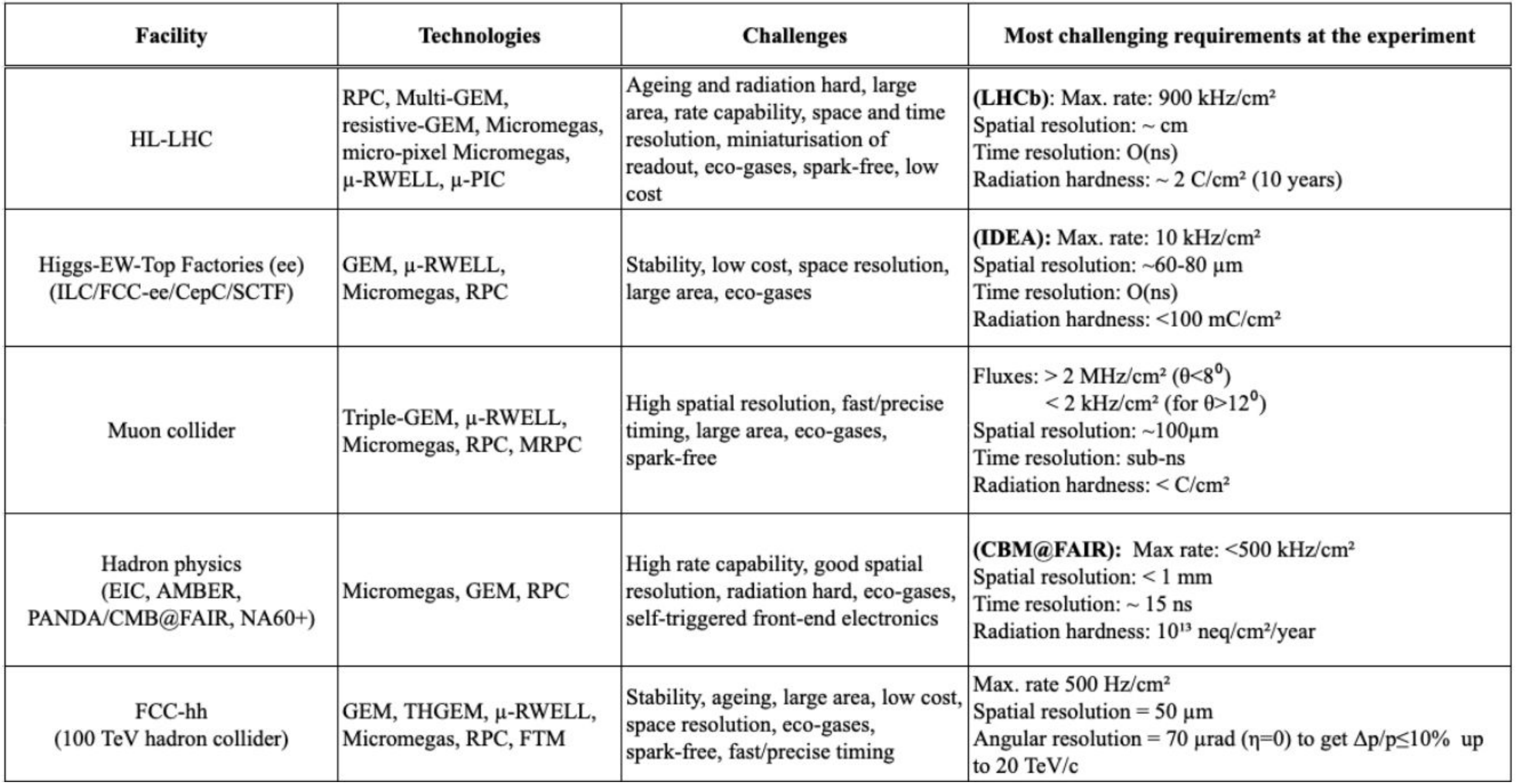
ECFA Detector R&D Roadmap



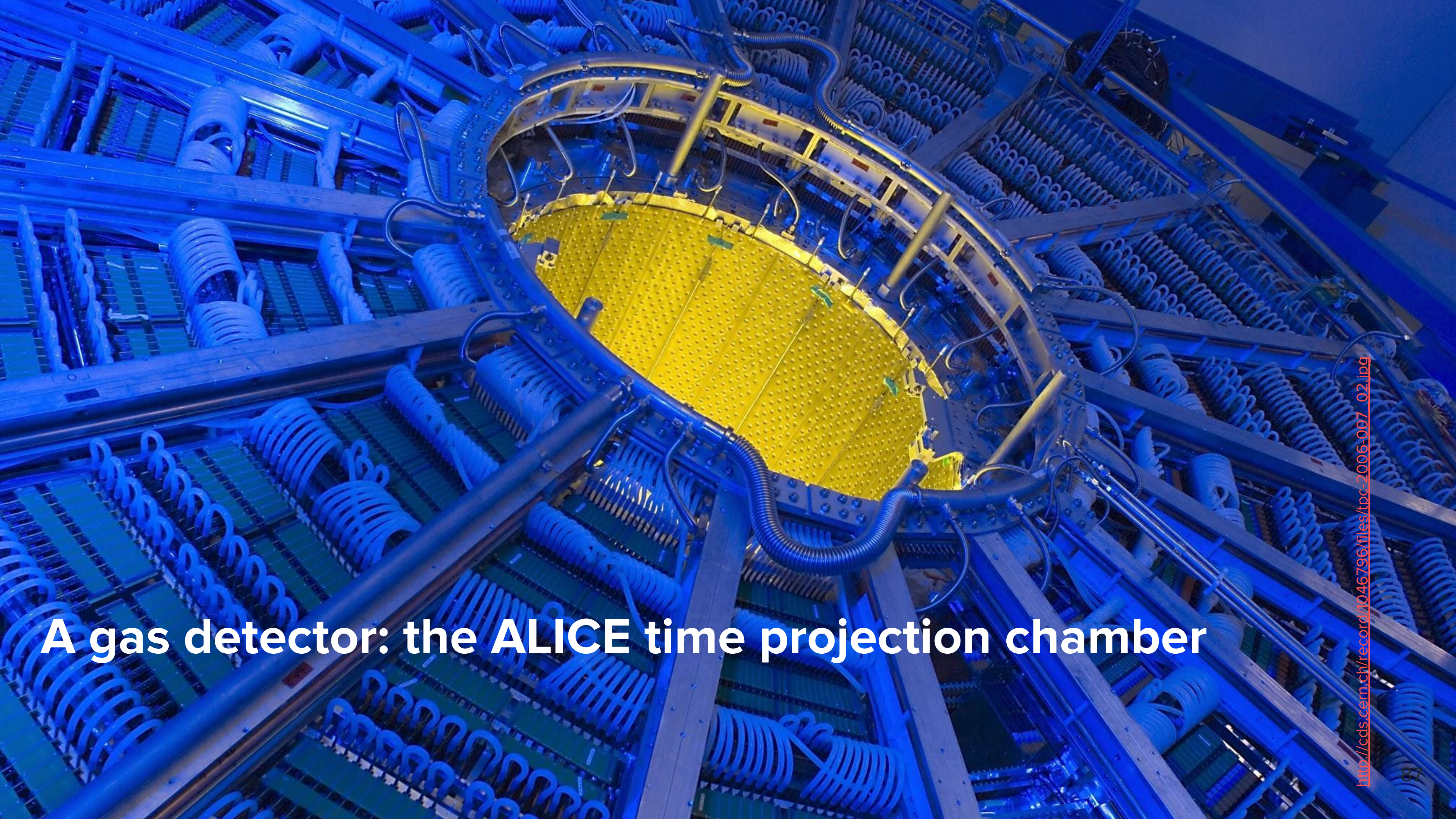
- A new collider sets new requirements on detectors
- Existing R&D is used for design of these detectors
- Existing experiments are used for proof of operation of such detectors and inspiration for new detectors
- R&D is still needed to meet requirements at new colliders!

Additional material

Gas detectors at future facilities: muon systems



Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm^2 Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm^2 (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA):** Max. rate: 10 kHz/cm^2 Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm^2
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm^2 ($\theta<8^0$) < 2 kHz/cm^2 (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm^2
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR):** Max rate: <500 kHz/cm^2 Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{13} neq/cm^2/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm^2 Spatial resolution = 50 μm Angular resolution = 70 μrad ($\eta=0$) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

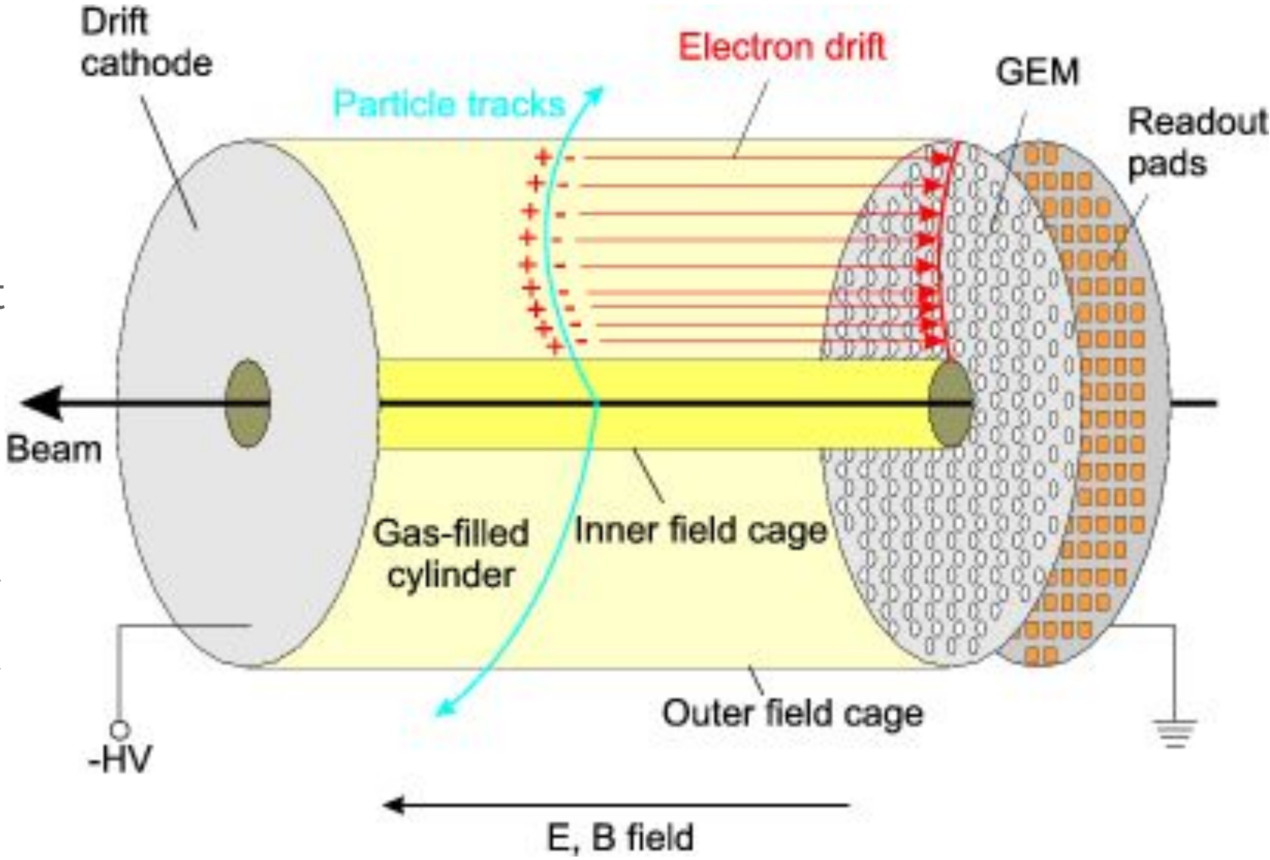


A gas detector: the ALICE time projection chamber

http://cds.cern.ch/record/1046796/files/tpc-2006-007_02.jpg

TPC

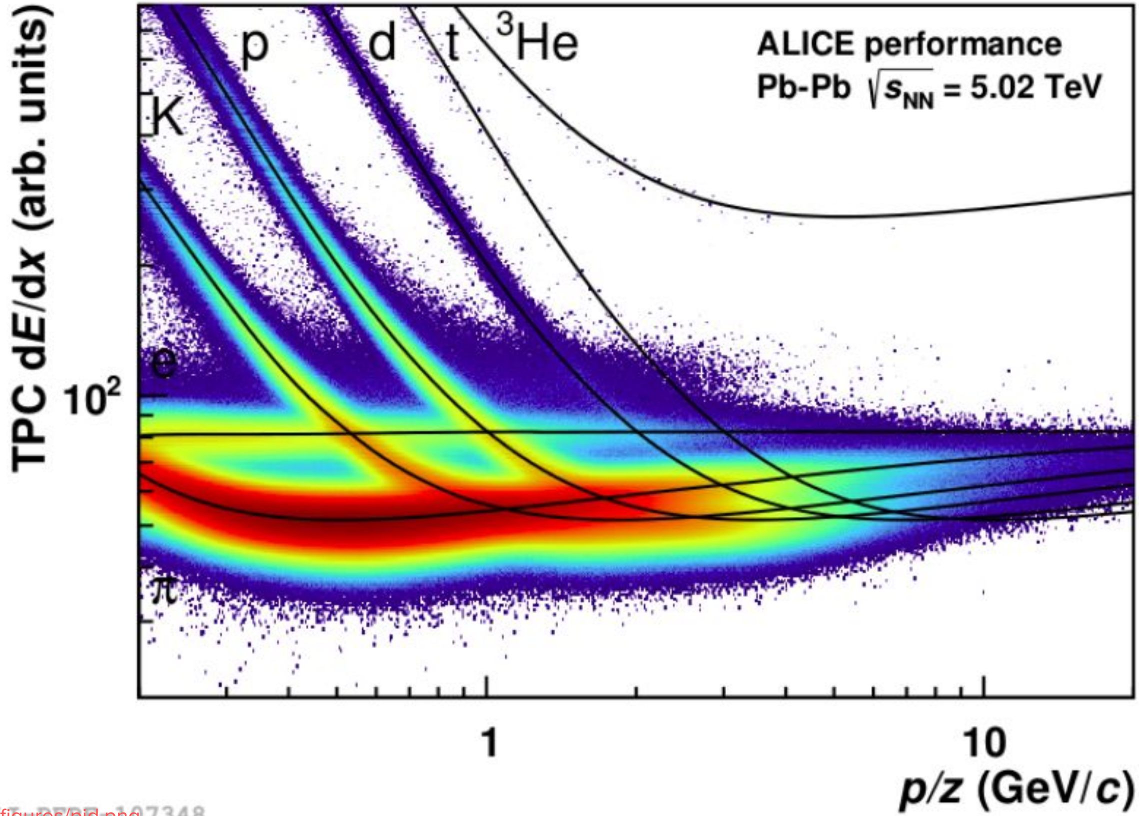
1. Ionization of gas in **chamber** with electric field causes electron drift
2. Signal gets amplified, in this case by gas electron multipliers ➔ electron avalanche
3. Readout pads can detect signal that can be **projected** onto trajectory
4. z (along beam) information from **timing**



http://aliceinfo.cern.ch/Public/Objects/Chapter2/DetectorComponents/tpc_operation.gif

ALICE time projection chamber: particle identification

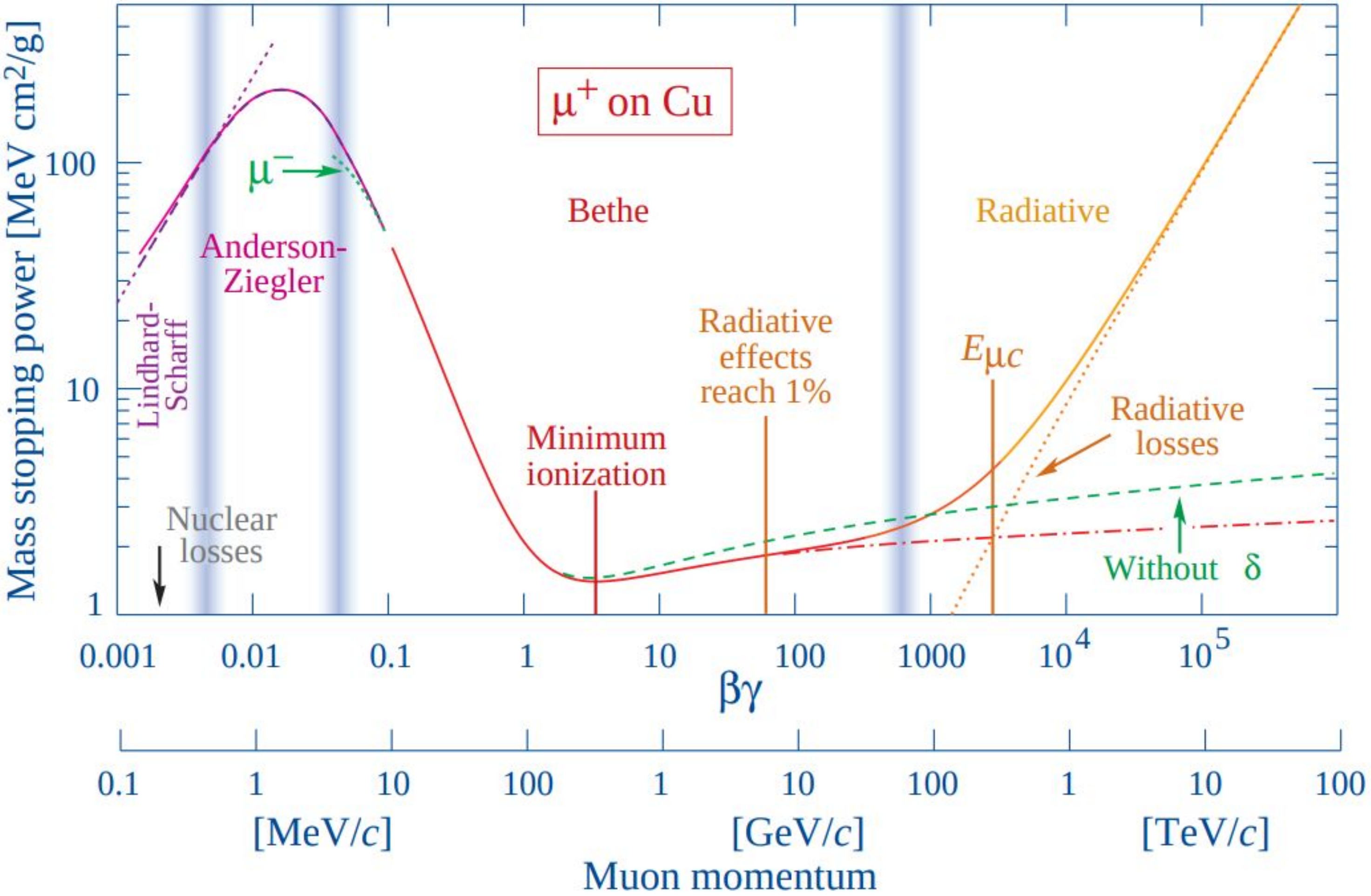
- Every point is one measurement!
- Can identify particles for low momenta
- For higher momenta, all particles behave like a minimum ionizing particle (MIP)



https://scx1.b-cdn.net/csz/news/800/2015/55d25b5d82741.png

https://alice-doc.github.io/alice-analysis-tutorial/analysis/figures/pid.png

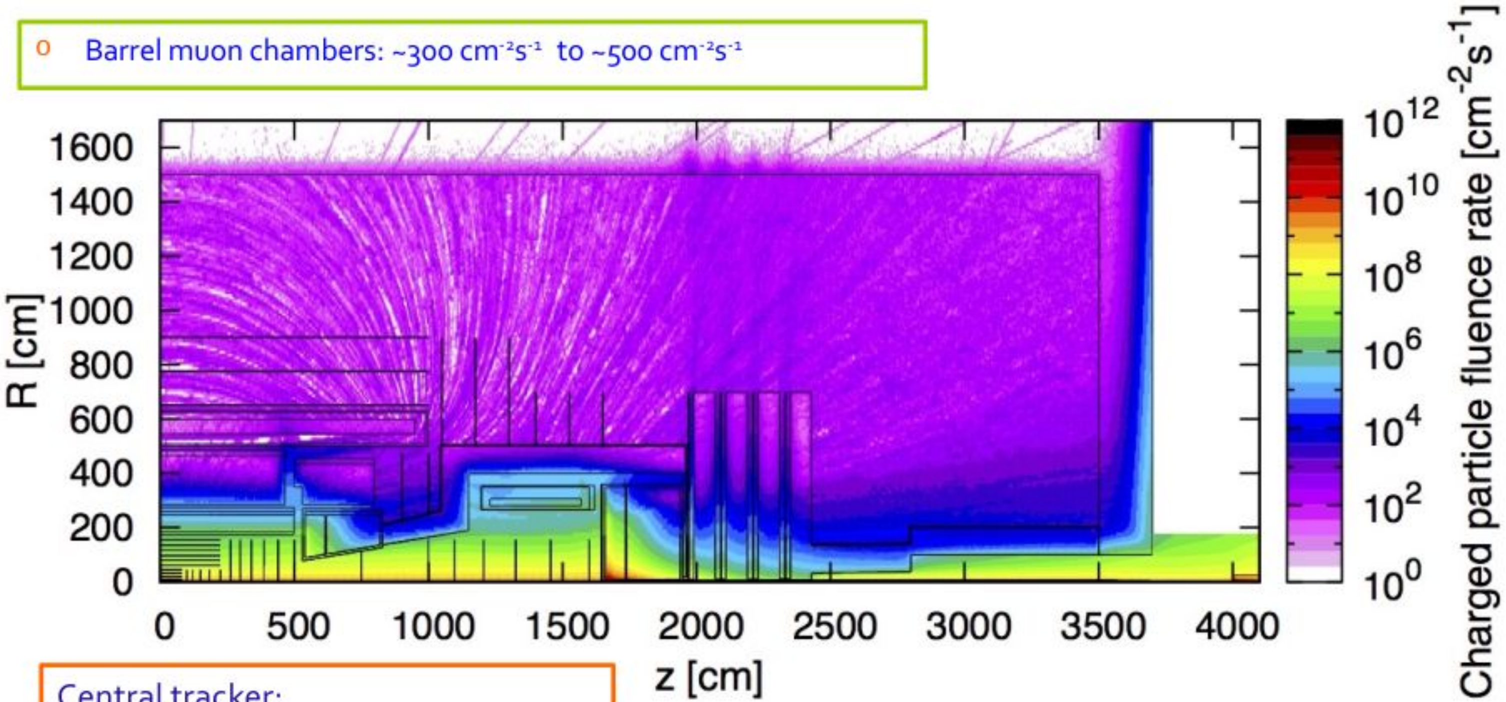
Ionization loss



http://pdg.lbl.gov/2018/reviews/rpp2018-rev-passage-particles-matter.pdf

From Werner Riegler

- Barrel muon chambers: ~300 $cm^{-2}s^{-1}$ to ~500 $cm^{-2}s^{-1}$



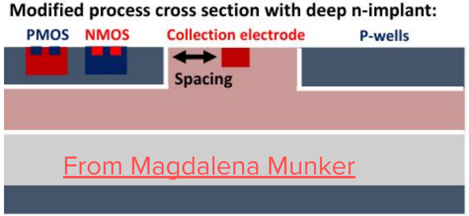
Central tracker:

- first IB layer (2.5 cm): ~1.2 10^{10} $cm^{-2}s^{-1}$
- external part: 3 10^{6} $cm^{-2}s^{-1}$

Other fast timing examples

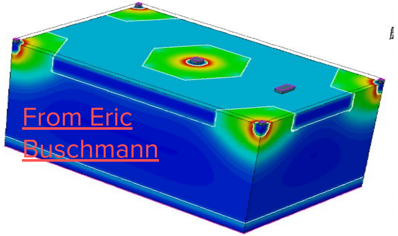
Many more possibilities for fast timing detectors

- With avalanche gain
  - Sub-geiger mode (LGADs, APDs)
    - DC-coupled
    - AC-coupled
  - Geiger mode (SPADs)
- Without avalanche gain
  - Hybrid
    - Planar
    - 3D electrodes
  - Monolithic
    - BiCMOS (SiGe)
    - CMOS
    - HV-CMOS



From Magdalena Munker

Larger spacing for fast charge collection but low capacitance



From Eric Buschmann

Hexagonal pixels

MonPicoAD

FASTPIX

ARCADIA

RD50

Fast sensors at the LHC experiments

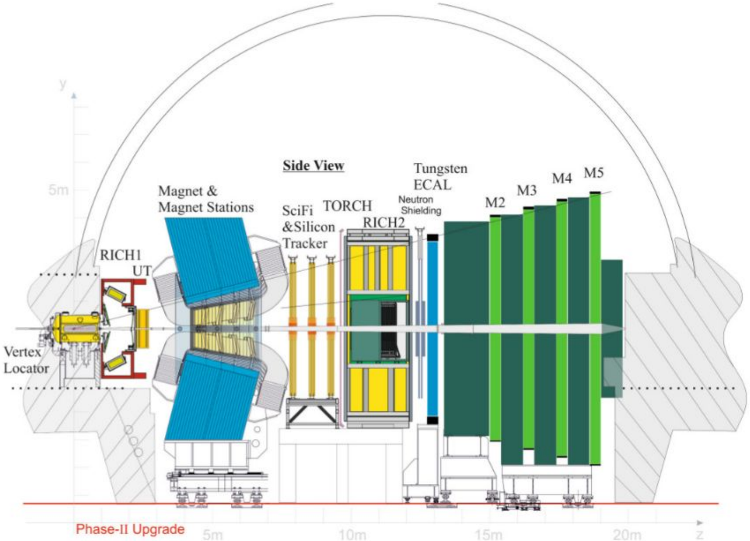
Fast timing detectors for LHCb

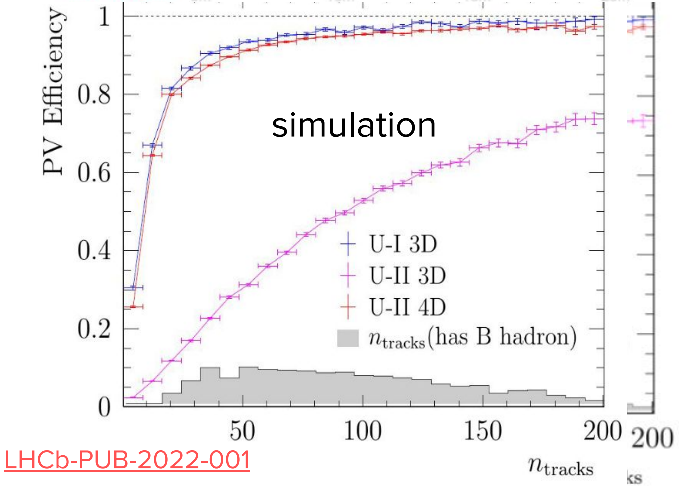
Environment and requirements

- $250fb^{-1}$ up to $350fb^{-1}$
- fluence of Φ_{eq} = 6e16 / cm^2 at 5.1 mm
- Expected pileup 50: 25 times that of today!
- Need a track time resolution of 20ps
- Collision rate: 2e34 /cm^2/s: 50 times that of today!
- Now upgradedfor 5x collision rate

Good time resolution from one of:

- Thin planar hybrid
- 3D hybrid
- MAPS
- LGADs



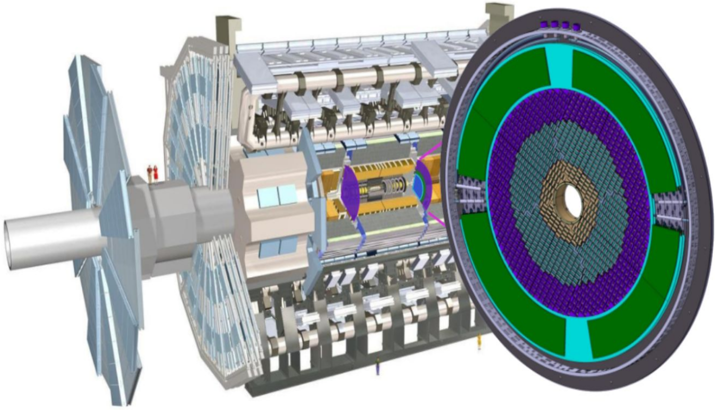


From LHCb-PUB-2022-001

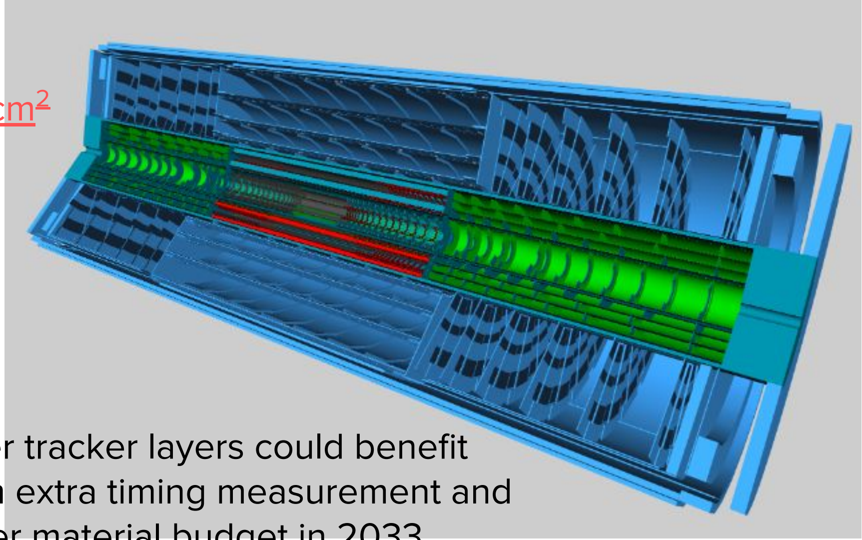
ATLAS

High luminosity LHC: high particle rates!
ATLAS ITk will see Φ_{eq} = 2.2e16 / cm^2

High granularity timing detector: LGADs from 2026
Replacements in 2033 TDR

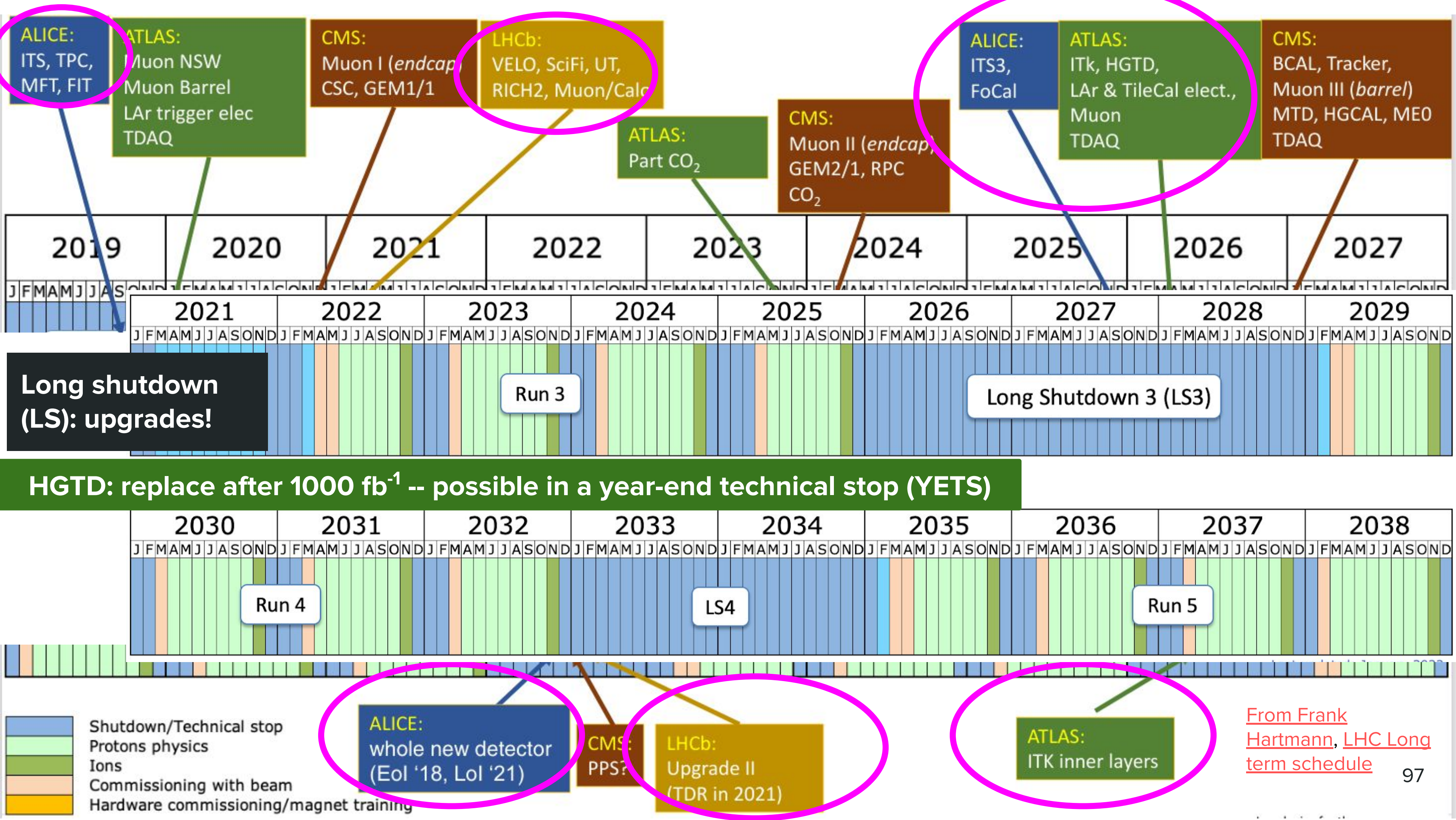


ATLAS inner tracker 2026 onward (TDR)



Inner tracker layers could benefit from extra timing measurement and lower material budget in 2033

Material budget of ITk per layer ~3% X_0
ALICE material budget per layer **now**: 0.35% **planned**: 0.05%



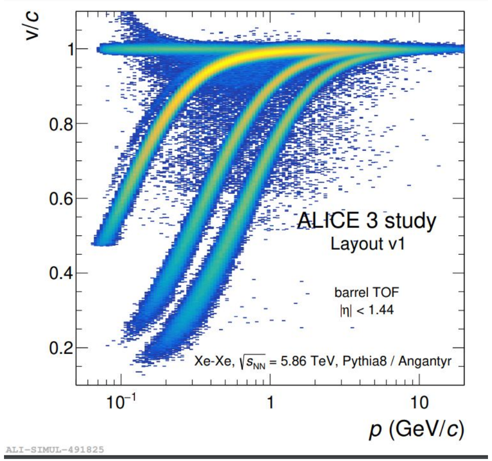
Long shutdown (LS): upgrades!

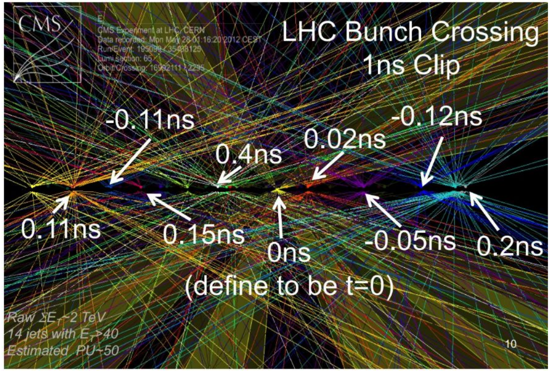
HGTD: replace after 1000 fb^{-1} -- possible in a year-end technical stop (YETS)

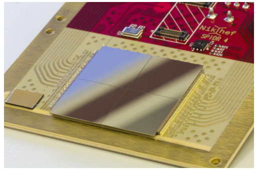
From Frank Hartmann, LHC Long term schedule

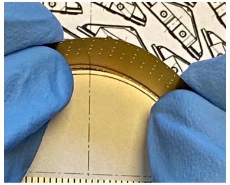
Summary: picosecond timing with solid state detectors

- Can improve particle identification
- Can improve tracking
- Can be used for 4D tracking
- Different sensors are under investigation
- Measuring the time resolution is not trivial
- Nikhef detector R&D group works with fast timing pixel detectors for upgrades of the LHC experiments and beyond



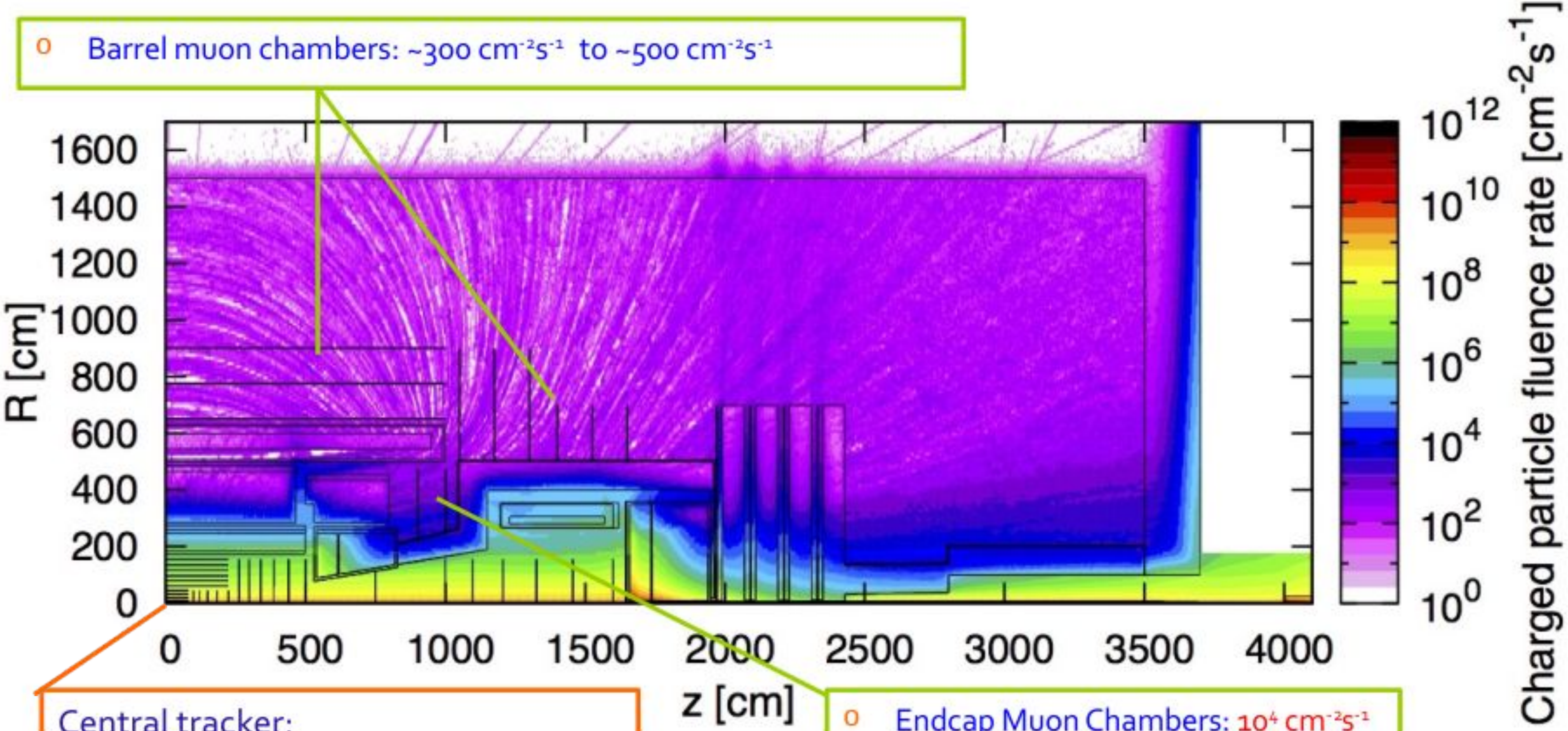






Charged particle fluence at L=30x10^{34}cm^{-2}s^{-1}

From Werner Riegler



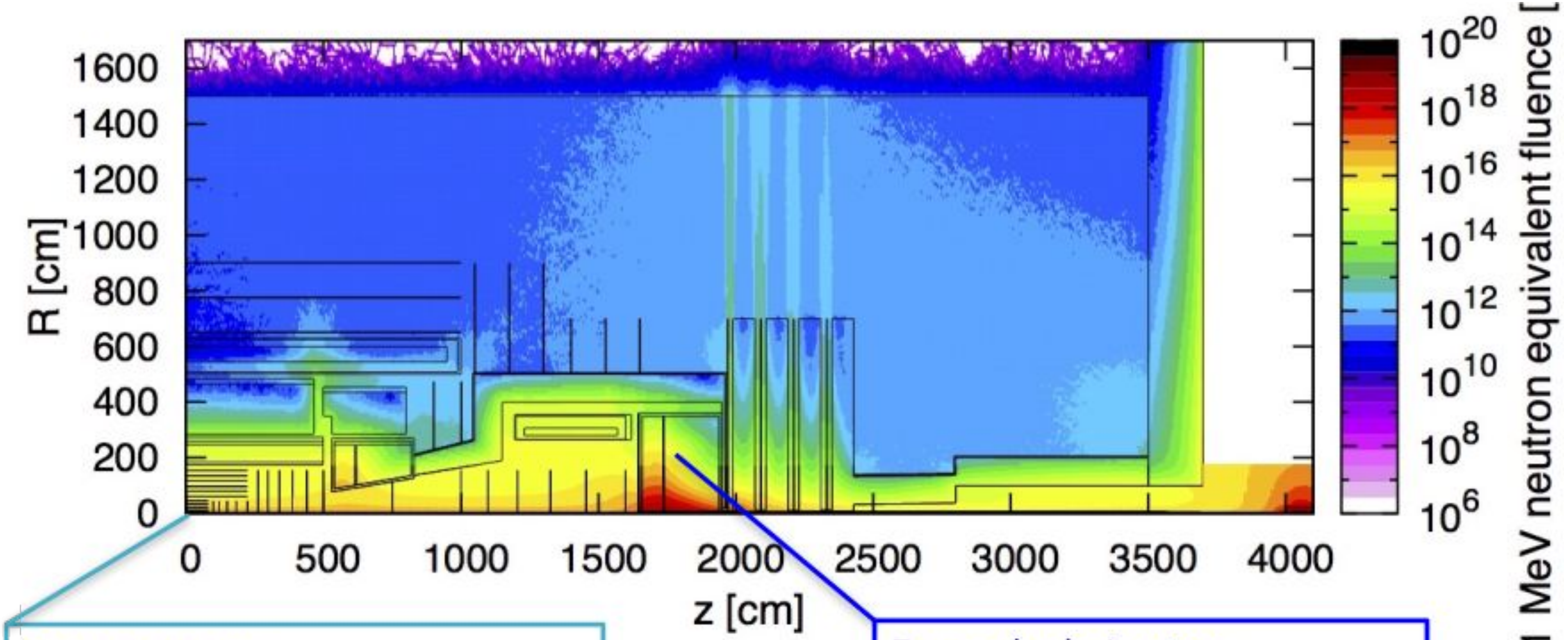
- Barrel muon chambers: ~300 cm^{-2}s^{-1} to ~500 cm^{-2}s^{-1}

- Endcap Muon Chambers: 10^{4} cm^{-2}s^{-1}

Central tracker:
- first IB layer (2.5 cm): ~1.2 10^{10} cm^{-2}s^{-1}
- external part: 3 10^{6} cm^{-2}s^{-1}

From Werner Riegler

1 MeV neutron equivalent fluence for 30ab^{-1}



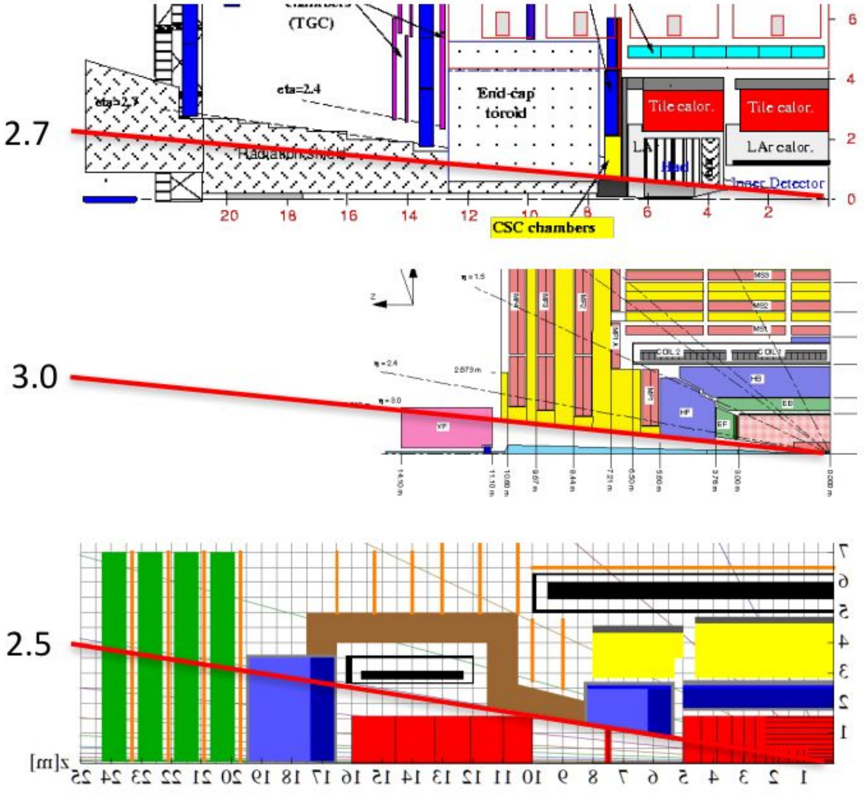
M.I. Besana, FCC week 2017

Central tracker:
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Forward calorimeters:
- maximum at ~5 10^{18} cm^{-2} for both the EM and the HAD-calo
- 10^{16} cm^{-2} at R=2 m

From Werner Riegler

Radiation in ATLAS, CMS, and FCC



The forward calorimeters are a very large source of radiation (diffuse neutron source).

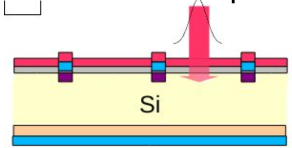
In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is inside enclosed by the return Yoke.

For the FCC, the forward calorimeter is moved far out in order to reduced radiation load and increase granularity.

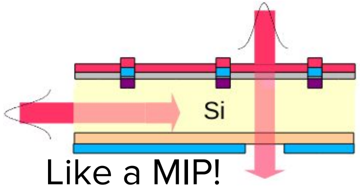
✉ A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.

Injection of a signal: transient current technique

Red 660nm = 1.9 eV
Penetrates few µm below surface
1 photon = 1 electron-hole pair



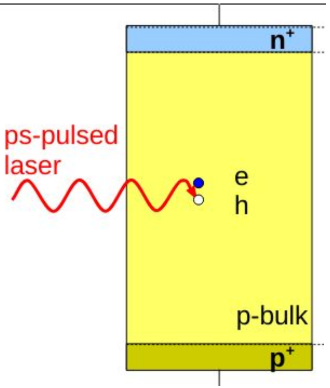
Infrared 1060nm = 1.17 eV
Penetrates deep into sensor
1 photon = 1 eh pair



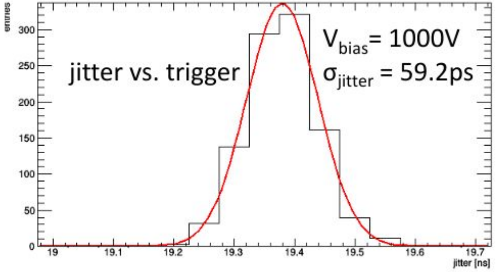
Like a MIP!

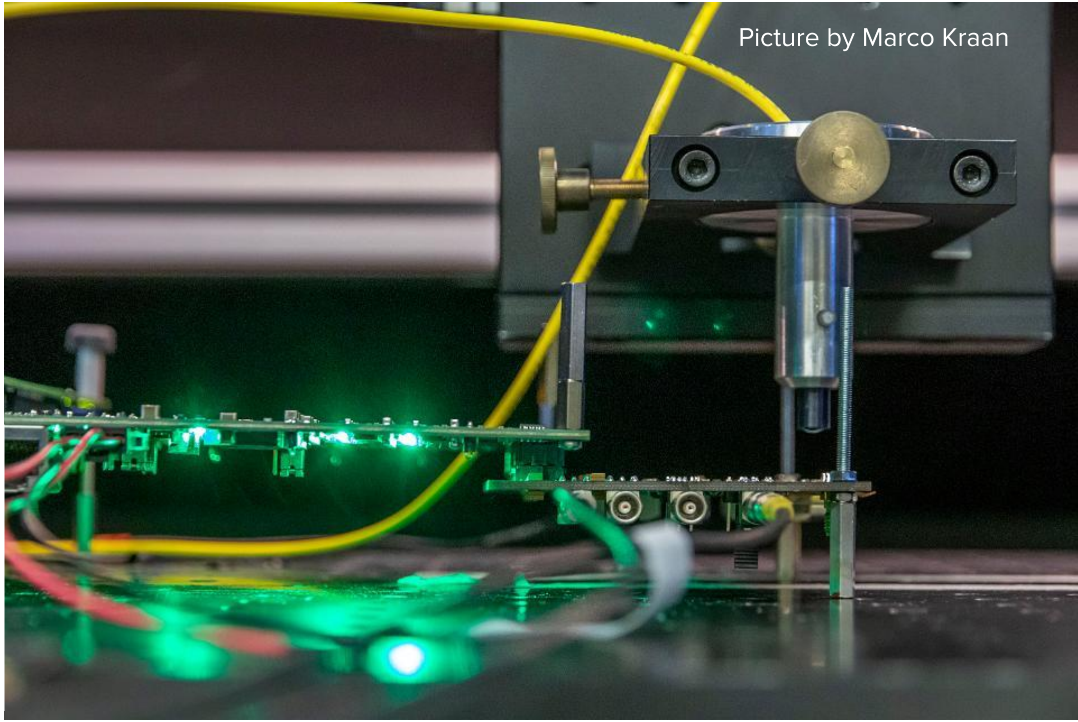
From C. Gallrap

2D spatial resolution



From Marco Fernandez



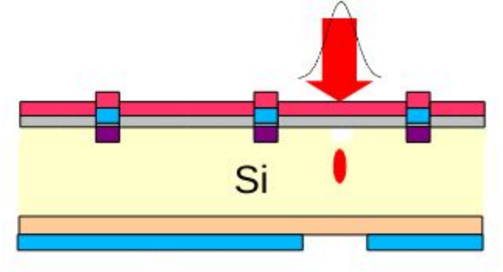


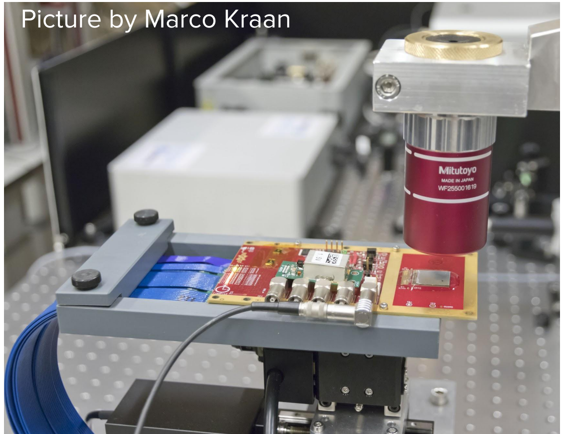
Single photon absorption laser and RD50 HR-HV MAPS at Nikhef

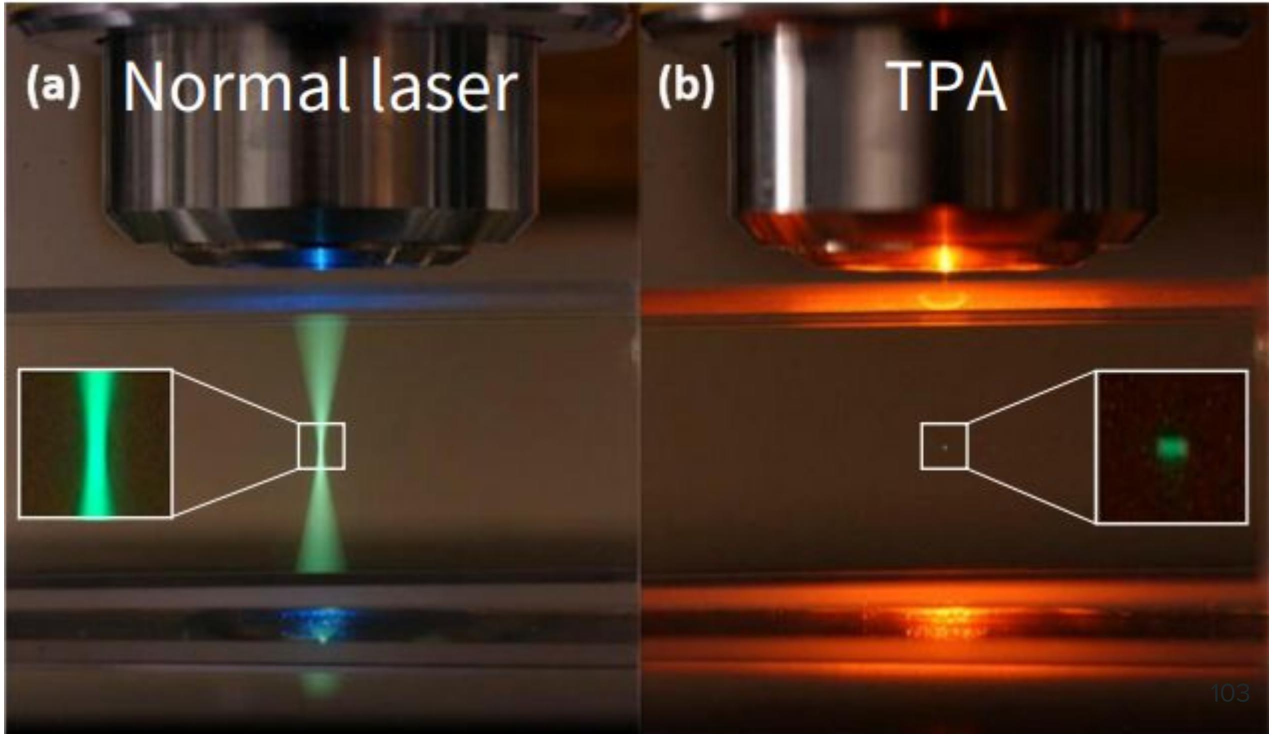
Two-photon absorption transient current technique

3D spatial resolution
1550 nm = 0.8 eV: smaller than silicon band gap!
→ 2 photons = 1 electron-hole pair

380 fs – 5.5 nJ – 1 µm wide spot
fast – powerful – precise




Picture by Marco Kraan

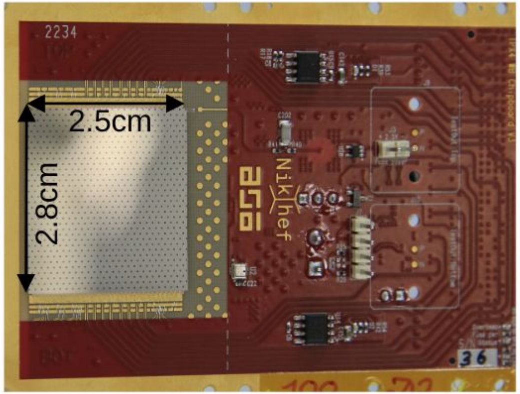


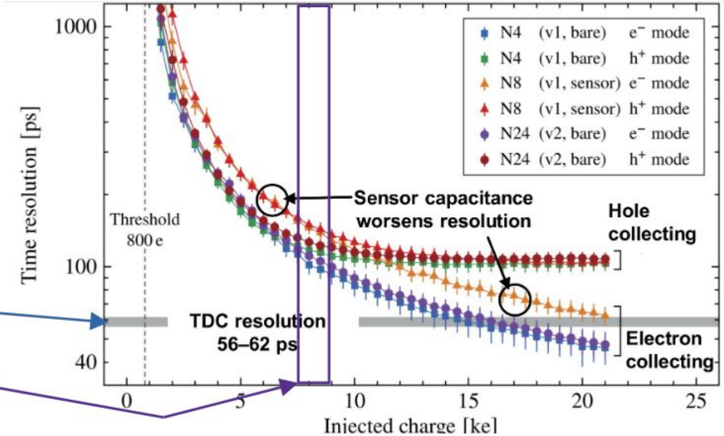
Improved TDC resolution: sensor becomes important

Moving beyond digital limits

- Older ASICs
  - Timepix3 σ_{TDC} ~ 450 ps
- Newer ASICs
  - **Timepix4** **σ_{TDC} ~ 62 ps**
- Next goal:
  - Picopix $\sigma_{TDC} < 20$ ps

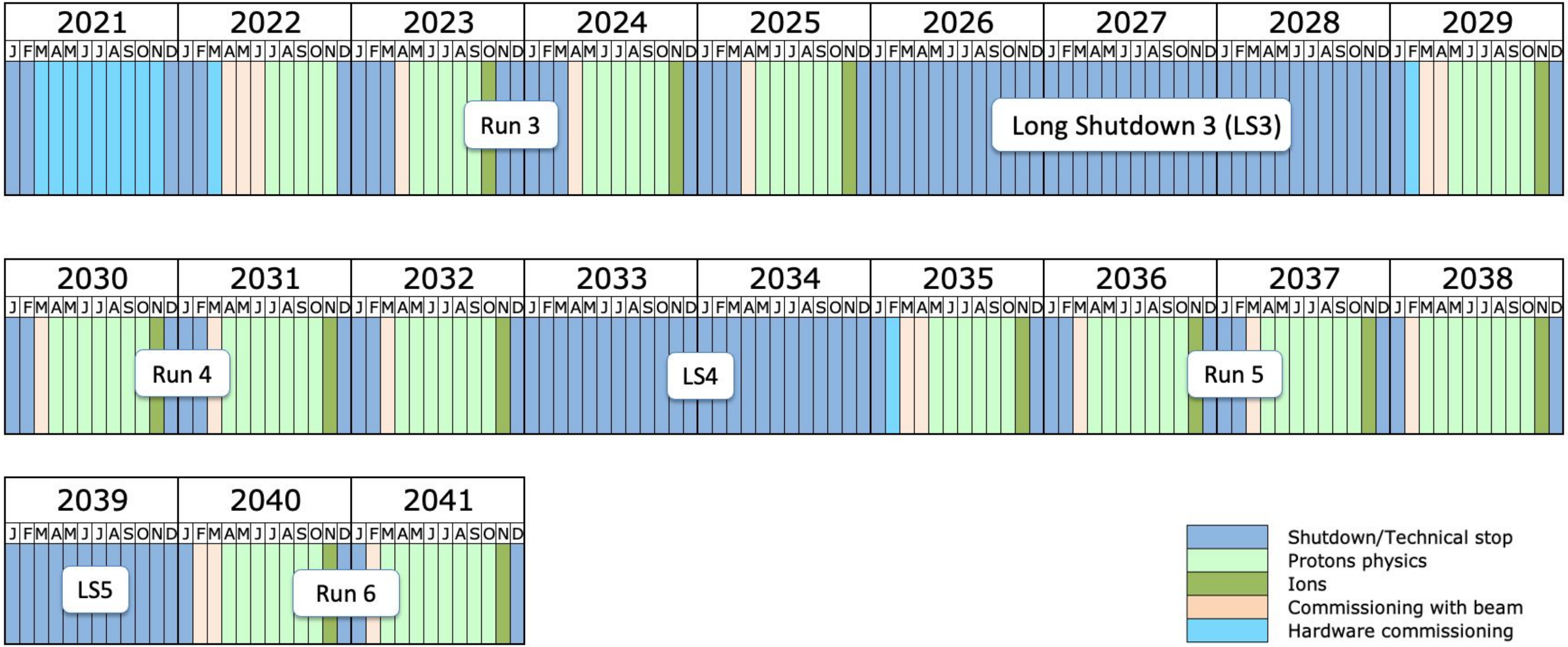
- Impact of other contributions begin to be significant
  - Only capacitive load from sensor
    $\sigma_{Front\text{-}end}$ ~ 100 ps





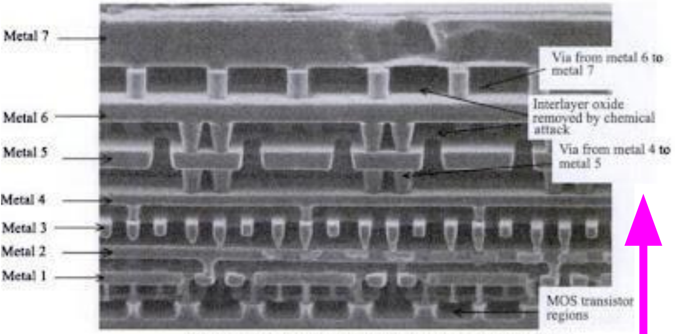
Kevin Heijhoff

From Uwe Krämer

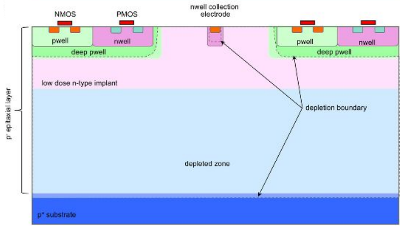


Last update: April 2023

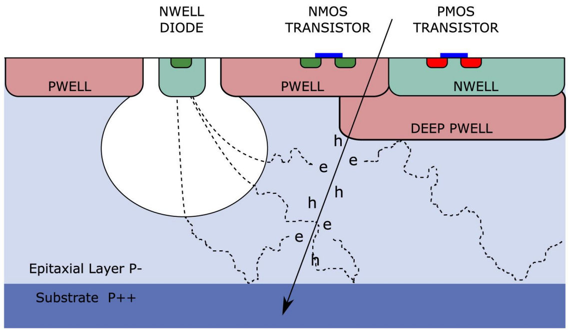
Interconnected metal layers on top

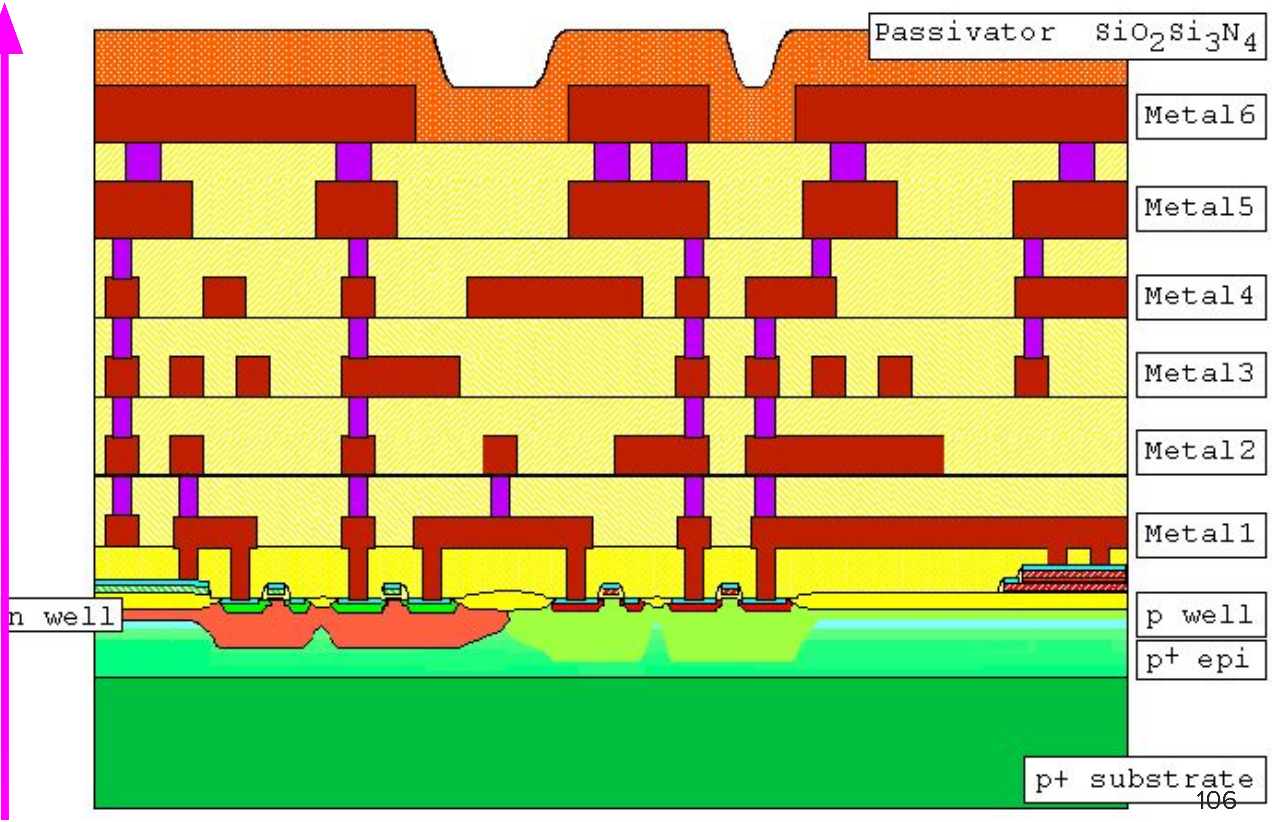


Cross-section of a 0.12 µm technology (*Courtesy:* Fujitsu)



50 µm thick MAPS

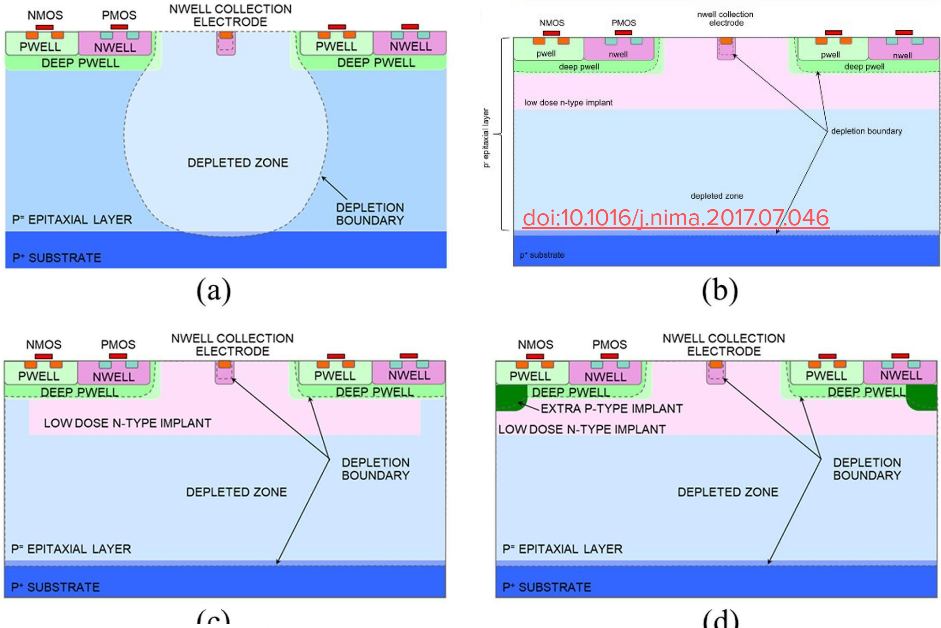




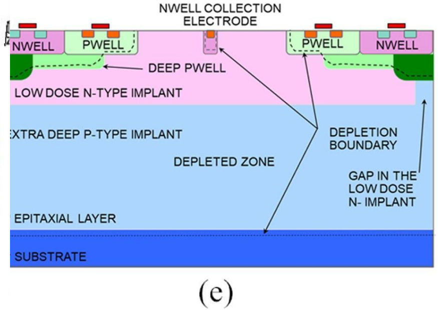
Fast MAPS example: FASTPIX

FASTPIX ATTRACT project:

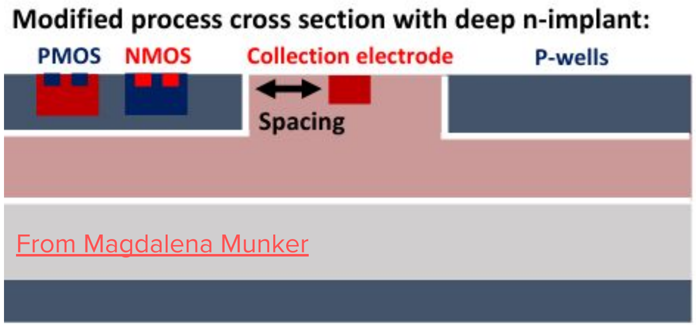
- Designed for tens of ps; measured 120-130 ps time resolution
- Designed for 20 uW power consumption
- Process optimization
- Larger spacing for fast charge collection but low capacitance
- Hexagonal pixels to reduce edge effects



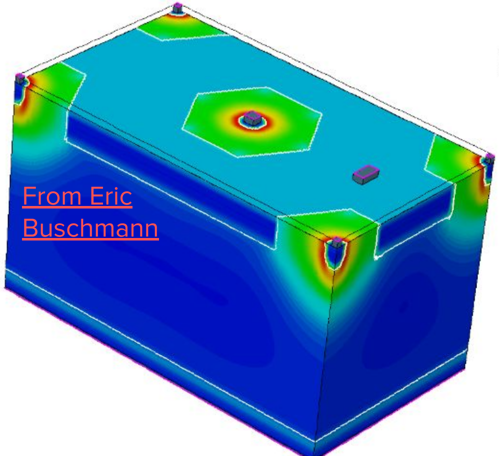
doi:10.1016/j.nima.2017.07.046



Kugathasan et al., Nucl. Instr. Meth. A 979 (2020), doi:10.1016/j.nima.2020.164461

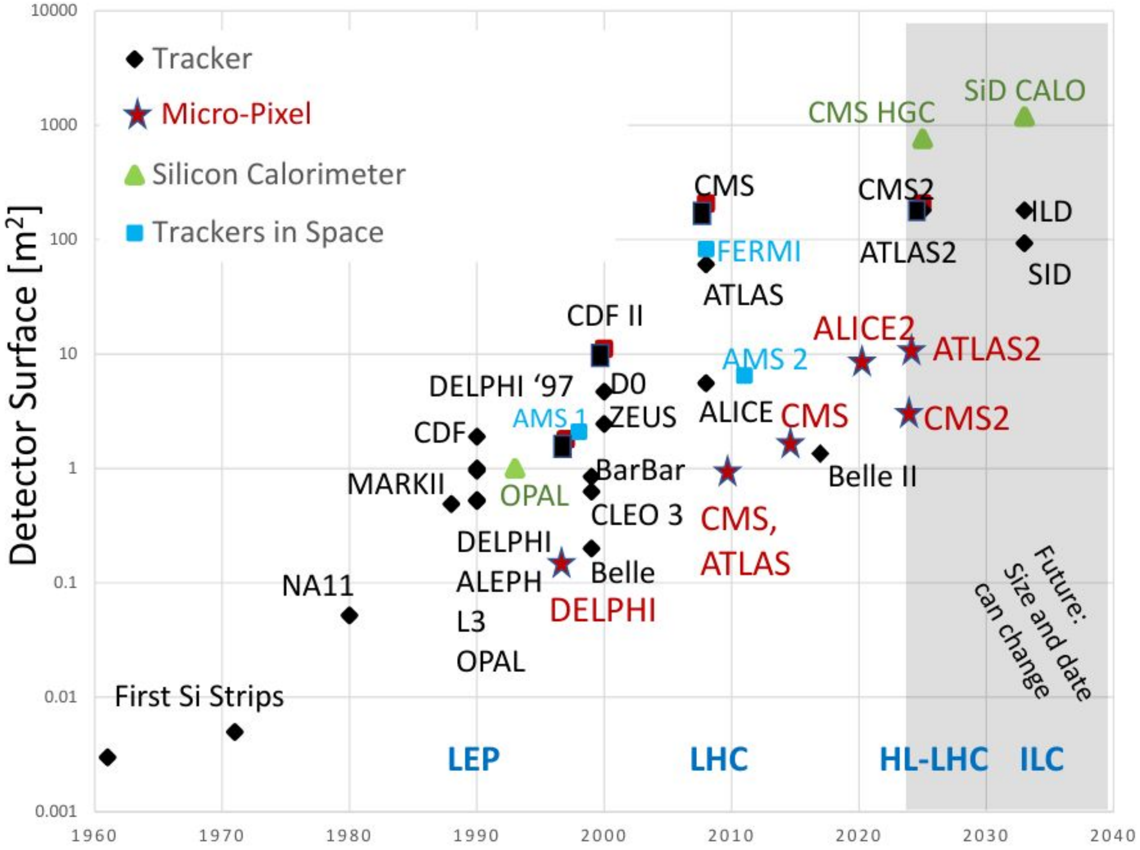

Modified process cross section with deep n-implant:

From Magdalena Munker



From Eric Buschmann

Tracking and vertex detector sizes



FCC-h
(no number)

Largest pixel detector: ALICE
Largest silicon tracker : CMS

Cell size **goes down significantly**
Cell count **goes up significantly**

We are counting in GIGA these days

A silicon tracking detector

200 m^2 CMS silicon strip tracker
The largest tracker ever built

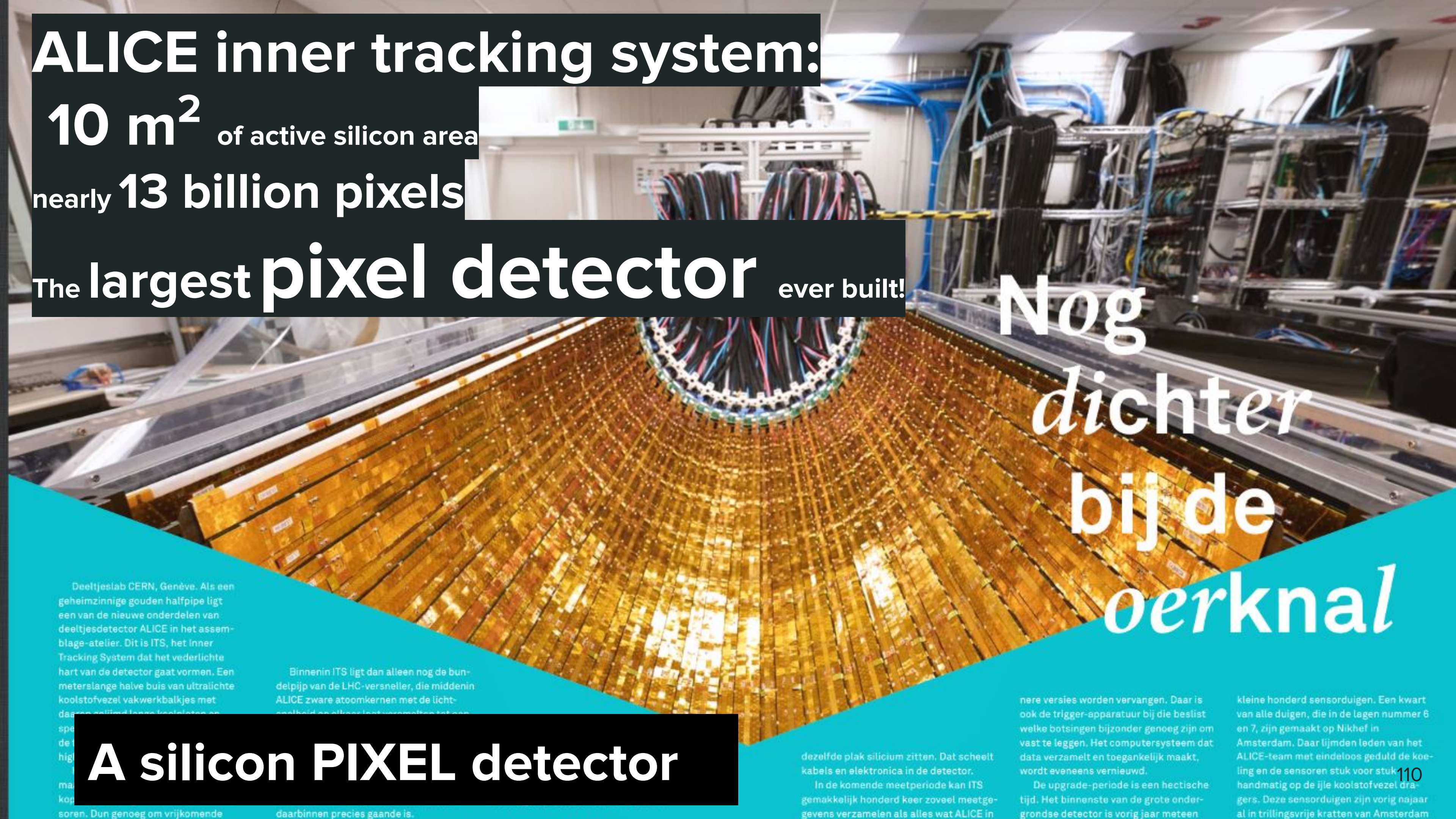
https://www.lhc-epistemologie.uni-wuppertal.de/fileadmin/lhcepistemologie/media/bilder/slider_home1_1200x600.jpg

ALICE inner tracking system:

10 m² of active silicon area

nearly 13 billion pixels

The largest pixel detector ever built!



Nog dichter bij de oerknal

Deeltjeslab CERN, Genève. Als een geheimzinnige gouden halfpipe ligt een van de nieuwe onderdelen van deeltjesdetector ALICE in het assemblage-atelier. Dit is ITS, het Inner Tracking System dat het vederlichte hart van de detector gaat vormen. Een meterslange halve buis van ultralichte koolstofvezel vakwerkbalkjes met

soren. Dun genoeg om vrijkomende

Binnenin ITS ligt dan alleen nog de bundelpijp van de LHC-versneller, die middenin ALICE zware atoomkernen met de licht-

daarbinnen precies gaande is.

dezelfde plak silicium zitten. Dat scheelt kabels en elektronica in de detector.

In de komende meetperiode kan ITS gemakkelijk honderd keer zoveel meetgegevens verzamelen als alles wat ALICE in

nere versies worden vervangen. Daar is ook de trigger-apparatuur bij die beslist welke botsingen bijzonder genoeg zijn om vast te leggen. Het computersysteem dat data verzamelt en toegankelijk maakt, wordt eveneens vernieuwd.

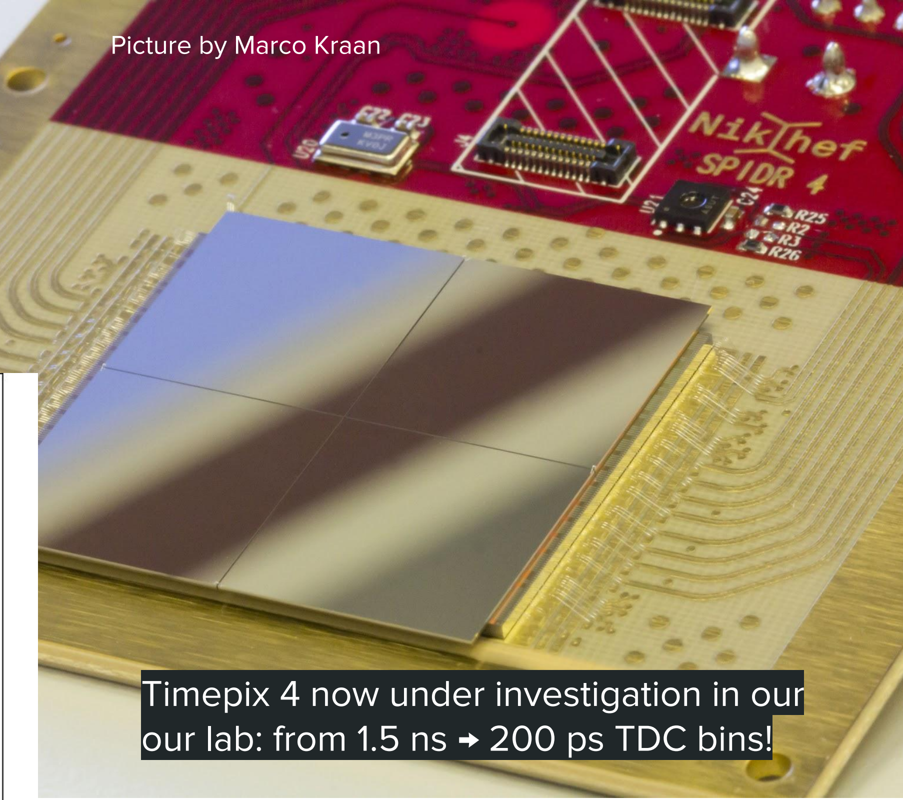
De upgrade-periode is een hectische tijd. Het binnenste van de grote ondergrondse detector is vorig jaar meteen

kleine honderd sensorduigen. Een kwart van alle duigen, die in de lagen nummer 6 en 7, zijn gemaakt op Nikhef in Amsterdam. Daar lijmden leden van het ALICE-team met eindeloos geduld de koeling en de sensoren stuk voor stuk handmatig op de ijle koolstofvezel dragers. Deze sensorduigen zijn vorig najaar al in trillingsvrije kratten van Amsterdam

A silicon PIXEL detector

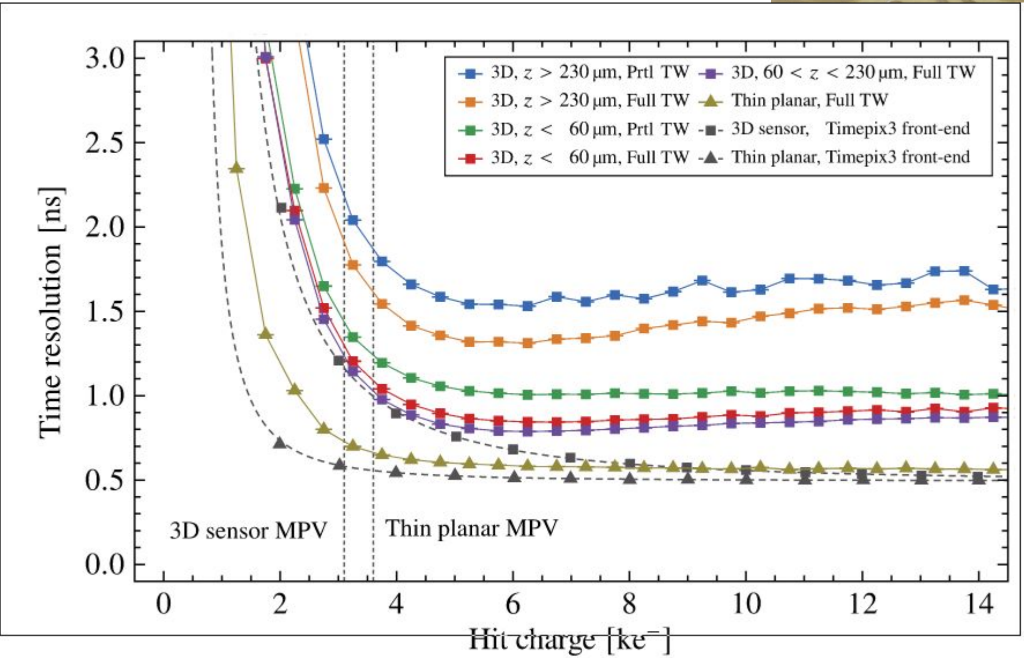
Some more examples of fast timing at Nikhef

Timepix: a Nikhef initiative



Picture by Marco Kraan

Timepix 3 with sensor: σ_t = 500-600 ps

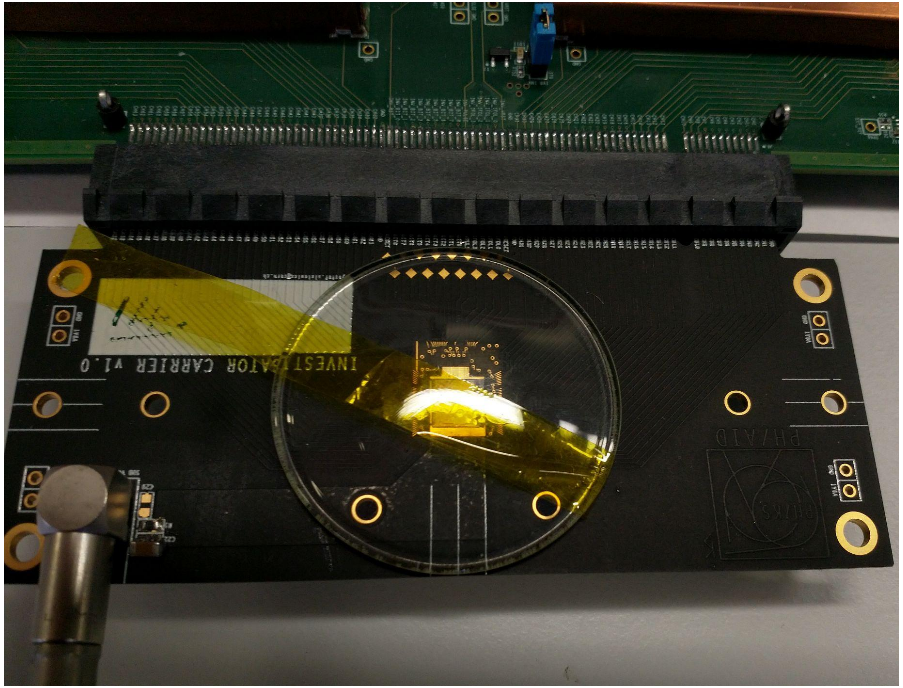


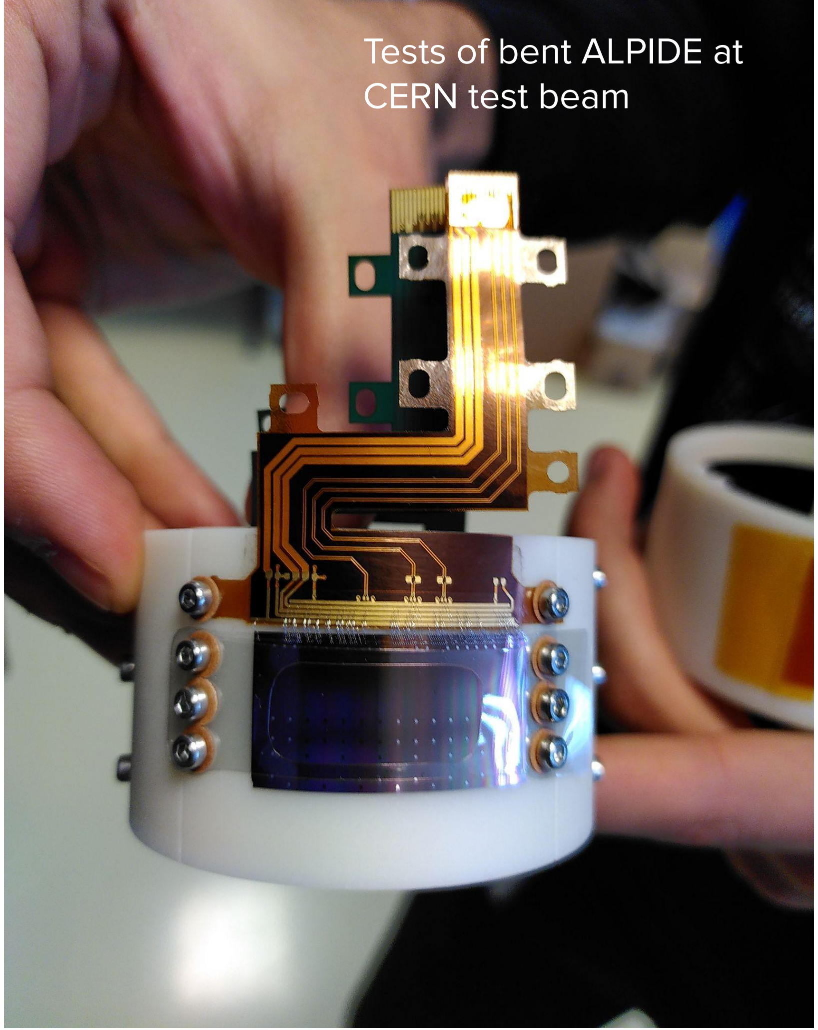
Timepix 4 now under investigation in our our lab: from 1.5 ns → 200 ps TDC bins!

K. Heijhoff et al 2021 JINST 16 P08009
doi:10.1088/1748-0221/16/08/P08009

ALICE3 fast timing with MAPS

Timing measurements: unoptimized chip already has only the order of 800 ps in the lab, O(ns) at test eam.

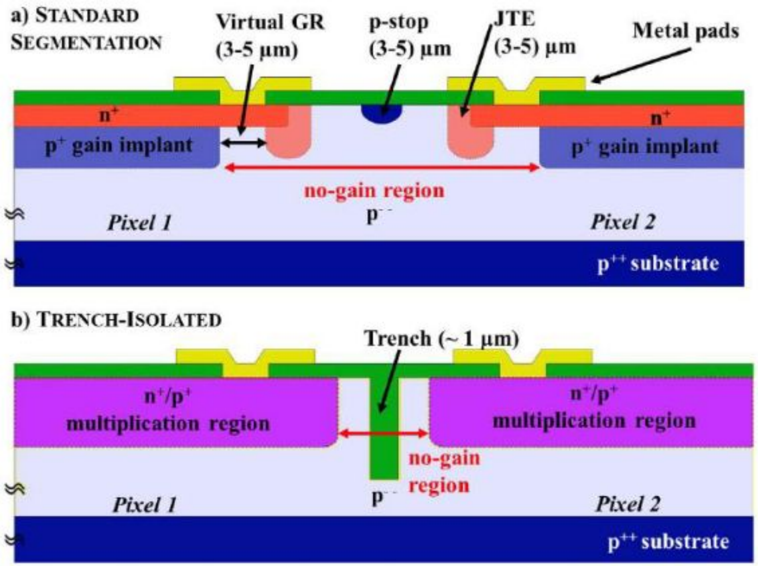




Tests of bent ALPIDE at CERN test beam

Trench isolated Low Gain Avalanche Diodes

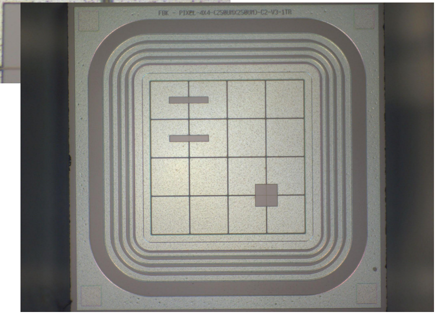
Larger sensitive area in the detector than standard LGADs: larger **fill factor**



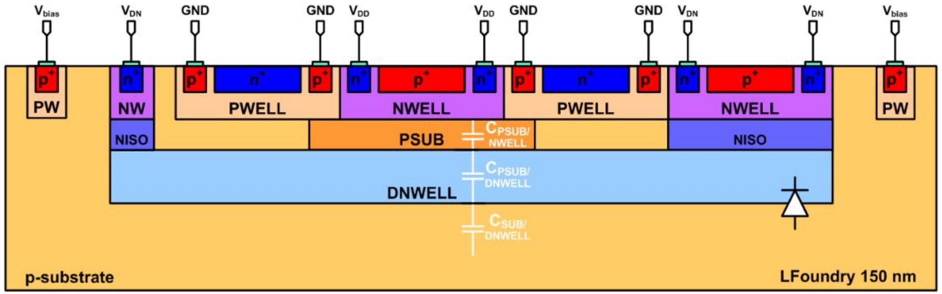
See also this talk at Vertex2021

Trench isolated LGAD will be bonded to Timepix4 ASIC

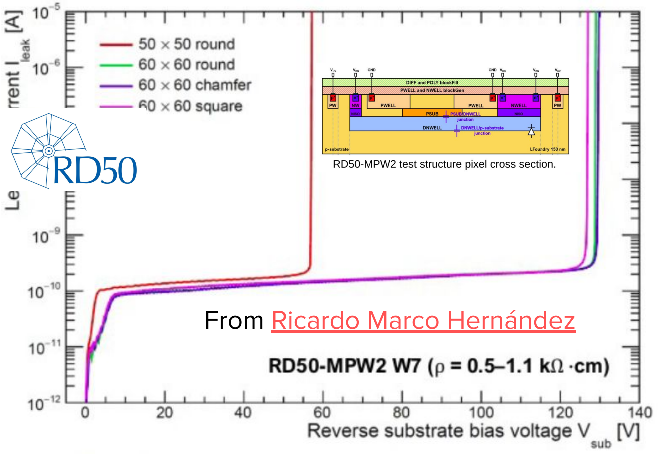
Need resolutions better than 10 um and 50 ps



Radiation hard depleted MAPS

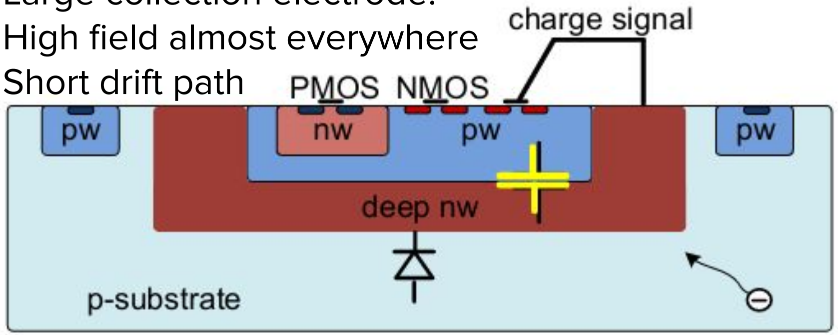


HV CMOS with a **larger collection electrode**:
fast collection time and **radiation tolerant.**

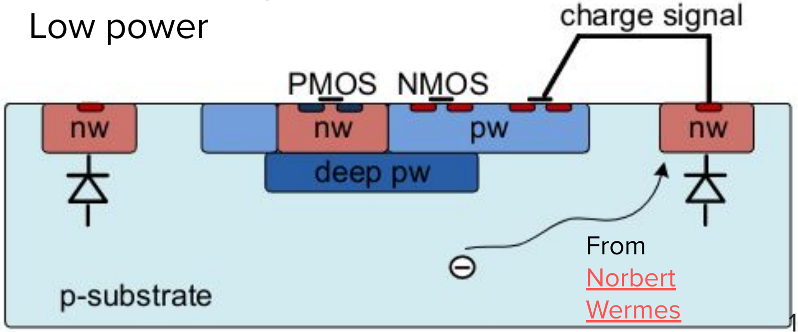


From Ricardo Marco Hernández

Large collection electrode:
High field almost everywhere
Short drift path



Smaller collection electrode:
Low sensor capacitance
Low power

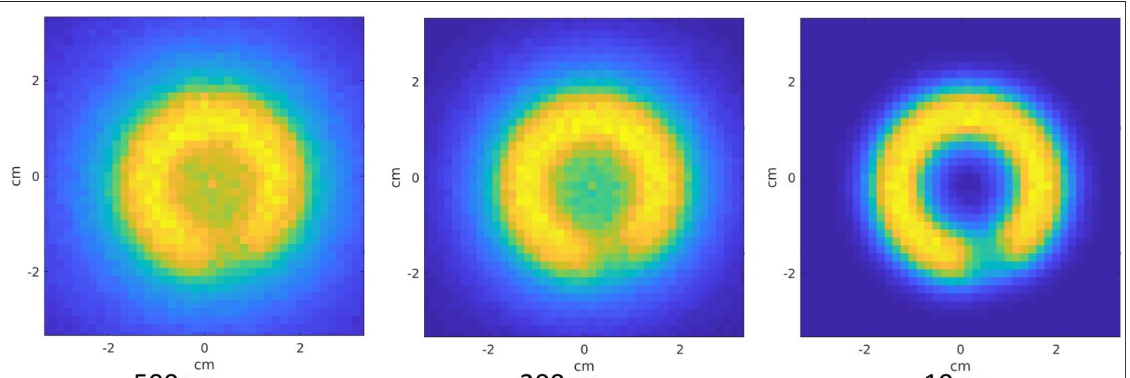


From Norbert Wermes

Applications beyond high energy physics

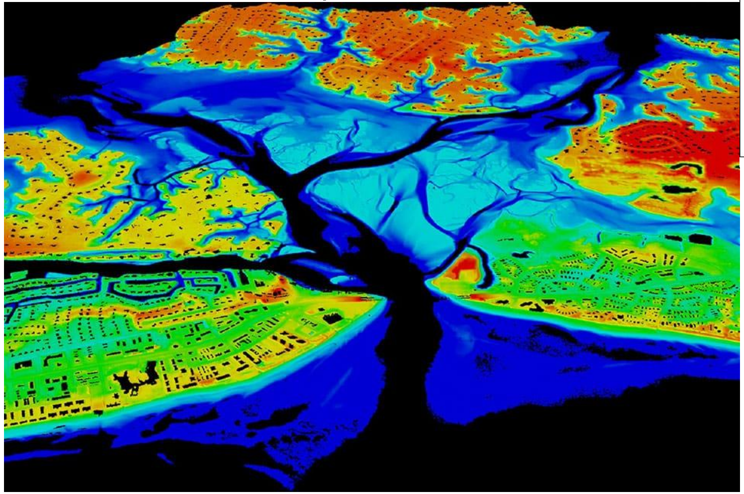
LiDAR, TOFPET, FLIM

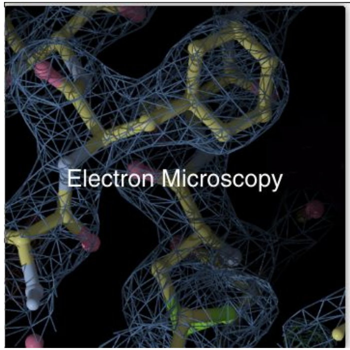
Time of flight positron emission tomography:
cardiac effect simulation
with a 4 cm diameter ring, 1 cm thick , with on 1 cm defect

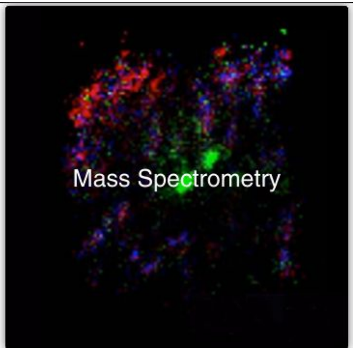


500 ps From M. Conti 200 ps 10 ps

Light detection and ranging (LiDAR) for
e.g. imaging earth’s biomass
905 nm → 20-50 µm active thickness







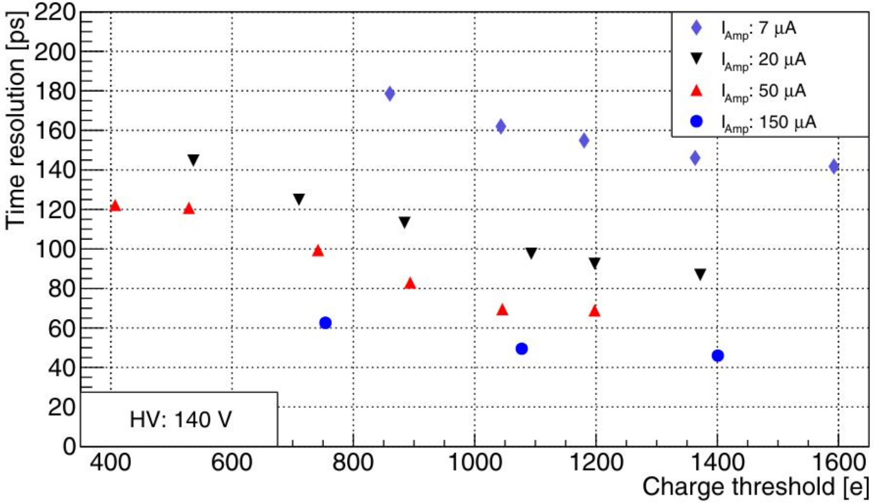
Fluorescence
lifetime
imaging
microscopy

https://velodynelidar.com Velodyne Lidar

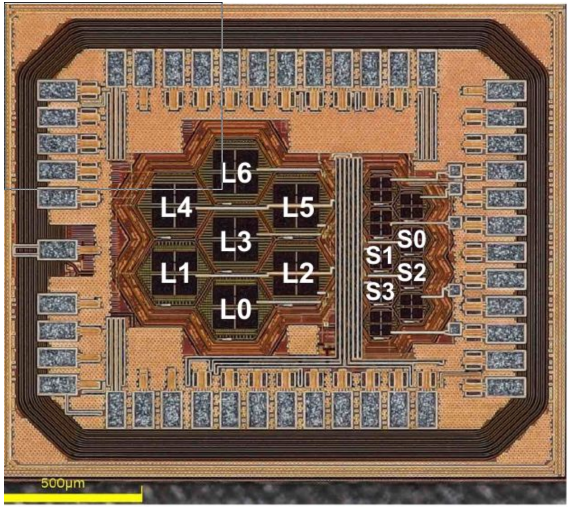
AMSTERDAM SCIENTIFIC INSTRUMENTS https://www.amscins.com

MonPicoAD ATTRACT project

- 140 ps at an amplifier current of 7 µA
- 45 ps at 150 µA



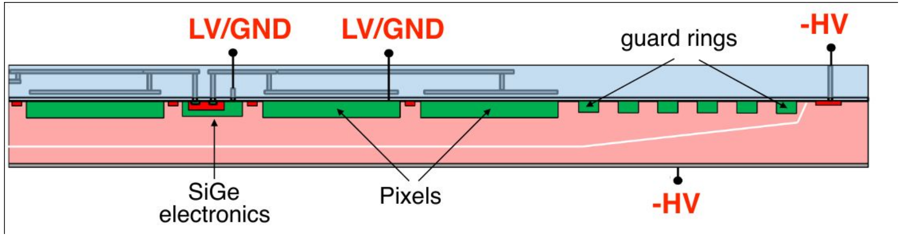
BiCMOS silicon germanium: SG13G2 technology from IHP Microelectronics



MonPicoAD

See also:

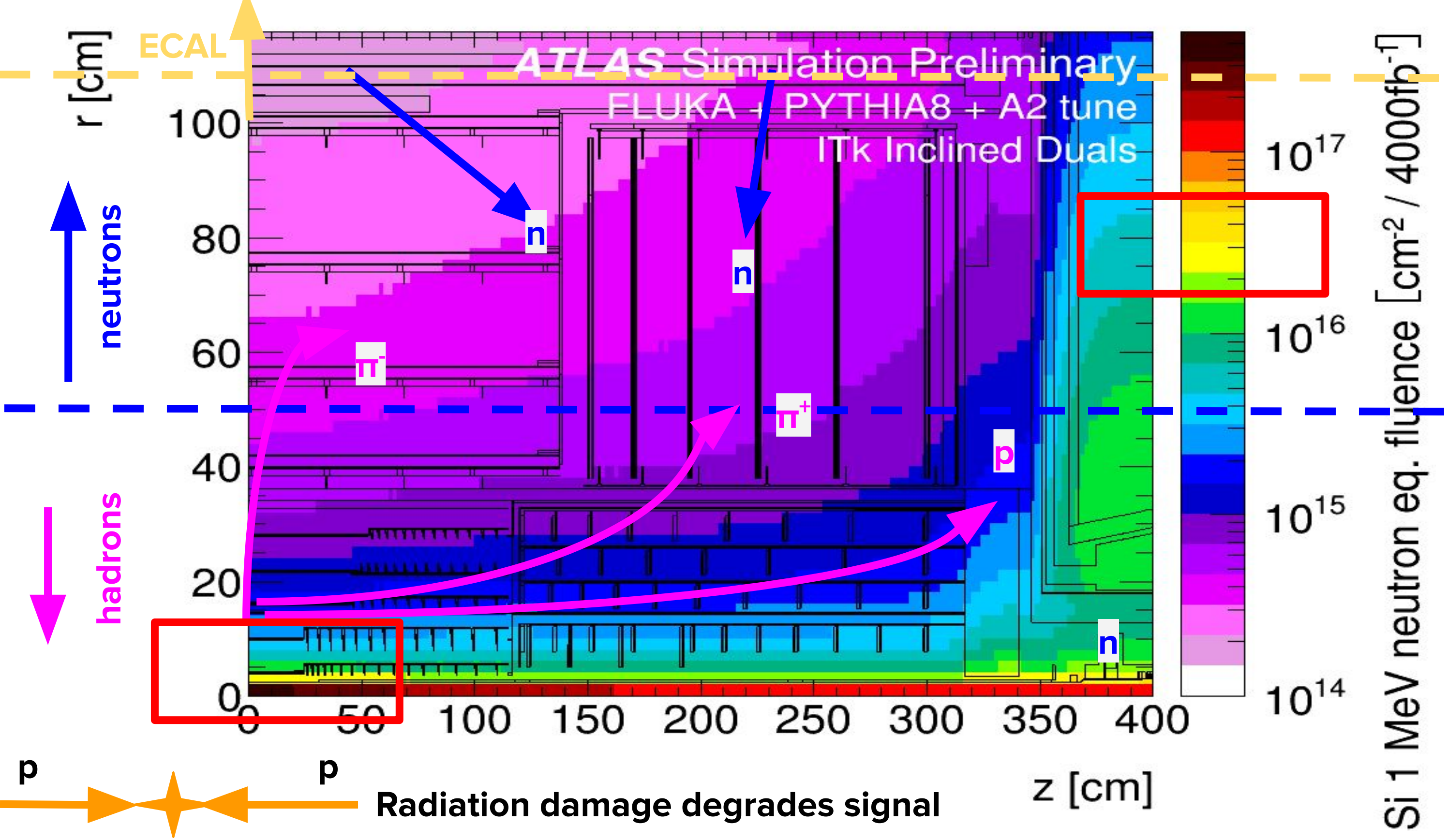
ARCADIA



L. Paolozzi et al 2020 JINST 15 P11025
doi:10.1088/1748-0221/15/11/P11025

Radiation damage

The particle detector dislikes particles

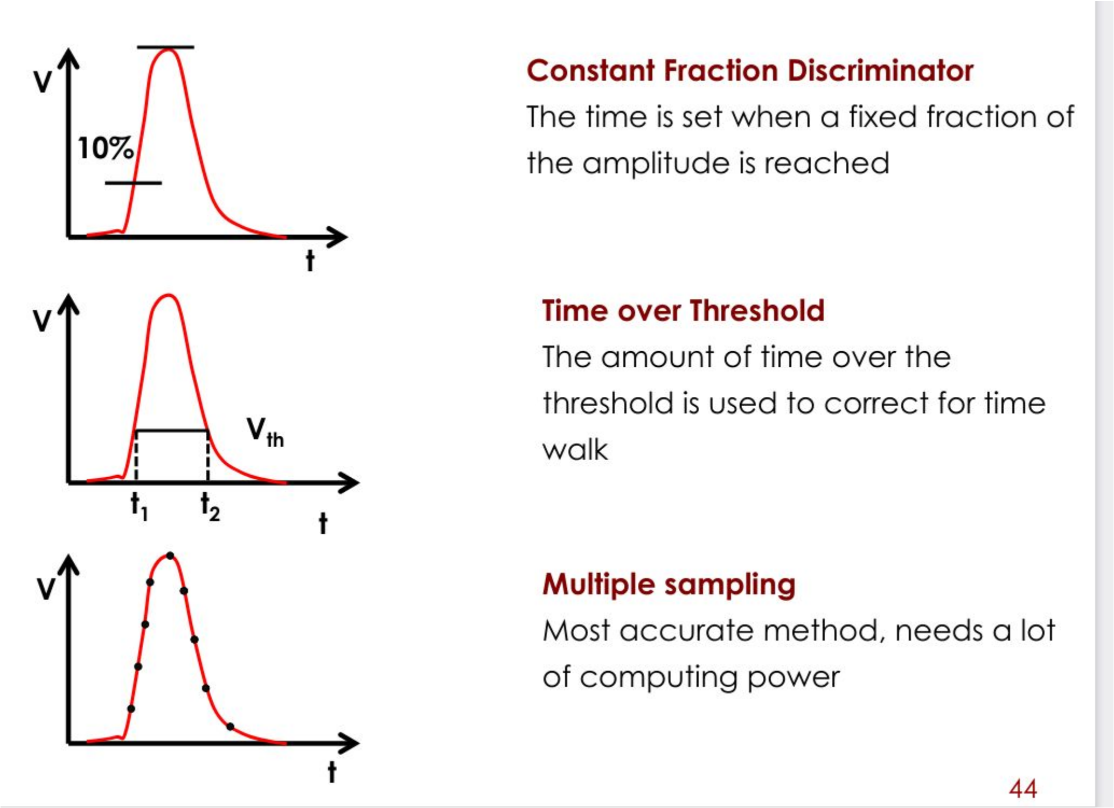


Radiation damage degrades signal

High luminosity LHC: high particle rates!
ATLAS
ITk will see
Φ_{eq} = 2.2e16 / cm^2

Particles damage the silicon sensor

Different circuits for measuring time



Constant Fraction Discriminator

The time is set when a fixed fraction of the amplitude is reached

Time over Threshold

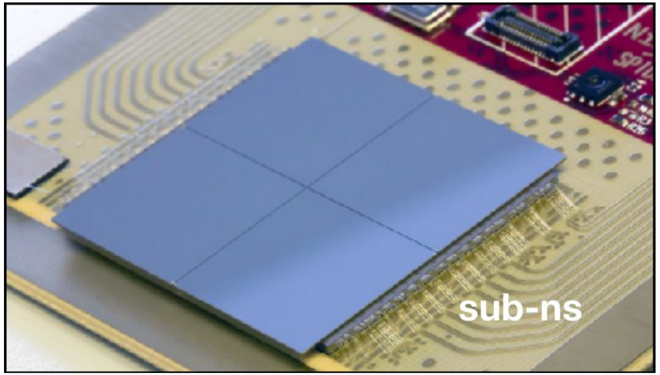
The amount of time over the threshold is used to correct for time walk

Multiple sampling

Most accurate method, needs a lot of computing power

Nikhef experience with fast ASICs and fast readout

Experience with development of
fast timing

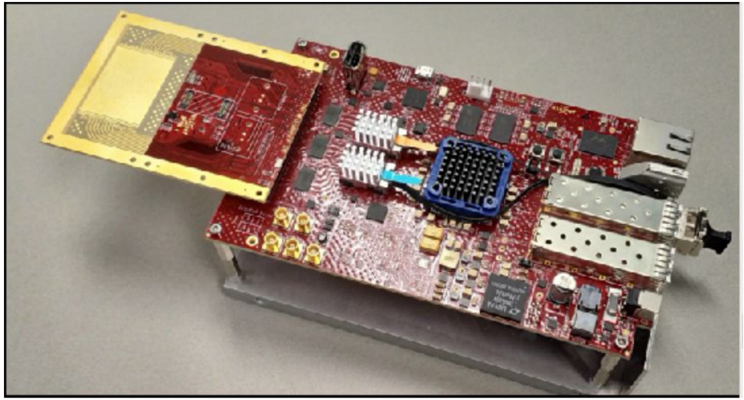


New Timepix 4 with 200 ps TDC time bins → ≈ 60 ps RMS time resolution
Developments continue to further improve time resolution

Nikhef in collaboration with CERN

Nikhef

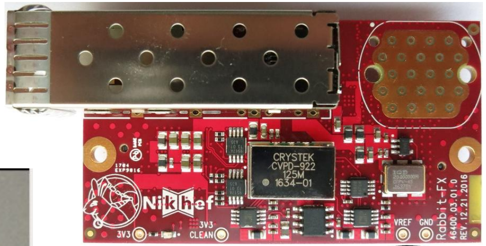
Experience with **Gigabit readout**



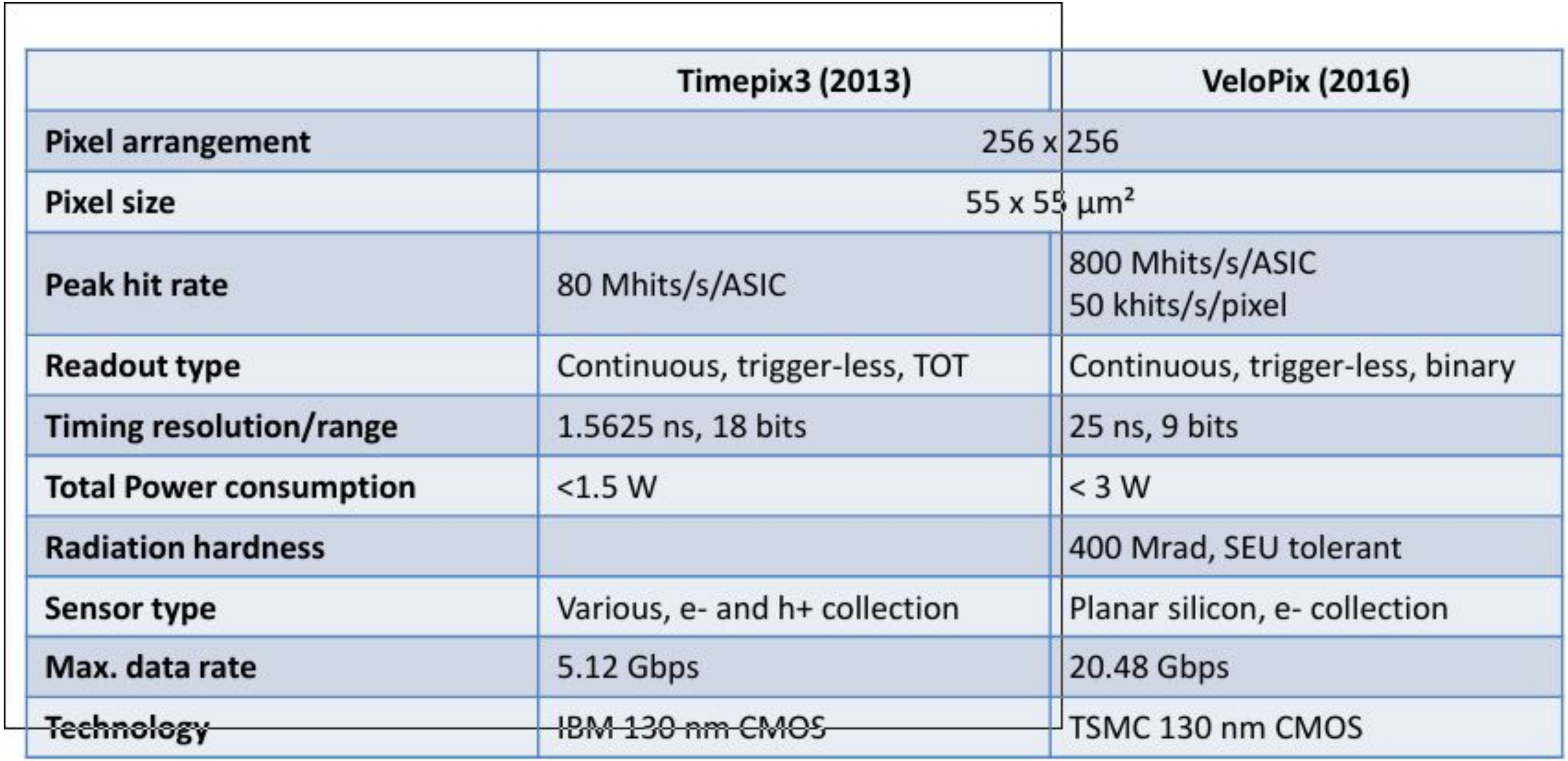
SPIDR4: Speedy PIxel Detector Readout developed for Timepix and Medipix chips

Nikhef in collaboration with CERN

Experience with **subnanosecond synchronization**



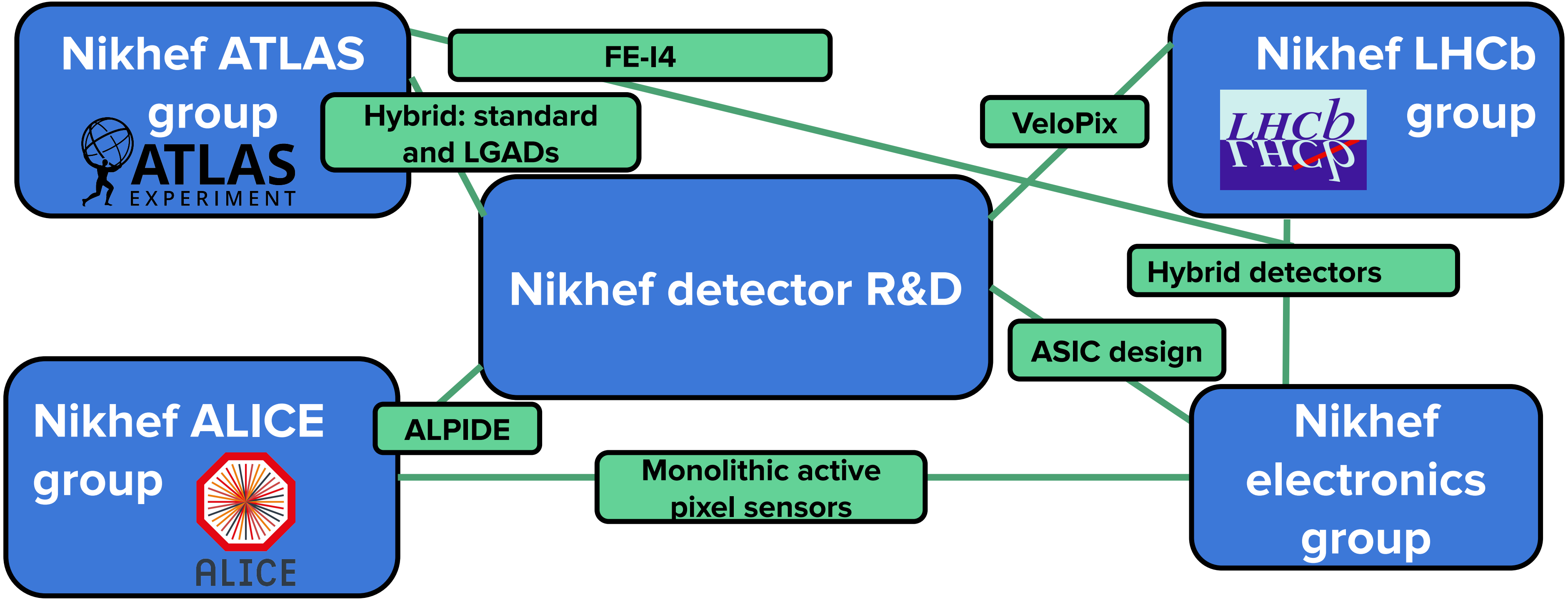
White Rabbit for subnanosecond synchronization over ethernet -- used by KM3Net, possibly ATLAS, ET-pathfinder



	Timepix3 (2013)	VeloPix (2016)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm²	
Peak hit rate	80 Mhits/s/ASIC	800 Mhits/s/ASIC 50 khits/s/pixel
Readout type	Continuous, trigger-less, TOT	Continuous, trigger-less, binary
Timing resolution/range	1.5625 ns, 18 bits	25 ns, 9 bits
Total Power consumption	<1.5 W	< 3 W
Radiation hardness		400 Mrad, SEU tolerant
Sensor type	Various, e- and h+ collection	Planar silicon, e- collection
Max. data rate	5.12 Gbps	20.48 Gbps
Technology	IBM 130 nm CMOS	TSMC 130 nm CMOS

From X. Llopart

Nikhef detector R&D with Nikhef LHC groups



Nikhef ATLAS group

FE-I4

Hybrid: standard and LGADs

VeloPix

Nikhef LHCb group

Nikhef detector R&D

Hybrid detectors

ASIC design

Nikhef ALICE group

ALPIDE

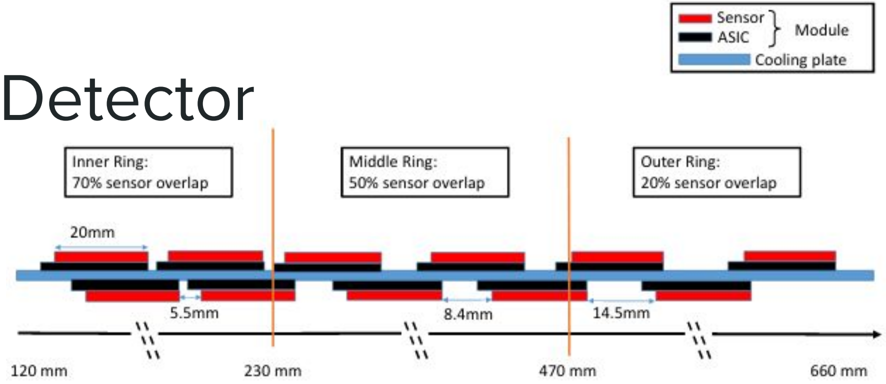
Monolithic active pixel sensors

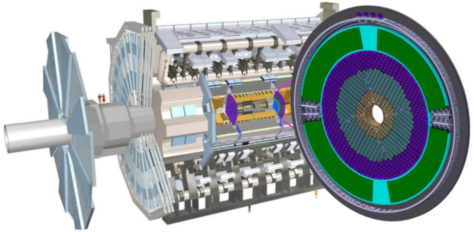
Nikhef electronics group

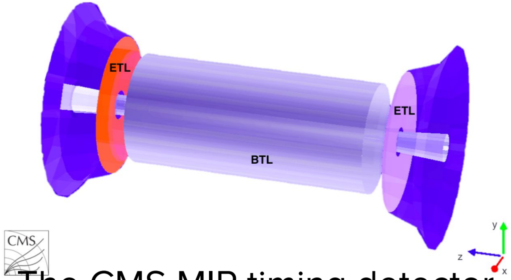
Work on fast timing in both MAPS and hybrid detectors

ATLAS High Granularity Timing Detector

- High lumi LHC: 4000 fb^{-1}
- z = ± 3.5 m
- Outside ITk
- In front of endcap calorimeters
- r = 120-640 mm
- CO_2 cooling @ -30 °C
- Overlapping double modules
- Time resolution per track (per hit) 25 ps (35 ps) for r = 120 mm
- After 4000 fb^{-1}: 42 ps (60 ps)
- Φ_{eq} = (5.5) 8.3e15 cm^{-2} , 7.5 (3.3) MGy
- **Half will be replaced**: < 230 mm after 1000 fb^{-1}, < 470 after 2000 fb^{-1}



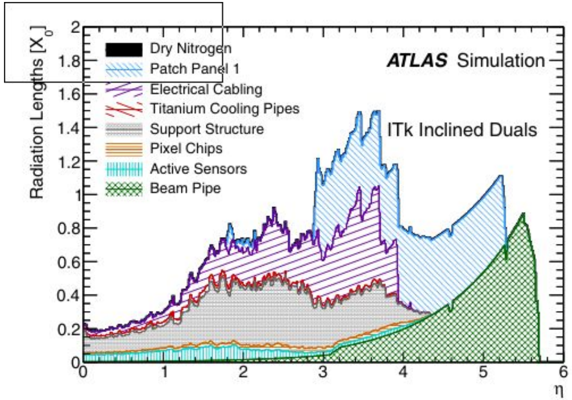


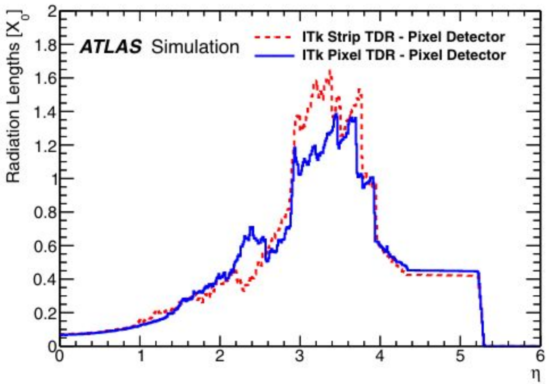


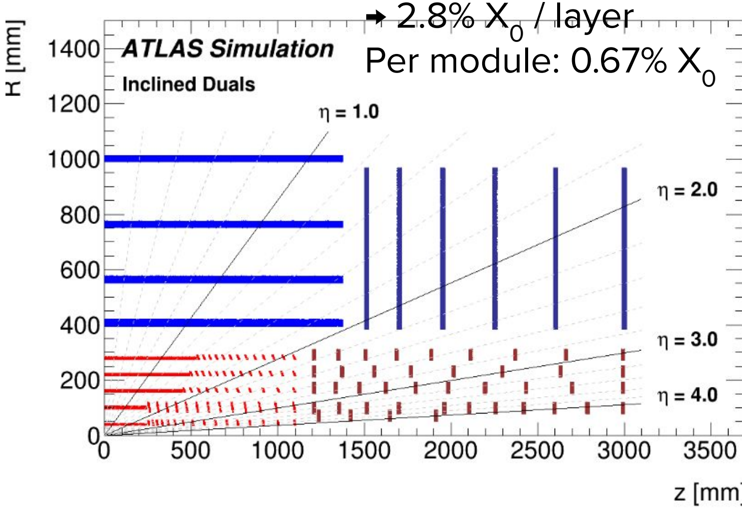
The CMS MIP timing detector also has a barrel layer with silicon photomultipliers

ITk TDR

ATLAS 2026 Inner Tracker (ITk) material budget



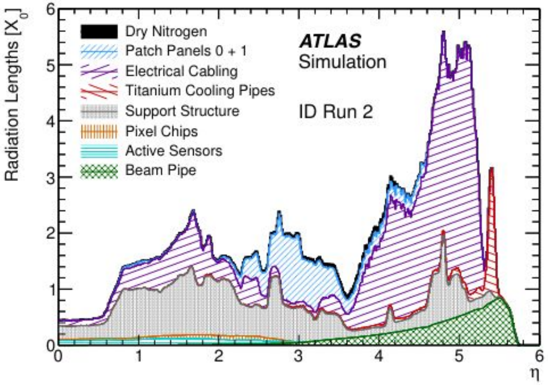


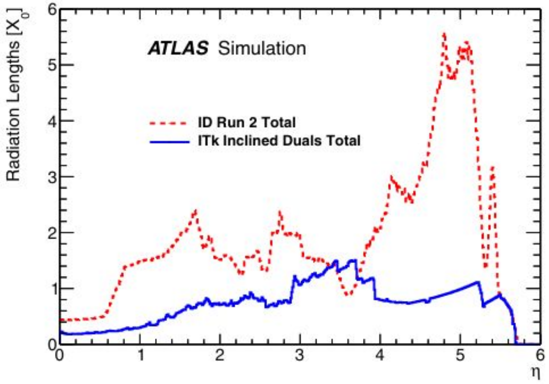


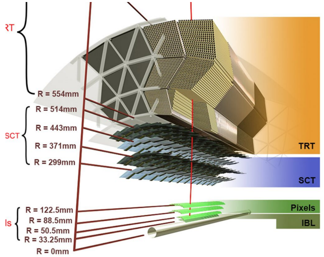
ITk: 9 layers, ~25%X_0

➜ 2.8% X_0 / layer

Per module: 0.67% X_0







Inner detector now:

4 layers, ~40%X_0

➜ 8% X_0 / layer