VCI 2019

VIENNA CONFERENCE ON INSTRUMENTATION

Instrumentation – state of the art and a look into the future

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CERN / EP

Abstract …

Progress in experimental physics relies often on advances and breakthroughs in instrumentation, leading to substantial gains in measurement accuracy, efficiency and speed, or even opening completely new approaches and methods.

The Experimental Physics Department of CERN has proposed a new technological R&D programme from 2020 onwards.

The programme covers the domains detectors, electronics, software and intimately connected domains like mechanics, cooling and experimental magnets.

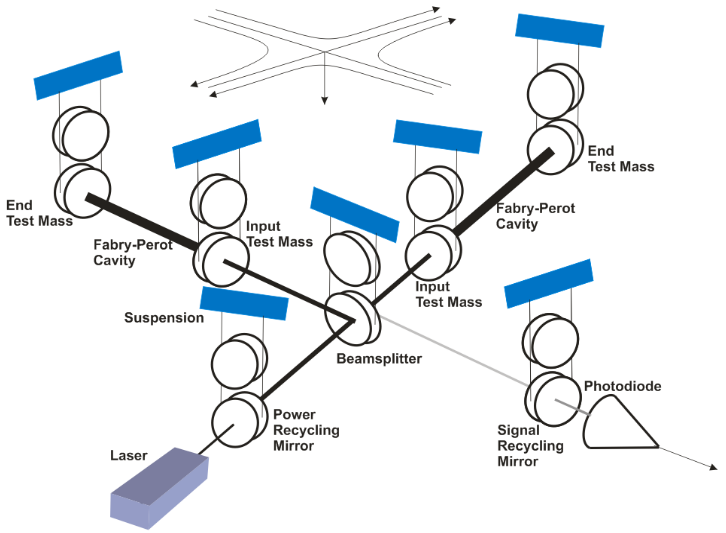
My mission (hopefully not impossible)

This talk will try to highlight new ideas, advances and breakthroughs presented at this conference and, whenever possible and meaningful, put them in relation to the planned R&D programme.

Is there a better example than Gravitational Waves ?

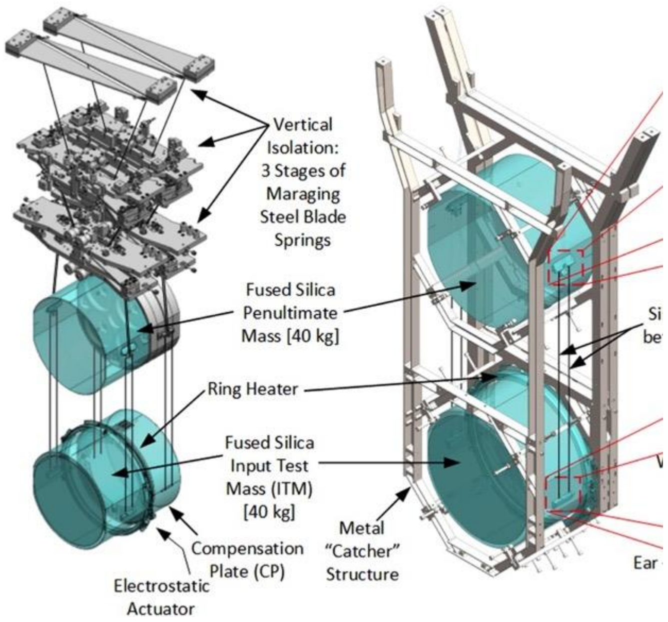
VCI highlights

Enhanced Michelson interferometry



+ extreme stability

+ perfect seismic isolation ... and noise fighting



Decades of systematic and innovative instrumentation R&D has been rewarded with the ground breaking discovery of grvitational waves, answering a century old question and **opening up a new way of astronomy**.

David Reitze: Searches for Gravitational Waves by LIGO and Virgo: Recent Results and Future Plans

Strategic R&D Programme on Technologies for future Experiments

- Concept
- Process
- Scope and themes
- Implementation & Budget

https://ep-dep.web.cern.ch/rd-experimental-technologies
(you find some more links there)

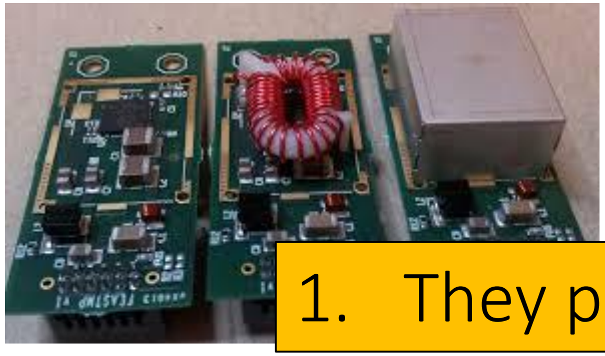
Excuses

- The new R&D program is an initiative of the CERN EP Department.
- My talk is therefore rather HEP / CERN – centric.
- Lots of excellent contributions to this conference remain unmentioned.

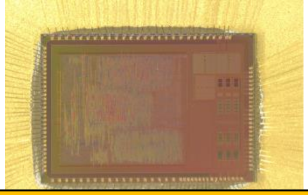
Quiz: What have these things in common ?

EP R&D

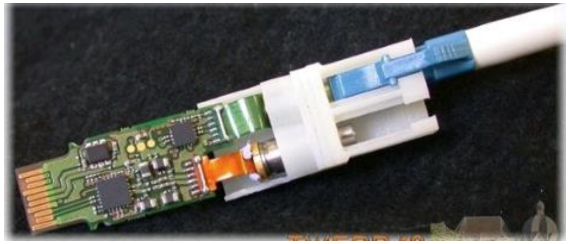
Rad hard DC-DC converters



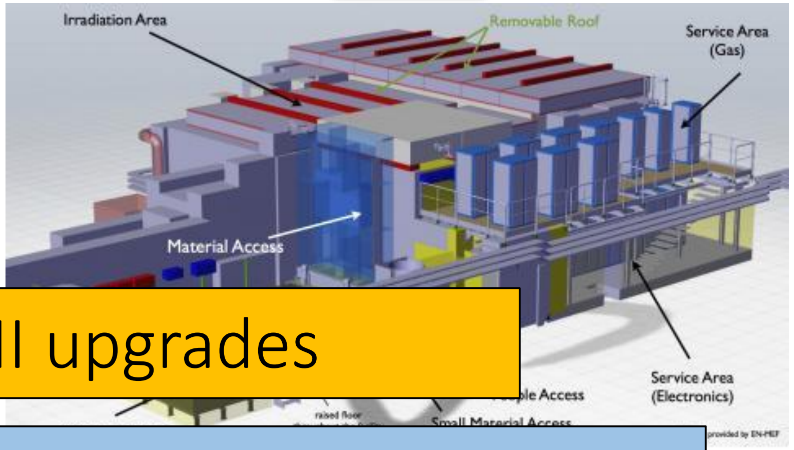
ASICs in 130 nm technology



Versatile links



GIF++

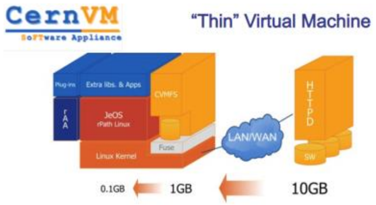


1. They play major roles in the LHC phase-I/II upgrades

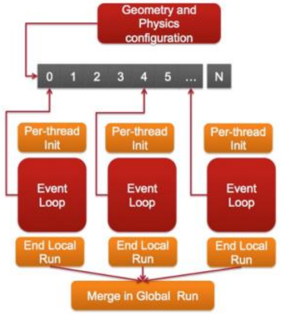
2. They were initiated/boosted during the ''White Paper'' R&D program

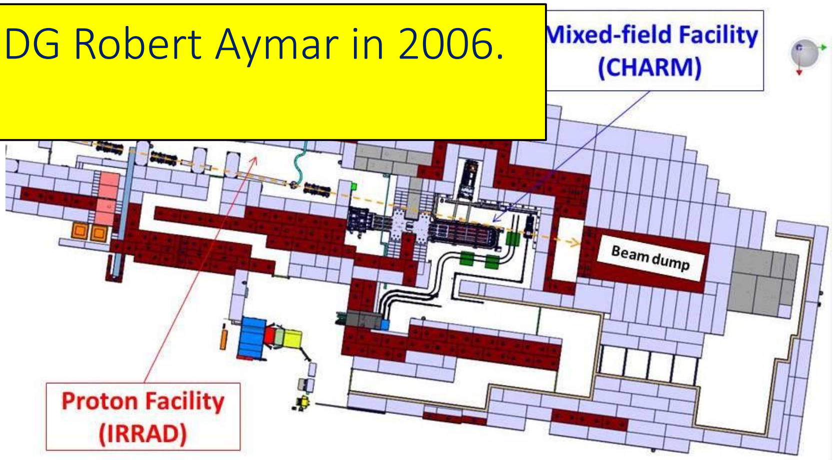
White Paper R&D program (2008-2011), based on an initiative of CERN DG Robert Aymar in 2006. R&D budget in PH department ~20 MCHF (60% of what was asked).

Virtualisation



Multi core architectures





A bit of history (for the younger generation)

EP R&D

In the 1990s, we had a large-scale R&D program, monitored by the Detector R&D Committee (DRDC)

http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html

RD-1	Scintillating fibre calorimetry at the LHC.	
RD-2	Proposal to study a tracking/preshower detector for the LHC.	
RD-3	Liquid argon calorimetry with LHC-performance specifications.	
RD-4	Study of liquid argon dopants for LHC hadron calorimetry.	
RD-5	Study of muon triggers and momentum reconstruction in a strong magnetic field for a muon detector at LHC.	
RD-6	Integrated high-rate transition radiation detector and tracking chamber for the LHC.	
RD-7	Proposal for Research and Development on a central tracking detector based on scintillating fibres.	
	⋮	
RD-18	New fast and radiation hard scintillators for calorimetry at LHC.	★ Crystal Clear Collaboration. KT collaboration contract
	⋮	
RD-42	(pCVD) diamond as a material for tracking detectors.	★ L
	⋮	
RD-47	High energy physics processing using commodity components HEP PC.	
RD-48	Further work on radiation hardening of silicon detectors.	
RD-49	Proposal for studying radiation tolerant ICs for LHC .	
RD-50	Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders	★ L
RD-51	Development of Micro-Pattern Gas Detectors Technologies	★ L
RD-52	Dual-Readout Calorimetry for High-Quality Energy Measurements	
RD-53	Next generation of readout chips for the ATLAS and CMS pixel detector upgrades	★ L

The two R&D programmes were crucial for:

- Design and construction of LHC (v1) detectors
- LHC phase I/II upgrades

★ active

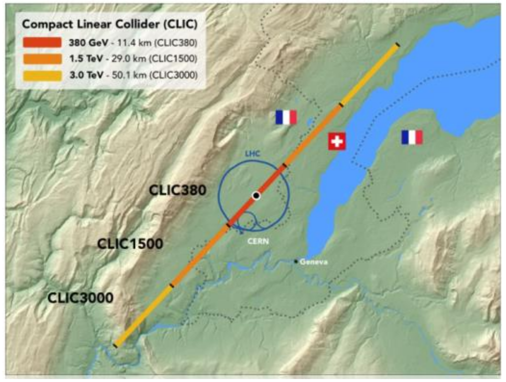
L LHCC monitored

At the high energy frontier: Experimental landscape beyond upgrades in LS3 is vague.
Update of ESPP (2018-2020) should give some hints (hopefully).

Current studies like FCC (hh/ee), ILC, CLIC, give us quite clear ideas what the future experimental challenges could be.

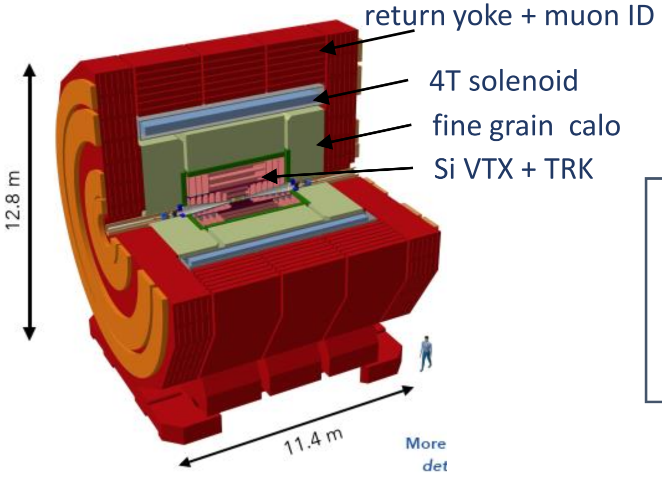
EP R&D

Lepton colliders



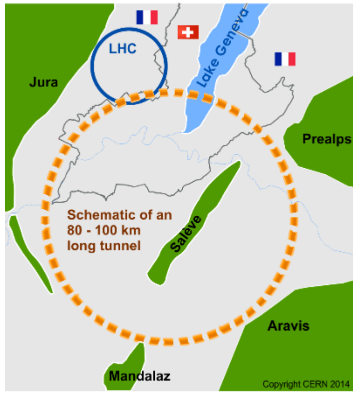
CLIC

- E_{CM} = 380 – 3000 GeV
- L = 1.5 – 6 $\cdot 10^{34}$



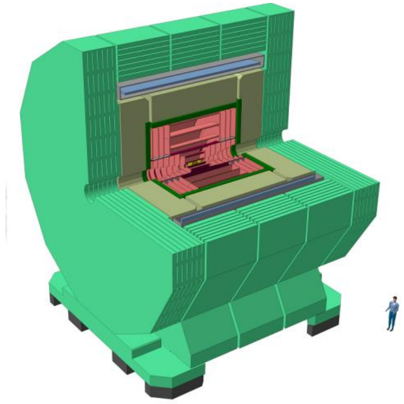
FCC-ee

- E_{CM} = 91 – 365 GeV
- L = 460 – 3 $\cdot 10^{34}$ $cm^{-2}s^{-1}$



FCC-ee studies are based on a CLIC-like Detector (CLD) scaled in size and B-field from the CLIC detector.

- Very high vertexing precision (impact parameter resolution)
- VTX & TRK with as little mass as possible
- Calorimeters with adequate segmentation for particle flow
- Radiation and data rates are no major problems



- Special bunch train structure (300 x 0.5ns)
  → triggerless readout of a full BT
  → power off on-det. electronics in-between BT

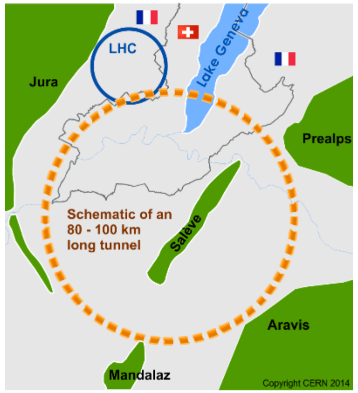
- There exists also an IDEA concept, optimised for tracker transparency (drift chamber), dual readout calorimeter behind a thin solenoid

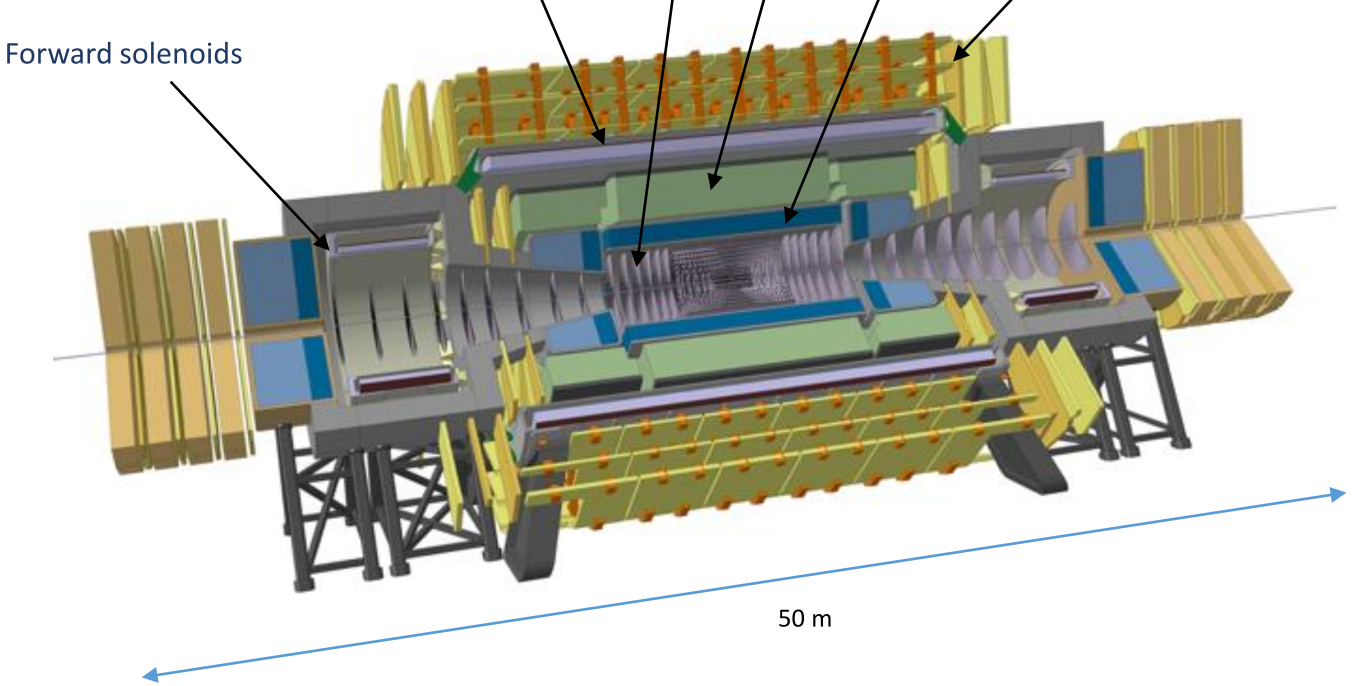
50 m

Circular hadron collider (FCC-hh), 100 TeV

w.r.t. HL-LHC ($L = 5 \cdot 10^{34}\ cm^{-2}s^{-1}$)

- E_{CM} ↗ x7
- L ↗ x6
- Ldt ↗ x10
- pile-up x 7 (μ = 1000) → timing !
- hit rates x 10
- data rates x 10
- radiation levels x 10
- Larger and stronger magnet





Considerations for an R&D programme

EP R&D

Development cycles are long: ~1 decade (see White Paper R&D)

R&D for LHC phase-II upgrades comes to an end around 2020

R&D requires expertise, experience, infrastructure and continuity.

→ It's the right time now to define a new R&D programme

But: The choice of the next accelerator/experiment is still unclear!

Let's define a 'strategic' technological R&D programme, rather than an experiment specific programme.

Its results shall enable future projects to develop and build optimal detectors.

Which topics ?

Essential detector technologies, but equally important are mechanics, infrastructure, electronics, software and experimental magnets

Resources are limited → Selection and priorities were needed. Focus on areas…

- where we have significant expertise and infrastructure
- where we play (need to play) a leading/ unique role
- which will be key for the success of future projects
- where a failure could be a show stopper

Process

Steering Committee: Formation of 8 working groups

20 Nov 2017

Kick-off meeting

- Announce idea at CERN
- Collect requirements, HL-LHC, FCC-(ee/hh), CLIC

Bottom-up! Lots of input from community, also from external groups. 480 people signed up to WGs!

16 March 2018

R&D workshop I

- working groups present ideas and R&D options.
- 450 participants

Negotiations with steering committee. A bit more top-down!

Some interaction with community

25 September 2018

R&D workshop II

- Selected topics
- Concrete work plans
- R&D report (draft)

Workshop 1, 16 March 2018

1 Nov 2018

EP retreat

- Presented plan and budget to EP dept. and Director General

WP1: Silicon Sensors

Module development

Novel hybrid pixel detectors
Ultimate time/space accuracy and rad hardness

Monolithic pixel detectors
Cost effective depleted CMOS for ee and hh

Simulation and characterization

Focus on Pixel Detectors

WP2: Gas Detectors

Solutions for large area gas based detector systems
GEMs, μ–megas or μRWELL
Industrialisation & performance scaling

Tools
- Gas studies,
- Simulation and modelling,
- Electronics and instrumentation

Novel technologies
- Very fast gas detectors
- Additive production techniques

WP3: Calorimetry + Light based

LAr
Electrodes, σ_t, high ionisation rates, feedthroughs

In/organic scint.
Tile-cal, hi segm. fibre cal., rad hard

Hi granularity Si
CMS HGCAL
+ …

RICH
- Light weight mirrors
- Low temp photosensor housing

SciFi
- Fibre light yield
- Fibre production techniques

WP4: Mechanics++

Low mass structures
- Vertex detectors
- Cryostats for calorimetry + magnets

Cooling techno-logies
- Methods (gas/liquid)
- Coolants (GWP)
- Piping and instrumentation

Interfaces and service architectures for automated installation and maintenance, in future high radiation environments

WP5: IC Technologies

CMOS

28 nm planar
16 nm FinFET
- Process selection
- Qualification
- Enablers

Design & micro Blocks
- Volt. ref.
- LN amp.
- ADC, DAC
- PLL,DLL, TDC
- …

Assembly Techno
- TSV
- 28 nm on 12''

Power distribution
- On-chip power management

WP6: High Speed Links

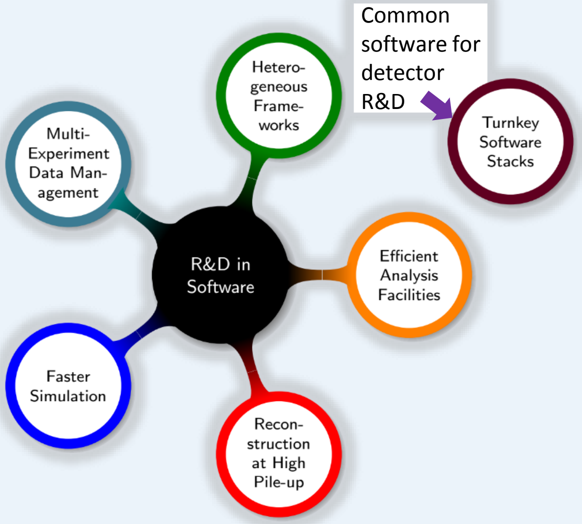
ASICs
- Aggregator /transmitter
- Optoelectronics drivers
- Low-mass elec-trical cable transmission

Opto-electronics
- Si Phot. system & chip design
- Si Phot. rad hardness
- Next-gen VCSEL-based optical link
- Si Phot. packaging

FPGA
FPGA-based system for testing and emulation

Focus on bandwidth + rad hardness

WP7: Software



WP8: Exp. Magnets

Reinforced Super Conductors and Cold Masses

Ultra-Light Cryostat Studies (with WP4)

Advanced Magnet Powering

Magnet Controls, Safety & Instrumentation

Design of a 4 T General Purpose Magnet Facility for Detector Testing

Implementation, organisation and Budget

- 8 work packages with 38 activities
- Launch activities in 2020 (gradually), for initially 5 years
- **Whenever there is thematic overlap, we search for cooperation with external groups.**
- Possibility to form new R&D collaborations (like RD50, RD51, RD53) is being discussed. → Bundle/focus activities. Attract new groups and resources.
- At CERN, main part of work will be carried by Fellows and Students. Embedded in existing work environments, supervised by experts.

We have worked out detailed work plans (milestones, deliverables) and cost estimates

- material
  longer term investment
  (lab, instruments)

- fellows
- students

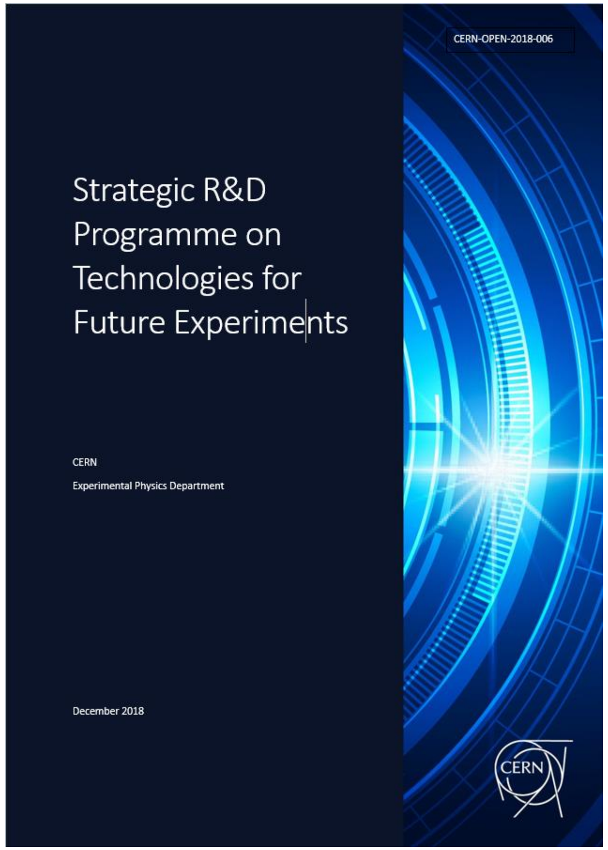
} 90 – 100 persons

CERN management is supportive, however we are lacking at this moment still a substantial part of the budget.

Summed over 5 years, this is a large investment

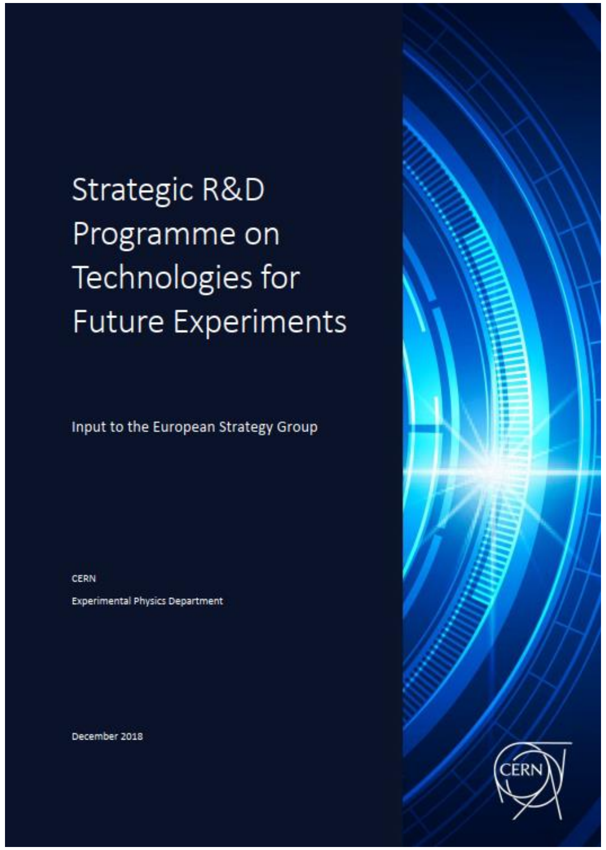
→ we have to ensure systematic follow-up, steering and transparent reporting

Documentation



R&D report, CERN-OPEN-2018-006,
~100 pages

https://cds.cern.ch/record/2649646

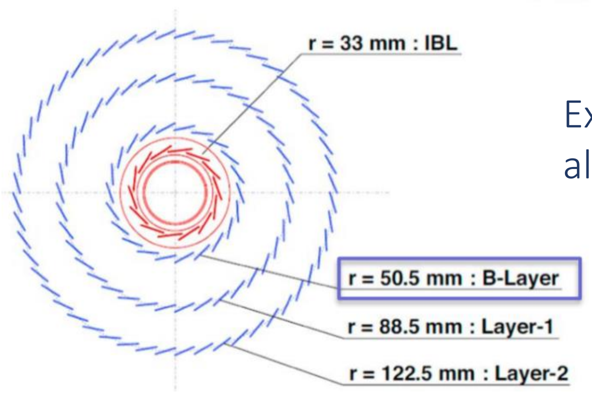


Input to the European Strategy Group, 10 pages
→ see EP R&D website

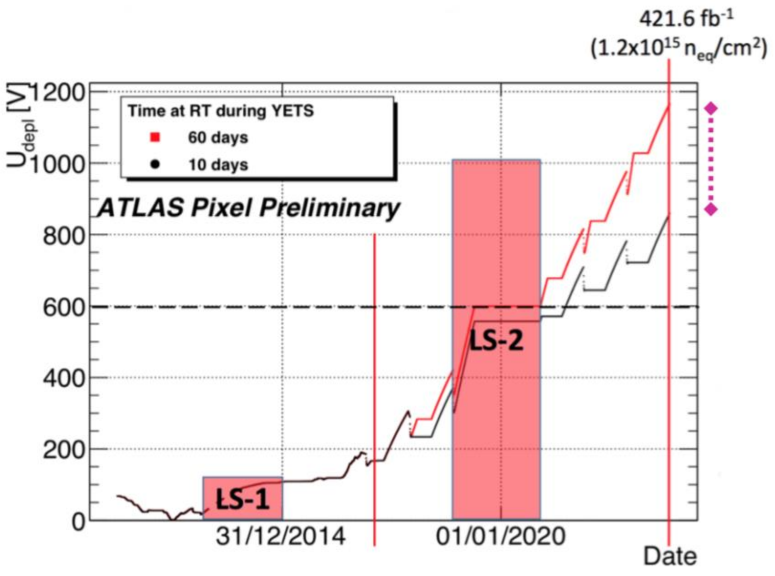
Solid state vertex and tracking detectors

Current ATLAS and CMS pixel detectors

VCI highlights



Excellent performance (ε > 98%), also at high PU (60)

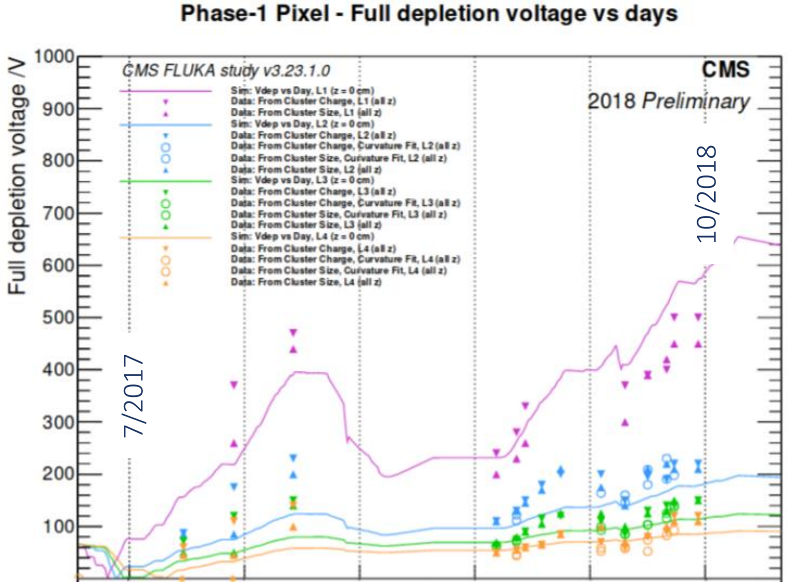


… but at the end of run 3 the detector will have reached its lifetime.

4 layers + endcap disks

A bit younger (installed only in 2017), with some new technologies (CO_2, DCDC,…) to be used in phase-2-

Excellent performance (ε > 97.5% on L1), up to $2x10^{34}$. L1 will be replaced in LS2.



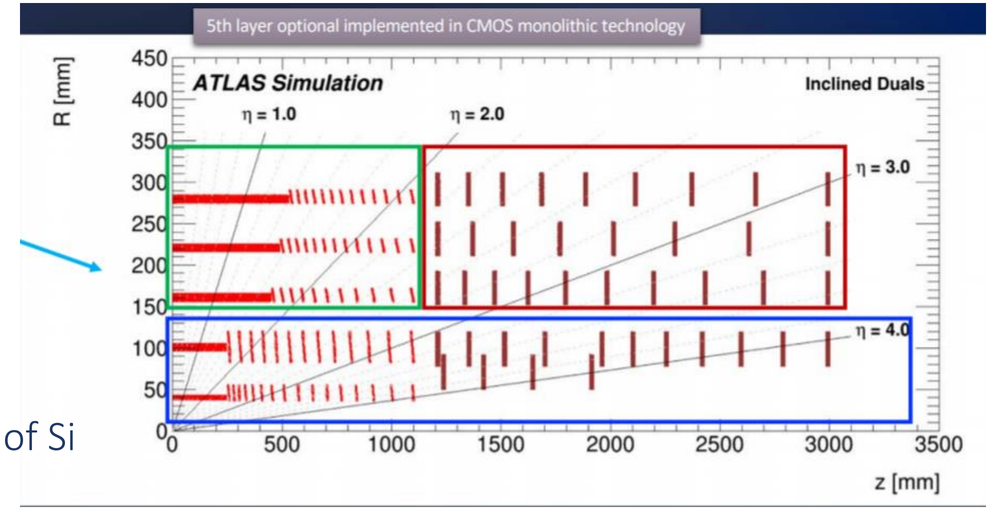
… but at the end of run 3 the detector will have reached its lifetime.

Kerstin Lantzsch: Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider

Benedikt Vormwald: Operational Experience of the Phase-1 CMS Pixel Detector

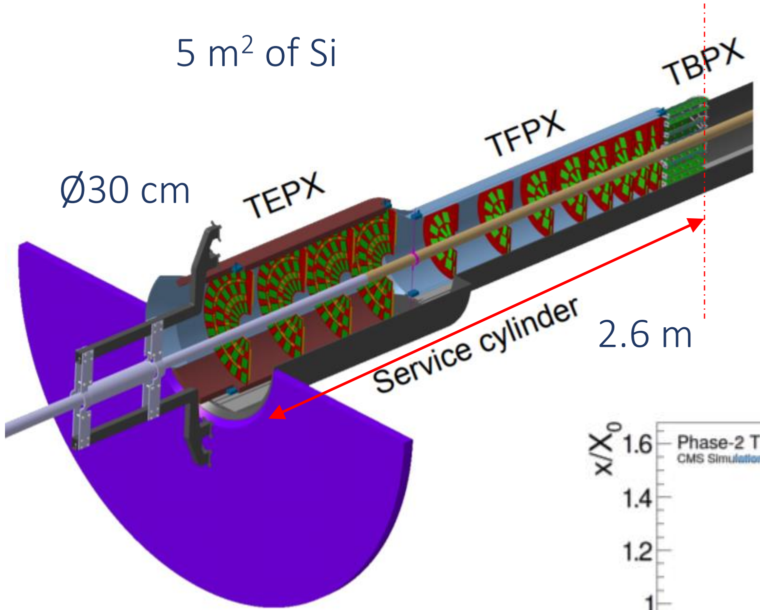
ATLAS and CMS pixel detectors for HL-LHC

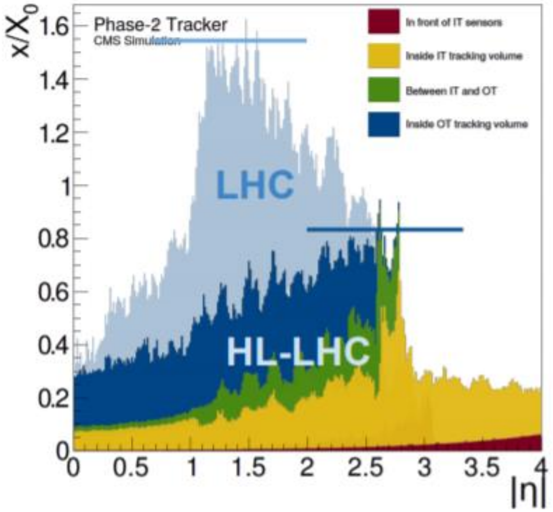
VCI highlights



13 m² of Si

5 m² of Si





Significant material reduction

Lots of common development and technologies:

- Pixel chips will be based on common RD53 development → First submission of **RD53A** (65 nm) worked!
  Planar n-in-p sensors
- 3D-sensors for innermost layer (CMS hasn't decided yet)
- CO_2 cooling
- Serial powering
- LpGBT

Lots of common development and technologies

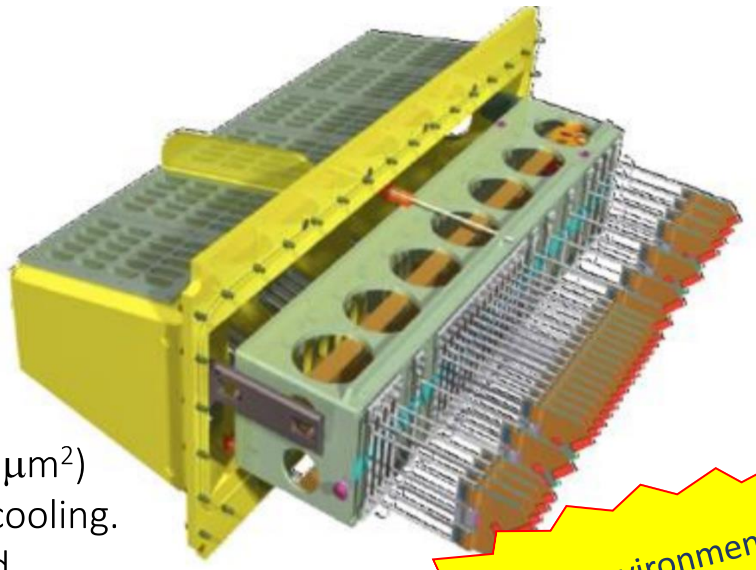
Tobias Flick, Module and System Test Development for the Phase-2 ATLAS ITk Pixel Upgrade

Giacomo Sguazzoni, The CMS Pixel Detector for the High Luminosity LHC

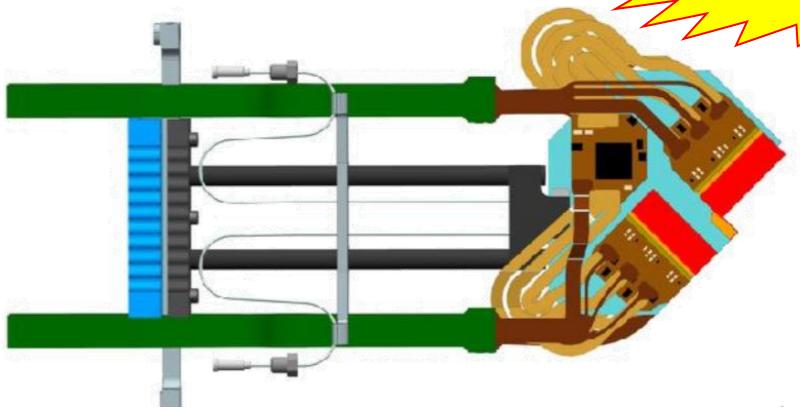
LHCb VELO upgrade I (LS2)

VCI highlights

L=2×10^{33} $cm^{-2}s^{-1}$
Up to 8×10^{15} n_{eq}/cm^2



Pixel design (55 x 55 μm^2) with micro-channel cooling. Better resolution and higher efficiency than current VELO.



Complex environment. Integration of very precise timing in pixel chip.

VELO upgrade II (LS4)

LHCb at L=1.5×10^{34} $cm^{-2}s^{-1}$, pile-up = 42

- Conditions 10 x more difficult than for upgrade I
- Move towards 4D tracker concept with addition of timing:

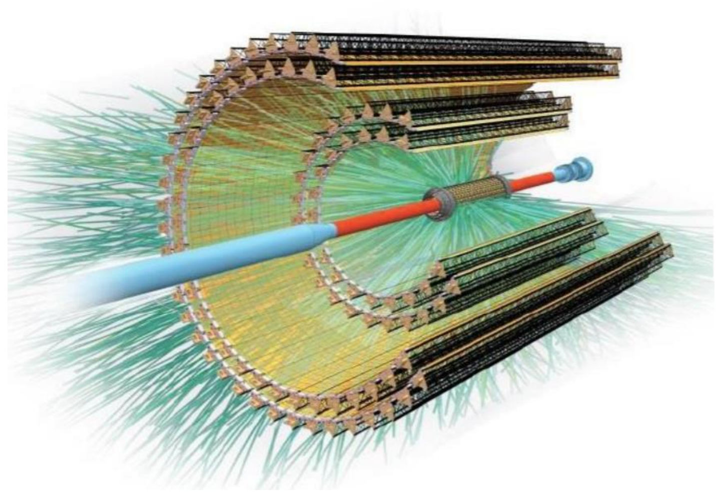
	LS2		LS4
	VeloPix (2016)	**Timepix4 (2018/19)**	**Possible future Picopix? (2024?)**
Technology	130 nm	65 nm	28 nm?
Pixel Size	55 x 55 μm	55 x 55 μm	55 x 55 μm?
Pixel arrangement	3-side buttable 256 x 256	4-side buttable 512 x 448	4-side buttable 256 x 256?
Sensitive area	1.98 cm^2	6.94 cm^2	1.98 cm^2?
Event Packet	24 bit	64-bit	64-bit?
Max rate	~400 Mhits/cm^2/s	178.8 Mhits/cm^2/s	~4000 Mhits/cm^2/s?
Best time resolution	25 ns	~200ps	~20-50 ps?
Readout bandwidth	19.2 Gb/s	≤81.92 Gb/s	~500 Gb/s?

Paula Collins, The LHCb Upgrade(s) and the VELO

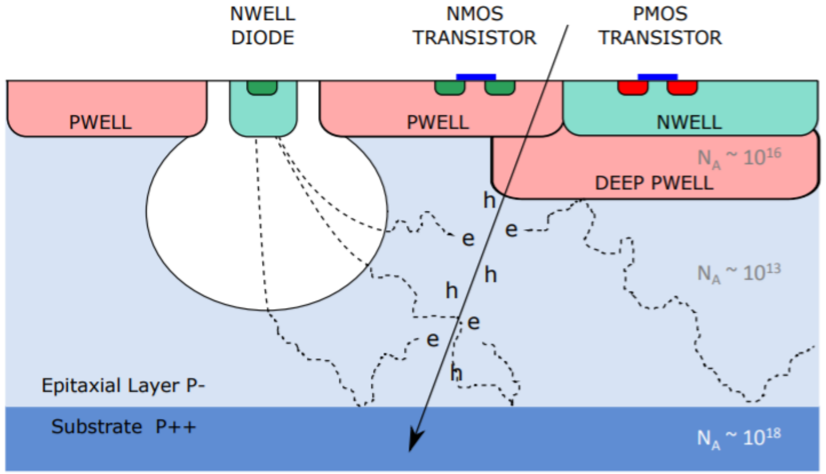
A new ITS for ALICE based on CMOS monolithic pixels

VCI highlights

A new ITS in LS2 (+ lots of other ALICE upgrades)

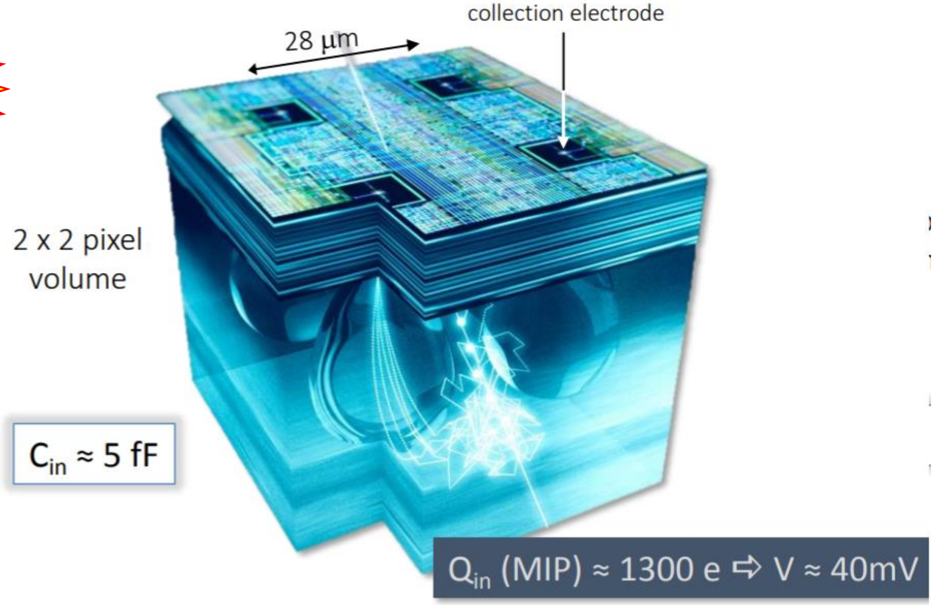


ALPIDE
CMOS Pixel Sensor using 0.18μ CMOS Imaging Process (TowerJazz 180 nm)



First MAPS tracker in a LHC experiment

- 7 layers
- 10 m^2 active silicon area (12.5 G-pixels)
- Pixel size 28 x 28 μm^2
- Spatial resolution ~5 μm
- **material / layer** 0.35%X_0 (inner layers)
- Power density < 40 mW / cm^2
- Max readout rate 100 kHz (Pb-Pb) 1MHz (pp)



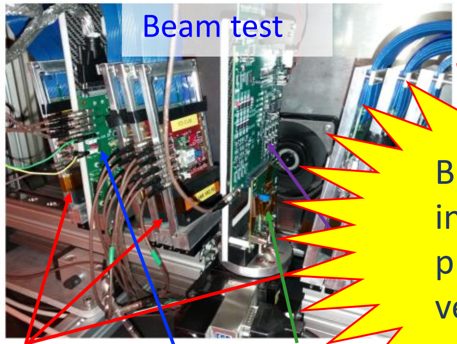
Wladyslaw H. Trzaska, New ALICE Detectors for Run3 and 4 at CERN LHC
Luciano Musa

CLIC vertex and tracker R&D

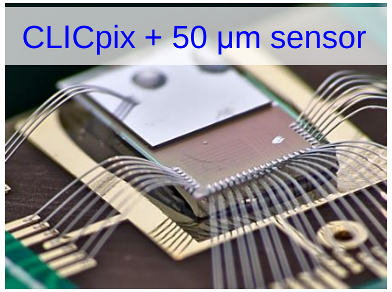
VCI highlights

Sensor + readout technologies

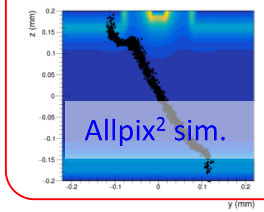
Sensor + readout technology	Currently considered for
Bump-bonded Hybrid planar sensors	Vertex
Capacitively coupled HV-CMOS sensors	Vertex
Monolithic HV-CMOS sensors	Tracker
Monolithic HR-CMOS sensor	Tracker
Monolithic SOI sensors	Vertex, Tracker

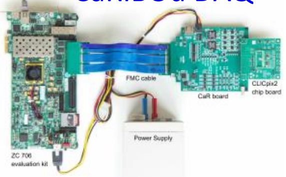


Broad and innovative R&D program on vertex detectors

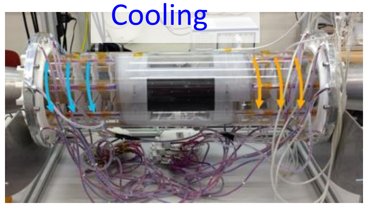


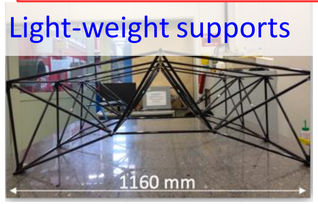
Simulation/Characterisation

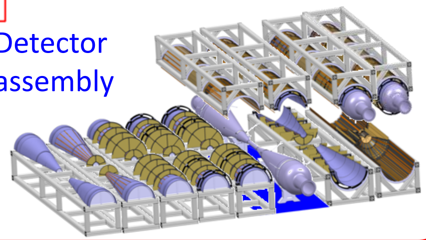




Detector integration







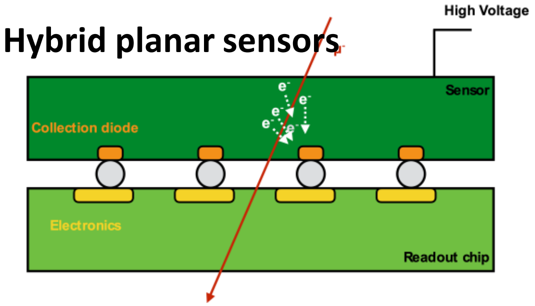
- Challenging requirements lead to extensive detector R&D program
- ~10 institutes active in vertex/tracker R&D
- Collaboration with ATLAS, ALICE, LHCb, Mu3e, AIDA-2020

Dominik Dannheim: Pixel detector R&D for CLIC

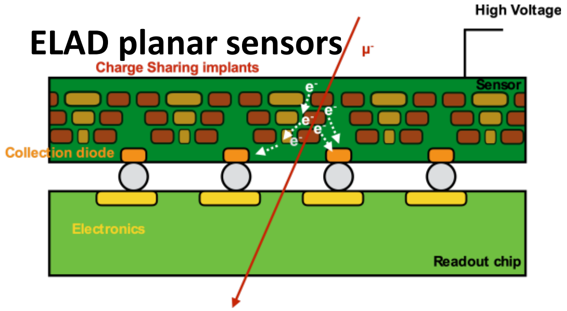
CLIC Sensor and readout R&D

VCI highlights

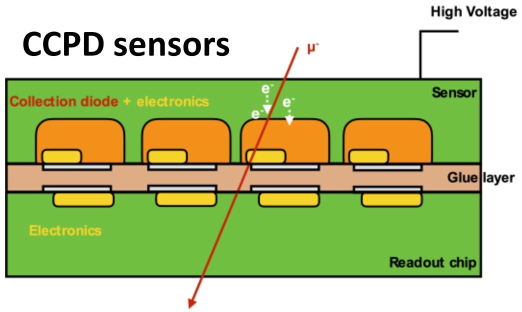
Hybrid planar sensors



ELAD planar sensors



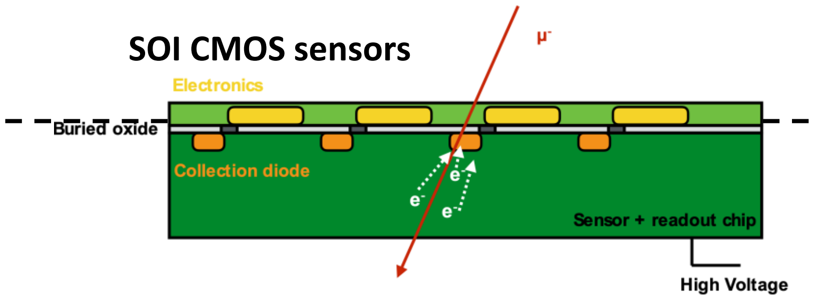
CCPD sensors



Hybrid detectors:

- Factorise r/o and sensor R&D
- Smallest feature-size ASICs
- Advanced sensor concepts
- Small pixels, highest performance → for inner layers

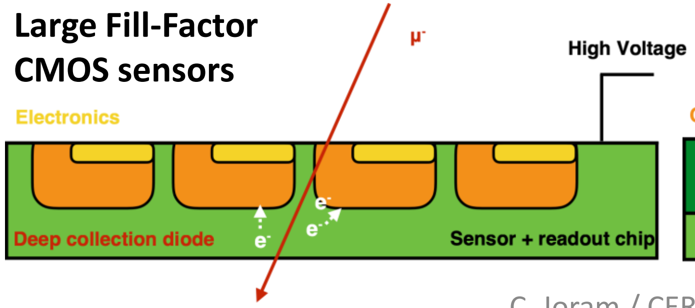
SOI CMOS sensors



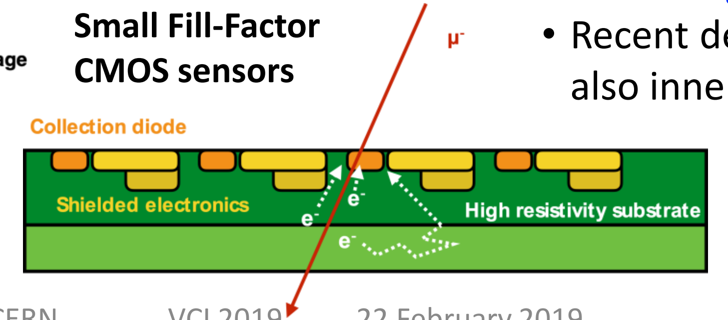
Monolithic CMOS sensors:

- Lowest material budget
- Medium feature-size
- Simplified construction
  → for large-area tracker
- Recent developments target also inner layers

Large Fill-Factor CMOS sensors



Small Fill-Factor CMOS sensors



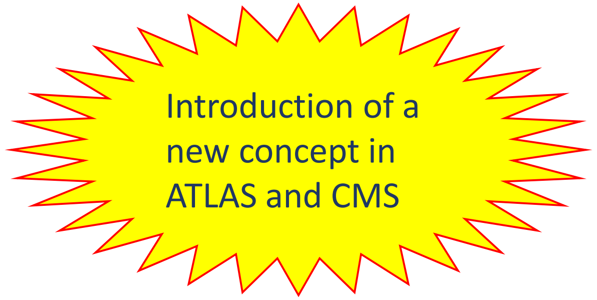
Dominik Dannheim: Pixel detector R&D for CLIC

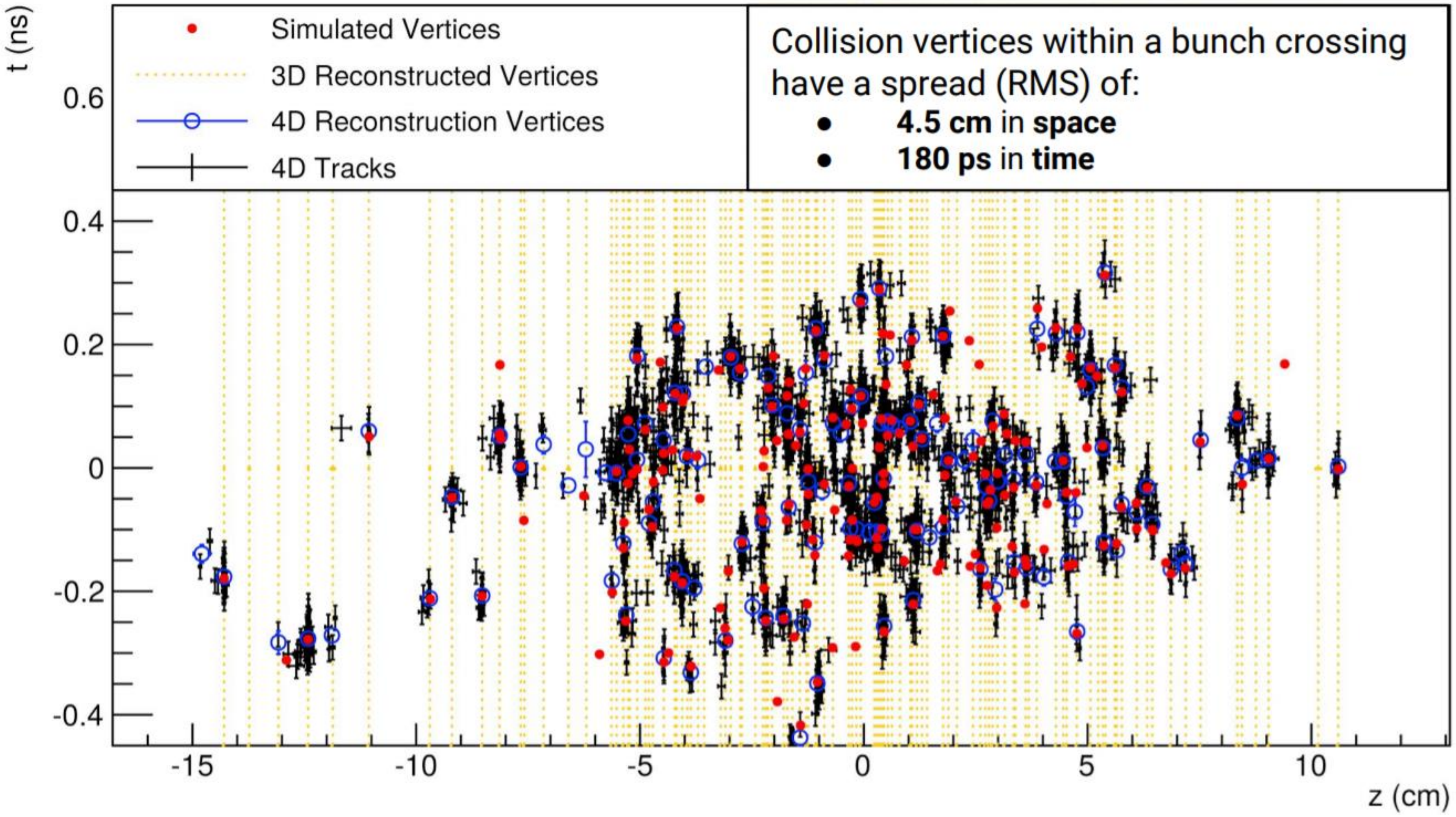
A clear trend: Fast timing to mitigate pile-up (but not only)

VCI highlights

Approach: time tagging of tracks with a resolution of 30-50 ps.

→ 4D vertex reconstruction
→ Requirement of time compatibility for track-vertex association





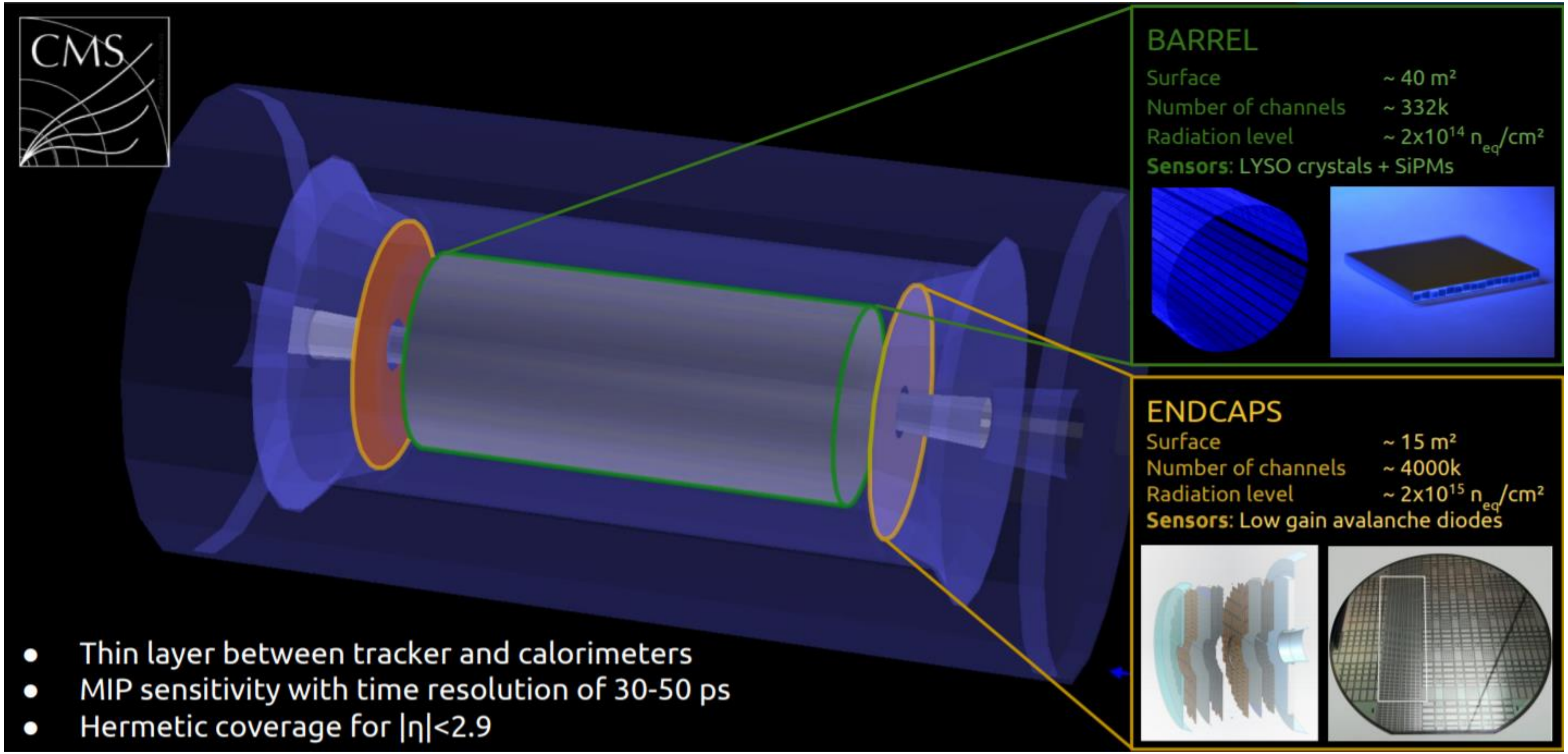
Marco Lucchini: Development of the CMS Mip Timing Detector

Development of the CMS Mip Timing Detector

Need to cope with radiation damage, both for BTL and ETL.

DCR of SiPM limits σ_t. Operate at -30 C.

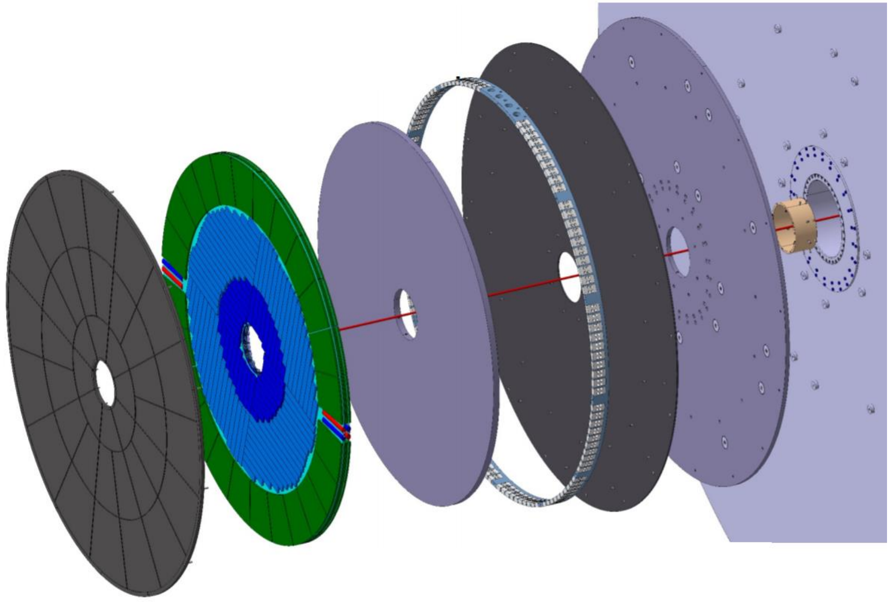
Radiation reduces gain of LGADs. Can be recovered by higher bias.

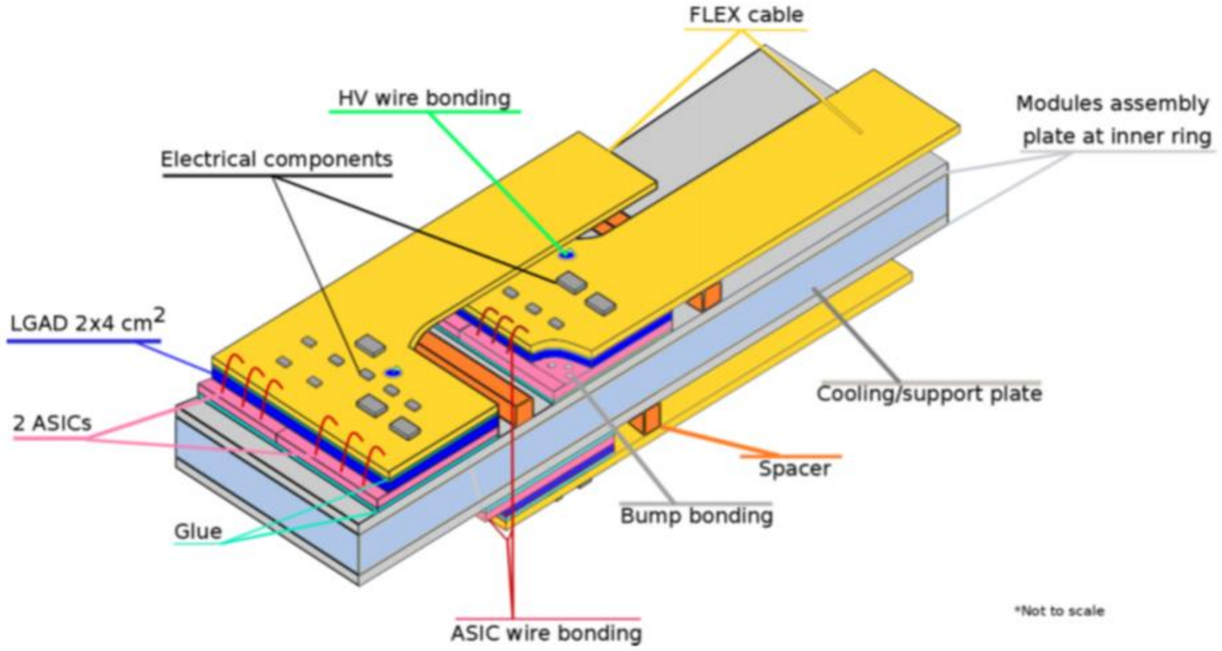


Marco Lucchini: Development of the CMS Mip Timing Detector

The ATLAS High Granularity Timing Detector

VCI highlights





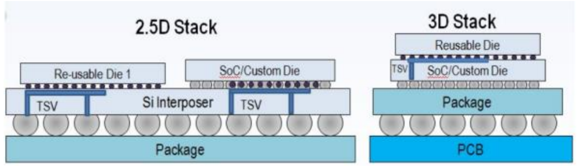
Very similar requirements
Very similar concept
Very similar performance

as CMS ETL

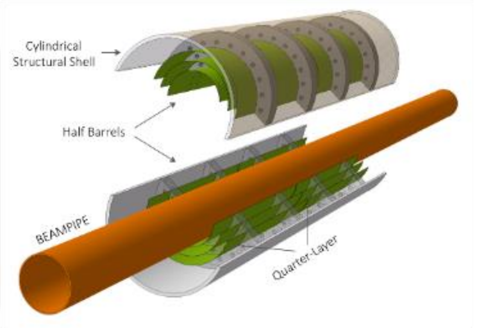
15x30 pixel sensors
LGAD, ALTIROC ASIC
1.3 mm × 1.3 mm pixels
2 or 3 hits per track (f(R)).

Bengt Lund-Jensen, The ATLAS High Granularity Timing Detector

WP1: Silicon Sensors

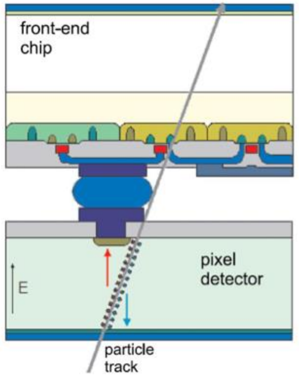


Study enabling technologies up to demonstrator level



Very high resolution, VERY low mass, stitched to wafer scale (e-e, e-A, AA exp.)

Hybrid Pixel Detectors



Target ultimate time/space accuracy and rad hardness

- Small pixels
- timing and high rate
- tile-able, minimized dead areas
- Thin planar active-edge sensors
- LGAD sensors for high-precision timing

Module development

Novel hybrid pixel detectors

Ultimate time/space accuracy and rad hardness

Monolithic pixel detectors

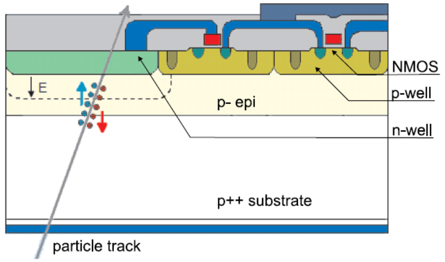
Cost effective depleted CMOS for ee and hh

Simulation and characterization

≥90 nm

<90 nm

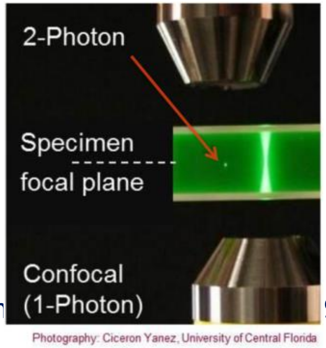
Monolithic Active Pixel Sensors



Very high rate (3 GHz/cm^2) and radiation hardness (10^{15} n_{eq}/cm^2) (pp exp.)

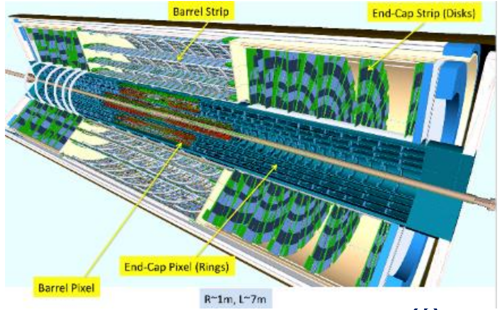
‘RD50-like’ studies

Example TPA-TCT



Tomasz Szumlak, RD50 status

Marcos Fernandez, TPA-TCT



Major ongoing Si detector projects (1/2)

Experiment / Timescale	Application Domain	Technology	Total detector size / Single unit size	Radiation environ-ment	Special Requirements /Remarks
ATLAS ITK Upgrade LS3	Hadron collider (Vertex + Tracking)	Si hybrid pixels (n-in-p planar, innermost layer 3D), Si Strips.	Total area: pixel 12.7 m^2, strips: 165 m^2. Single unit: Pixel: (20 x 12 mm^2), Strips: ~100 x 100 mm^2	Fluences up to 2 x 10^{16} MeV n_{eq}/cm^2	Option for outermost pixel layer: MAPS. RD53 ASIC 65 nm CMOS
CMS Tracker Upgrade LS3	Hadron collider (Vertex + Tracking)	Si Hybrid pixels (n-in-p planar, innermost layer 3D), Si Strips.	Total area: pixel 4.7 m^2, strips: 200 m^2. Single unit: Pixel: (20 x 12 mm^2) Strips: ~100 x 100 mm^2 , ~50 x 100 mm^2	Fluences up to 2 x 10^{16} MeV n_{eq}/cm^2	Special p_t modules in 3 outer strip layers. RD53 ASIC 65 nm CMOS
ALICE ITS Upgrade LS2	Heavy-Ion Physics (Tracking)	MAPS, 7 layers	Total area: ~ 10 m^2 Single unit: 30 x 15 mm^2	Fluences up to 1.7 x 10^{13} MeV n_{eq}/cm^2	0.3 $\%X_0$ per layer (inner barrel) 180 nm TowerJazz
LHCb VELO Upgrade LS2	Hadron collider (forward B physicis)	Si hybrid pixels (n-in-p planar),	Total area: 0.12 m^2 Single unit: 14 x 14 mm^2	Fluences up to 8 x 10^{15} MeV n_{eq}/cm^2	130 nm CMOS, 40 MHz Readout
LHCb UT Upgrade LS2	Hadron collider (forward B physicis)	Si strips (n-in-p planar),	Total area: ~9 m^2 Single unit: 100 x 100 mm^2	Fluences up to 3 x 10^{14} MeV n_{eq}/cm^2	
BELLE II PXD upgrade	e^+e^- collider (B physicis)	DEPFET pixels, 2 layers	Total area: 0.026 m^2 Single unit: 12.5 x 90 (123) mm^2	10 kGy / year	0.15% X0 per layer

Σ ~ 400 m^2 Si

VCI

Major ongoing Si detector projects (2/2)

VCI highlights

Experiment / Timescale	Application Domain	Technology	Total detector size / Single unit size	Radiation environ-ment	Special Requirements /Remarks
ATLAS HGTD LS3	Hadron collider (high granularity timing detector)	Si (macro) pixels, LGAD	Total area: 6.3 m^2 Single unit: 20 × 40 mm^2	Fluence up to 9 × 10^{15} n_{eq}/cm^2	1.3 x 1.3 mm^2 pixel size σ_t ~ 30 ps
CMS ETL LS3	Hadron collider (high granularity endcap timing layer)	Si (macro) pixels, LGAD	Total area: 5.4 m^2 Single unit: 20 × 40 mm^2	Fluence up to 2 x 10^{15} cm^2	1 x 3 mm^2 pixel size σ_t ~ 30 ps
CMS HGCAL LS3	Hadron collider (fine segmentation calorimeter)	Si pads + plastic scintillator tiles).	Total area: Si: ~ 600m^2, Scint. ~ 500 m^2 (à la CALICE) Single unit: Si: hexagons (~Ø190 mm) from 8’ wafers. Scint.: varying, ~10cm^2	Fluences 2 x 10^{14} - 1 x 10^{16} n_{eq}/cm^2	
ALICE FoCAL LS3	Heavy ion physics, forward	W-Si sampling, 24 layers	Total area: ~27 m^2 Si-sensors (2 types) low granularity (≈ 1 cm2), Si-pads high granularity (≈ 1 mm2), obtained with pixels (e.g. CMOS-MAPS)		Test beam 4 x 4 x 11 cm3 (W absorber), 39 M pixels

Σ ~ 640 m^2 Si

TOTAL ~ 1000 m^2 Si

Gas detectors

Use of greenhouse gases in the LHC

GHGs like R134a ($C_2H_2F_4$), CF_4, SF6, C_4F_{10}, … are used by several particle detector systems at the LHC experiments

Gas	GWP - 100 years
$C_2H_2F_4$	1430
CF_4	7390
SF_6	22800

R134a

EU 'F-gas' regulations limit their use and have an impact on their price and availability.

Topic of high importance

Four R&D lines for optimizing the use of gases
Different strategies can be combined together

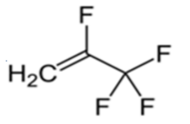
Optimization of current technologies
- Gas recirculation
- Careful operation
- Leak fixing wherever possible

Gas Recuperation
Recuperation of used gas

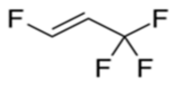
Abatement
Destruction of GHGs (unsatisfactory fallback solution)

Alternative Gases
New eco-friendly gases HFOs, …

- By volume, R134a, is the dominant gas at CERN (RPC)
- A prototype separation plant was able to separate off R134a from RPC exhaust at perfect quality, such that it can be reinjected.
- Alternative candidate gases are available, but require lots of studies.



HFO1234yf ($C_3H_2F_4$)
ODP 0
GWP 4



HFO1234ze ($C_3H_2F_4$)
ODP 0
GWP 6

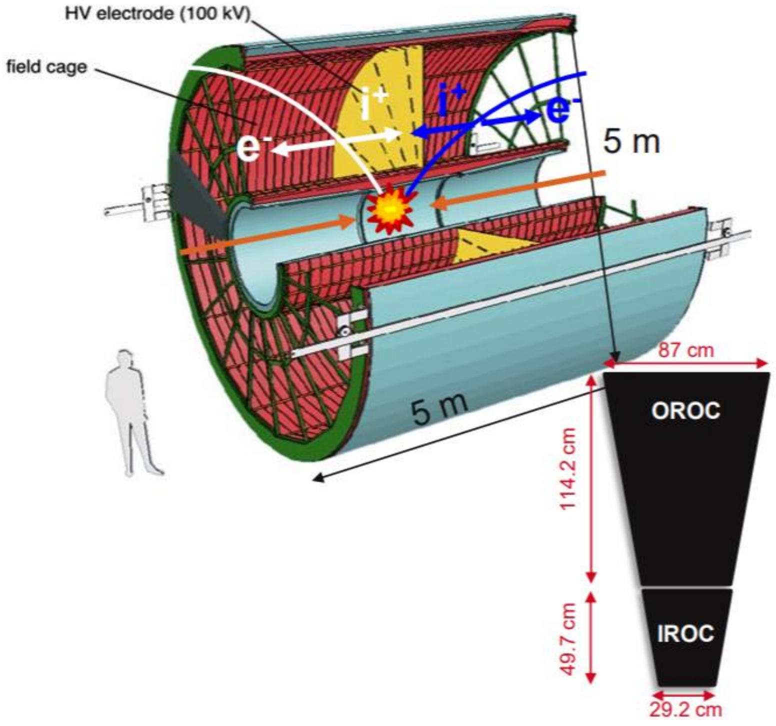
Roberto Guida, Beatrice Mandelli, R&D for the optimization of the use of greenhouse gases in the systems LHC particle detection

UPGRADE OF THE ALICE TPC

VCI highlights

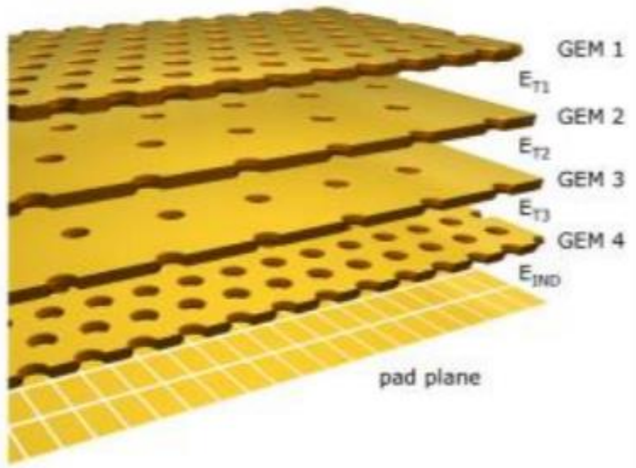
Current gated MWPC limits readout rate to few kHz.
From Run 3 on, ALICE will work at 50 kHz RO rate.

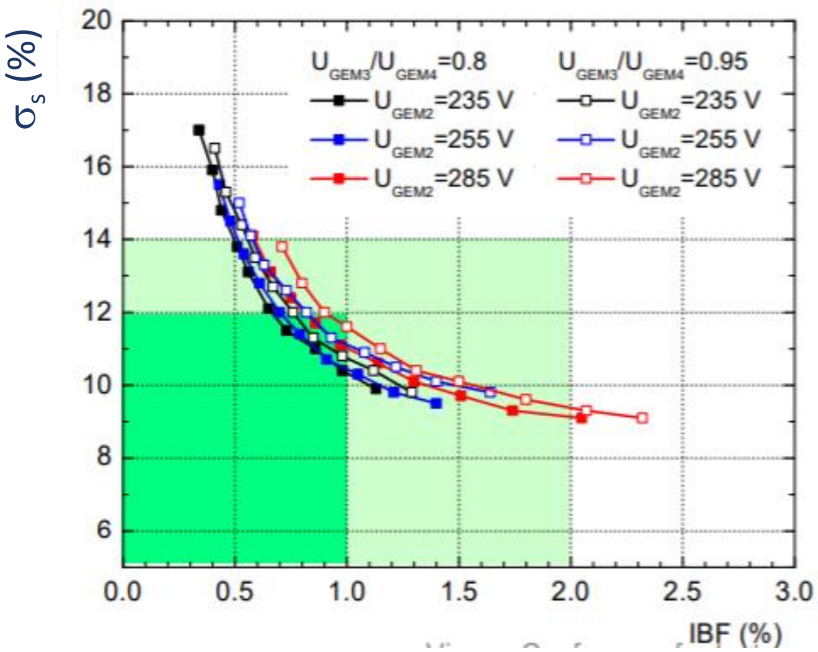
→ Ungated operation
→ Need a different method to supress Ion Back Flow (IBF) to max. 1%



Robert Muenzer, UPGRADE OF THE ALICE TPC

Solution: 4-GEM, staggered holes





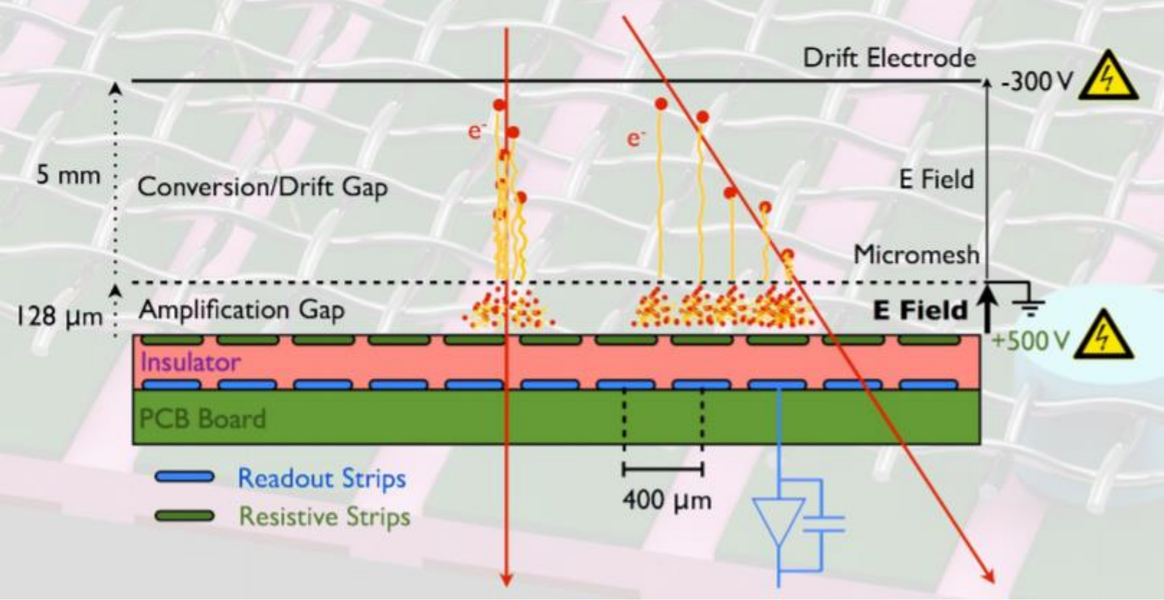
Arrival of MPGD in LHC experiments

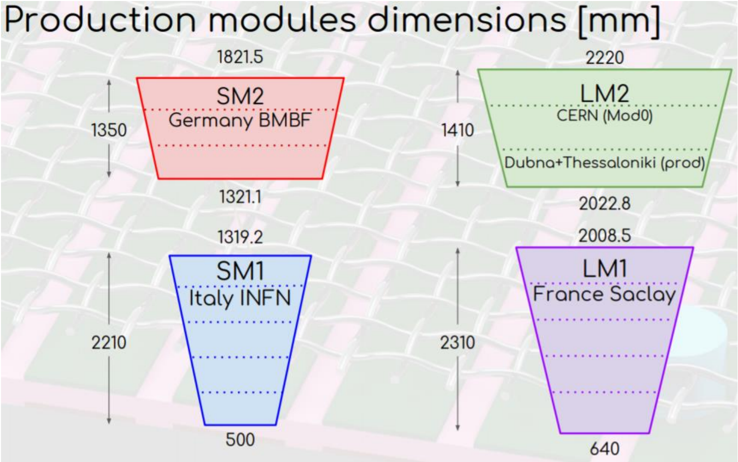
(not quite, there was TOTEM T2 already before)

Job essentially done! Most chambers produced and ready for installation.

ATLAS New Small Wheel

Resistive bulk μ–megas technology





Following HV instabilities, observed in Jan 2018, production was suspended.
Assembly / cleaning procedures established and harmonised. Some limited R&D.
Production resumed after review.

Test beam 2018:

- perpendicular tracks ok (σ_{core} ~ 63 μm + tails)
- Inclined tracks (micro TPC RO) under further study

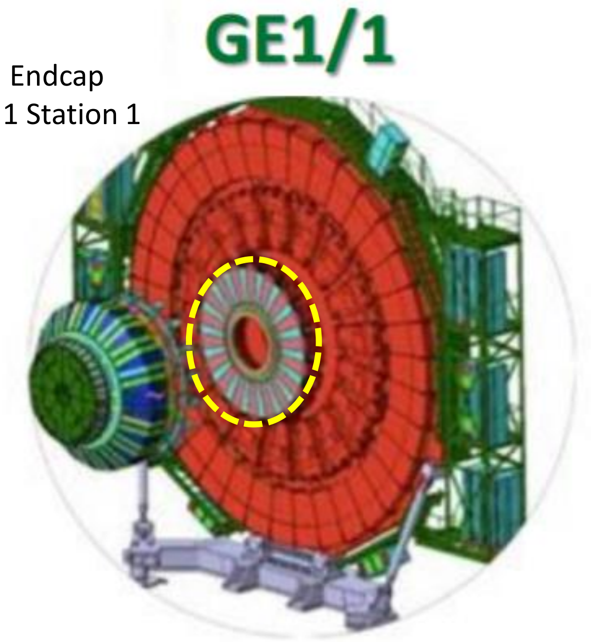
Largest μ–Megas chambers ever built (?)

Aimilianos Koulouris, ATLAS New Small Wheel - Micromegas production and performance

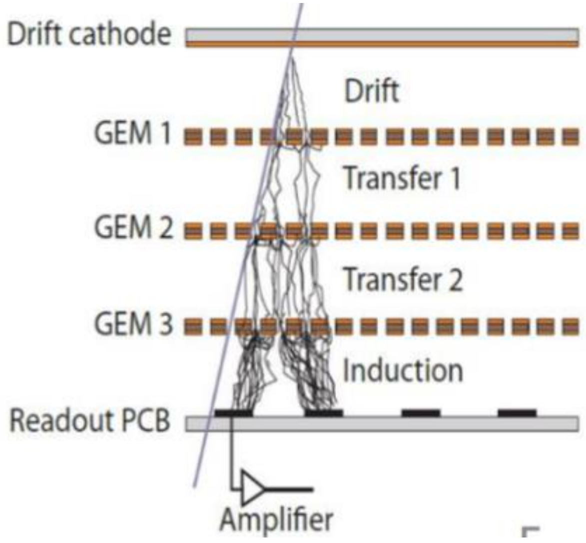
Upgrade of the CMS Muon System with GEM Detectors

VCI highlights

GEM Endcap
Ring 1 Station 1



Triple GEM technology

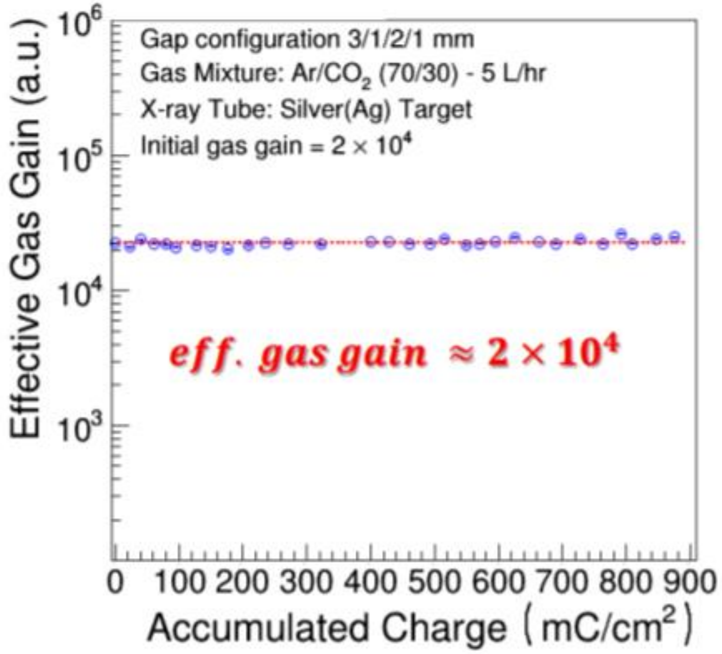


Largest GEM chambers ever built

- 144 chambers (145 m^2) to be installed during LS2
- 5 ch. already successfuly operated in CMS since 2017/2018.
- Much more to come in LS3.

All 144 chambers + spares produced.
Well defined QA program.

Longevity Studies at GIF++ facility and with dedicated X-ray source demonstrated full lifetime with safety factor 3.



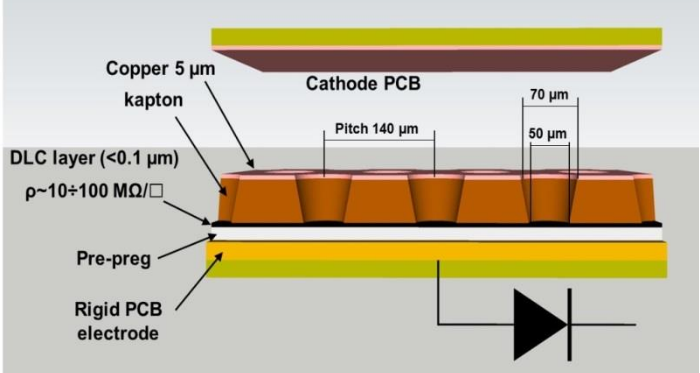
Francesco Fallavollita, Upgrade of the CMS Muon System with GEM Detectors

The µ-RWELL

Promising MGPD technology.

VCI highlights

The µ-RWELL architecture

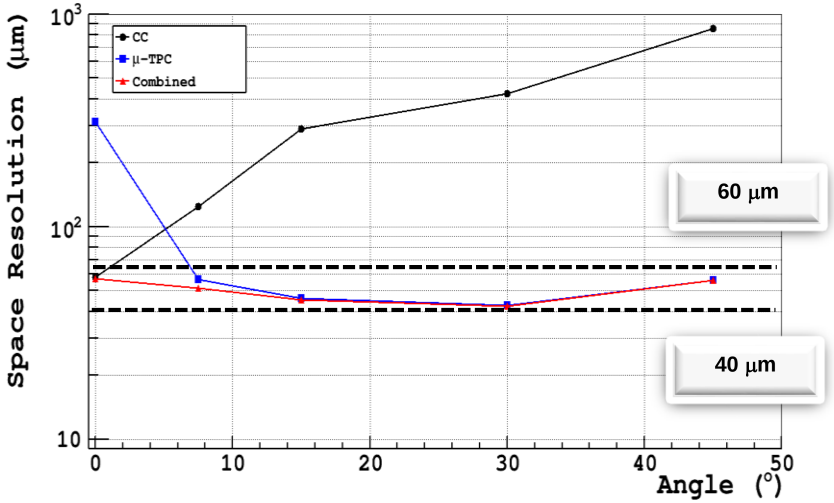


The µ-RWELL_PCB is realized by coupling:

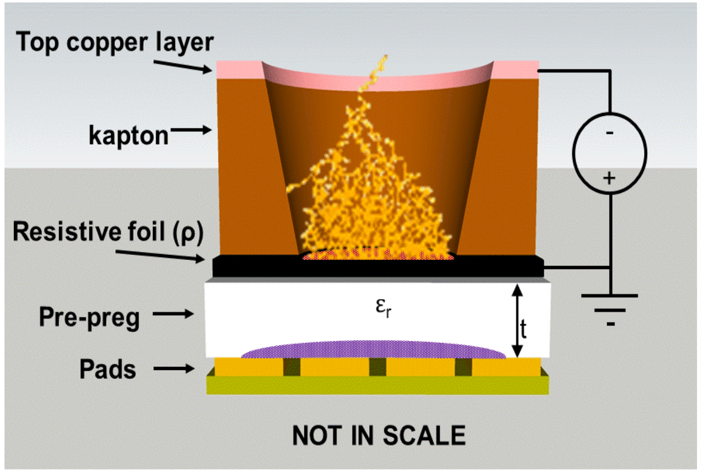
1. a WELL patterned Apical® foil acting as amplification stage
2. a resistive layer for discharge suppression
3. a standard readout PCB

Fully industrial process.
Tech. transf. to ELTOS (IT).

Space resolution w/uTPC

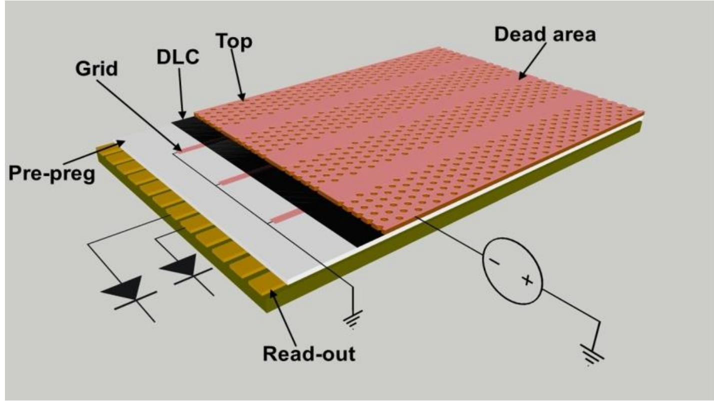


The principle of operation

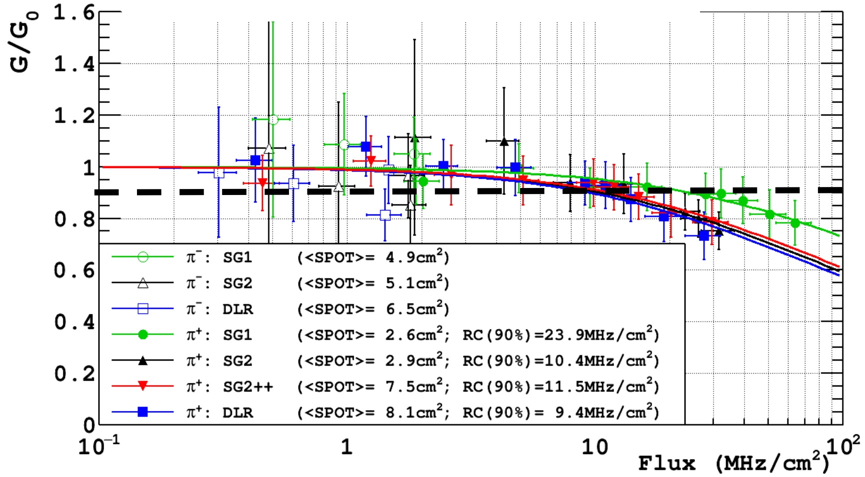


Gain ~ 10^4 **σ_t ~ 5.7 ns**

The SG high rate layout



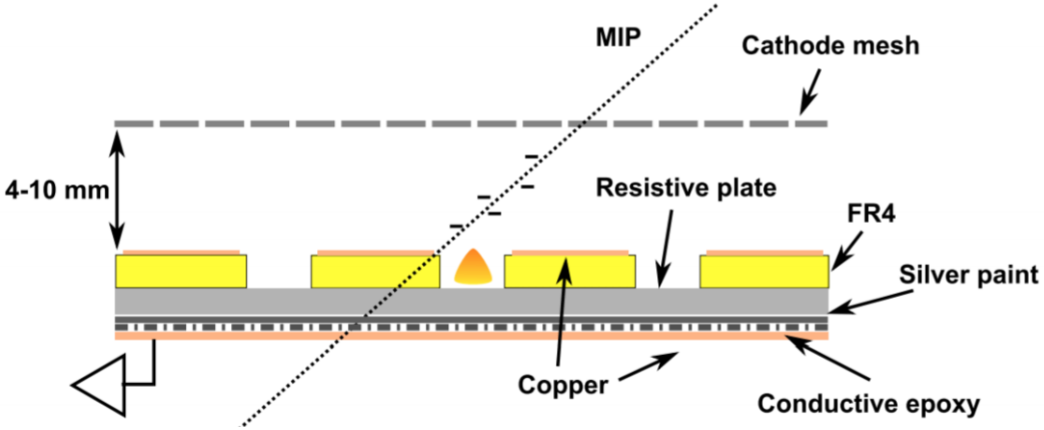
Rate capability ~10 MHz/cm²

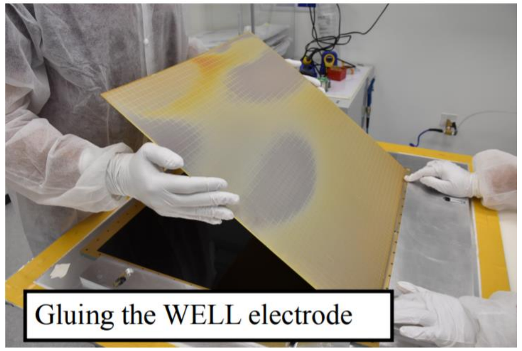


Giovanni Bencivenni: High space resolution µ-RWELL for high rate applications

(Semi) Digital HCAL (CALICE)

The Resistive Plate WELL (RPWELL), based on a thick GEM

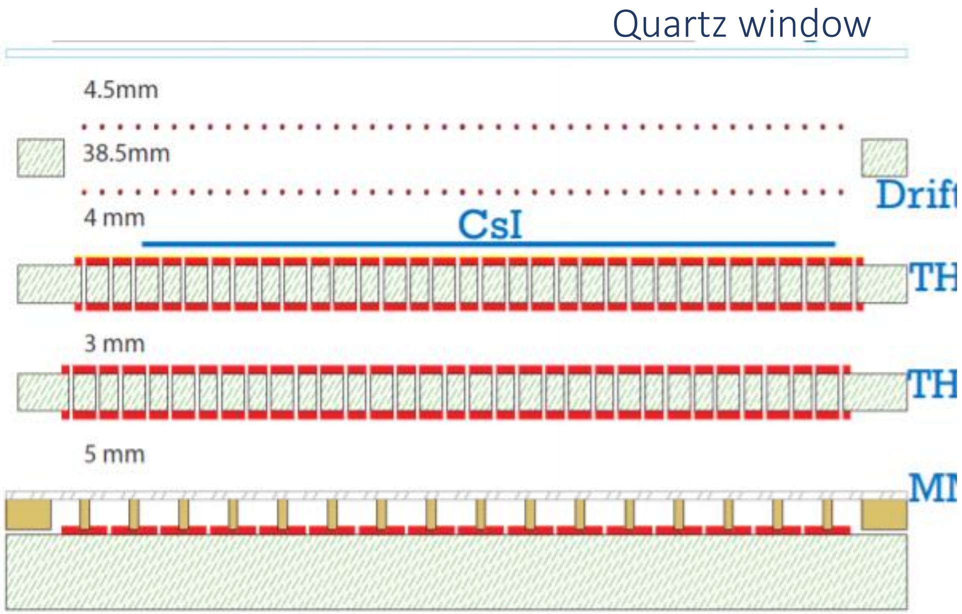




Gluing the WELL electrode

Shikma Bressler, Novel Resistive-Plate WELL sampling element for (S)DHCAL

COMPASS RICH-1

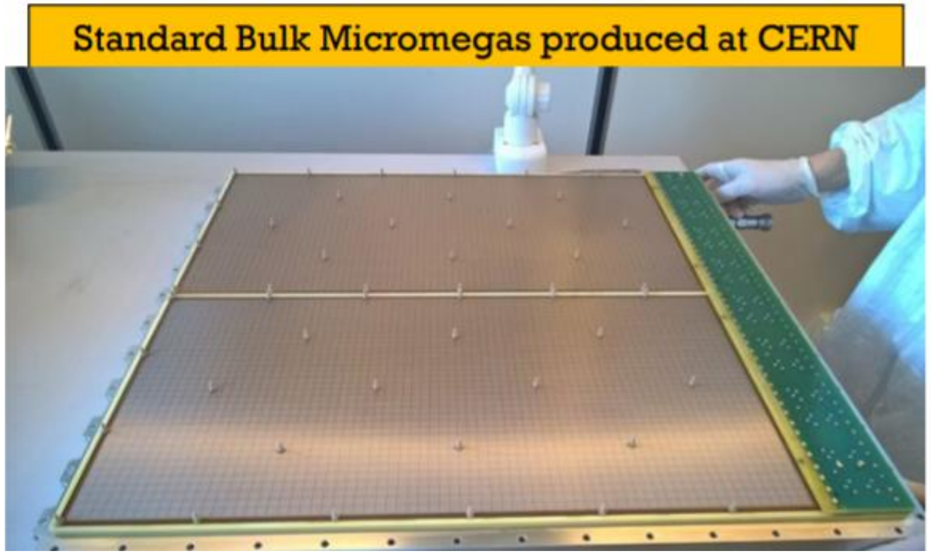


photocathode

Thick GEM

Thick GEM

μMegas

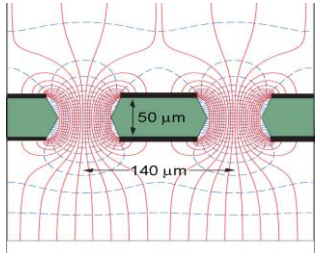


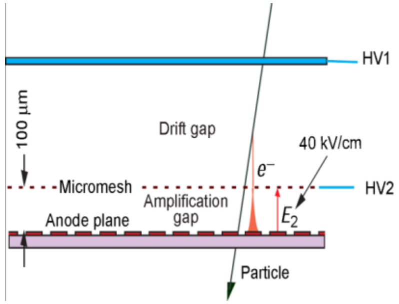
Yuxiang Zhao, MPGD based photodetector of COMPASS RICH-1

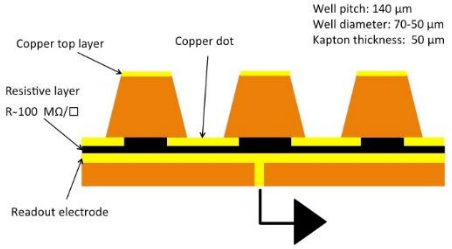
WP2: Gas Detectors

EP R&D

- Any future large scale HEP experiment will rely on gas detectors (TRK, MUON, TRIG).
- Areas may be huge (1,000-10,000 m^2)! ➔ Need reliable cost effective technologies.
- Industrialisation of gas detector construction is still difficult.







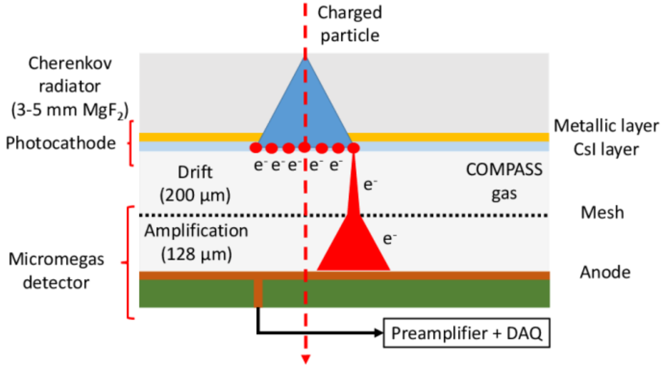
- Use of environment unfriendly gases has become an issue (similar for cooling fluids).
- Recuperate or find replacements for gases like CF_4, $C_2H_2F_4$ and SF_6, which have a huge GWP.
- Scalable Readout System and instrumentation for lab highly appreciated by community

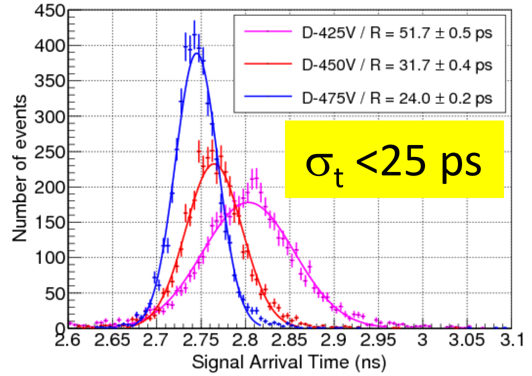
Solutions for large area gas based detector systems

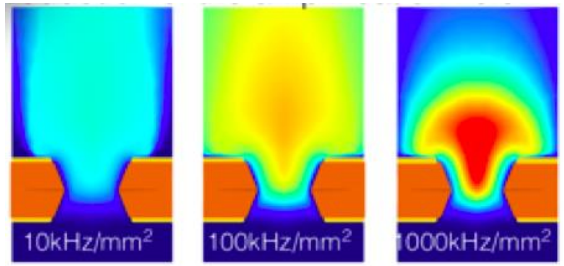
GEMs, µ–megas or µRWELL

Industrialisation & performance scaling

Tools	Novel technologies
• Gas studies, • Simulation and modelling, • Electronics and instrumentation	• Very fast gas detectors • Additive production techniques







COMSOL: Space Charge effects at high rate in a GEM detector.

A large part of the gas detector community is well connected via RD51 in which CERN plays a central role.

Major ongoing gas detector projects

Experiment / Timescale	Application Domain	Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ATLAS Muon Upgrade LS2	High Energy Physics (Tracking/Triggering)	Bulk resistive Micromegas + small strip Thin Gap Chambers (sTGC)	Total area: 2500 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**MM only:** **Max. rate**:15 kHz/cm^2 **Spatial res.:** <100µm **Time res.:** ~ 10 ns **Rad. Hard.:** ~ 0.5C/cm^2	- Redundant tracking and triggering; Challenging constr. in mechanical precision:
CMS Muon Upgrade LS2	High Energy Physics (Tracking/Triggering)	GEM (3x)	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.:** ~100µm **Time res.:** ~ 5-7 ns **Rad. Hard.:** ~ 0.5 C/cm^2	- Redundant tracking and triggering
ALICE TPC Upgrade LS2	Heavy-Ion Physics (Tracking + dE/dx)	GEM (4x) w/ TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300µm **Time res.:** ~ 100 ns **dE/dx:** 12 % (Fe55) **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
T2K ND280 2 TPCs	Neutrino physics	Bulk resistive Micromegas	Total area: 2.3 m^2 Single unit 34 x 42 cm^2	**Spatial res.:** ~800µm per space point	2% X_0

Partly extracted from : Maxim Titov, CPAD Instrumentation Frontier Workshop 2018, Providence, USA, December 10, 2018

Total ~2700 m^2

+ many others – also in nuclear physics and other fields

Calorimetry

CMS High Granularity Calorimeter for HL-LHC

VCI highlights

CMS endcap region:

- PbWO4 crystal transmission loss due to radiation damage
- Worsening energy resolution due to increased pileup

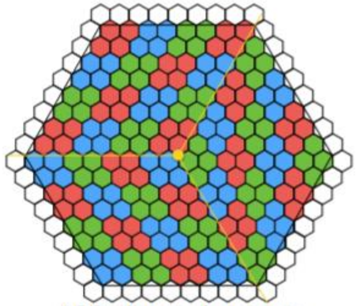
→ Build a fine segmented 'particle flow' calorimeter, ECAL + HCAL combined.

→ Use Si sensors as long as radiation and particle flow requires, then switch to cheaper scintillator tiles + SiPM (à la CALICE).

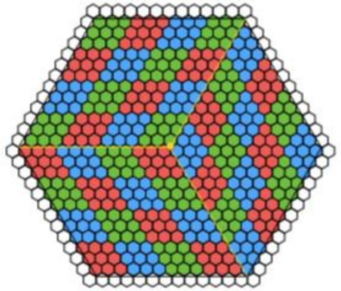
→ CE-E: Si, Cu & CuW & Pb absorbers, 28 layers, 25 X0 & ~1.3λ

→ CE-H: Si & scintillator, steel absorbers, 24 layers, ~8.5λ

→ Si pad sensors from 8'' wafers. Different sensor geometries and thicknesses (300, 200, 120 μm) to get best radiation hardness.

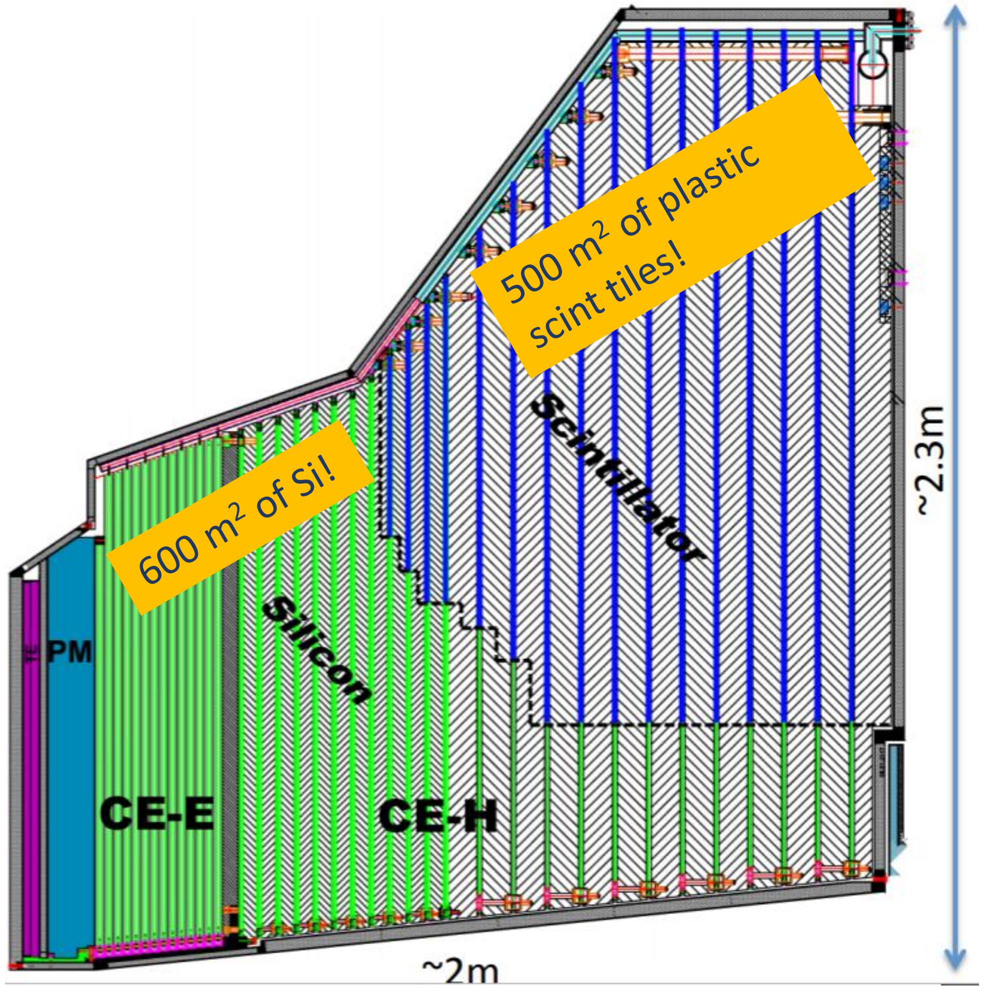


192-channel sensor



432-channel sensor

Test beam results (2016-2018) show that performance is well understood.
Also intrinsic time resolution is very high (25 ps).



A great concept!

but from a technical point of view, a VERY challenging detector!

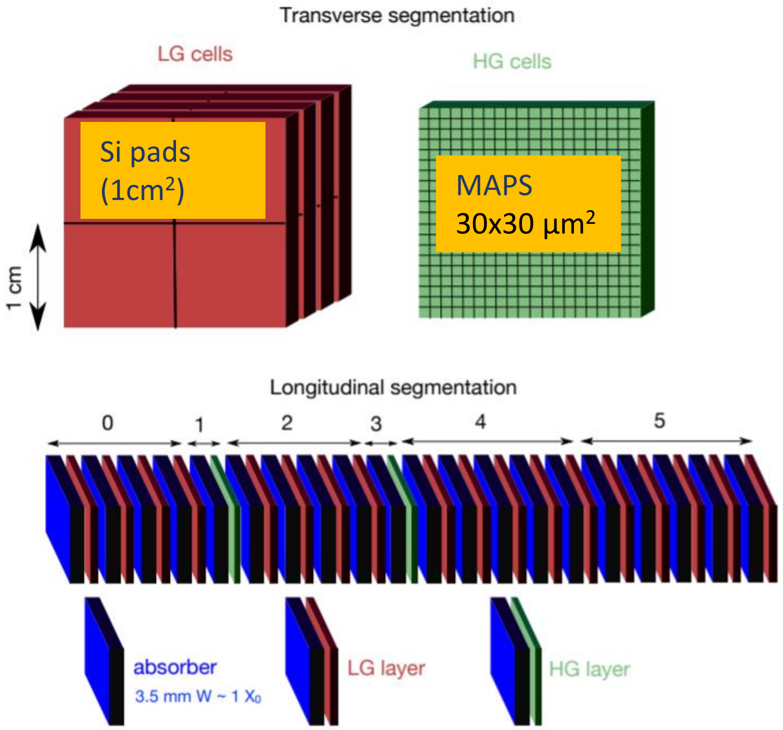
Rachel Yohay ,The CMS High Granularity Calorimeter for High Luminosity LHC

Pushing it further… ALICE FoCal

(for LS3, not yet approved)

VCI highlights

Motivation: Measure Parton Density Functions (PDF) at low parton momentum fraction by measuring the yield of direct photons at forward rapidities → Need highly granular readout and a small Molière radius



Naomi van der Kolk: FoCal - a highly granular digital calorimeter

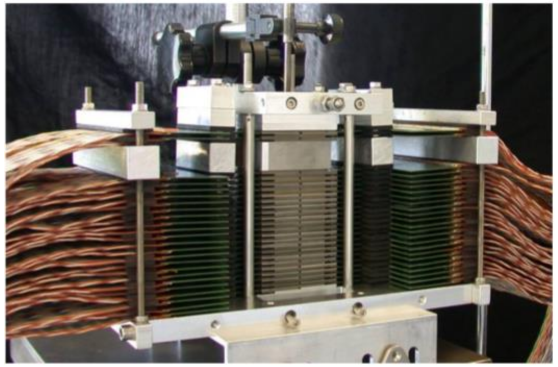
Full detector

- 1 m^2 surface

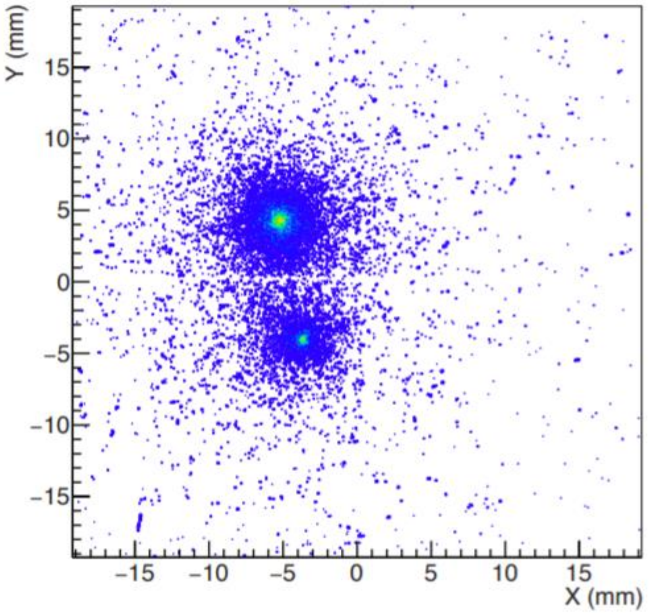
Digital ECAL prototype:

- number of pixels above threshold ~ deposited energy
- Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 with a pixel size: 30x30 µm2
- 24 layers of 4 sensors each: active area 4x4 cm2 , 39 M pixels
- 3 mm W absorber for 0.97 X0 per layer R_M ~ 11 mm

Performance published in JINST 13 (2018) P01014

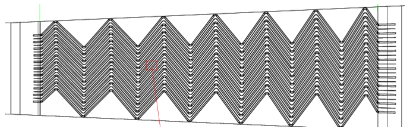


Hitmap over all layers of a two-particle event

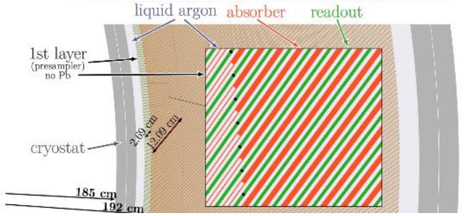


WP3: Calorimetry + Light based detectors

Liquid Argon calorimetry
radiation hard and flexible (segmentation) technology. Ref. design for FCC-hh, but potentially also interesting for FCC-ee.



From accordion ⬇ to straight inclined structures



Focus on electrode design, time resolution, LAr properties, high ionisation rates, cryogenic feedthroughs.

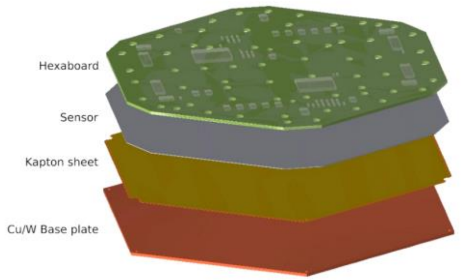
LAr
Electrodes, σ_t, high ionisation rates, feedthroughs

In/organic scint.
fibre cal., rad hard, Tile-cal, hi segm.

Hi granularity Si
CMS HGCAL
+ …

Support initially CMS HGCAL and start later on more specific developments

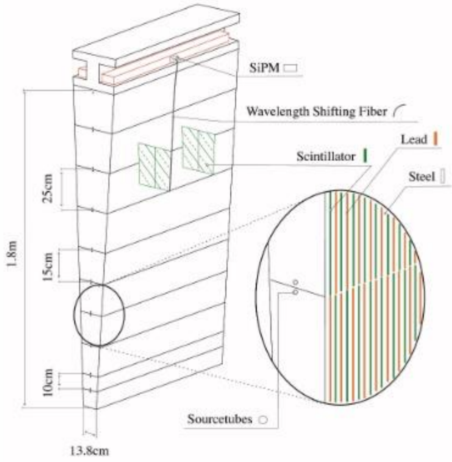
192-432 pads, ~cm^2 area, optimized for particle flow calorimetry



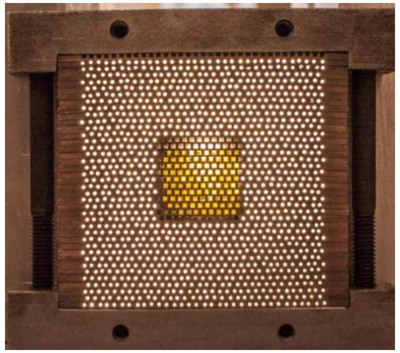
Scintillator based calorimetry.

- Good choice for hadronic calorimetry (FCC-hh,ee, CLIC, ILC, SHiP) and LHCb ECAL upgrade II
- Material R&D (scint, WLS), photodetectors (SiPM) at low temperatures, calo type, timing.
- Profit from RD18 (Crystal Clear) expertise!
- Concentrate initially on 2 technologies

  - Fine segm. Tile-cal like HCAL (FCC-hh)
  - Hi segm. fibre ECAL studies (LHCb motivated).



a)



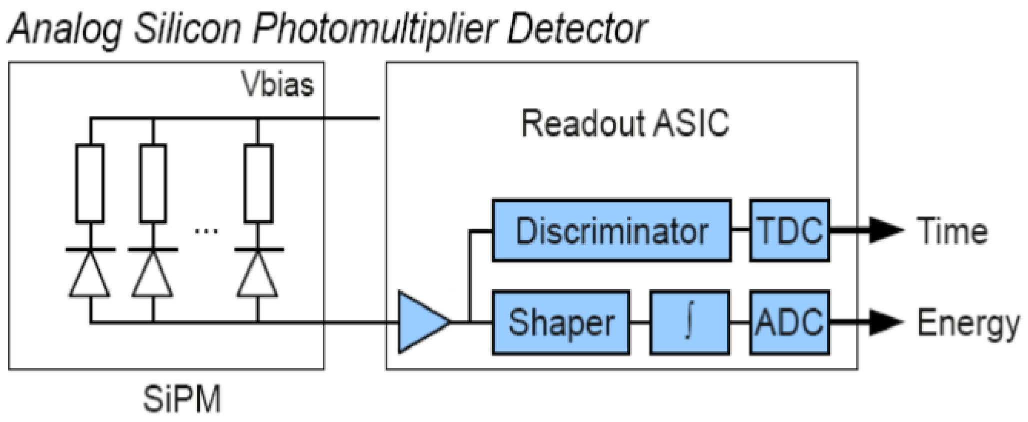
VCI highlights

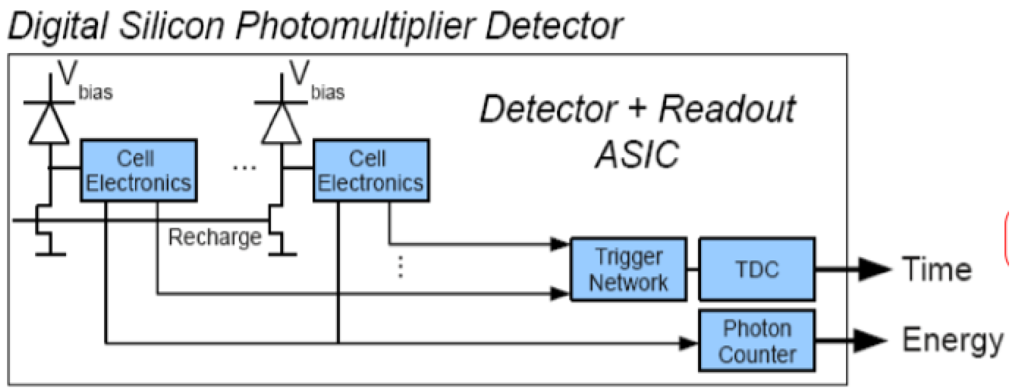
Light based detectors

SiPMs

- The SiPM has become a pretty mature detector (it took about 20 years to arrive here)
- Numerous suppliers, numerous applications (growing), also in industrial sector
- Still growing understanding of operation and limitations
- Significant and gradual progress in many aspects (PDE, AP, DCR, CT, timing, ….)
- Reasonable radiation hardness (depends on application and operational conditions). So far no magical trick has been found.

Not so new anymore, but still VERY active field!





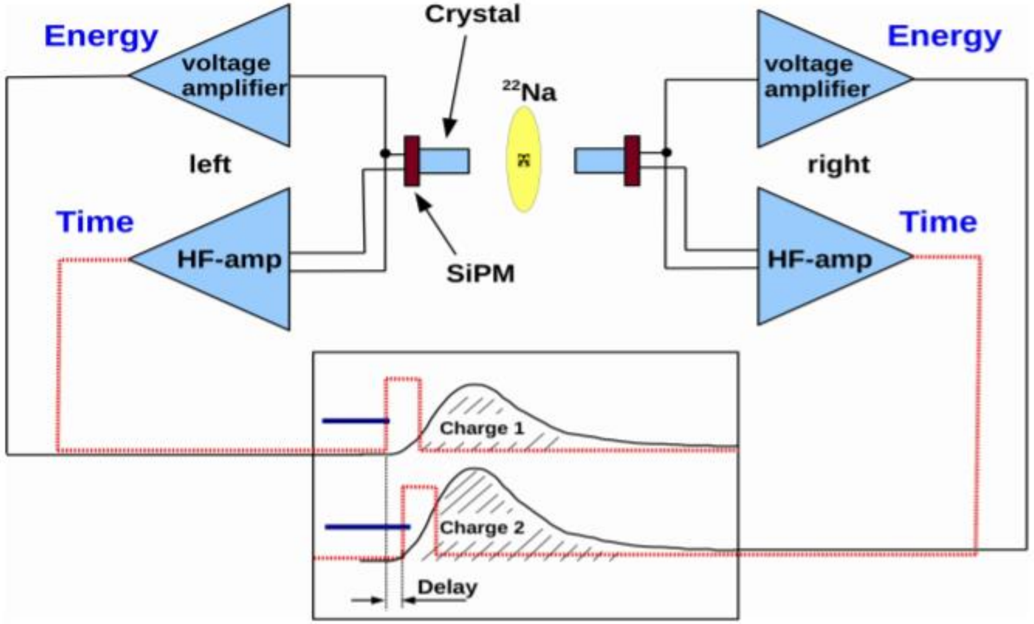
- EP R&D programme doesn't foresee specific R&D on SiPM. We rely on numerous groups in several communities who continue to push this development further.

Gianmaria Collazuol
The Silicon Photomultiplier - Status and Perspectives

Timing again! Where are the limits?

SiPM + Scintillator

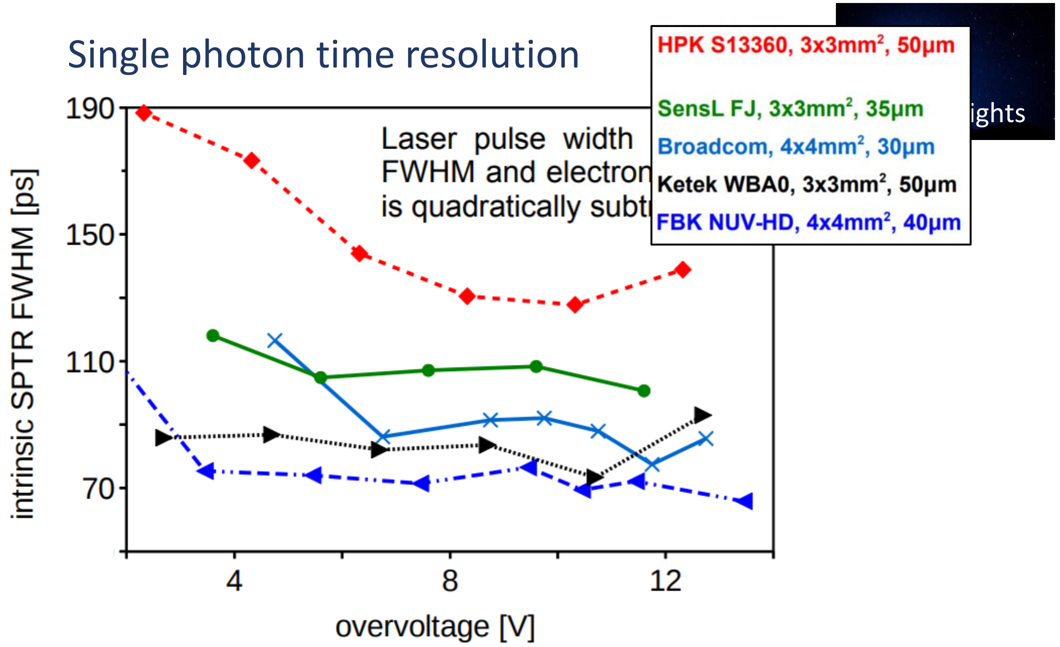
Systematic study, medically (PET) motivated, of best coincidence time resolution



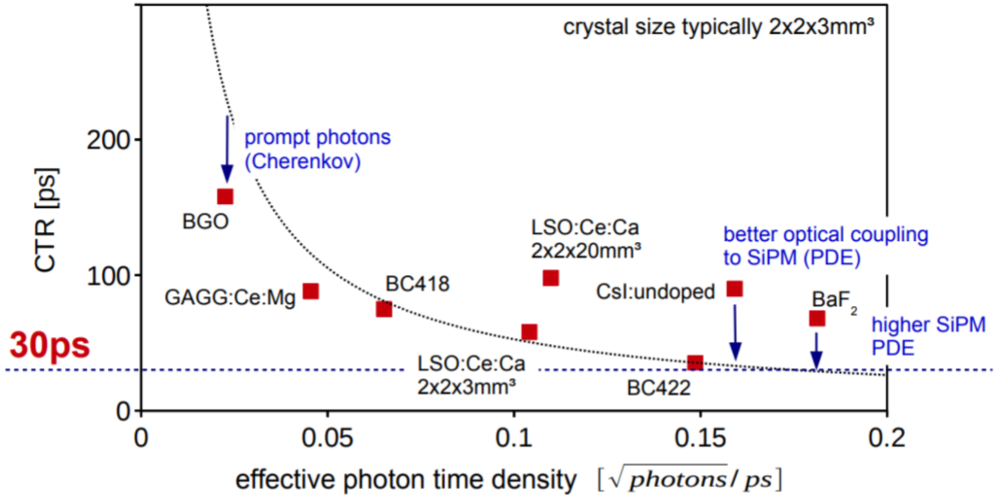
Clean systematic study

Stefan Gundacker, Experimental advances in photon detection time resolution limits of SiPMs and scintillator based detectors

Single photon time resolution



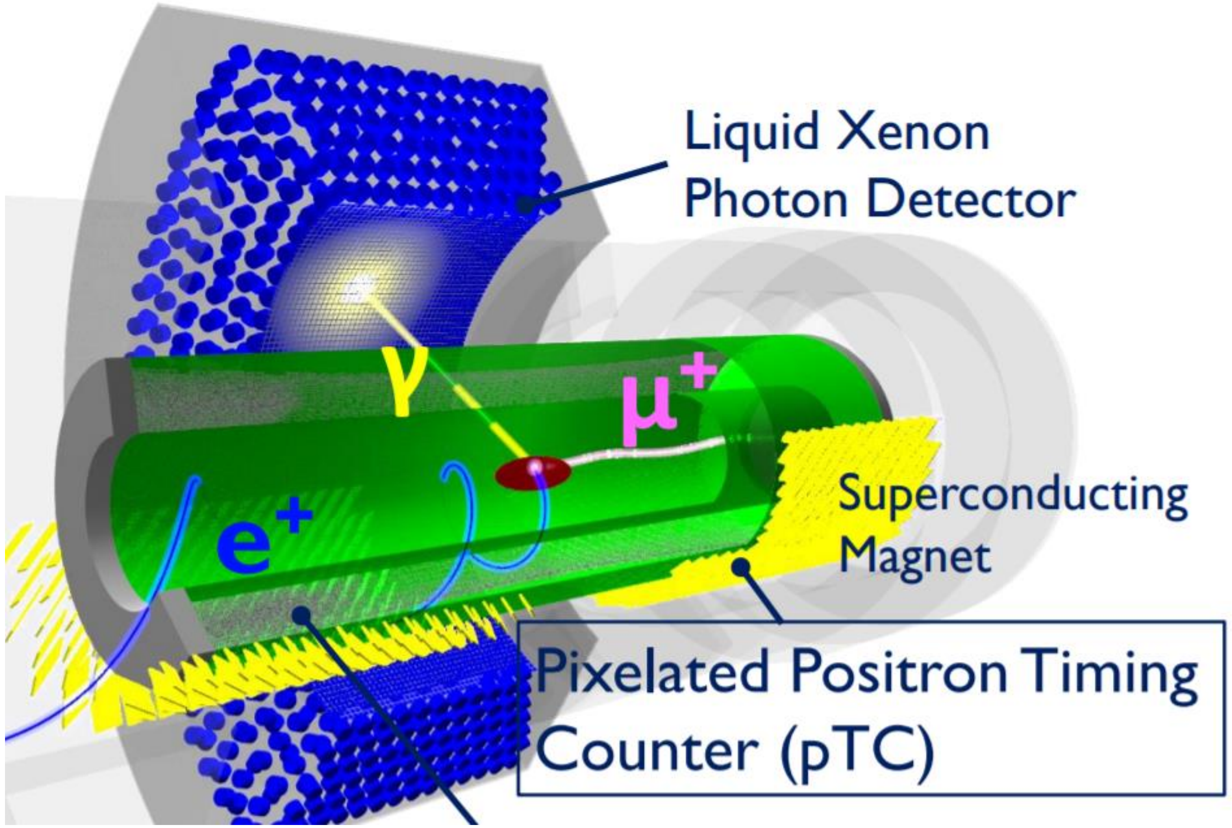
Coincidence time resolution (511 keV)

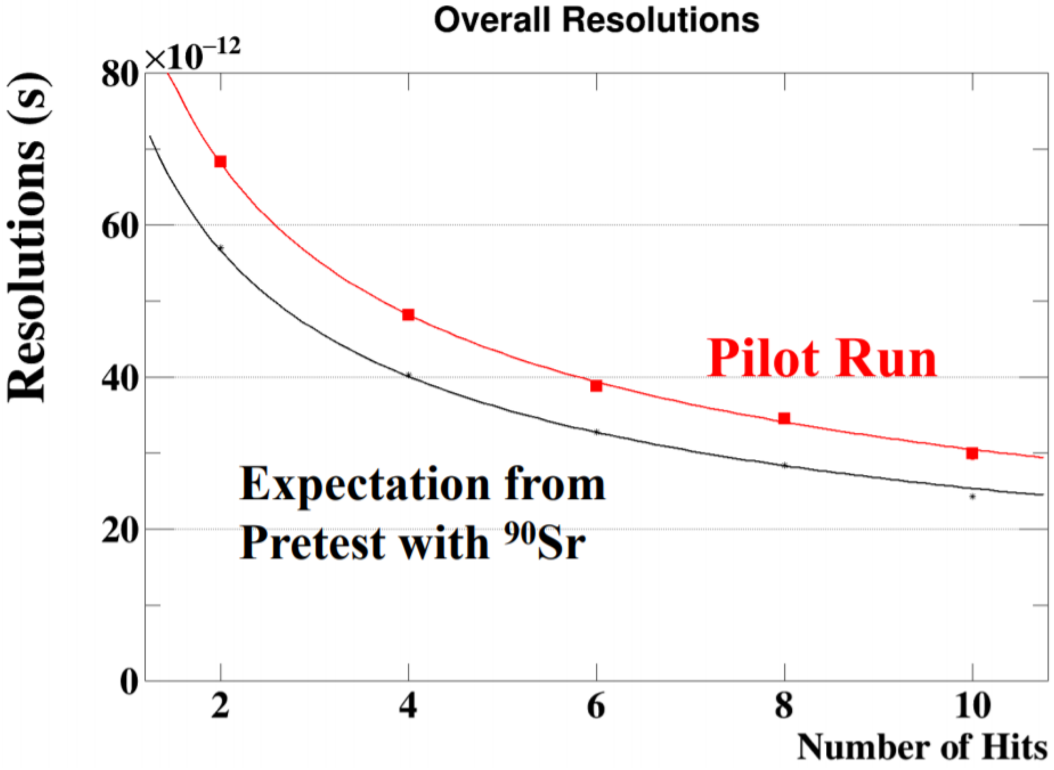


MEG II experiment

Search for $\mu^+ \rightarrow e^+ \gamma$

VCI highlights





pTC consist of fast plastic scintillator tiles with 2 x 6 SiPM readout.
Positron hits on average 8.8 tiles

From pilot run (2017): Required timing resolution of 40 ps can be achieved.

Miki Nishimura, Full System of Positron Timing Counter in MEG II

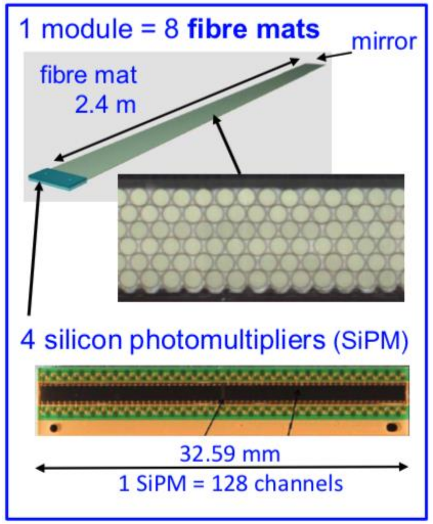
LHCb Scifi

A detector which can only be built thanks to SiPMs

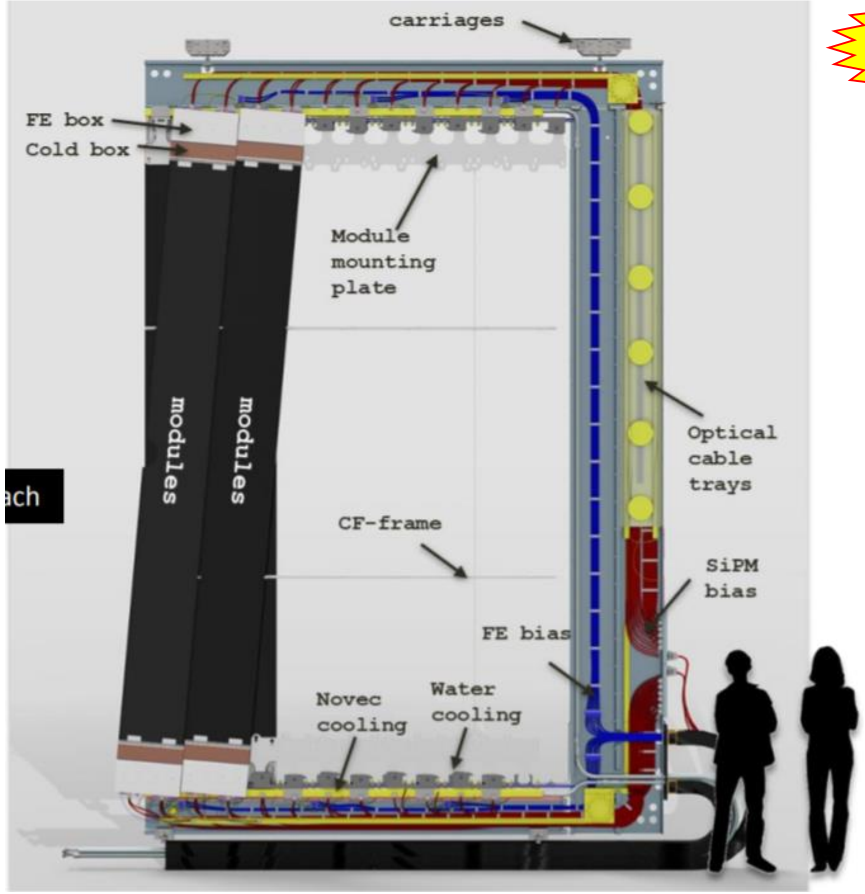
VCI highlights

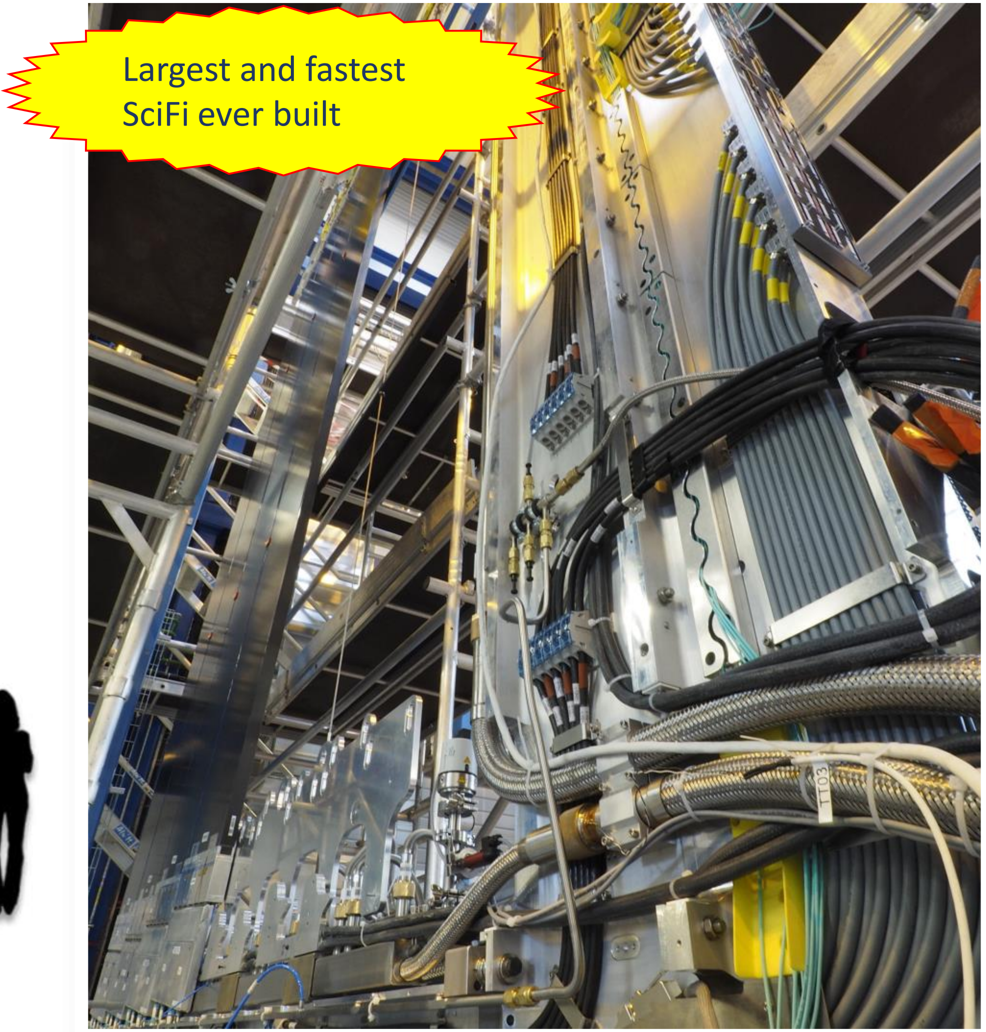
Tracking with scintillating fibres
100 μm precision over 340 m2

0.25 mm fibres
SiPM arrays (128 ch)
1% X0 per layer
40 MHz readout



1 of 12 C-frames



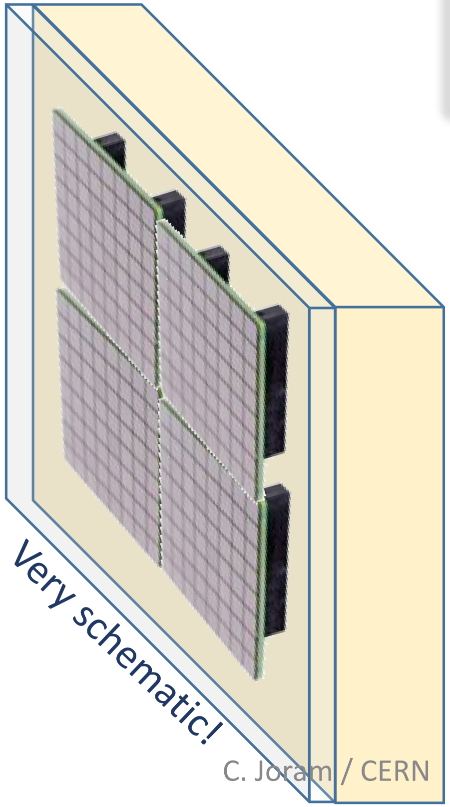


Lukas Gruber, LHCb SciFi Upgrading LHCb with a Scintillating Fibre Tracker

WP3: Calorimetry + Light based detectors

EP R&D

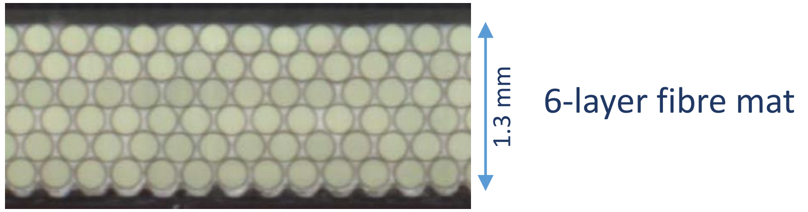
- LHCb relies fully on π/k identification by a **RICH**
- Detector is currently upgraded (LS2)
- HPD → MaPMT + new RO electronics
- Yet another upgrade is foreseen for LS4 (~2030)
- New optics and MaPMT → SiPM arrays (at low T)
- Concentrate on engineering aspects (with WP4)



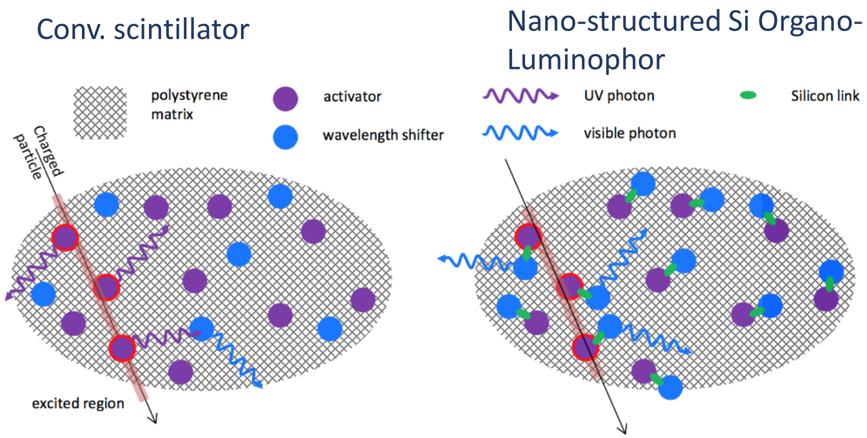
RICH
- Light weight mirrors
- Low temp photosensor housing

SciFi
- Fibre light yield
- Fibre production techniques

- LHCb builds currently the world's largest **SciFi tracker**



- Radiation damage / occupancy may require to replace/upgrade central part (LS3, LS4).
- R&D on fibres: faster and brighter! NOL concept?
- New ways to construct fibre mats, e.g. by 3 D printing?



VCI VIENNA CONFERENCE ON INSTRUMENTATION

Major ongoing calorimeter and light based detector projects

VCI highlights

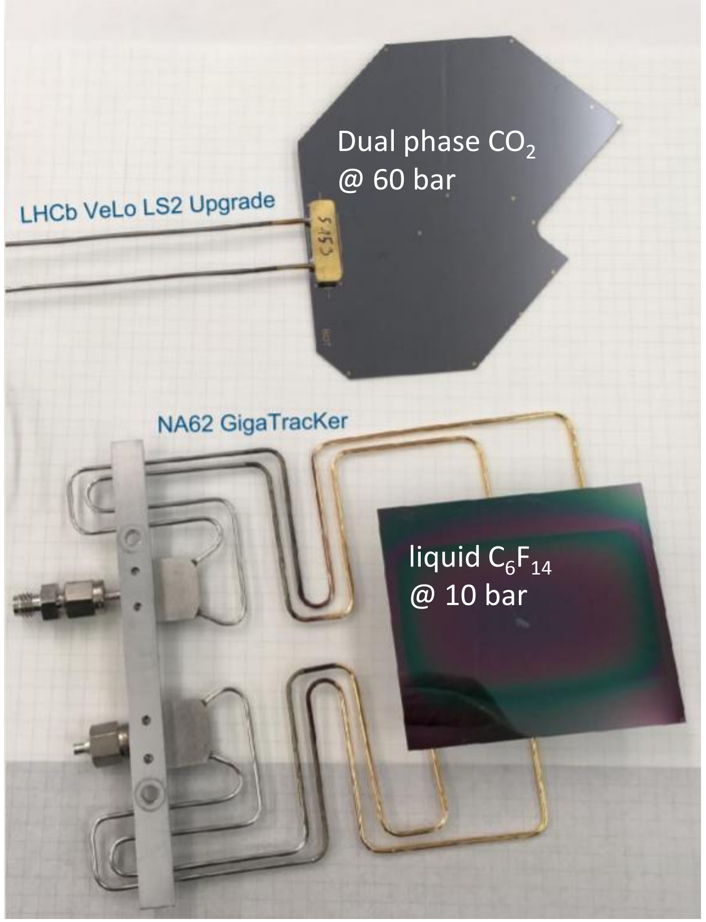
Experiment / Timescale	Application Domain	Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
LHCb SciFi LS2	High Energy Physics (Tracking)	Plastic scintillating fibres, SiPM readout	Total area ~340 m^2 Single unit (module): ~2.5 m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.:** ~70µm **Time res.:** 25 ns (BC) **Rad. Hard.:** up to 30 kGy	
LHCb RICH upgrade LS2	High Energy Physics (Particle ID)	Multi-Anode PMT	Total area: ~4.3 m2 3072 MaPMTs (26 x26 and 52 x 52 mm^2)		New optics in RICH1. New photodetectors for RICH and RICH2. 40 MHz readout.
CMS HGCAL LS3	Hadron collider (fine segmentation calorimeter)	Sampling, Si pads + plastic scintillator tiles, SiPM readout	Total area: Si: ~ 600m^2, Scint. ~ 500 m^2 (à la CALICE) Single unit: Si: hexagons (~Ø190 mm) from 8’’ Scint.: varying, ~10cm^2	**Fluence** 2 x 10^{14} - 1 x 10^{16} n_{eq}/cm^2	
ALICE FoCAL LS3 ?	Heavy ion physics, forward	W-Si sampling, 24 layers	Total area: ~27 m^2 Si-sensors (2 types): low gran. (≈ 1 cm2), Si-pads high gran. (≈ 1 mm2), obtained with pixels (e.g. CMOS-MAPS)		Test beam 4 x 4 x 11 cm3 (W absorber), 39 M pixels
CMS BTL LS3	High Energy Physics (Barrel Timing Layer)	LYSO + SiPM	Total area: ~36.5 m^2 LYSO crystal: 11 x 11 mm^2 SiPM : 4 mm^2 with pixels (e.g. CMOS-MAPS)	Fluence up to 2 x 10^{14} n_{eq}/cm^2	Test beam 4 x 4 x 11 cm3 (W absorber), 39 M pixels
BELLE II ARICH	e^+e^- collider (B physicis)	Focusing Aerogel + HAPD readout	14 m2 aerogel + 1.2 m2 HAPD		

Total active area ~870 m^2 (scint + photosensitive) + 630 m^2 Si

Mechanics++

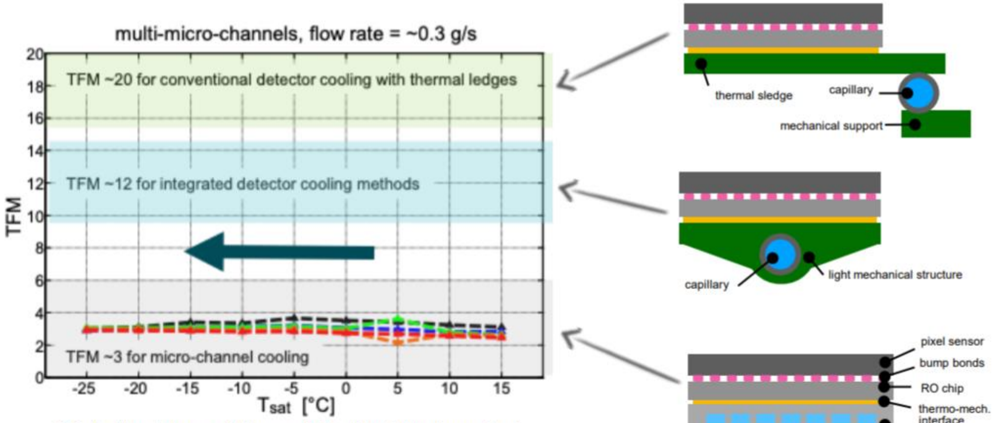
Silicon Microchannel Cooling Plates

Very efficient way of detector cooling, successfully applied to NA62 GTK. Will be used in LHCb VELO upgrade (LS2).



A. Mapelli, Silicon Microchannel Cooling Plates

$$\text{TFM} = \frac{T_{sensor} - T_{fluid}}{\text{power density}}$$

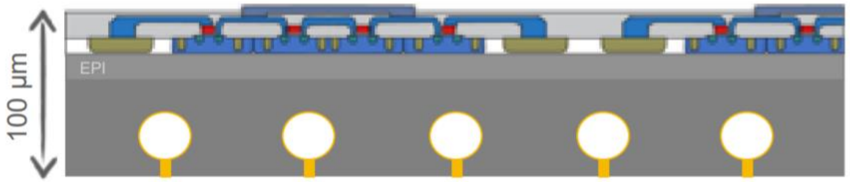


CO_2 boiling *Thermal Figure of Merit (TFM)* at constant flow rate 0.3 g/s and various Tsat

Désirée Hellenschmidt, Poster 78, VCI2019

Production of Si micro channel cooling plates in a sophisticated multi-step process!

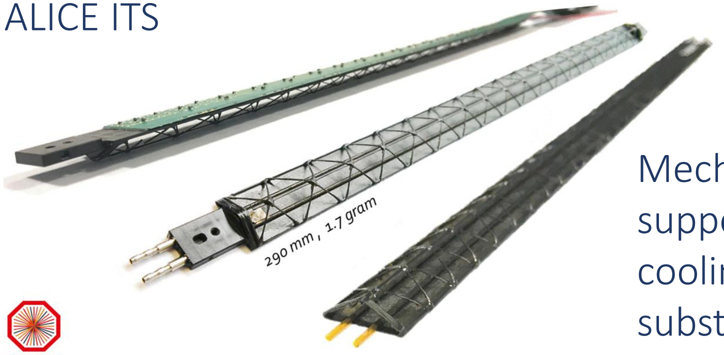
Future: Possible integration in a (CMOS pixel chip)



Filling of trenches (e.g. PECVD, Parylene)

WP4: Detector Mechanics^{++}

ALICE ITS



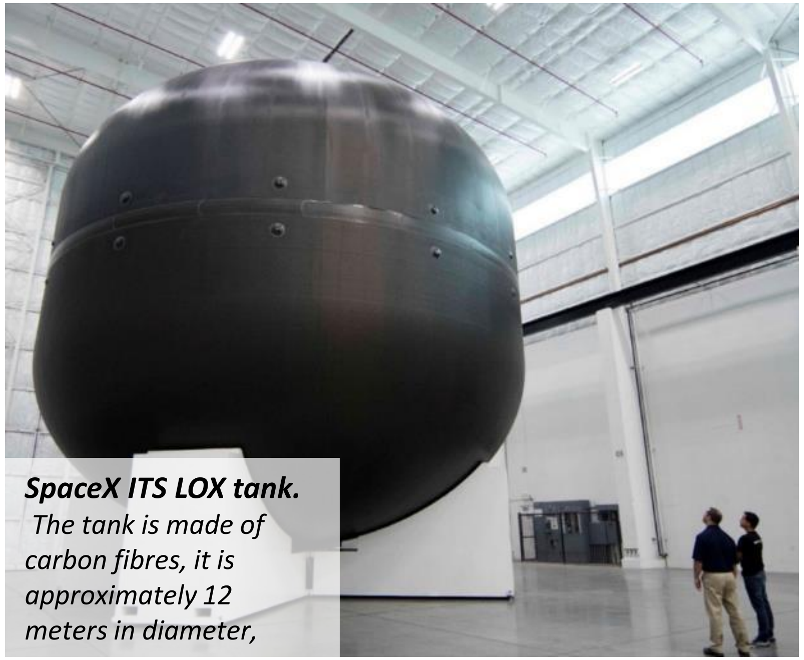
Mechanical support + cooling substrate

Low mass structures
- Vertex detectors
- Cryostats for calorimetry + magnets

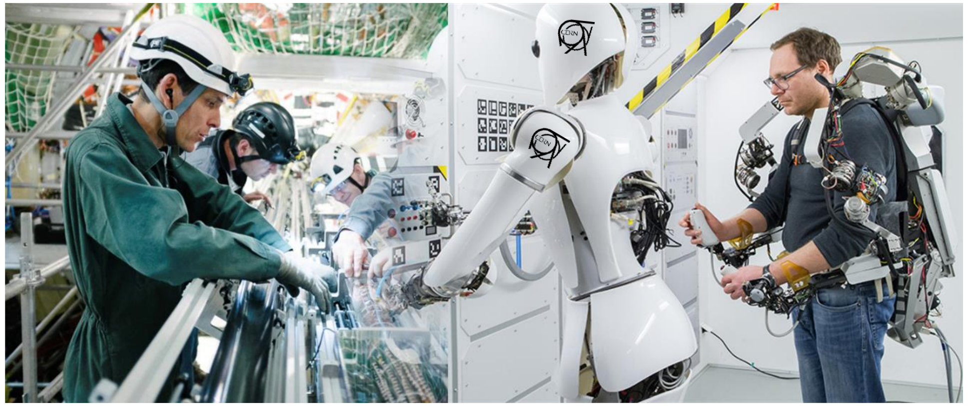
Cooling techno-logies
- Methods (gas/liquid)
- Coolants (GWP)
- Piping and instrumentation

Interfaces and service architectures for automated installation and maintenance, in future high radiation environments

- Low power, low mass → gas cooling
- High power, low T → CO_2 2-phase cooling (more mass)
- Other coolants. CO_2/N_2O ?
- Primary compressor based on CO_2
- Pipework and instrumentation



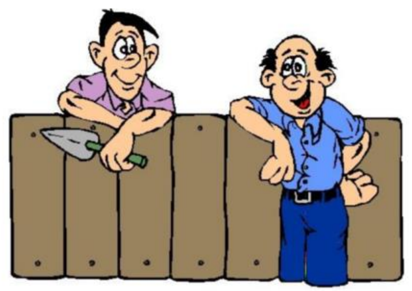
SpaceX ITS LOX tank.
The tank is made of carbon fibres, it is approximately 12 meters in diameter,



… and the far far (far) future ?

VCI highlights

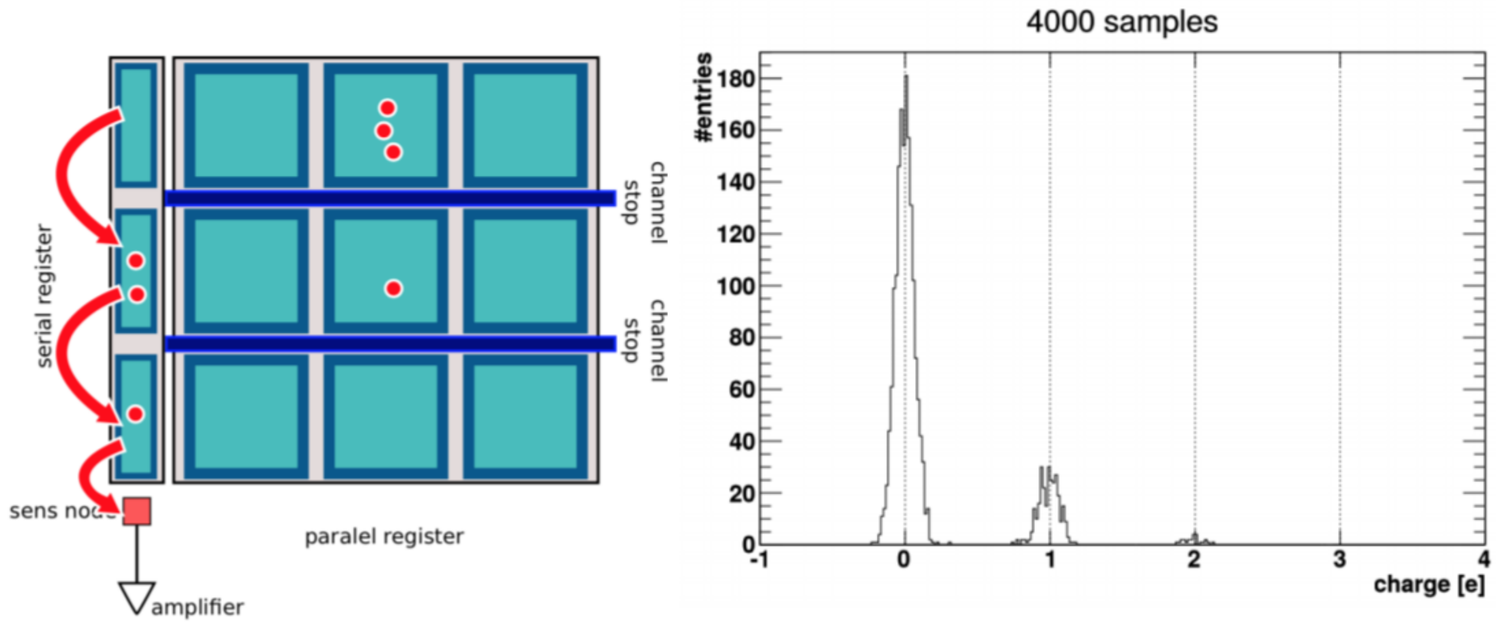
Quantum Sensors for HEP and HEP technology for Quantum Science



neighbors with the right tools can help each

A new world is emerging, with new tools and methods. How can we profit from each other?

Skipper CCD. Modified sense node allows for repetitive non-destructive readout.
→ **Device become single photon / single electron sensitive**



We will probably not yet see ‘Quantum sensors’ at the next (LHC) upgrade, but we definitely need to keep an eye on this exciting field.

A little bit of DEPFET ?

However, device is slow (ms) and likes to operate cold (140 K)

Juan Estrada: Quantum Sensors for HEP and HEP technology for Quantum Science.

Conclusions

...hard to draw conclusions about a **future** R&D programme

- Instrumentation is crucial for progress in physics
- VCI has again given a fantastic overview on detector R&D, construction, applications, performance
- CERN will launch next year a strategic R&D programme on technologies for future experiments
- Join us!

- Thanks to the committees
  - Interesting program
  - Excellent organisation
  - Warm hospitality

- Looking forward to VCI 2022!

BACK-UP Slides

Requirements on future Silicon detectors

Parameter \ Experiments	LHC	HL-LHC	SPS	FCChh	FCCee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{17}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G****)	8G****)	20 G	20M ***)	240k
Surface inner tracker [m^2]	2	10	0.2	15	1	1
Surface outer tracker [m^2]	200	200	-	400	200	140
Material budget per inner detection layer [X_0]	0.3%*) - 2%	0.1%*) - 2%	2%	1%	0.3%	0.2%
Pixel size inner layers [μm^2]	100x150-50x400	~50x50	~50x50	25x50	25x25	<~25x25
BC spacing [ns]	25	25	>10^9	25	20-3400	0.5
Hit time resolution [ns]	<~25–1k*)	0.2**)–1k*)	40 ps	~10^{-2}	~1k ***)	~5

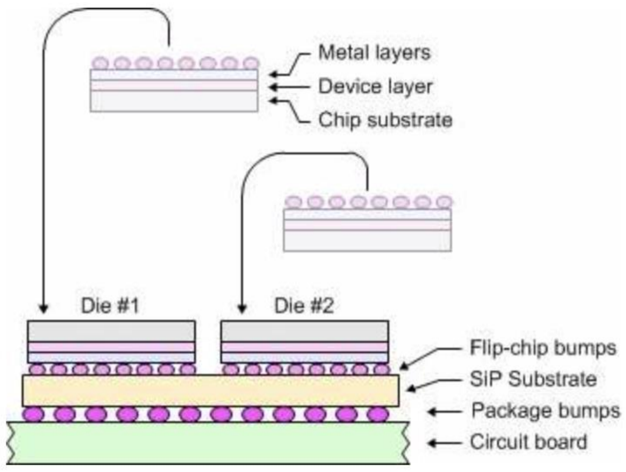
- In general, at least an order of magnitude more radiation hardness than at LHC.
- High time resolution O(10ps)
- High hit rate / data rate
- Very low material budget

Convenors: Dominik Dannheim, Luciano Musa, Heinz Pernegger, Petra Riedler. Contributions from: Duccio Abbaneo, Michael Campbell, Victor Coco, Paula Collins, Michael Moll, Walter Snoeys + many from outside CERN

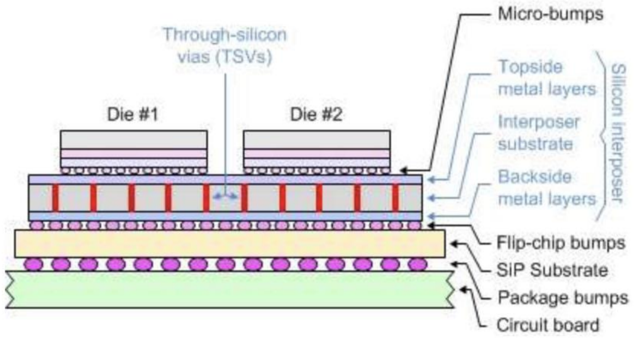
Table 2: Basic detector parameters for the tracking and calorimetry of the CLD and CLIC detectors.

Parameter	CLD	CLIC
Vertex, hit position resolution (μm)	3	3
Vertex, maximum silicon pixel size (μm^2)	25×25	25×25
Vertex, hit time-stamping capability (ns)	10 - 1000	10
Vertex, max. material budget per layer (X_0)	0.3%	0.2%
Vertex, inner radius (mm)	17	31
Tracker, hit position resolution (μm)	7	7
Tracker, maximum silicon cell size ($\mu m \times$ mm)	50×(1-10)	50×(1-10)
Tracker, hit time-stamping capability (ns)	10 - 1000	10
Vertex, max. material budget per layer (X_0)	2%	2%
Tracker, outer radius (cm)	215	150
ECal cell size (mm^2)	5×5	5×5
ECal hit time resolution (ns)	1	1
HCal cell size (mm^2)	30×30	30×30
HCal hit time resolution (ns)	1	1

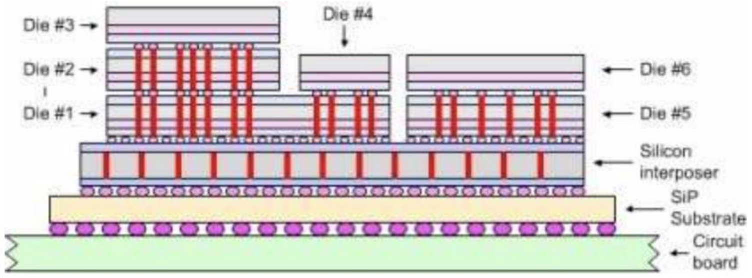
https://www.eetimes.com/document.asp?doc_id=1279540



A traditional 2D IC/SiP



A 2.5D IC/SiP using a silicon interposer and through-silicon vias (TSVs)

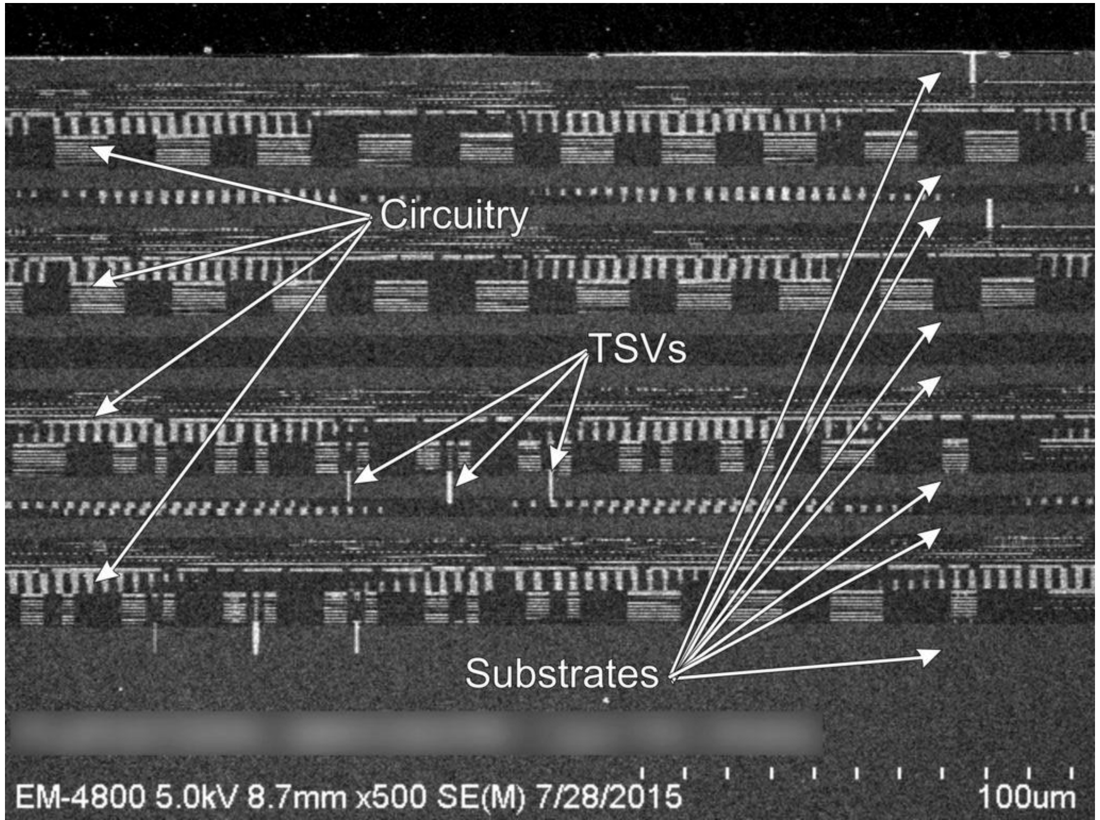


A more complex "True 3D IC/SiP"

MIT Lincoln Lab:
https://ilp.mit.edu/newsstory.jsp?id=21262

https://www.i-micronews.com/category-listing/product/amd-high-bandwidth-memory.html

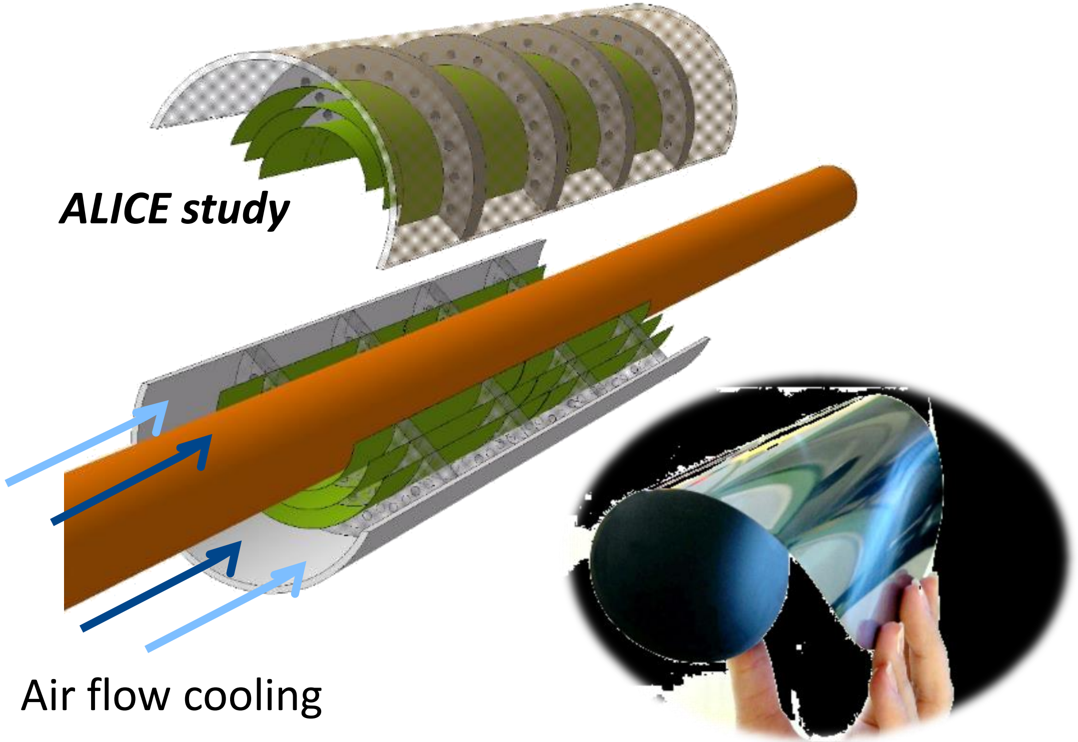
https://nhanced-semi.com/technology/about-3d-ics/



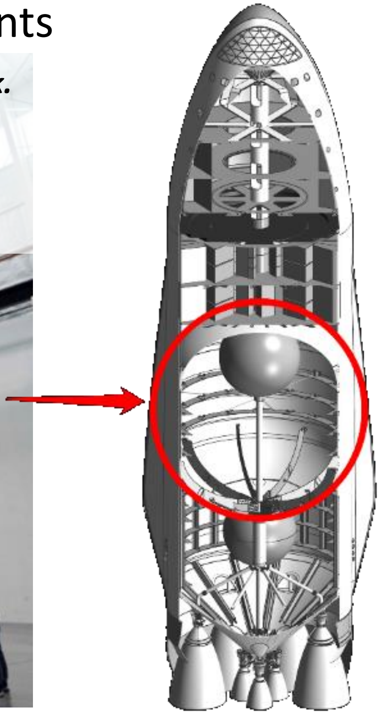
WP4: Detector Mechanics^{++}

- **Activity 1** **Low mass mechanical structures for…**
  - **Task-1** … future Tracking Detectors
  - **Task-2** … future cryostats for Calorimeters and Detector Magnets

- Structure Design
- Cooling Design
- Materials
- Processes
- Integration
- Installation
- Maintenance
- Environment and Stability



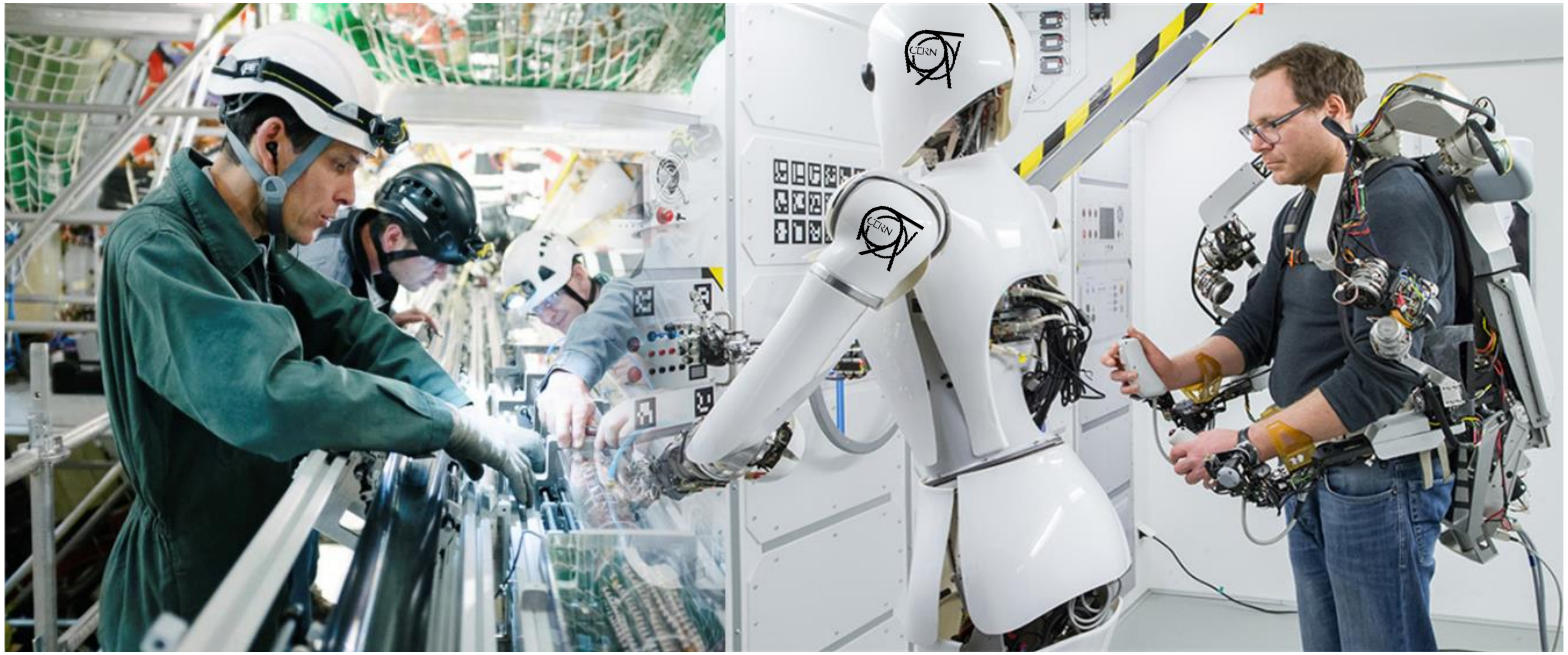
Learn from latest industrial developments



Convenors: Corrado Gargiulo and Antti Onnela

Activity 2 New detector interfaces and services architectures for automated installation and maintainability in future high radiation environments

Today → Tomorrow (or later)



At a certain moment such technologies will be badly needed. The required investment will be substantial.

Activity n.3 High-performance cooling for future detectors

- Future lepton collider: operation at ambient temperature may be a viable solution → 'simple' air cooling or liquid cooling for complex detector geometry
- Future hadron collider: more powerful cooling and also lower coolant temperature:

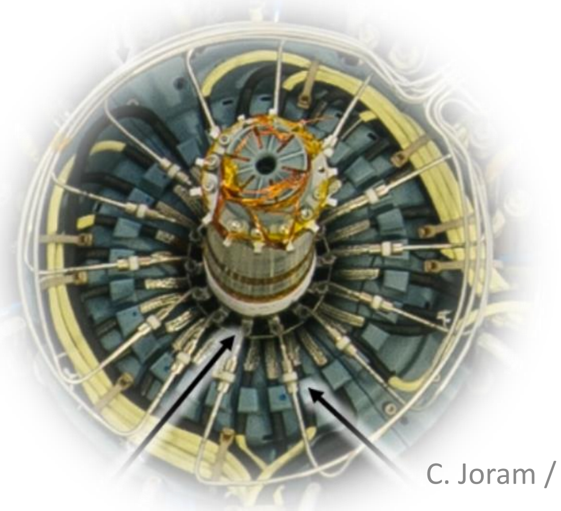
  → CO_2/N_2O are promising coolants, which are in addition environment-friendly

- **Cooling pipework and instrumentation** for large distributed systems

***Cold transfer lines** in hadron collider detectors need to be **insulated** from the surroundings and installed in congested spaces.*

***R&D on cheap and rad hard sensors** for pressure and flow reading*

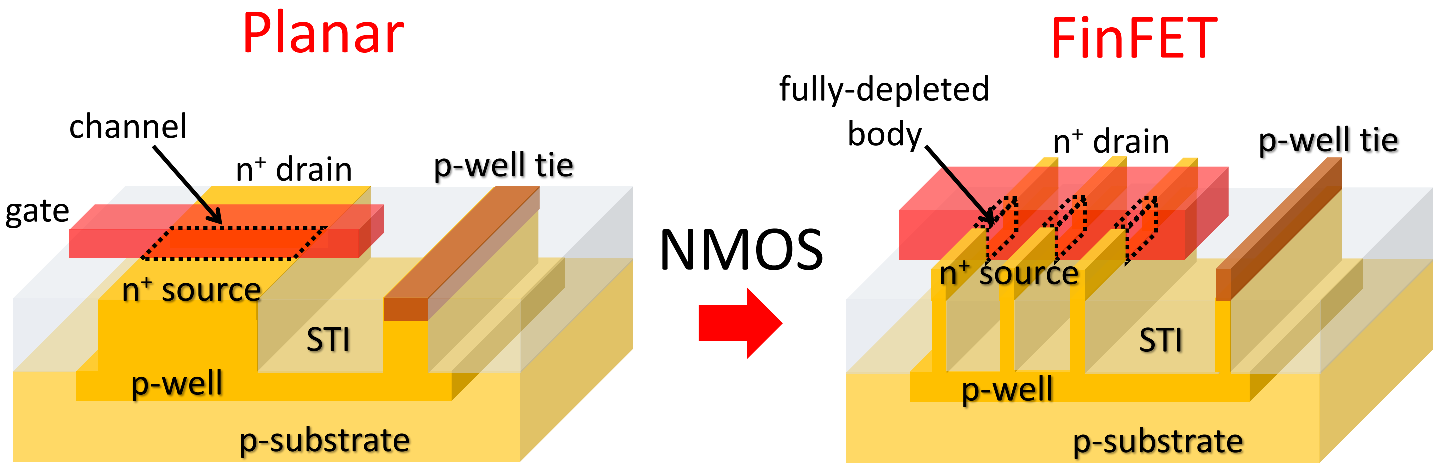
Minimize material budget of pipework



WP5: Integrated Circuits

- Large parts of HEP community rely on CERN as technology platform (toolkits, libraries) and entry point to foundries

- Current HEP ASIC designs are in 130 and 65 nm technology ⇔ industry is already at 7 nm (and below)
- Following the evolution should give performance increase (e.g. higher IO speed), but requires VERY substantial resources and efforts
- Standing still is anyway no option, as currently used processes will become unavailable.
- Below 22 nm, transistors are produced in FinFET technology, complicating design and fabrication process significantly.



Convenors: Michael Campbell and Federico Faccio

1. Chose and evaluate technology

2. Develop building blocks for ASICs

EP R&D

Survey technologies:
- 28nm planar
- 16nm FinFET

Activity 1
CMOS and assembly Technologies

CMOS Technologies

Radiation effects

CAD tools with emphasis on:
- reference design workflows
- mixed-signal design of complex chips (SOC)
- collaborative tools

Enablers (DKit, FrameContract, NDA, training)

Custom digital logic compilers

CMOS-related Assembly Technologies

Through-Silicon Vias (TSV)
CMOS wafer stacking

TSV increase data throughput. WP will bring TSV technology to 28 nm on 12'' wafers

Longer term: wafer stacking may make bump bonding obsolete

Activity 2
Design and IPs

Low-voltage and low-power design

Study of noise and matching performance

Design of circuit functions:
- Voltage reference generators
- Low-noise amplifiers
- Conversion: ADC, DAC
- Timing circuits: PLLs, DLLs, TDC
- Line drivers/receivers

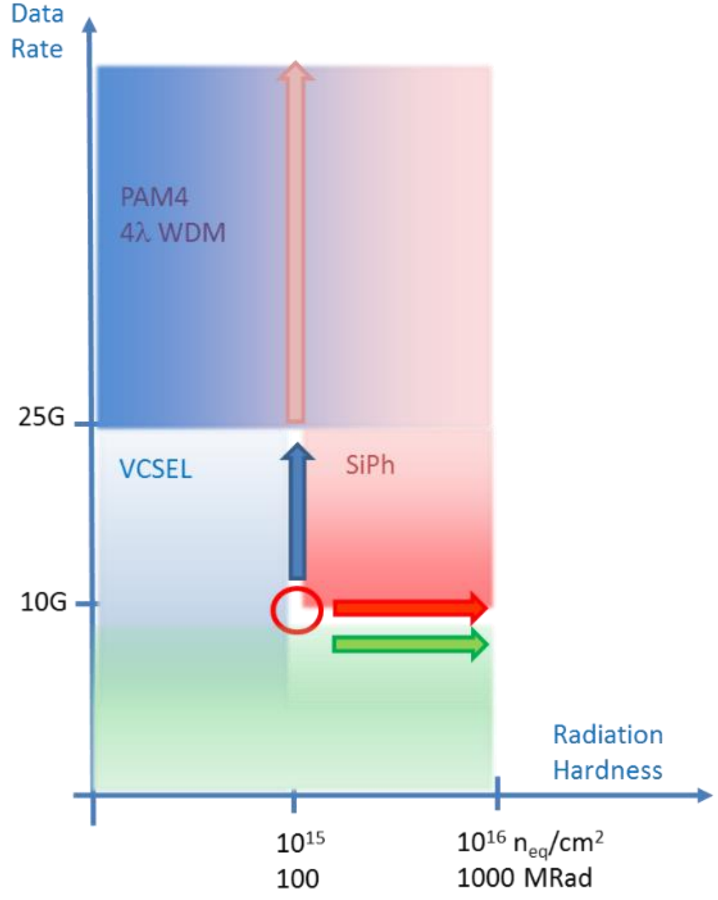
Power distribution

High efficiency POL converter (Vin >25V)
IP blocks for on-chip power management: converters and regulators

Improve on existing FEAST2 DCDC converters. Increased voltage rating (25V), rad hard, small, B-tolerant

WP6: High Speed Links

- Under development for HL-LHC: lpGBT 10 Gbps SER/DES + VCSEL drivers + TIA (65 nm)
- How to go beyond 10 Gbps and cope with higher radiation levels?



Ongoing development
HL-LHC, 2020
LpGBT-VL+ project

Future developments:

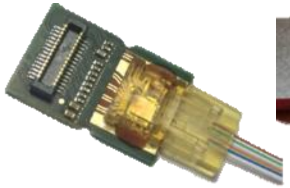
- Higher Data rates
- Si Photonics
- λ Multiplexing and multi-level signalling (PAM)
- Low mass copper links

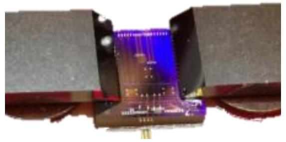
3 R&D activities were identified:

- ASICs

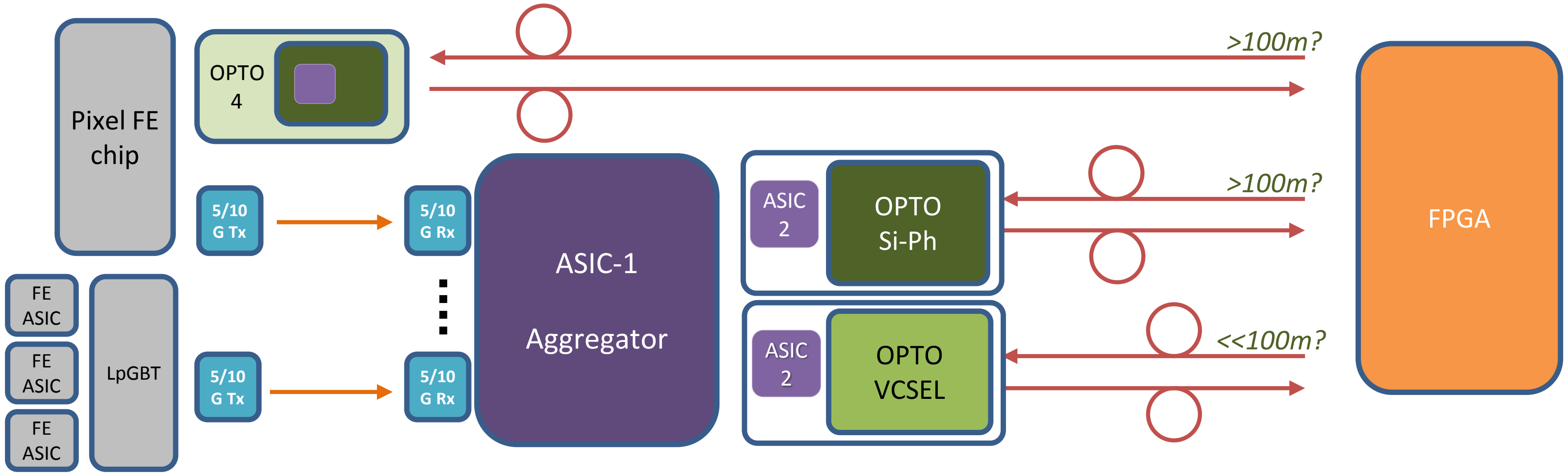
- FPGAs

- Optoelectronics

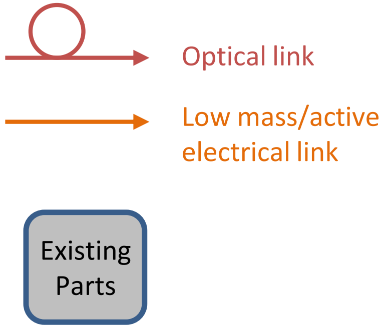




Convenors: P. Moreira and Francois Vasey



Activity	Task	Description
ASICs	ASIC-1	Very high data rate aggregator/transmitter
	ASIC-2	Optoelectronics drivers
	ASIC-3	Low-mass electrical cable transmission (active cable)
FPGA	FPGA-1	FPGA-based system testing and emulation
OPTO	OPTO-1 & 2	Silicon Photonics System & Chip Design
		Silicon Photonics Radiation Hardness
	OPTO-3	Next-generation VCSEL-based optical link
	OPTO-4	Silicon Photonics packaging



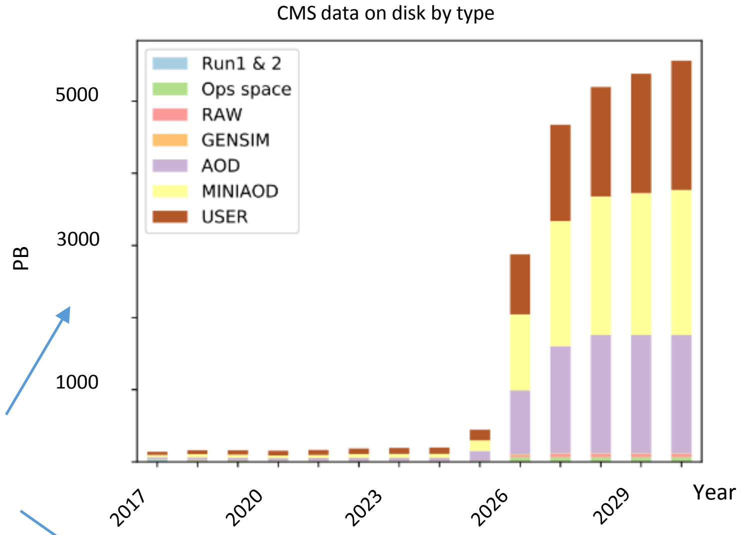
WP7: Software

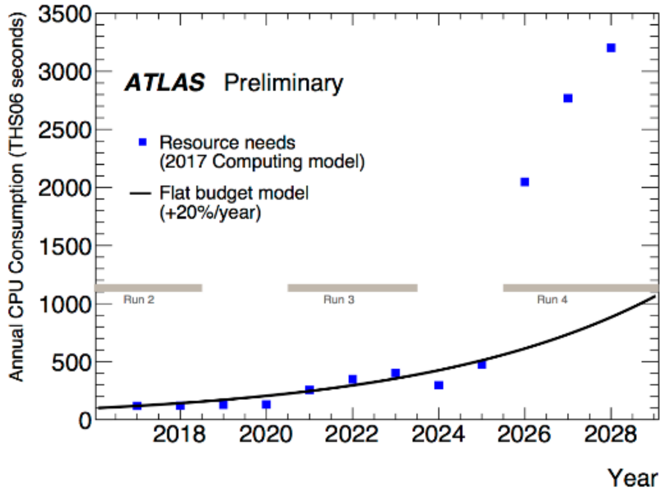
EP R&D

Major HEP Software Challenges for the 2020s

1. An order of magnitude higher event rates and event complexities at future hh colliders
2. Changing hardware landscape
   Specialized and more parallel processors and storage devices
3. …

HL-LHC is far from being a solved problem for software and computing



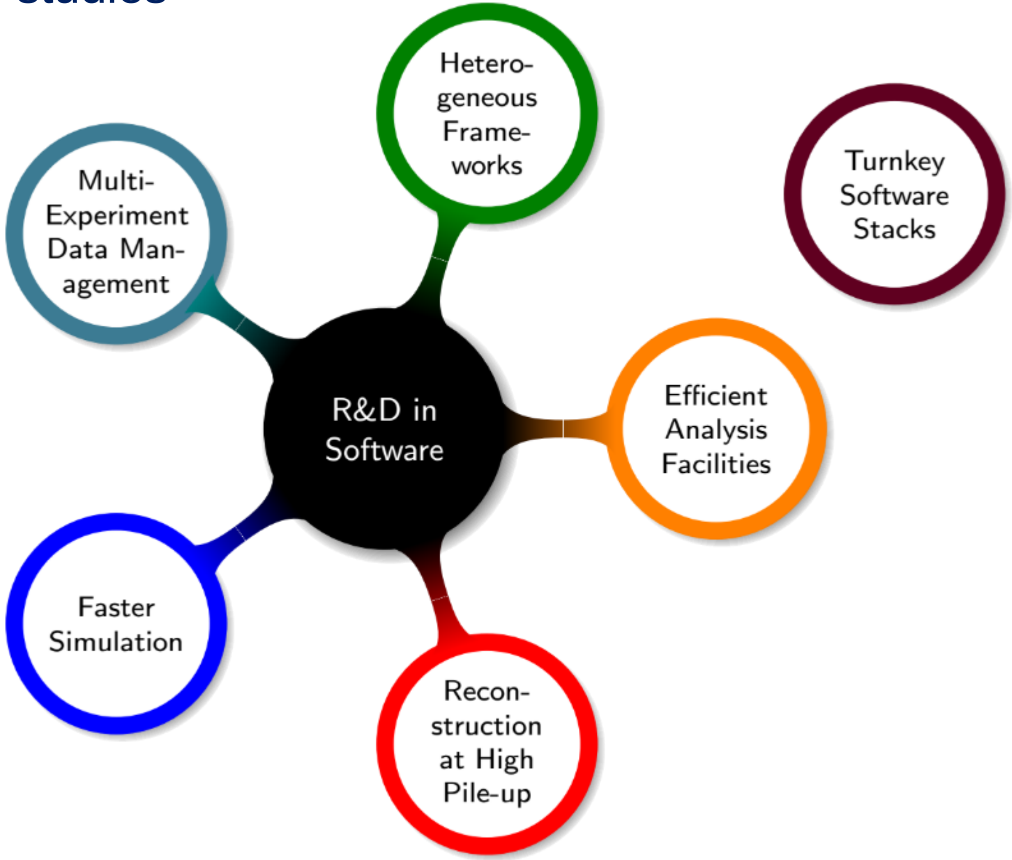


Whatever the future, we pass through the HL-LHC on the way

HEP Software Foundation Community White Paper maps out that path

Convenors: Graeme Stewart and Jakob Blomer

- 5 research lines addressing HEP software challenges
- Turnkey software stacks supporting of detector studies



Simulation: aim for 1 order of magnitude speed-up

Reconstruction: algorithms, hardware, ML for tracking with ultrahigh pile-up

Analysis: smart dataflow and bookkeeping to cope with 1-2 order of magn. higher event numbers and complexity.

Heterogenous computing: Use of hardware accelerators (GPU, FPGA, TPU, ASIC, etc.) across a large number of nodes

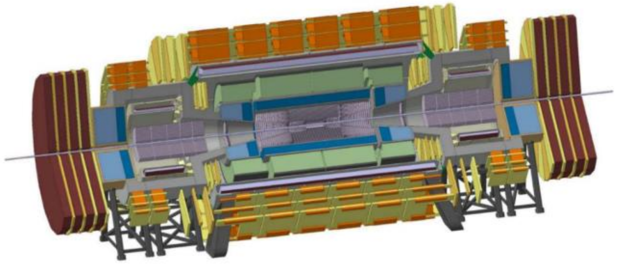
Data management across experiments: allows dynamic resource sharing. Examples are Rucio, DIRAC, ALiEN

Turnkey Software Stacks: Aim at a low-maintenance common core stack for FCC and CLIC that can “plug-in” a detector concept under study

WP8: Detector Magnets

Collider	FCC-hh	FCC-hh	FCC-hh	FCC-ee	FCC-ee	CLIC	LHC	LHC
Detector concept	baseline	baseline	alter-native	IDEA	CLD	baseline	CMS	ATLAS
Magnet type	central solenoid	forward solenoid	forward dipole	central solenoid	central solenoid	central solenoid	central solenoid	central solenoid
Location w.r.t. calorimeter	behind	N/A	N/A	in front	behind	behind	behind	in front
B-field (T)	4	4	4 Tm	2	2	4	3.8	2
Inner bore radius (m)	5.0	2.6	N/A	2.1	3.7	3.5	3	1.15
Coil length (m)	19	3.4	N/A	6	7.4	7.8	12.5	5.3
Current (kA)	30	30	16.6	20	20 or 30	~20	18.2	7.7
Current density A/mm2	7.3	16.1	27.6	??	??	13	12	
Stored energy (GJ)	~12.5	0.4	0.2	~0.2	~0.5	~2.5	2.3	0.04
Mat. budget incl. cryostat				~1 X_0		<1.5 λ		
Cavern depth (m)	≤ 300	≤ 300	≤ 300	≤ 300	≤ 300	~100	100	~75

FCC with very large barrel and forward 4T solenoids



5 proposed activities

1. Advanced Magnet Powering for high stored energy detector magnets
2. Reinforced Super Conductors and Cold Masses
3. Ultra-Light Cryostat Studies
   Coord. By WP4 (mechanics)
4. New 4 tesla General Purpose Magnet Facility for Detector Testing
   Only study, no construction ($).
5. Innovation in Magnet Controls, Safety & Instrumentation
   Will use above 4T magnet as use case.

Convenors: Herman Ten Kate and Benoit Cure

1. **Advanced Magnet Powering for high stored energy detector magnets** → to improve stability and quench protection, reduce recovery and energy consumption.

2. **Reinforced Super Conductors and Cold Masses** → basis for building very low X_0 magnets (if solenoid inside e.m. calo).

3. **Ultra-Light Cryostat Studies**

→ part of a more general study in WP4 for light weight vessel structures (LAr calo, magnets, cryo SiPM box).

↓ Design will be influenced by above technologies

CMS – 20 kA switch breakers for powering and discharging lines.

4. **New 4 T General Purpose Magn Facility for Detector Testing** → many detectors and equipment will have to work at 4 T. Today, there is no adequate test infrastructure available. Only design study is part of R&D. Budget O(10 M) for construction must come from a different source.

5. **Innovation in Magnet Controls, Safety & Instrumentation** → Sensors, electronics, DAQ for quench protection, magnet control, magnetic measurements

← Instrumentation development can use 4T facility as use case.

R&D topics

Working Groups → packages	Convenors
WP 1: Silicon detectors	Heinz Pernegger, Luciano Musa, Petra Riedler, Dominik Dannheim
WP 2: Gas detectors	Christoph Rembser, Eraldo Oliveri
WP 3: Calorimetry and light based detectors	Martin Aleksa, Carmelo D'Ambrosio
WP 4: Detector Mechanics^{++}	Corrado Gargiulo, Antti Onnela
WP 5: IC technologies	Federico Faccio, Michael Campbell
WP 6: High Speed Links	Paolo Moreira, Francois Vasey
WP 7: Software	Graeme Stewart, Jakob Blomer
WP 8: Detector Magnets	Herman Ten Kate, Benoit Cure

Steering committee

Philippe Farthouat, Roger Forty, Patrick Janot (FCC-ee), Christian Joram (coordinator), Manfred Krammer (chair), Lucie Linssen (CLIC), Pere Mato, Burkhard Schmidt, Werner Riegler (FCC-hh)