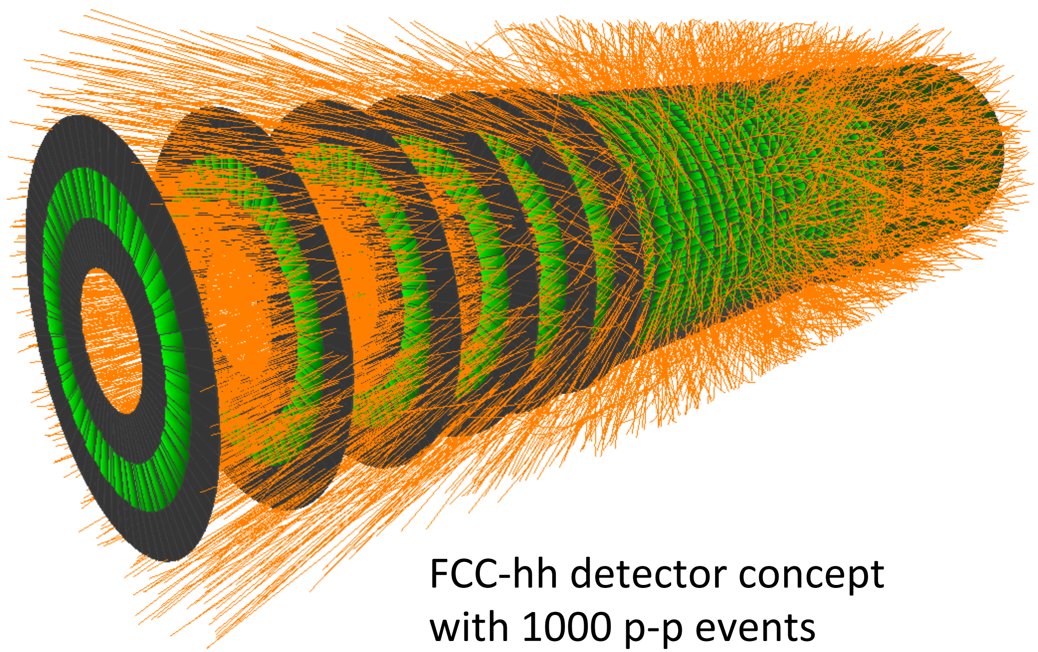
CERN Atlas Team’s RD towards future detectors and experiments

H. Pernegger / EP-ADE

On behalf of …

- Many thanks for all the input from
  - M. Aleksa
  - D. Alvarez
  - A. Catinaccio
  - N. Ellis
  - M. Elsing
  - A. Henriques
  - P. Riedler
  - A. Salzburger
  - W. Snoeys
  - H. Ten Kate
  - J. Troska



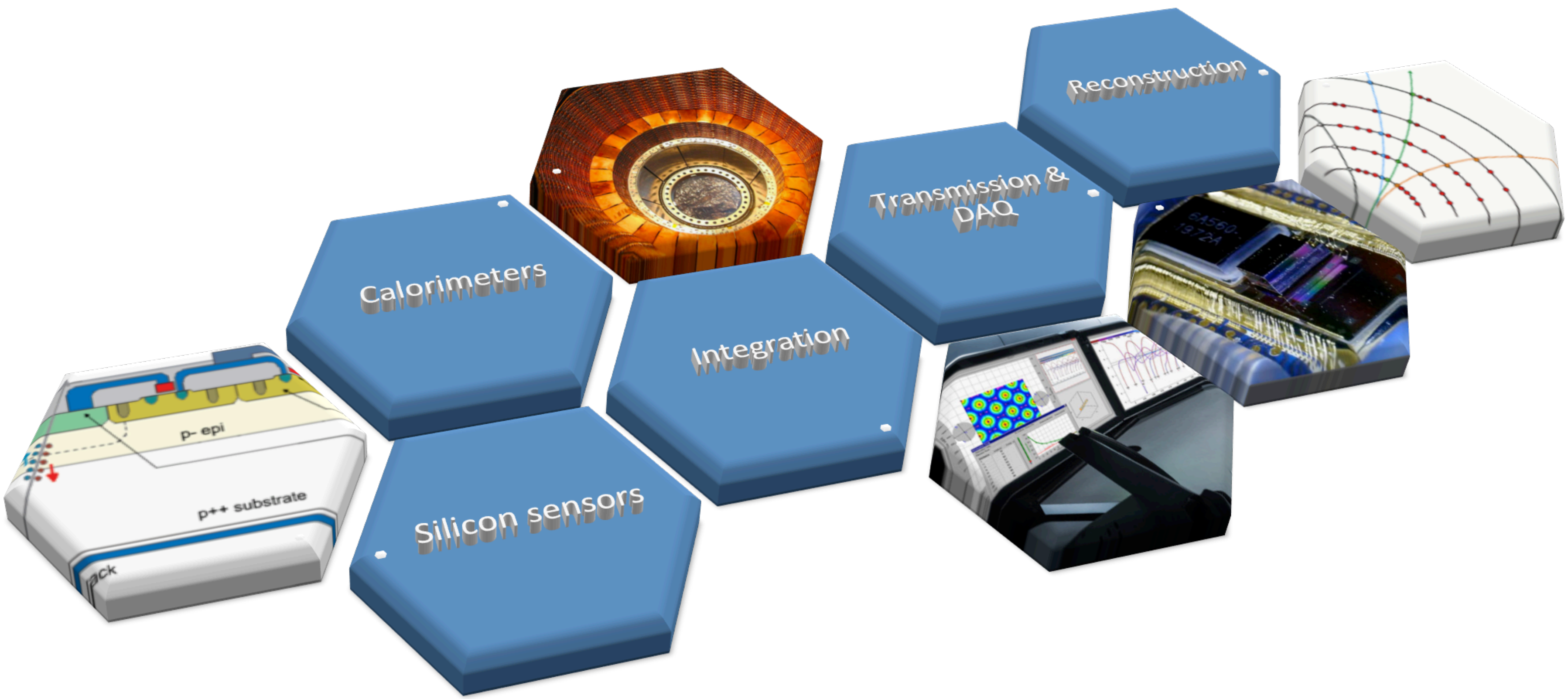
FCC-hh detector concept
with 1000 p-p events
with ACTS fast simulation

The current RD in the Cern Atlas Team

- Goal : Explore and innovate new technologies for **Future Detectors(-upgrades) and Experiments**

- **Innovate key experimental technologies** during 2020 to 2026
  - Identify Technologies for Future Detector Systems
  - Establish (and test!) their key benefits and strategic values in view of future requirements
  - Implement in demonstrators and experiment's applications
  - Foster strategic partnerships with related industrial partners and research institutions

The RD activity map



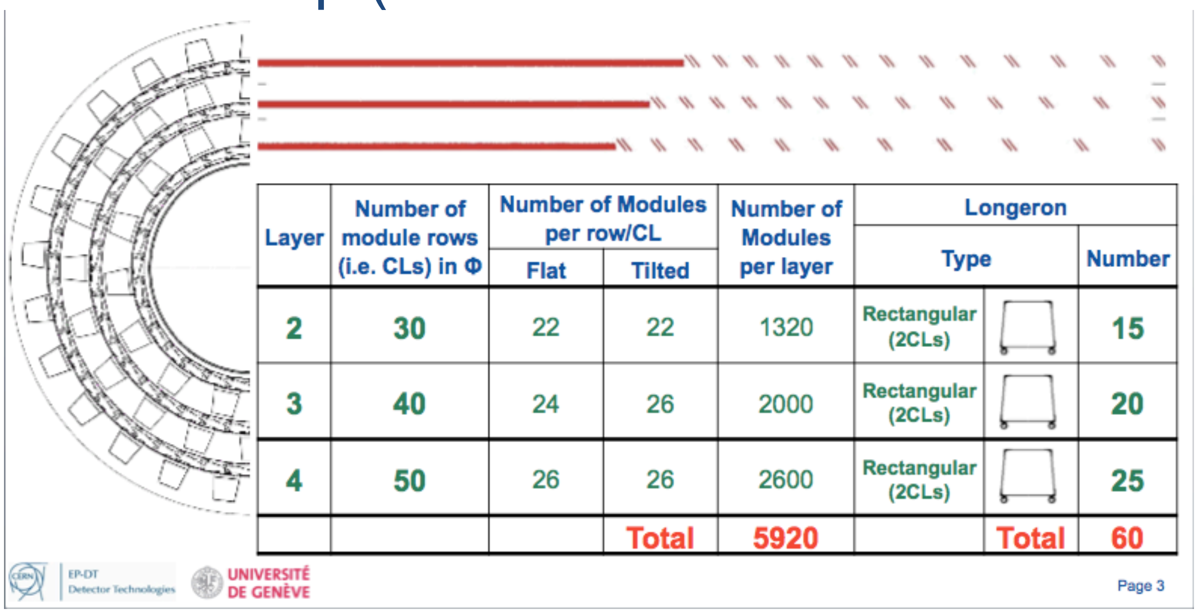
- RD activities by CAT members for Atlas and beyond

Trackers

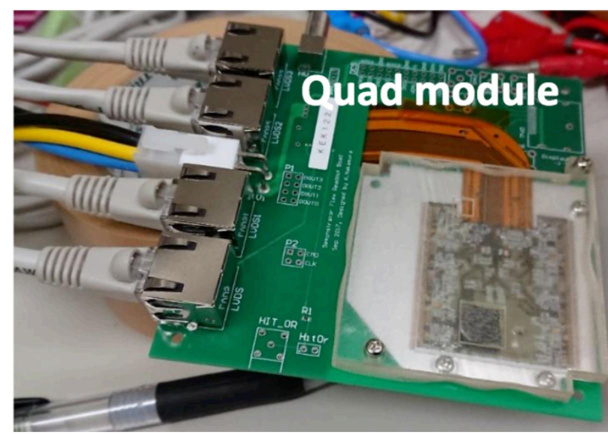
sensors, modules and their readout

Silicon (Hybrid - Pixel)

- ATLAS ITK Pixel : CAT contributes significantly to the development and construction of the Phase 2 ITK Pixel Outer Barrel
  - **Hybrid–Planar Modules** with RD53-developped FE chip (current modules based on FEI4)

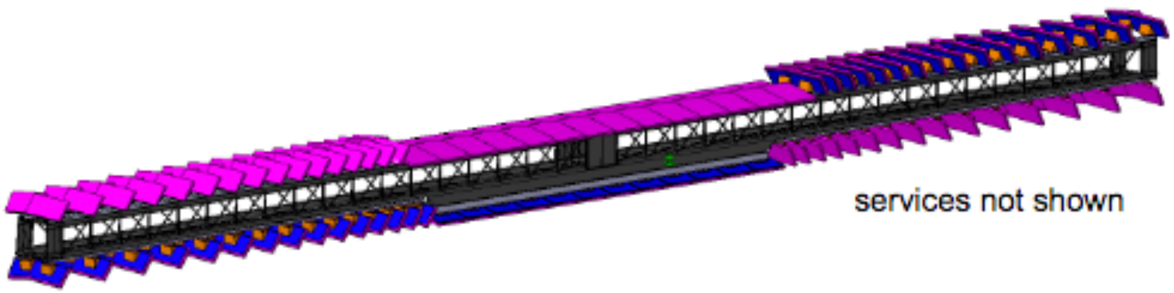


Layer	Number of module rows (i.e. CLs) in Φ	Number of Modules per row/CL		Number of Modules per layer	Longeron	
		Flat	Tilted		Type	Number
2	30	22	22	1320	Rectangular (2CLs)	15
3	40	24	26	2000	Rectangular (2CLs)	20
4	50	26	26	2600	Rectangular (2CLs)	25
			Total	5920	Total	60

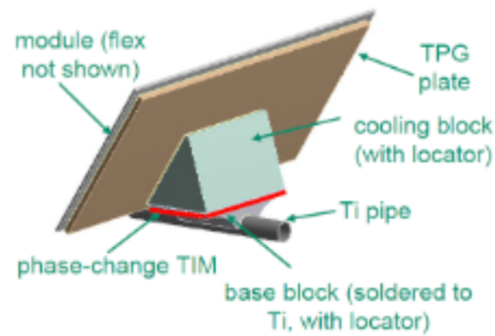


Silicon (Hybrid - Pixel)

- Development of large structures for future Pixel tracker : **Future Tracker Demonstrators**
  – Immediate and mid-term future on integration of new hybrid pixel modules to large assemblies
  – Detector, Electronics and Mechanics system integration
  – Tight collaboration with EP-DT and several Atlas institutes



TRUSS longeron for layer 2 and layer 3 (1.6 m)
4 cooling lines
52 flat quad and 124 inclined double modules



Inclined module on cell

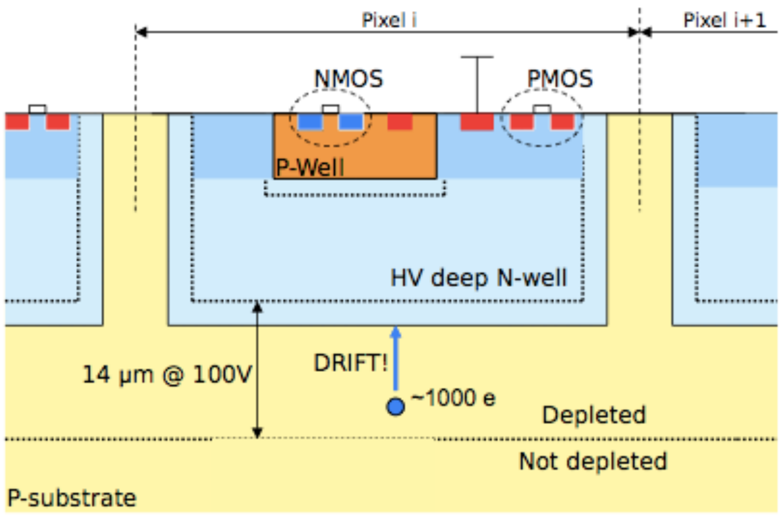
Radiation hard CMOS sensors

Advantages over “classic” p-in-n sensors or traditional Monolithic Active Pixel Sensors (MAPS)

- Full CMOS allows complex electronics in active area of pixel matrix
- Thin and high-resolution trackers
- **Large depleted volume increases sensitivity and provides efficient detection after irradiation**

CAT is a leading member of the ATLAS CMOS Development Collaboration

- 25 institutes – RD on radiation hard CMOS sensors since 4 years
- Monolithic CMOS sensors are developed as option for the **outermost ITK Pixel Barrel layer**

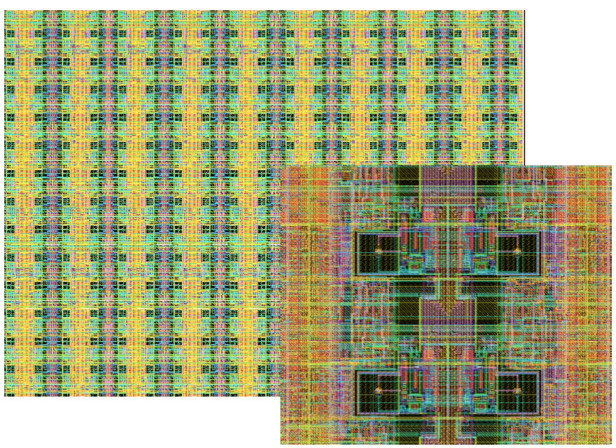


- CMOS is much higher volume than our specialty high-resistivity planar sensors
  - Significantly lower price than our present silicon sensors due to high volume and larger wafers
- CMOS Modules costs ~ factor 4 less than hybrid (no bumpbonding, no extra FE-chip)

ATLAS CMOS sensors

TowerJazz

- Two large scale demonstrators MALTA and Monopix:
  - 20x20mm and 20x10mm
  - Focus on small electrodes
  - MALTA: Asynchronous matrix readout (no clock distribution over the matrix)
  - MonoPix : Column Drain Read-Out

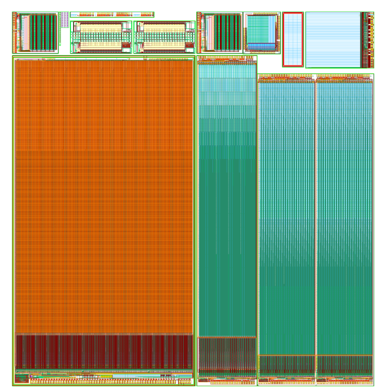


- CAT & ESE lead development

AMS

ATLAS (monolithic)

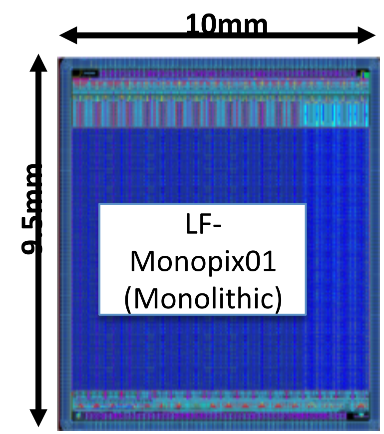
- Additional production step – isolated PMOS
- 80 and 200 Ohm.cm wafers
- Reticle Size about 21mm x 23mm



LFoundry

Monopix01, LF2 and Coolpix1

- Received Apr. 2017
- “Demonstrator size”
- 50 x 250 μm² pixels
- Fast standalone R/O



Participate in development through tests

CMOS for Future Trackers

- **From ALICE to ATLAS: Radiation hardness, response time, hit rates**

	ALICE ITS	ATLAS Outer Pixel	ATLAS Inner Pixel
NIEL [n_{eq}/cm^2]	10^{13}	10^{15}	10^{16}
TID	<1Mrad	80 Mrad	2x500Mrad
Response Time [ns]	2000	25	25
Hit rate [MHz/cm^2]	10 + SF	100-200	2000

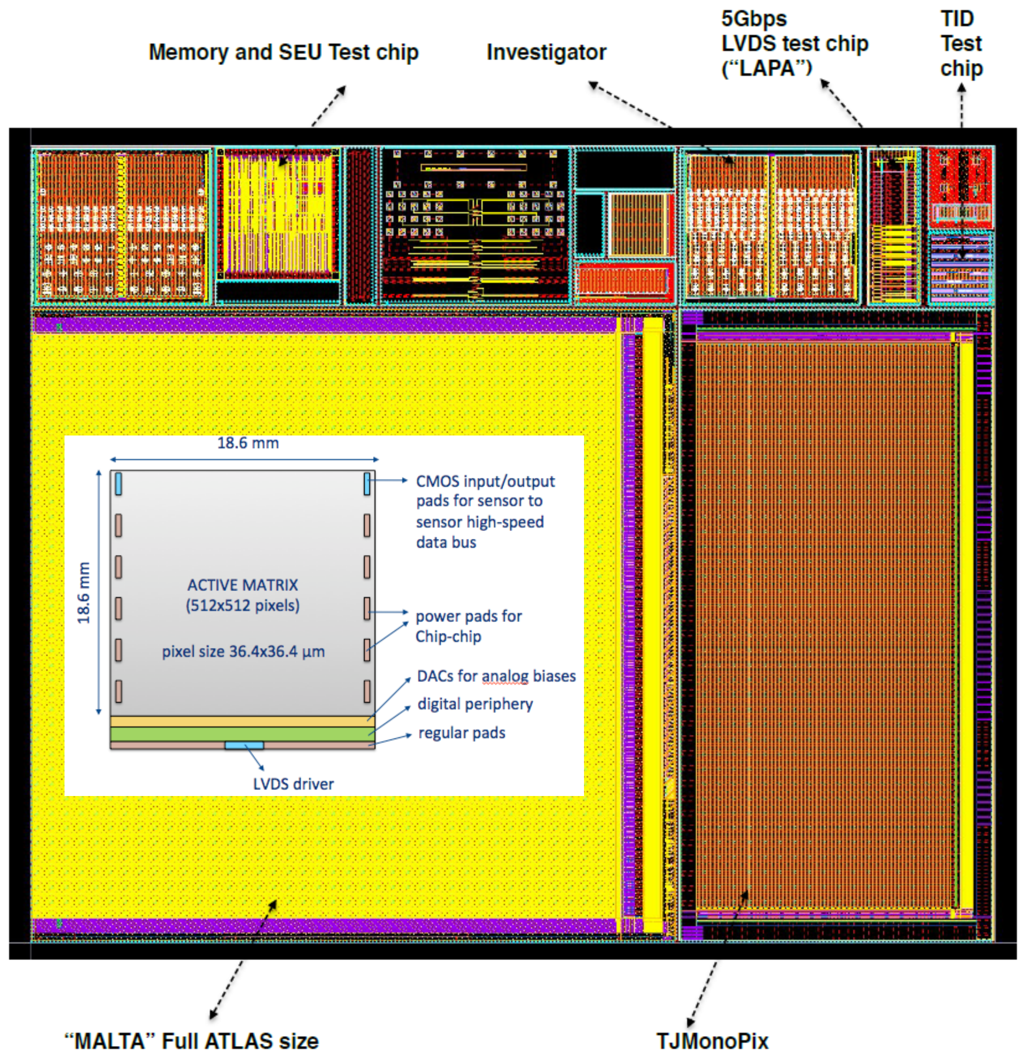
Key parameters need factor ~100 Performance gain

- **Collect signal by drift through fully depleted sensor (DMAPS)**:
  - TowerJazz developments in close collaboration with ALICE ITS (L. Musa/ALICE) for optimzed processes
- **Dedicated designs** for high hit rates and fast response
  - New architecture developments in collaboration with ESE (W.Snoeys/ESE)
- **CMOS** sensor post processing and **module integration**
  - Large area module concept and new interconnects technology with DT (P. Riedler/DT)

TJ MALTA for ATLAS

- Monolithic pixel sensor for the outer layers of the ATLAS experiment was investigated using the TowerJazz ALICE Investigator test chip
- “MALTA” = **M**onolithic sensor from **AL**ICE **T**o **A**TLAS
- Large-scale demonstrators with different readout architectures and optimized analog performance

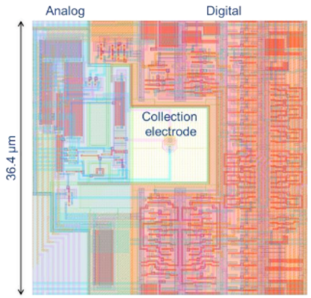
- **The ATLAS “MALTA” chip**
  - Novel asynchronous readout architecture for high hit rate capability with 40bit parallel data bus for streaming
  - Features Sensor-to-Sensor high-speed signal transmission
  - Chip-to-Chip power distribution



Lead design: W. Snoeys /ESE

RD towards future CMOS trackers

- Thin and High-resolution **DMAPS for innermost layers**: new processes and novel designs for next levels of radiation hardness, hit-rate capability and reduction of material
  - Improve tracking performance using thin sensors and small pixels

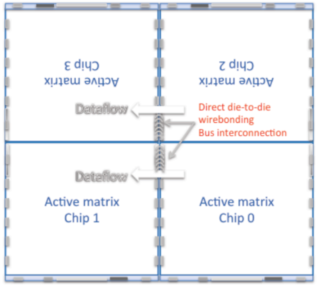


- Hit rates >>GHz/cm^2
- Pixel sizes of 25x25x25 μm^3 or less
- Sensor chains without flex circuits
- Optimized power consumption

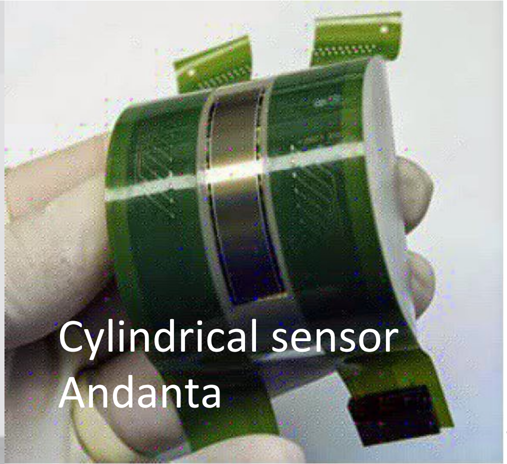
4 CMOS chips (MALTA) chained to one CMOS Quad Module

Use direct die-to-die wire-bonding to interconnect data IO between chips

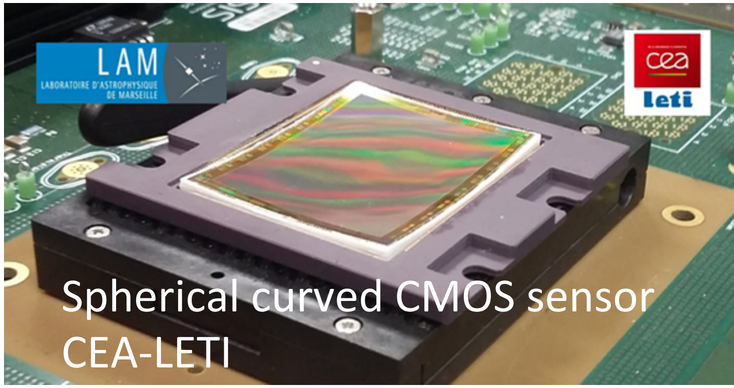
All high speed chip signals routed in silicon (and not on flex to reduce flex mass and maintain signal integrity at high speeds)



- Developed **"stitched" designs for large sensors**
  - Chain sensors for large area trackers and large acceptance
  - Exploit mechanical flexibility of thin sensors in cylindrical or spherical geometry



Cylindrically Curved CCD (Convex)



Pixel R&D in Post Processing

P. Riedler, R. Cardella / EP-DT

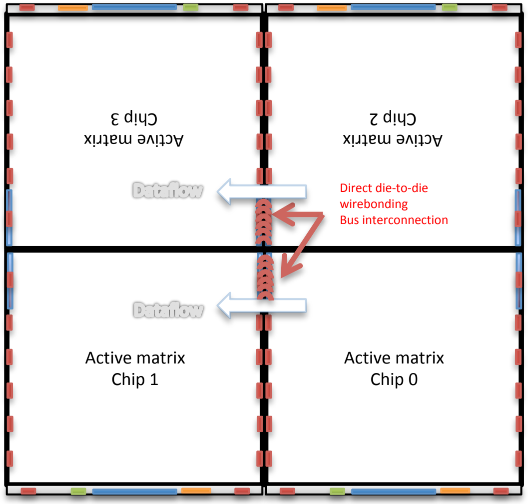
CMOS sensor post-processing is key for integrated multi-sensor modules

- High interconnection reliability using new industrial developments
- High throughput and assembly out-sourcing

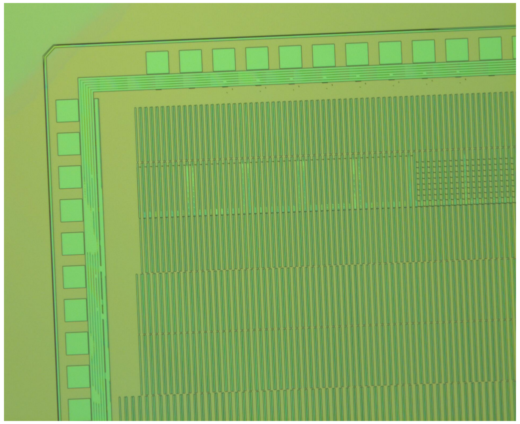
In 2017 submission in modified 0.18 um TowerJazz CMOS imaging process including:

- Design of dedicated test structures to study interconnection techniques and module assembly (chip-to-chip transfer on module level)
- Replace flex routing and wire bonding with On-silicon redistribution-layers (RDL) and direct solder bumping

Fabrication of pad wafers in autumn 2017 ongoing



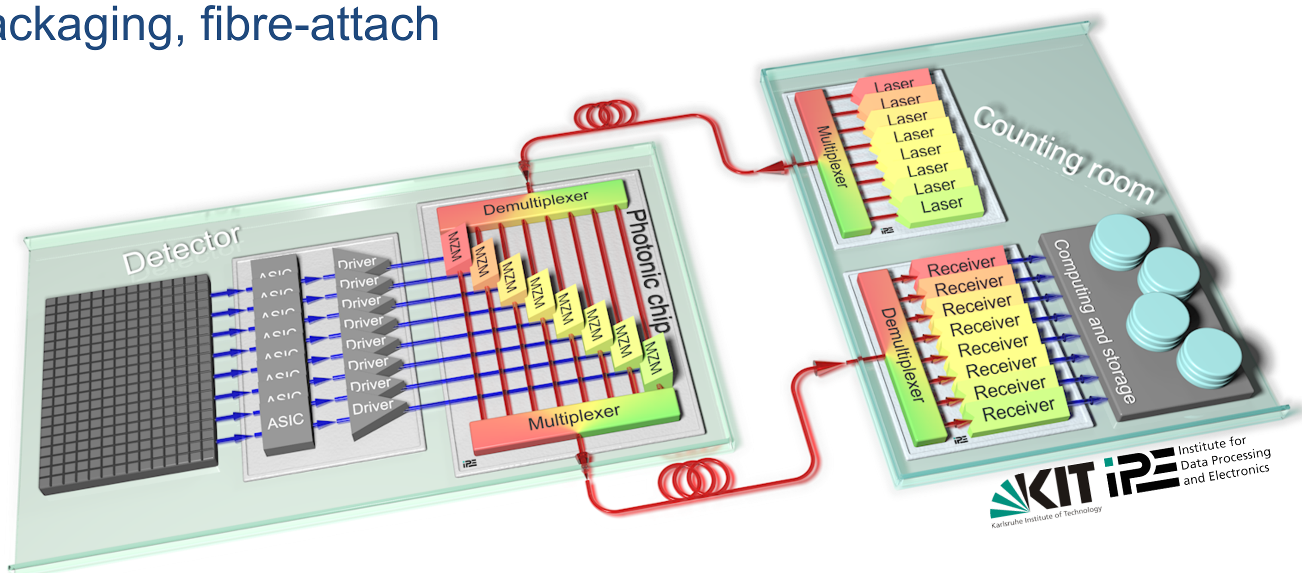
Quad module with chip-to-chip connections



Pad wafer for assembly tests

R&D for Photonics

- Detectors with high-data rate need new ways of integrated data transmission : Couple data fibre directly to ASIC via photonics chip
- First Step is finding/designing Radiation Tolerant Modulator
- Then building a system requires
  - Driving & receiving electronics
  - Understanding optical system margins
  - Designing a fully-fledged system chip taking advantage of potential for SiPh/ Detector integration
  - Packaging, fibre-attach



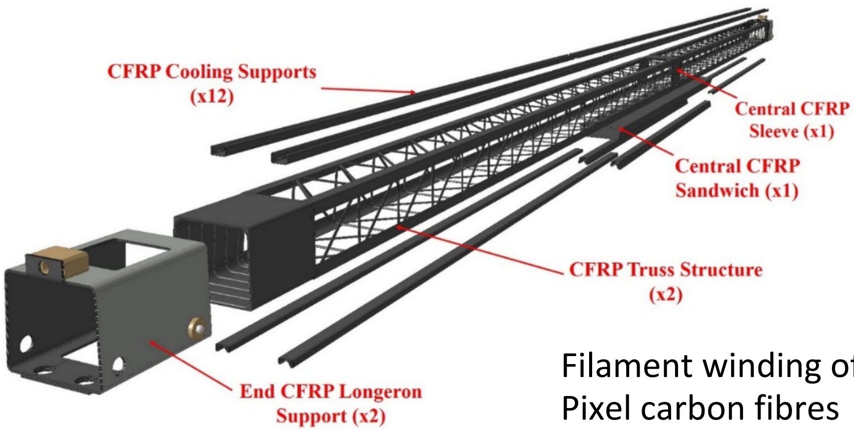
J. Troska
F. Vasey
EP-ESE

Integration

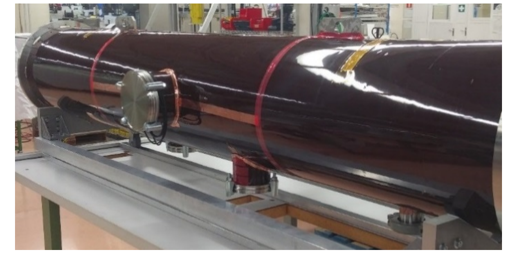
DAQ, mechanics and magnets

– Ultra Light Carbon Composites Structures (On detector Thermal management solutions (Cooling & Advanced Materials)

A. Catinaccio, D. Alvarez / EP-DT



Filament winding of Pixel carbon fibres staves (ATLAS ITK)



Thermal management Materials characterisation

Example of filament winding with dry carbon fibres

Composite characterization:

- **Ultra light Structures** integrating **high thermal conductive composites**
- Toughened composite matrixes and **behavior under high radiation**

Composite processing & Monitoring techniques

- **Filament winding techniques**, RTM (Resin Transfer Molding) techniques
- **Composites on line health monitoring** with embedded sensors: integration of sensors directly in composite parts in order to record data and control integrity of the carbon parts under load

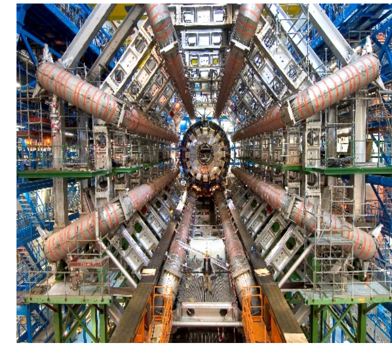
DAQ and trigger

- Compared to detectors, we feel there is less need for dedicated R&D in trigger and DAQ
- The focus of R&D is mainly on technology tracking (electronics, informatics, etc.) and developing new ideas in TDAQ in an evolutive way.
- Within EP, technology tracking related to electronics and associated systems (e.g. power, cooling, etc.) is already well covered by our colleagues in ESE.
- CERN already has an information-technology tracking unit in the form of OpenLab.
- Some aspects of technology tracking, e.g. high-performance data networks for DAQ systems, are addressed directly by the Experiments (CERN and also outside groups).
- It will be important to study the potential of improved software-based triggers, making use of modern commercial processors, as an alternative to custom hardware for future projects

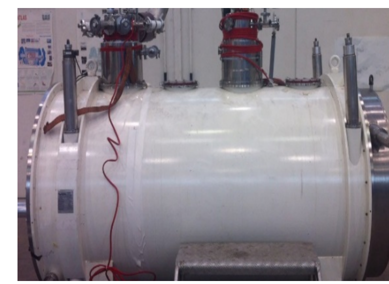
N. Ellis/CAT

- Large concern is preserving knowledge for operating and repairing the systems up to medio 2040.
- This requires a next-generation team with ATLAS specific operations & repair knowledge to warrant another 22 years of operation.
  - Sc Coil, Cryostats, Vacuum, Cryogenics, Current Leads, …..
  - Examples of interventions that may happen (again): leaking in-vessel isolators, non-standard ECT bellows repair, etc…
  - upgrading Facility Magnets for Detector testing e.g. in North Area (Vertex 1, 2, Morpurgo);
  - The team maintains skills by also accepting design, construction, repair requests from non-LHC experiments

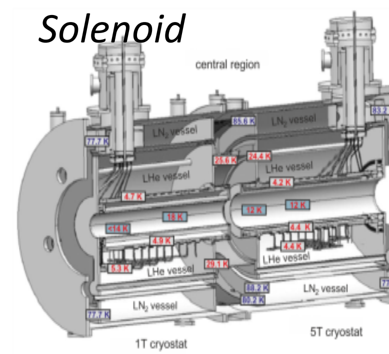
design CLIC Detector Magnet, LHeC detector and IR magnets, AEgIS, overhaul & repair COMPASS, Rexebis magnet repair, design (Baby)-IAXO, design PANDA Solenoid for FAIR, design and construction of BabyMIND etc.



ATLAS Magnet System



COMPASS 2T Solenoid



AEgIS 2&5T Solenoids

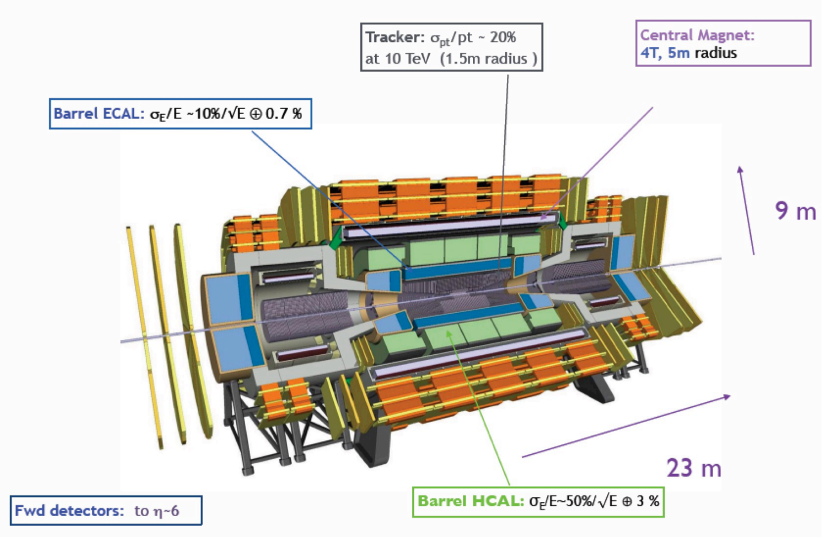
H. Ten Kate/CAT

Calorimeters

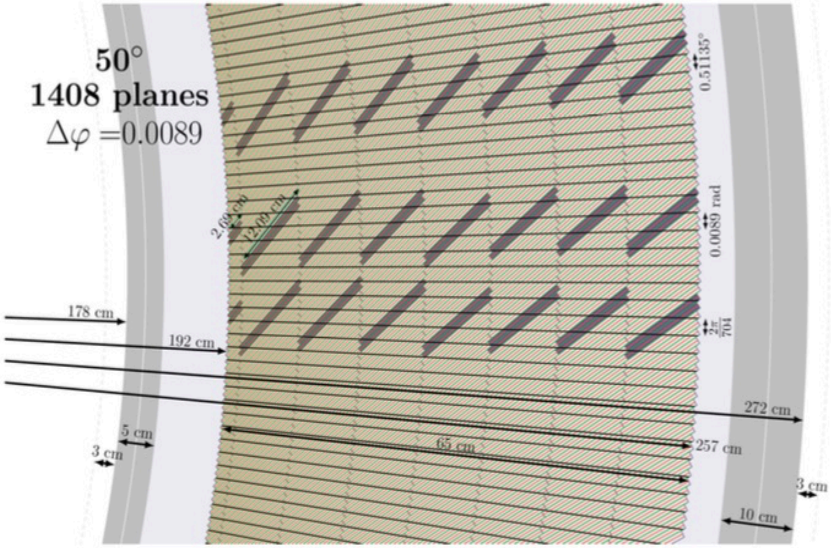
higher granularity and timing

R&D Projects FCC-hh Calorimetry

- **R&D on granularity limits of a noble liquid calorimeter:**
  - High granularity will be essential for future calorimeters (3D imaging, pile-up suppression, particle ID, jet substructure,…)
  - Granularity invrease → fine segmented read-out electrodes (RD on design of multi-layer PCBs as electrodes).
  - Design of electrodes structures and construction of small test module demonstrators



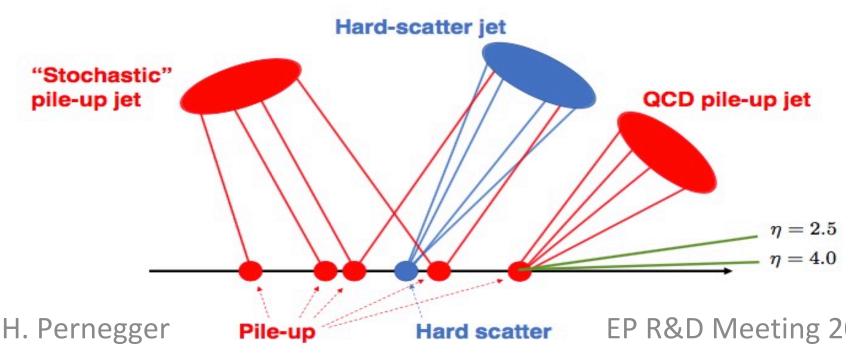
- **R&D on novel feedthrough technologies and low-material cryostat** (collaboration with CERN cryo lab and industry):
  - Increasing signal density in cryogenic feedthrough to ~ 50/cm^2 which is a ~ factor 10 more than in ATLAS (ATLAS is using glass sealed metallic pins)
  - Focus on RD on feedthrough density and required reliability for 20 years of operation in close collaboration with industry
  - Survey of existing technologies, adaptation and optimization, design of test feed-through, cold tests and electrical tests of these test feed-throughs.

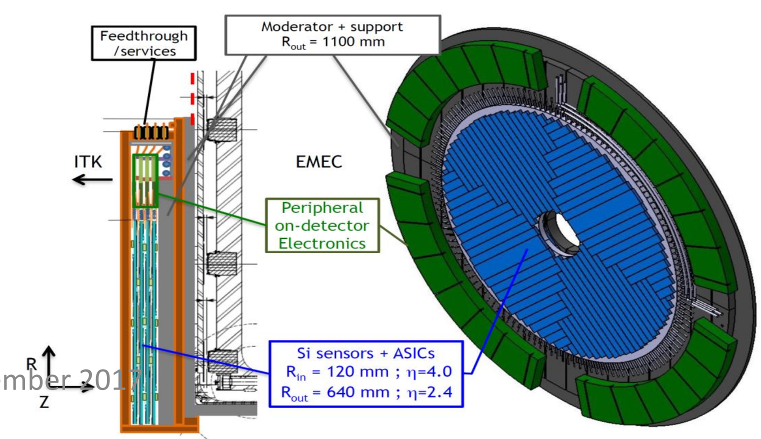


M. Aleksa /CAT

Timing Detectors ATLAS and FCC-hh

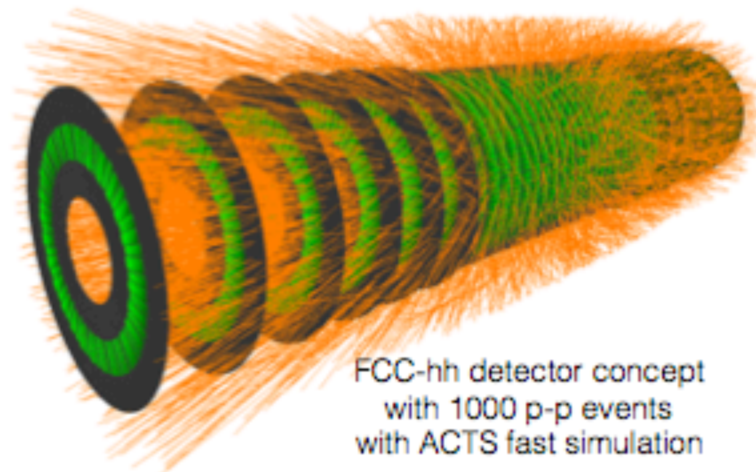
- HL-LHC and FCC-hh: Timing information to disentangle particles originating from the primary vertex from soft particles from other pile-up vertices.
- ATLAS planning for HGTD (2.4 < |η|<4.0)
- **R&D on limits of timing resolution for noble liquid calorimeters to exploit potential of present detector and future noble lquide calorimeters**:
  - R&D on timing resolution of noble liquid calorimeters with the goal of further improving the timing resolution for high energy deposits (possibly down to ~20ps) and MIPs
  - Small prototypes of promising designs should be realized and tested in testbeams.
- **R&D on LGAD sensors for ATLAS high granularity timing detector (HGTD) and FCC-hh (participation in RD50 collaboration strong collaboration with industry):**
  - Close collaboration with RD50 collaboration for optimzation of LGAD sensors
  - Optimizing the fill factor and Thickness of the sensors,
  - Radiation hardness (Ga doping instead B)
  - Production of real-size modules of 2x4cm^2 around 1mm^2 granularity: fulfilling requirements: σ_t=30ps per MIP up to 10^{16} n(1MeV eq.)/cm^2





Reconstruction

Optimized reconstruction software for the future



FCC-hh detector concept
with 1000 p-p events
with ACTS fast simulation

Project to <u>preserve</u> and <u>enhance</u> LHC track reconstruction software for future **detectors** and **computing infrastructure**

A flexible, **open source R&D testbed**:
- facilitate collaboration across experiments and external contributors, e.g. machine learning experts
- allow for novel algorithms and detector components (e.g. timing, track lets)

A **high-performant toolbox** for track reconstruction based on LHC experience
- modern code and software concepts to allow for concurrent computing
- support high luminosity and high precision tracking algorithms

Currently developers from ATLAS, LHCb, FCC-hh http://acts.web.cern.ch/ACTS/

- supporting: FCC-hh, Tracking machine learning challenge

ACTS Mission statement

Detector description | **Magnetic field**

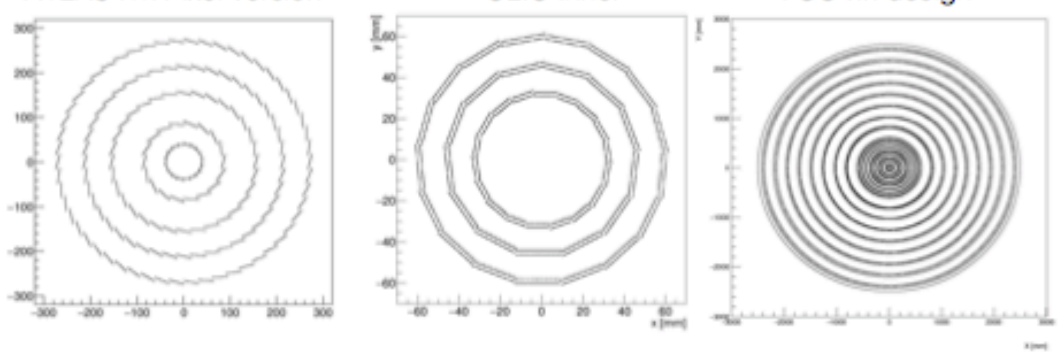
ACTS plugin
(from Geant4, ROOT, etc.)

ACTS plugin
(from ROOT, txt file)

Track reconstruction tools, fast simulation

Examples:

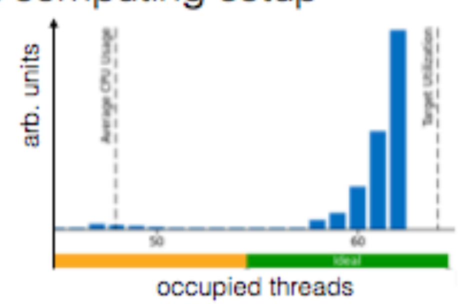
ATLAS ITk Pixel version | CLIC Inner | FCC-hh design



Tools implemented to be executed in concurrent computing setup

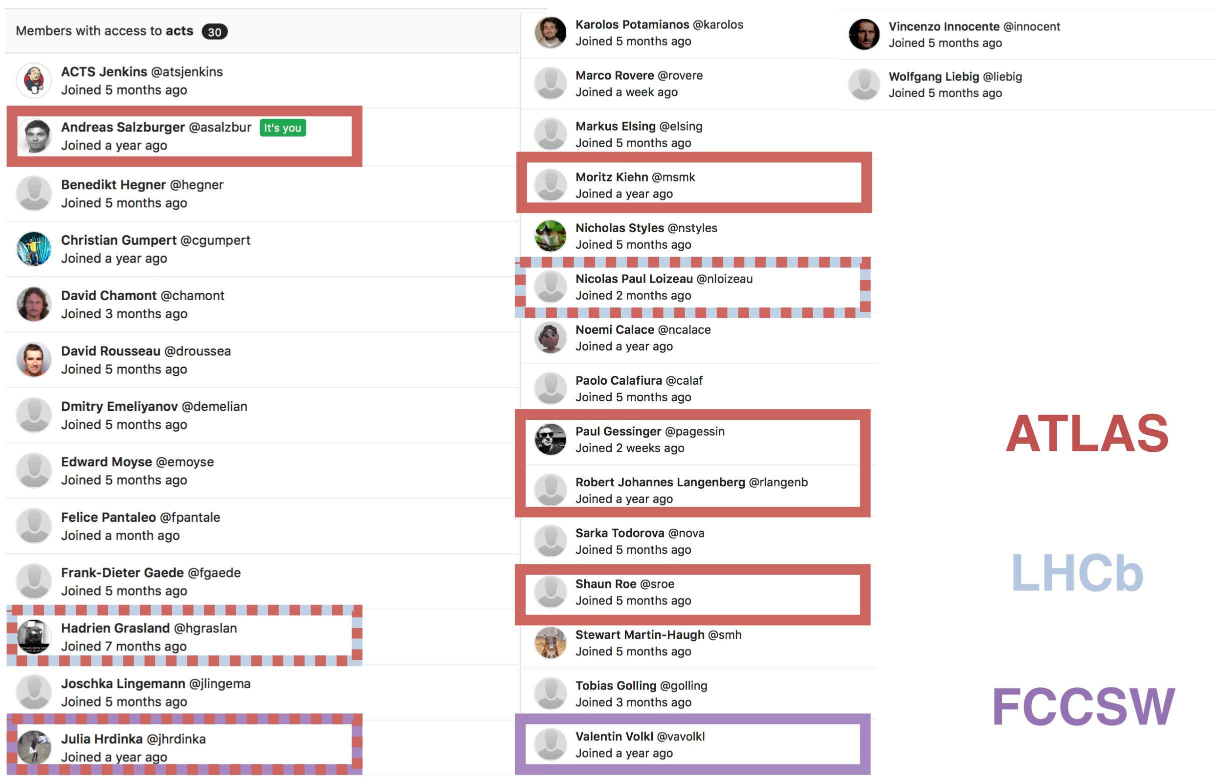
- flexibility needed to react to future computing hardware architectures (many cores, GPUs, …)

Example: ACTS fast simulation on a 64 thread machine, occupying ~60 threads most of the time



ACTS – across experiments

- ACTS is already an inter-experiment development



Summary & Outlook

- Developments for HL-LHC have sparked vivid RD in the CERN ATLAS Team
- RD activities are focused and target performance gains in HL-LHC but also beyond
- They include RD in tracking detectors (CMOS sensors, modules and integration), calorimeters and timing detectors as well as reconstruction software
- For R&D in CAT we collaborate tightly with EP-DT and EP-ESE as well as other LHC experiments
- We look forward to strengthen this R&D in view of the big challenges ahead for future experiments beyond HL-LHC