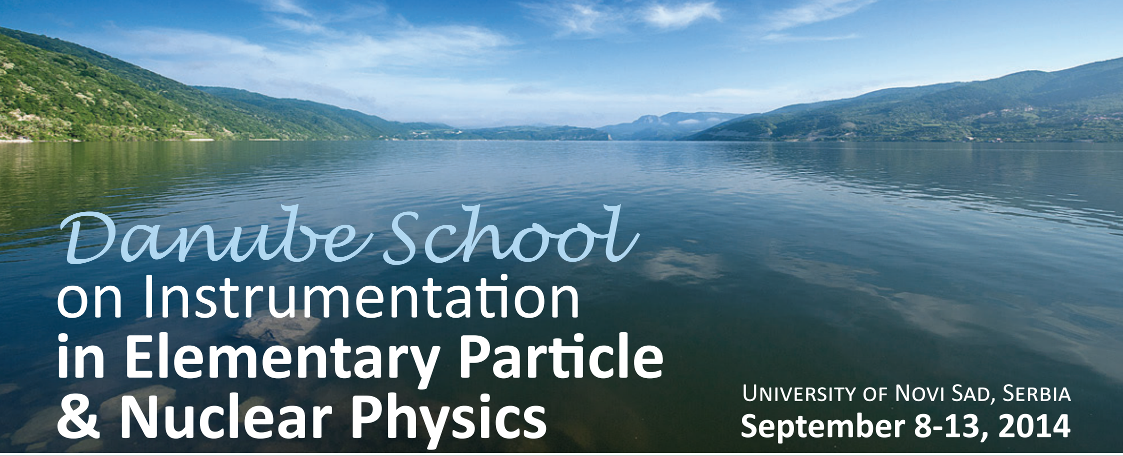


Challenges for Novel Experiments at Future Accelerators

Ingrid-Maria Gregor, DESY

Thanks to:
Phil Allport , Ties Benke, Cinzia da Via , Ulrich Husemann, Fabian Hügging, Uli Koetz, Frank Simon, Norbert Wermes, Marc Winter...

Outline

- Tracking Detectors
  - Silicon Vertex Detectors
  - Silicon Tracking Detectors
  - Gaseous Detectors (Trackers and Muon Spectrometers)
- Calorimeters
  - ILC/CLIC R&D
  - HL-LHC R&D
- Read-out and Triggering
- Conclusions

Lectures Program

- Particles Interactions with matter - 2h – *W.Riegler, CERN*
- Silicon Detectors for HEP and Nuclear Physics - 2h – *J.Ninkovic – Max Planck Society Semiconductor Laboratory, Munich, Germany*
- Electromagnetic and Hadronic Calorimetry - 2h – *R. Paramatti, INFN Rome, Italy*
- Gaseous Detectors - 2h – *M.Titov, IRFU, France*
- Particle Identification and photo-detectors - 2h – *S. Kopar, J.S.Institute Ljubljana, Slovenia*
- Electronics & Signal Processing - 2h - *M.Friedl, HEPHY, Vienna, Austria*
- Magnets systems – 2h – *H.Ten Kate – CERN*
- Application of Physics to Medicine - 2h – *P. Cerello, INFN Torino, Italy*

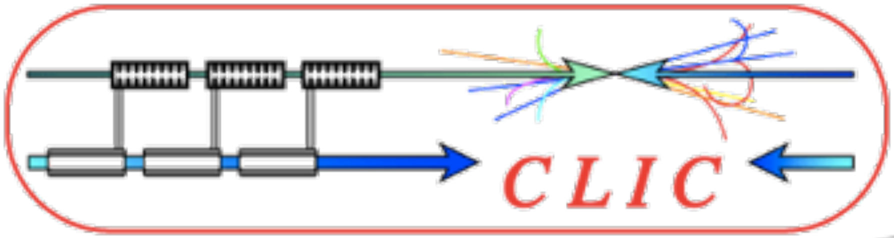
Some bias in the selection of the most important detectors ...

Introduction

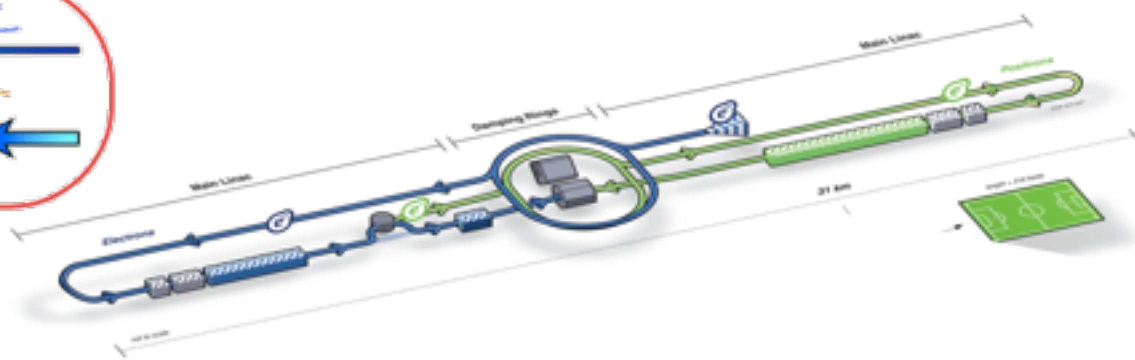
Future Facilities

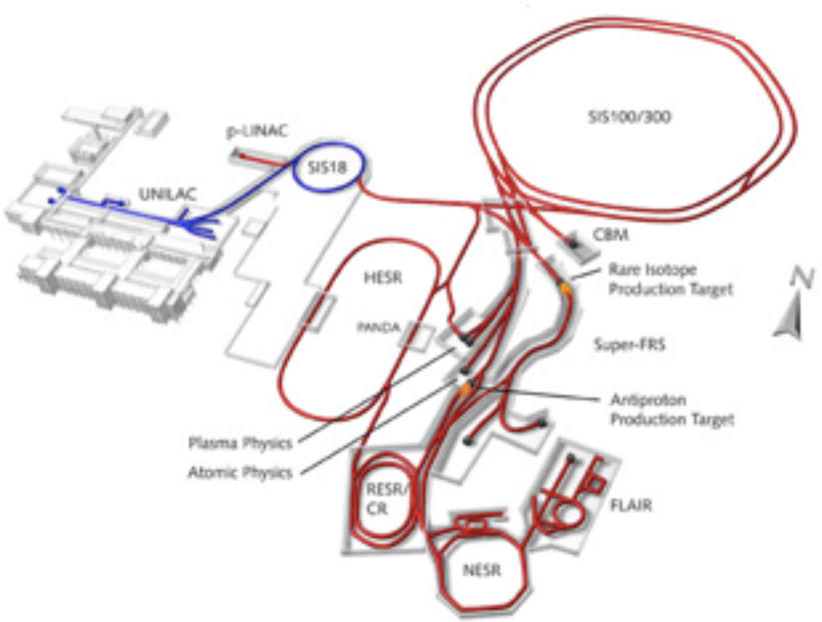
incomplete list …

Precision physics,
rare processes
high data rates

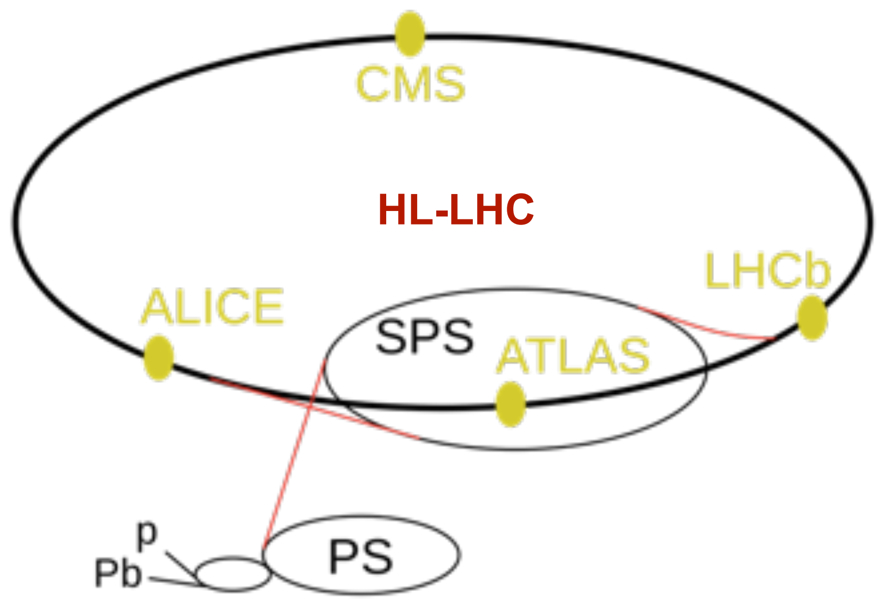


CLIC: Electron – positron collider
proposal phase



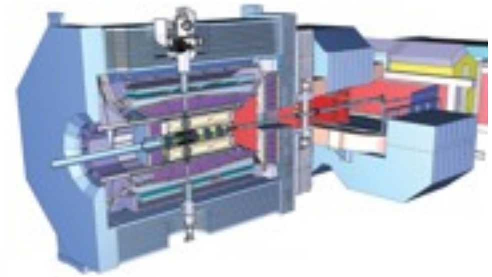


FAIR: Facility for Antiprotons and Ions Research,
under construction



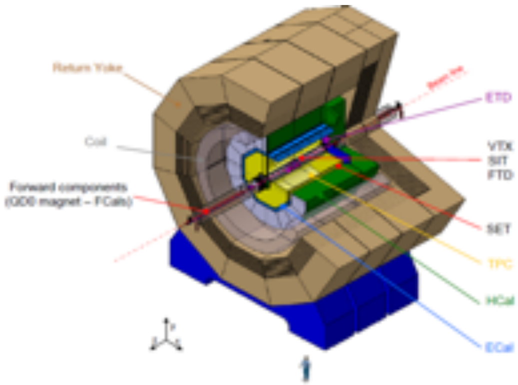
HL-LHC: high luminosity upgrade of the LHC

Future Experiments

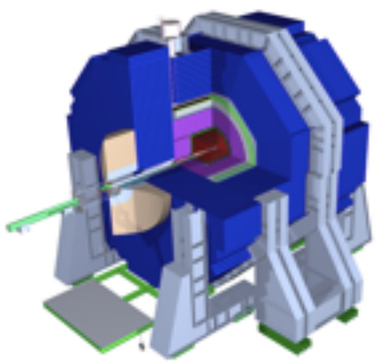


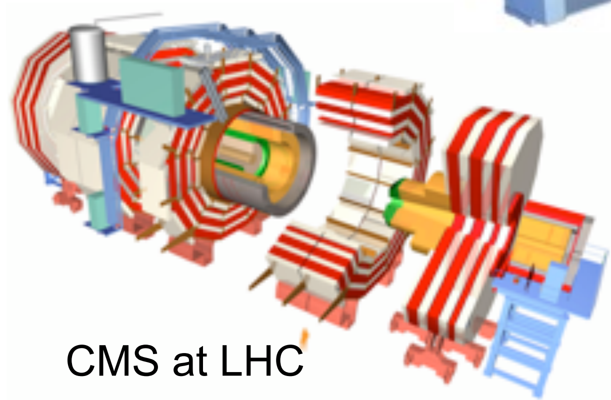
PANDA at FAIR

ILD at the ILC/CLIC



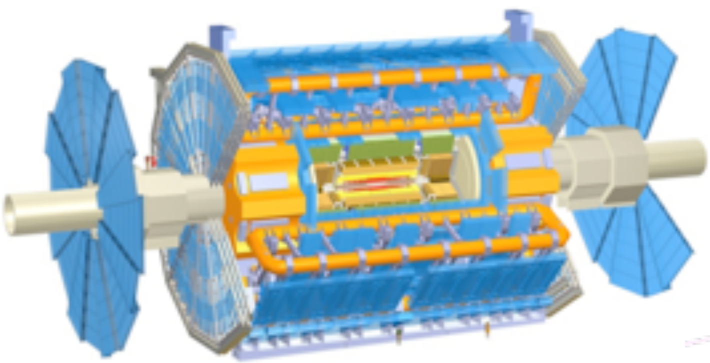
SiD at the ILC/CLIC



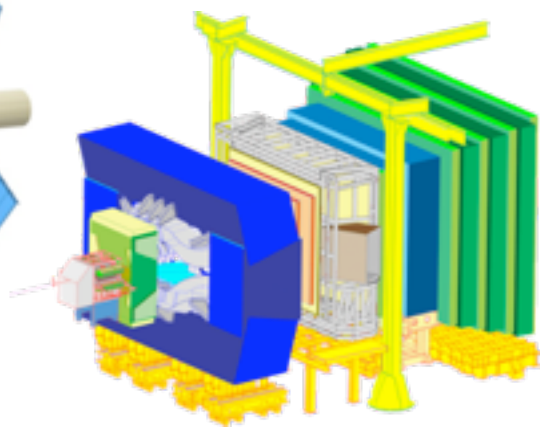


CMS at LHC

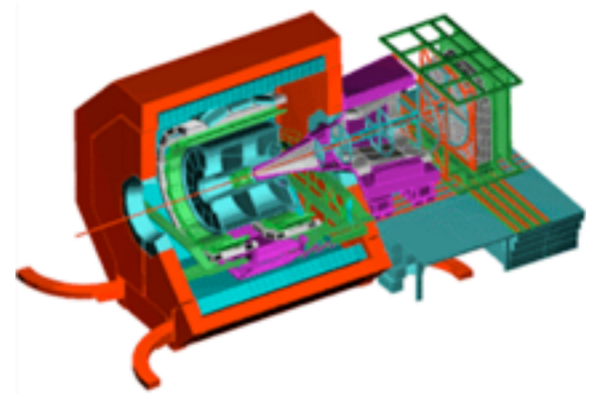
ATLAS at LHC



LHCb at LHC



ALICE at LHC



not to scale !!

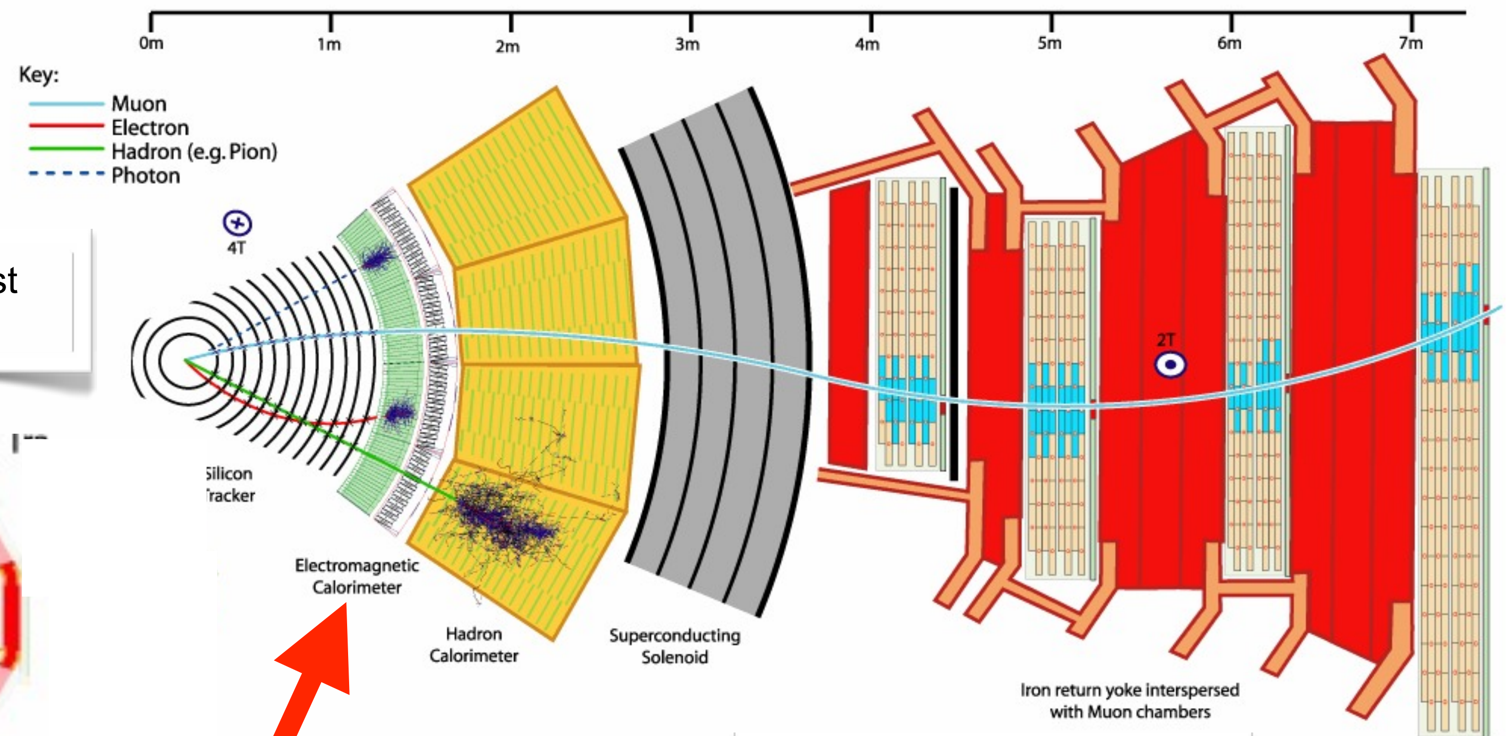
Particle Physics Detector Overview

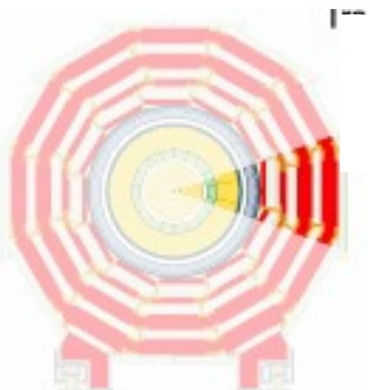
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption

Muon-Detectors: Identification and precise momentum measurement of muons outside of the magnet

Vertex: Innermost tracking detector





Transverse slice through CMS

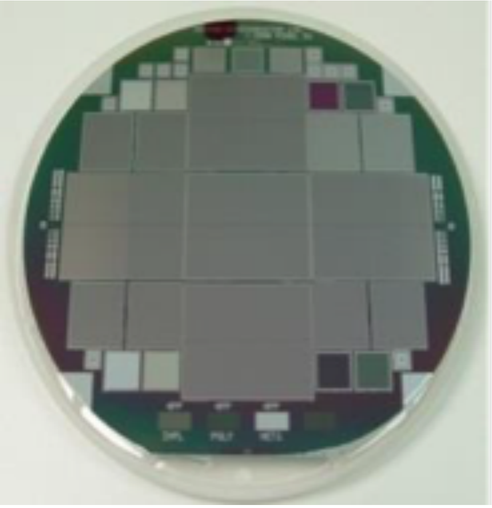
Good energy resolution up to highest energies

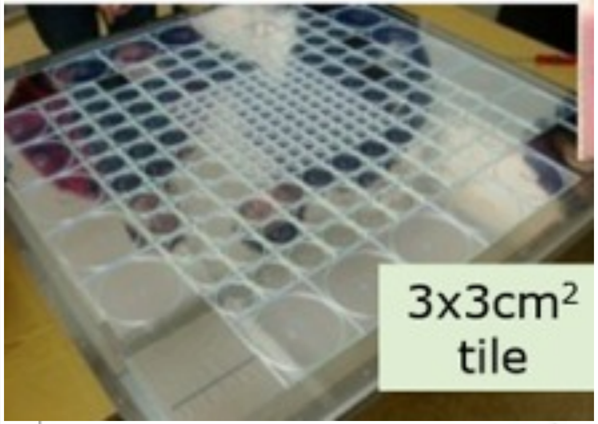
Radiation hard (hadron collider)

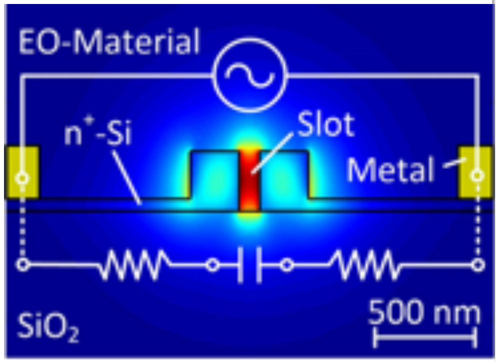
picture: CMS@CERN

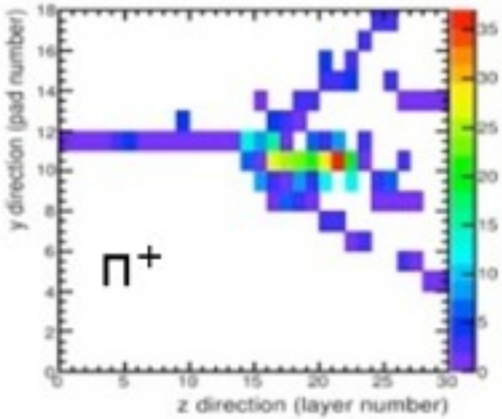
The Challenges

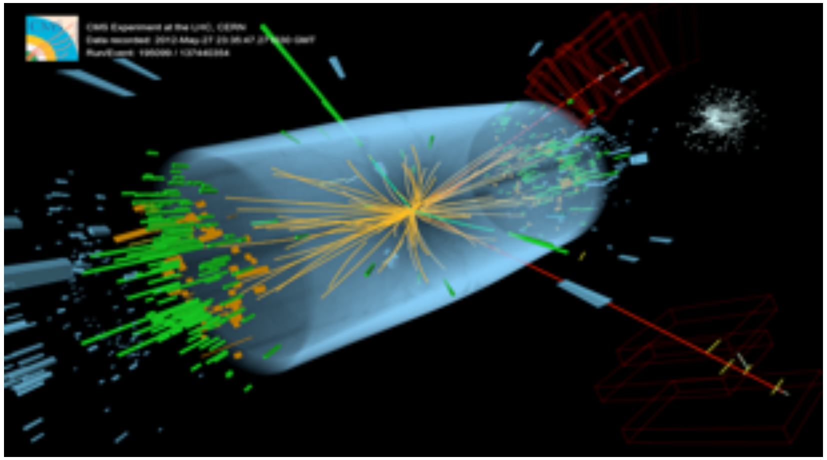
- Precision (resolution)
- Granularity
- Power consumption
- Readout speed
- Material budget

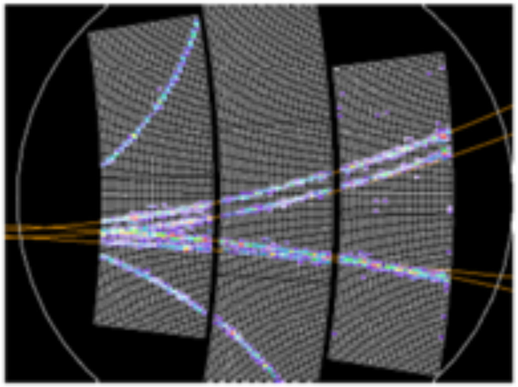












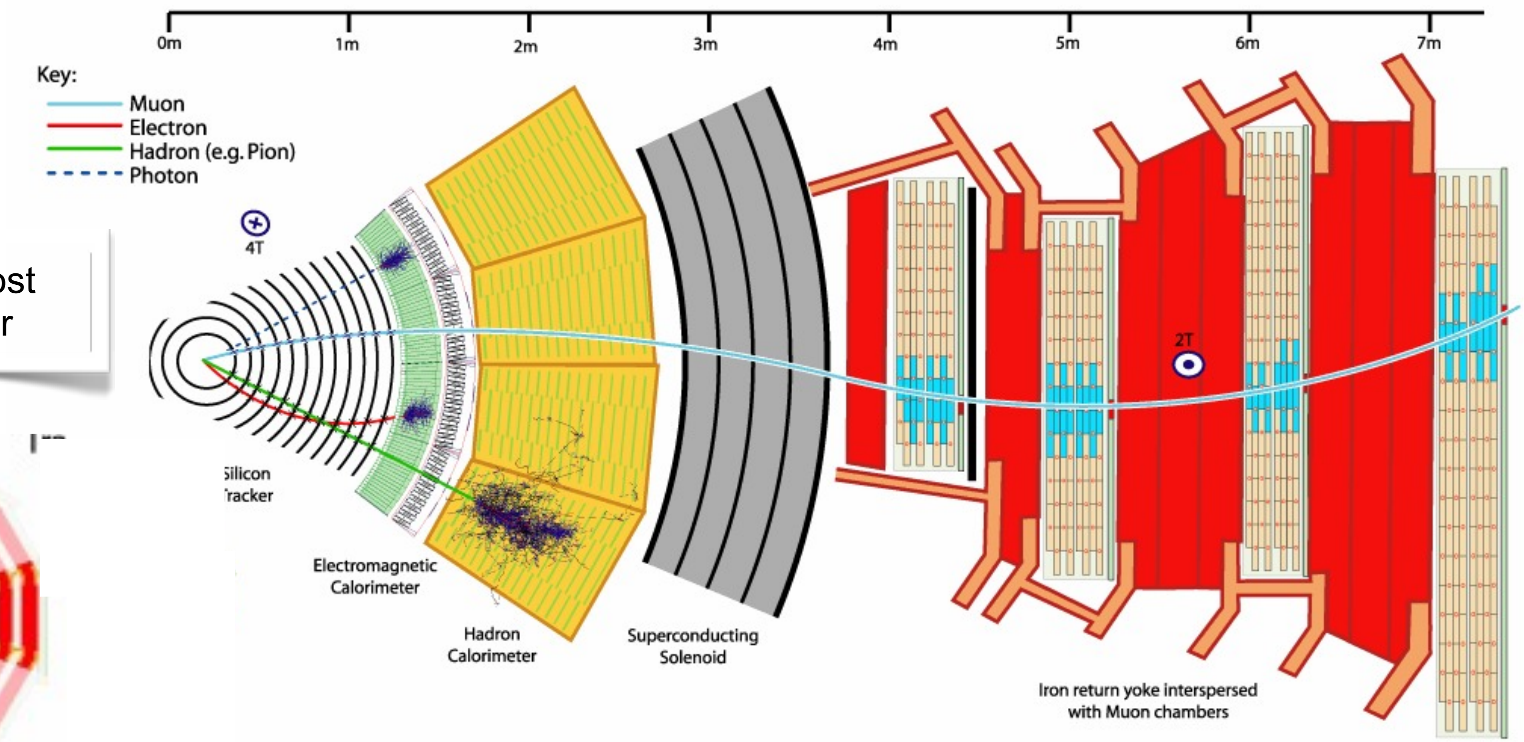
Tracking Detectors

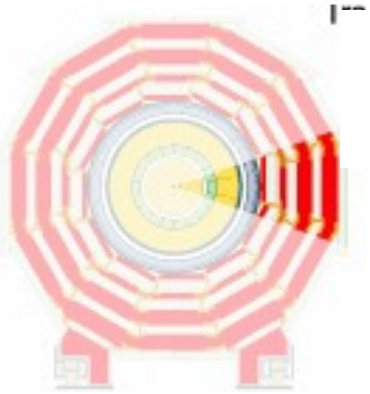
Particle Physics Detector Overview

Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

Tracker: for muons ...

Vertex: Innermost tracking detector

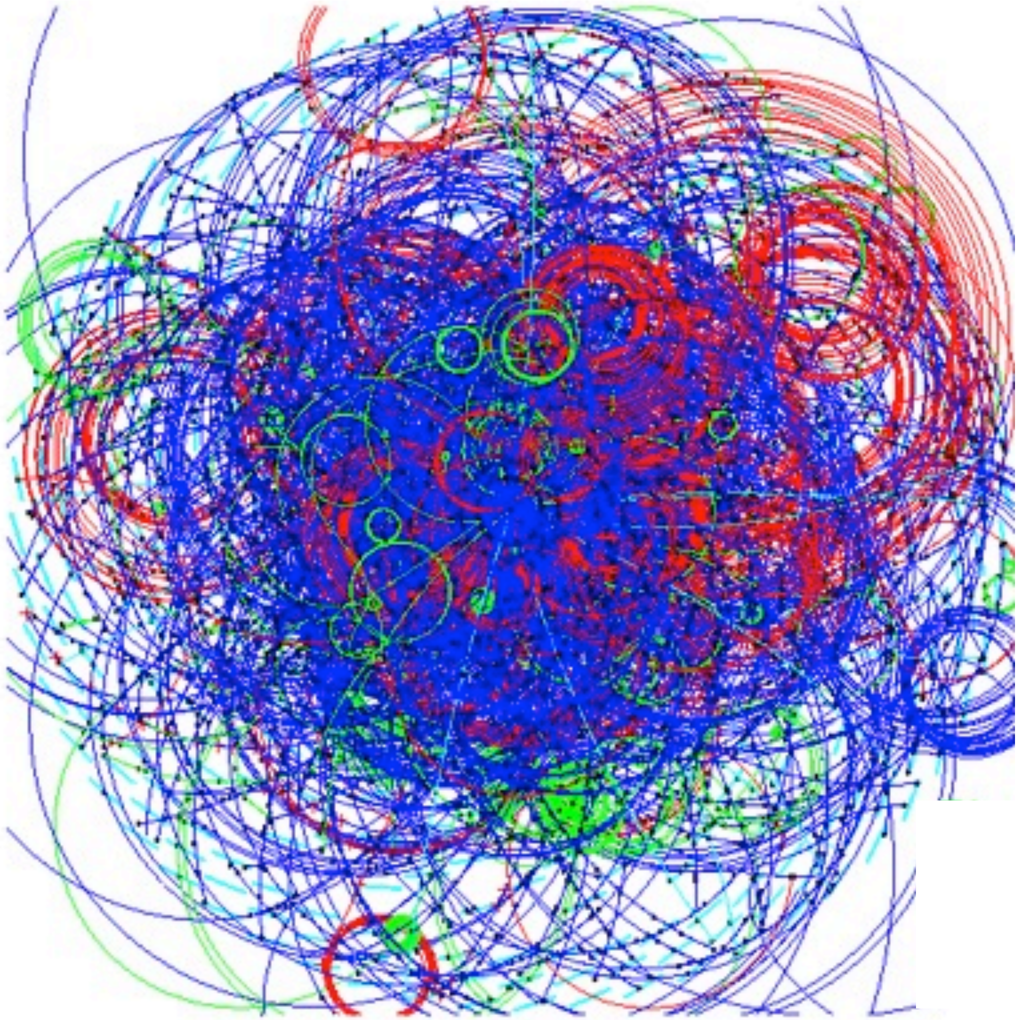




Transverse slice through CMS

picture: CMS@CERN

Inner Tracking Detectors

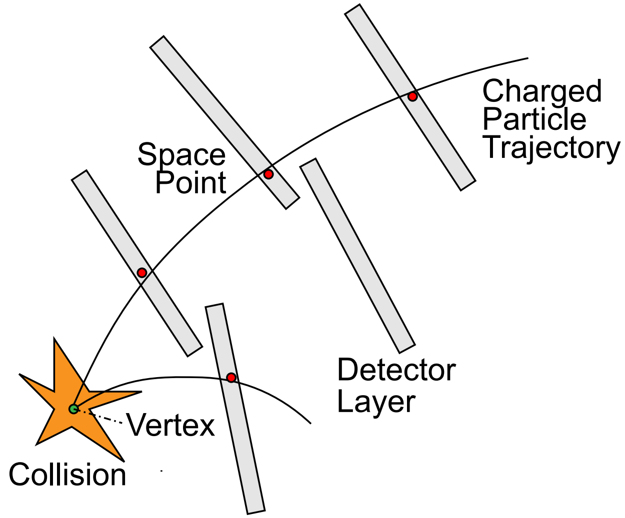


Example: Search for
$H \rightarrow Z^0 Z^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

=> reconstruction of
high tracks with
+ **high efficiency**
  • single track ε > 95%
+ **momentum resolution**
  • $\Delta p_t/p_t$ = 0.01 pt [GeV]

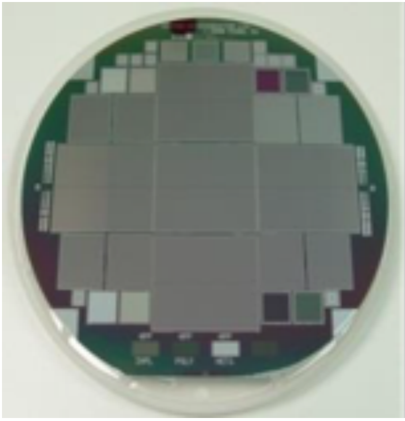
LHC requirement

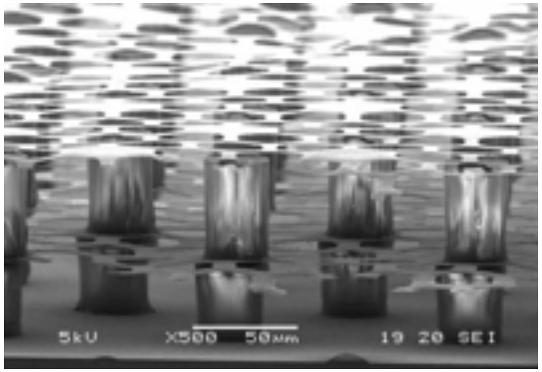
Tracking Detectors

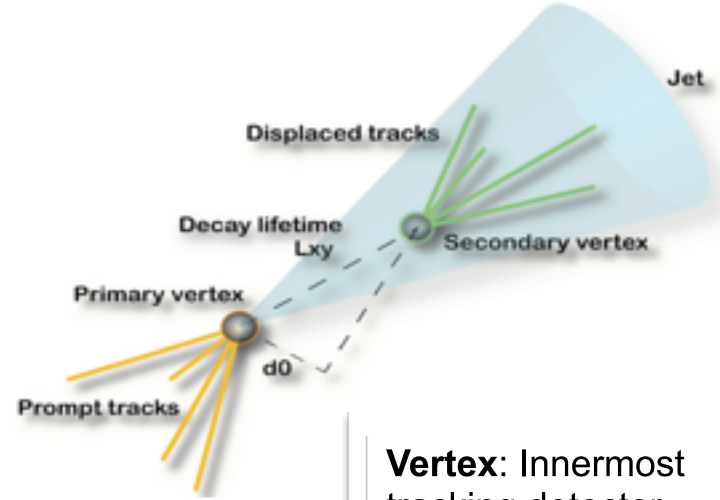


- Precise measurement of track and momentum of charged particles due to magnetic field.
- High energy
  - Small fraction of energy deposited in instrument
- The trajectory should be disturbed minimally by this process (reduced material)

- Charged particles ionize matter along their path.
  - Tracking is based upon detecting ionisation trails.
  - An “image” of the charged particles in the event







Vertex: Innermost tracking detector

Vertex Detector Challenges

- Main challenge: identify c quark and $\tau^{\pm}$ lepton jets
- life time ~10-12 sec => ~100um

  => particles decay within the vacuum beam pipe
- reconstruct decay products

Trend in tracking detectors: pixellised detectors installed very close to the beam interaction region

- Minimal distance limitations:
  - beam pipe radius
  - beam associated backgrounds
  - density of particles produced at the IP

Perfect pixels:
- very small pitch (~20 µm)
- very thin material (~50 µm)
- high readout speed
- super radiation hard
- smart trigger capabilities

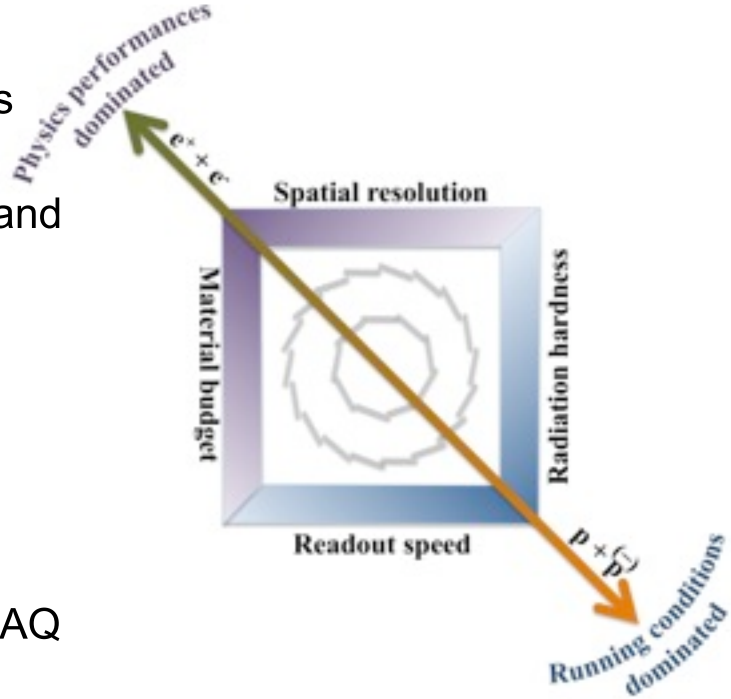
Figure of merit for the VXD:
Impact Parameter Resolution

$$\sigma_{r\phi} \approx \sigma_{rz} \approx a \oplus b/(p\sin^{3/2}\vartheta)$$

Accelerator	a (µm)	b (µm)
LEP	25	70
Tevatron	10	40
LHC	<12	<70
RHIC-II	12	19
ILC/CLIC	<5	<10

Optimising = Compromising

- Conflict between physics performance driven parameters and running condition constraints:
  - Physics performance: spatial resolution (small pixel) and material budget (thin sensors) + distance to IR
  - Running conditions: read-out speed and radiation tolerance (HL-LHC: 10 times LHC)
  - Moreover :
    - ➡ limitations from maximum power dissipation compatible
    - ➡ limitations from highest data flow acceptable by DAQ



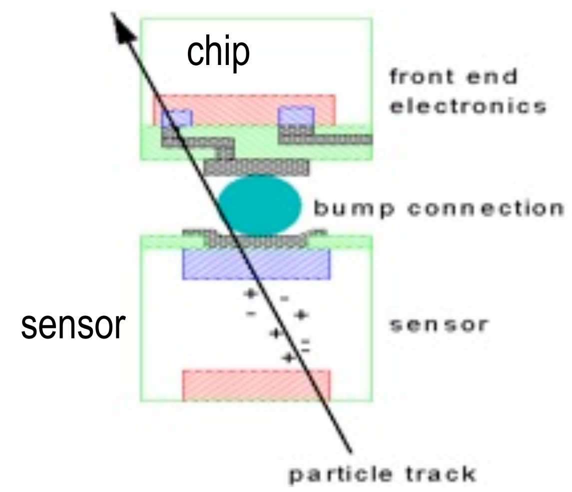
- Ultimate performance on all specifications cannot be reached simultaneously
  - each facility & experiment requires dedicated optimisation (hierarchy between physics requirements and running constraints
  - there is no single technology best suited to all applications
  - explore various technological options
  - motivation for continuous R&D (optimum is strongly time dependent)

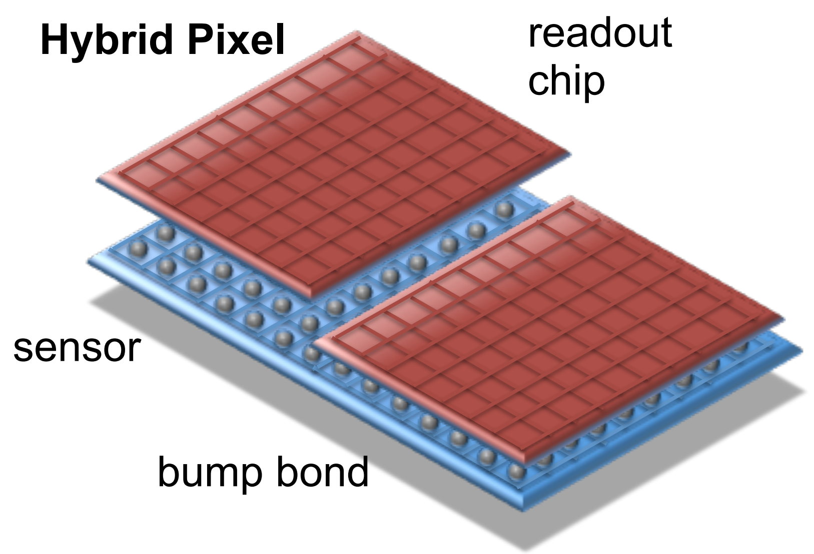
Hybrid Pixels – "classical" Choice HEP

- The read-out chip is mounted directly on top of the pixels (bump-bonding)
- Each pixel has its own read-out amplifier
- Can choose proper process for sensor and read-out separately
- Fast read-out and radiation-tolerant

… but:

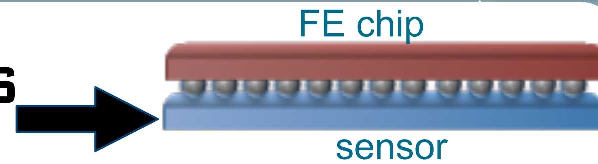
- Pixel area defined by the size of the read-out chip
- High material budget and high power dissipation





- CMS Pixels (current and upgrade)
- ATLAS Pixels (current and upgrade)
- Alice: 50 µm x 425 µm
- LHCb VELO (upgrade)
- Phenix upgrade
- CBM @FAIR
- PANDA @FAIR
- …

Sensors for Hybrid Pixels



Planar Sensor

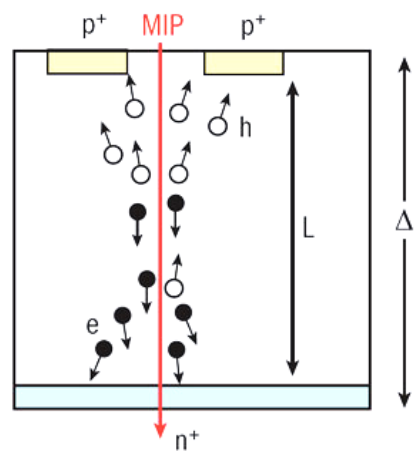
- current design is an n-in-n planar sensor
- silicon diode
- radiation hardness proven up to 2.4 * 10^{16} p/cm^2
- problem: HV might need to exceed 1000V

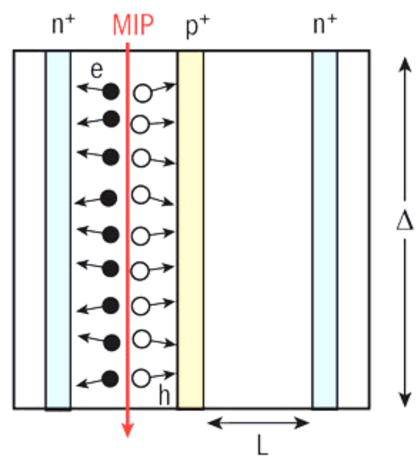
3D Silicon

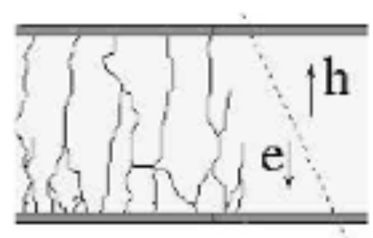
- Both electrode types are processed inside the detector bulk instead of on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Low charge sharing

CVD (Diamond)

- Poly crystalline and single crystal
- Low leakage current, low noise, low capacitance
- Radiation hard material
- Operation at room temperature possible
- Drawback: 50% signal compared to silicon for same X_0 but better S/N ratio (no dark current)





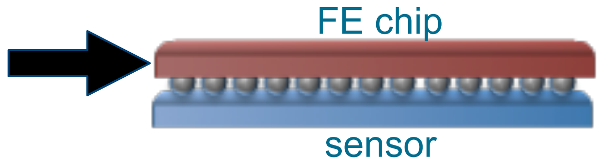


CERN RD42

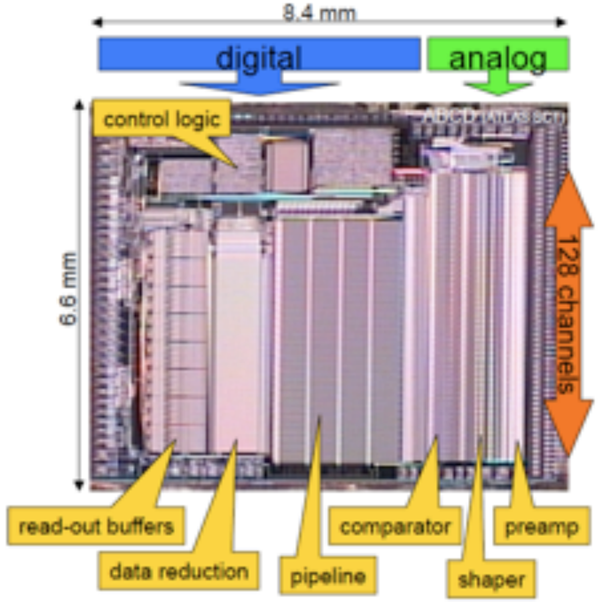
Very strong R&D efforts to develop sensors for future LHC applications!

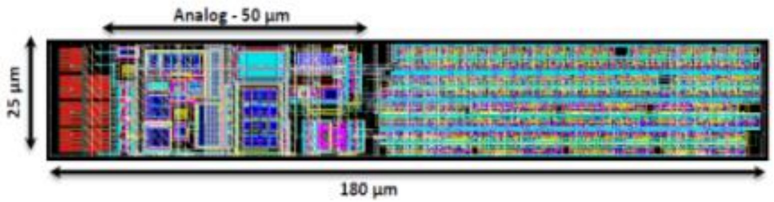
CERN RD50

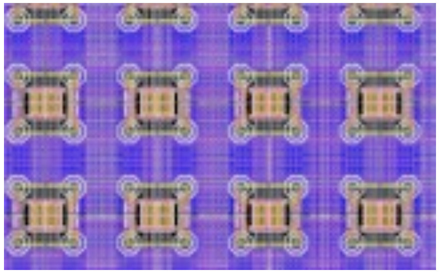
FE Chip Developments



- Modern chip technologies enable
  - high channel density
  - pre-amplification, data storage etc. very close to the detector
  - reduced noise
  - low power dissipation
  - industrial production
- integration density is growing rapidly
- Need fine lithography ASIC technology to allow pixel sizes of as small as ~50µm×50µm







CERN RD53

ATLAS HL-LHC Pixels:

- Cell size: 50x50 µm^2
- Compatible with 50x50 and 25x100 µm$_2$ pixels
- 65 nm technology
- Up to 2 Gb/s output bw
- Full size prototype in 2 years
- Could read all the layers at up to 1.5 Mhz L0 rate

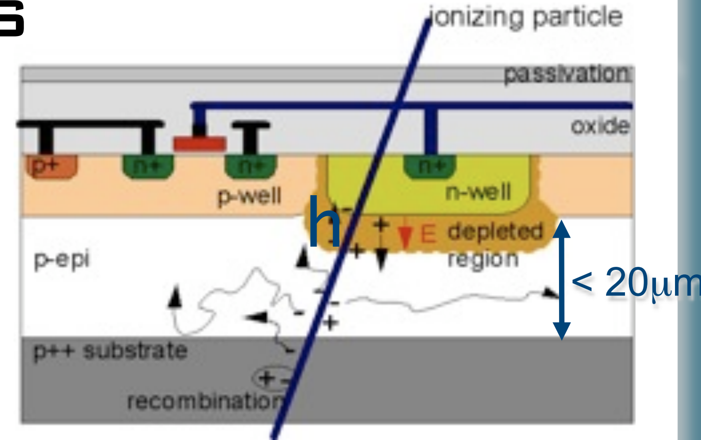
Monolithic Pixel Sensors

- Some applications require extremely good spatial resolution (factor 2-5 better than at LHC) and very low material in the tracker (ILC, CLIC, ALICE…)
- Hybrid pixel sensors: factor 10 too thick for such applications
- Technologies which have sensor and readout electronics in one layers -> monolithic approach

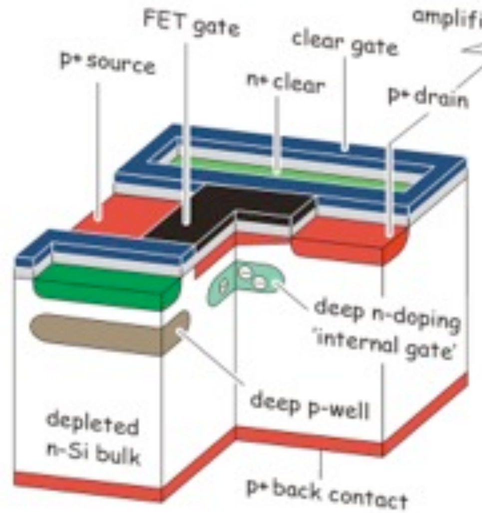
- Four different technologies under study for ILC vertex detector
  - CCD, DEPFET, CMOS, and 3D

- Baseline technology for real experiments
  - DEPFET for Belle II @KEK (Japan)
  - Mimosa MAPS for Star @ RHIC (USA)

- Newest development: In HR/HV-CMOS charge collection through drift greatly improves speed and radiation hardness. Use at pp collision rates → HL-LHC Upgrades?



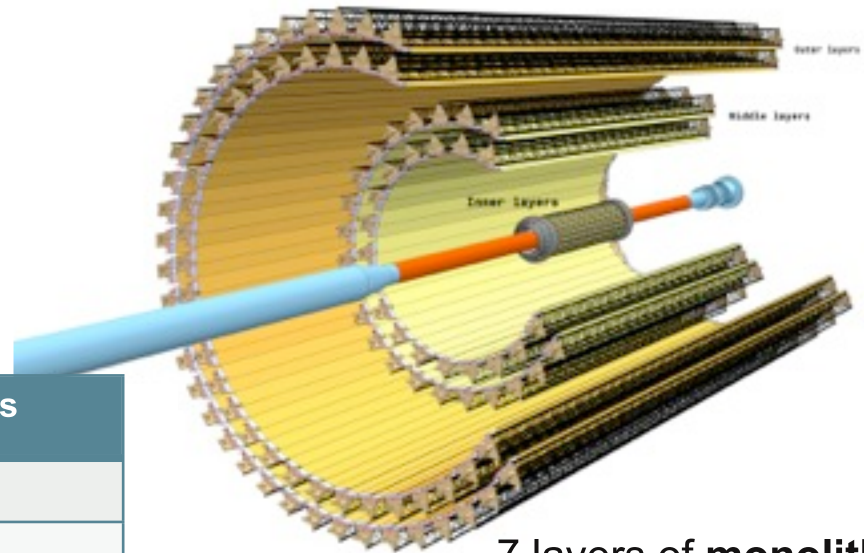
Example:
Mimosa MAPS



DEPFET

Example: ALICE ITS Pixel Detector

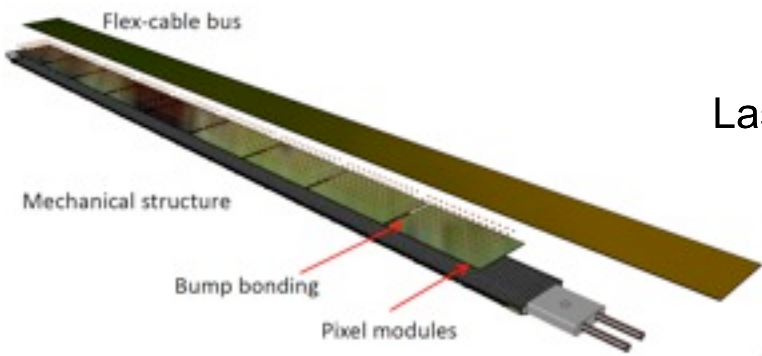
- Improve impact parameter resolution by a factor of 3
- Improve standalone tracking capability and p_T resolution by means of increased granularity
- LHC environment (radiation) with ILC like requirements …



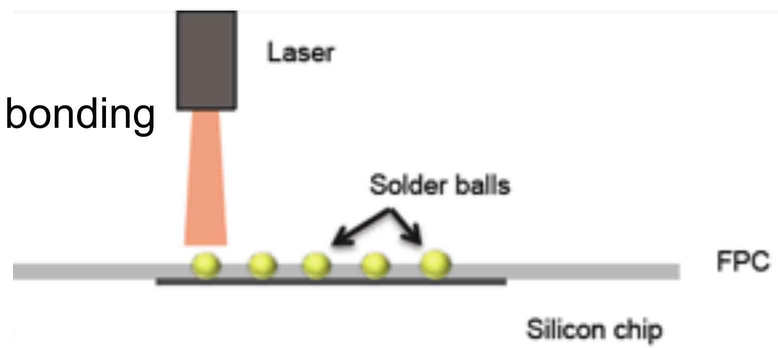
7 layers of **monolithic pixel** detectors

Parameter	Inner Layers	Outer Layers
Si thickness	50 µm	
Material budget / layer	0.3%X_0	0.8%X_0
Intr. Spatial Resolution	5 µm	30 µm
NIEL radiation hardness (1 MeV neq/cm2)	1×10^{13}	3×10^{10}

comparison: 300 µm Silicon ~ 0.3% X_0
no cooling, no mechanical support ...

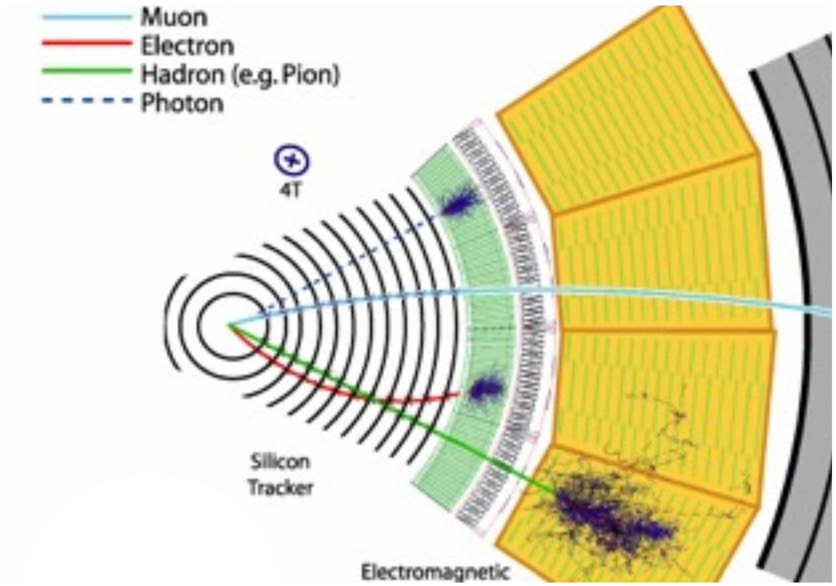


Laser bonding

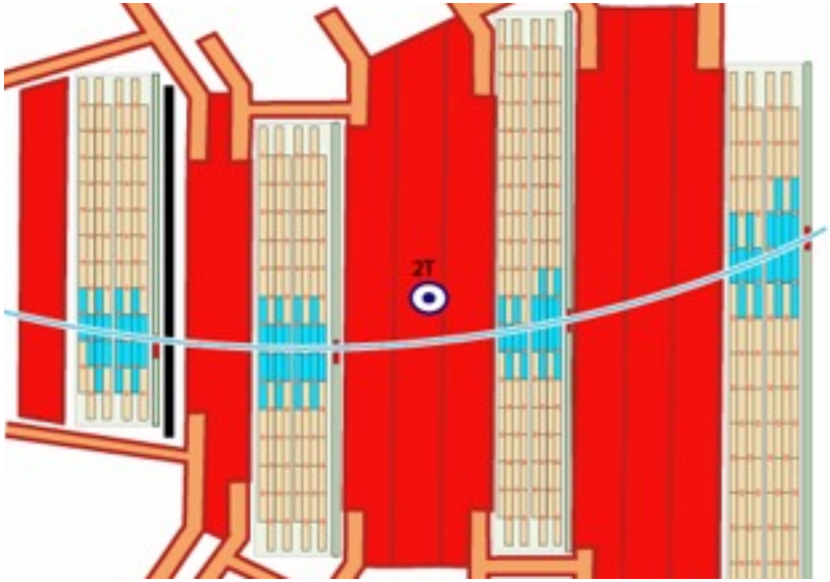


More Tracker

- Tracking system extend in multiple layers up to the magnet bore/ calorimeter
  - Pixel detectors too expensive, too difficult to make, too much material to cover this area
  - Further tracking detectors needed



- HL-LHC inner tracker:
  - radiation hardness, rate, material budget
  - solution: silicon tracking detectors
- Other experiments:
  - gaseous detector, fibre tracker, ….

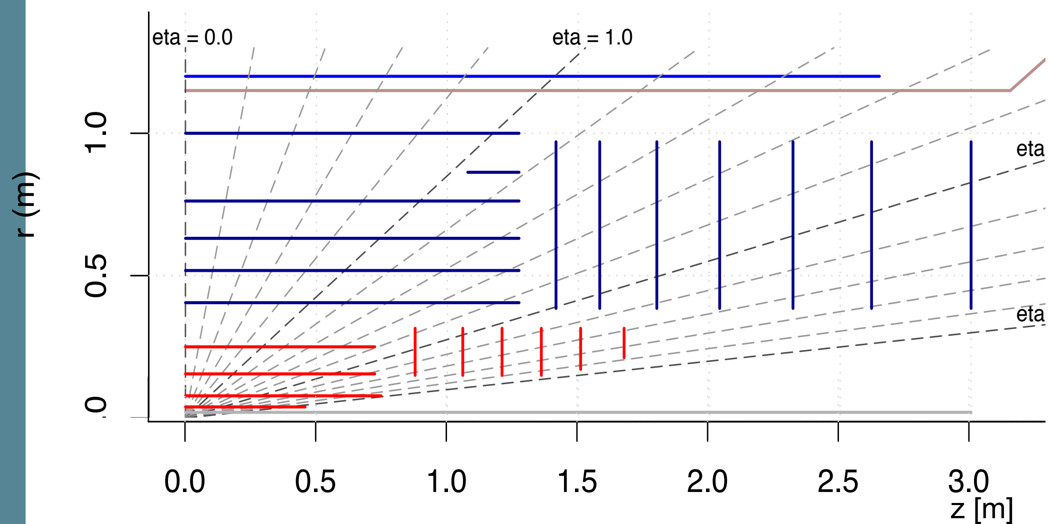


ATLAS and CMS Tracker for HL-LHC

- Similar granularity
  - Strip pitch ~ 70-90 µm & length ~ 2.5 to 5 cm
  - Pixel pitch ~ 25-30 µm and ~ 100 µm length
- Challenges:
  - radiation damage (ok)
  - bandwidth, trigger
  - size, production, costs !!

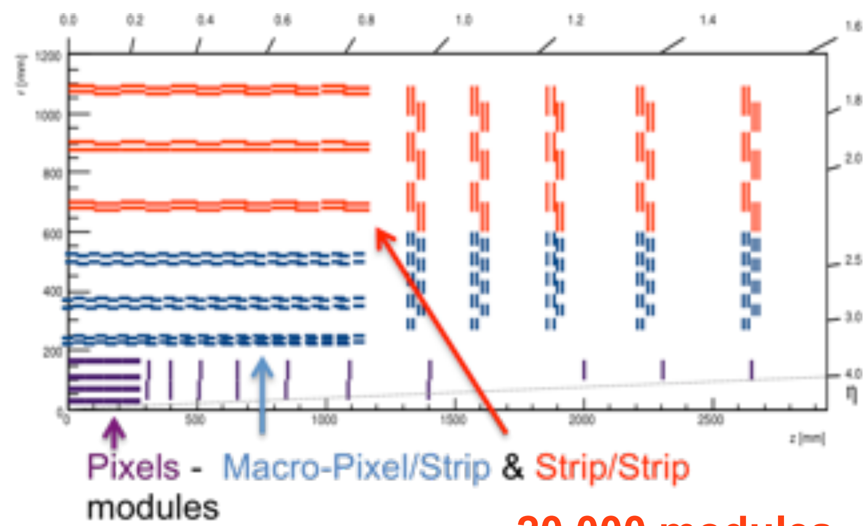
		ATLAS	CMS
Pixels	Layers (B+EC)	4 + 6	4 + 10
	Area	8.2 m²	4.6 m²
Strips	Layers (B+EC)	5.1 + 7	6 + 5
	Area	**193 m²**	**218 m²**

ATLAS



20.000 modules

CMS

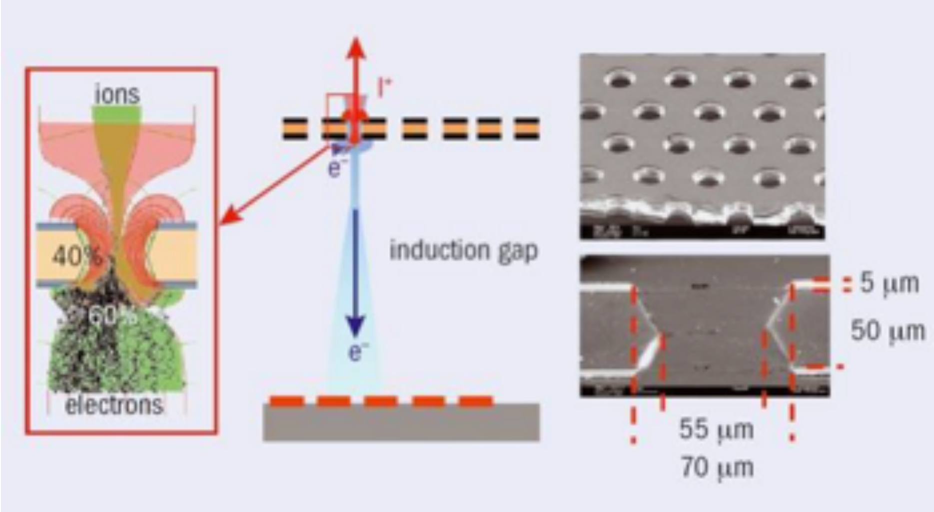


20.000 modules

Both trackers similar on first view but in details rather different.

Gaseous Detectors

- Granularity
- Robustness
- Very low material
- Relative low cost for large volumes
- Intrinsically radiation tolerant



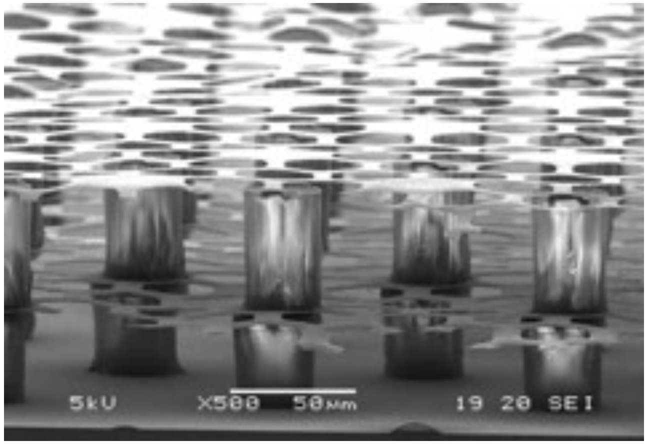
Applications in
- Tracking detectors (low occupancy)
- Calorimetric detectors
- Muon systems
- Other experiments

Focus of new developments:
Gas amplification systems based on
Micro pattern gas detectors

CERN RD51

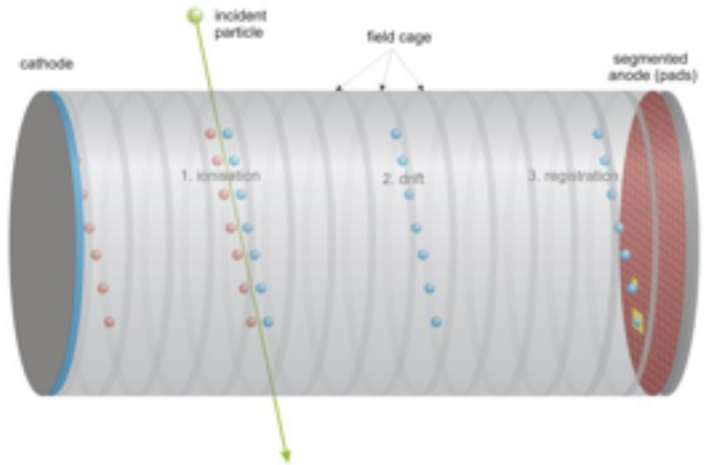
Integration of
gas amplification
into Silicon technology:

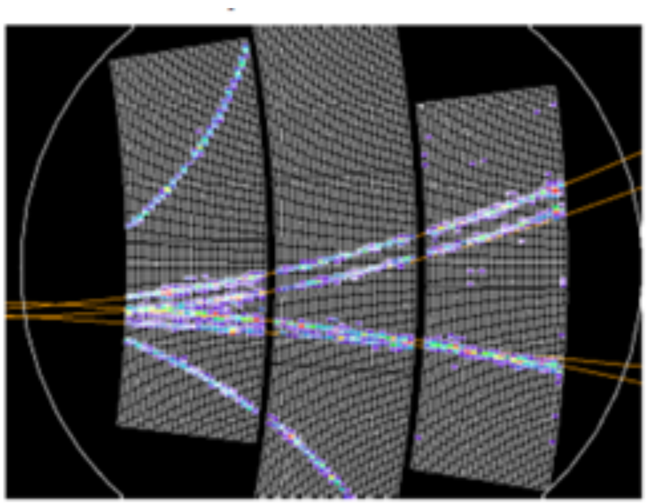
INGRID and friends



Time Projection Chamber

- Builds on successful experience of PEP-4, ALEPH, ALICE, DELPHI, STAR, ...
- Large number of space points, making reconstruction straight-forward
- dE/dx ⇒ particle ID, bonus
- Minimal material in tracking volume, valuable for barrel calorimetry
- Tracking up to large radii
- New readouts promise to improve robustness

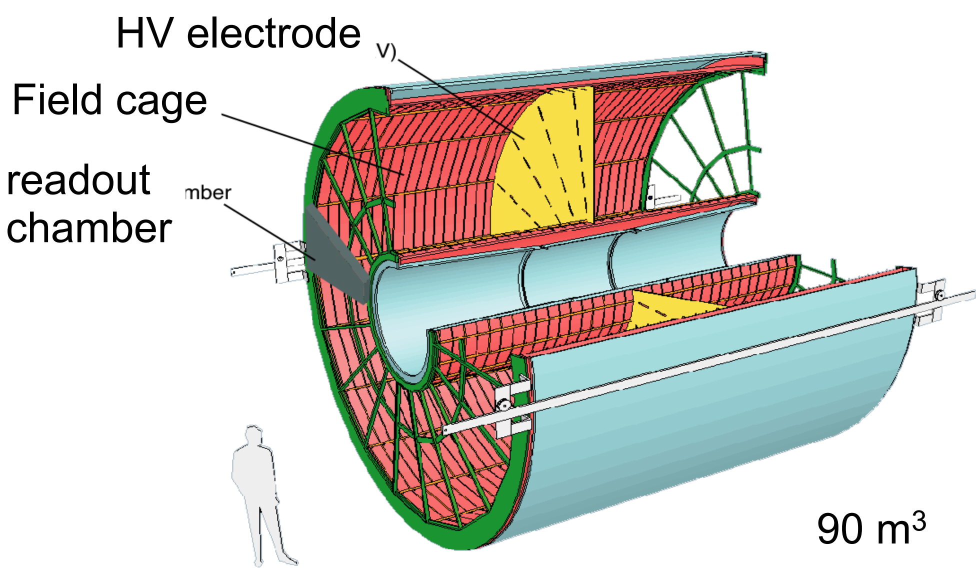




LCTPC is designing a time projection chamber for the LC experiment ILD (ILC and CLIC)

Gaseous Detectors at HL-LHC

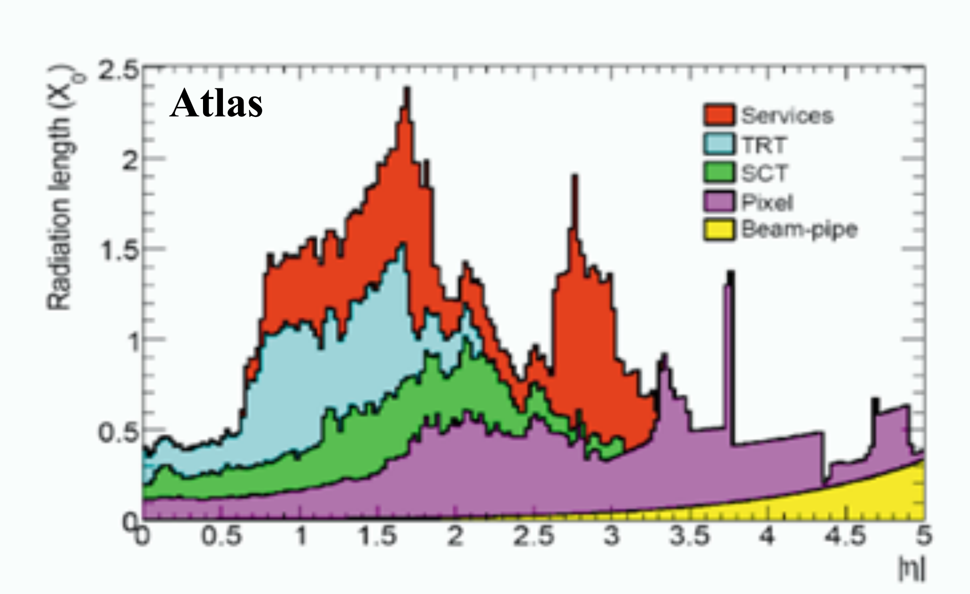
- Main R&D activities for ATLAS and CMS are for new muon chambers in the forward directions.
- Increased rate capabilities and radiation hardness
- Improved resolution (online trigger and offline analyses)
- Improved timing precision (background rejection) Technologies
  - Gas Electron Multiplier detectors (LHCb now, ALICE TPC - CMS forward chambers)
  - Micro-pattern gas and Thin Gap Chambers (TGCs) (ATLAS forward chambers)
  - Resistive Plate Chambers (RPCs) - low resistivity glass for rate capability - multi-gap precision timing (CMS forward chambers)



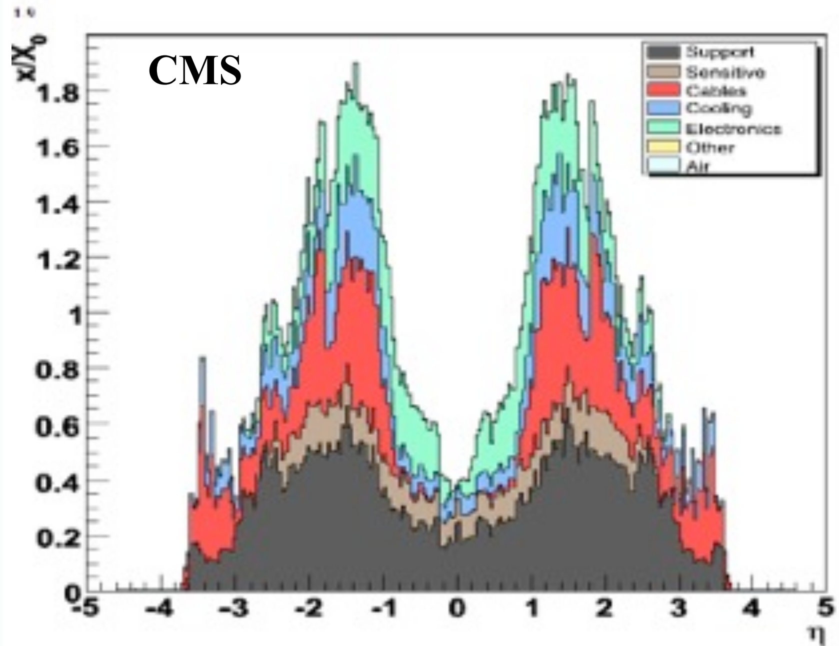
Challenge for ALICE upgrade:
high readout rate too fast for gated readout mode
solution: triple GEM detectors

Material Budget of LHC Experiments

CMS & ATLAS both slipped considerable in keeping X/X_0 originally aimed for !



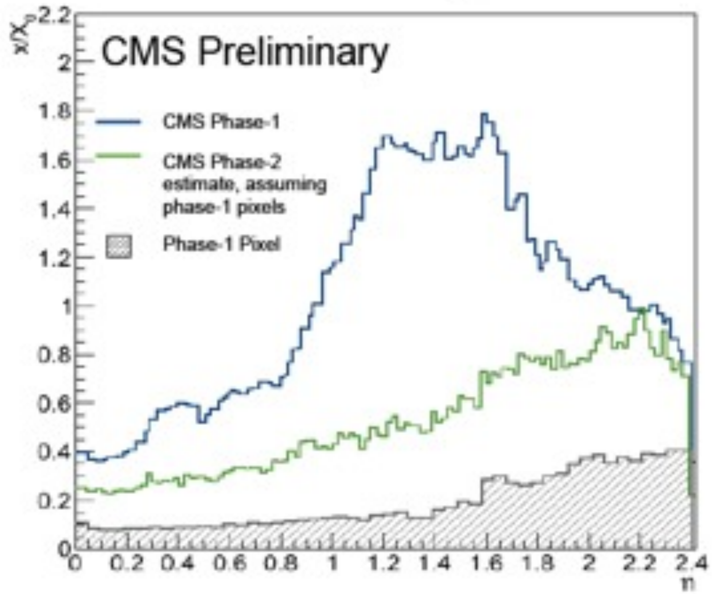
$\vert\eta\vert$	radiation length	interaction length
< 1	$\sim 0.2\, X_0$	$\sim 0.05\, \lambda$
< 3.3	$\lesssim 0.5\, X_0$	$\lesssim 0.2\, \lambda$



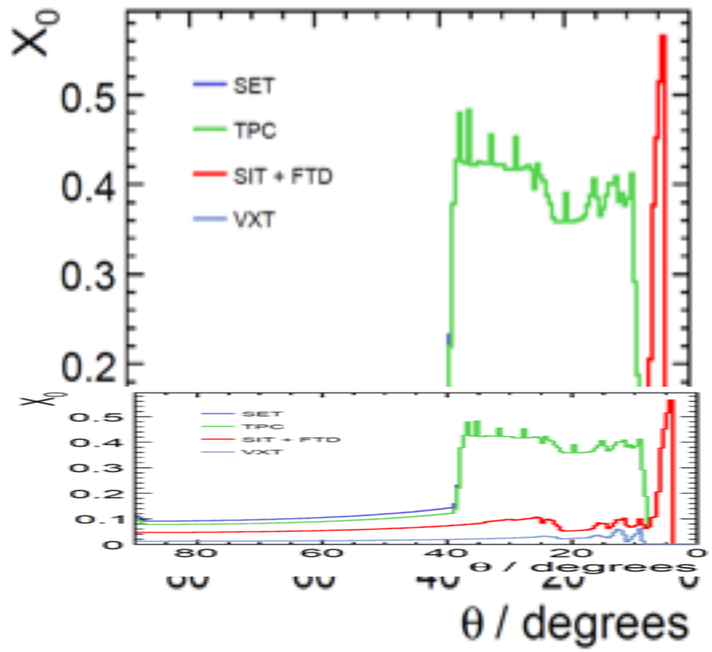
Old argument that Silicon would be too thick is not really true ==> **power & cooling**

The Material Challenge at ILC

CMS tracker upgrade scenario:
reduce by factor 2

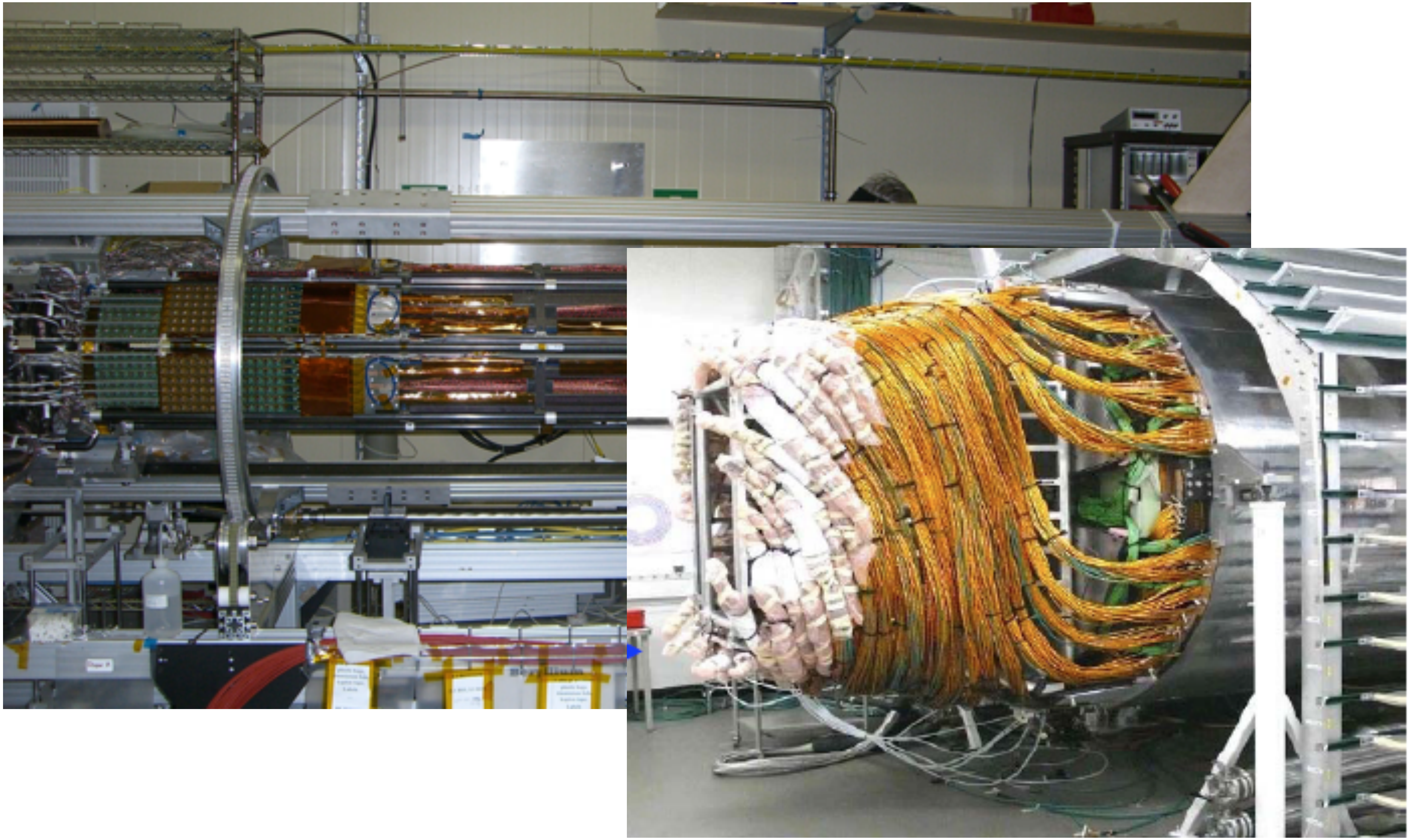


ILD estimate



R&D done within LC and LHC communities has paved the way towards significantly thinner detectors.
But be aware of services…

Services = Material



Power Management

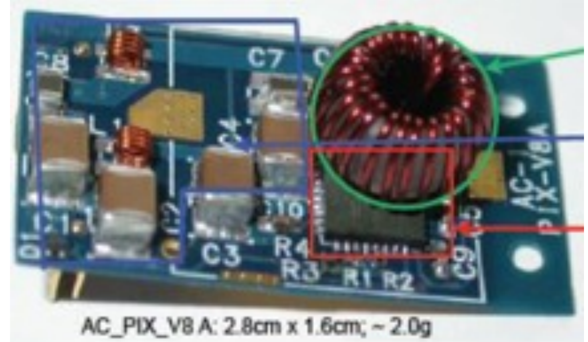
Powering:

- Services are major part of material budget -> need to reduce material
- LHC tracking detectors increase of channel -> not even the space for all services
- ILC tracking detectors -> very limited material budget
- Advanced powering schemes can help:
  - DC-DC
  - serial powering
  - power capacitors
  - pulsed powering (ILC)

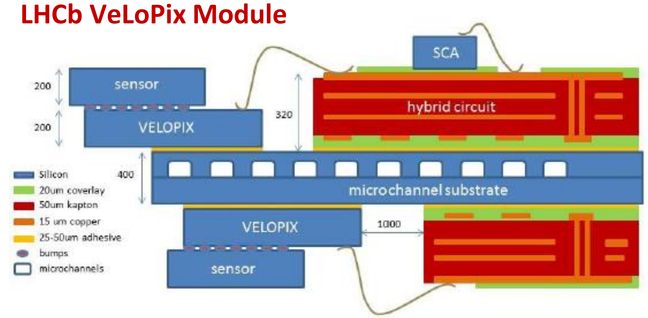
Cooling:

- LHC detectors need to cool silicon sensors extremely low
  - CO_2 cooling current solution
- micro-channel cooling for some detectors a solution
- for non-LHC detectors air cooling an option:
  - low mass
  - sufficient for ILC/ CLIC conditions?

Powering and cooling are difficult for all detectors but are most challenging for tracking detectors.



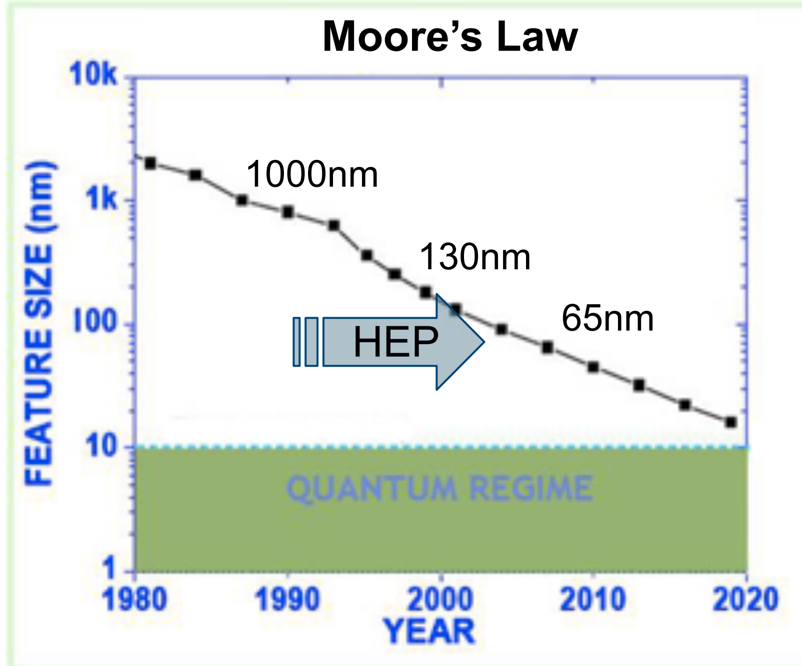
LHCb VeLoPix Module

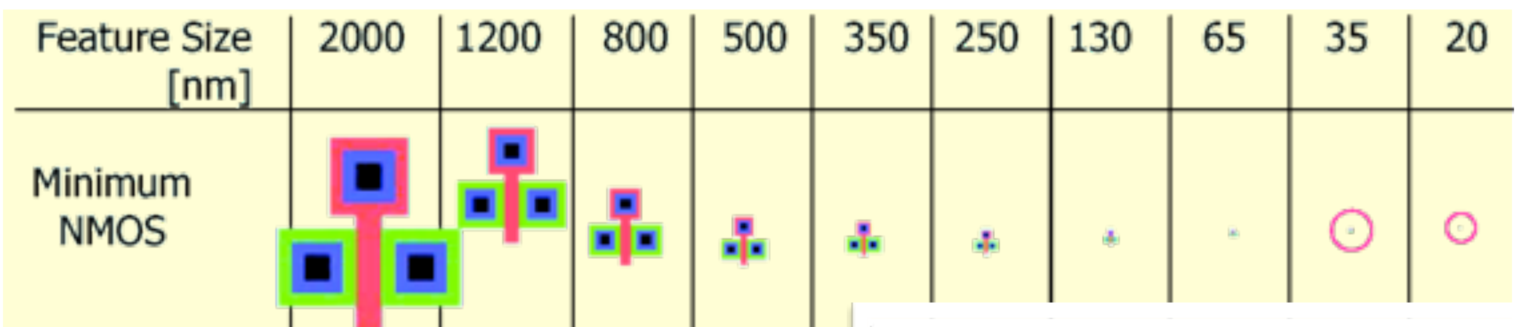


Challenge: Scaling Roadmap

- All detector types rely on modern chip technologies
- New technology generation every ~2 years
- From 1970 (8 μm) to 2014 (22 nm) (industrial application)
- End of the road ? Power dissipation sets limits

- HEP nowadays at 90nm and 130nm
- **Problem**: by the time a technology is ready for HEP -> “old” in industry standards



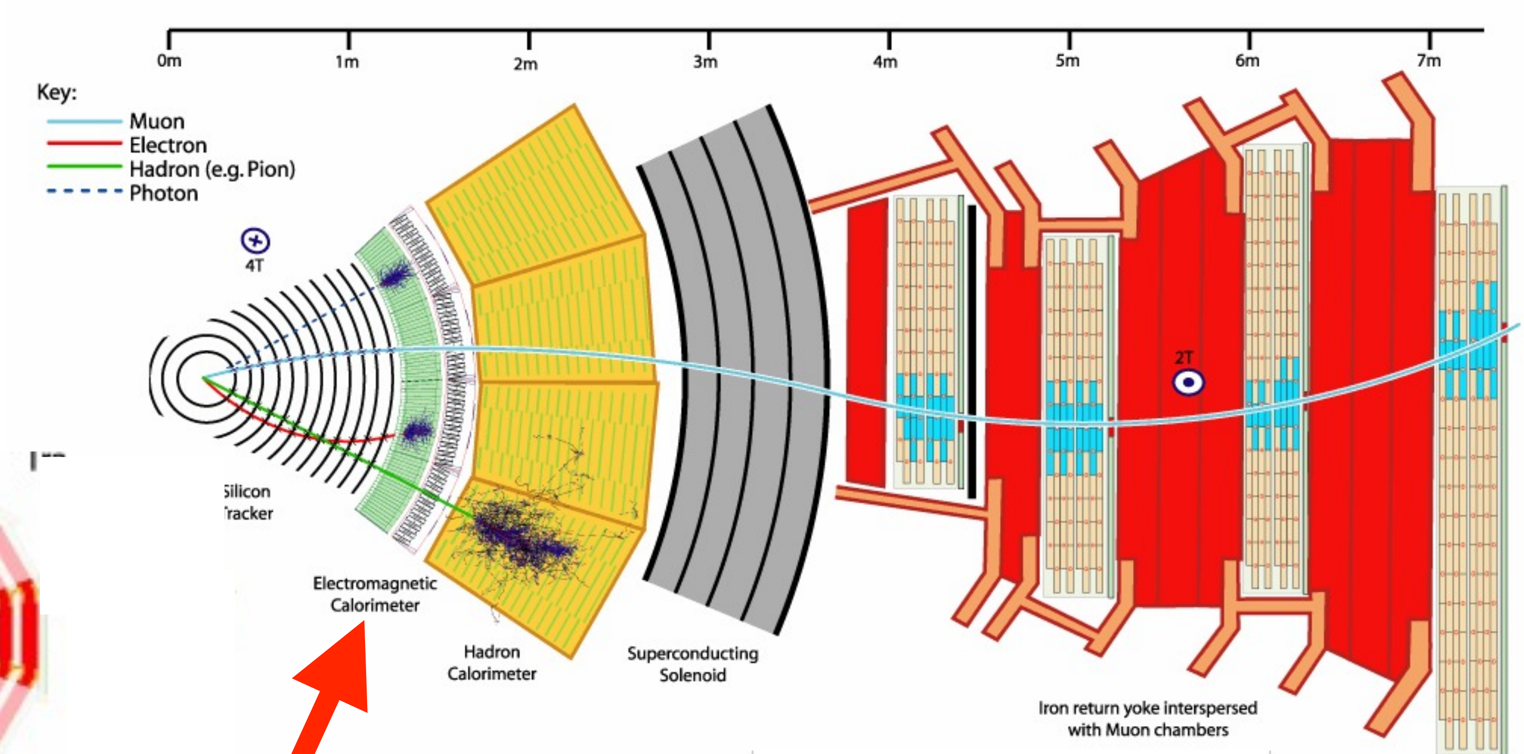


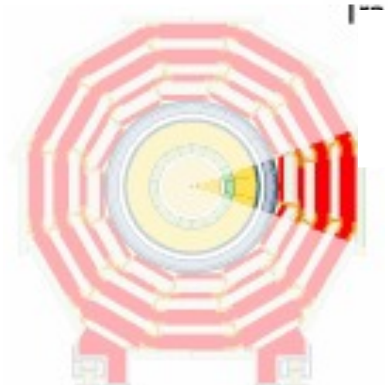
Also this is a challenge for all systems but most striking for tracking detectors.

Calorimeter

Particle Physics Detector Overview

Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption





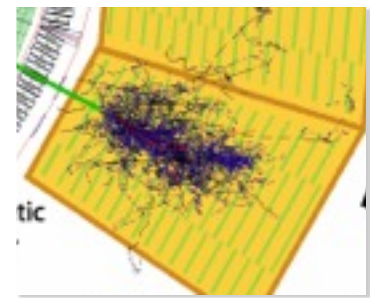
Transverse slice through CMS

Good energy resolution up to highest energies

Radiation hard (hadron collider)

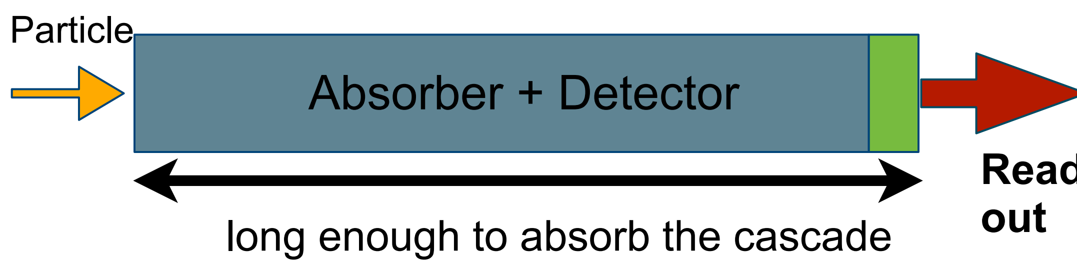
picture: CMS@CERN

Calorimeter in a nutshell

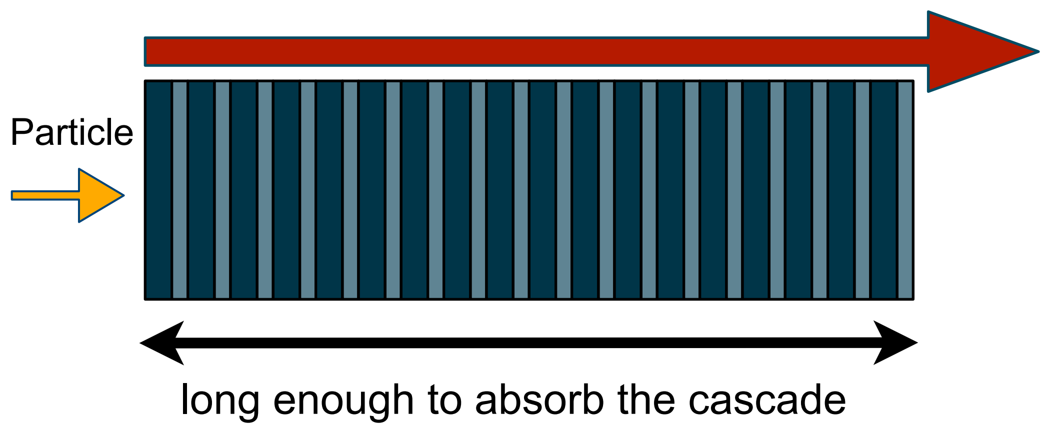


- Energy measurement of photons, electrons and hadrons through total absorption
  - Particles release their energy in matter through production of new particles => shower
  - Number of particles in shower is proportional to the energy of the incidental particle
- Two different types of calorimeters are commonly used (“classic”)

- **Homogeneous Calorimeter**
  - The absorber material is active
  - The overall deposited energy is converted into a detector signal

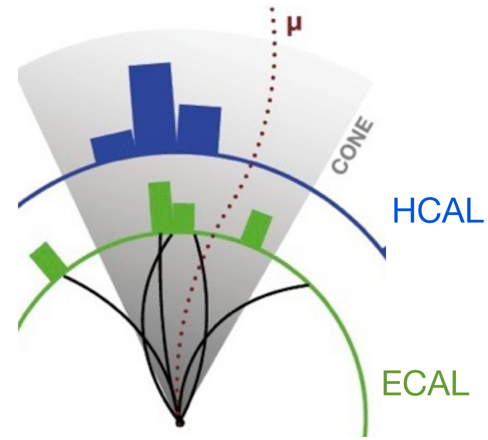


- **Sampling Calorimeter**
  - A layer structure of passive material and an active detector material
  - Only a fraction of the deposited energy is “registered”

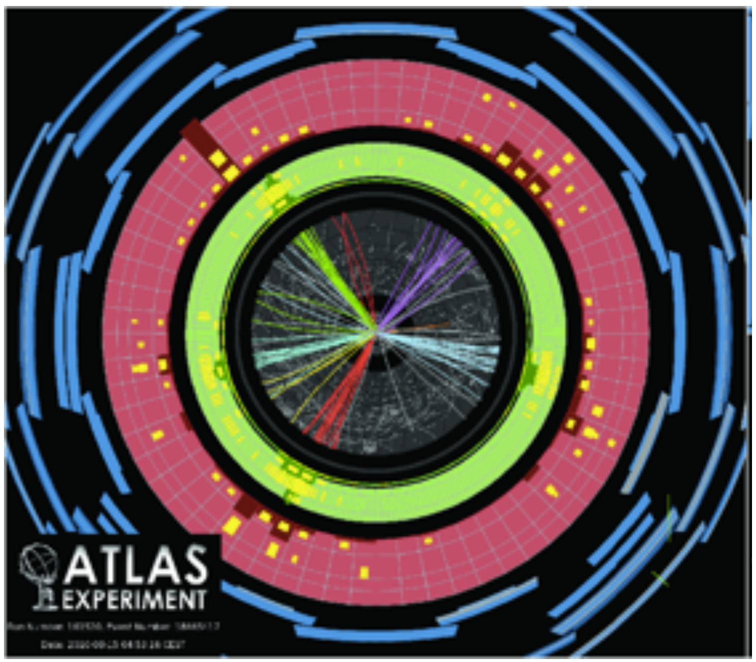


Current Frontiers in HEP Calorimetry

- Multi-jet final states (outgoing quarks, gluons)
  - At high energies the measurement of jets is crucial
  - Missing energy reconstruction - Invisible particles



The principle of jet reconstruction: Sum energy in a cone (geometry etc given by jet finding algorithm) to determine energy of original parton



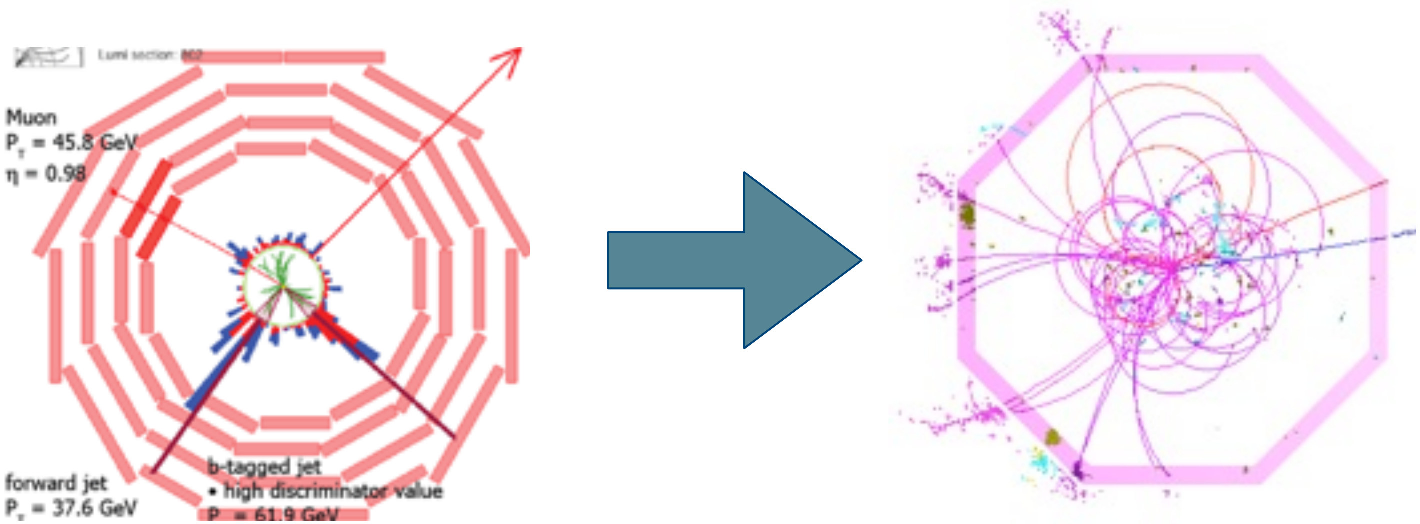
The limitations:

- Neutral hadrons, photons from neutral pion decay: Cannot just sum charged tracks
- The calorimeter with the worst energy resolution (the HCAL) drives the performance for jets!

Current Frontiers in HEP Calorimetry

- The goal for next-generation experiments: A quantum leap in jet energy resolution:
  - A factor ~2 improvement compared to current state of the art
    - Motivated by the requirement to separate heavy bosons W, Z, H in hadronic decays

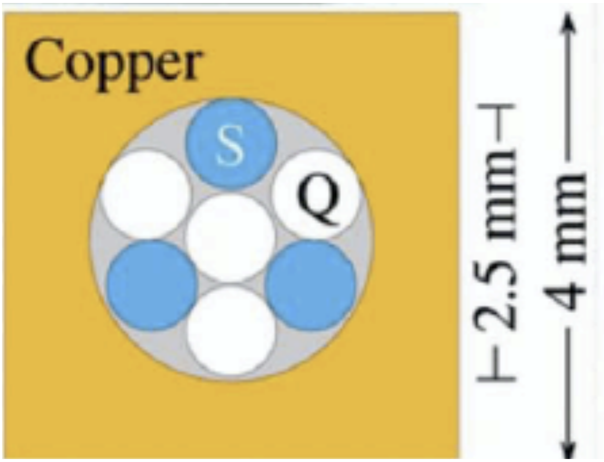
- Two approaches:
  - Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons: Dual / Triple readout calorimetry
  - Precise reconstruction of each particle within the jet, reduction of HCAL resolution impact: Particle Flow Algorithms & Imaging Calorimeters

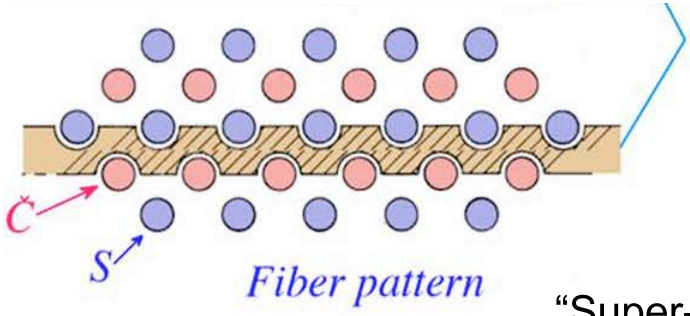


The DREAM Principle

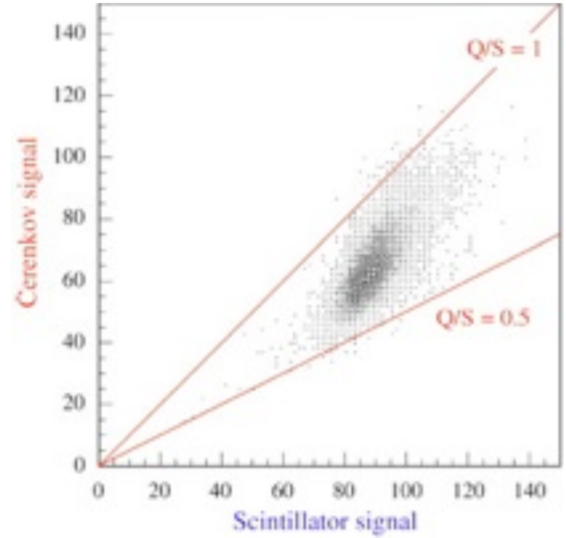
- **D**ual **rea**dout **m**odule: Two active media
  - Scintillating fibers: Sensitive to all charged particles in the shower
  - Quartz Cherenkov fibers: Sensitive to relativistic particles: EM only
  - Very different e/h: S ~ 1.4, Q ~ 5

  - Energy reconstructed by combining scintillator and Cherenkov signals: event-by-event correction for em-fraction





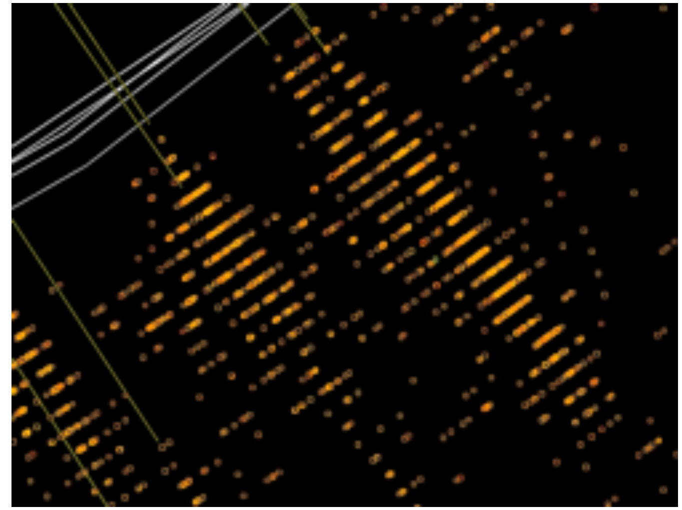
"Super-DREAM"

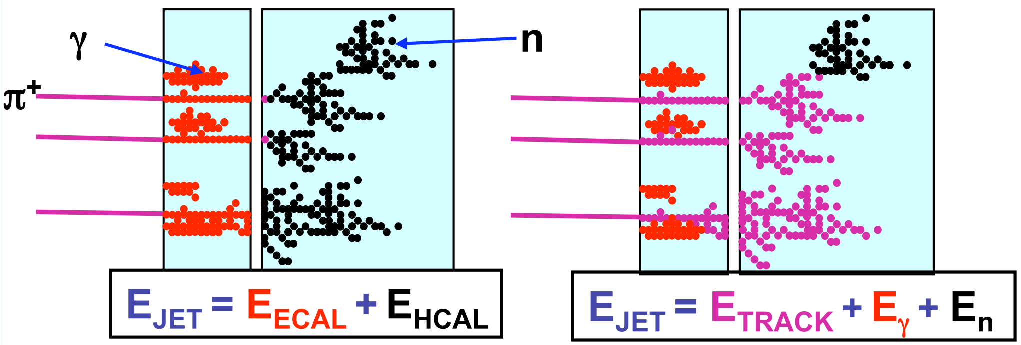


CERN RD52

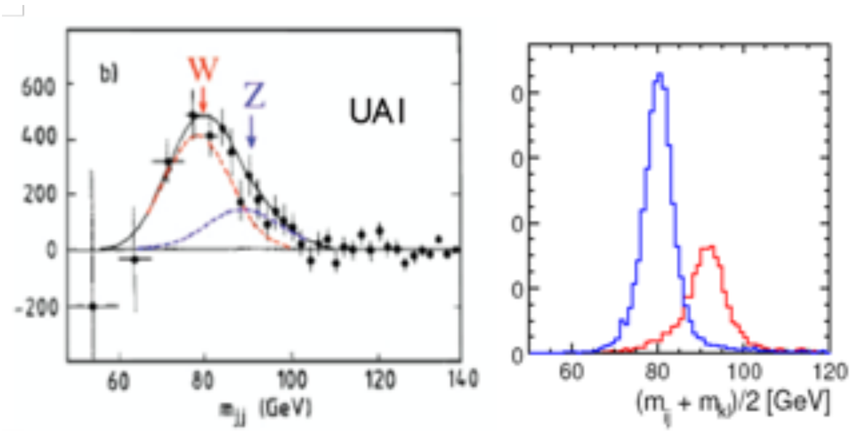
Particle Flow - Jets from Individual Particles

- Improve jet energy reconstruction by measuring each particle in the jet with best possible precision
  - Measure all charged particles in the tracker (60% charged hadrons)
    - Significantly reduce the impact of hadron calorimeter performance: Only for neutral hadrons
    - Measure only 10% of the jet energy with the HCAL, the “weakest” detector: significant improvement in resolution





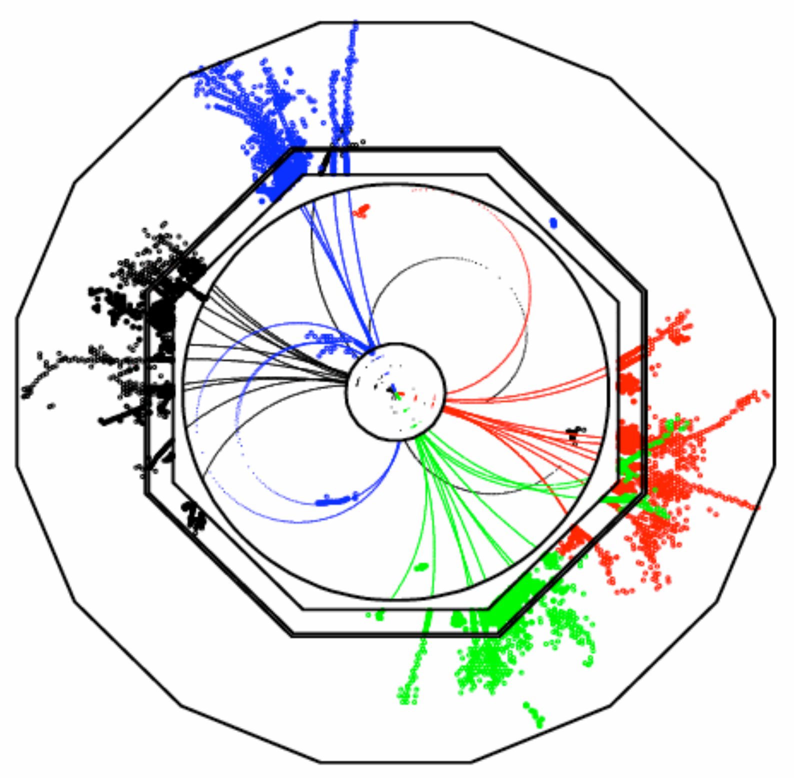
Traditional approach Particle Flow approach



Particle flow = granularity
Optimize relative to particle flow performance

Imaging Cals: Making PFA Happen

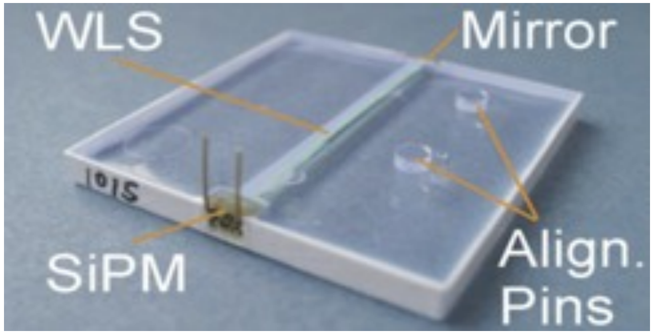
- For best results: High granularity in 3D - Separation of individual particle showers
  - Granularity more important than energy resolution!
  - Lateral granularity below Moliere radius in ECAL & HCAL
  - In particular in the ECAL: Small Moliere radius to provide good two-shower separation - Tungsten absorbers
    - Highest possible density: Silicon active elements - thin scintillators also a possibility
  - And: Sophisticated software!

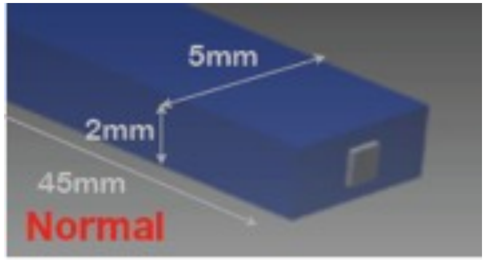


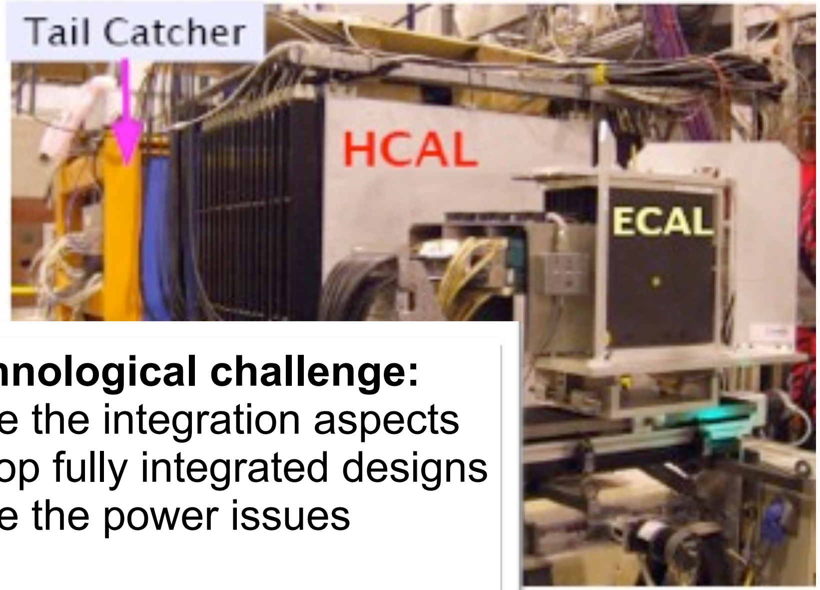
Extensively developed & studied for Linear Collider Detectors: Jet energy resolution goals (3% - 4% or better for energies from 45 GeV to 500 GeV) can be met

Scintillator Based Calorimeter

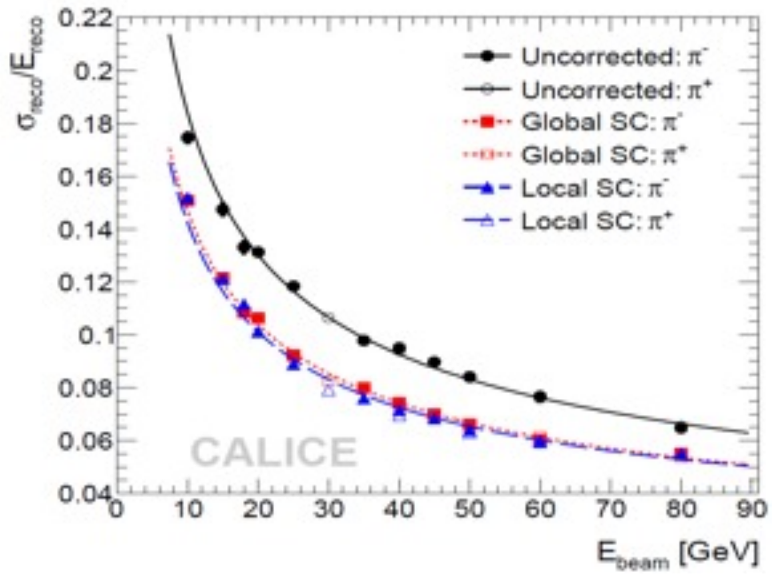
- Availability of SiPM allows highly granular scintillator based designs
- HCAL: 3x3cm^2 segmentation of 3mm thick scintillator read out by SiPM through wavelength shifting fiber (Elimination of WLS under study)
- Software compensation (e/p ~1.2) technique was show to work well through beam tests: 58%/E$^{1/2}$ → 45%/E$^{1/2}$





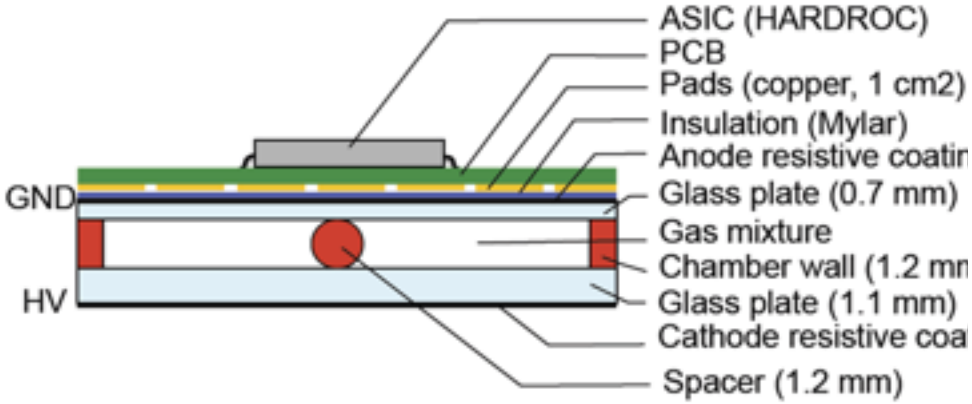


Key technological challenge:
- Handle the integration aspects
- Develop fully integrated designs
- Handle the power issues
- Costs



Digital Calorimetry

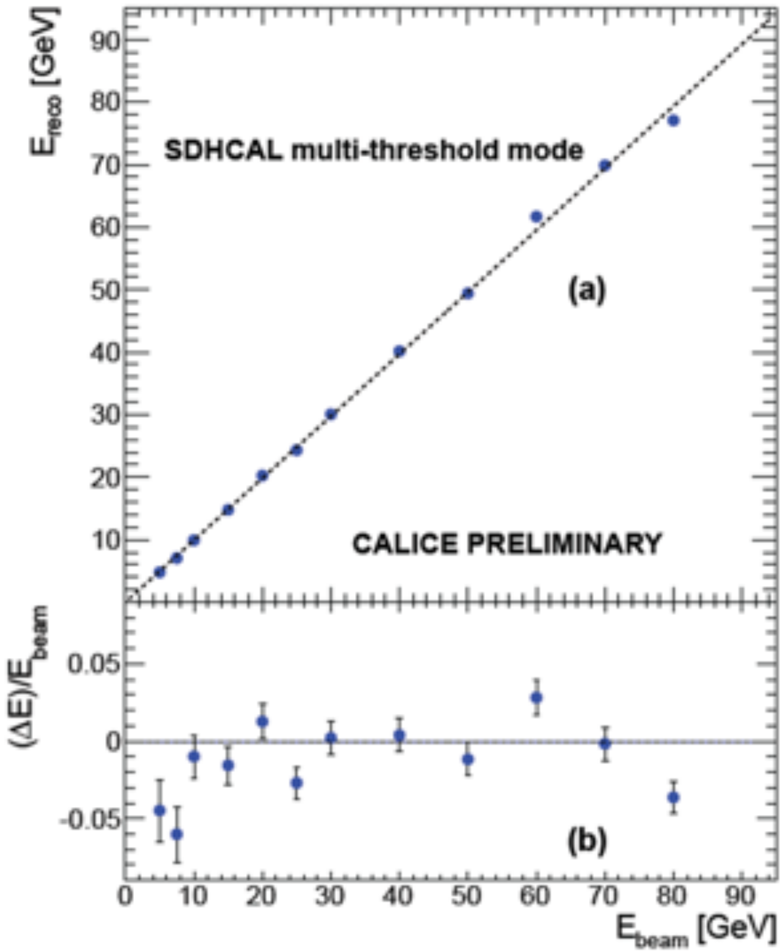
- Measure the energy of a particle through the number of cells hit
- Was tried already in the 80's (unsuccessfully), has seen a renaissance lately due to the availability of very granular systems.



Key technological challenge:
- Handle the integration aspects
- Develop fully integrated designs
- Handle the power issues
- Costs

Active medium: gas RPC's

Test beam results from a large prototype detector



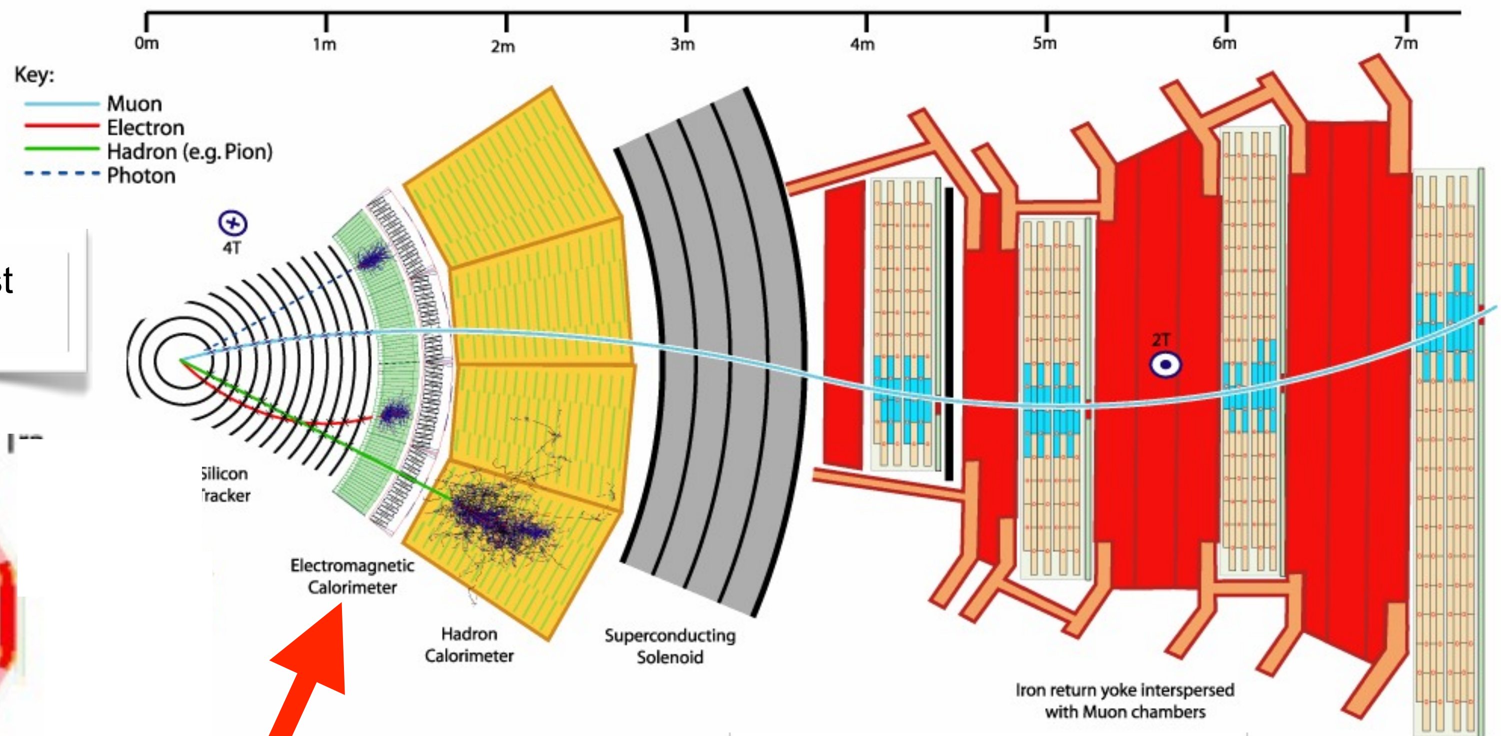
Particle Physics Detector Overview

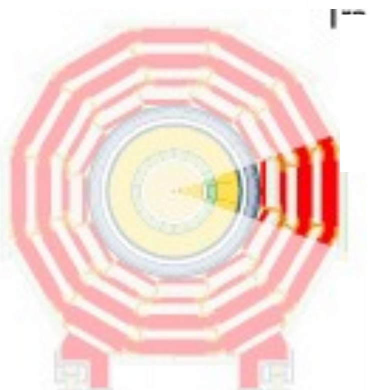
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption

Muon-Detectors: Identification and precise momentum measurement of muons outside of the magnet

Vertex: Innermost tracking detector





Transverse slice through CMS

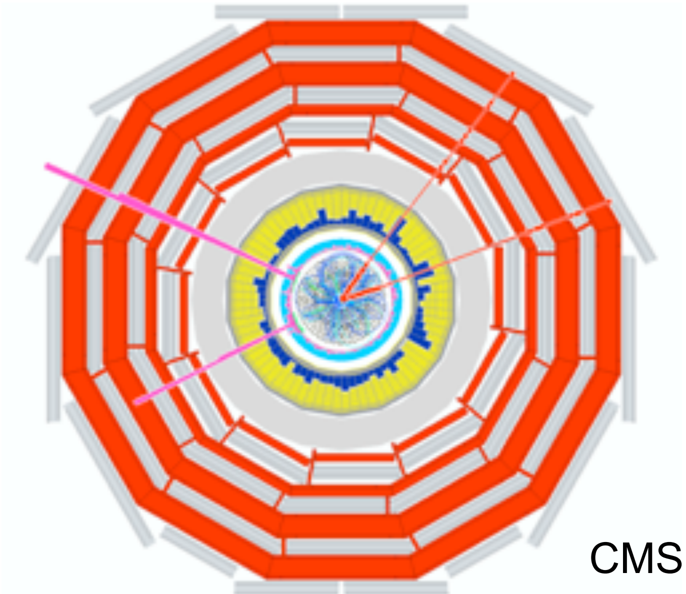
Good energy resolution up to highest energies

Radiation hard (hadron collider)

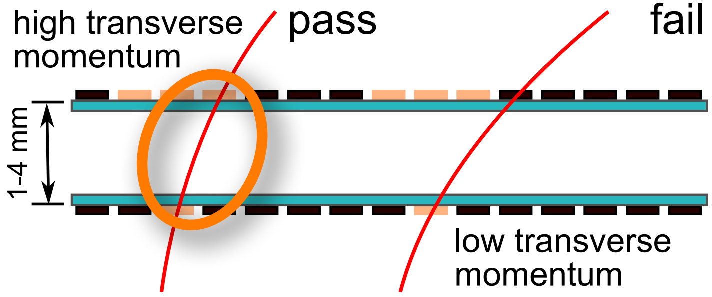
picture: CMS@CERN

Triggering

- Collisions every e.g. 25 ns with many simultaneous interactions
- A lot of information stored in the detectors - we need all information
- Electronics too slow to read out all information for **every** collision
- But: a lot of the interactions are very well known - we only want rare events
- "Trigger" is a system that uses simple criteria to rapidly decide which events to keep when only a small fraction of the total can be recorded.
  - "Classic" approach



CMS

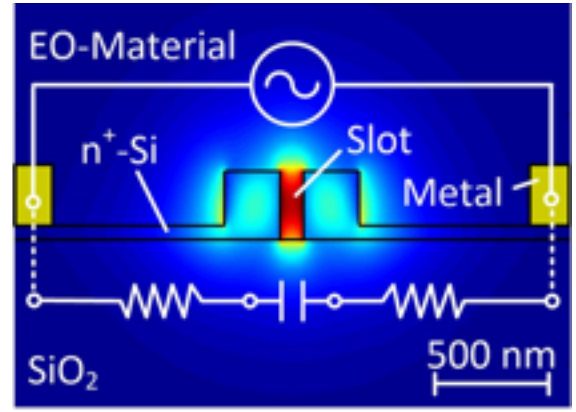


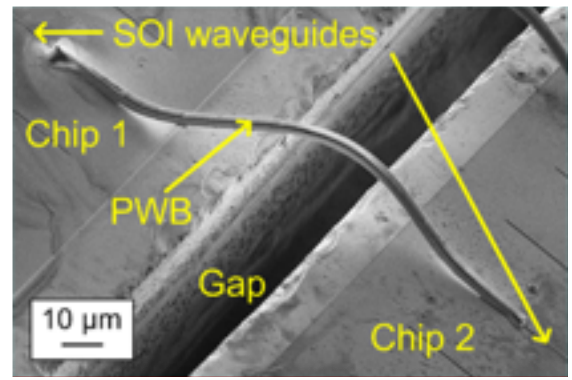
Example: HL-LHC CMS tracker

- Modern detectors need to be read out smarter
- Track trigger (H1, CDF, ATLAS FTK, CMS...)
  - trigger on interesting tracks directly with tracking system
  - complex implementation in system
  - i.e. self seeding -> smart electronics to detect high momentum tracks
- Trigger less
  - requires very fast data readout and even smarter offline software

Data Transfer

Optical transmission on a chip: waveguides





Modern detectors

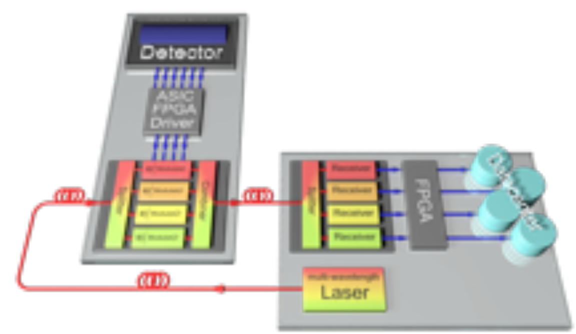
- Highly granular systems: many channels
- Untriggered systems (PANDA, ILC, LHCb): large continuous data flow
- LHC upgrade

Need high bandwidth compact ways to get the data out: TB/s

- Use of small feature size ASICs fast (10Gb/s) electrical+optical links with custom devices on-detector (low mass, compact and radiation-hard)
- Also need ever more powerful and more complex FPGAs for data handling
- Where possible send digitized data off-detector for every bunch crossing

  (40MHz at LHC) leading to ~10^5 Gb/s total bandwidths
- LHCb/ILC detectors: full triggerless operation, all data shipped to data acquisition

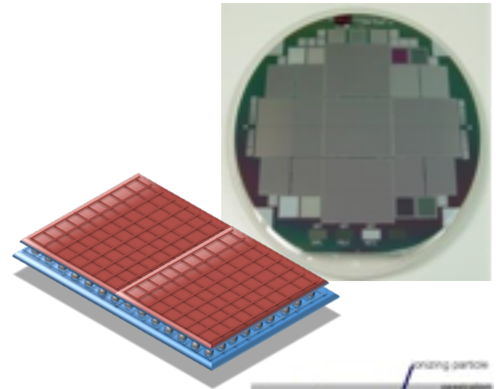
Integrate optical communication on the chips

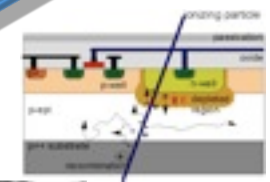


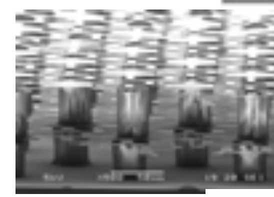
Conclusions

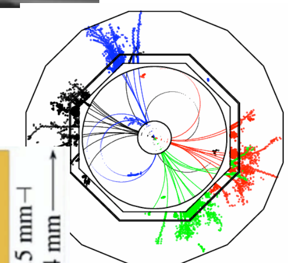
- Tracking detectors: more granular, very small material budget, faster, HL-LHC: extremely radiation hard
- Calorimeters: imaging calorimeters for particle flow are the next generation to measure new physics
- Also “low tech” such as services and cooling needs to be high tech to meet the challenges
- Only rough overview of a broad range of topics
  - Missing: many developments in electronics, data acquisition, monitoring, alignment, global engineering, radiation protection and many other areas ...

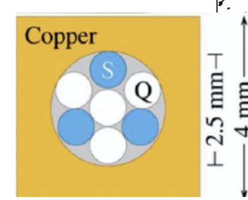
- Progress with detector technology is just about keeping pace with the requirements for future facilities
  - Resources are very tight despite much better coordination of effort between experiments
- Sizeable and highly dedicated community engaged in detector R&D
- Detector R&D in particle physics is an area where each sub-topic fills a conference series in itself -> you will learn a lot about this in the coming week.



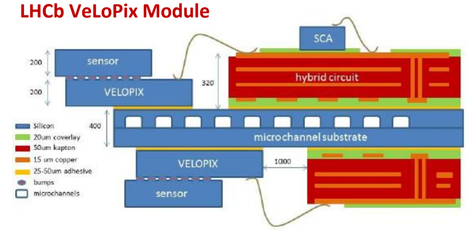








LHCb VeLoPix Module



Some Useful Links

- ECFA HL-LHC (2013): https://indico.cern.ch/event/252045/other-view?view=standard
- ACES 2014: https://indico.cern.ch/event/287628/other-view?view=standard
- CALOR 2014 http://indico.uni-giessen.de/indico/conferenceTimeTable.py?confId=164#20140407.detailed
- AWLC 2014: https://agenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=6301
- Neutrino 2014: https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=8022
- RD50 (2014): https://indico.cern.ch/event/307015/other-view?view=standard

Tracking Detectors: Challenges

- Radiation and rate requirements for HL-LHC silicon sensors are challenging but look to be manageable
  - attention more on material reduction, read-out, trigger, layout and cost optimisation including alternative technologies
- Different challenges with vertex detectors for e^+e^-
  - ultimate low mass (0.15% X_0/layer) with complex engineering and integration issues
  - precision time-stamp (~ns for CLIC) and < 5μm spatial resolution
- ILC/CLIC trackers target very high resolution
- Services matter:
  - low mass cooling and compact, radiation-hard optical+ electrical links with HV/LV multiplexing (very large numbers of channels running at LV drawing high currents → big potential power loss in cables)
- Large area detectors need close links with industry to develop processes for mass production
- Scintillating fibres and straws (NA62, Mu2e) provide excellent alternatives for several key applications

Performance Improvement

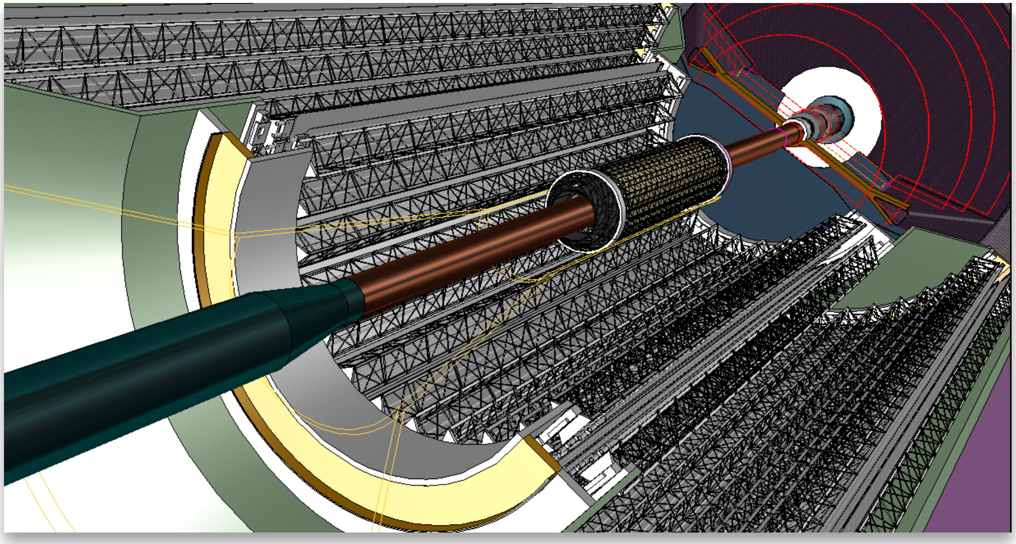
	Increase granularity at large radii	Increase granularity close to the IP (small pixels)	Increase number of pixellated layers	Reduce material
Fast and efficient pattern recognition in high pileup	ATLAS, CMS	ATLAS, ALICE, CMS, LHCb	ALICE, CMS, LHCb	
Improve momentum resolution at low pT				ATLAS, ALICE, CMS, LHCb
Improve momentum resolution at high pT	ATLAS, CMS			
Improve tracking efficiency	ALICE			ATLAS, ALICE, CMS, LHCb
Improve impact parameter resolution		ATLAS, ALICE, CMS, LHCb		
Improve two-track separation		ATLAS, ALICE, CMS, LHCb		
Reduce photon conversions				ATLAS, ALICE, CMS, LHCb

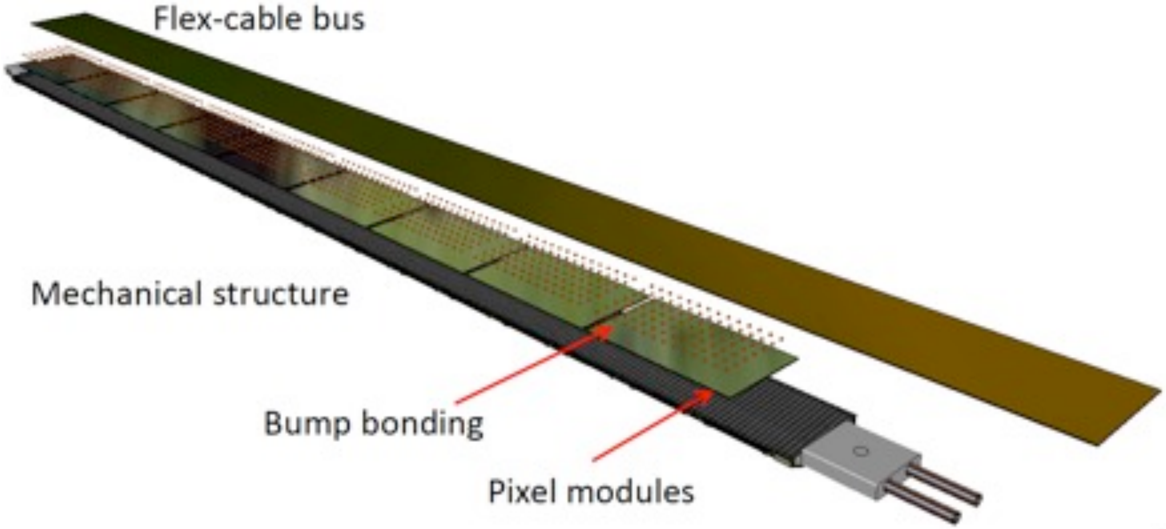
Conclusions

- Trends in technology enable to address the challenges in modern particle detectors
  - some trends. not independent
- Segmentation
  - Vertex elements with 20 µm and smaller features
  - Calorimetry employing silicon elements
  - Micro Pattern Gas Detectors (MPGD) applications
- Integration
  - Microelectronics
  - Mechanical sophistication
- Speed
  - Faster electronics, low noise and low power
- Materials
  - Rad-hard, robust, thin, etc.
- Radiation immunity
  - Understanding damage mechanisms and annealing design optimization

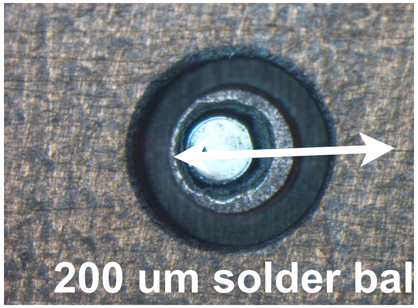
ALICE Pixel R&D

- Inner Barrel: 3 layers
- Outer Barrel: 4 layers
- Detector module (Stave) consists of
  - Carbon fiber mechanical support
  - Cooling unit
  - Polyimide printed circuit board
  - Thinned Silicon sensor chips

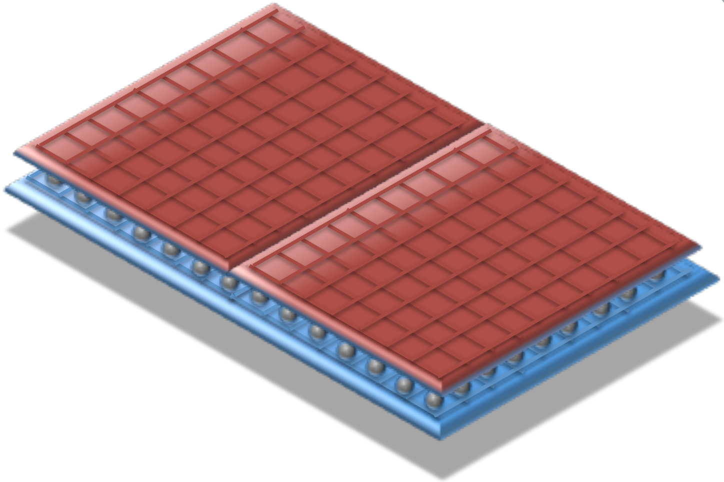




25 G-pixel detector, 10.3 m²

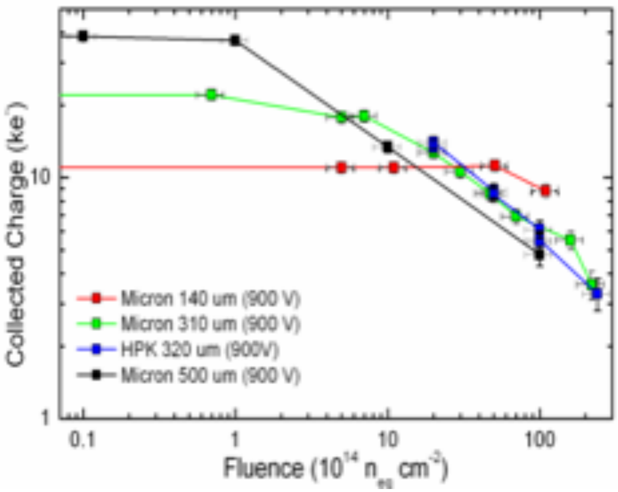


Pixel Detectors

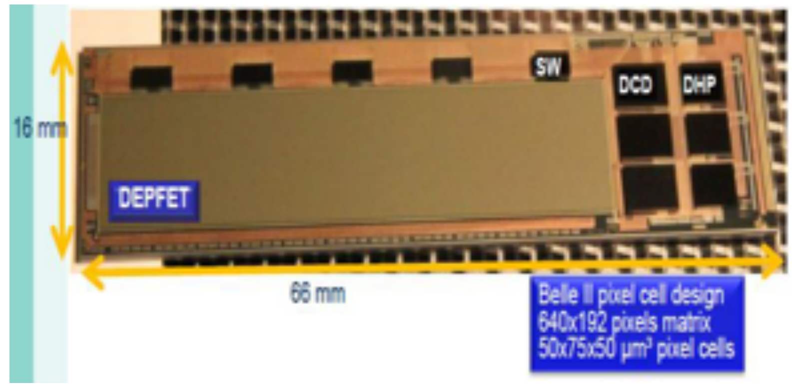


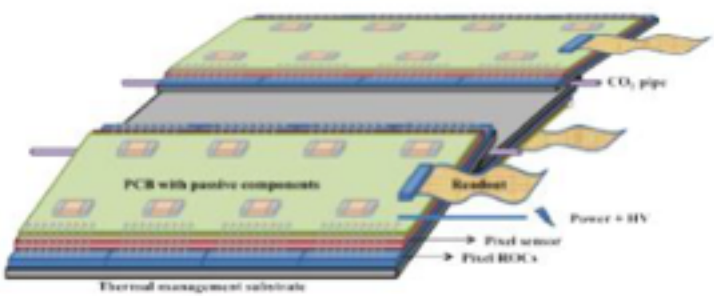
LHC: radiation hardness is key parameter

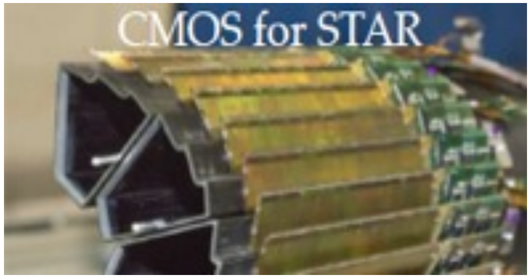
Trends:
- Small pixels
- Low mass
- Local intelligence

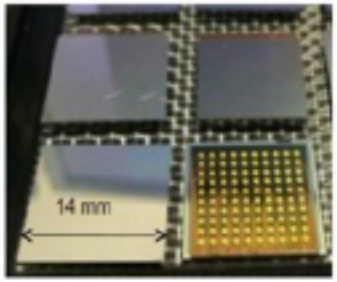


Different technologies
Hybrid pixels with various sensor materials
CMOS
DEPFET
FPCCD
3D
Chronopixel
SoI



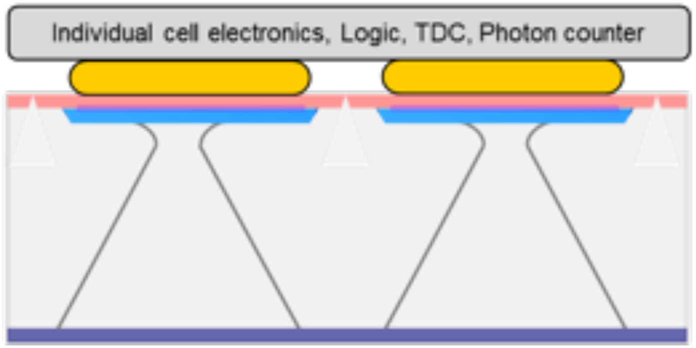






SiPM Developments

Ultra fast particle tracker - ***High energy physics application***



Silicon based photo detectors:

- Allow granular scintillator based detectors
- Applications in many other areas

Commercially available
New development: digital SiPM

- Readout every pixel
- Broad applications

Ultra fast single photon sensitive imager – ***Photon science***