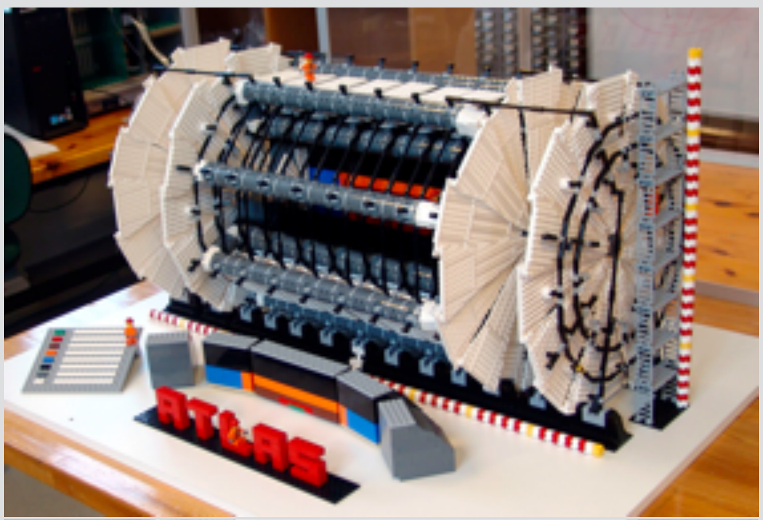
Instrumentation and Detectors

Ingrid-Maria Gregor
DESY



AEPSHEP 2016

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Asia-Europe-Pacific School of HEP

Overview

Part 1

Part 2

Part 3

V. Building an Experiment

Current HEP Detector R&D

- Detector development is always an important topic in high energy physics
- Technical demands are constantly increasing due to new challenges in particle physics
  - higher occupancy, smaller feature size, larger trigger rates, radiation level, …..

- New HEP detector projects are planned for
  - Detector upgrades during different LHC phases up to HL-LHC (ATLAS, CMS, ALICE, LHCb)
  - Detector R&D for a future linear collider (ILC and CLIC)
  - Belle II (construction phase starting)
  - PANDA and CBM @Fair
  - …..

source: “CMS Particle Hunter”

How to do a particle Physics Experiment

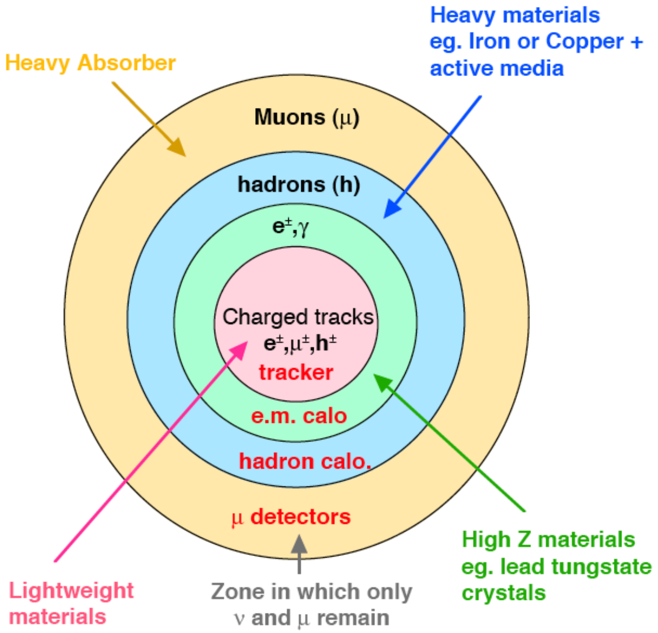
- Recipe:
  - get particles (e.g. protons, antiprotons, electrons, …)
  - accelerate them
  - collide them
  - observe and record the events
  - analyse and interpret the data
- Ingredients needed:
  - particle source
  - accelerator and aiming device
  - simulations
  - detector
  - trigger
  - recording devices
- many people to:
  - design, build, test, operate accelerate
  - design, build, test, calibrate, operate, understand the detector
  - analyse data
  - lots of money to pay all this ….

Pic: DESY

typical HERA collaboration: ~400 people
LHC collaborations: >2000 people

Conceptual Design of HEP Detectors

- Need detailed understanding of
  - processes you want to measure ("physics case")
  - signatures, particle energies and rates to be expected
  - background conditions
- Decide on magnetic field
  - only around tracker?
  - extending further ?
- Calorimeter choice
  - define geometry (nuclear reaction length, X0)
  - type of calorimeter (can be mixed)
  - choice of material depends also on funds



at a collider experiment

- Tracker
  - technology choice (gas and/or Si?)
  - number of layers, coverage, …
  - pitch, thickness, ….
  - also here money plays a role

Detailed Monte Carlo simulations need to guide the design process all the time !!

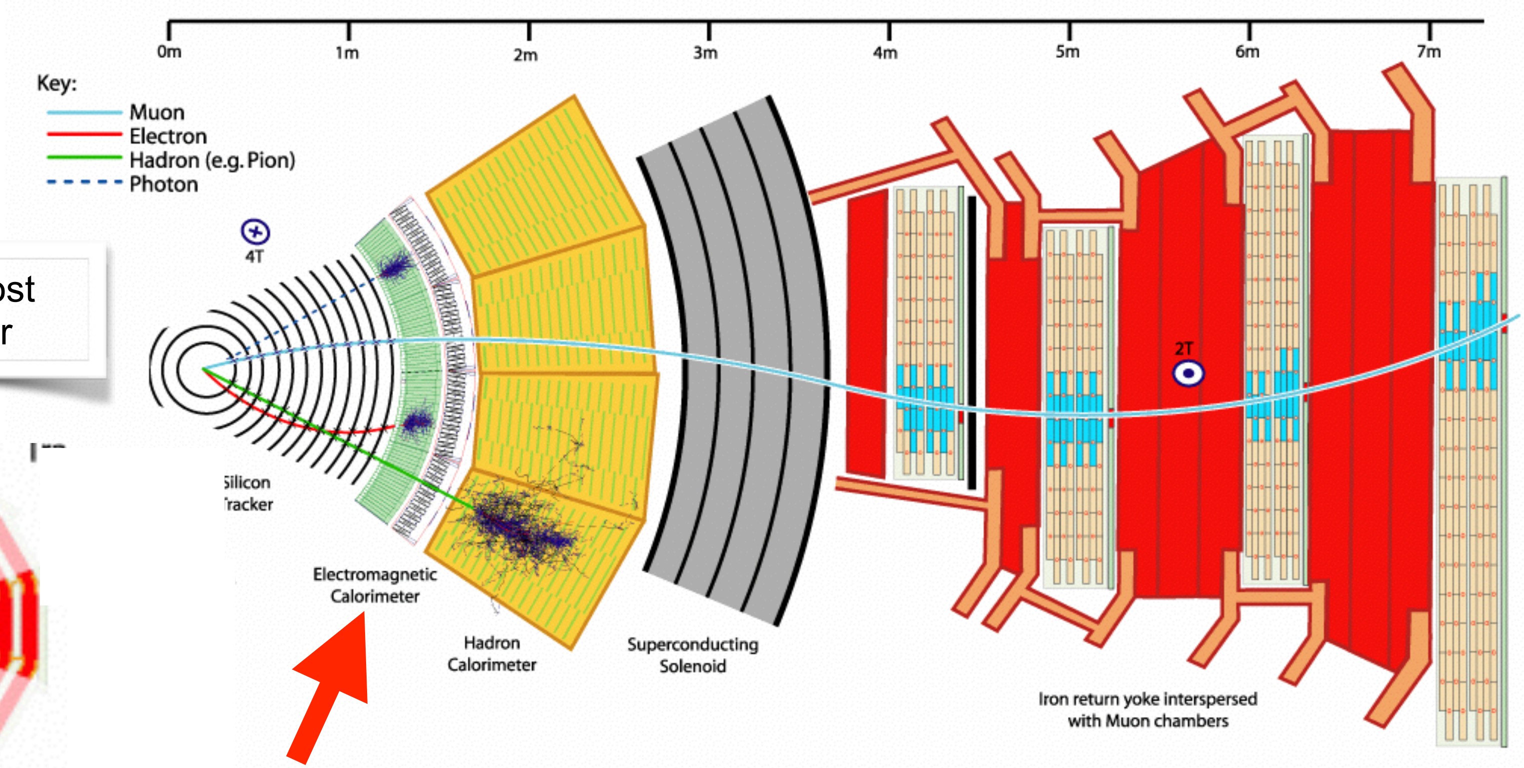
HEP Detector Overview

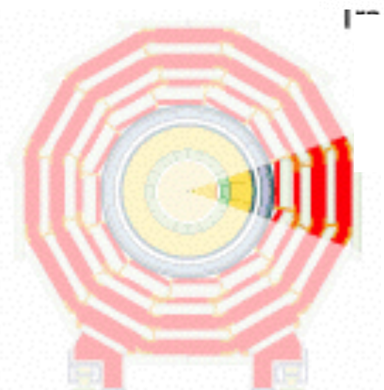
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

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

picture: CMS@CERN

A magnet for a LHC experiment

- **Wish list**
  - big: long lever arm for tracking
  - high magnetic field
  - low material budget or outside detector (radiation length, absorption)
  - serve as mechanical support
  - reliable operation
  - cheap
  - ….

www.positoons.de

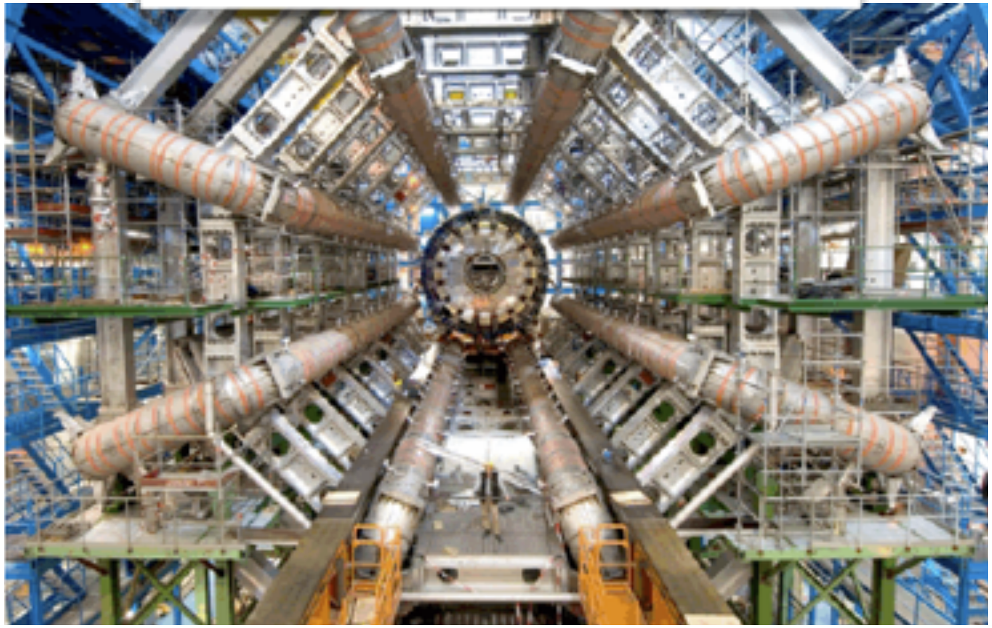
Eierlegende Wollmilchsau

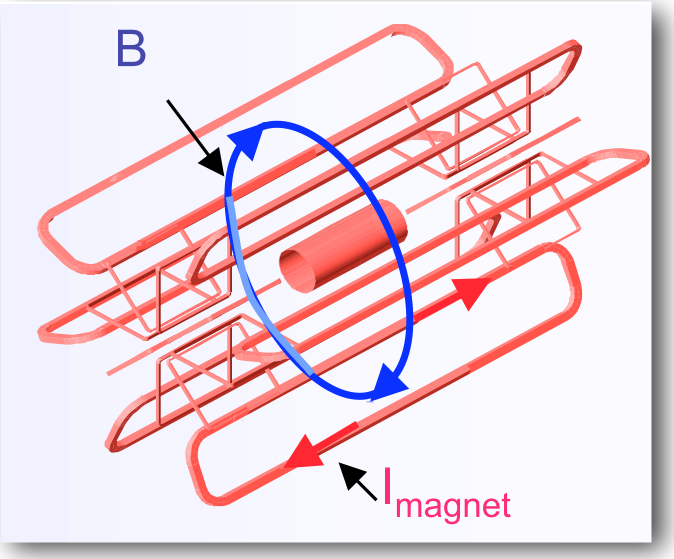
- **ATLAS decision**
  - achieve a high-precision stand-alone momentum measurement of muons
  - need magnetic field in muon region -> large radius magnet

- **CMS decision**
  - single magnet with the highest possible field in inner tracker (momentum resolution)
  - muon detector outside of magnet

Magnet-Concepts: ATLAS -> Toroid

the largest magnet in the world



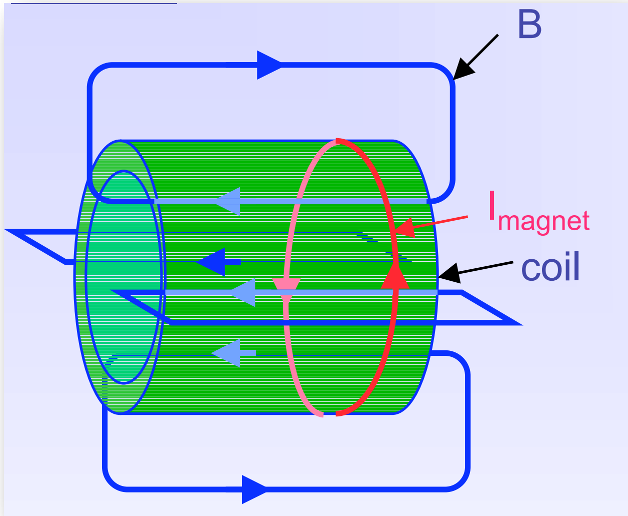


- Central toroid field outside the calorimeter within muon-system: <4 T
  - Closed field, no yoke
  - Complex field
- Thin-walled 2 T Solenoid-field for trackers integrated into the cryostat of the ECAL barrel

+ field always perpendicular to $\vec{p}$
+ relative large field over large volume
- non uniform field
- complex structure

Magnet-Concepts: CMS -> Solenoid

Largest solenoid in the world:



- super conducting, 3.8 T field inside coil
- weaker opposite field in return yoke (2T)
- encloses trackers and calorimeter
- 13 m long, inner radius 5.9 m, I = 20 kA, weight of coil: 220 t

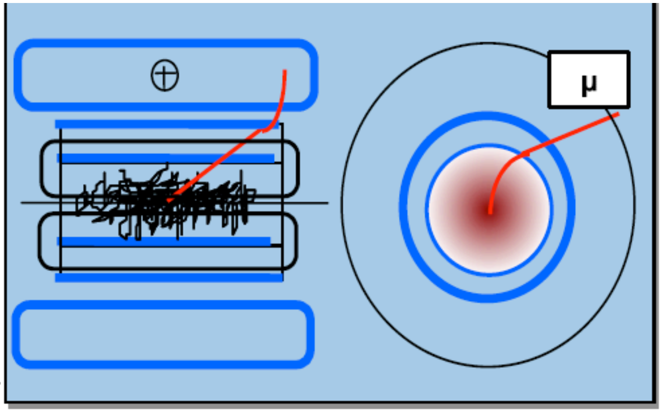
\+ large homogeneous field inside coil
\+ weak opposite field in return yoke
\- size limited (cost)
\- relative high material budget

Muon Detectors

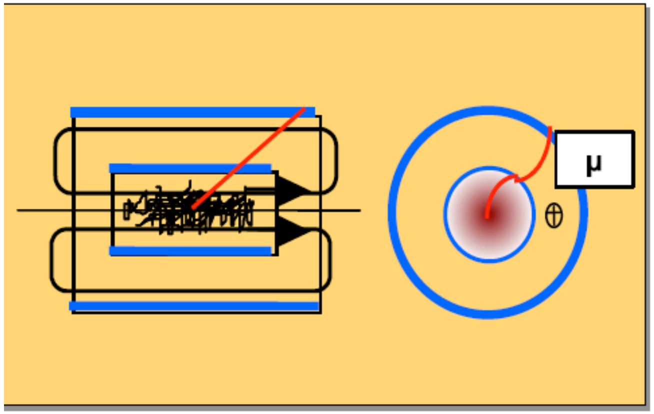
another tracker outside of the magnet

- Identification and precise momentum measurement of muons outside of the magnet
- Benchmark design for muon detectors:
  momentum measurement better than 10% up to 1 TeV.
  - $\Delta pT/pT \approx 1/BL^2$
- ATLAS
  - independent muon system -> excellent stand capabilities
- CMS:
  - superior combined momentum resolution in the central region;
  - limited stand-alone resolution and trigger capabilities (multiple scattering in the iron)
- ATLAS and CMS have both a combination of different gas detectors in the larger radius
  - Drift tubes
  - Resistive plate chambers
  - Multi-wire proportional chamber

ATLAS

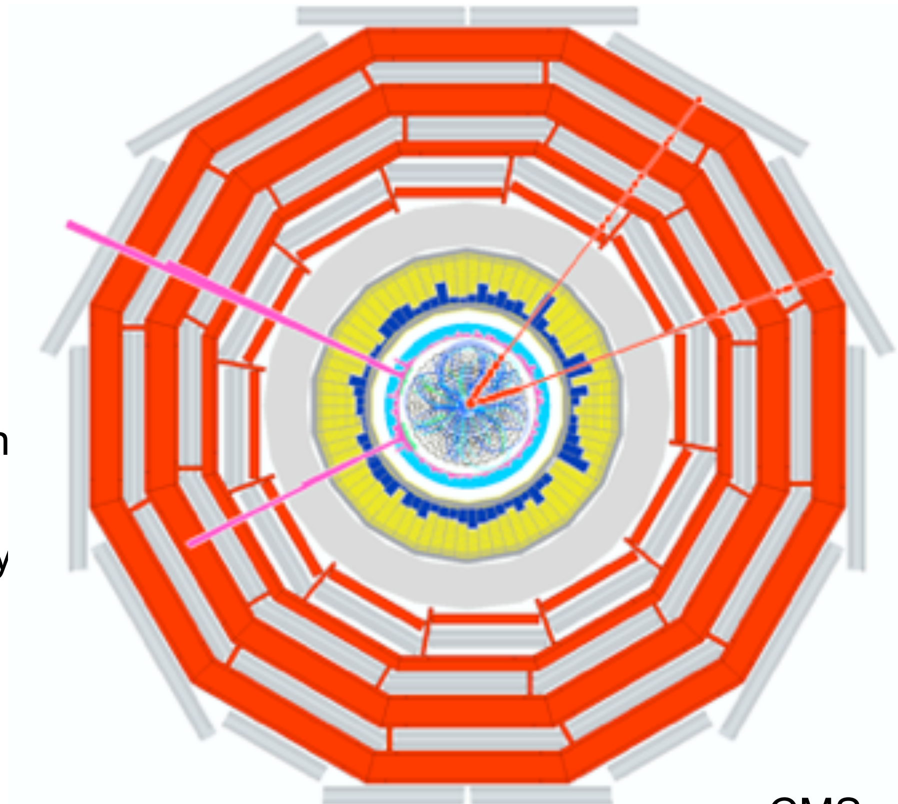


CMS

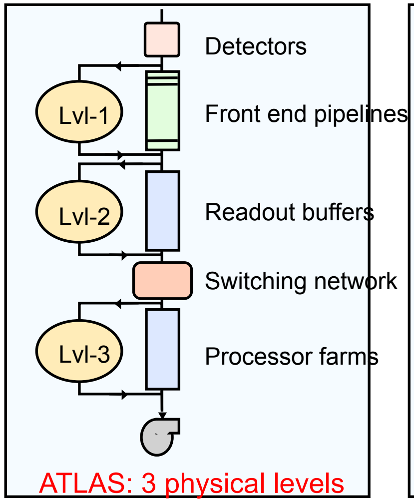


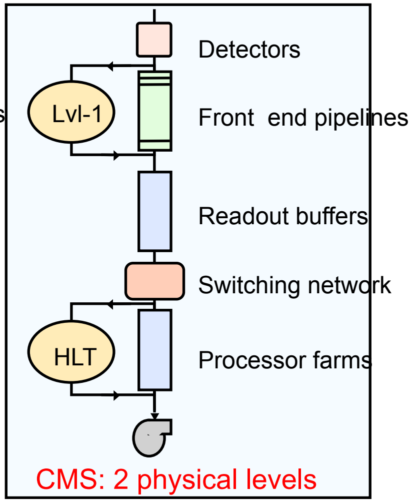
Data reduction by Triggering

- Collisions every 25 ns with many simultaneous interactions
- A lot of information stored in the detectors.
- Electronics too slow to read out all information for **every** collision
  - 40 MHz * 1MB (event size) ~ 320 Tbps
- But: a lot of the interactions are very well known - we only want rare events
- “Trigger” : system using simple criteria to rapidly decide which events to keep.

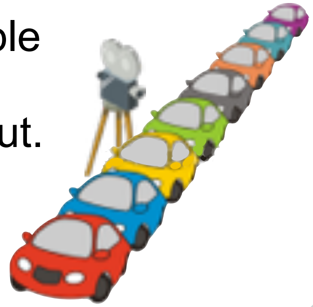


CMS





Fast detector systems detect possible interesting signature and trigger the inner detector systems to be read out. Other events are discarded.



Experimental Constraints

Different experiments have very different **trigger** requirements due to operating environments

- Timing structure of beam (HERA: 10MHz, LHC: 40MHz, ILC: bunch train structure, …)
- Rate of producing physics signals of interest
- Rate of producing backgrounds

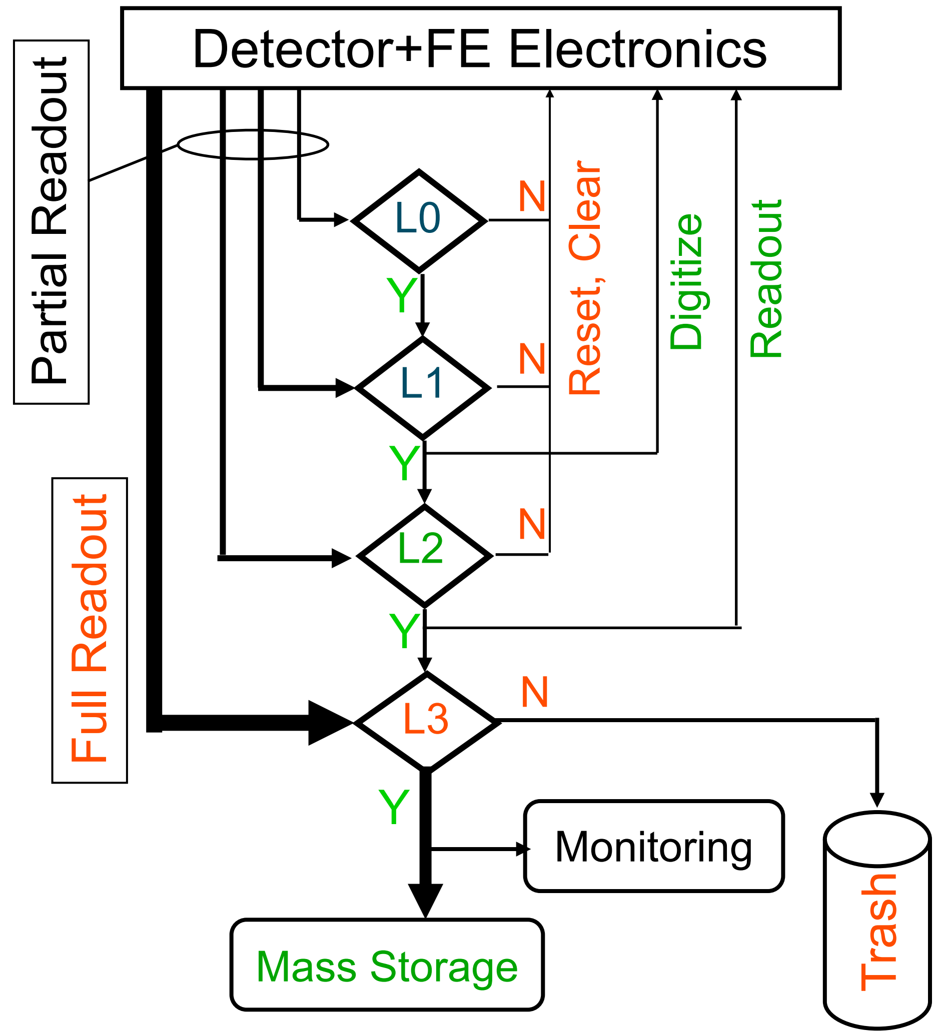
- **Cosmic Ray Experiments**
  - no periodic timing structure, background/calibration source for many other experiments
- **Fixed Target Experiments**
  - close spacing between bunches in train which comes at low repetition rate (~Hz)
    - backgrounds from un-desirable spray from target
    - cosmics are particularly a background for neutrino beams
- **e+e- colliders**
  - very close bunch spacing (few nsec), beam gas and beam wall collisions
- **ep collider**
  - short bunch spacing (96ns), beam gas backgrounds
- **pp/ppbar collider**
  - modest bunch spacing (25-400ns), low produced soft QCD

Multi-Level Trigger Systems

High Efficiency ⟷ **Large Rejection**

- Can't achieve necessary rejection in a single triggering stage
- Reject in steps with successively more complete information
  - L0 – very fast (<~bunch x-ing), very simple, usually scint. (TOF or Lumi. Counters)

    Few expts use a L0 anymore
  - L1 – fast (~few μs) with limited information, hardware
  - L2 – moderately fast (~10s of μs), hardware and sometimes software
  - L3 – Commercial processor(s)

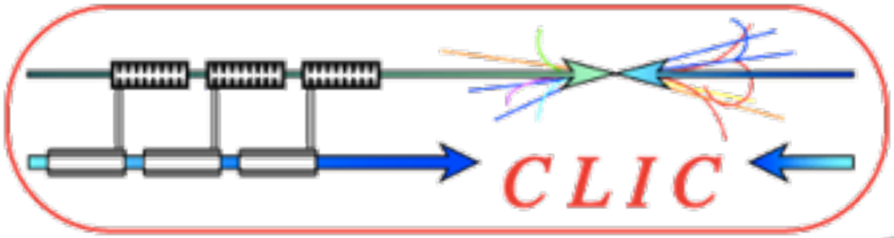


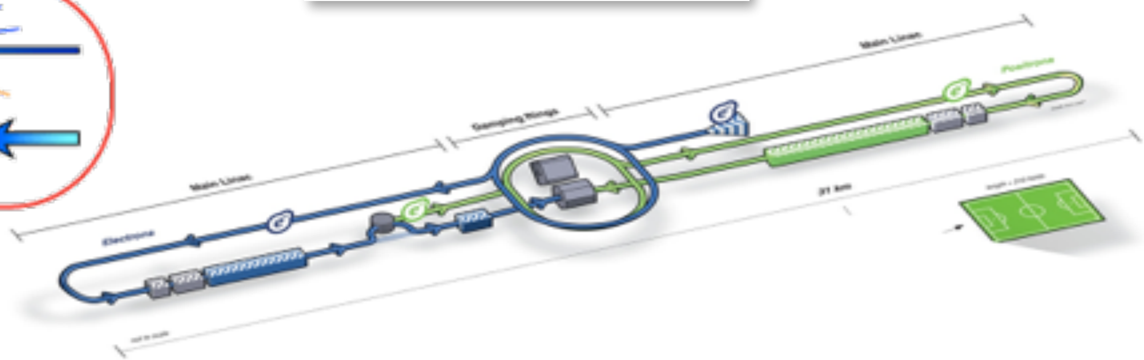
VI. Challenges for Future Experiments

Future Facilities

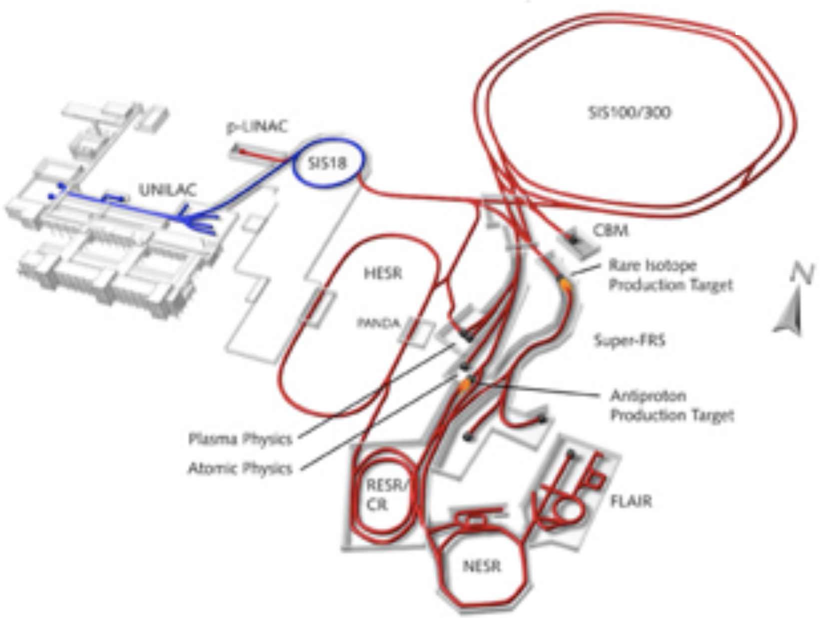
incomplete list …

Precision physics,
rare processes
high data rates

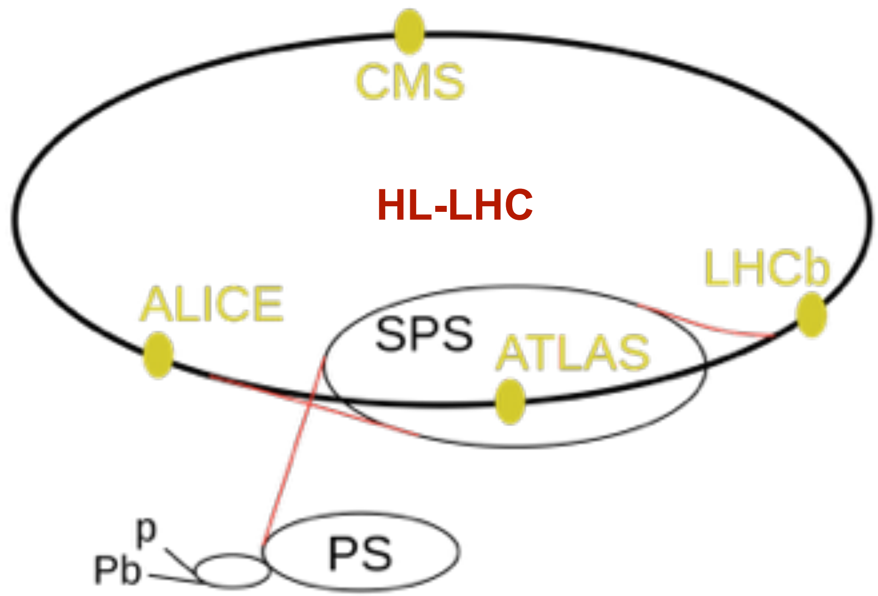




CLIC: Electron – positron collider
proposal phase



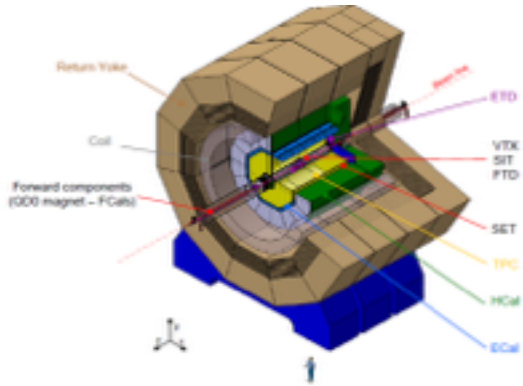
FAIR: Facility for Antiprotons and Ions Research,
under construction



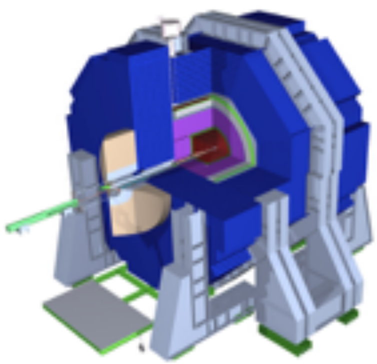
HL-LHC: high luminosity upgrade of the LHC

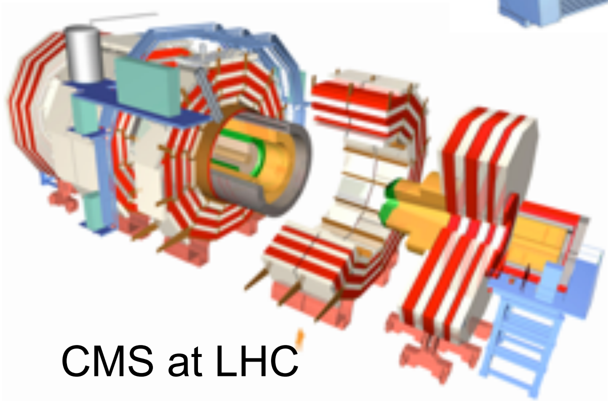
Future Experiments

ILD at the ILC/CLIC

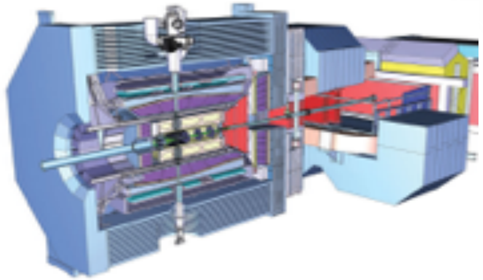


SiD at the ILC/CLIC



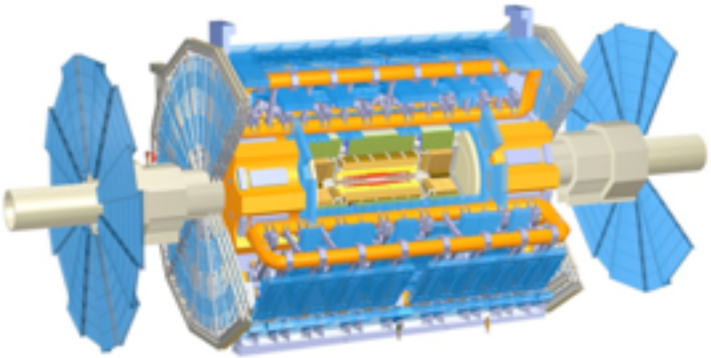


CMS at LHC

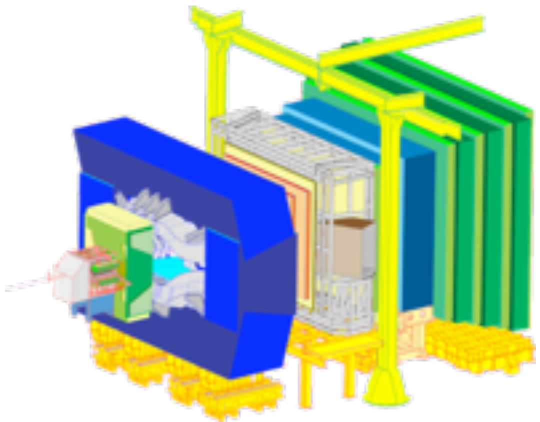


PANDA at FAIR

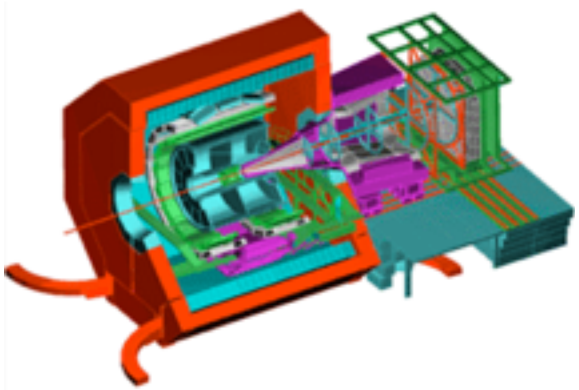
ATLAS at LHC



LHCb at LHC



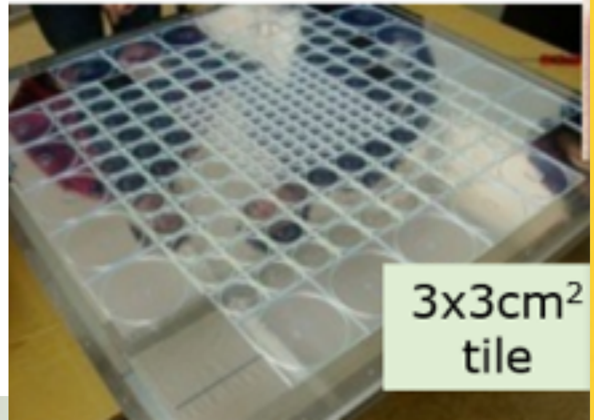
ALICE at LHC

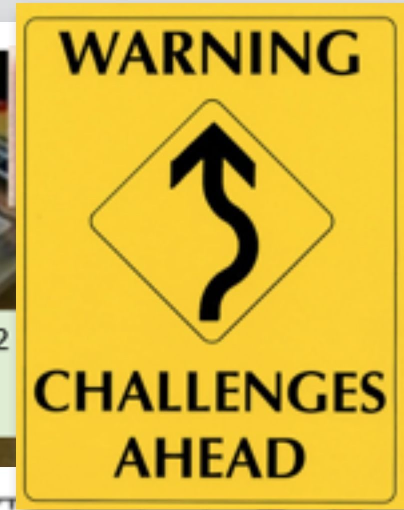


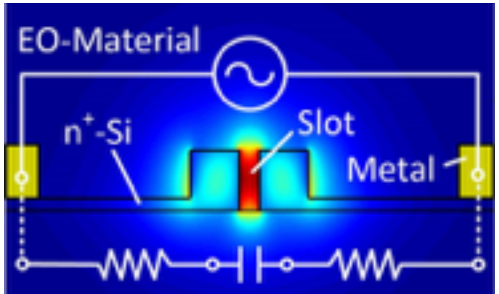
not to scale !!

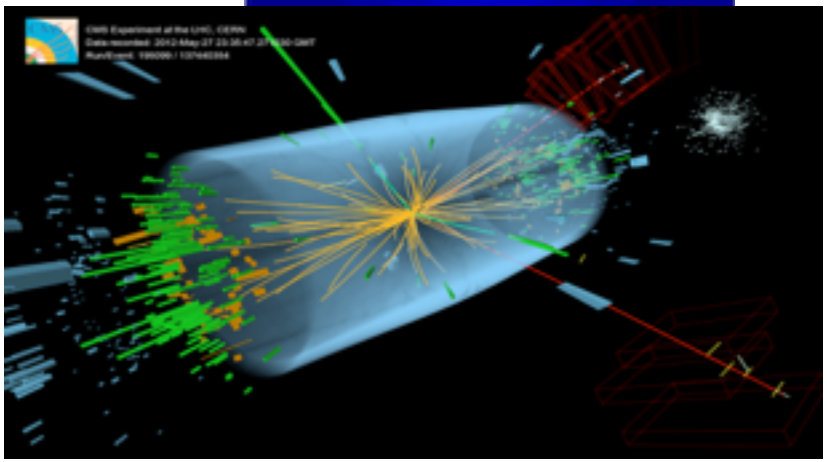
The Challenges

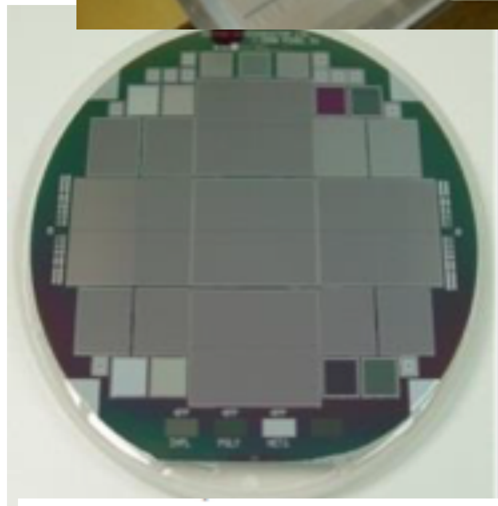
- Precision (resolution)
- Granularity
- Power consumption
- Readout speed
- Material budget

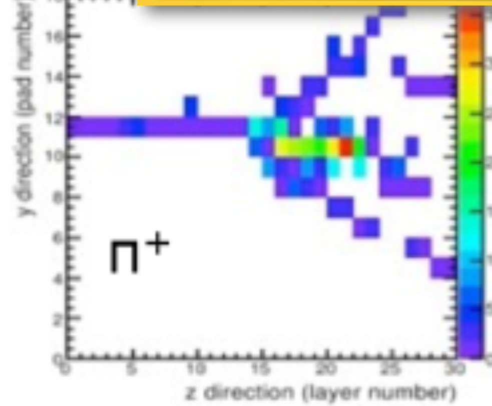


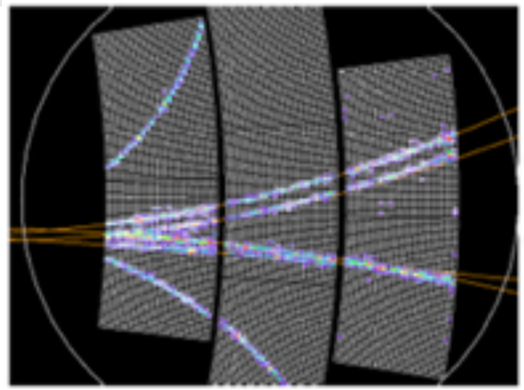






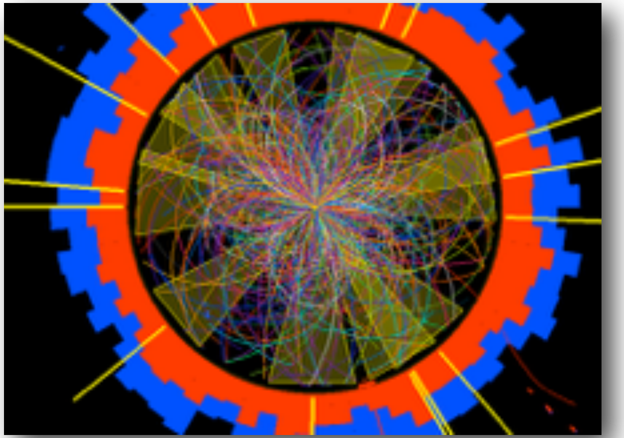




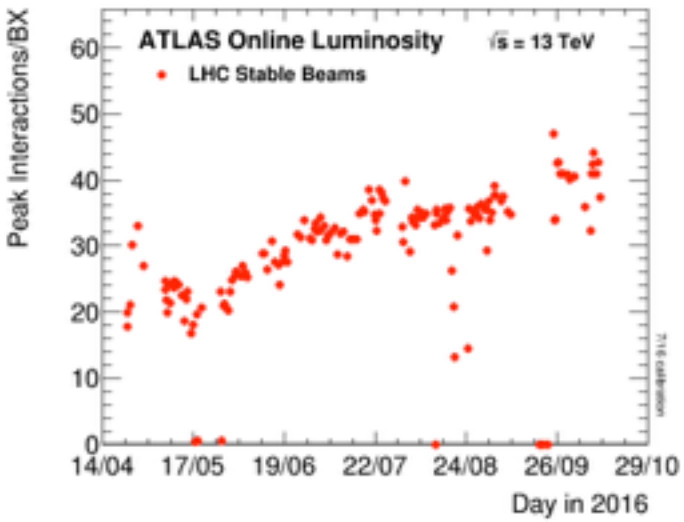


Features Making Life Difficult ...

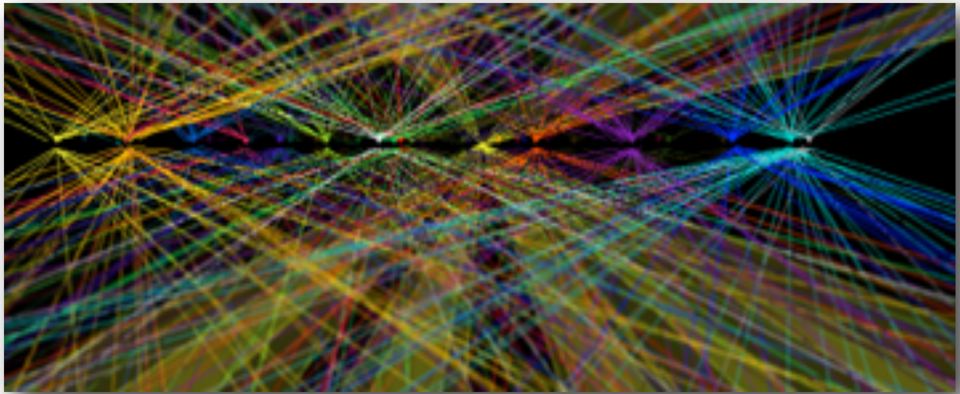
- LHC detectors must survive for 10 years or more of operation
  - Radiation damage to all components
  - Problem pervades whole experimental area (neutrons).



- Detectors must provide precise timing and be as fast as feasible
  - 25 ns is the time interval to consider.
- Detectors must have excellent spatial granularity
  - Need to minimise **pile-up effects.**



Pile-up: the number of collision events that take place for each bunch crossing.



pictures: ATLAS

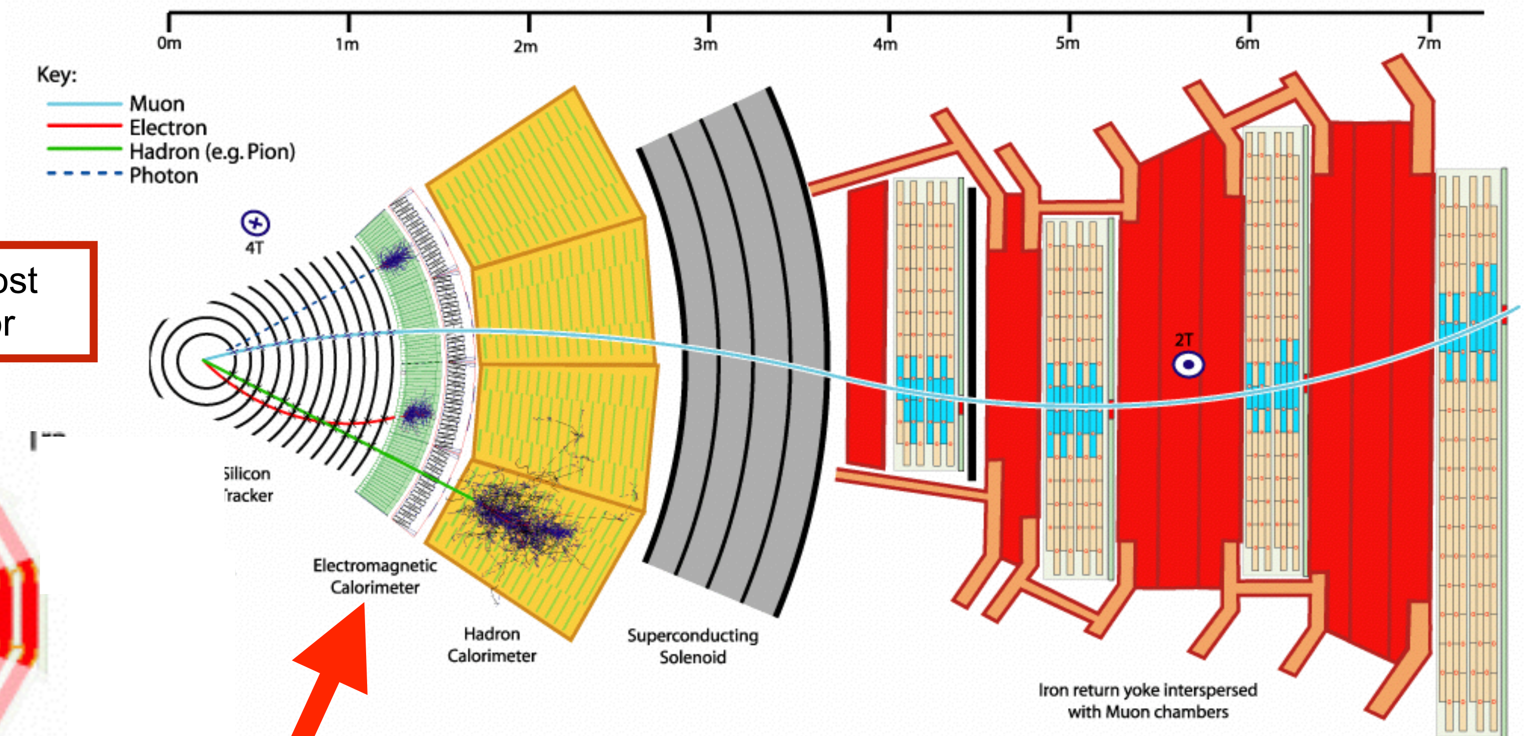
HEP Detector Overview

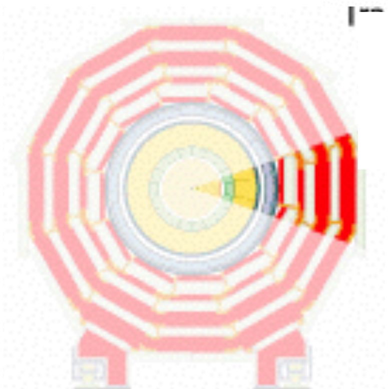
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

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

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

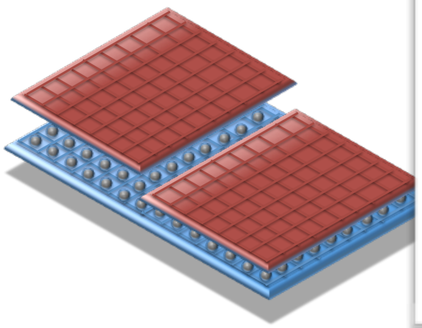
Trend in tracking detectors: pixellised detectors installed very close to the beam interaction region

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

Figure of merit for the VXD:
Impact Parameter Resolution

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

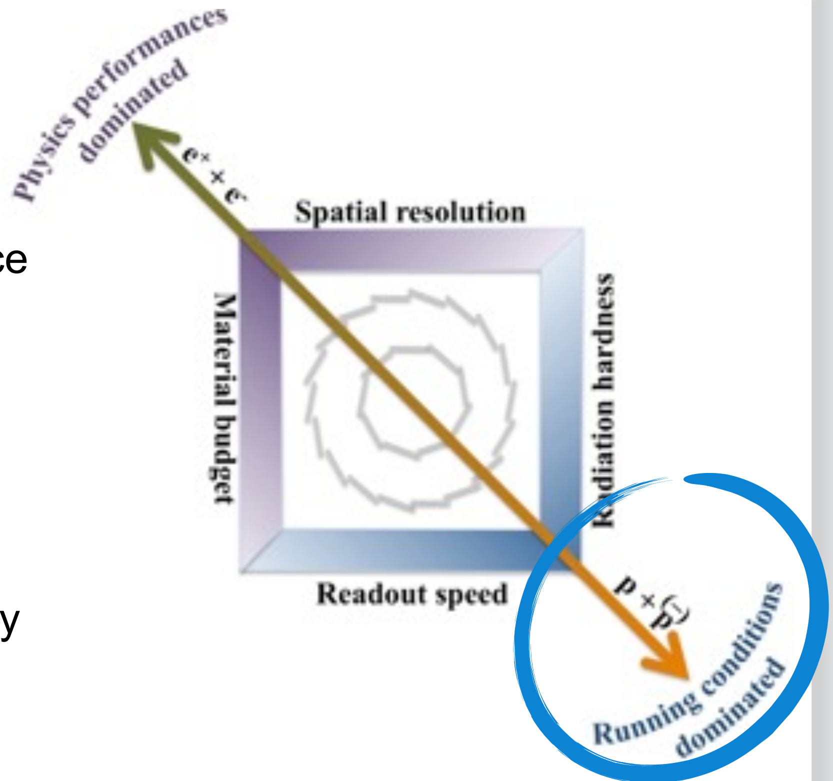
Accelerator	a (µm)	b (µm)
LEP	25	70
Tevatron	10	40
LHC	<12	<70
RHIC-II	12	19
ILC/CLIC	<5	<10



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

Optimising = Compromising

- Conflict between physics performance 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
    - ➡ limitations from highest data flow acceptable by DAQ



- Ultimate performance **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)

Performance Improvement

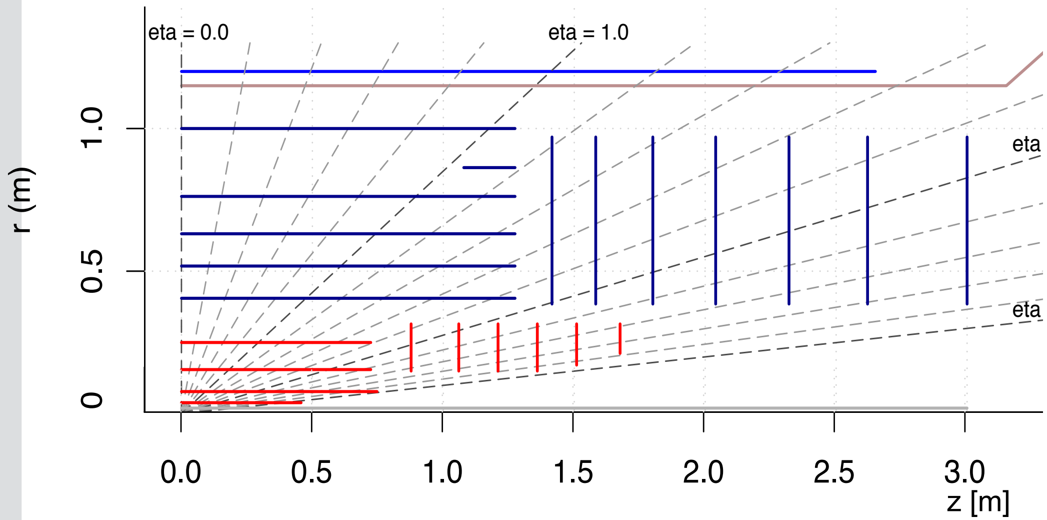
	Increase granularity at large radii	Increase granularity close to the IP (small pixels)	Increase number of pixellated layers	Reduce material
Fast and efficient pattern recognition in high pileup	ATLAS, CMS	ATLAS, ALICE, CMS, LHCb	ALICE, CMS, LHCb	
Improve momentum resolution at low pT				ATLAS, ALICE, 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

Pixels for HL-LHC

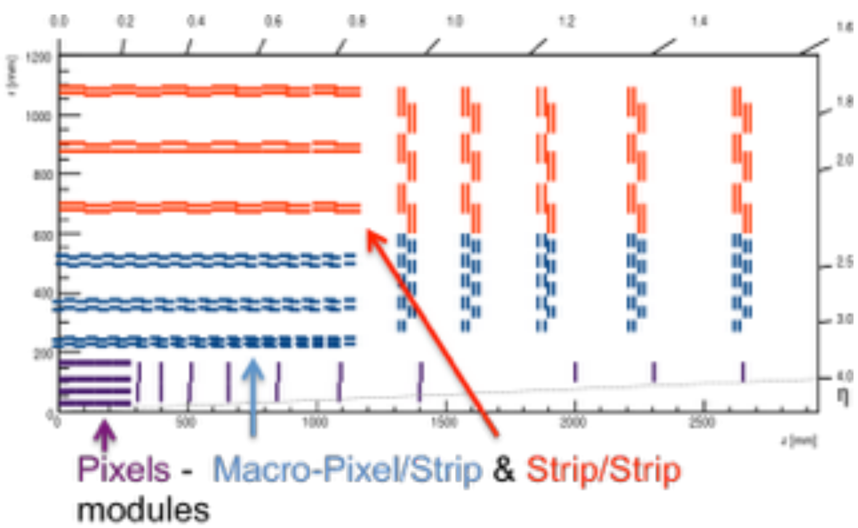
- HL-LHC: upgrade of LHC to reach integrated 3000fb-1
- instantaneous luminosity up to $7.5 \times 10^{34}\ cm^{-1}s^{-1}$
- Challenges for pixel detector:
  - radiation damage (factor 10 x LHC)
  - bandwidth, trigger
  - size, production, costs
- "Classic" approach of hybrid pixels is currently baseline for both experiments

		ATLAS	CMS
Pixels	Layers (B+EC)	4 + 6	4 + 10
	Area	8.2 m^2	4.6 m^2
Strips	Layers (B+EC)	5.1 + 7	6 + 5
	Area	**193 m^2**	**218 m^2**

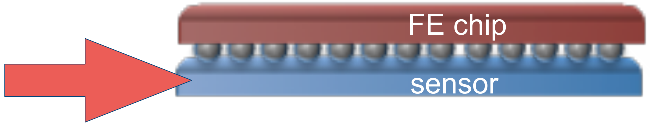
ATLAS



CMS

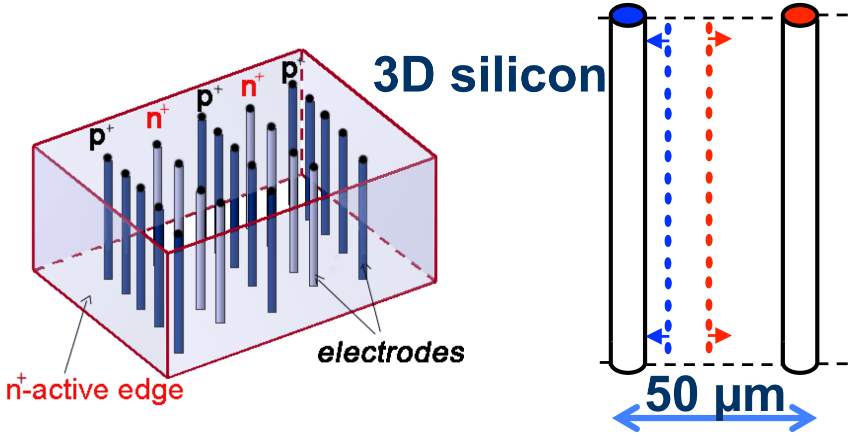


NEW TECHNOLOGIES

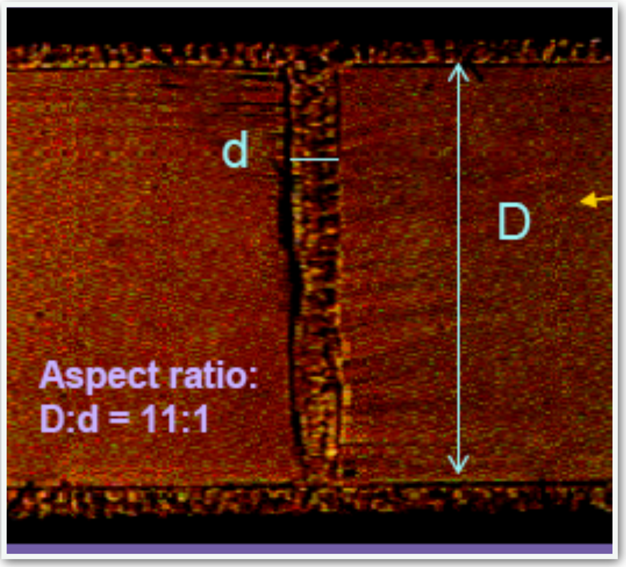


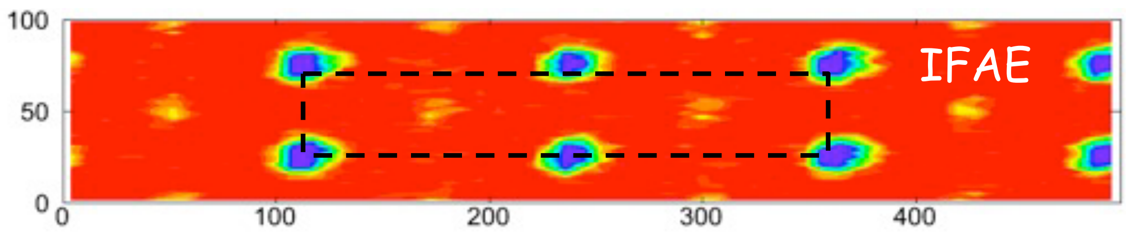
3D Silicon

- Both electrode types are processed inside the detector bulk
- Charge collected by implants in pixels
  - max. drift and depletion distance set by electrode spacing
  - reduced collection time and depletion voltage
  - low charge sharing
  - lower leakage current and power dissipation
  - radiation tolerant



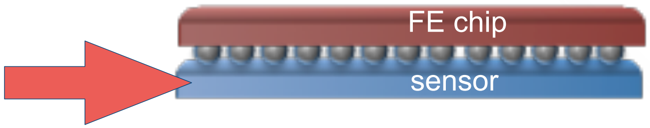
- First use case -> ATLAS IBL





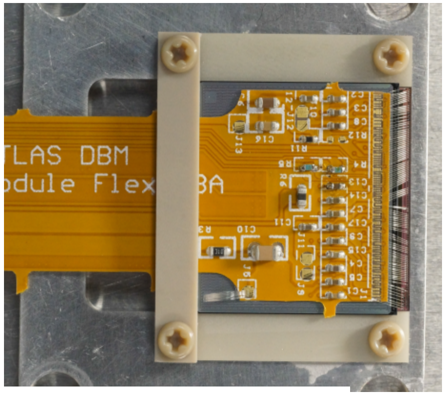
Efficiency measured at test beam

New Technologies

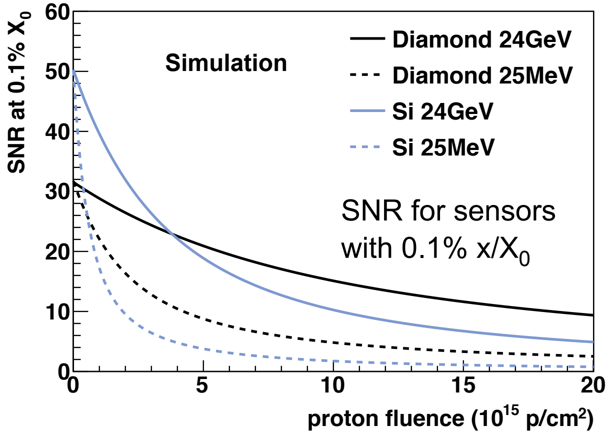


Diamond Sensors

- Chemical vapor deposition (CVD) diamond
  - band gap 5.5 eV (silicon: 1.1 eV)
  - displacement energy 42 eV/atom (silicon: 15 eV)
  - only 60% as many charge carriers as silicon
  - radiation tolerant
  - low Z



- Some issues:
  - availability (only two suppliers)
  - reduced charge collection after irradiation
  - difficulties with bump bonging



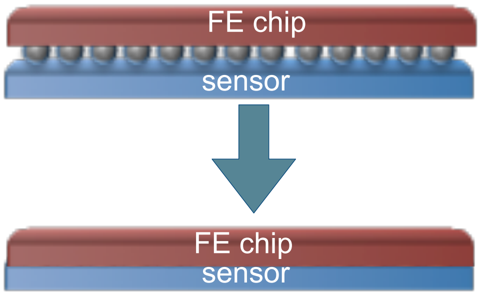
arXiv:1206.6795

- Used in ATLAS and CMS beam monitoring, current and replacement
- Diamonds remain an option for inner pixels (HL-LHC)
  - fluences in excess of 10^{16} n_{eq} show acceptable signal degradation
  - stable operation at low thresholds (1000e or lower)
  - sensor supply suitable for 1-2 m² should be possible

Future:
Combination of 3D and pCVD

New Alternative: CMOS

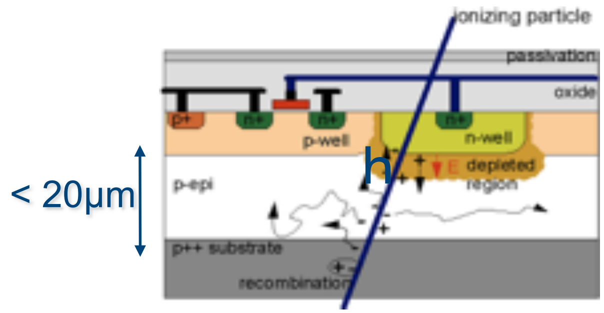
- Use of commercial CMOS technologies for replacement of sensor or even full hybrid (monolithic)
  - possible advantages: integration, cost, power consumption and material budget
  - currently in two experiments: DEPFET in Belle-II and MAPS in STAR but only for moderate radiation suited



Monolithic = front-end electronics on same substrate as active sensor

- Classical CMOS sensors:
  - typically no backside processes
  - signal charge collection mainly by diffusion -> moderate radiation tolerance (Diffusion is suppressed by trapping < 10^{15} n_{eq}/cm^2)

Main **challenge for HL-LHC**: need combination of
- tolerance to displacement damage (depletion)
- integration of complex circuitry without efficiency loss
- keep using commercial technology

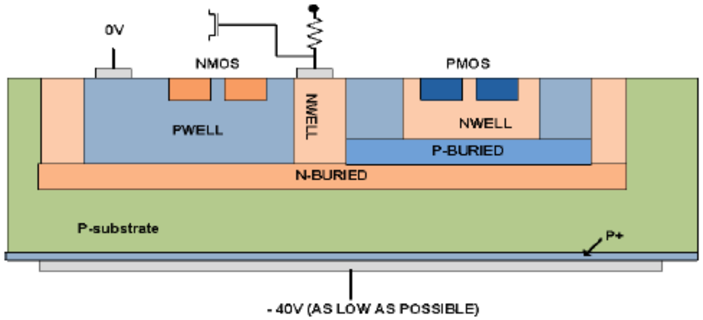


"Classic" CMOS sensor based on diffusion Mimosa

Pixel: $10^{16} n_{eq}/cm^2$
Strips: $10^{15} n_{eq}/cm^2$

HR/HV CMOS

- HV/HR-CMOS: in pixel collection electrodes plus readout circuitry
- Depletion either through high voltage (HV) or high resistivity substrate (HR)
- Charge is collected by drift, good for radiation tolerance
- But: risk of coupling circuit signals into input -> careful design required
- Being followed up by ATLAS (pixels and strip); CMS starting to look into it



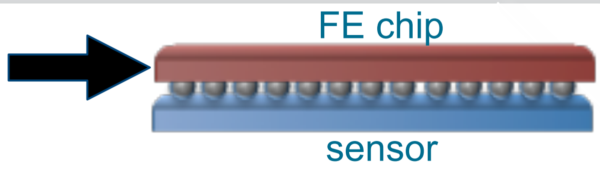
- Current results are very **encouraging**
  - indication of good radiation tolerance
  - optimisation of signal and efficiency is one of next steps

Example:

A technology which could be used to build a **dream** tracker:

- fully monolithic but radiation hard
- high resolution
- thin material
- cost effective

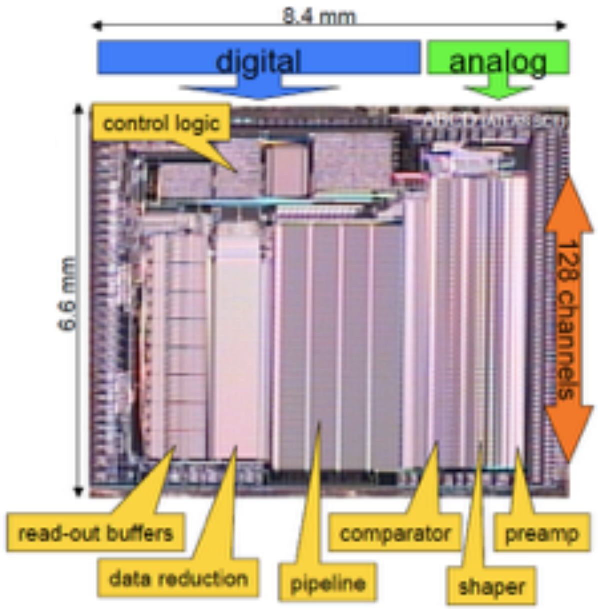
FE Chip Developments



- Modern chip technologies enable
  - high channel density
  - pre-amplification, data storage etc. very close to the detector
  - reduced noise
  - low power dissipation
  - industrial production

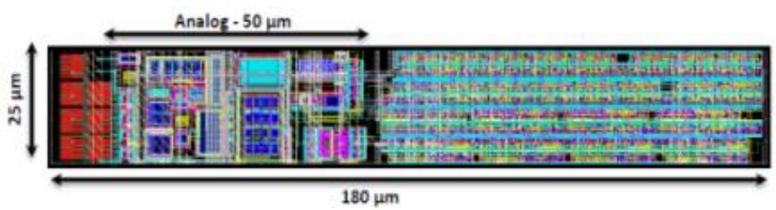
- integration density is growing rapidly

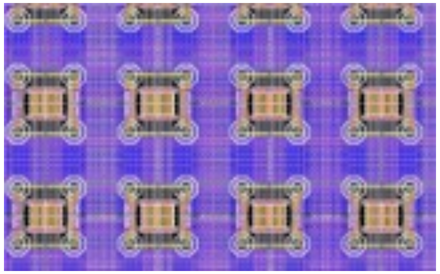
- Need fine lithography ASIC technology to allow pixel sizes of as small as ~50µm×50µm



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



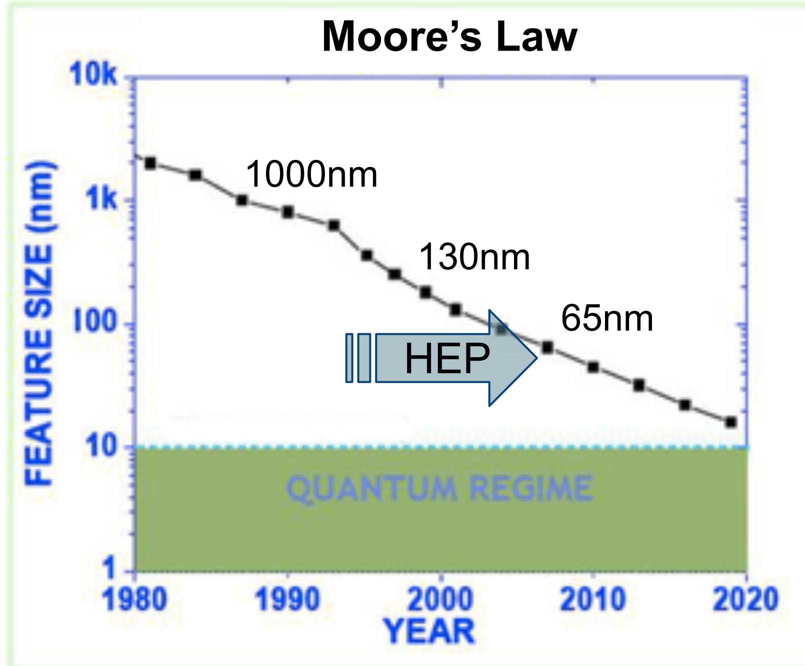


CERN RD53

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

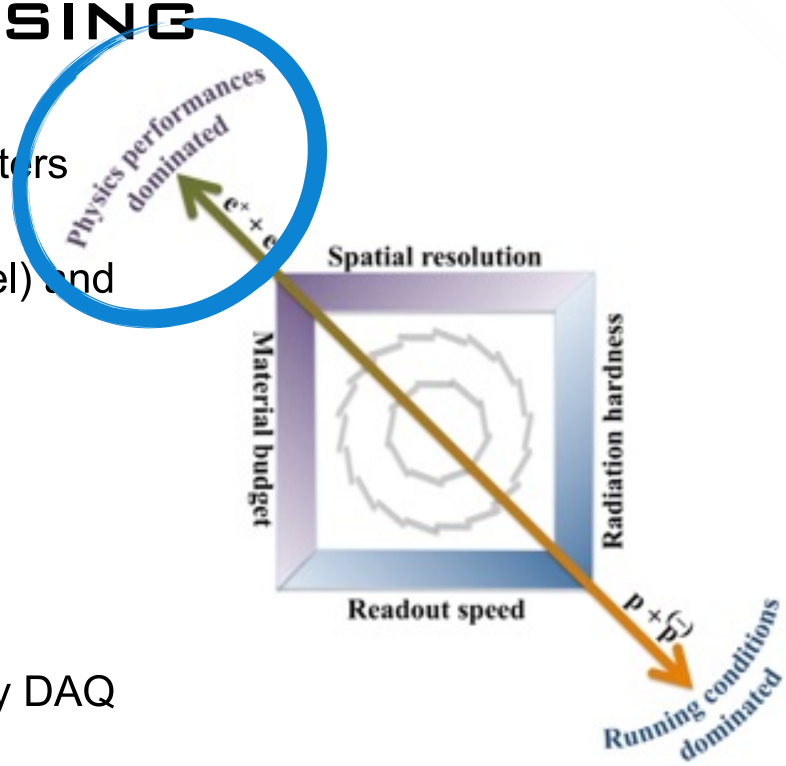


Feature Size [nm]	2000	1200	800	500	350	250	130	65	35	20
Minimum NMOS										

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

Optimising = Compromising

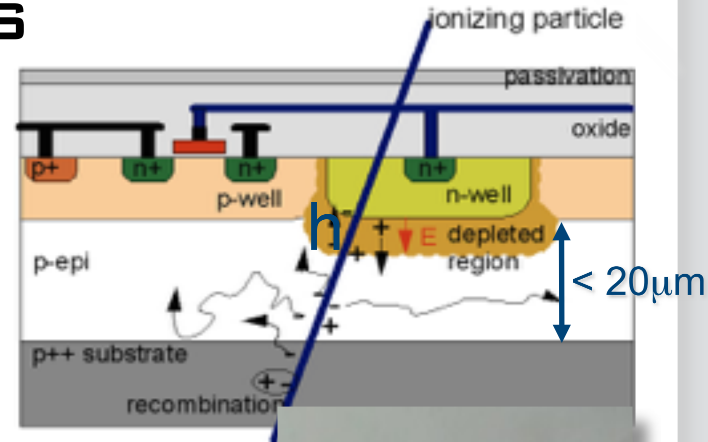
- Conflict between physics performance driven parameters and running condition constraints:
  - Physics performance: spatial resolution (small pixel) and material budget (thin sensors) + distance to IR
  - Running conditions: read-out speed and radiation tolerance (HL-LHC: 10 times LHC)
  - Moreover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



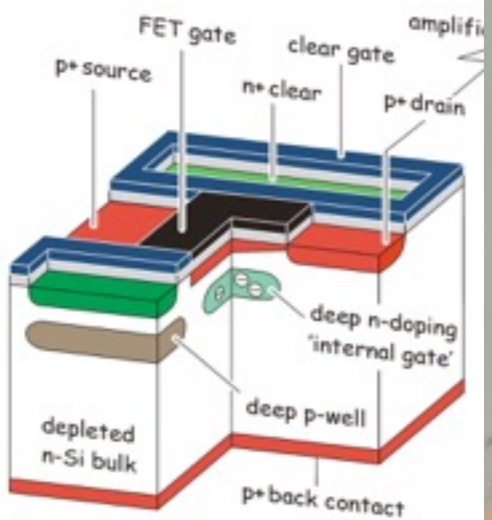
- Ultimate performance on all specifications cannot be reached simultaneously
  - each facility & experiment requires dedicated optimisation (hierarchy between physics requirements and running constraints
  - there is no single technology best suited to all applications
  - explore various technological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

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?



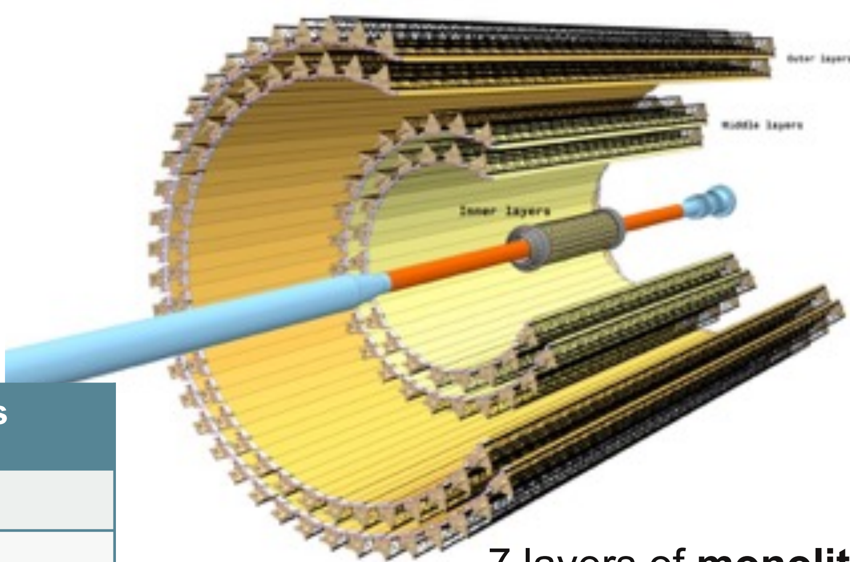
Example:
Mimosa MAPS



DEPFET

Example: ALICE ITS Pixel Detector

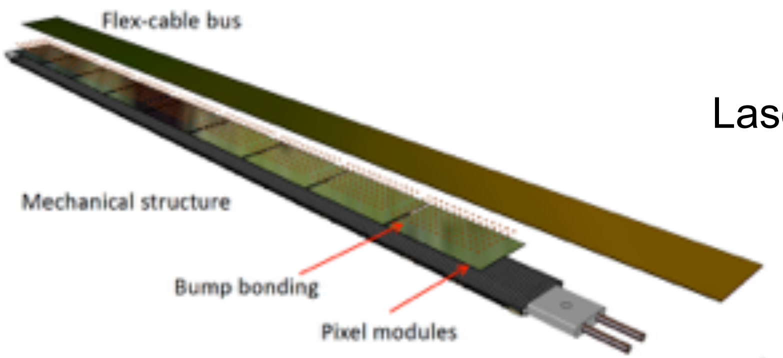
- Improve impact parameter resolution by a factor of 3
- Improve standalone tracking capability and p_T resolution by means of increased granularity
- LHC environment (radiation) with ILC like requirements …



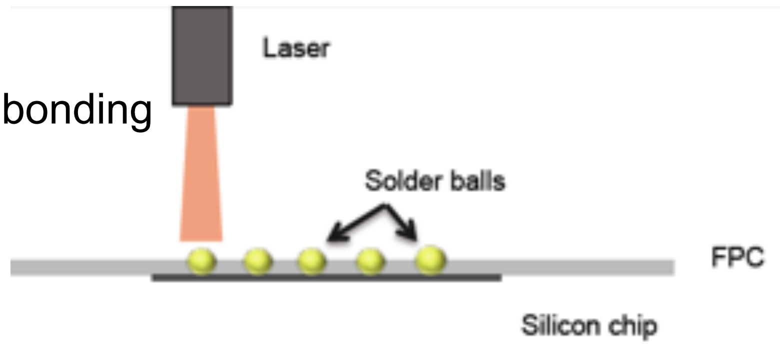
7 layers of **monolithic pixel** detectors

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 x 10^{13}	3 x 10^{10}

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

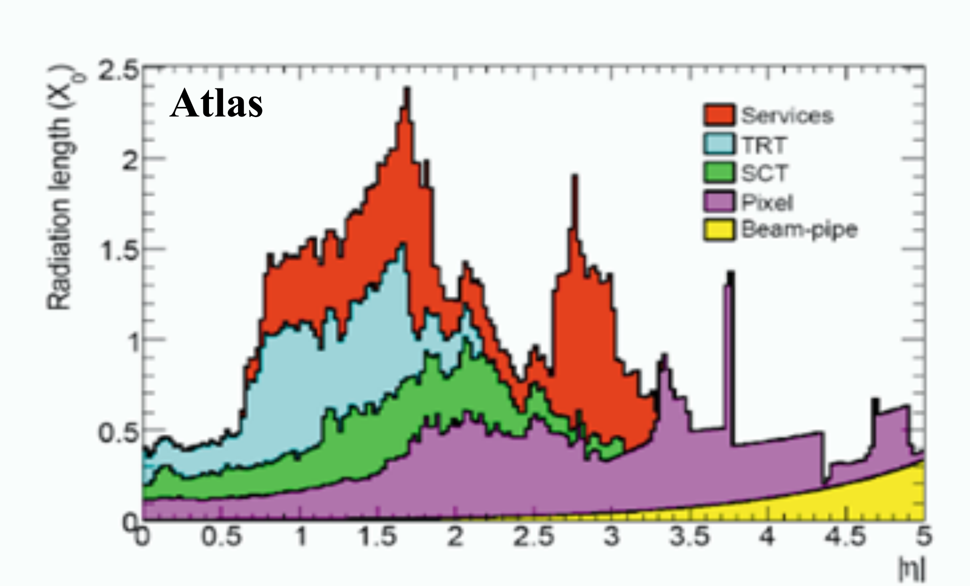


Laser bonding

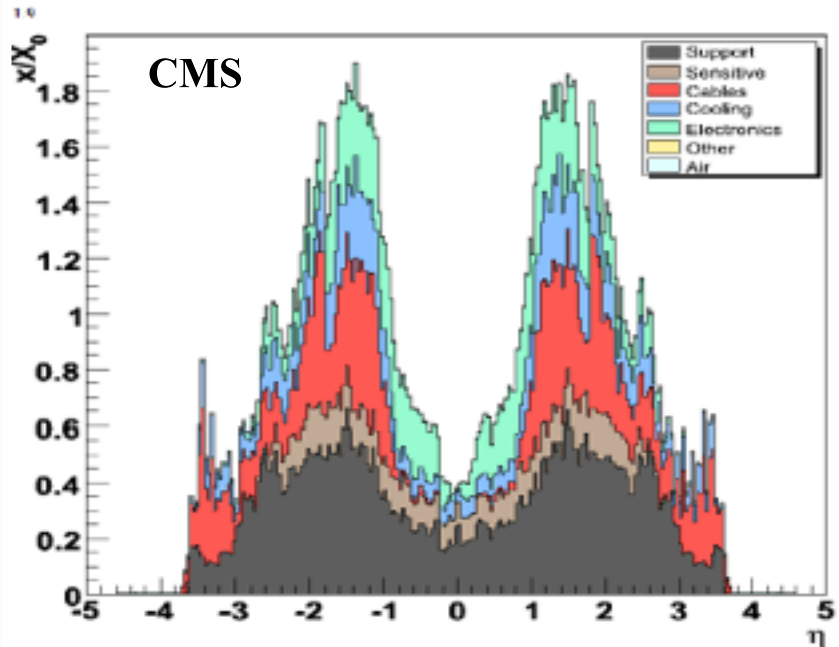


Another Challenge ...

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



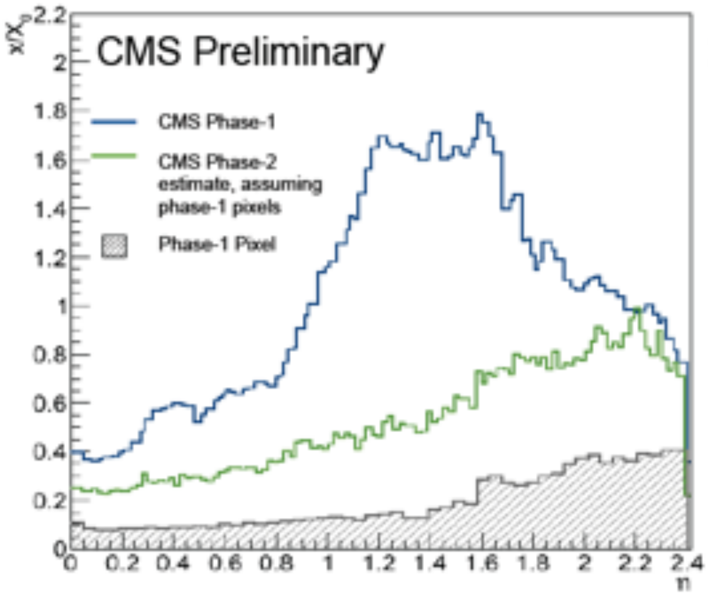
$\lvert\eta\rvert$	radiation length	interaction length
< 1	$\sim 0.2\,X_0$	$\sim 0.05\,\lambda$
< 3.3	$\lesssim 0.5\,X_0$	$\lesssim 0.2\,\lambda$



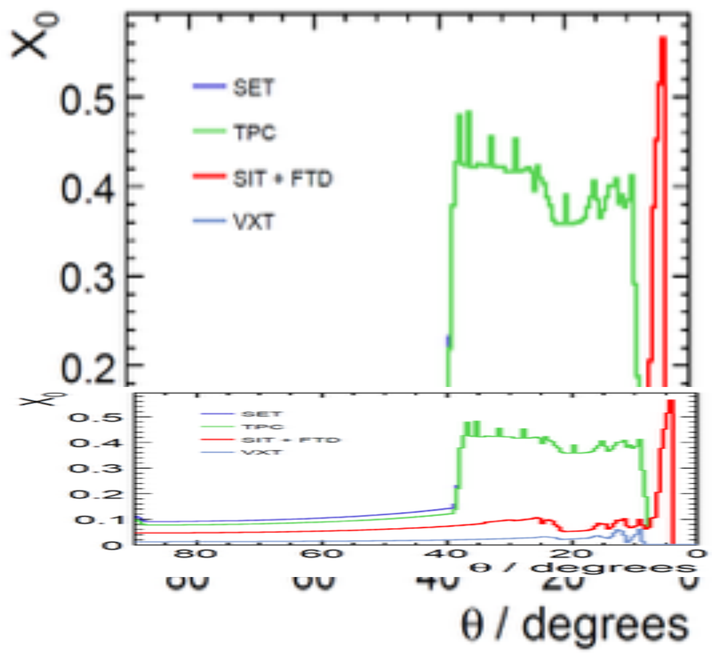
Old argument that Silicon would be too thick is not really true ==> **power & cooling**

The Material Challenge at ILC

CMS tracker upgrade scenario:
reduce by factor 2

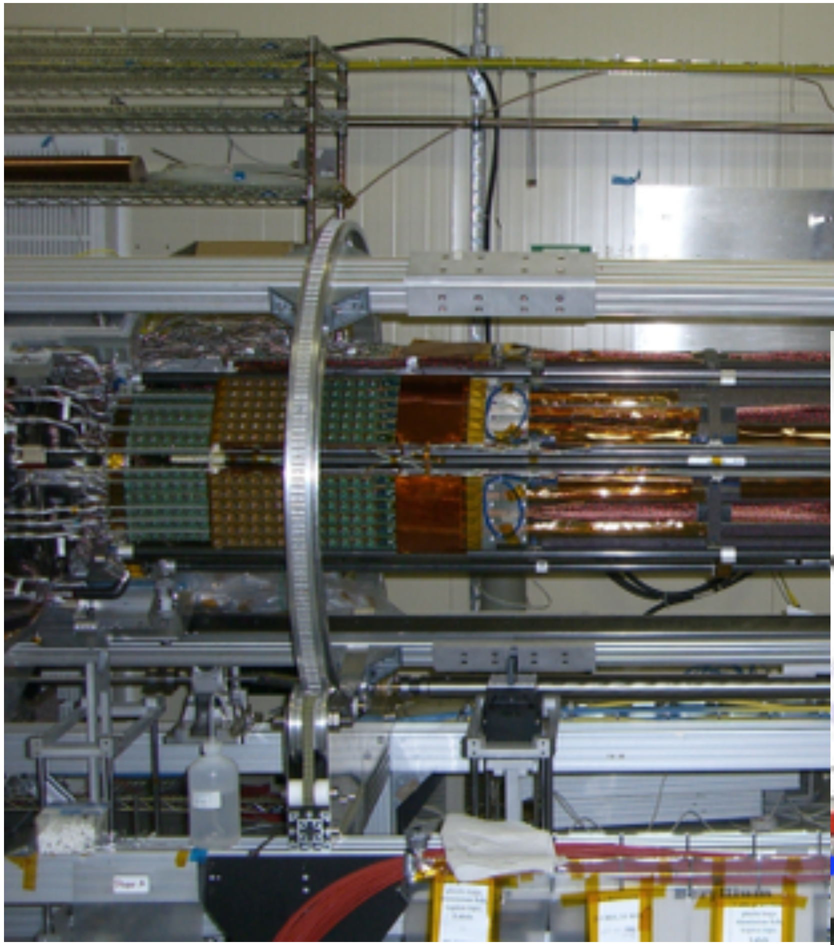


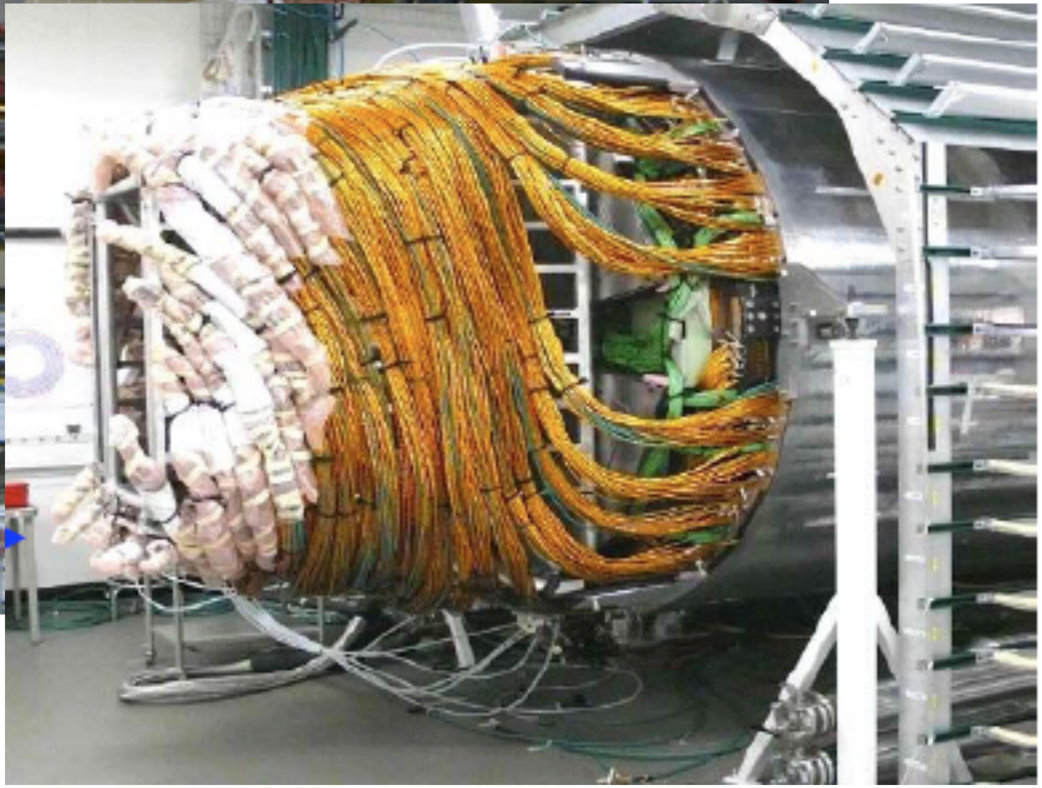
ILD estimate



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

Services = Material



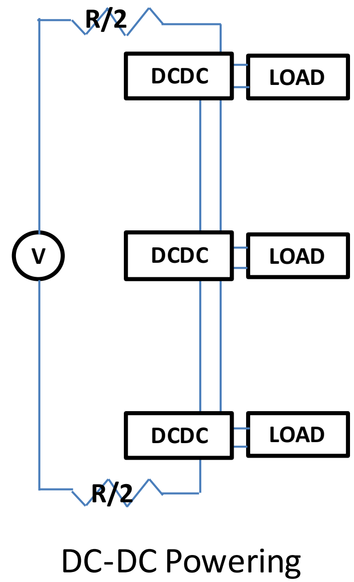


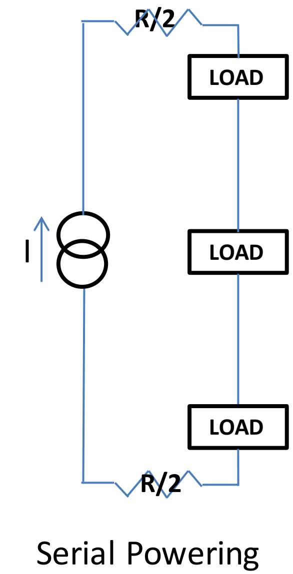
Powering (HV and LV)

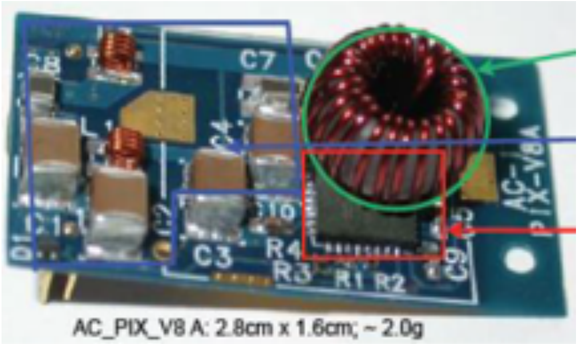
- General problem but most difficult for innermost tracking detector as all “services” (cables, cooling…) are additional material in front of the calorimeter -> need to reduce material
- But: each sensor needs to be biased separately (HV), each front-end chip powered (LV)….
  - ATLAS pixels: each module ~70kg cables

- LHC tracking detectors increase of channel -> not even the space for all services
- ILC tracking detectors -> very limited material budget

- Advanced powering schemes needed.



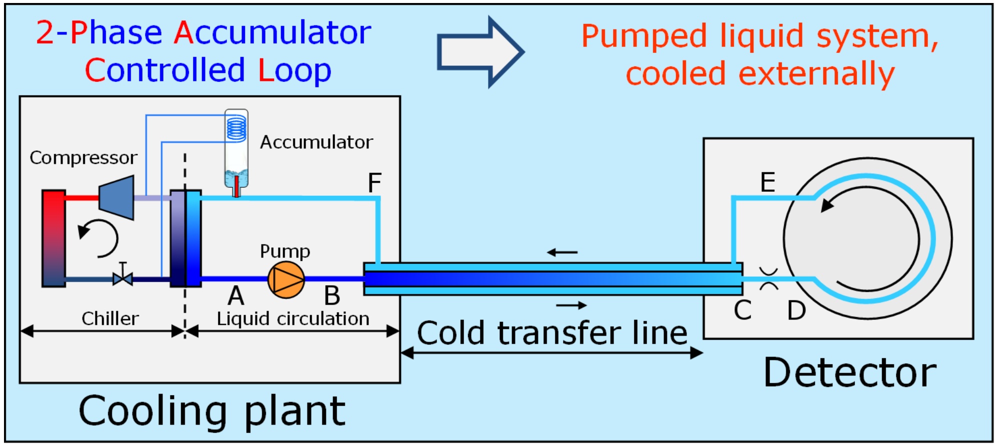


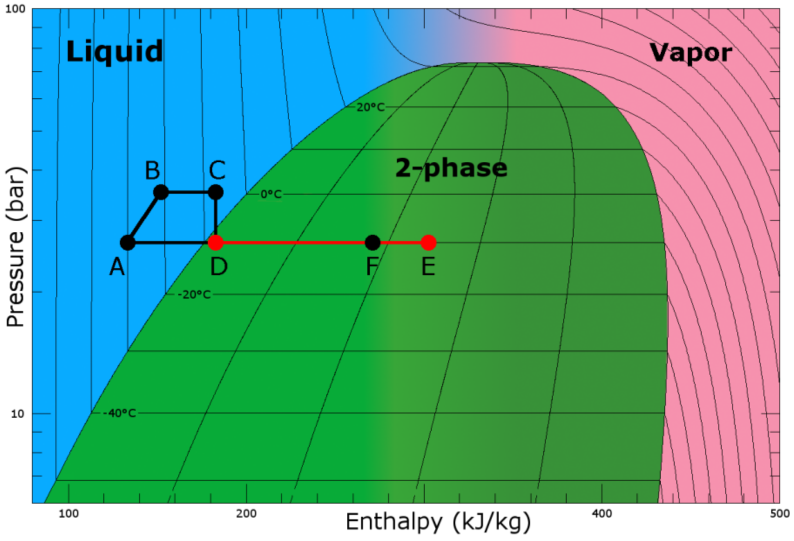


Both concepts allow massive reduction of power cables. Choice of concept is strongly depending on the specific requirements of the detector in planning.

Cooling

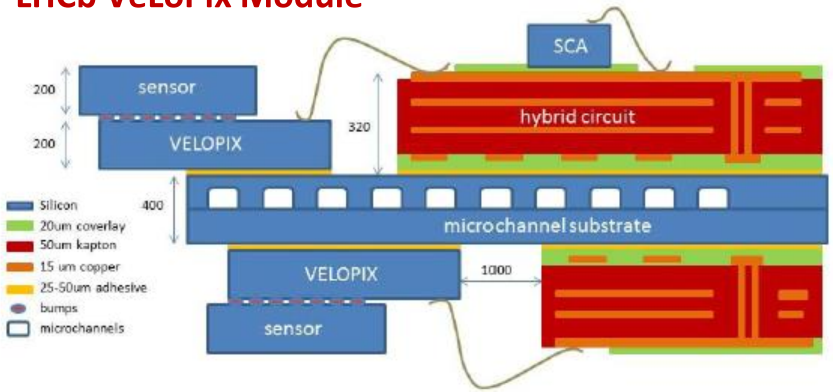
- LHC detectors need to cool silicon sensors extremely low
  - CO_2 cooling current solution
  - low material high pressure cooling circle





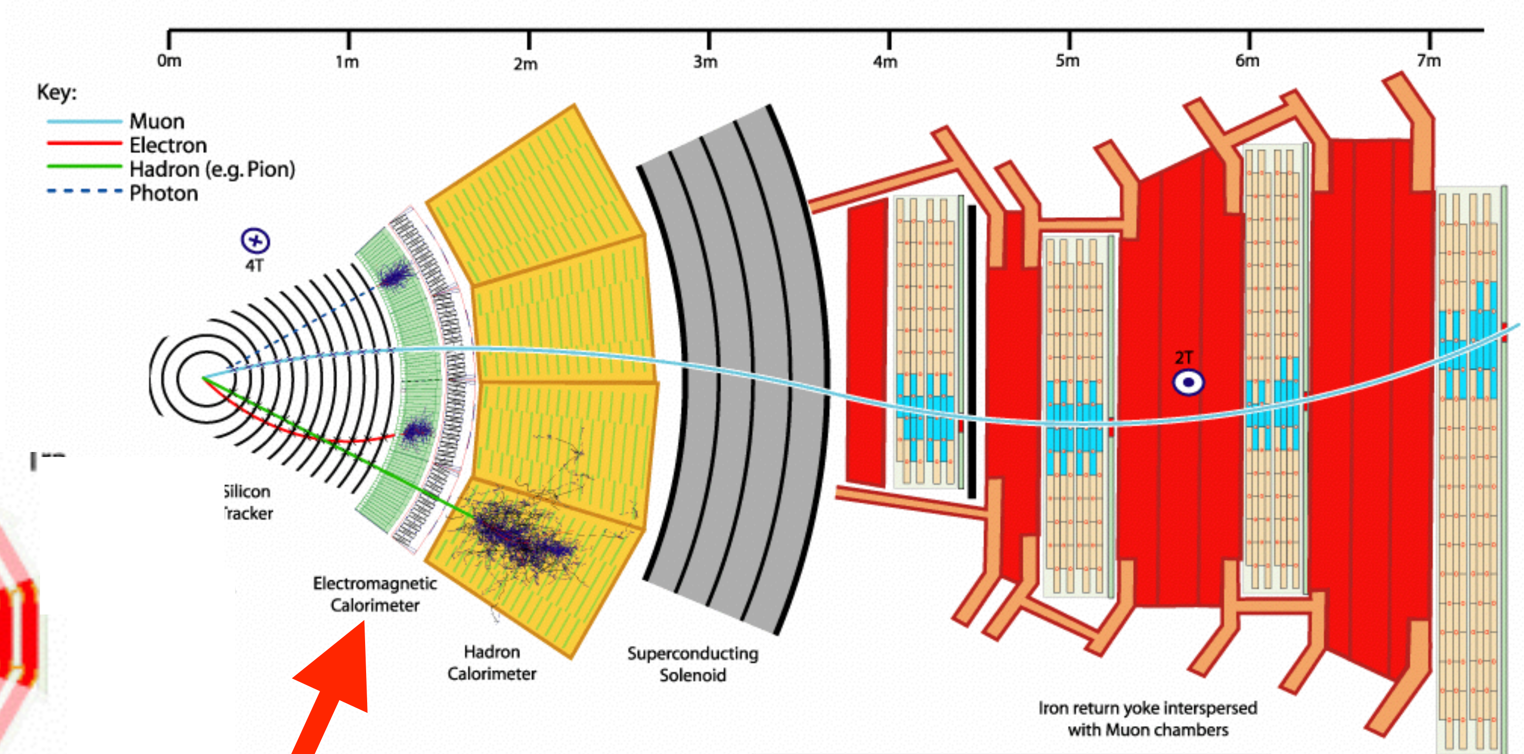
- Micro-channel cooling for some detectors a solution
- for non-LHC detectors air cooling an option:
  - low mass
  - sufficient for ILC/ CLIC conditions?

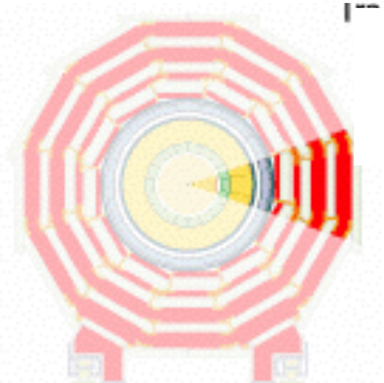
LHCb VeLoPix Module



Particle Physics Detector Overview

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





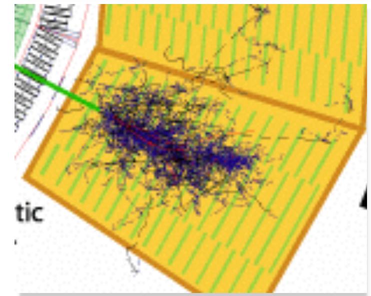
Transverse slice through CMS

Good energy resolution up to highest energies

Radiation hard (hadron collider)

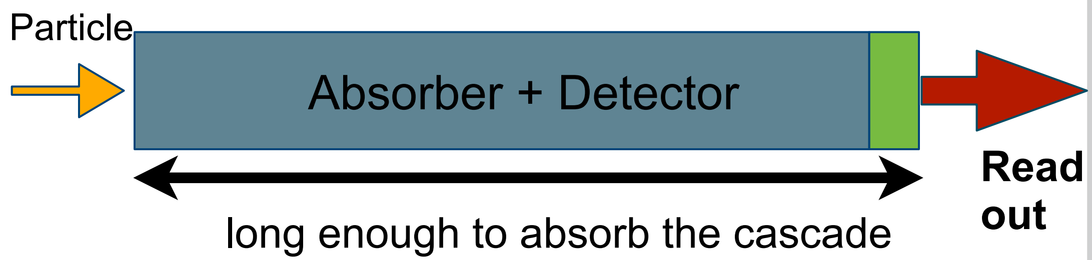
picture: CMS@CERN

Calorimeter Recap

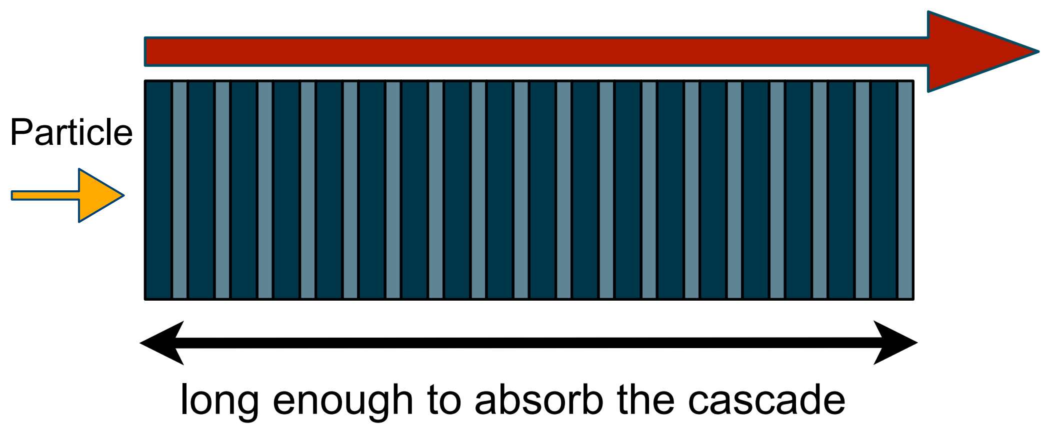


- Energy measurement of photons, electrons and hadrons through total absorption
  - Particles release their energy in matter through production of new particles => shower
  - Number of particles in shower is proportional to the energy of the incidental particle
- Two different types of calorimeters are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

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



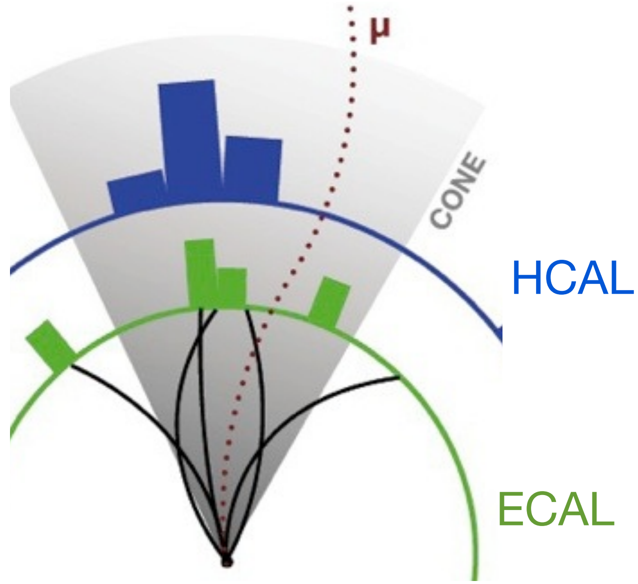
- **Sampling Calorimeter**
  - A layer structure of passive material and an active detector material
  - Only a fraction of the deposited energy is "registered"

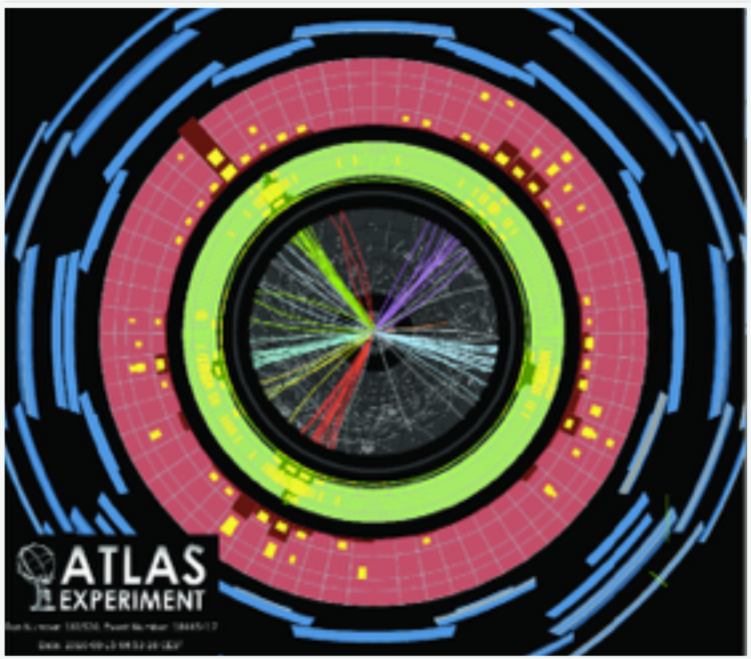


Current Frontiers in HEP Calorimetry

- 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



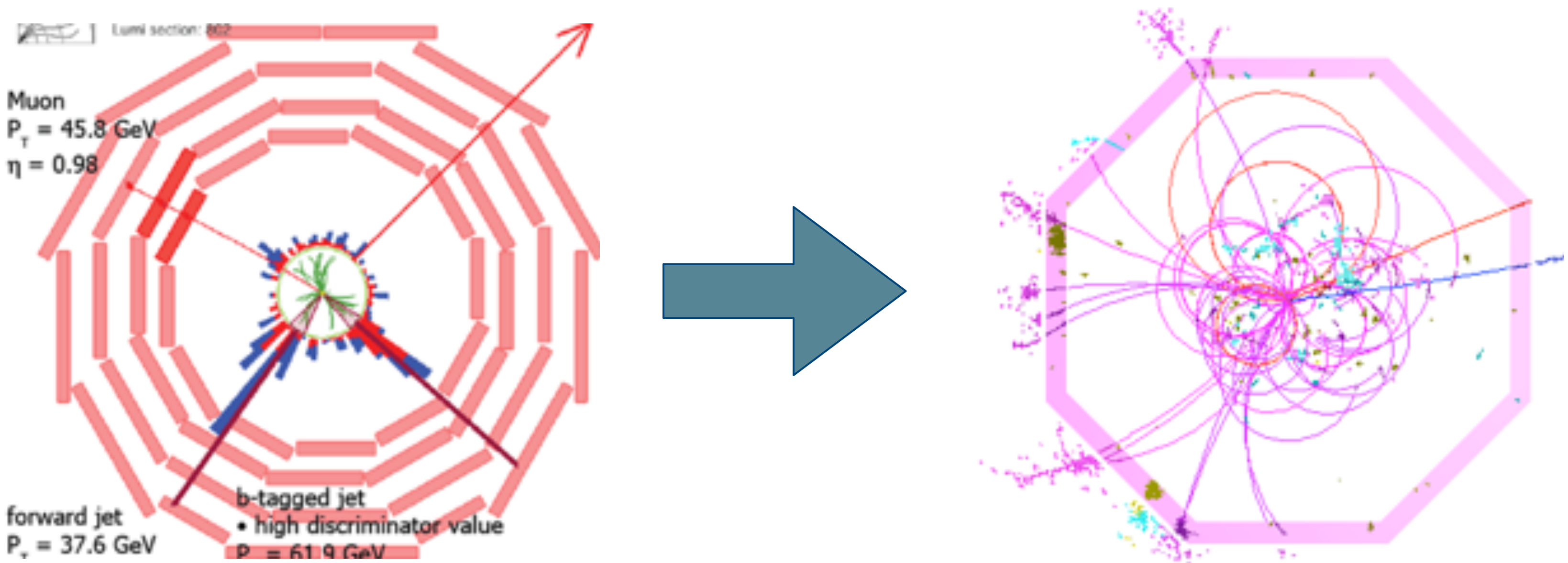


The limitations:

- 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

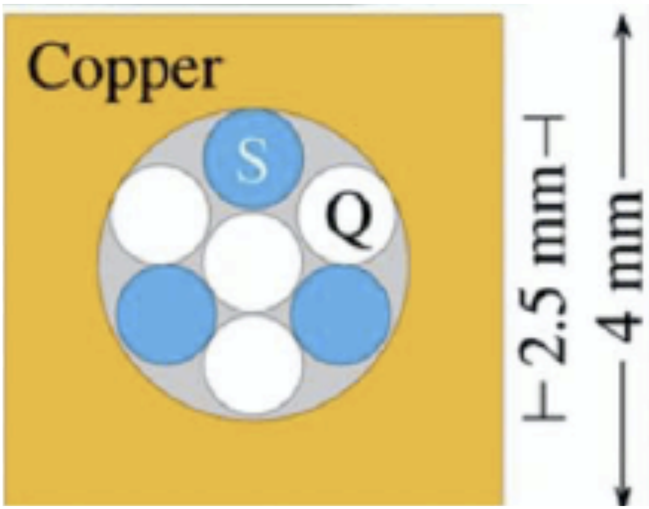
- The goal for next-generation experiments: A quantum leap in jet energy resolution:
  - A factor ~2 improvement compared to current state of the art
    - Motivated by the requirement to separate heavy bosons W, Z, H in hadronic decays
- **Two approaches:**
  - Substantial improvement of the energy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

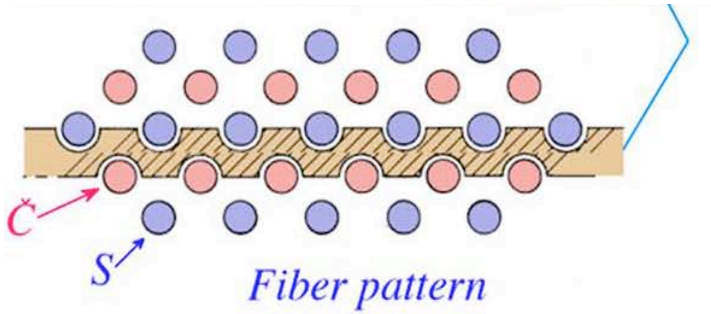


The DREAM Principle

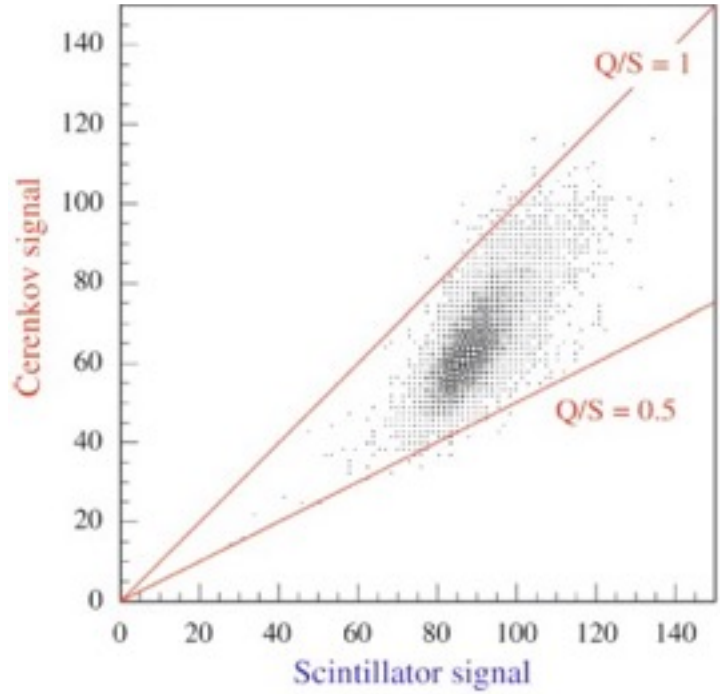
- **Dual readout module**: Two active media
  - Scintillating fibers: Sensitive to all charged particles in the shower
  - Quartz Cherenkov fibers: Sensitive to relativistic particles: EM only
- Very different e/h: S ~ 1.4, Q ~ 5

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





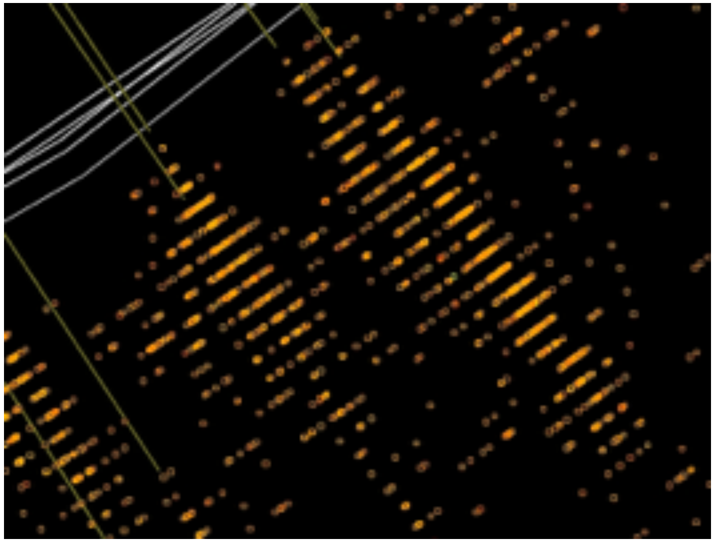
“Super-DREAM”

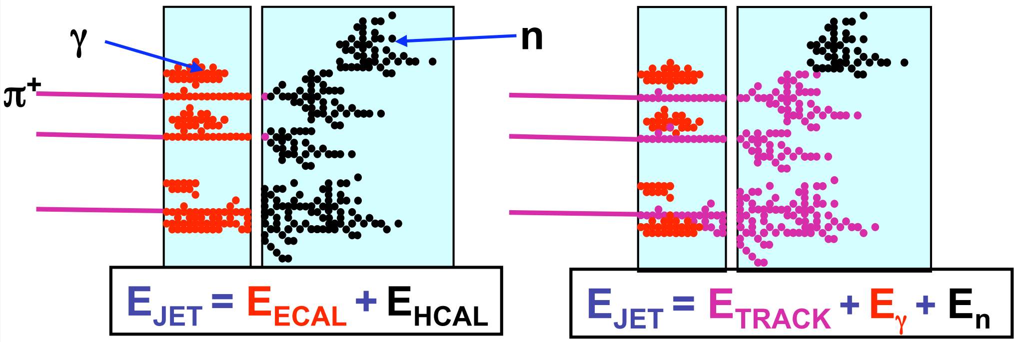


CERN RD52

Particle Flow - Jets from Individual Particles

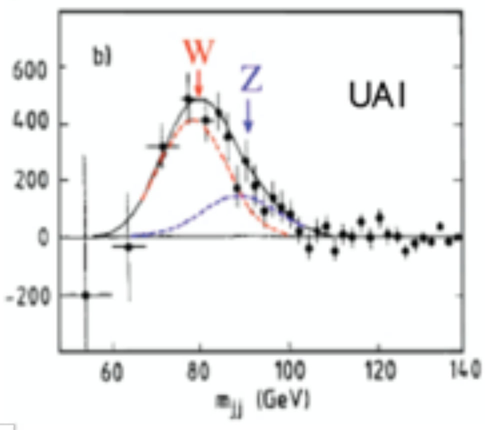
- Improve jet energy reconstruction by measuring each particle in the jet with best possible precision
  - Charged particles tracked by tracker
  - Photons reconstructed in ECAL
  - Neutrons in ECAL and HCAL
- This is supposing that it is possible to disentangle for each particle the deposited energy in the calorimeter.



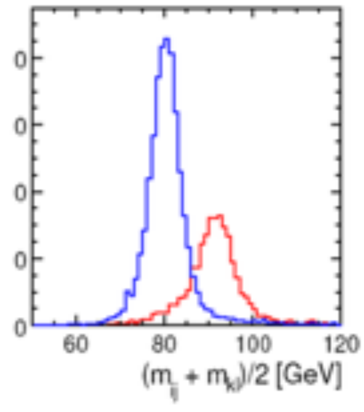


Particle flow = granularity
Optimize relative to particle flow performance

Traditional approach

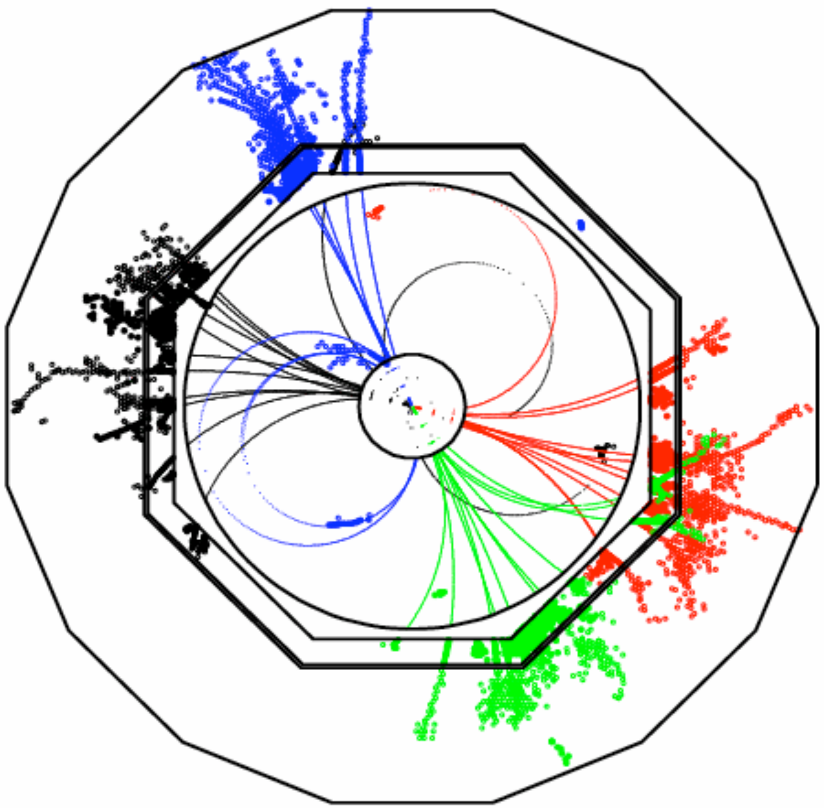


Particle Flow approach



Imaging Cals: Making PFA Happen

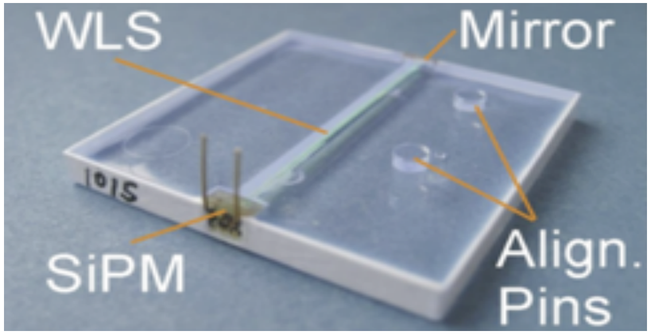
- For best results: High granularity in 3D - Separation of individual particle showers
- Granularity more important than energy resolution!
  - Lateral granularity below Moliere radius in ECAL & HCAL
  - In particular in the ECAL: Small Moliere radius to provide good two-shower separation - Tungsten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

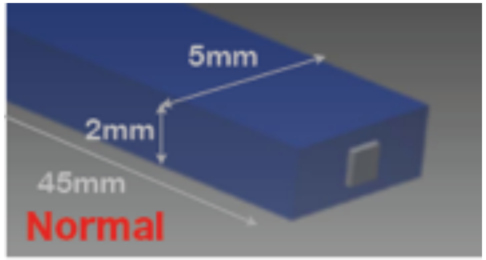


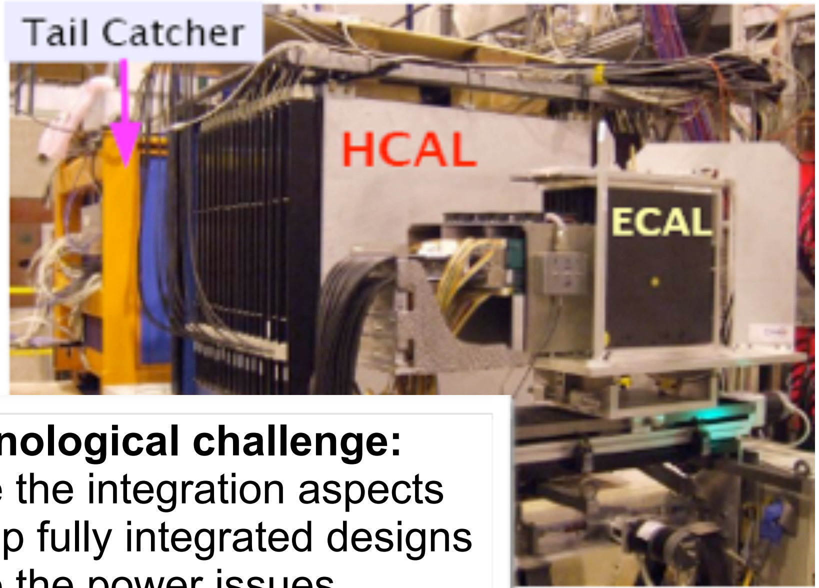
Extensively developed & studied for Linear Collider Detectors: Jet energy resolution goals (3% - 4% or better for energies from 45 GeV to 500 GeV) can be met

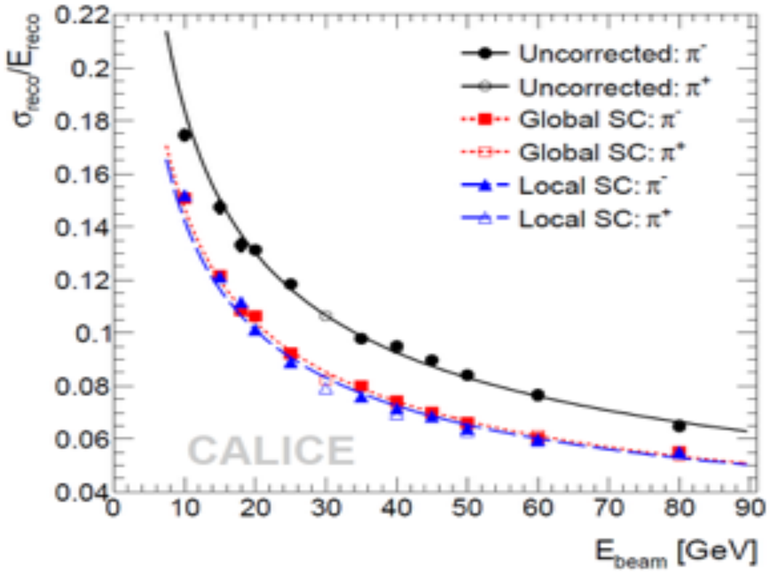
Scintillator Based Calorimeter

- 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$^{1/2}$





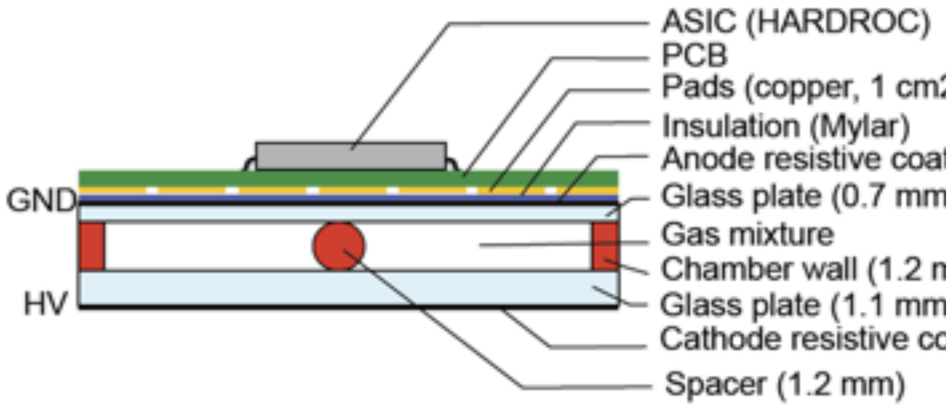




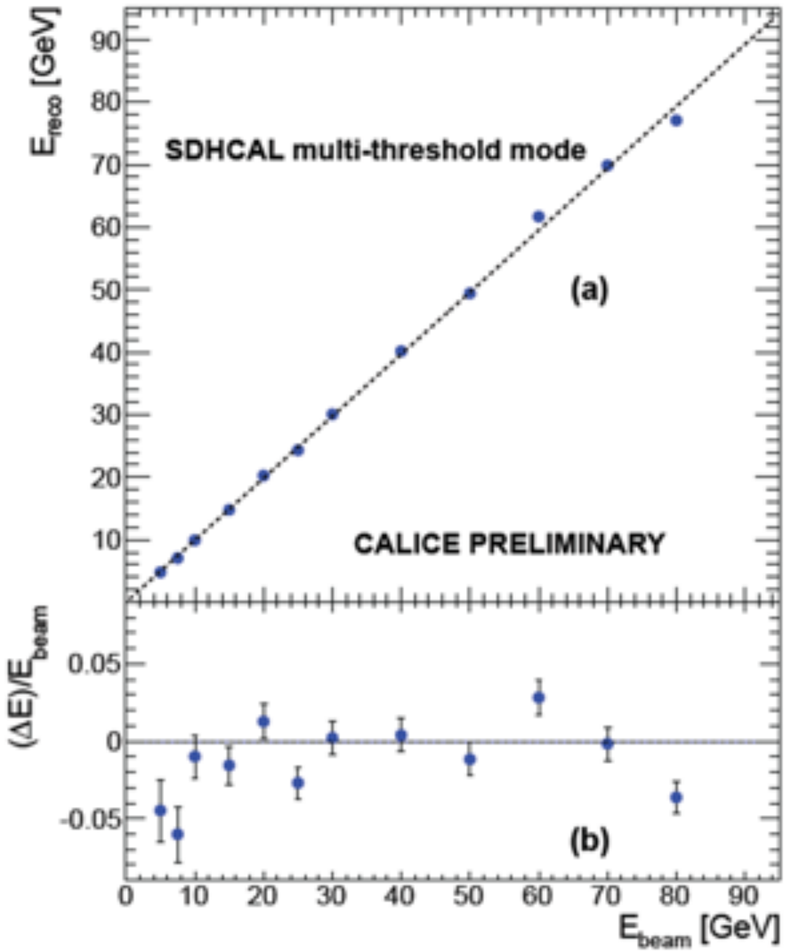
Key technological challenge:
- Handle the integration aspects
- Develop fully integrated designs
- Handle the power issues
- Costs

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.



Test beam results from a large prototype detector



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

Active medium: gas RPC's

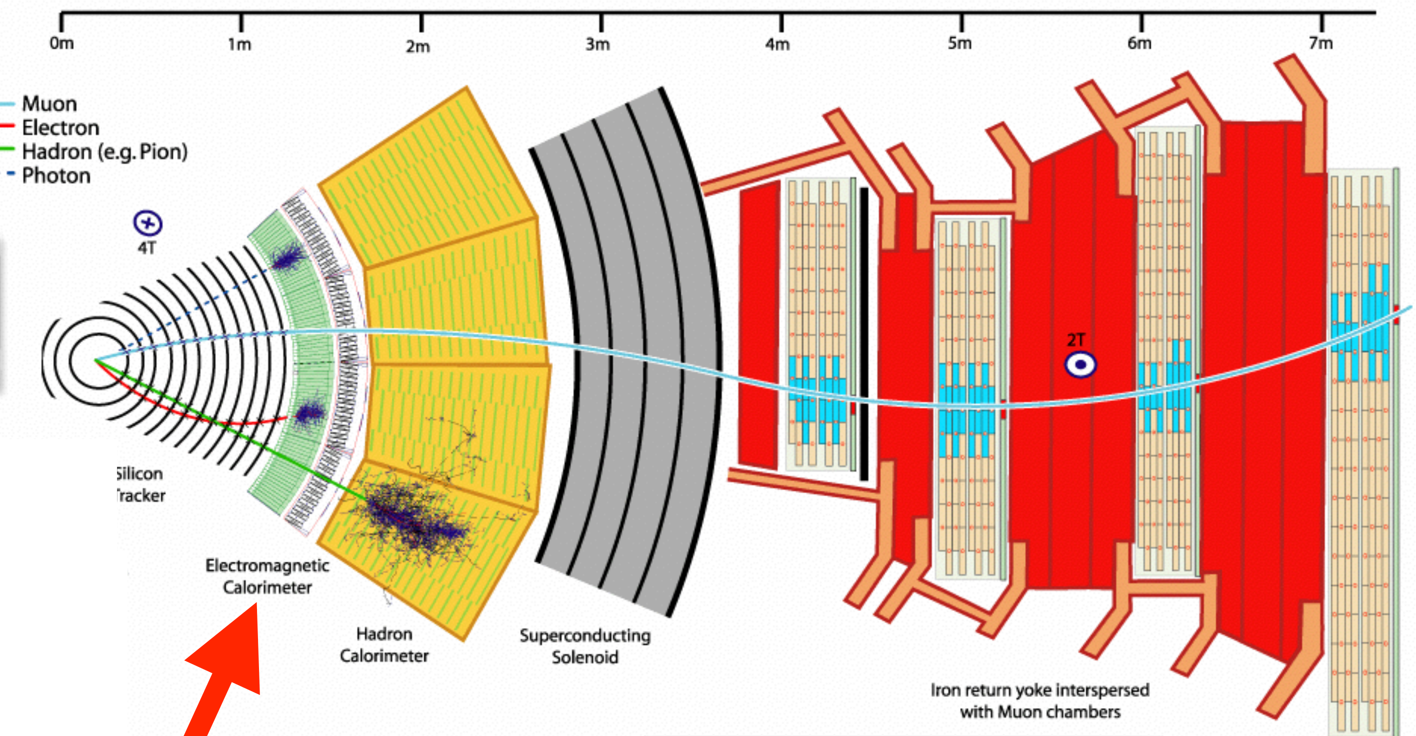
Particle Physics Detector Overview

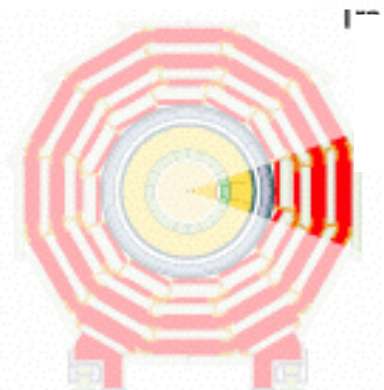
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

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

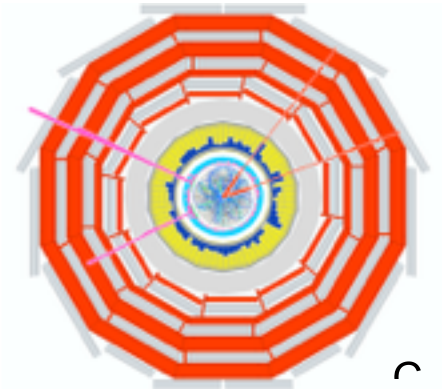
Good energy resolution up to highest energies

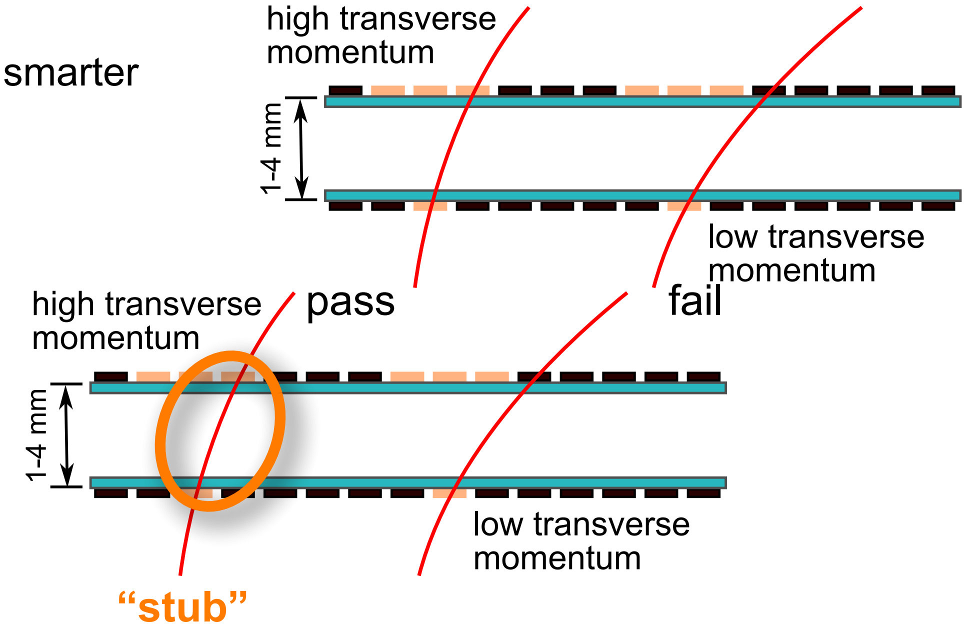
Radiation hard (hadron collider)

picture: CMS@CERN

Track Triggering

- 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





Example: HL-LHC CMS tracker

Data Transfer

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

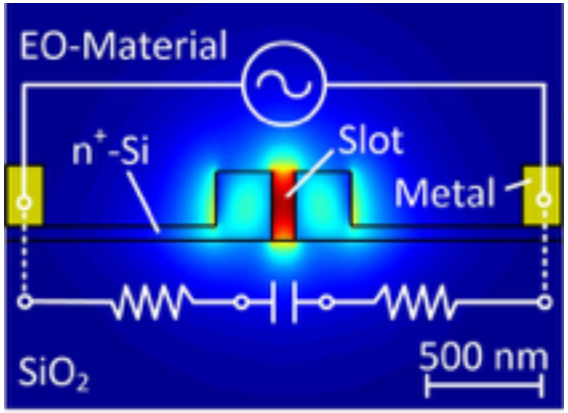
Need high bandwidth compact ways to get the data out: TB/s

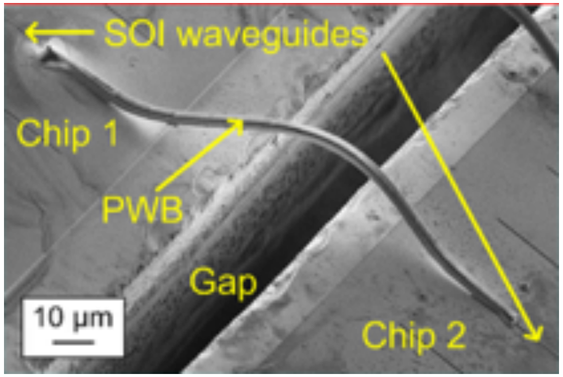
- Use of small feature size ASICs fast (10Gb/s) electrical+optical links with custom devices on-detector (low mass, compact and radiation-hard)
- Also need ever more powerful and more complex FPGAs for data handling
- Where possible send digitised data off-detector for every bunch crossing

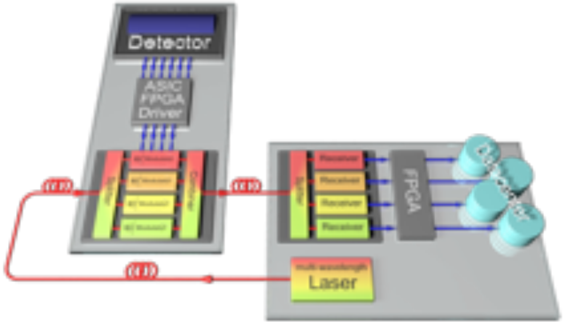
  (40MHz at LHC) leading to ~10^5 Gb/s total bandwidths
- LHCb/ILC detectors: full triggerless operation, all data shipped to data acquisition

Integrate optical communication on the chips

Optical transmission on a chip: waveguides



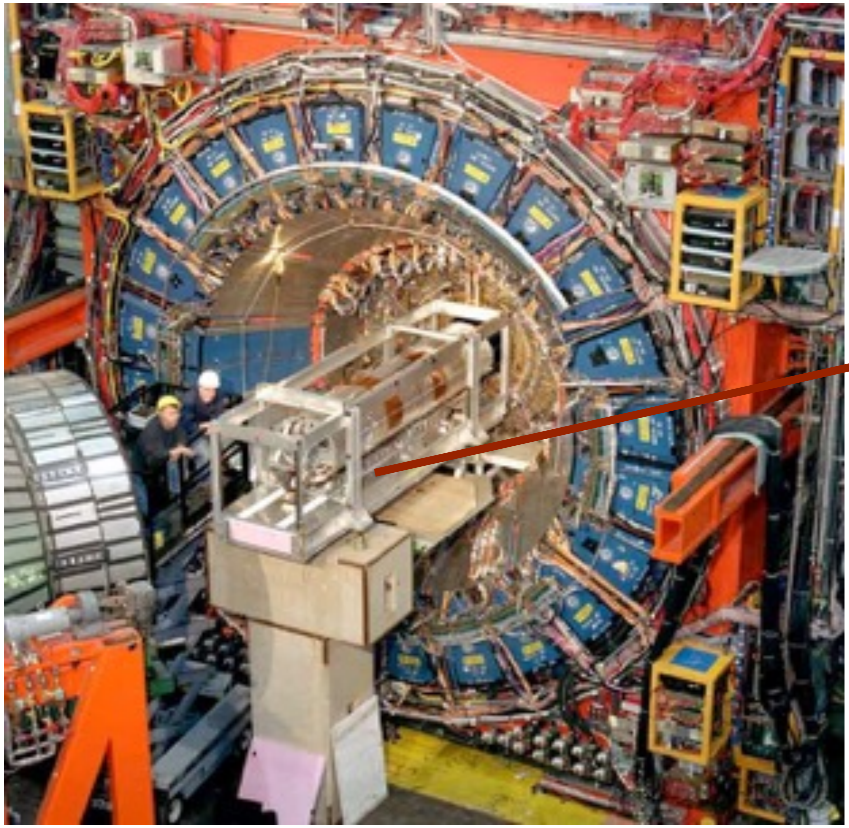


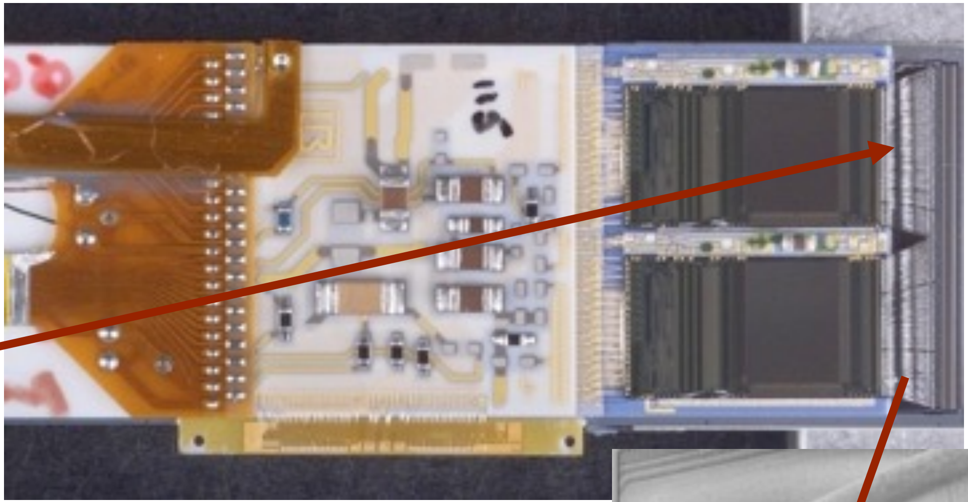


V. Real Life Examples And What Can Go Wrong ...

Problems with Wire Bonds (CDF, D0)

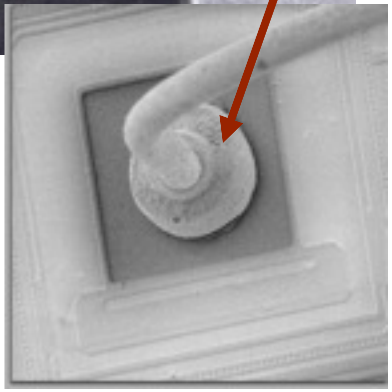
- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- During test pulse operation, Lorentz force on bonding wires (perpendicular to magnetic field) …





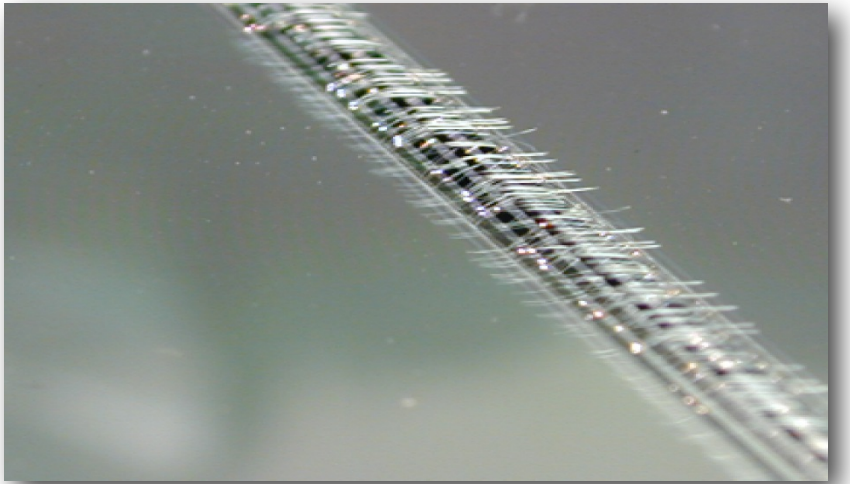
…breaks wire bonds between detector and read out.

during running

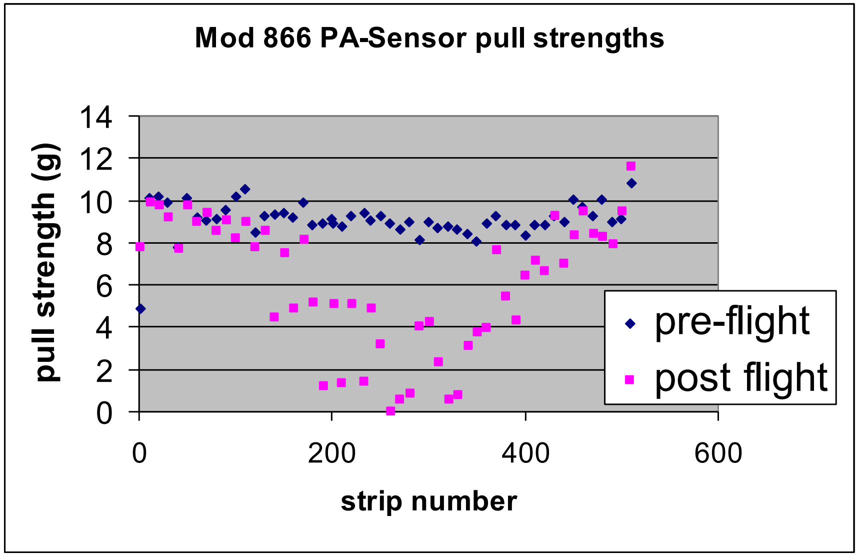


More Wire Bond Wreckage

- Quality of wires is tested by pull tests (measured in g)
- During CMS strip tracker production quality assurance applied before and after transport (via plane)
- Wire bonds were weaker after flight
- Random 3.4 g NASA random vibration test causes similar damage



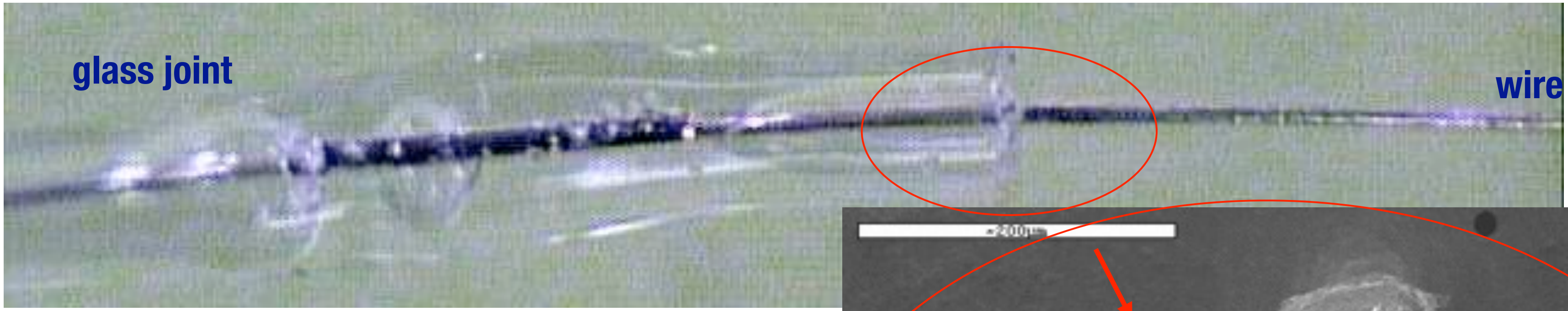
- Problem observed during production -> improved by adding a glue layer
- No further problems during production

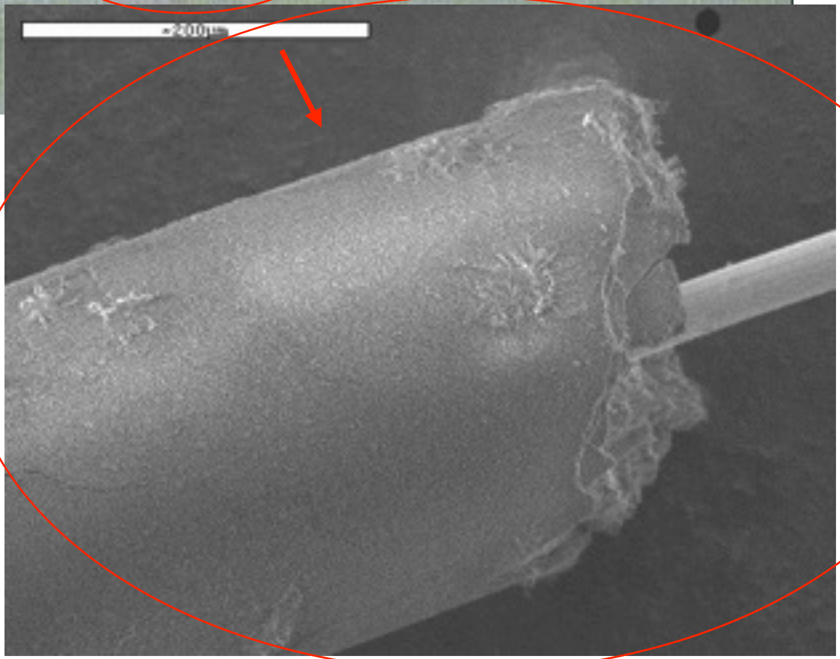


during production

Unexpected problems ATLAS barrel TRT

- Gas mixture: 70% Xe + 20 CF_4 + 10% CO_2
- Observed: destruction of glass joint between long wires after 0.3 - 0.4 integrated charge (very soon after start up)





At high irradiation C_4F turns partially into HF,F,F2 (hydrofluoric acid)
-> attaches Si-based materials in the detector

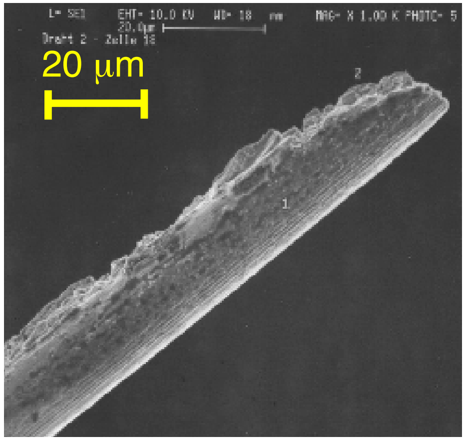
- Changed gas mixture,
  - after ~10 years of R&D with old mixture

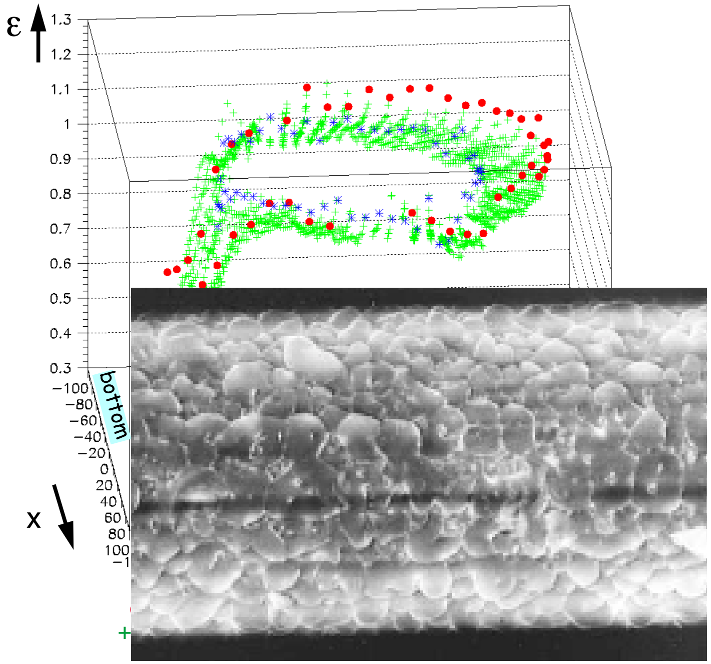
during production

Wires H1 Central Jet Chamber

during running

- Outer tracker of H1 ->
- Broken Wires in CJC1
- Observation / possible reason:
  - remnants from gold plating process lead to complex chemical reactions
- new design of crimp tube: jewels • better quality control



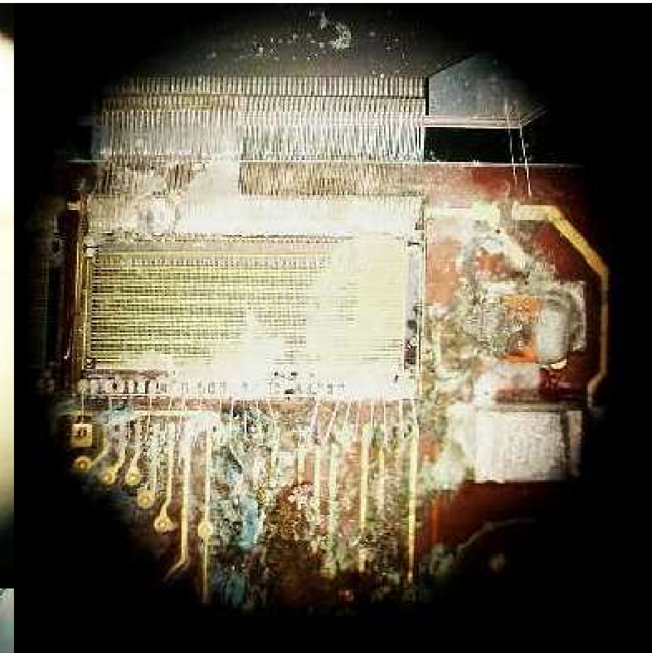


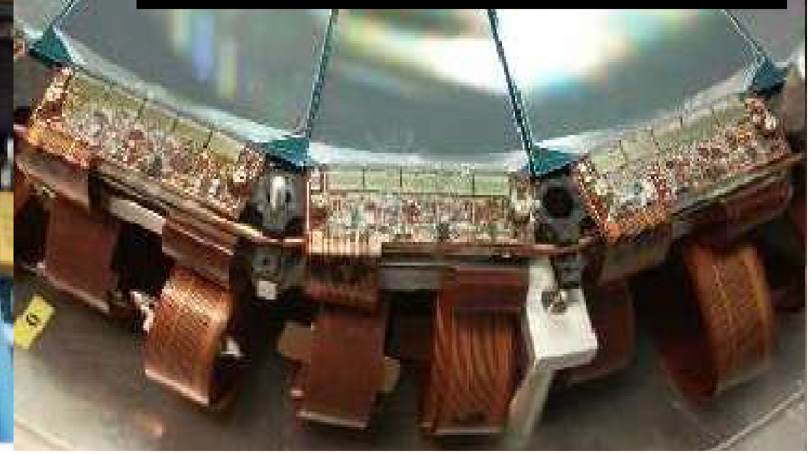
- Sense Wire Deposits in CJC2
- Observation / possible reason:
  - y dependence implies most likely gas impurity
- Consequences:
  - sense wires replaced
  - changes in gas distribution
  - increased gas flow

Water Damage in Tracker ...

during running

- H1@HERA FST in 2004
- Imperfect crimp + hardening of plastic => water leak
- Water condensation => damage
- Tracker segment had to be rebuilt



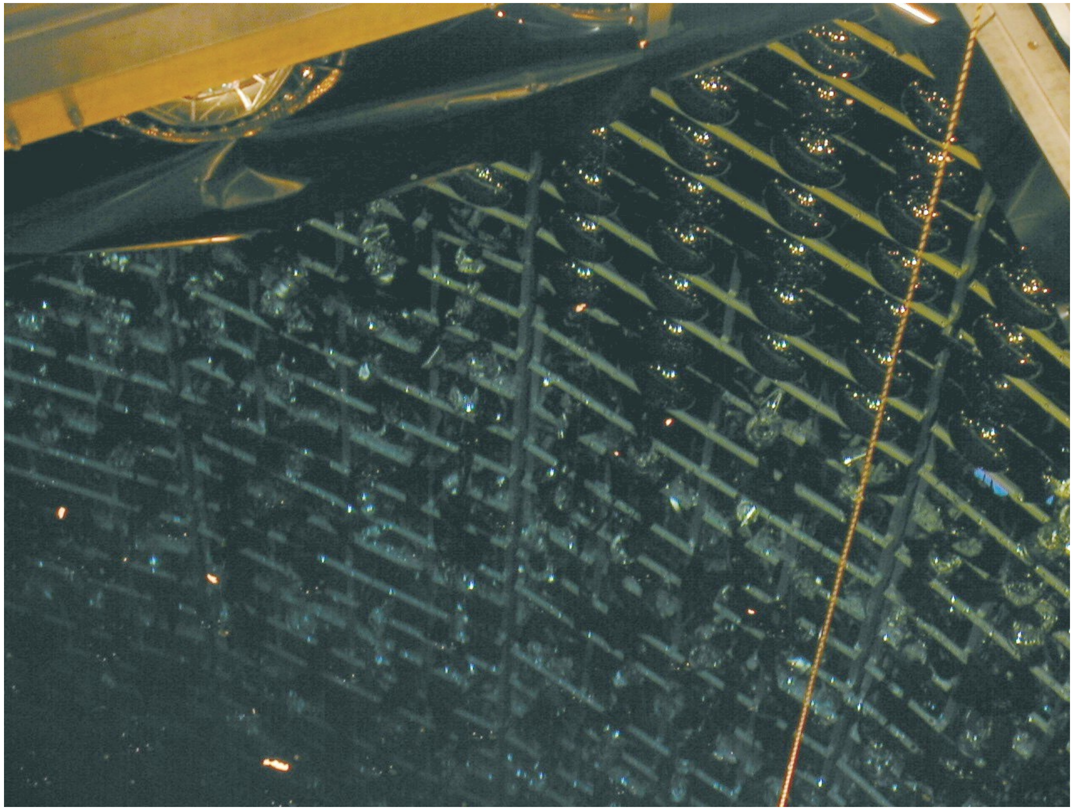


Imploded PMTs @ Superkamiokande

- On November 2001 a PMT imploded creating a shock wave destroying about 6600 of other PMTs (costing about $3000 each)

- Apparently in a chain reaction or cascade failure, as the shock wave from the concussion of each imploding tube cracked its neighbours.
- Detector was partially restored by redistributing the photomultiplier tubes which did not implode.

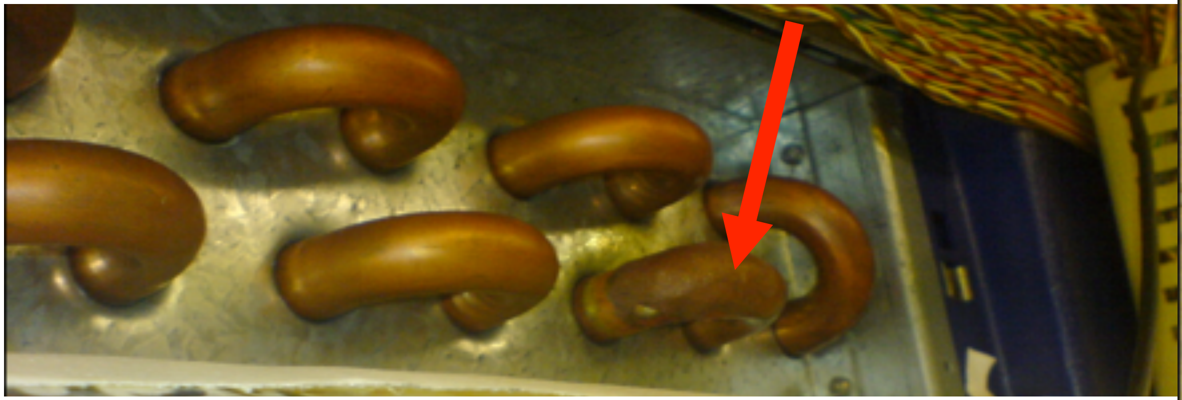
during running



Pic: unknown source….

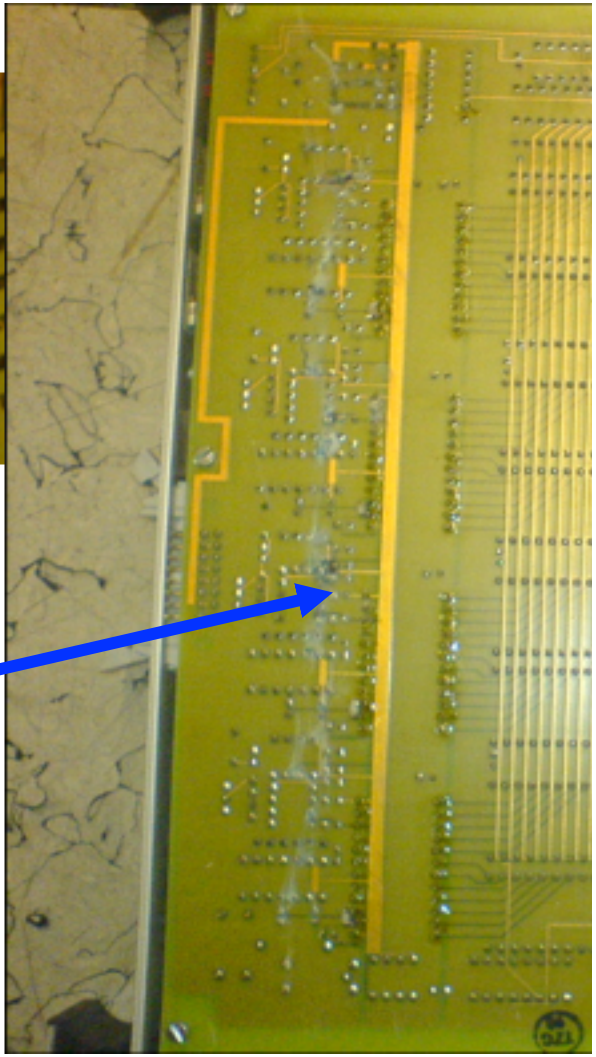
ZEUS - one of many Water Leaks

- Where ever you chose to cool with a liquid - it will leak one day !



- Micro hole in copper hose led to water in the digital card crates
- Four crates were affected, but only seven cards were really showing traces of water
- Of course this all happened on a Saturday morning at 7am ….

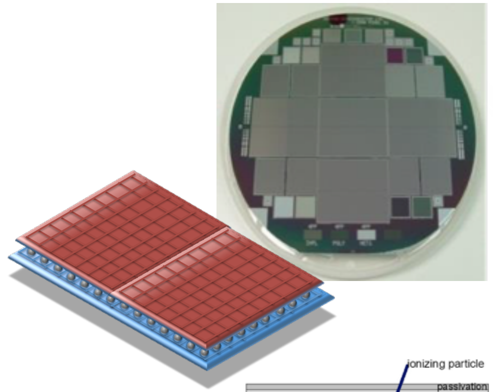
during running

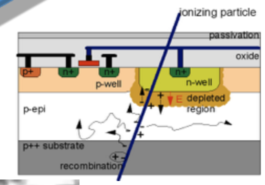


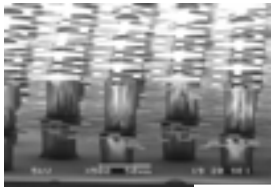
Summary

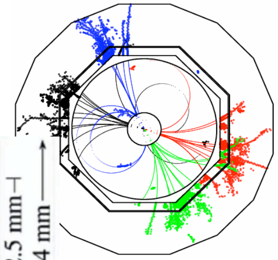
- Tracking detectors: more granular, very small material budget, faster, HL-LHC: extremely radiation hard
- Calorimeters: imaging calorimeters for particle flow are the next generation to measure new physics
- Also “low tech” such as services and cooling needs to be high tech to meet the challenges
- 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 ...

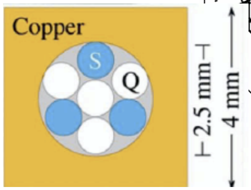
- Progress with detector technology is just about keeping pace with the requirements for future facilities
  - Resources are very tight despite much better coordination of effort between experiments
- Sizeable and highly dedicated community engaged in detector R&D
- Detector R&D in particle physics is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



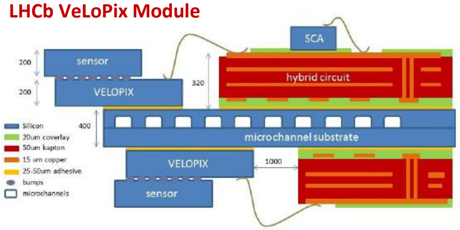






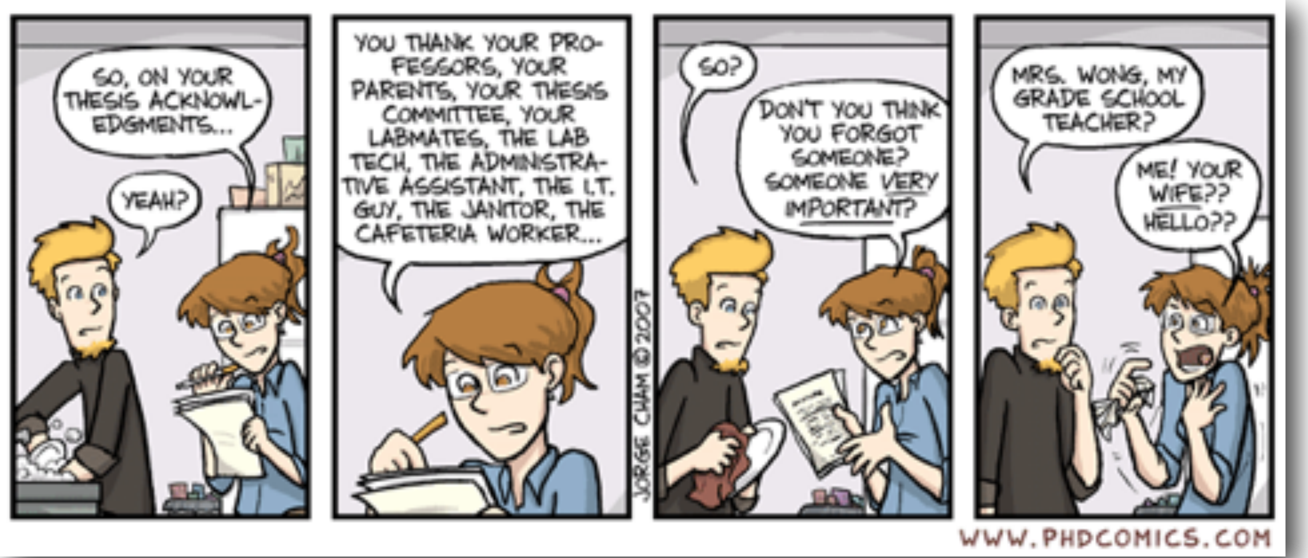


LHCb VeLoPix Module




Thank You !!
Photo credit: Shutterstock

Important ....



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Jim Virdee

Christoph Rembser

Carsten Niehbuhr

Marc Winter

Doris Eckstein

Christian Joram

Steinar Stapnes

…freaky husband ;-)

Literature

Text books:

rather old books by now

C.Grupen: *Particle Detectors,* Cambridge UP ^{2}2008, 680p
D.Green: *The physics of particle Detectors,* Cambridge UP 2000
K.Kleinknecht: *Detectors for particle radiation,* Cambridge UP, ^{2}1998
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R. Wigmans: *Calorimetry*, Oxford Science Publications, 2000

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further reading:
The Large Hadron Collider - The Harvest of Run 1; Springer 2015