International Conference on
Accelerator Optimization
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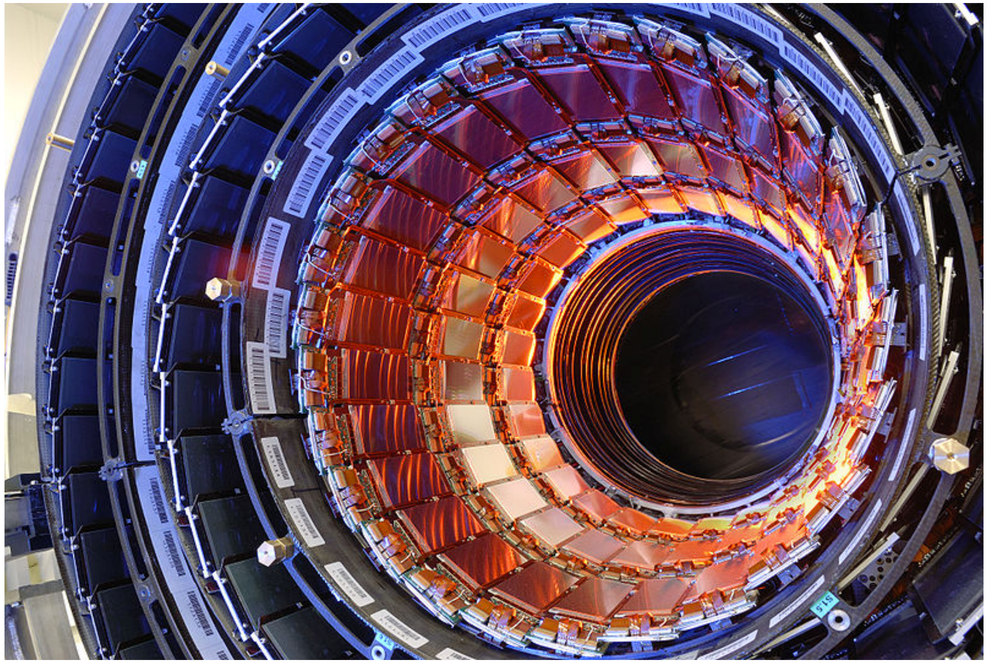
Next Generation Detector Technologies

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

- Introduction
- 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



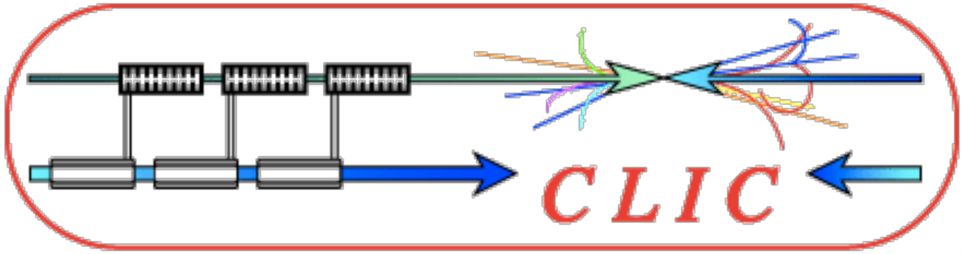
Disclaimer
Some bias in the selection of the most important detectors:
* mostly HL-LHC and ILC detectors
* focus on tracking systems

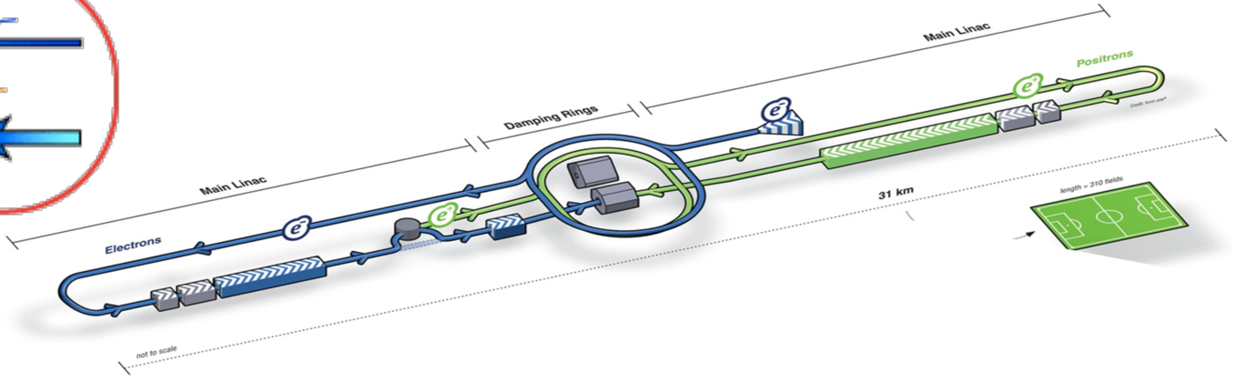
Introduction

Future Facilities

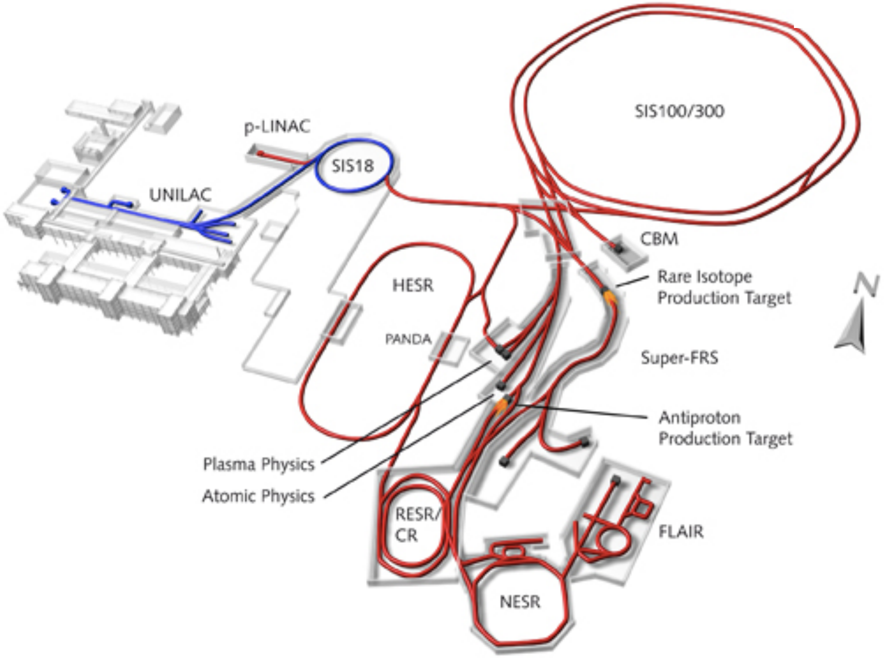
incomplete list …

Precision physics,
rare processes
high data rates

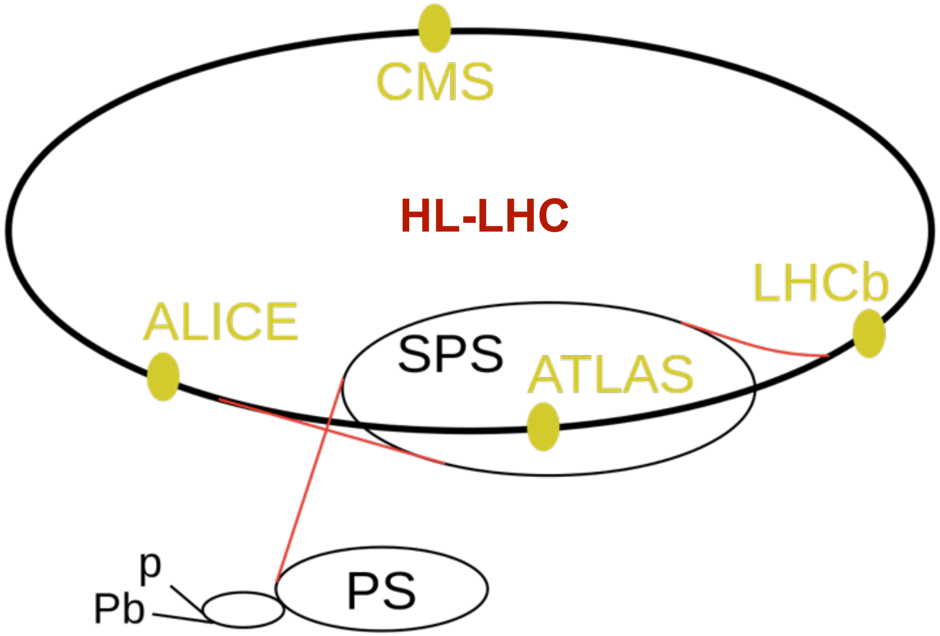




CLIC: Electron – positron collider
proposal phase



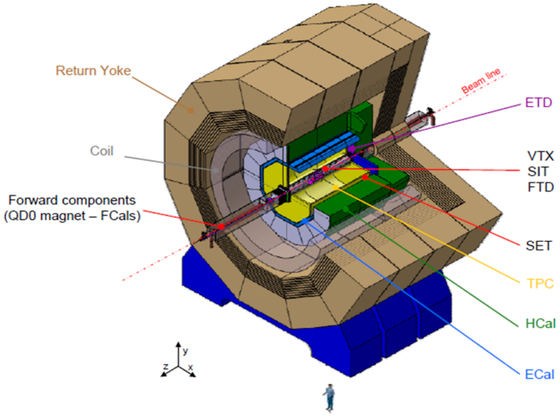
FAIR: Facility for Antiprotons and Ions Research,
under construction



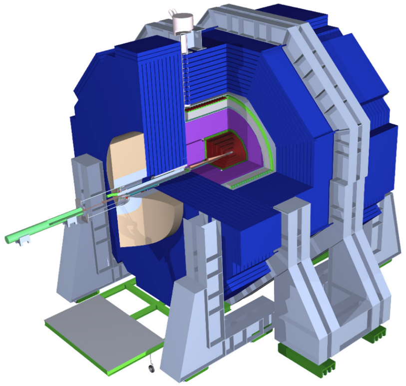
HL-LHC: high luminosity upgrade of the LHC

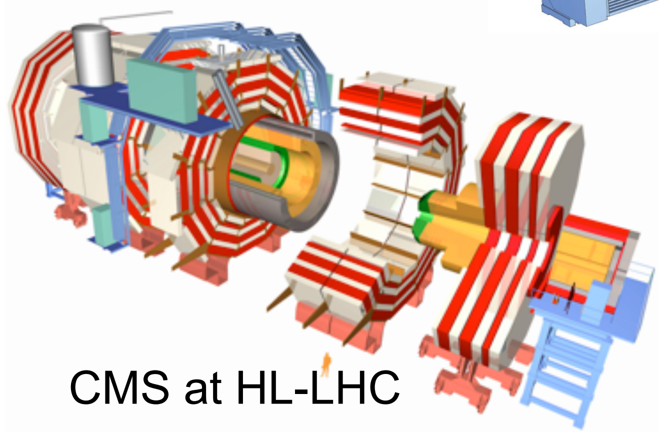
Future Experiments

ILD at the ILC/CLIC

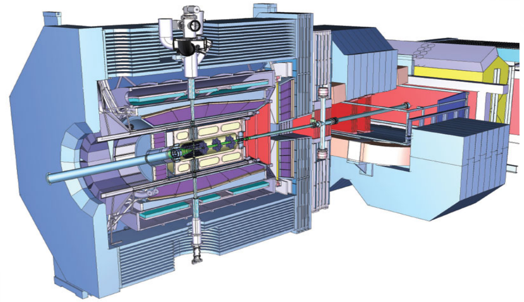


SiD at the ILC/CLIC



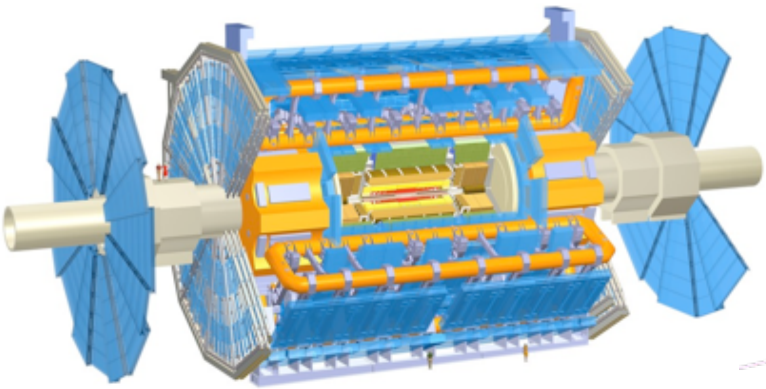


CMS at HL-LHC

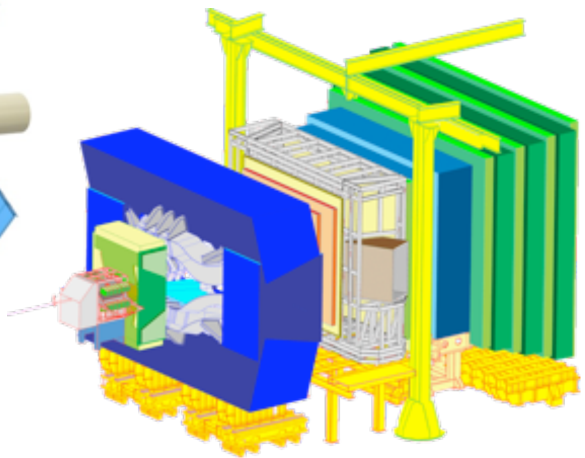


PANDA at FAIR

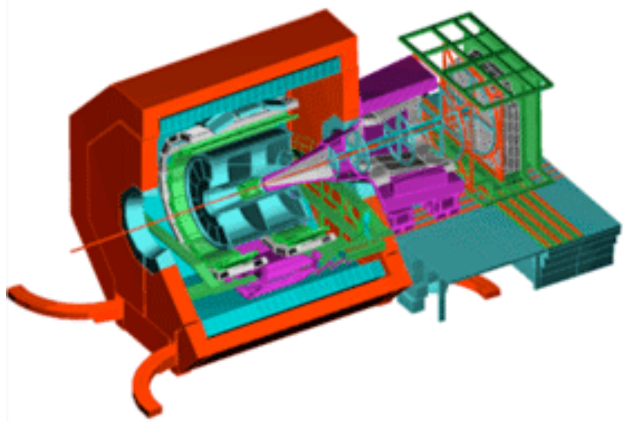
ATLAS at HL-LHC



LHCb at LHC



ALICE at LHC



not to scale !!

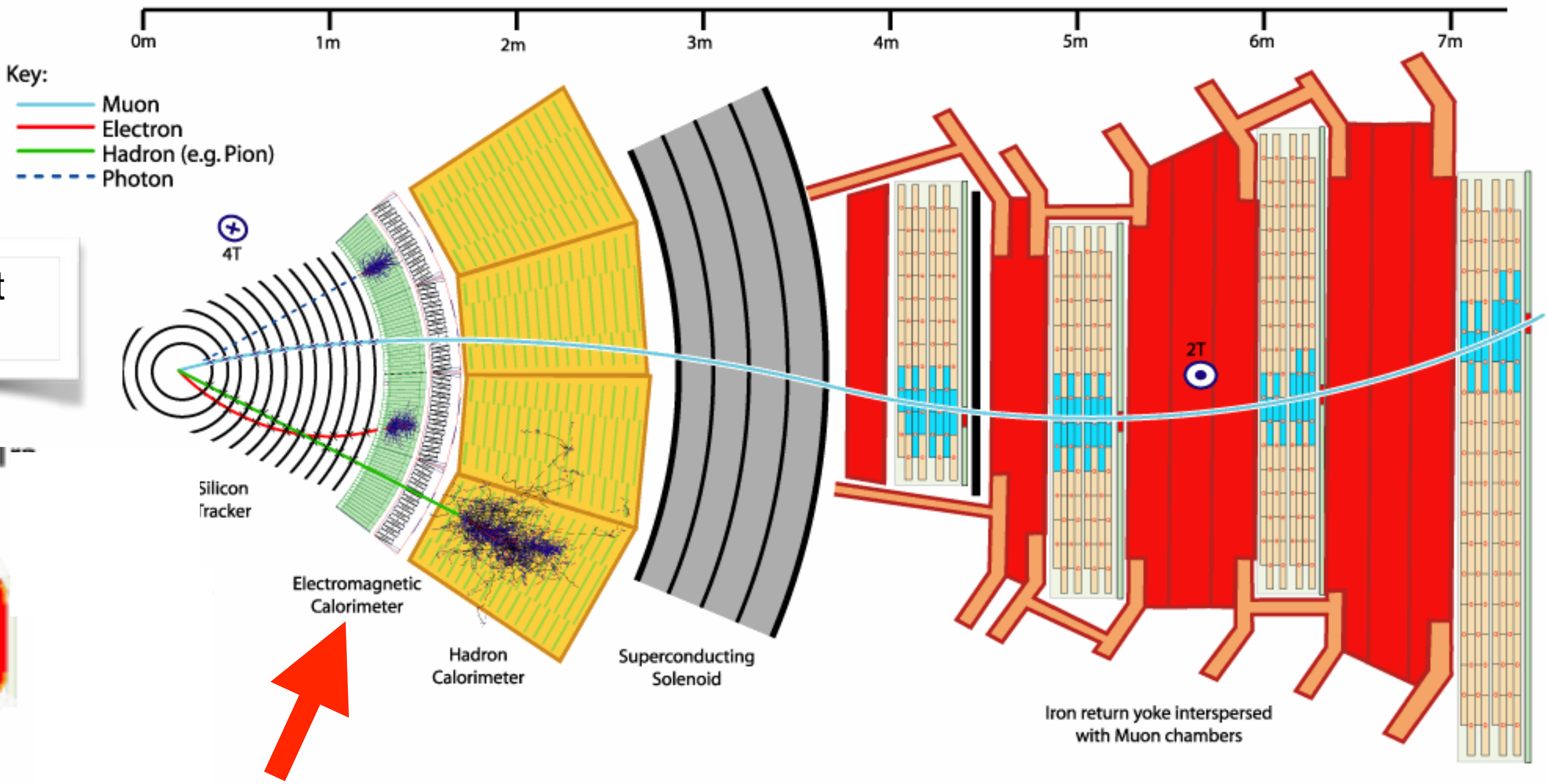
Particle Physics Detector Overview

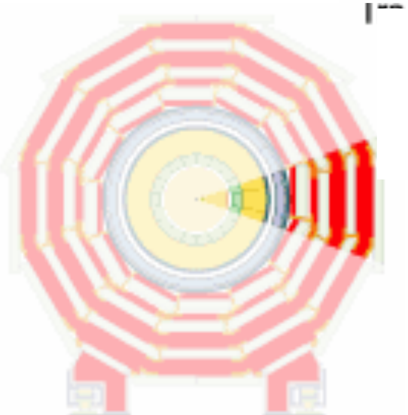
Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

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

picture: CMS@CERN

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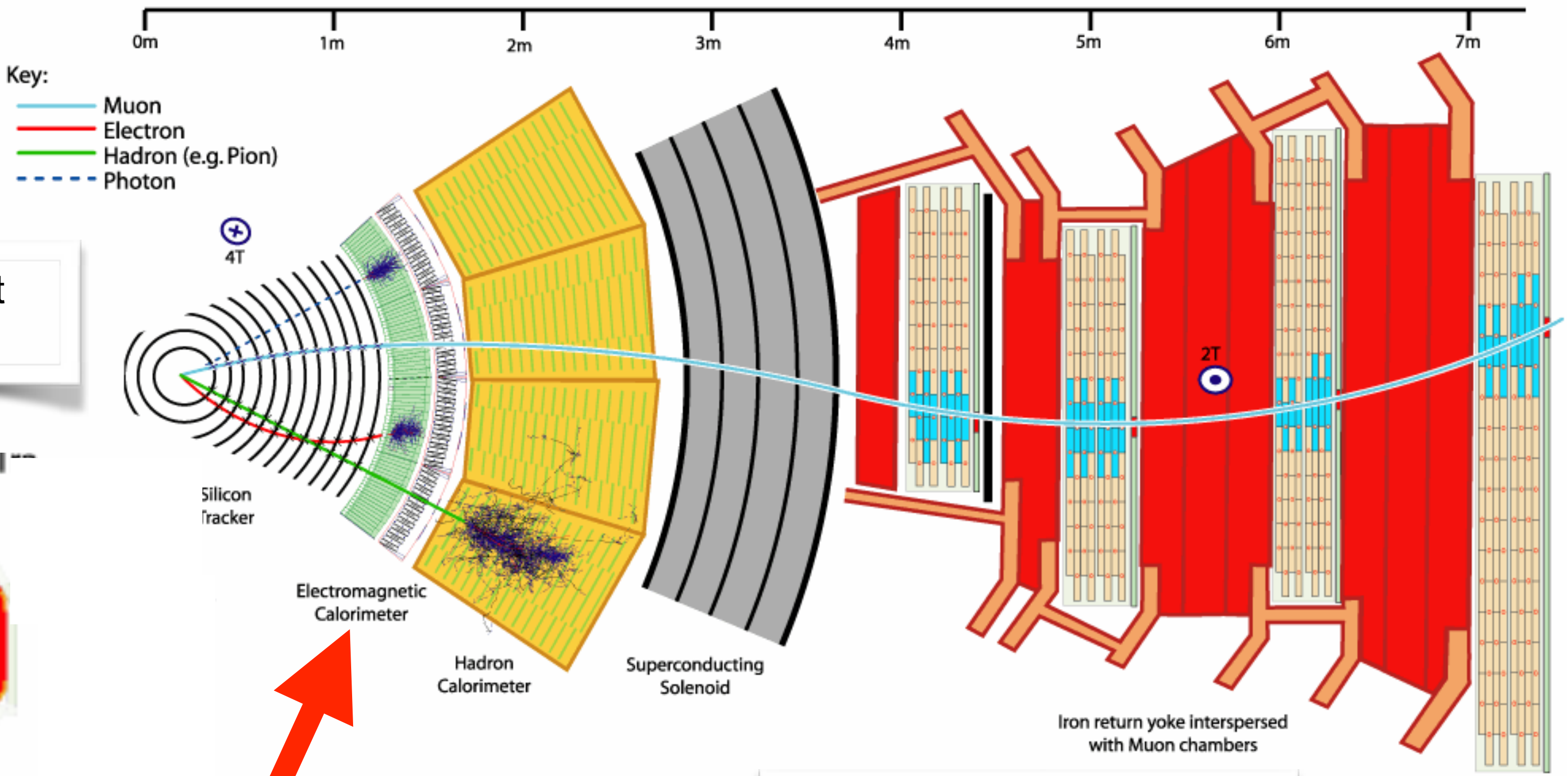
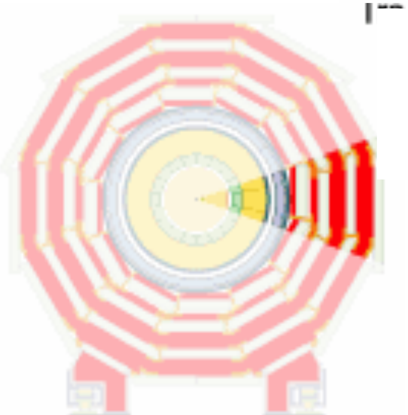




Transverse slice through CMS

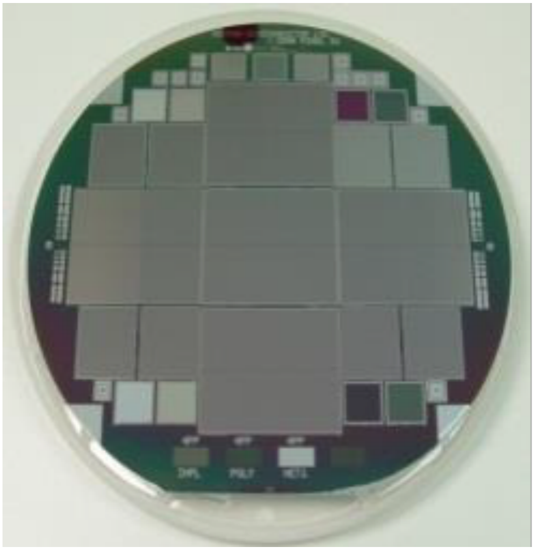
Good energy resolution up to highest energies

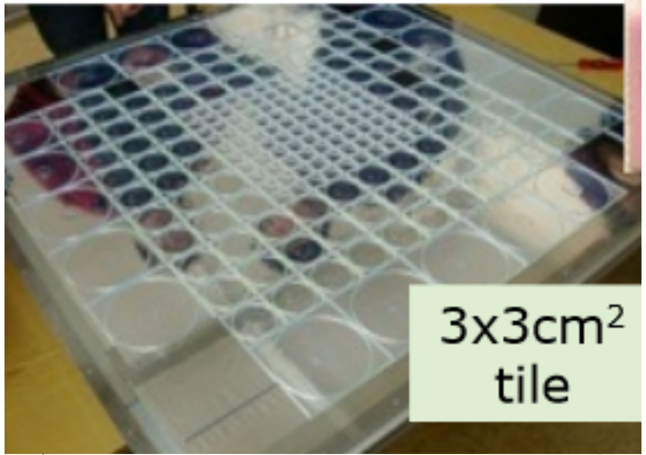
Radiation hard (hadron collider)

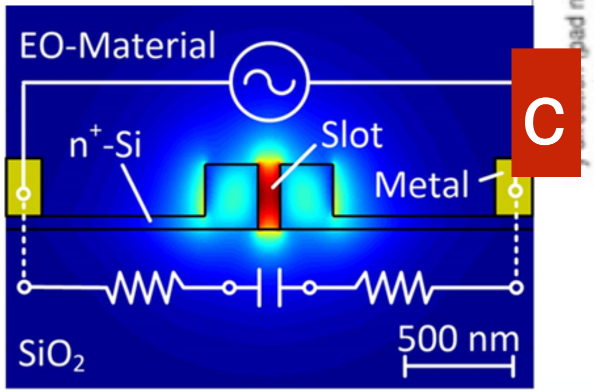
picture: CMS@CERN

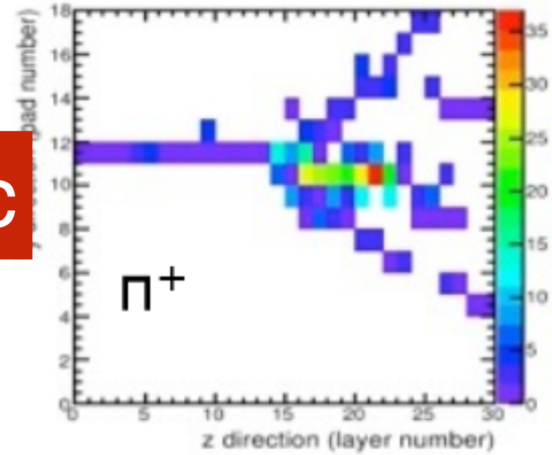
The Challenges

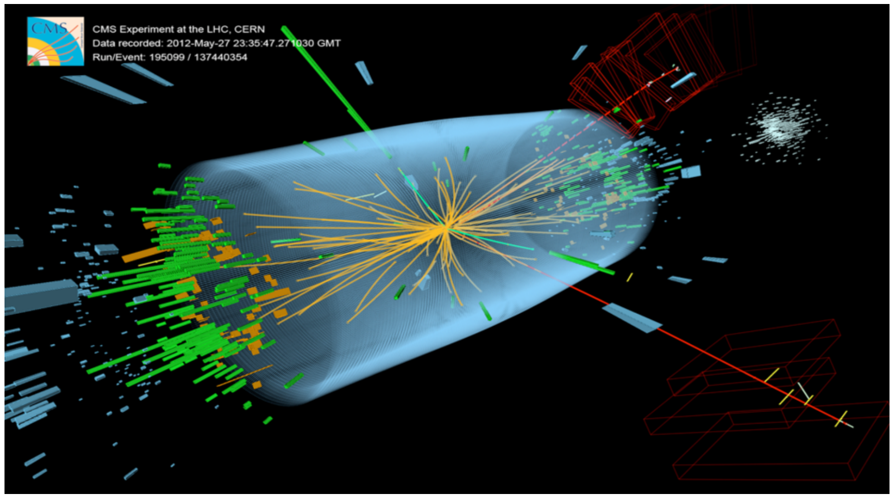
- Precision (resolution)
- Granularity
- Power consumption
- Readout speed
- Material budget
- ….

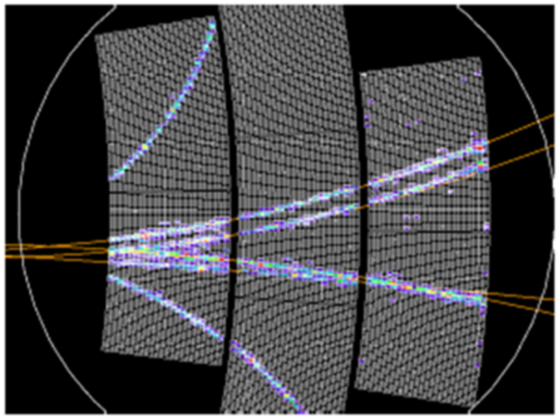












Tracking Detectors

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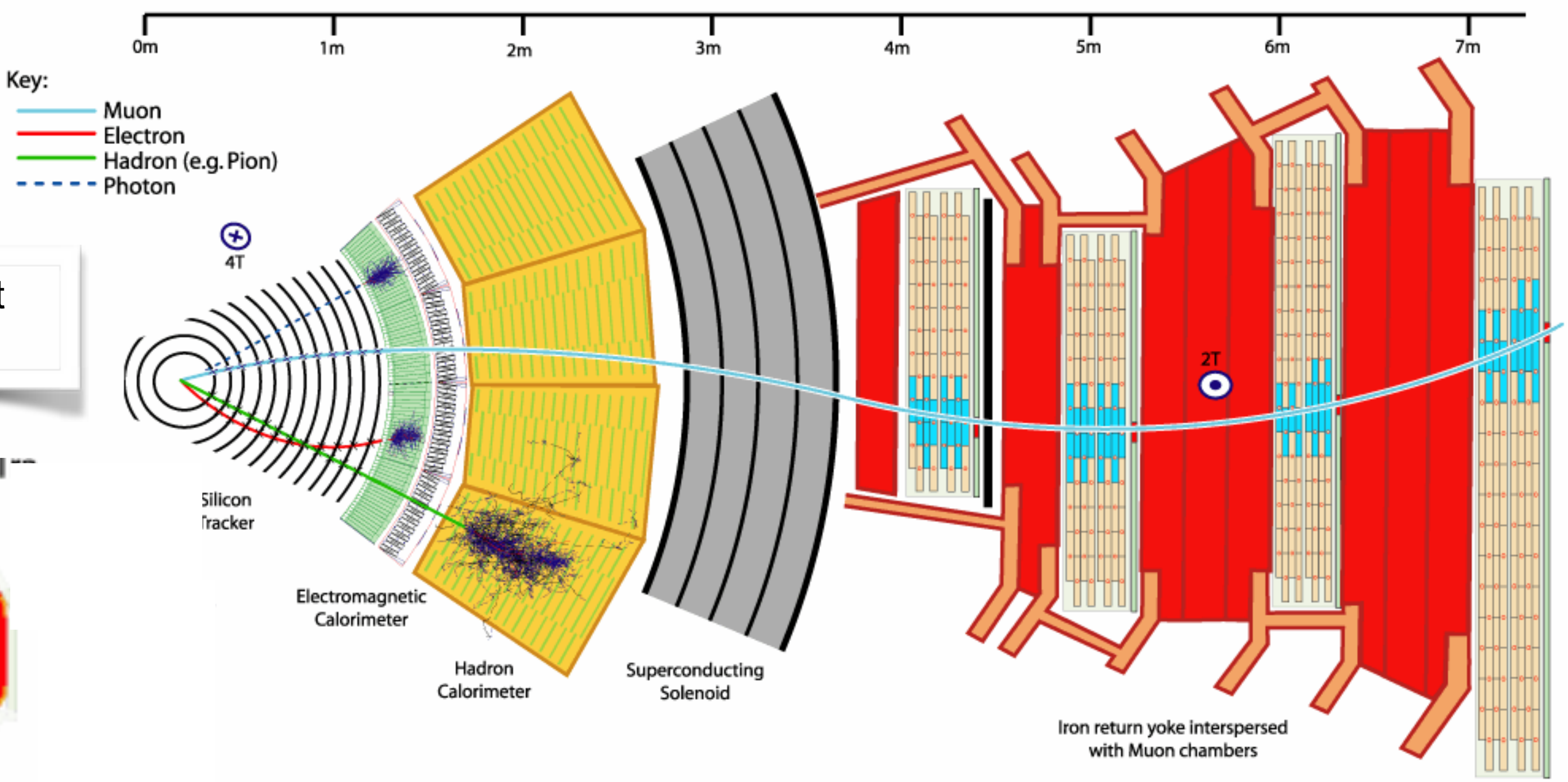
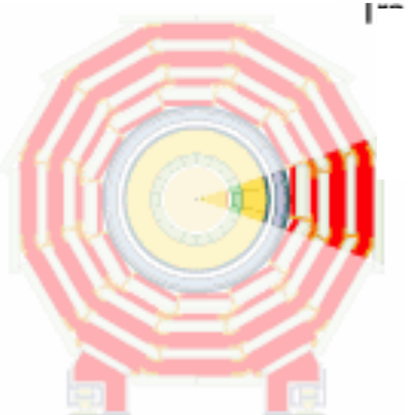
Tracker: for muons ...

Vertex: Innermost tracking detector





Transverse slice through CMS

picture: CMS@CERN

Vertex Detector Challenges

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

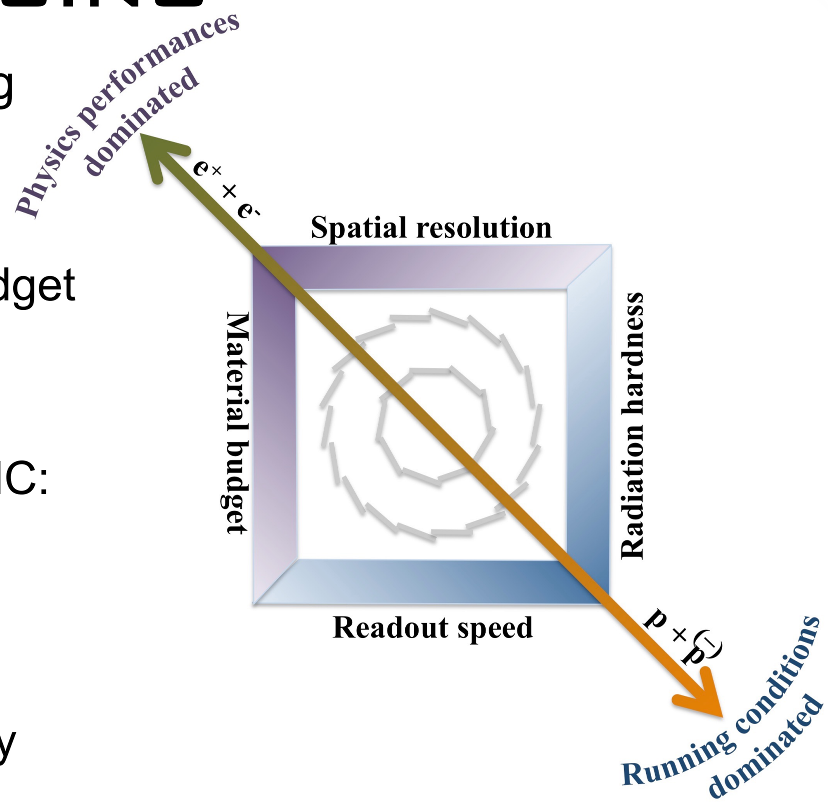
$$\sigma_{r\phi} \approx \sigma_{rz} \approx a \oplus b/(p\sin^{3/2}\vartheta)$$

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

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 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



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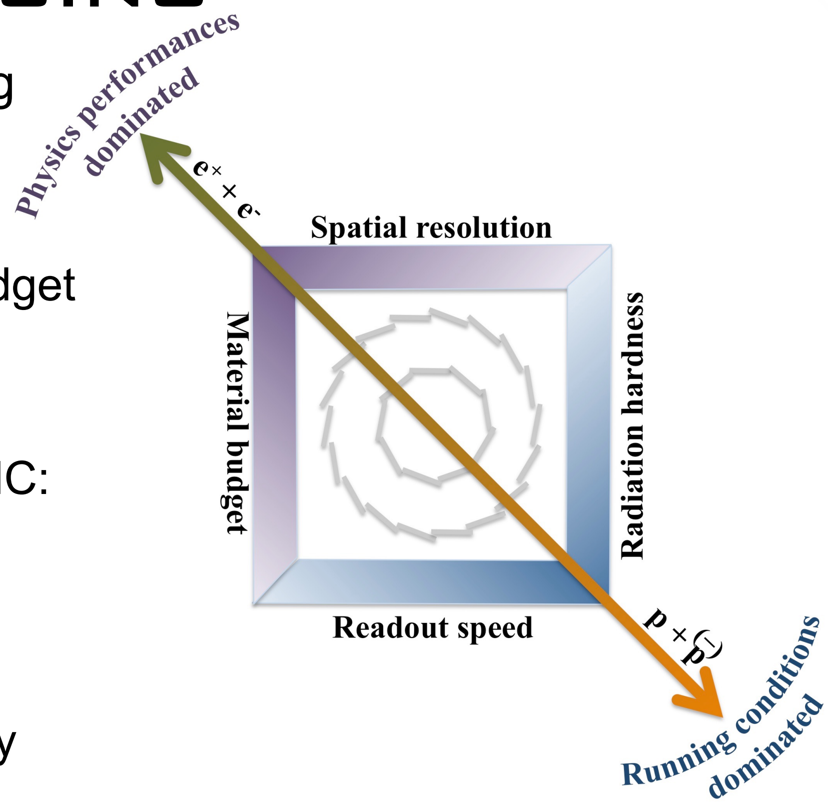


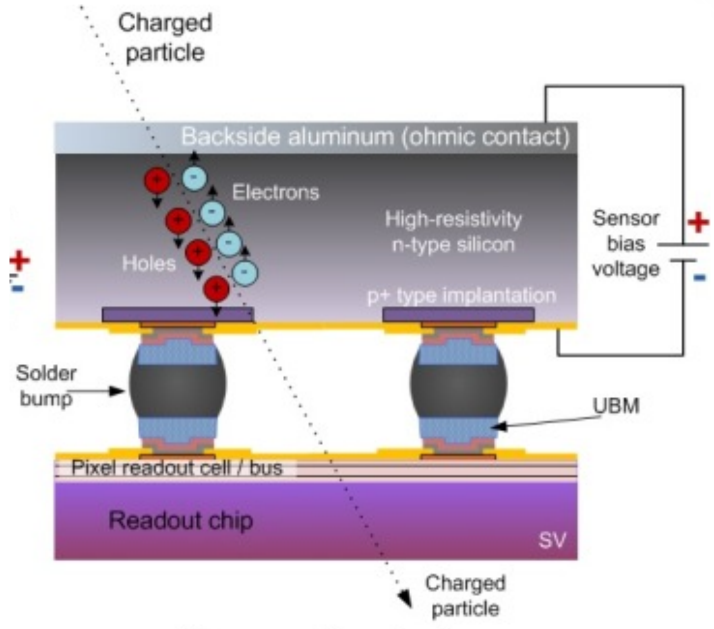
- Ultimate performance on all specifications cannot be reached simultaneously
  - each facility & experiment requires dedicated optimisation
  - there is no single technology best suited to all applications
  - explore various technological options
  - motivation for continuous R&D

Hybrid Pixels – "classical" Choice HEP

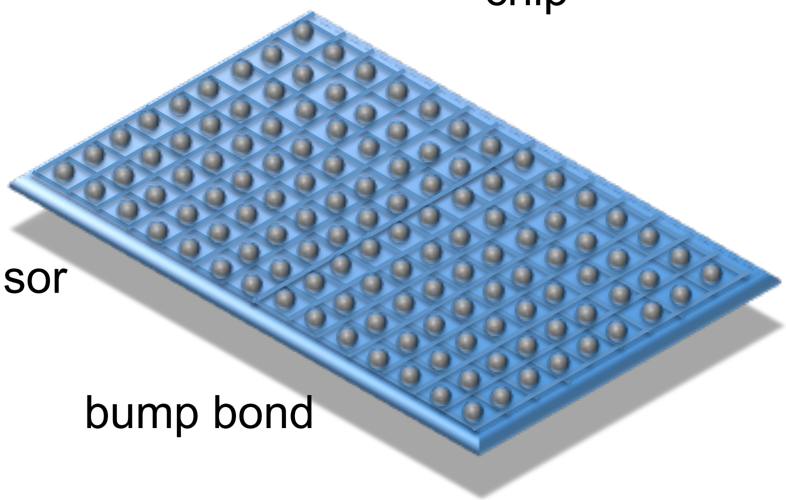
- The read-out chip is mounted directly on top of the pixels (bump-bonding)
- Each pixel has its own read-out amplifier
- Can choose proper process for sensor and read-out separately
- Fast read-out and radiation-tolerant

… but:

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



Cross-sectional cut



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

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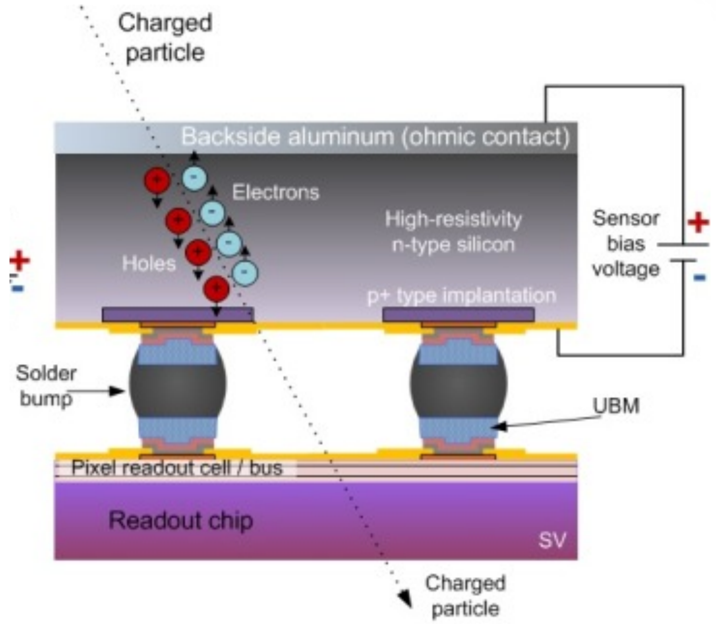

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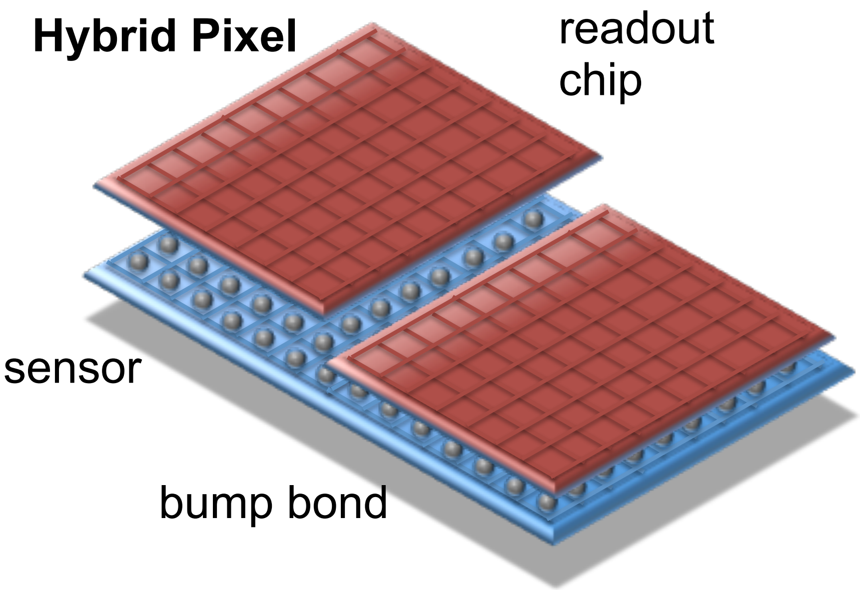

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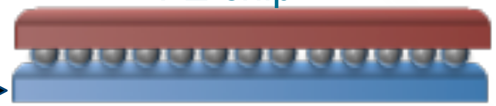
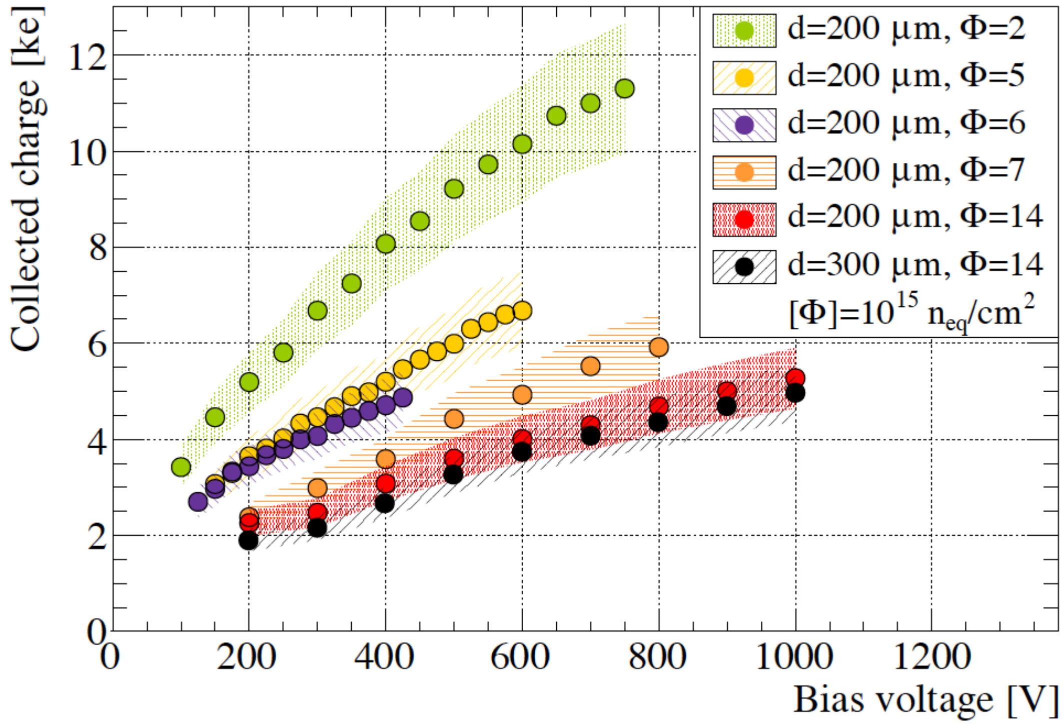
Sensors for Hybrid Pixels

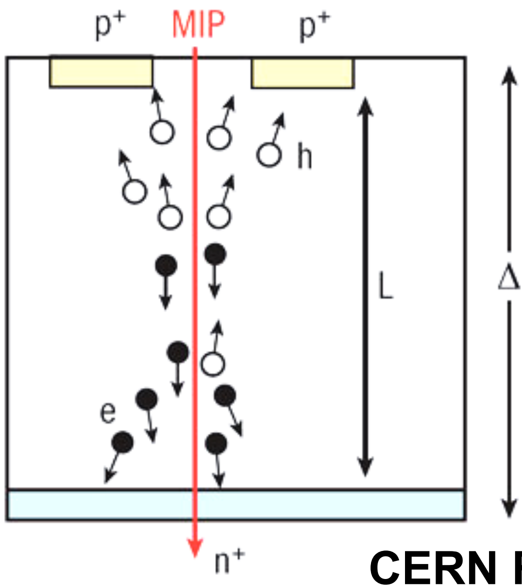


"Classic": Planar Sensor

- 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



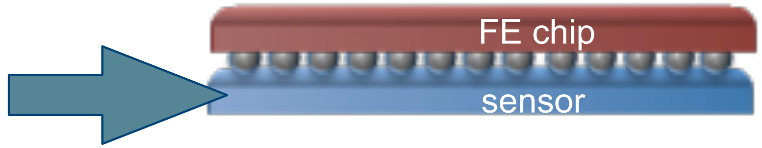
S.Terzo Ph.D.thesis,TUM



CERN RD50

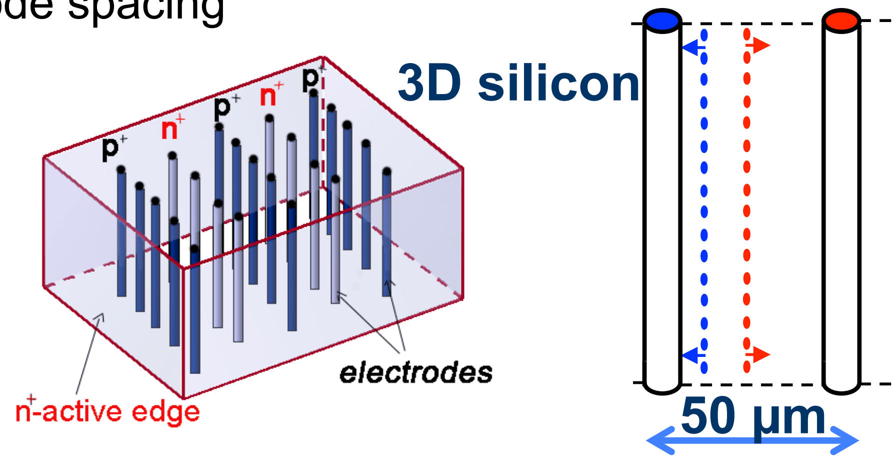
Very strong R&D efforts to develop sensors for future LHC applications!

New Sensors Types

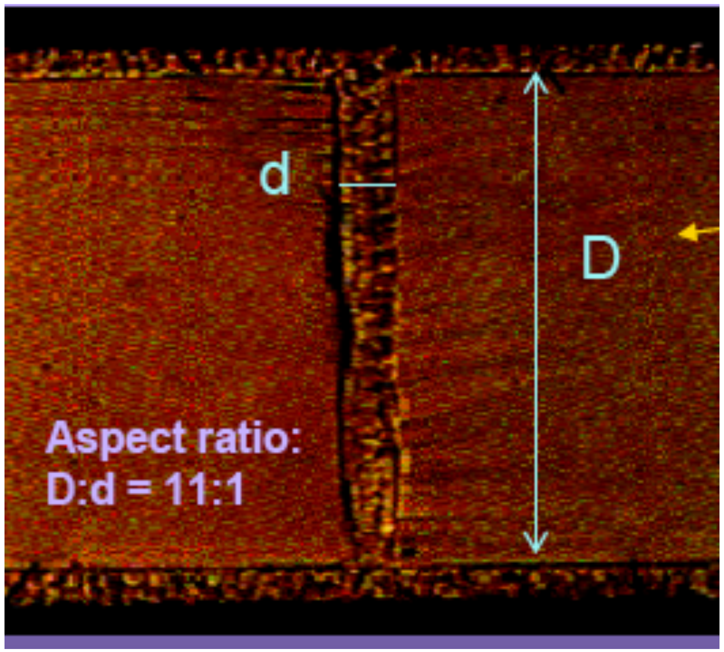


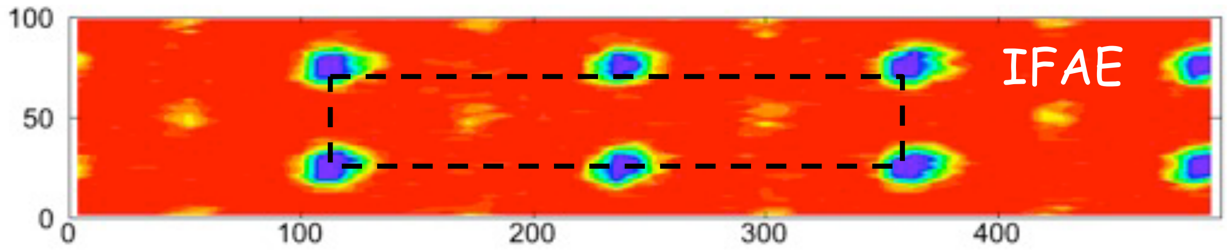
3D Silicon

- 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



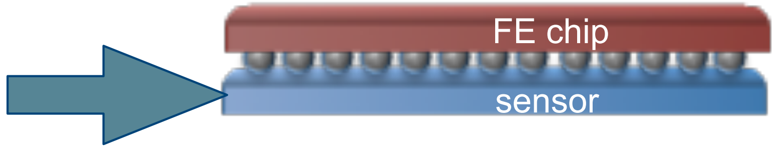
- First use case -> ATLAS IBL (25%)





Efficiency measured at test beam

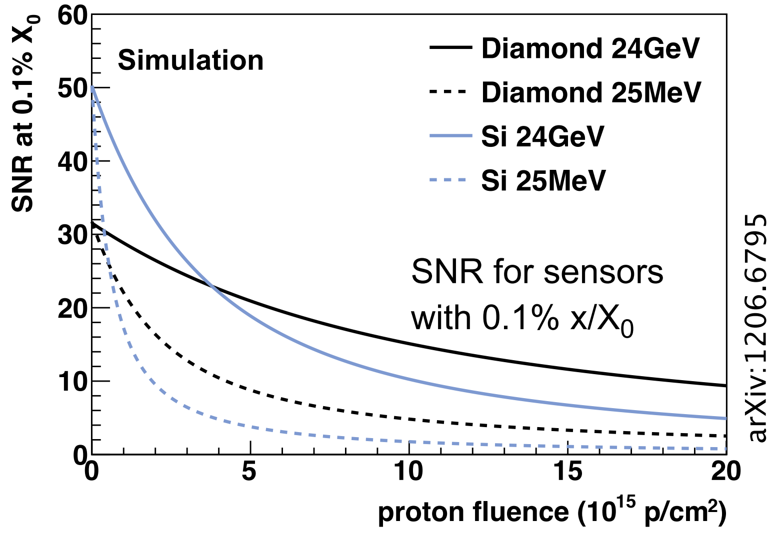
New Sensors Types



Diamond Sensors

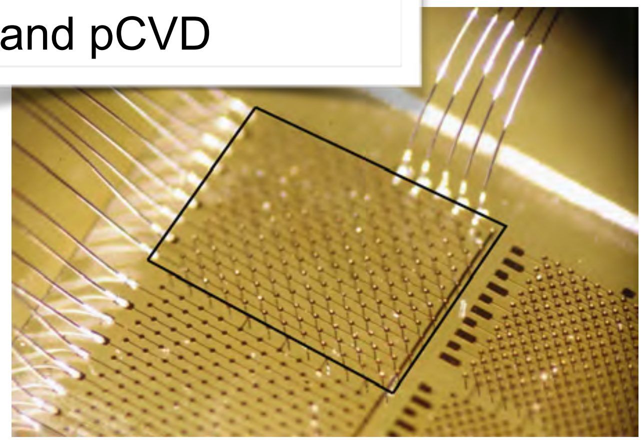
- Chemical vapor deposition (CVD) diamond
  - band gap 5.5 eV (silicon: 1.1 eV)
  - only 60% as many charge carriers as silicon
  - radiation tolerant !!
  - low Z

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



- Used for beam monitoring at LHC
- 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
- Next generation: combi of diamond and 3D
  - first tests show larger signal than standard cells

Future:
Combination of 3D and pCVD

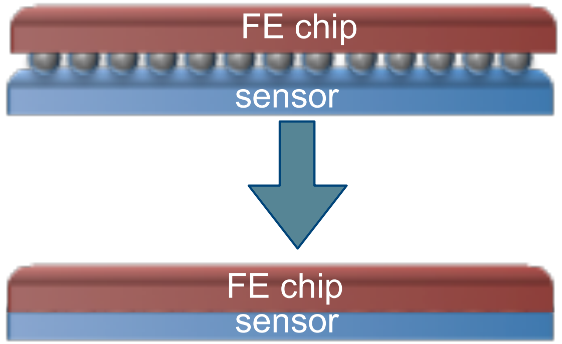


published in NIM A 786 (2015) p97

New Alternative: CMOS

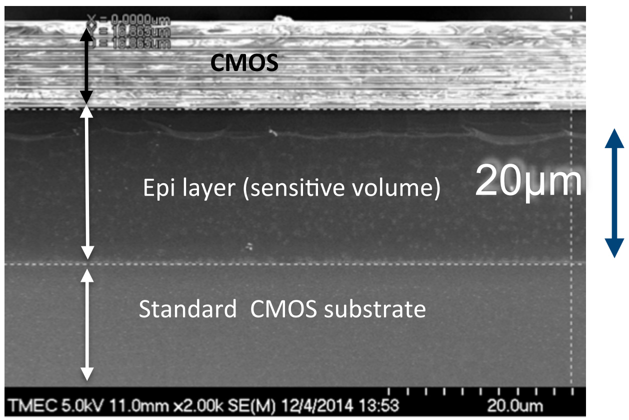
hot topic in ATLAS for HL-LHC !

- Use of commercial CMOS technologies for replacement of sensor or even full hybrid (monolithic)
  - possible advantages: integration, cost, power consumption and material budget
  - currently few experiments:
    - DEPFET for Belle-II
    - MAPS in STAR
    - ALICE for ITS



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)



SEM picture: epi thickness 20µm

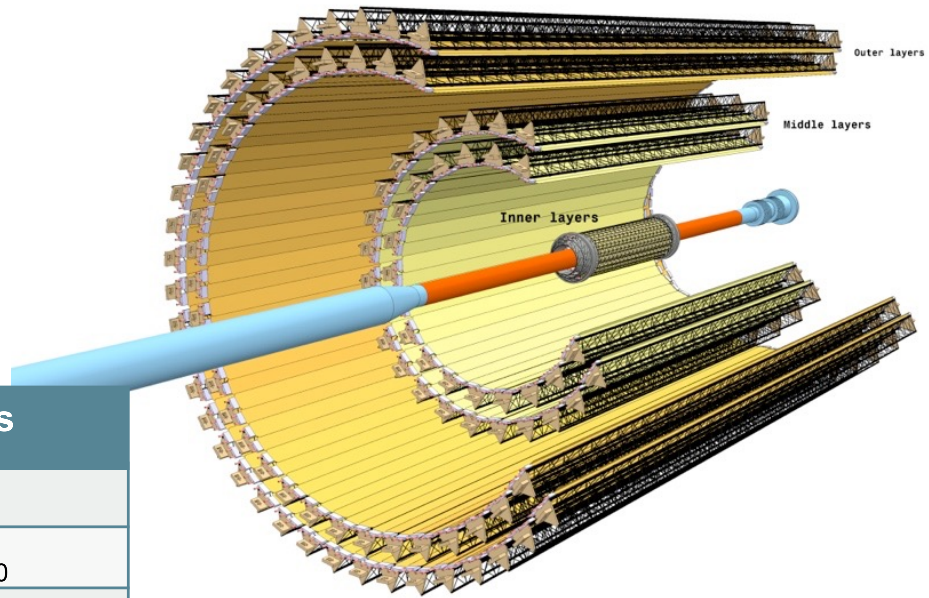
Epi layer

Main **challenge for HL-LHC**: need combination of

- tolerance to displacement damage (depletion)
- integration of complex circuitry without efficiency loss
- keep using commercial technology

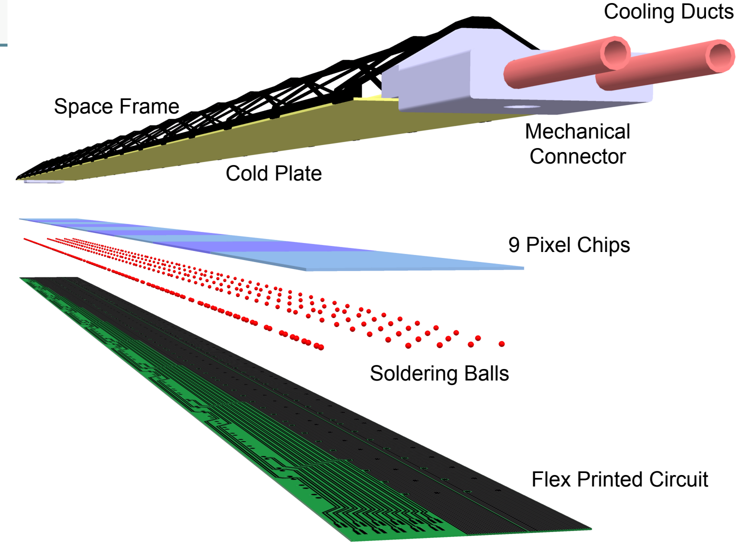
Example: ALICE ITS Pixel Detector

- Improve impact parameter resolution by a factor of three
- Improve standalone tracking capability and p_T resolution by means of increased granularity
- Tower Jazz 0,18 µm CMOS process as baseline

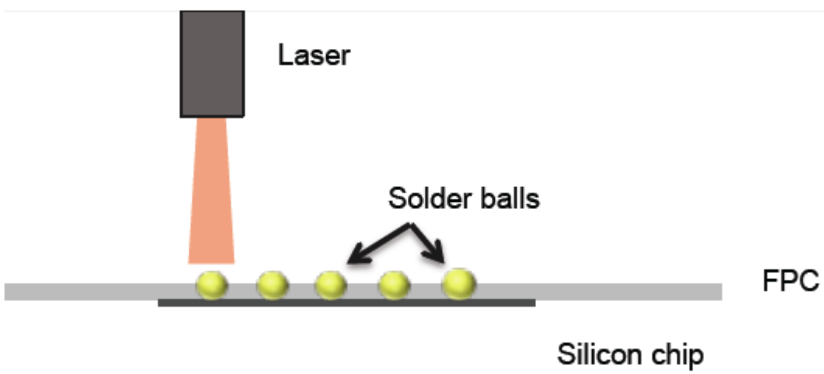


7 layers of **monolithic pixel** detectors

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}



Laser bonding

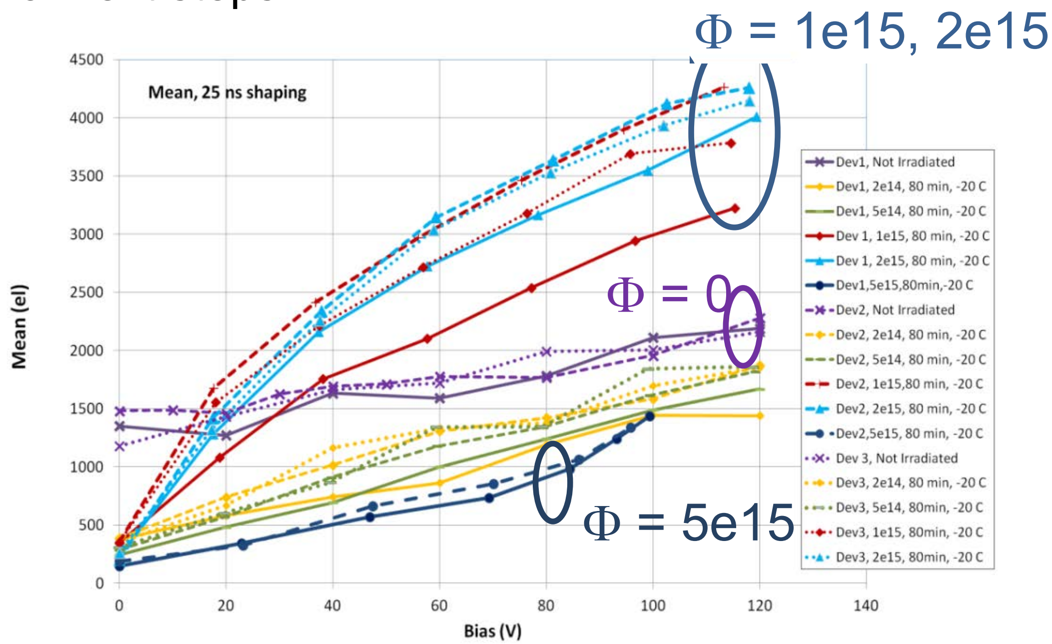


CMOS for HL-LHC ?

- 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
- Being followed up by ATLAS (pixels and strip)
- First results are **encouraging**
  - indication of good radiation tolerance
  - optimisation of signal and efficiency is one of next steps

Example:

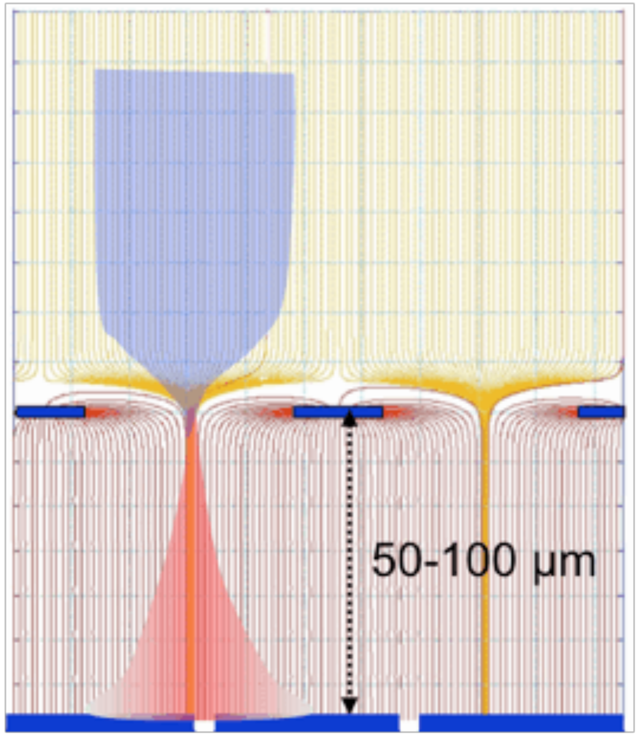
A technology which could be used to build a **dream** tracker:
- fully monolithic but radiation hard
- high resolution
- thin material
- cost effective



Gaseous Detectors

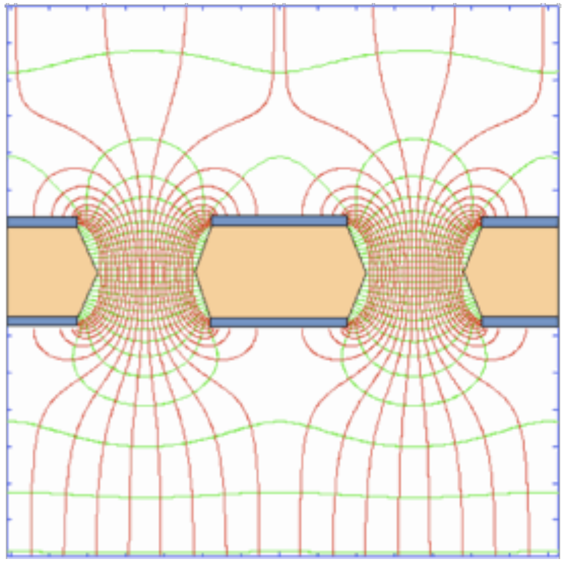
- Largely improved spacial resolution and higher particle rates:
  - Micro pattern gas detectors
- a number of developments were started, some with a lot of problems
- two technologies are currently the most successful: GEMs and MicroMegas

- MicroMegas: Avalanche amplification in a small gap



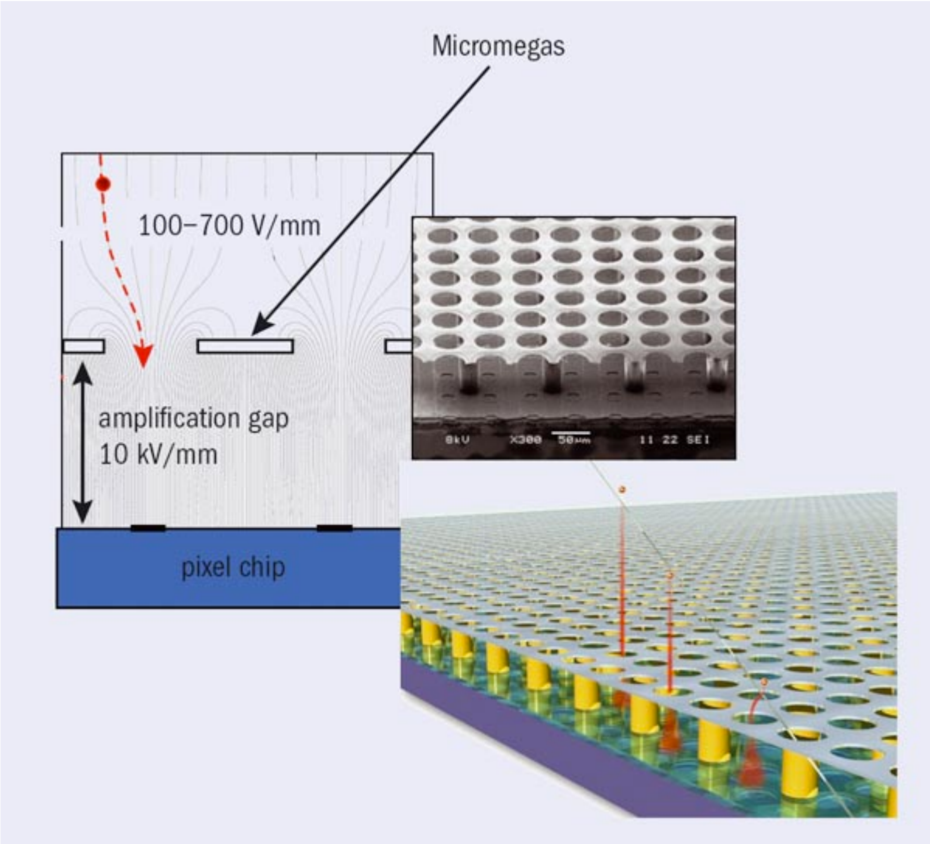
Y. Giomataris et al, NIM A376, 29(1996)

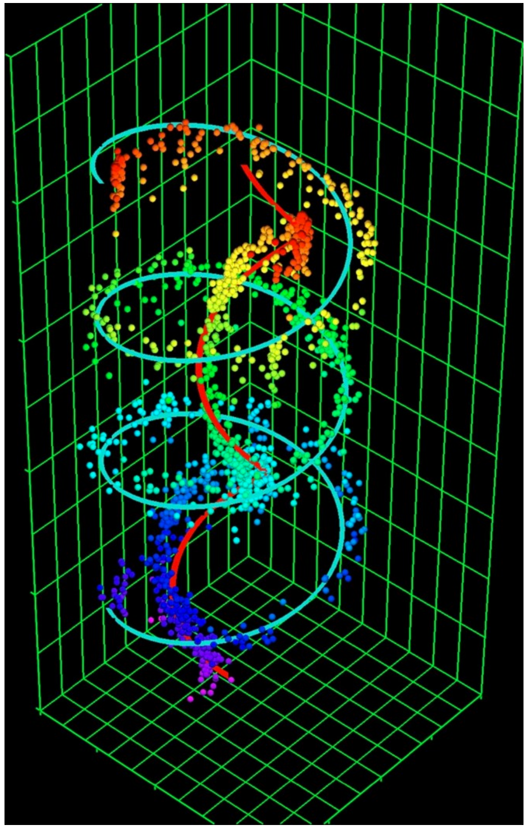
- GEM: Gas Electron Multiplier: Gas amplification in small holes in a special foil



MPGDs as next generation detector

- Combination of gas detectors and Silicon
  - Integration of MPGDs with pixel read out chips
- Amplification and read out made of silicon





CERN RD51

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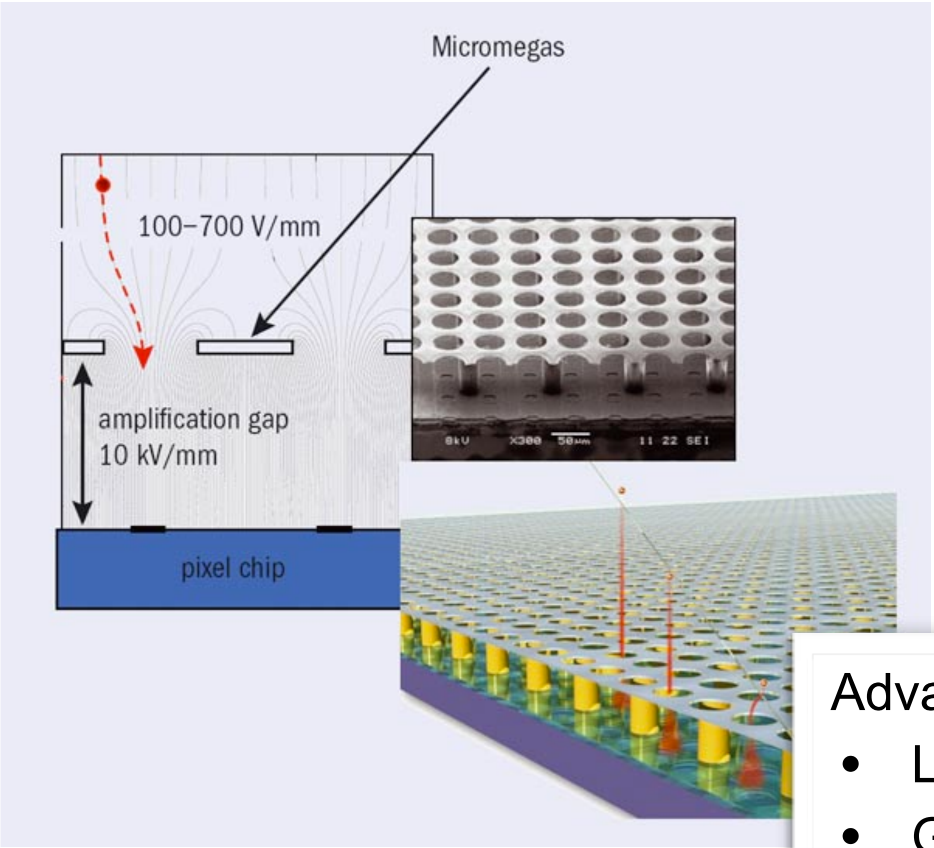
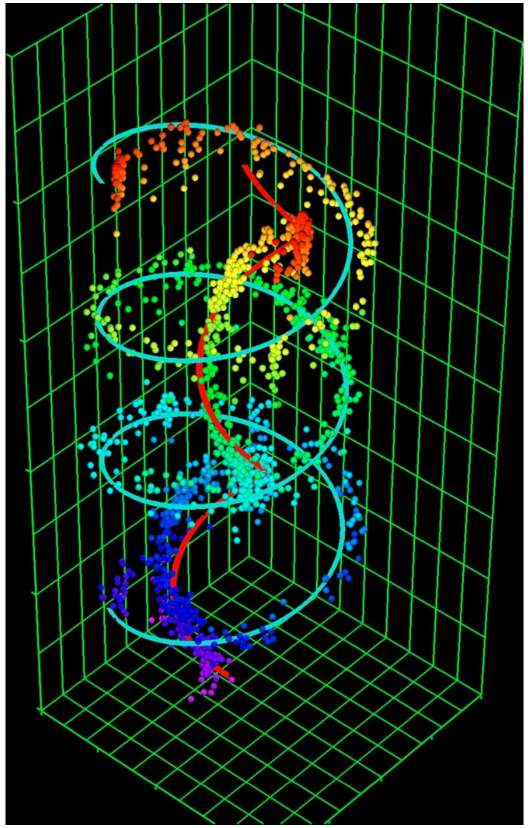
- Amplification and read out made of silicon





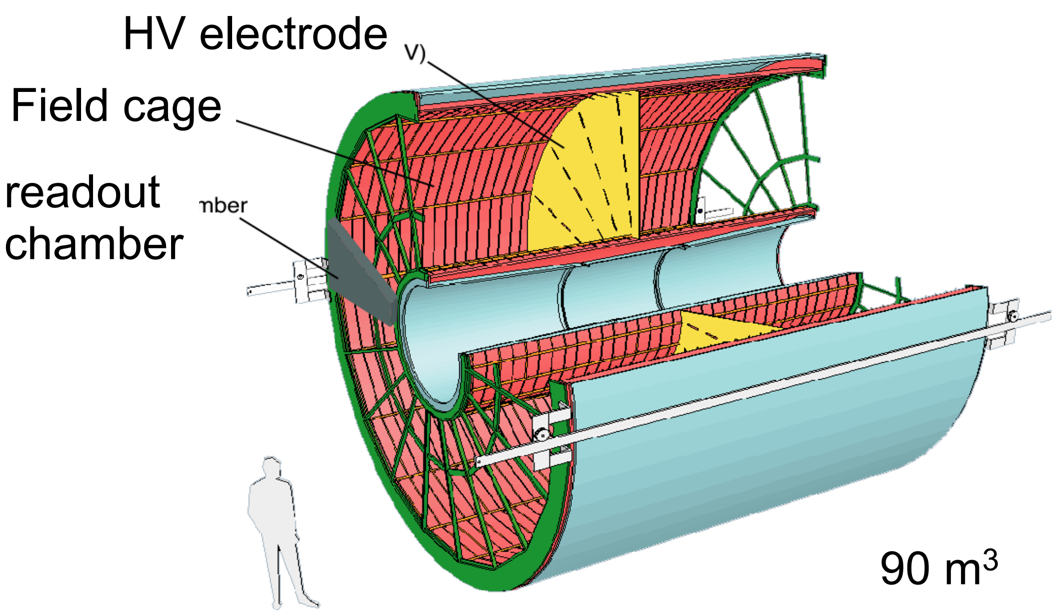
Advantages of gas detectors:

- Low radiation length
- Gas can be replaced regularly: Reduction of radiation damages!

CERN RD51

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

Power Management

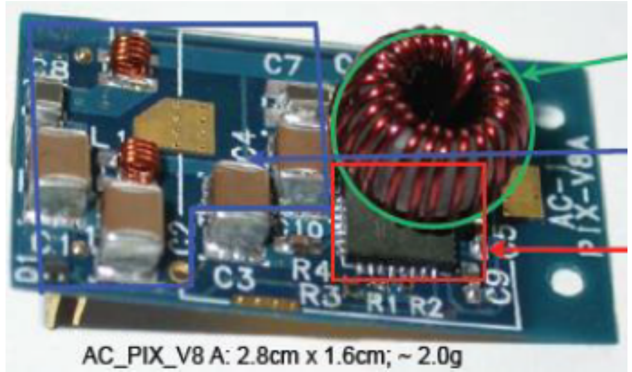
Powering:

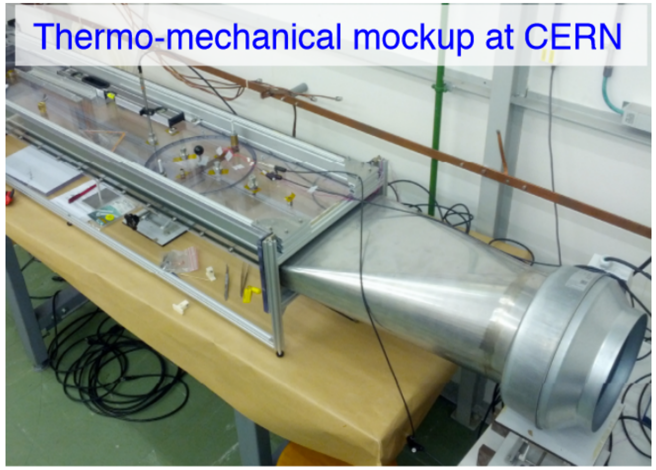
- Services are major part of material budget -> need to reduce material
- LHC tracking detectors increase of channel -> not even the space for all services
- ILC tracking detectors -> very limited material budget
- Advanced powering schemes can help:
  - DC-DC
  - serial powering
  - power capacitors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

Cooling:

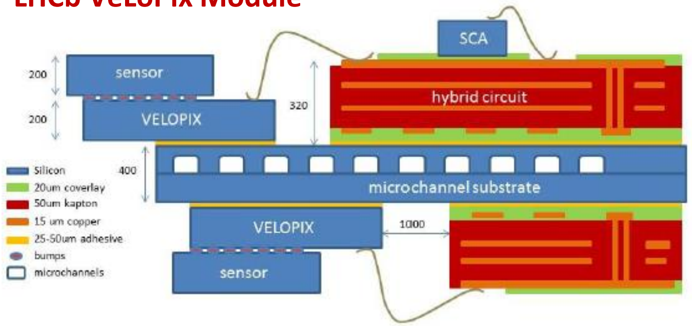
- LHC detectors need to cool silicon sensors extremely low
  - CO_2 cooling current solution
- micro-channel cooling for some detectors a solution
- for non-LHC detectors air cooling an option:
  - low mass
  - sufficient for ILC/ CLIC conditions?

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





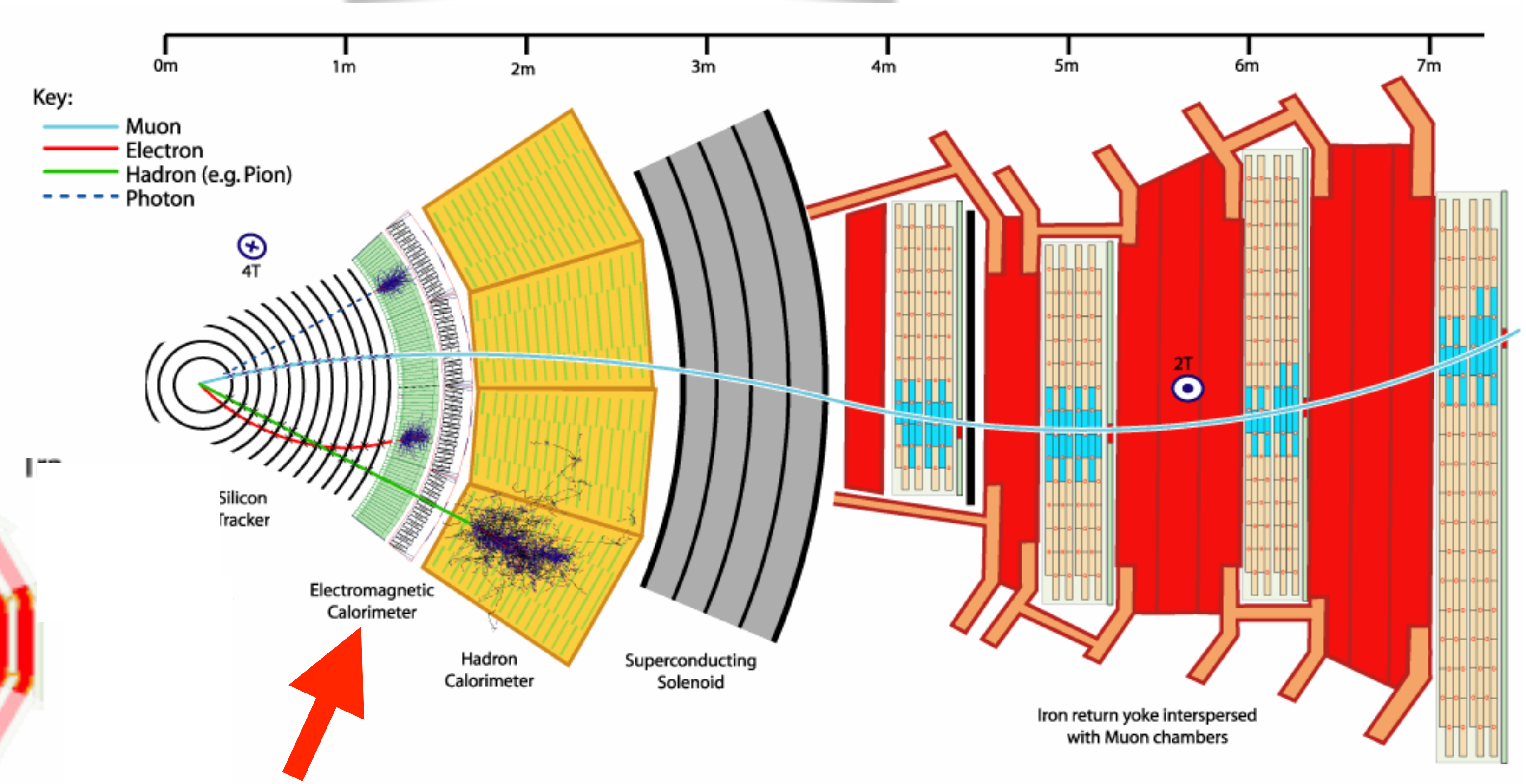
LHCb VeLoPix Module

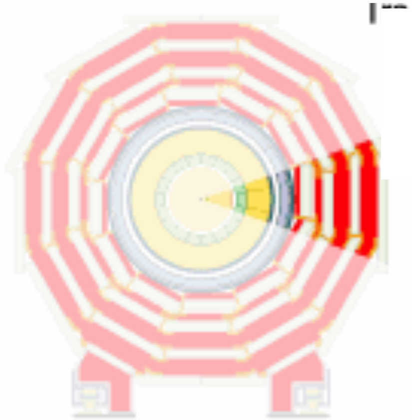


Calorimeter

Particle Physics Detector Overview

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





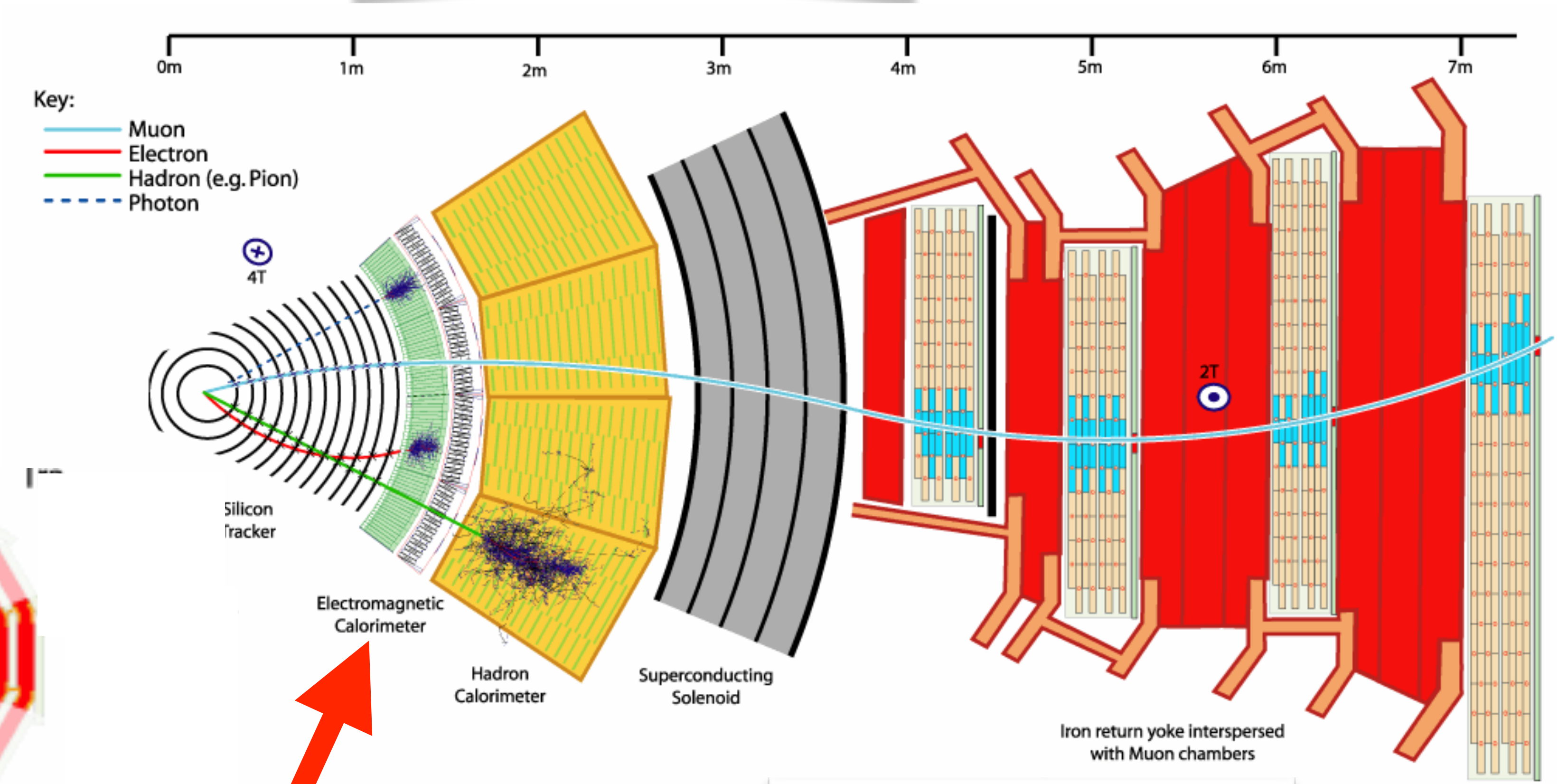
Transverse slice through CMS

Good energy resolution up to highest energies

picture: CMS@CERN

Particle Physics Detector Overview

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



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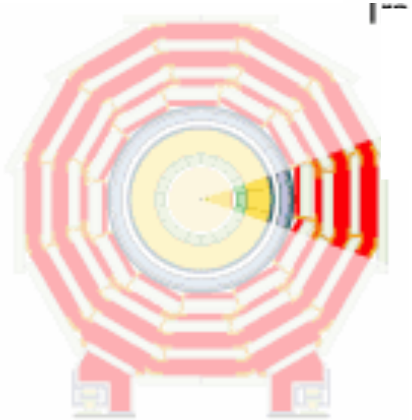


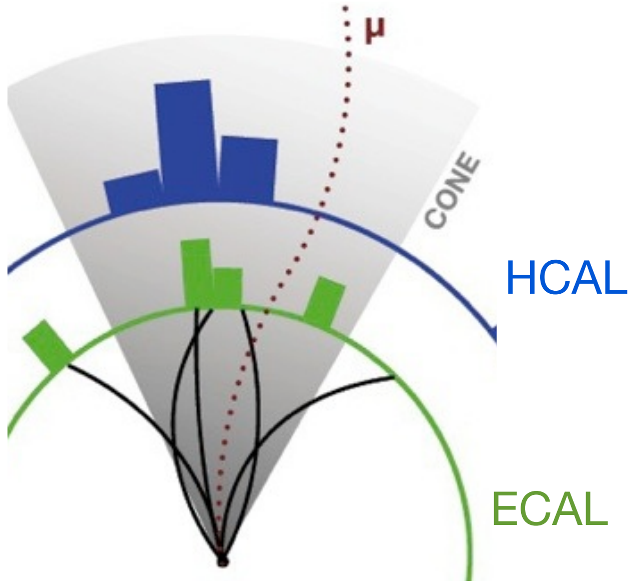
Transverse slice through CMS

Good energy resolution up to highest energies

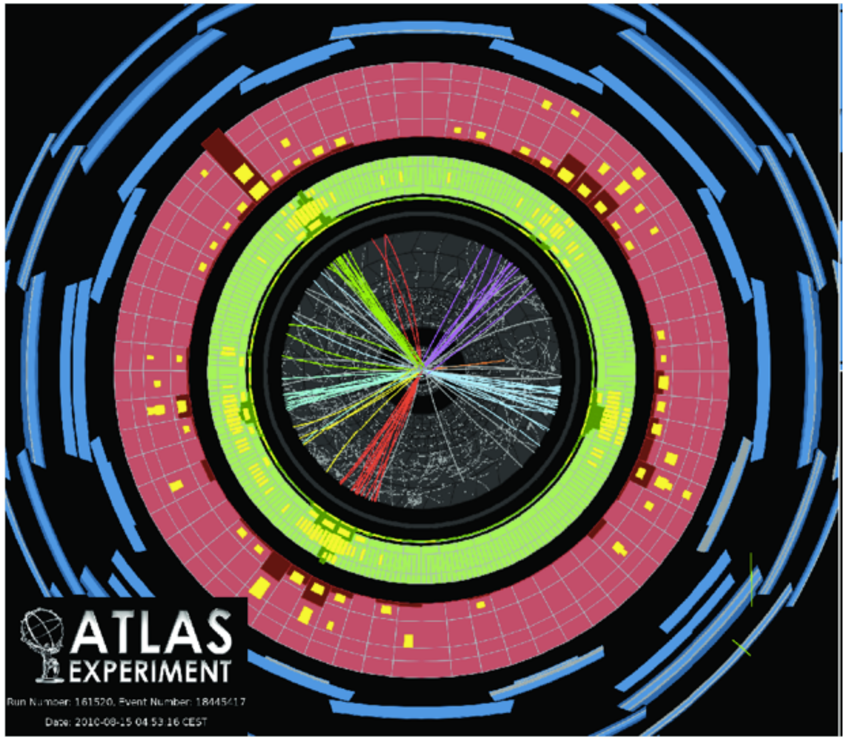
Radiation hard (hadron collider)

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



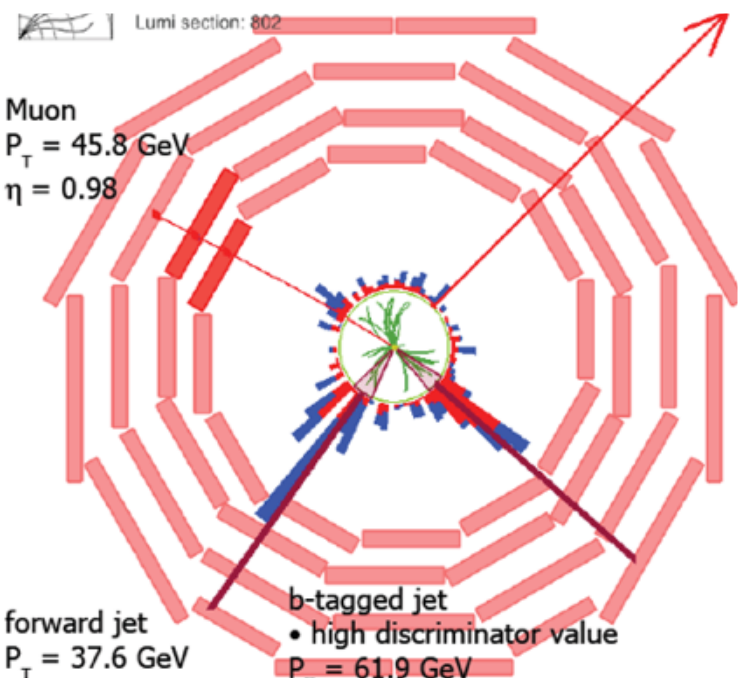
The limitations:

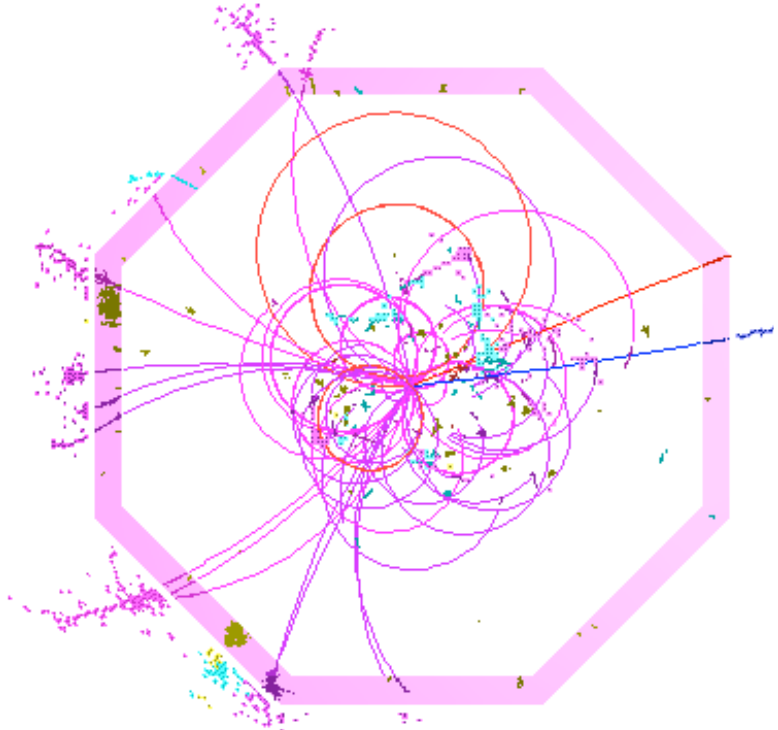
- Neutral hadrons, photons from neutral pion decay: Cannot just sum charged tracks
- The calorimeter with the worst energy resolution (the HCAL) drives the performance for jet measurements!

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

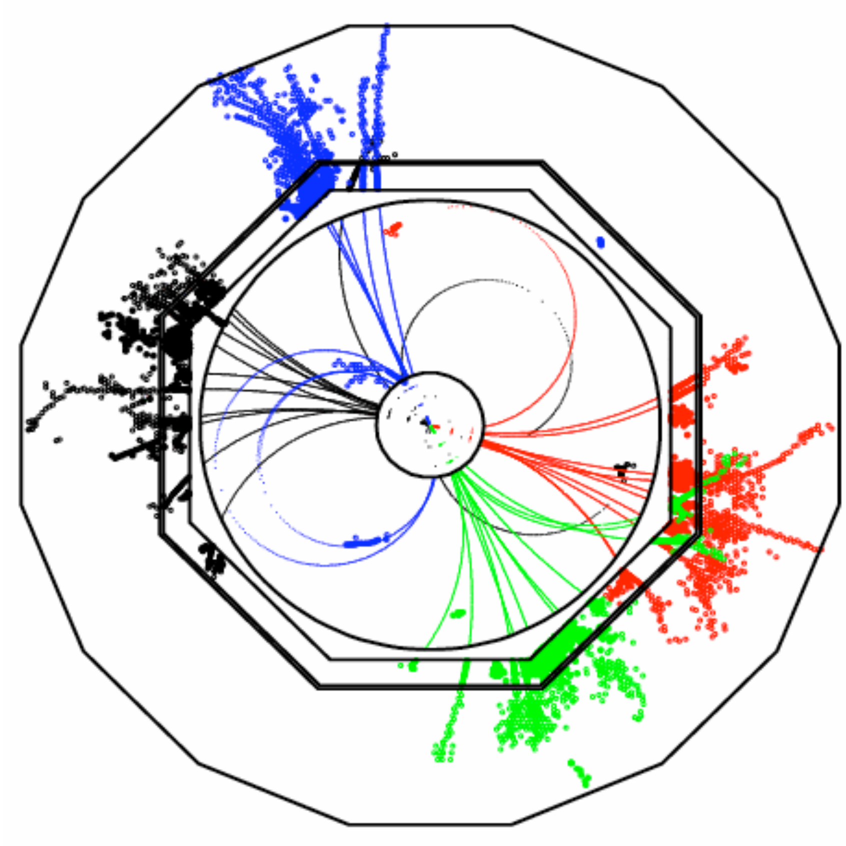
- **Two approaches:**
  - Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons: **Dual / Triple readout** calorimetry
  - Precise reconstruction of each particle within the jet, reduction of HCAL resolution impact: **Particle Flow** Algorithms & Imaging Calorimeters





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: provide good two-shower separation - Tungsten absorbers
    - Highest possible density: Silicon active elements - thin scintillators also a possibility
  - And: Sophisticated software!



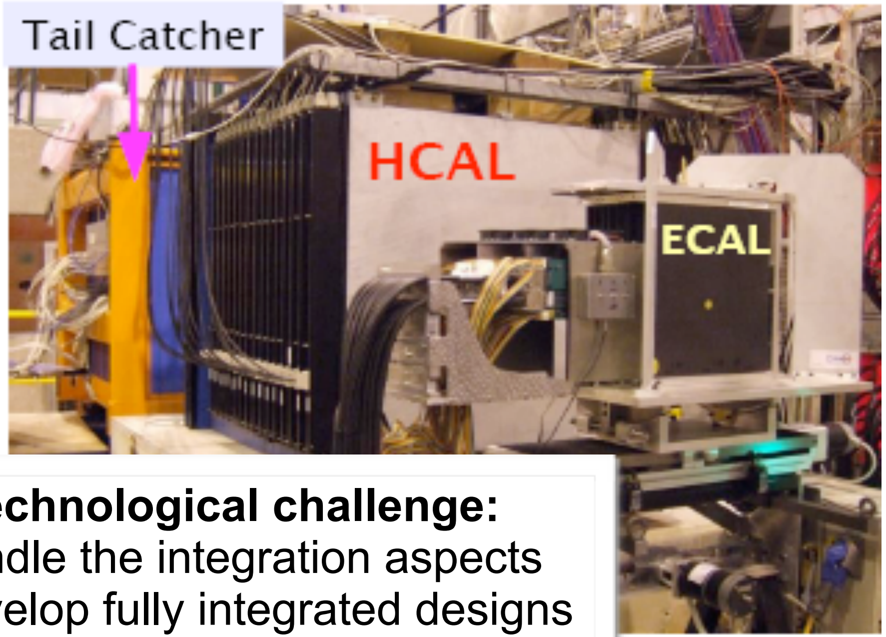
Extensively developed & studied for Linear Collider Detectors: Jet energy resolution goals (3% - 4% or better for energies from 45 GeV to 500 GeV) can be met

Scintillator Based Calorimeter

- 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$^{1/2}$

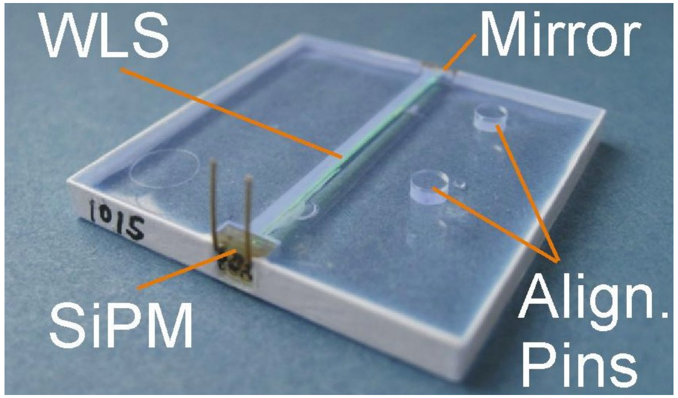
Silicon based photo detectors:

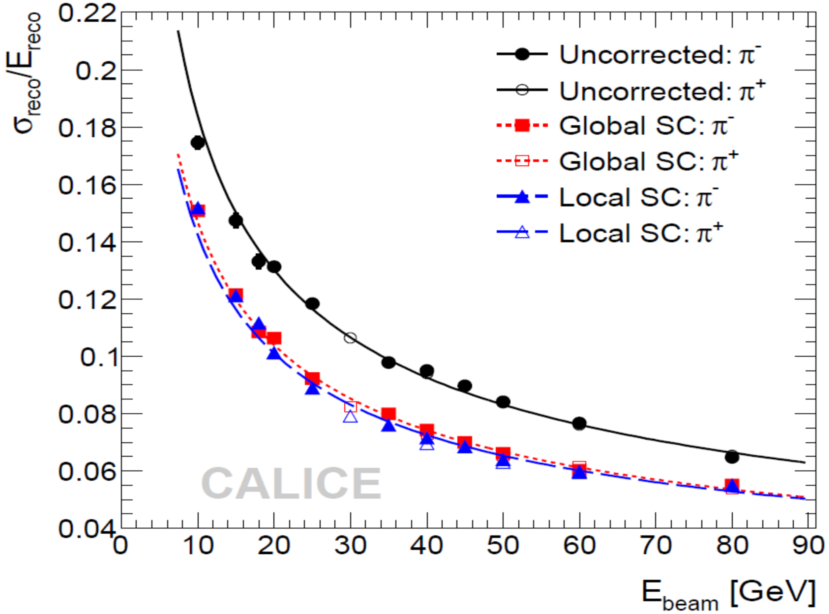
- Allow granular scintillator based detectors
- Applications in many other areas



Key technological challenge:

- Handle the integration aspects
- Develop fully integrated designs
- Handle the power issues
- Costs

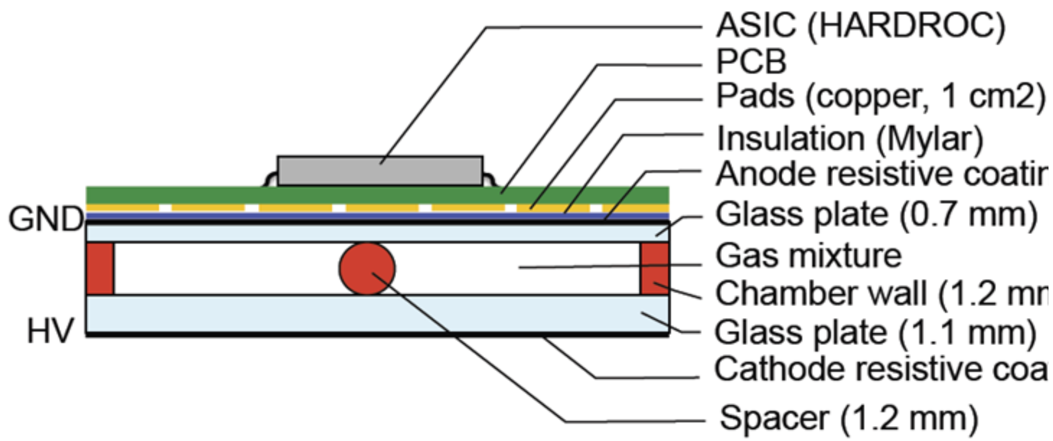


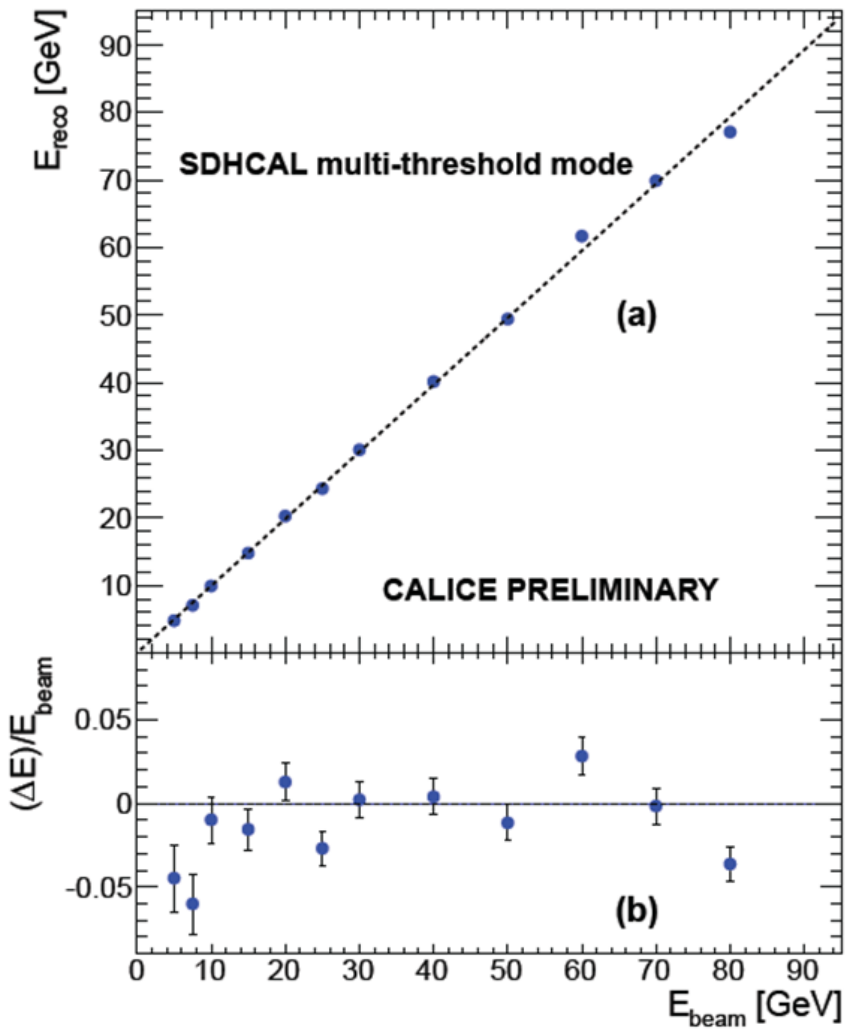


Digital Calorimetry

- 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
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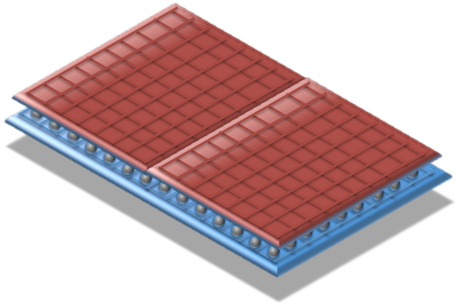
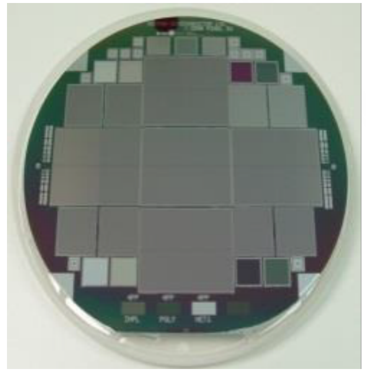
- Costs

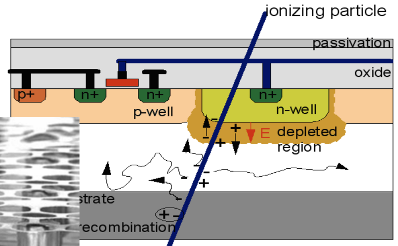
Active medium: gas RPC's

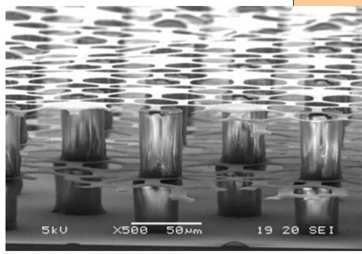
Conclusions

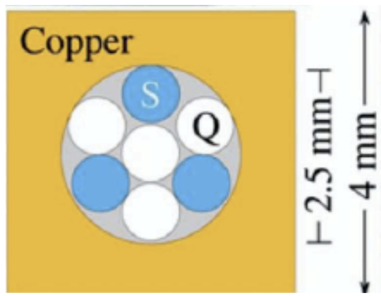
- Trends in technology enable to address the challenges in modern particle detectors
  - some trends. not independent
- Segmentation
  - Vertex elements with 20 µm and smaller features
  - Calorimetry employing silicon elements
  - Micro Pattern Gas Detectors (MPGD) applications
- Integration
  - Microelectronics
  - 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

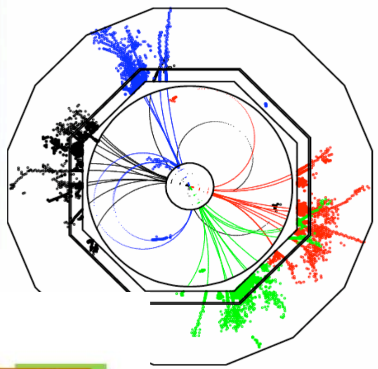












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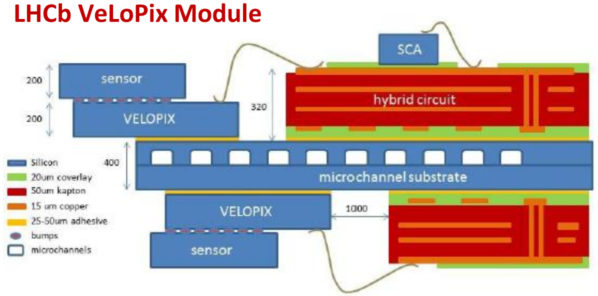

Performance Improvement

	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