Introduction a la session instrumentation

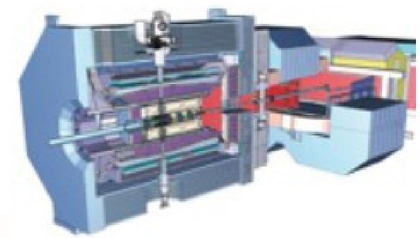
Thibault

Signal → Physical information

- Ionization - “free” charge
- Scintillation - “free” light
- Cherenkov radiation
- Transition radiation
- Magnetic induction
- Phonons, acoustic, heat
- ....?

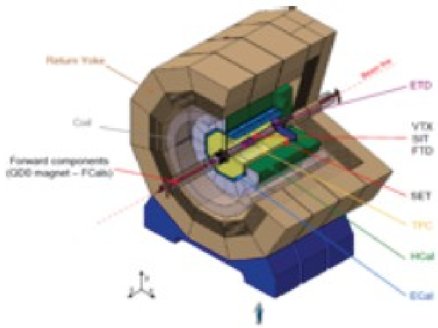
- Energy
- Momentum
- Velocity
- Trajectory direction
- Particle identification
- Charge
- Patterns
- Causality
- Time

Future experiments

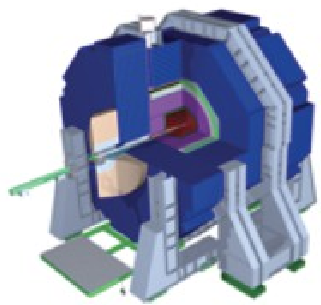


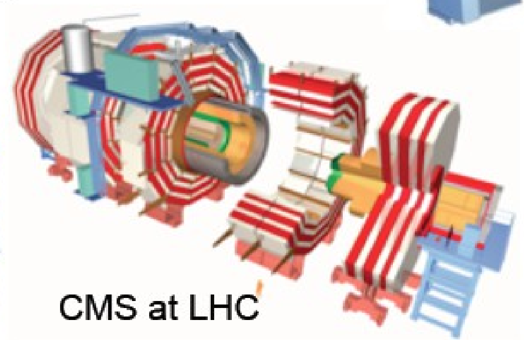
PANDA at FAIR

ILD at the ILC/CLIC



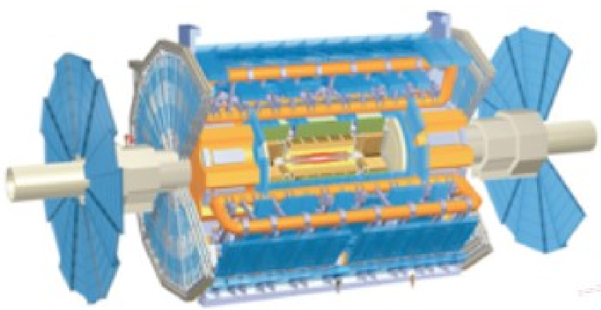
SiD at the ILC/CLIC



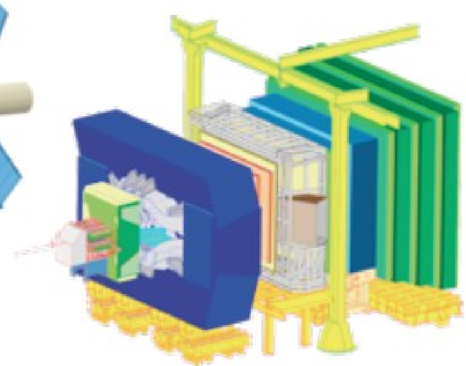


CMS at LHC

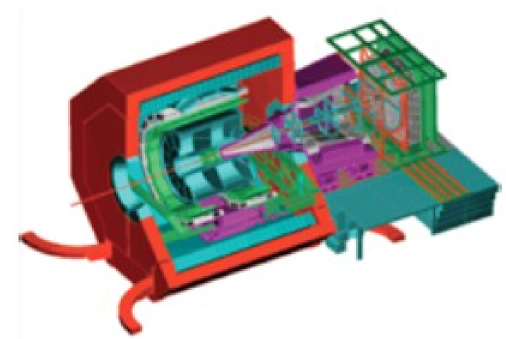
ATLAS at LHC



LHCb at LHC



ALICE at LHC



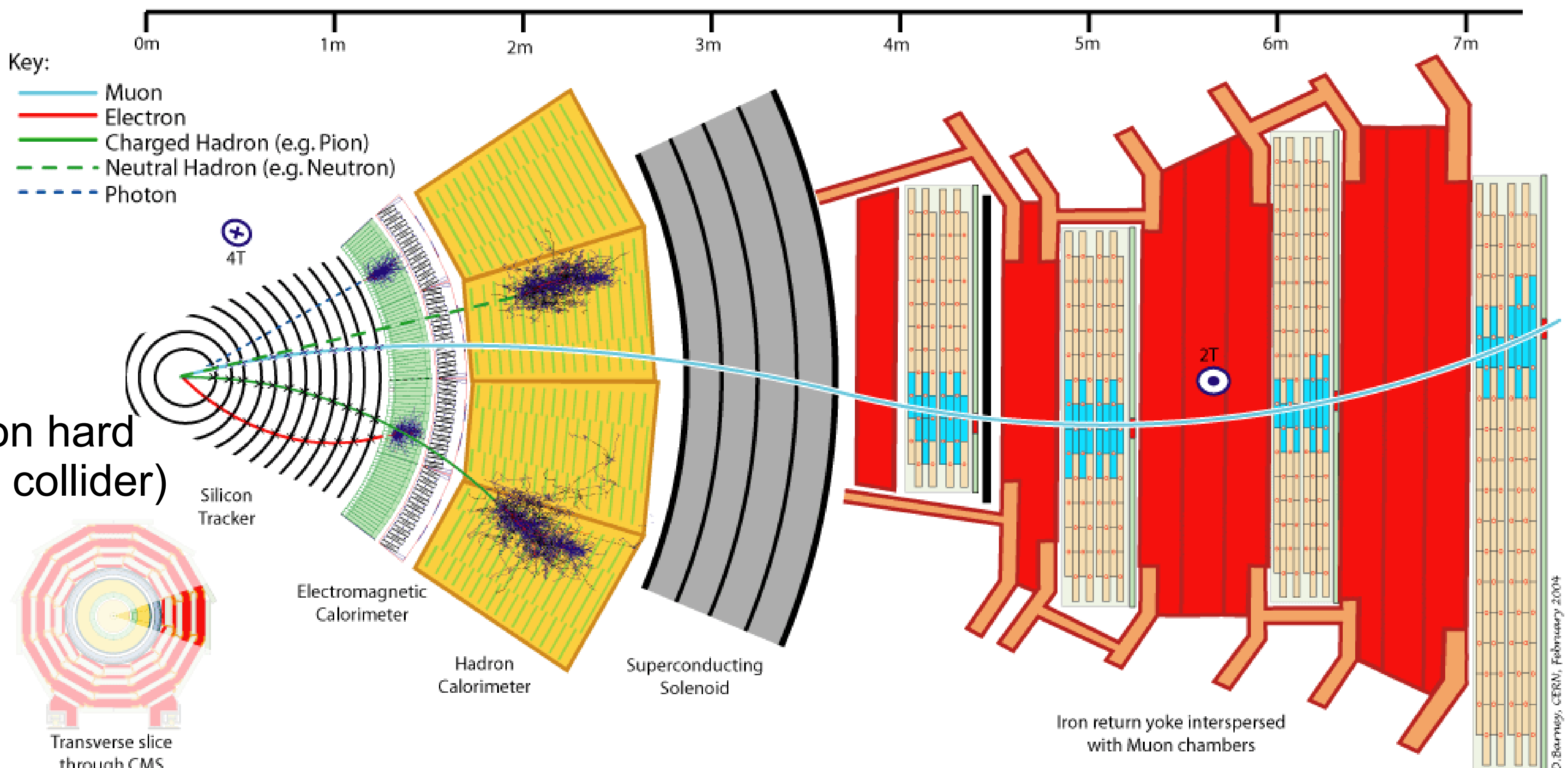
not to scale !!

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

Radiation hard
(hadron collider)

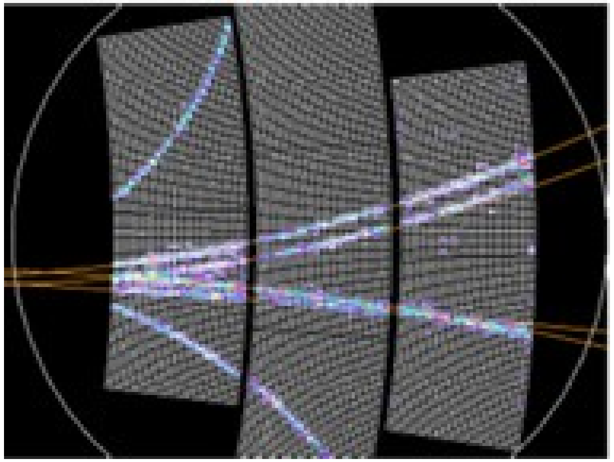


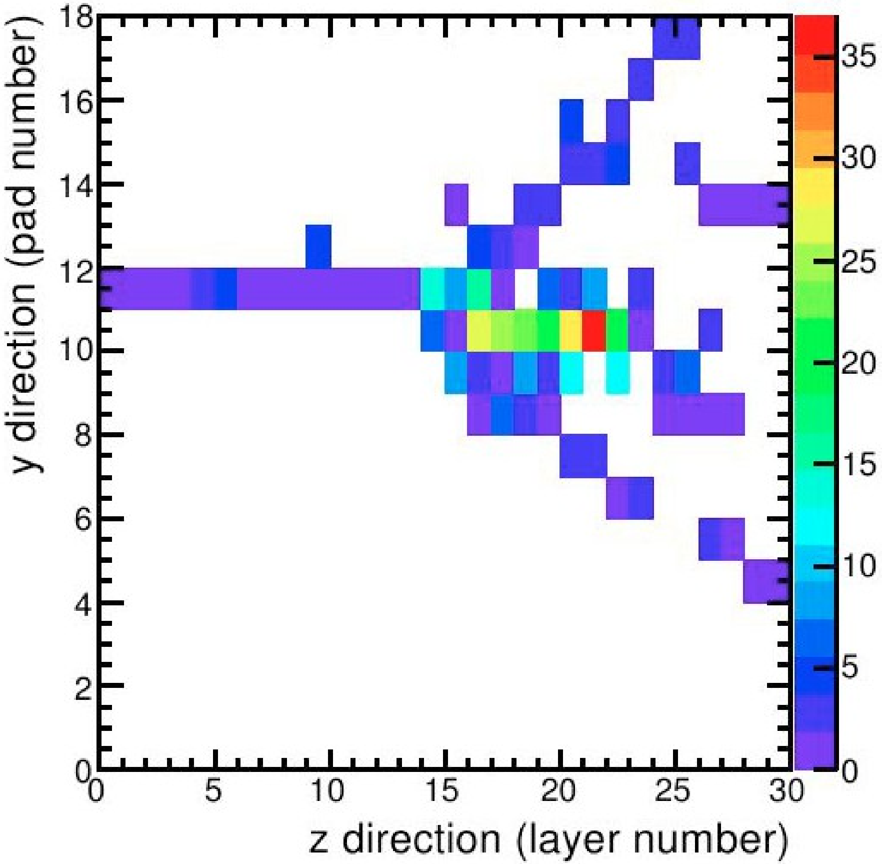
Good energy resolution up to highest energies

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

Challenges

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





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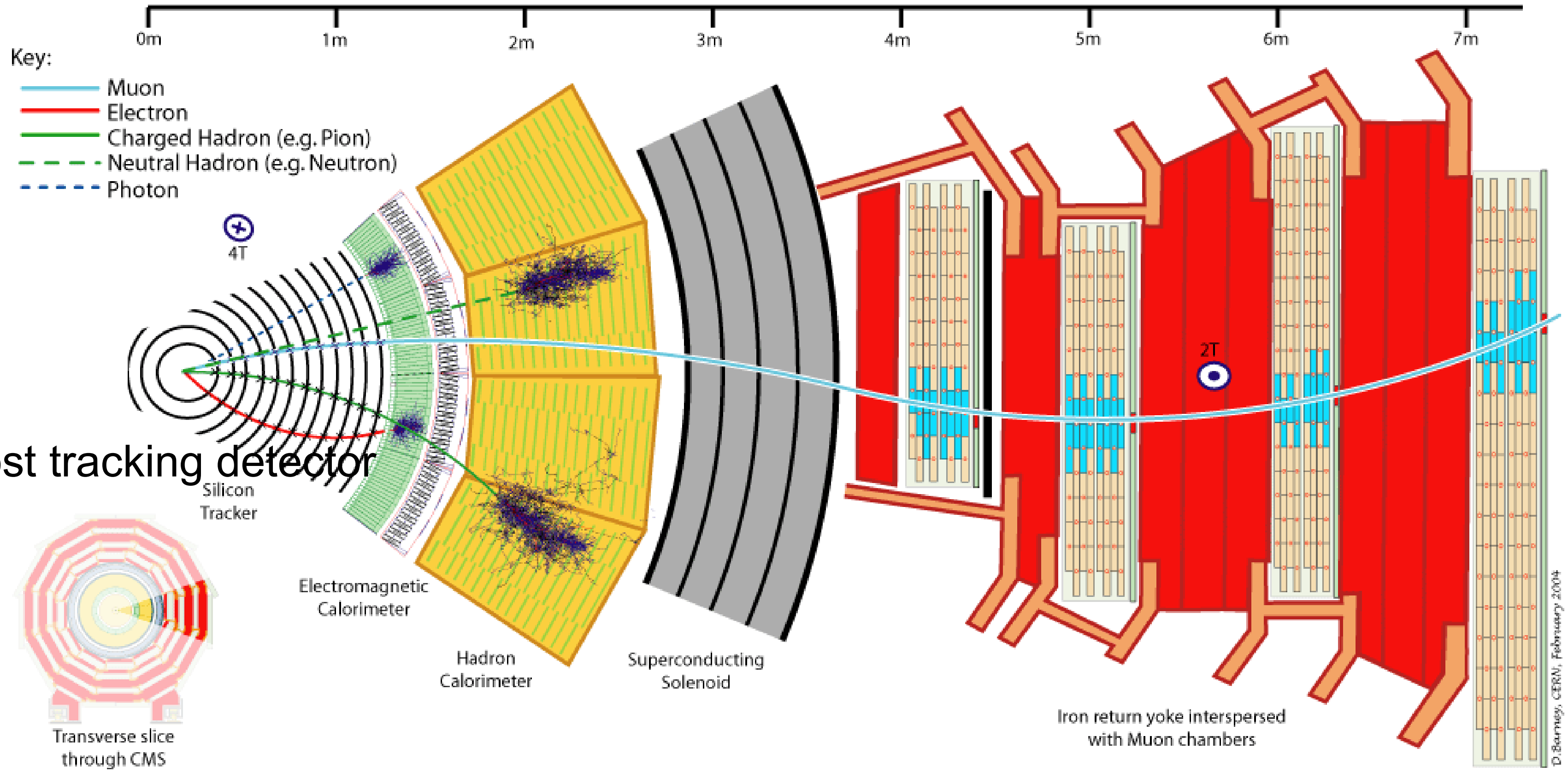


Vertex:
Innermost tracking detector

Good energy resolution up to highest energies

Muon-Detectors: Trackers...

Vertex detector

- **Main challenge:** identify c quark and 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

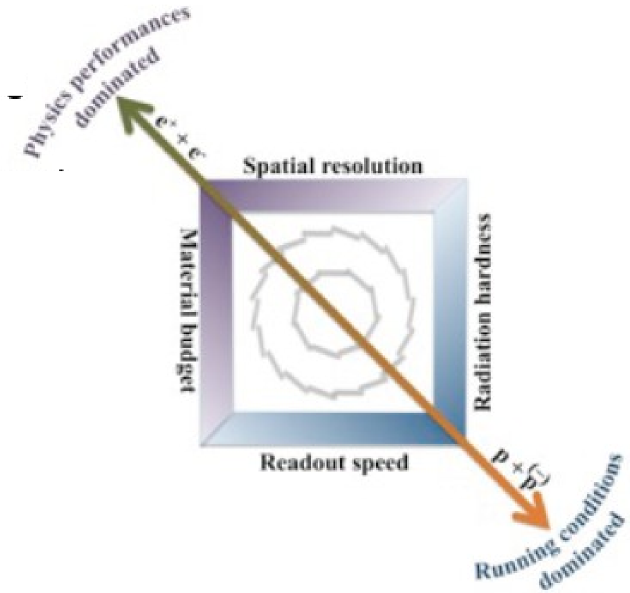
Perfect pixels:

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

Optimising

Conflict between physics performance driven parameters and running condition constraints:

- Physics performance: spatial resolution (small pixel) and material budget (thin sensors)
- 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

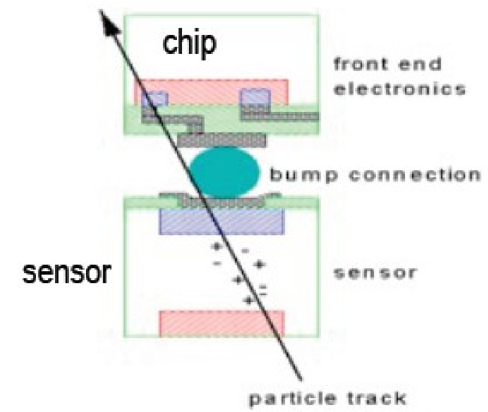
- each facility & experiment requires dedicated optimisation (hierarchy between physics requirements and running constraints
- there is no single technology best suited to all applications
- explore various technological options
- motivation for continuous R&D (optimum is strongly time dependent)

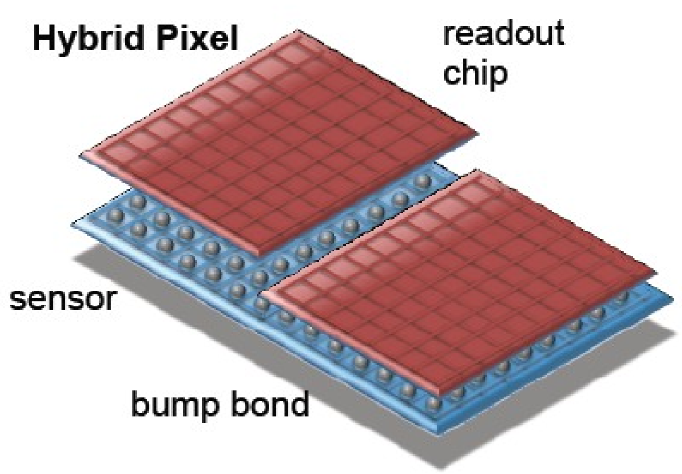
Hybrid pixels

- 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





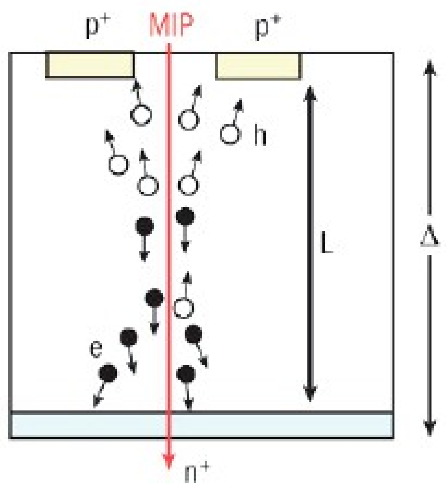
CMS Pixels (current and upgrade)
ATLAS Pixels (current and upgrade)
Alice: 50 μm x 425 μm
LHCb VELO (upgrade)
Phenix upgrade
CBM @FAIR
PANDA @FAIR

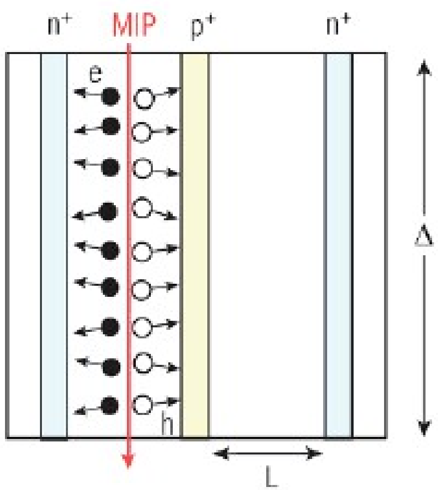
Sensor for hybrid pixels

Planar Sensor
- current design
- 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

CVD (Diamond)
- Poly crystalline and single crystal
- Low leakage current, low noise
- Radiation hard material
- Operation at room temperature possible
- Drawback: 50% signal compared to silicon for same X0 but better S/N ratio

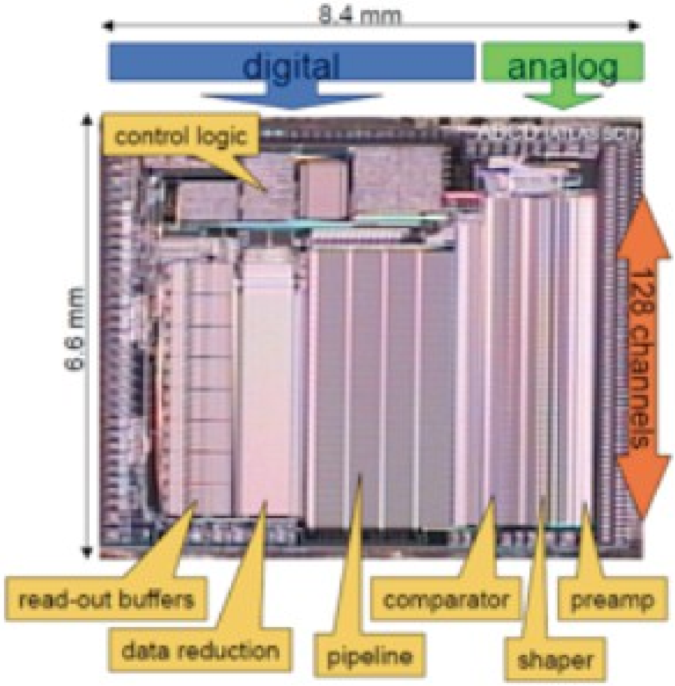




Very strong R&D efforts to develop sensors for future LHC applications!

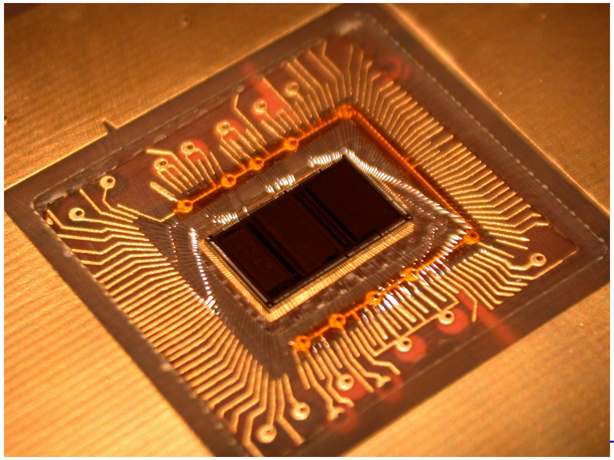
FE Chip development

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

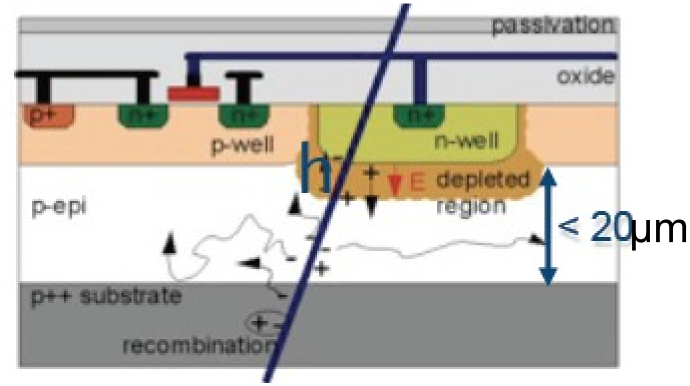


Integration density is growing rapidly

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



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

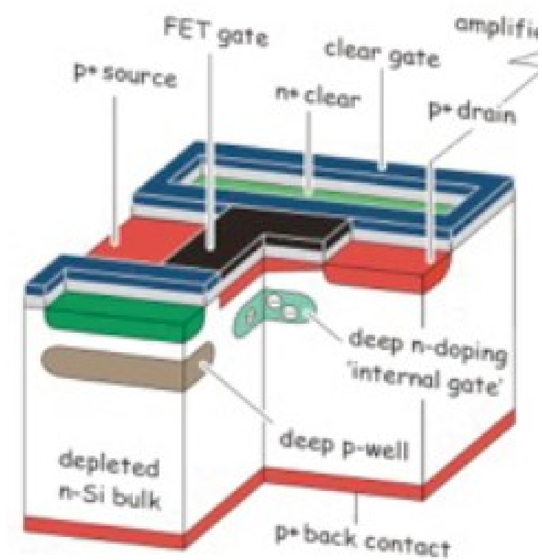
Four different technologies under study for ILC vertex detector

- 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?



DEPFET

More tracker

Tracking system extend in multiple layers up to the magnet/calorimeter

- Pixel detectors too expensive, too difficult to make, too much material to cover this area
- Further tracking detectors needed

HL-LHC inner tracker:

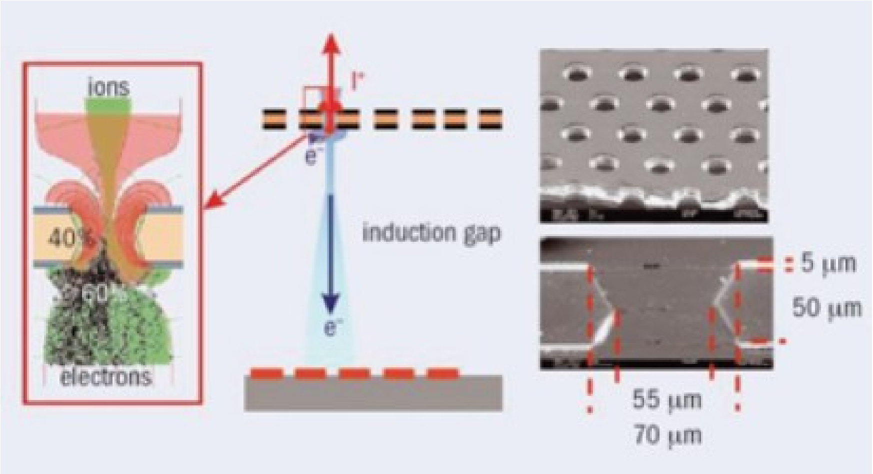
- radiation hardness, rate, material budget
- solution: silicon tracking detectors

Other experiments:

- gaseous detector, fibre tracker, ….

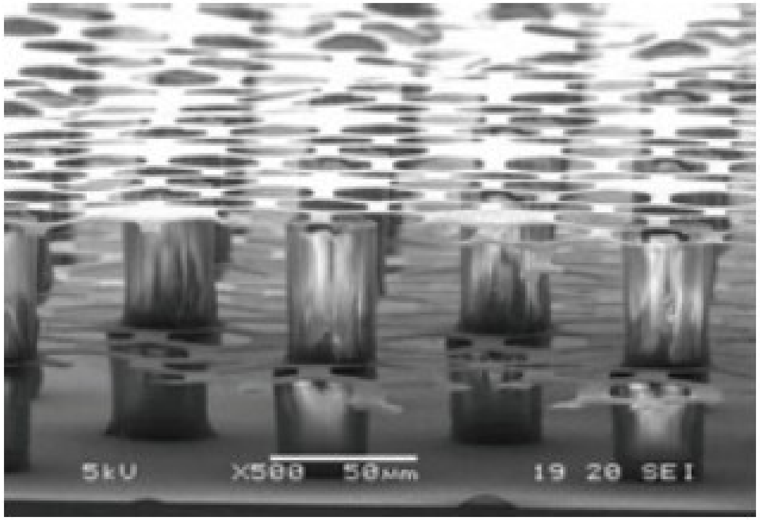
Gaseous detectors

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



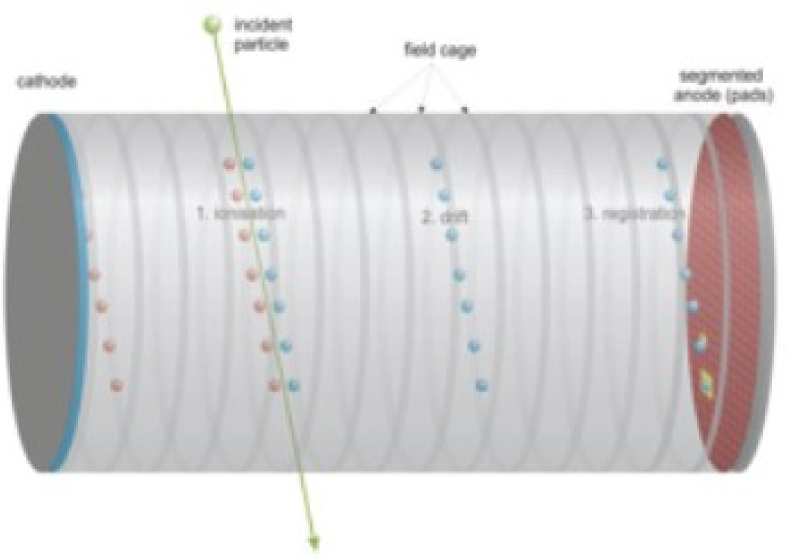
Applications in

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



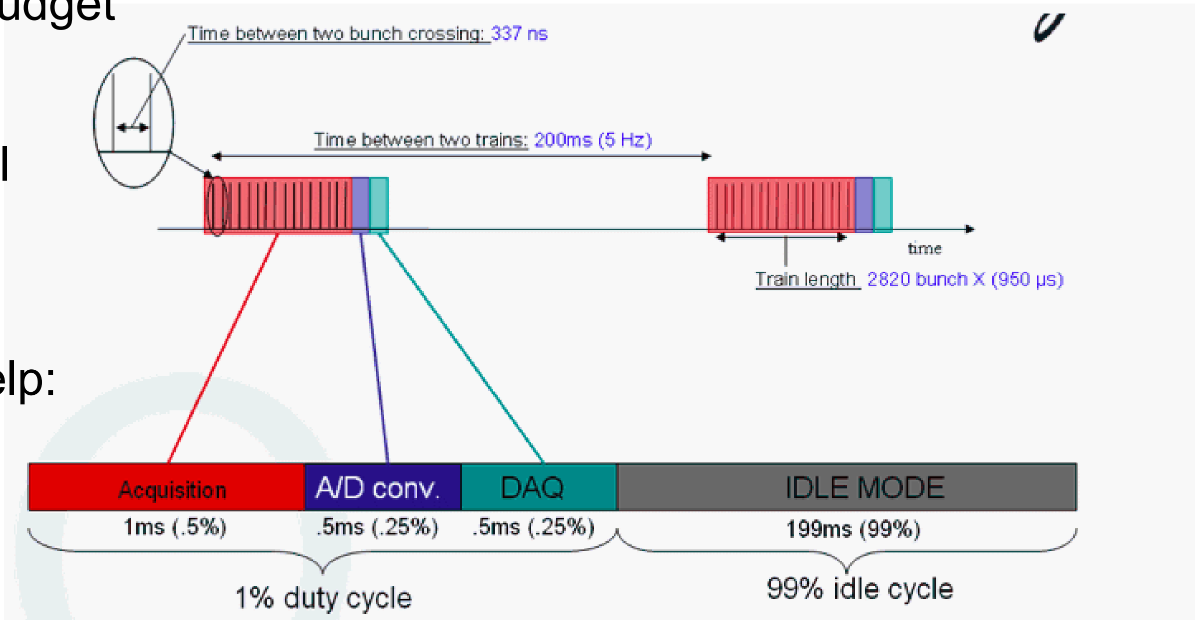
Time Projection Chamber

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



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)

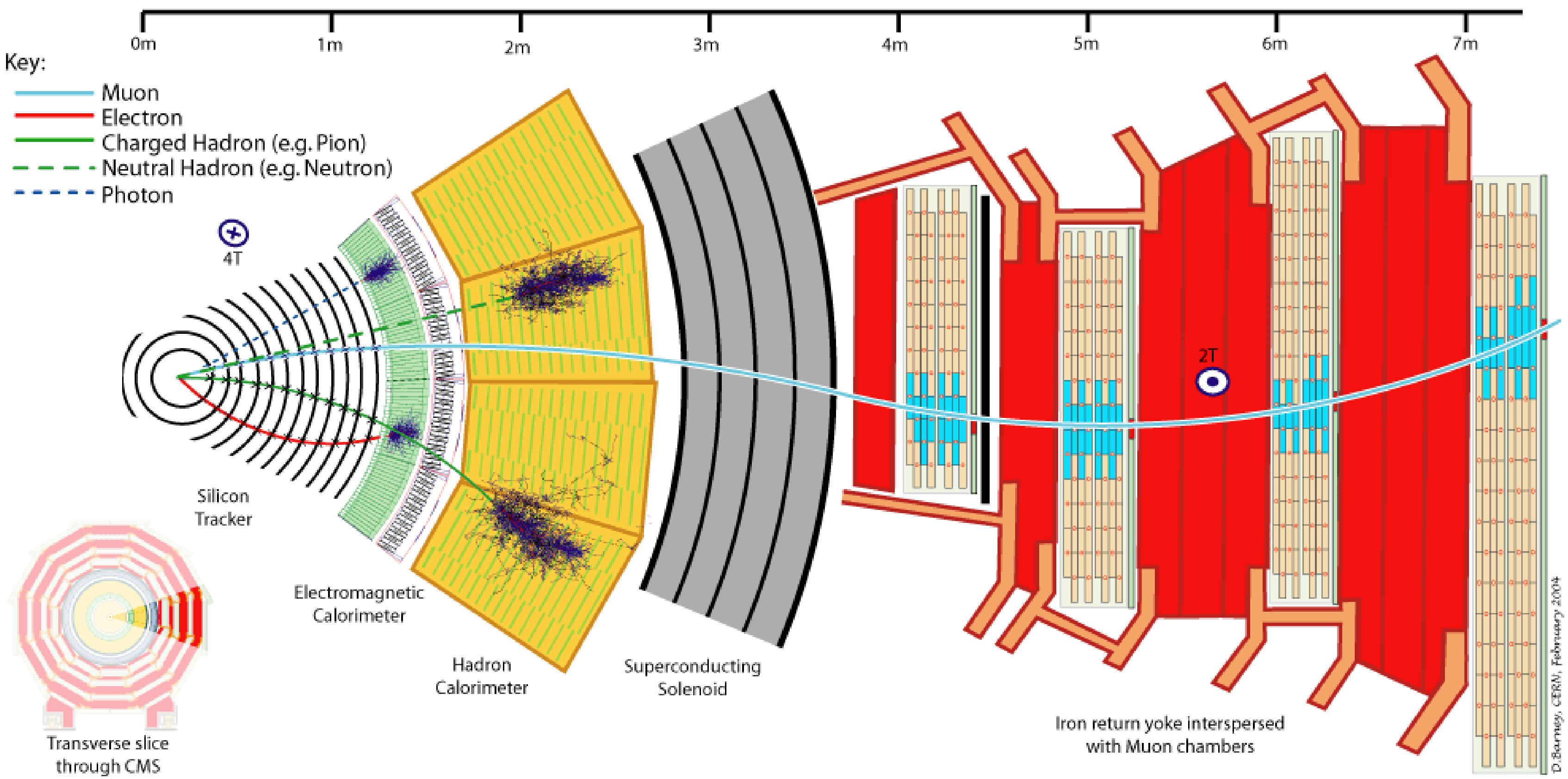


Cooling:
- LHC detectors need to cool silicon sensors extremely low
  - CO_2 cooling current solution
- micro-channel cooling for some detectors a solution
- for non-LHC detectors air cooling an option:
  - low mass
  - sufficient for ILC/ CLIC conditions?

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

Particle Physics Detector Overview

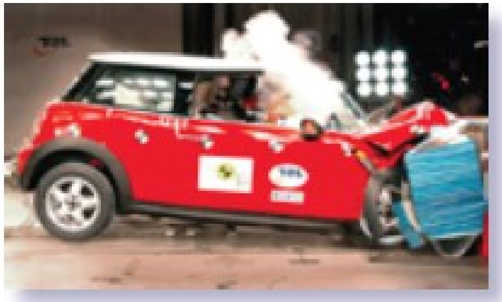
Calorimeter:
Energy measurement of photons, electrons and hadrons through total absorption

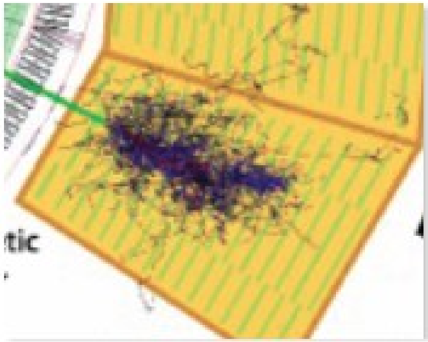


Good energy resolution up to highest energies

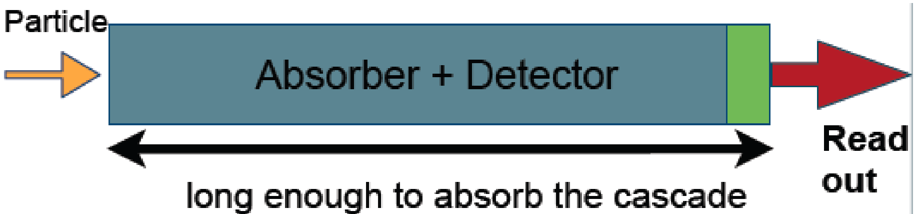
Calorimetry

- 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")

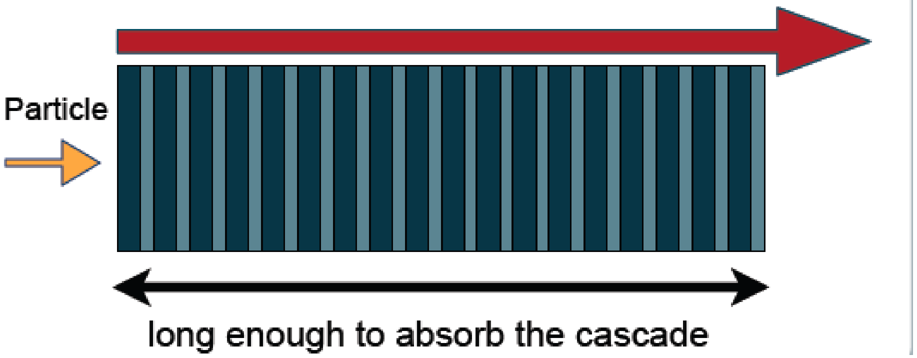




Homogeneous Calorimeter :
The absorber material is active
The overall deposited energy is converted into a detector signal



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



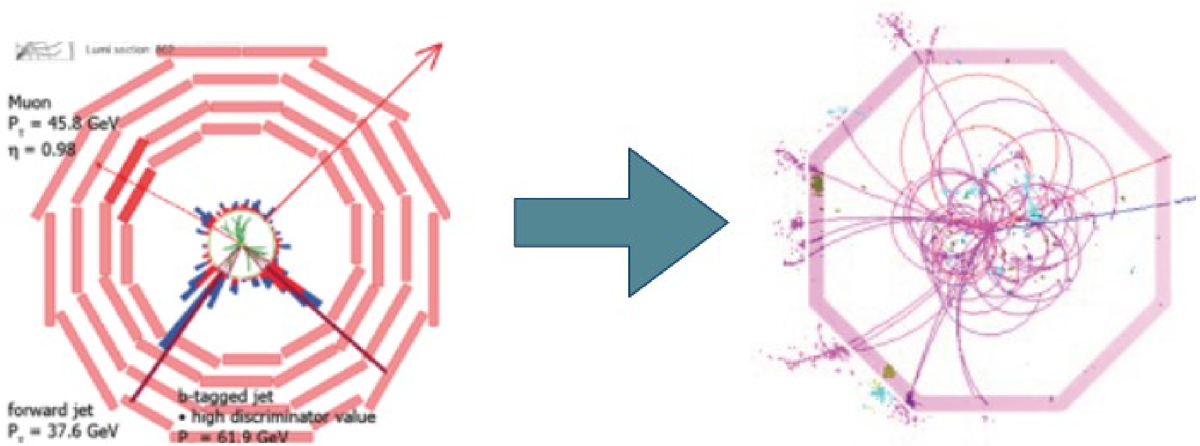
Frontiers in HEP calorimetry

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:

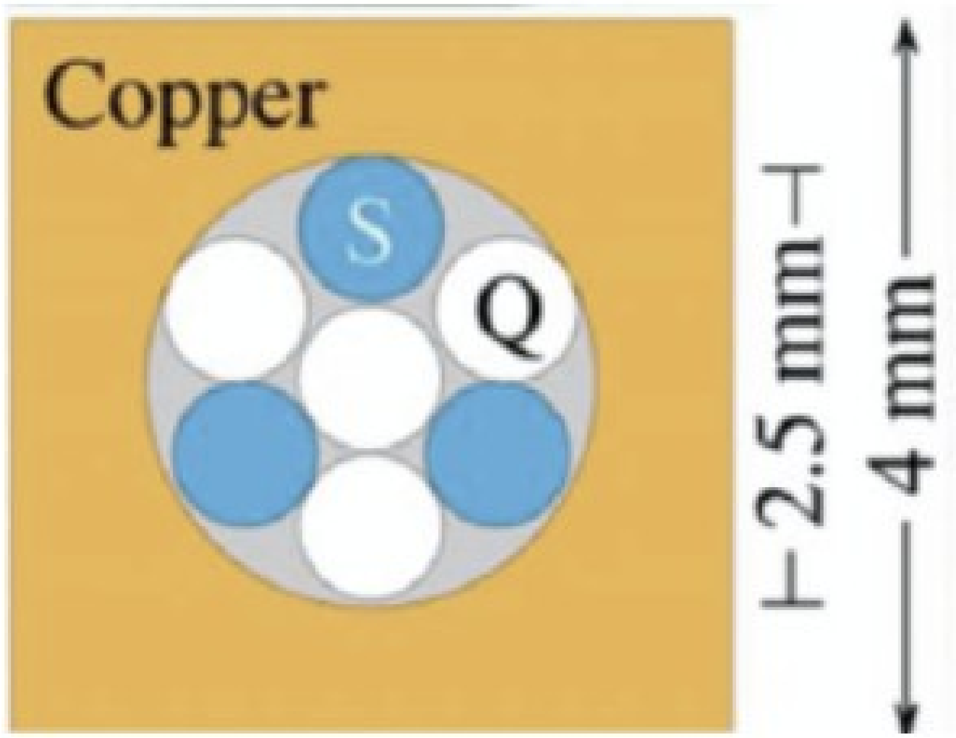
- Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons: Dual / Triple readout calorimetry
- Precise reconstruction of each particle within the jet, reduction of HCAL resolution impact: Particle Flow Algorithms & Imaging Calorimeters



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

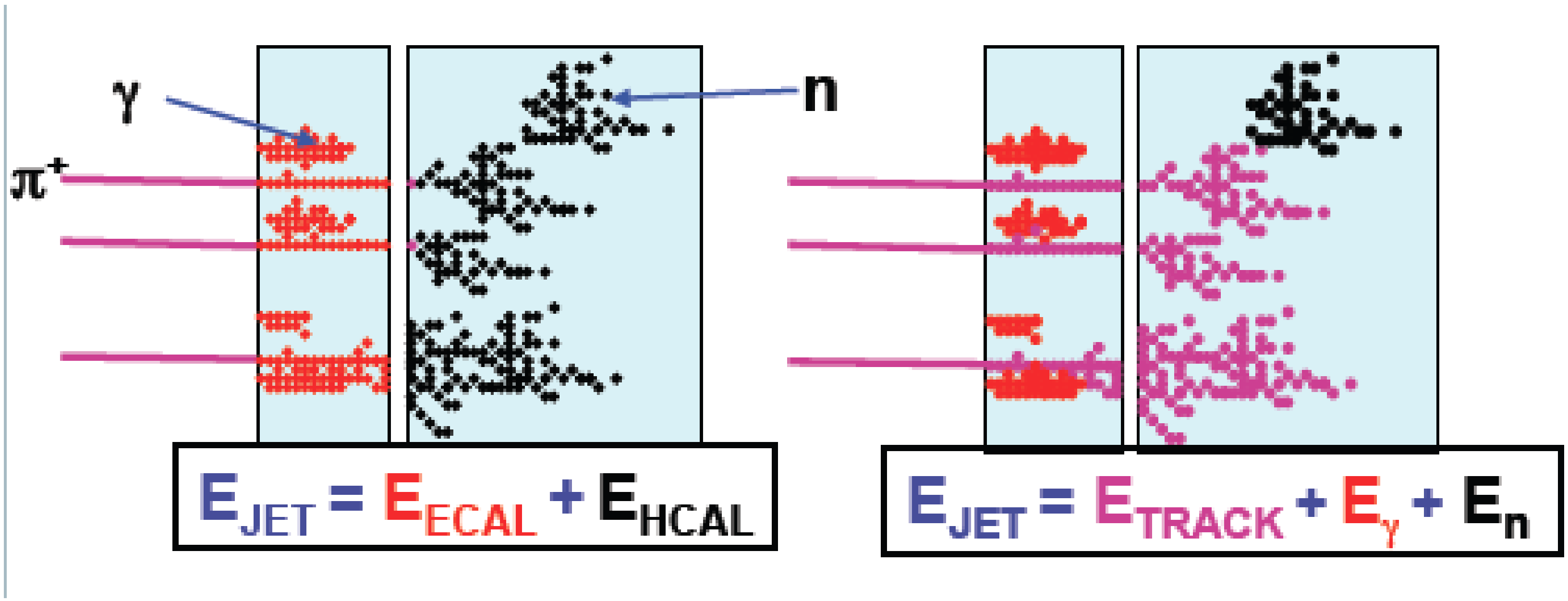
- Very different e/h: S ~ 1.4, Q ~ 5
- Energy reconstructed by combining scintillator and Cherenkov signals: event-by-event correction for em-fraction



Particle flow

Improve jet energy reconstruction by measuring each particle in the jet with best possible precision

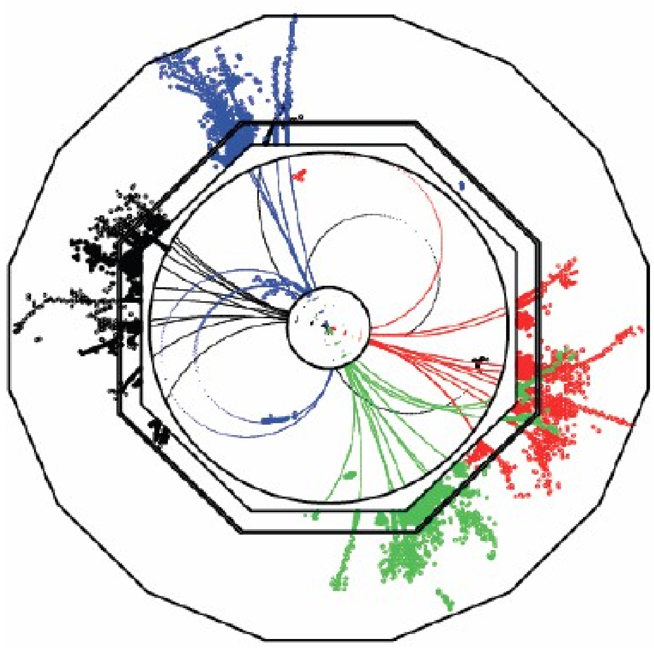
- Measure all charged particles in the tracker (60% charged hadrons)
- Significantly reduce the impact of hadron calorimeter performance: Only for neutral hadrons
- Measure only 10% of the jet energy with the HCAL, the “weakest” detector: significant improvement in resolution



Imaging calorimeters: 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!



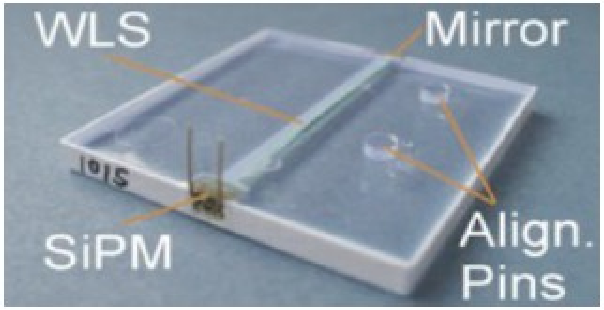
Extensively developed & studied for Linear Collider Detectors:
Jet energy resolution goals (3% - 4% or better for energies from 45 GeV to 500 GeV) can be met

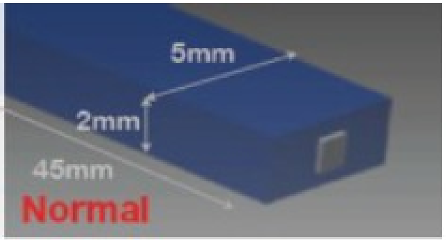
Scintillator based calorimeter

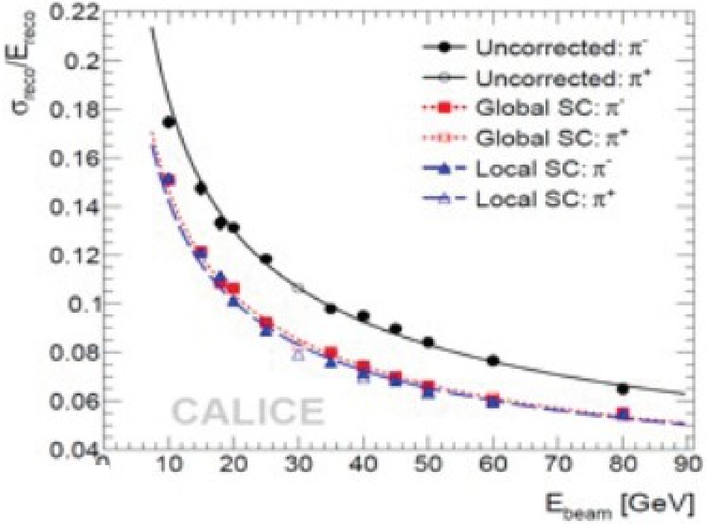
Availability of SiPM allows highly granular scintillator based designs

HCAL: 3x3 cm^2 segmentation of 3 mm 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$^{1/2}$





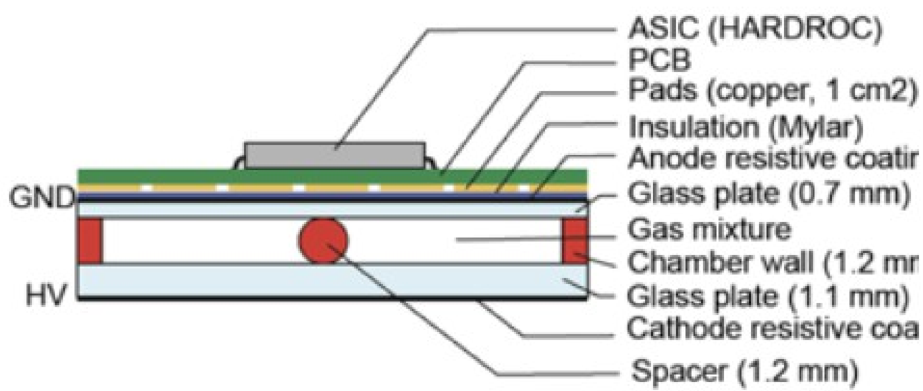


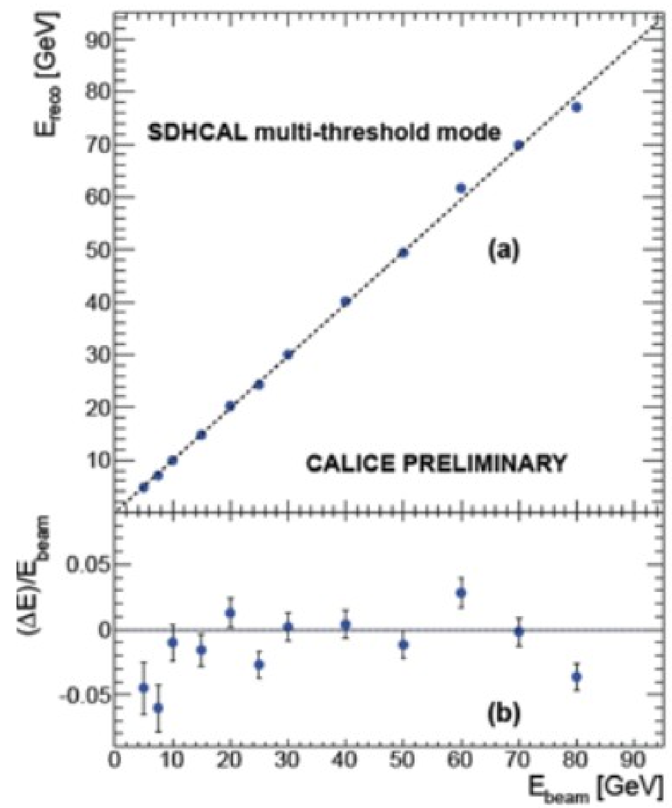
Key technological challenge:
- Handle the integration aspects
- Develop fully integrated designs
- Handle the power issues
- Costs

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.





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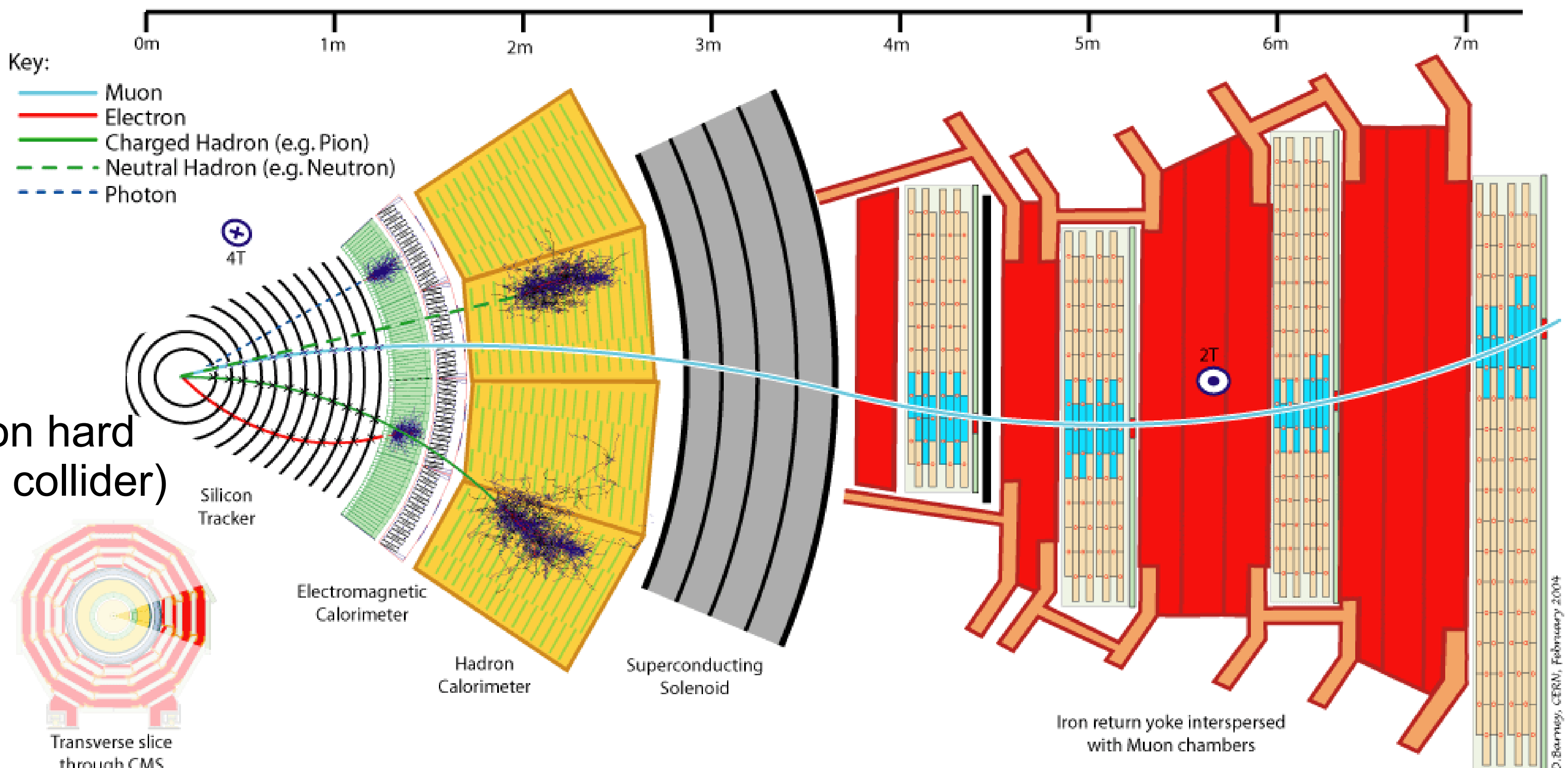

Good energy resolution up to highest energies

<u>Muon-Detectors:</u>
Identification and precise momentum measurement of muons outside of the magnet.

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

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

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 ~105 Gb/s total bandwidths
- LHCb/ILC detectors: full triggerless operation, all data shipped to data acquisition

Integrate optical communication on the chips

Conclusion

Not only big experiments....

Vous en avez assez des personnes qui vous envoie des dizaines de pages de corrections sur votre dernière note alors que vous ne les connaissez pas ?

Vous en avez assez de vous battre pour présenter vos résultats dans votre WG ?

Vous en avez assez que Georges soit le 1er auteur de tous vos papiers ?

==> Construisez votre propre expérience
==> Prenez et analysez vos propres données