Tracking Detectors for Collider Experiments

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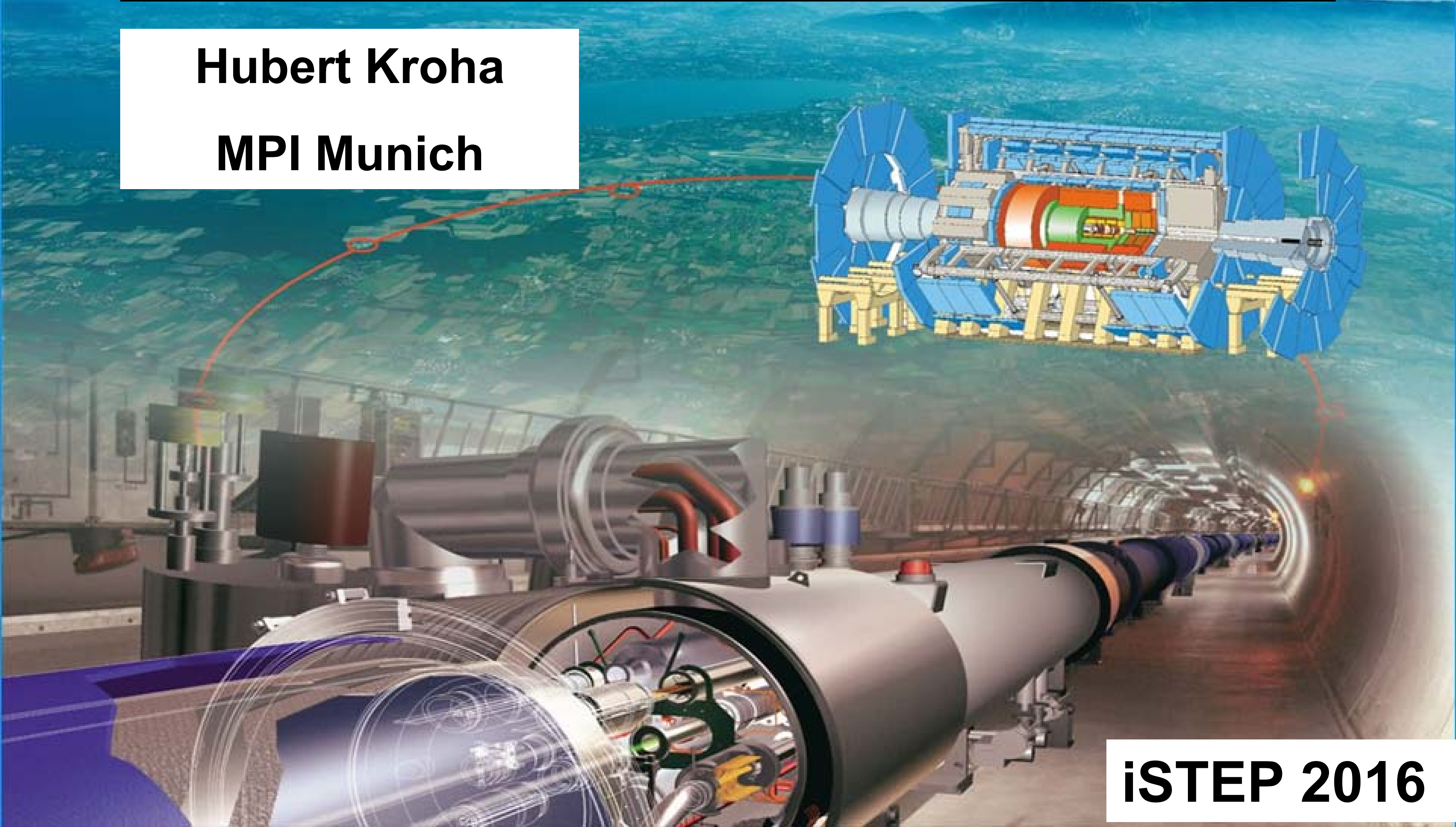


iSTEP 2016

Overview

- Detector concepts and systems at e^+e^- and pp colliders of the past 30 years and for the future.
- Charged particle inner tracking detectors:
  - Gaseous detectors
  - Solid state semiconductor (crystalline silicon) detectors
- Outer muon tracking and trigger detectors
  - Gaseous detectors
- Challenges in detector technology at the Large Hadron Collider (LHC)
- Challenges for future high-luminosity & high- energy colliders

Collider Detector Concepts and Systems

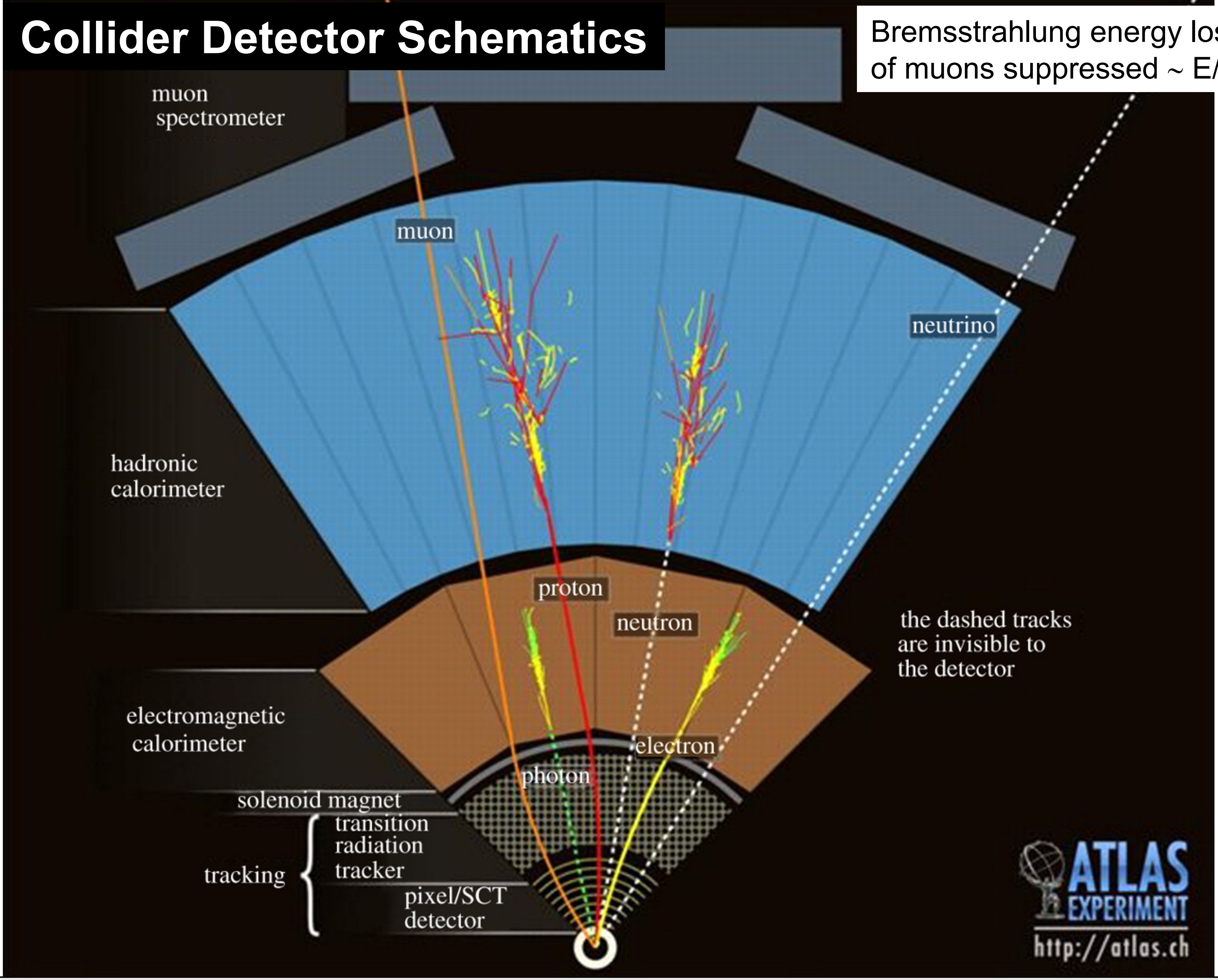
- Hermetic detectors, coverage of almost thefull solid angle around the interaction point.
- Concentric cylindrical detector layers in the central "barrel" part, closed by endcap wheels (disks) in the forward/backward directions.

- Detectors at high-energy $e^+ e^-$ colliders: LEP and beyond.
- Detectors at hadron colliders:

Tevatron (pp), LHC and high-luminosity (HL)-LHC (pp), future pp colliders.

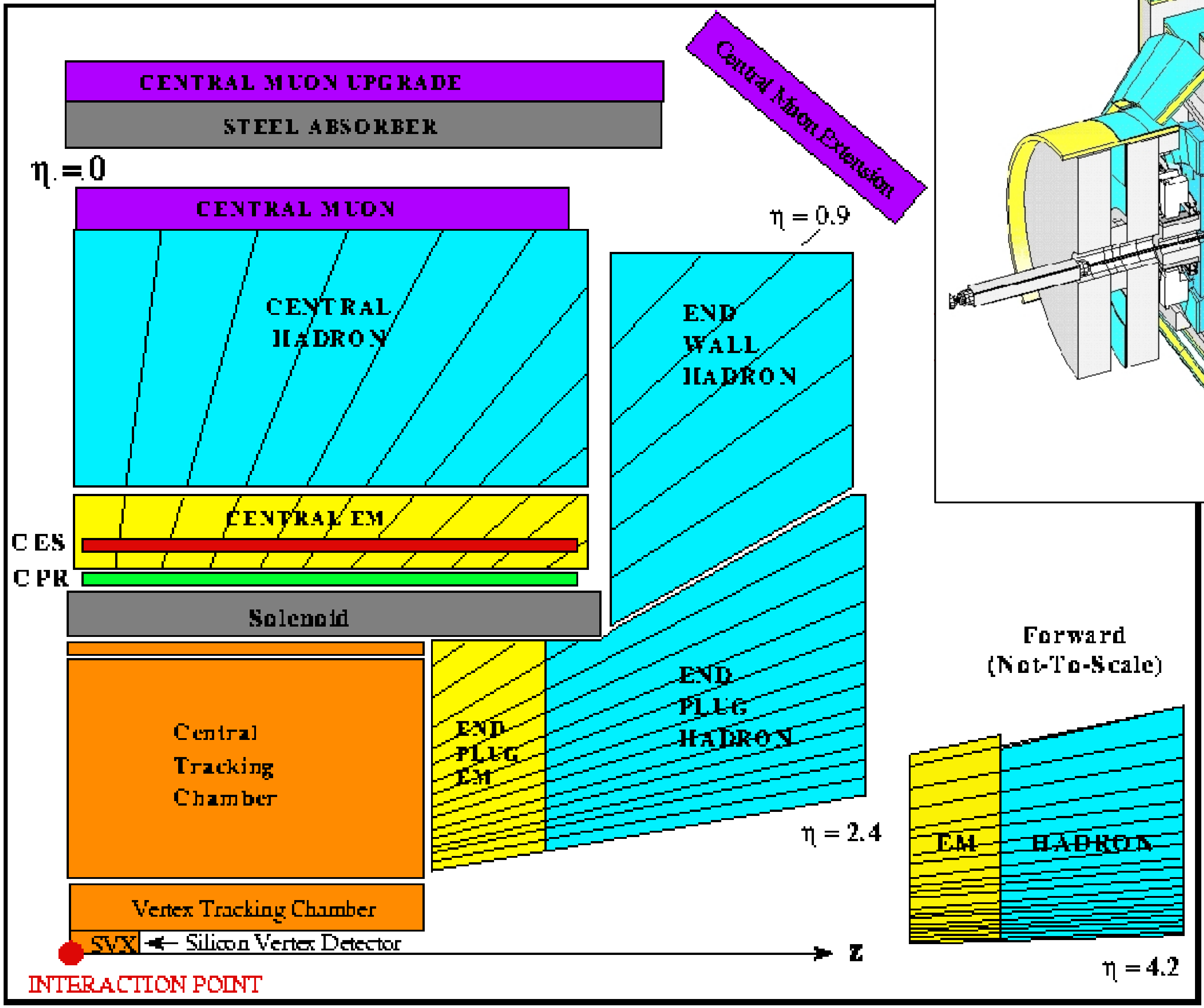
Collider Detector Schematics

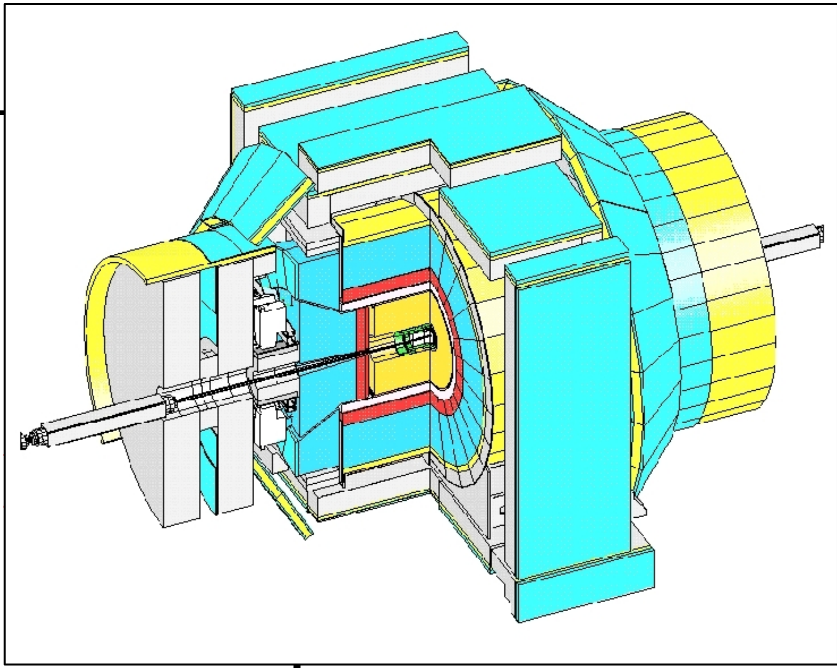
Bremsstrahlung energy loss of muons suppressed ~ E/m^2



Collider Detector Schematics

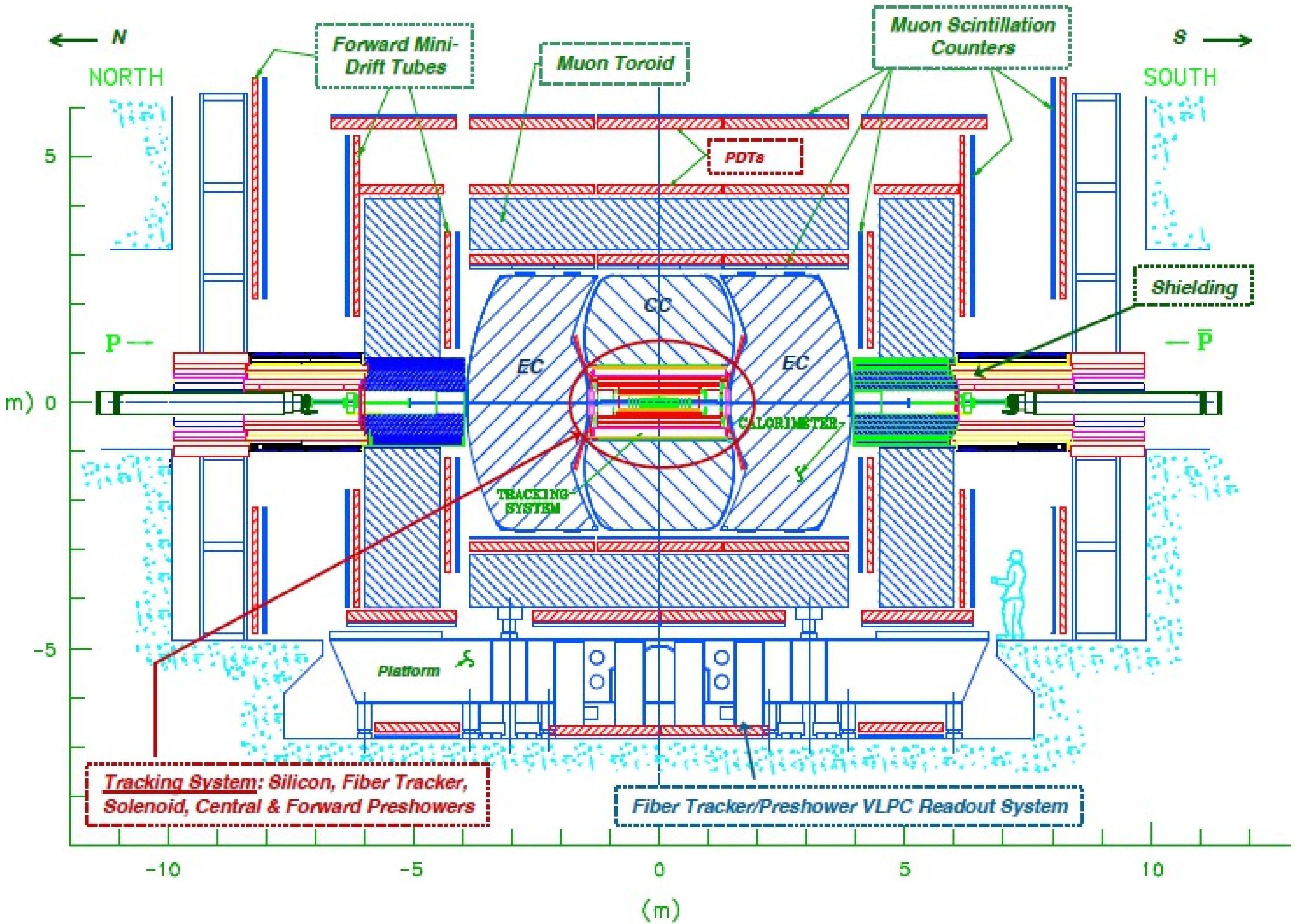
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$





The CDF Detector at the Tevatron

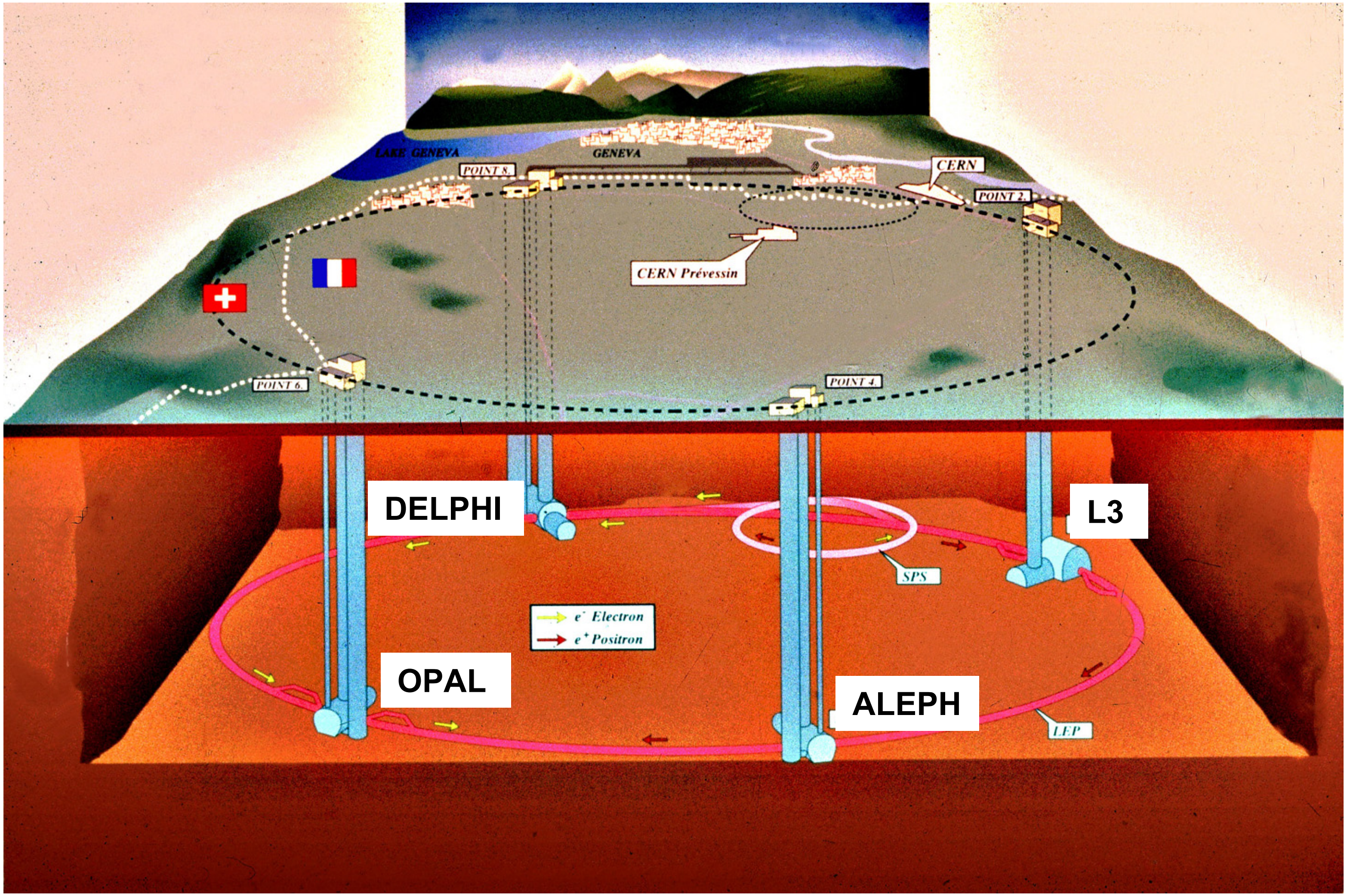
The D0 Detector at the Tevatron



Examples: Electron-Positron Colliders

LEP at CERN, the largest so far, 27 km circumference, 1989-2000.

Electroweak precision measurements at the Z resonance, and above up to 208 GeV.



LEP detectors: first collider experiments with full solid angle coverage

A typical LEP experiment: **The ALEPH Detector**

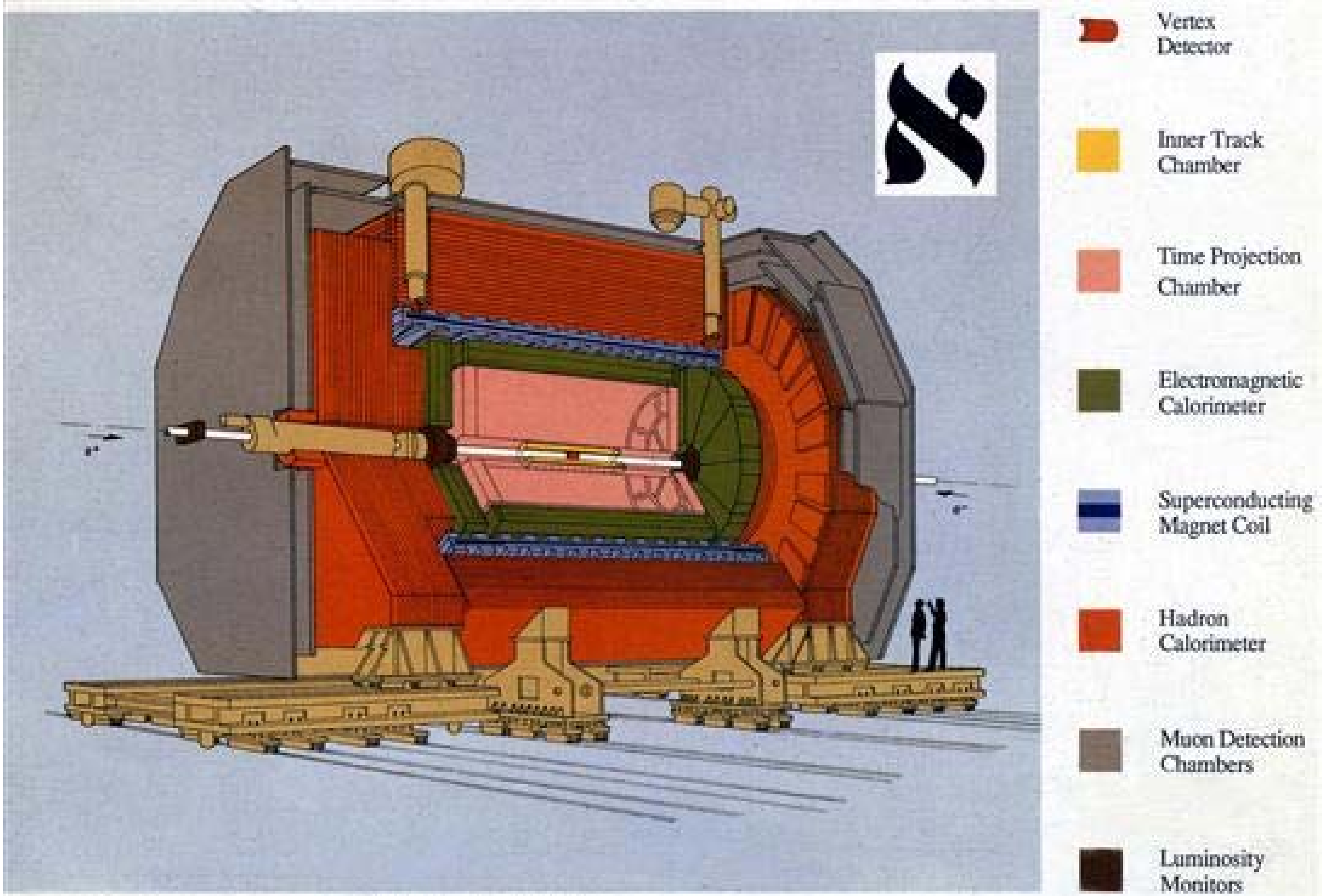


Fig. 1 - The ALEPH Detector

Other e+e– Colliders and Experiments:

Highest center-of-mass energies at their time, before LEP and SLC (search for the top quark):

PEP at SLAC (1979-90): Mark II (first central multi-wire drift chamber, first Si VTX detetector), PEP-4 (first TPC) detectors, max. E_{cms} = 29 GeV.

PETRA at DESY (1978-86): Cello, Jade, Mark-J, Pluto, Tasso detectors, max. E_{cms} = 45 GeV, "discovery of the gluon" (3-jet events).

TRISTAN at KEK (1986-95): VENUS, SHIP, TOPAZ, AMY detectors, max. E_{cms} = 64 GeV.

B meson physics experiments at the ϒ(4S) resonance, E_{cms} = 10.58 GeV:

DORIS at DESY (1974-93): Pluto (first superconducting solenoid), ARGUS detectors ($B\bar{B}$ mixing).

CESR at Cornell Univ. (1979-2008): CUSB, CLEO I, II and CLEO-c detectors.

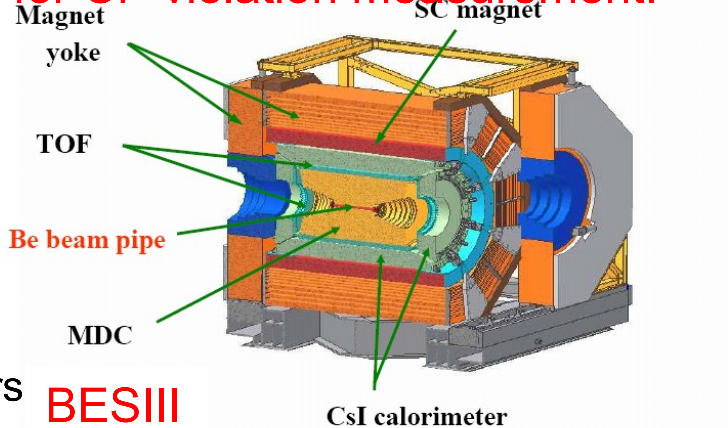
"B factories" with asymmetric beam energies at ϒ(4S) for CP violation measurement:

PEP-II at SLAC (1999-2008): BaBar detector

KEKB at KEK (since 1999): Belle I, II detectors (highest e^+e^- luminosity → SuperKEKB).

Charm, τ physics at E_{cms} = 2.0 − 4.2 GeV:

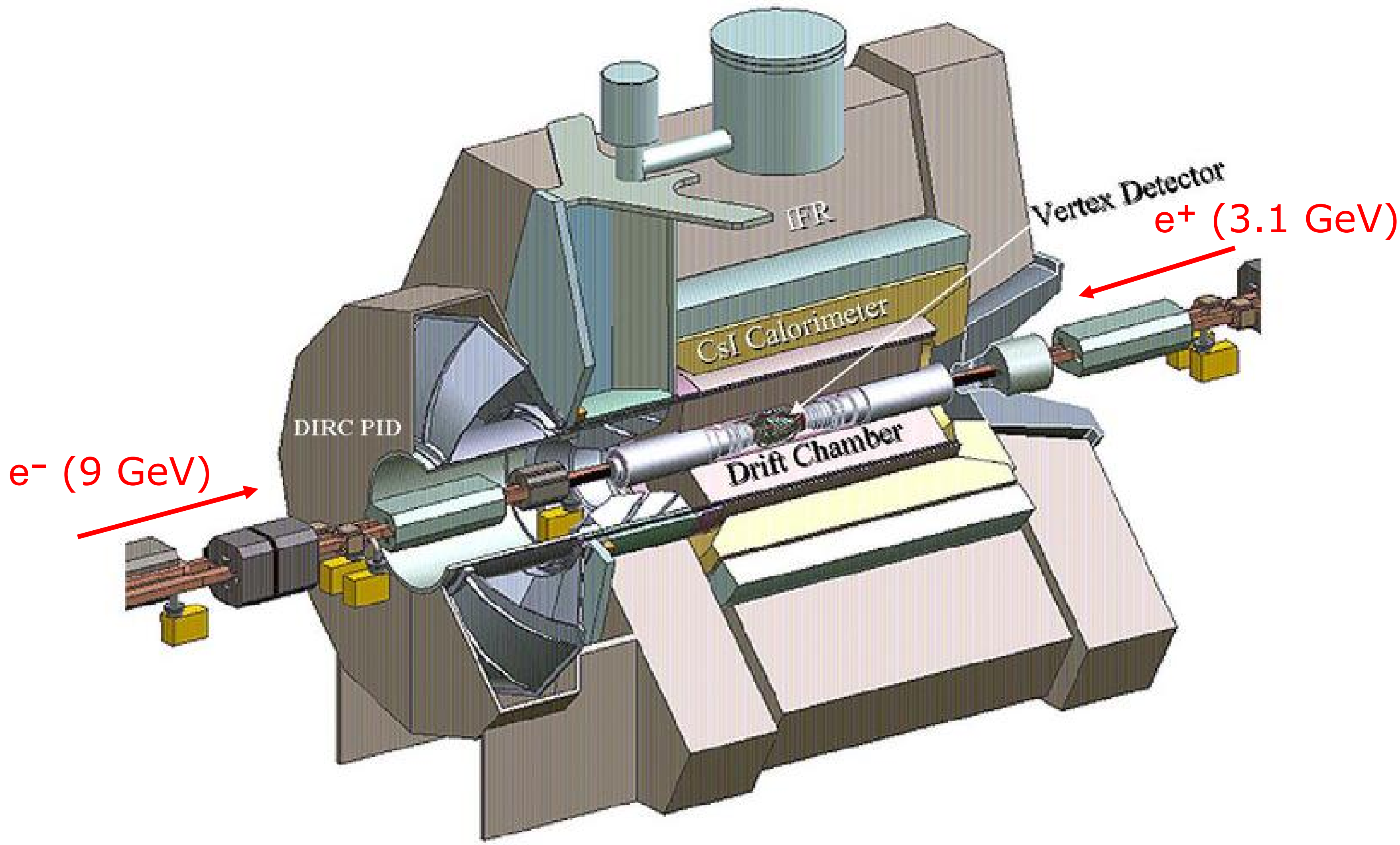
BEPC at IHEP Beijing (since 1988): BES I, II, III detectors



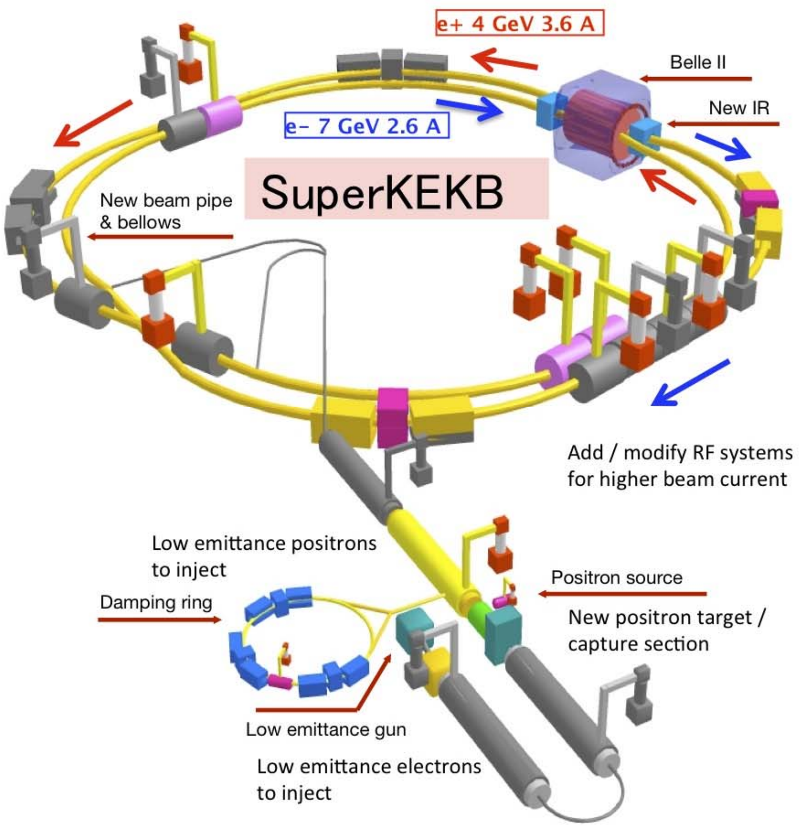
BESIII

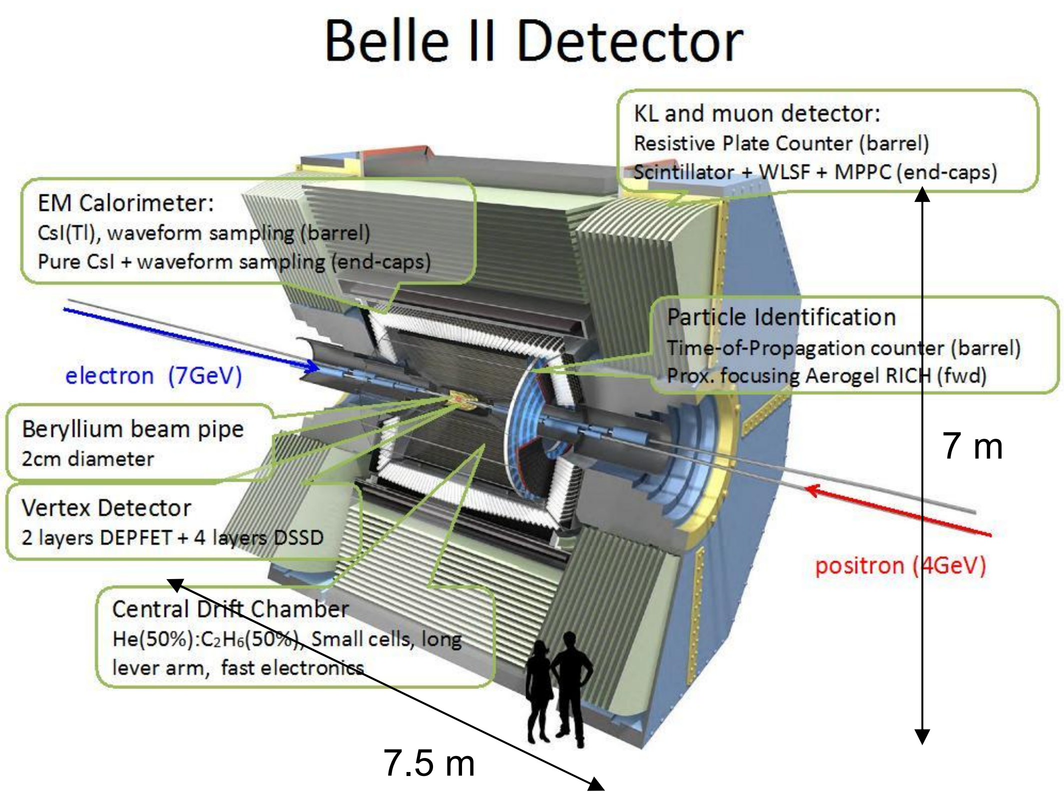
Babar Detector at the SLAC Asymmetric B Factory

ϒ(4S) system boosted in electron beam direction.
Asymmetric detector coverage hermetic in forward direction.



B Meson Factory Experiments: Belle II at SuperKEKB



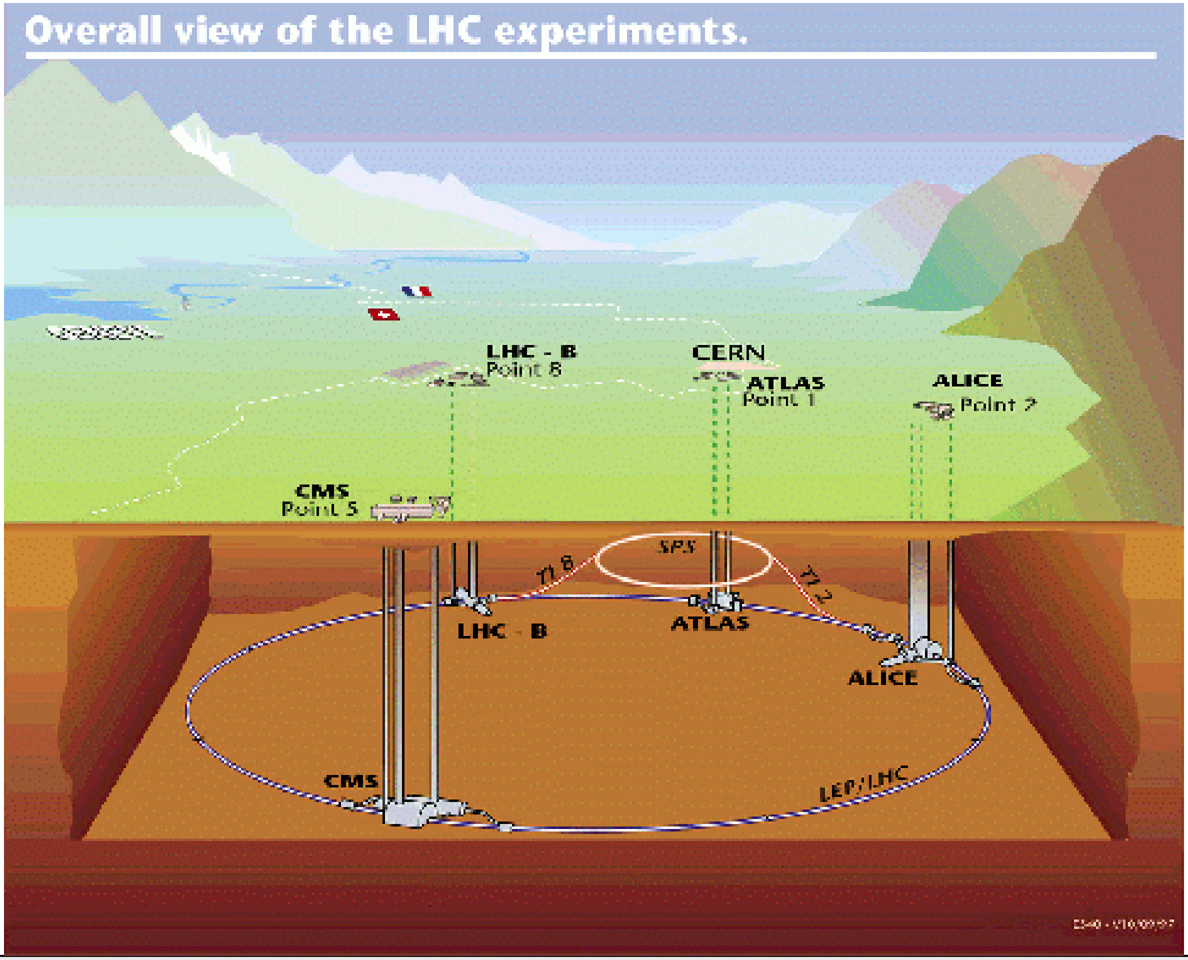


Examples: Hadron Colliders

The Large Hadron Collider LHC, successor of LEP in the tunnel since 2009, with the highest pp energies, E_{cms} = 7, 8 13 (14) TeV, and luminosities.

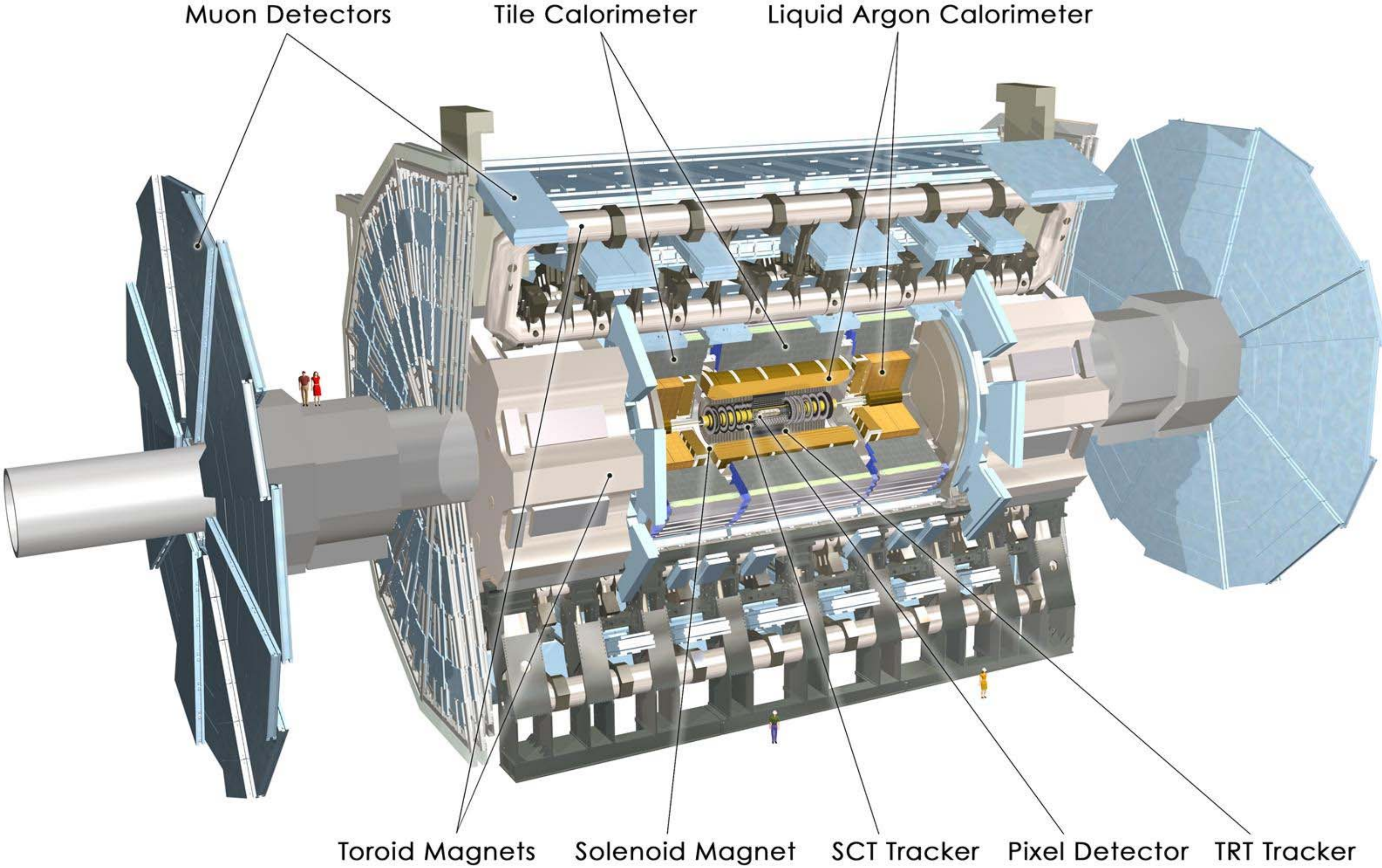
1200 superconducting dipole magnets. First hermetic proton collider experiments: **ATLAS and CMS.**

Discovery of the Higgs boson 2012 and search for physics beyond the Standard Model.



The ATLAS Detector at the LHC
with large Muon Spectrometer and SC Toroid Magnets

Standalone muon momentum measurements in the world's largest air-core magnet for the first time in a collider detector.



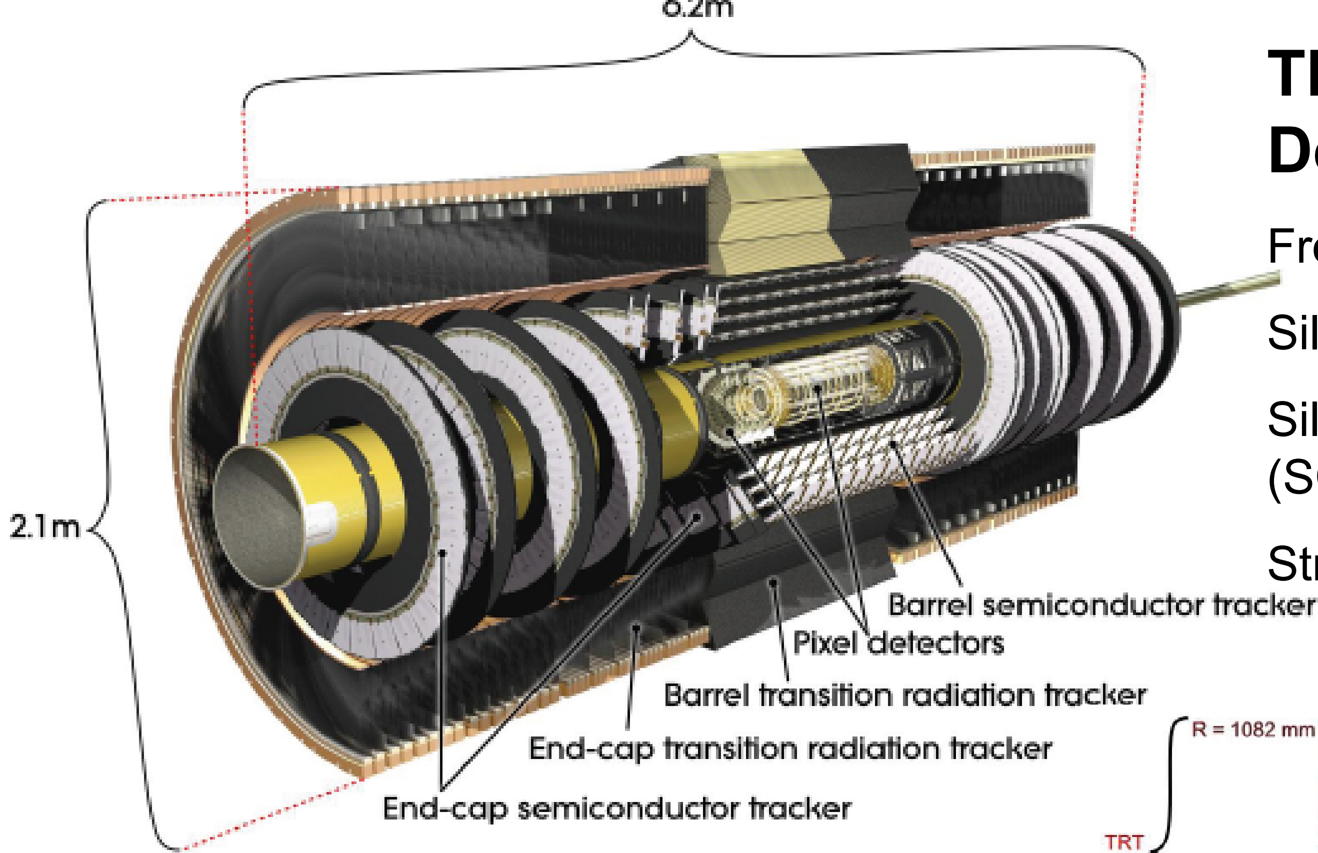
The Inner Tracking Detector of ATLAS

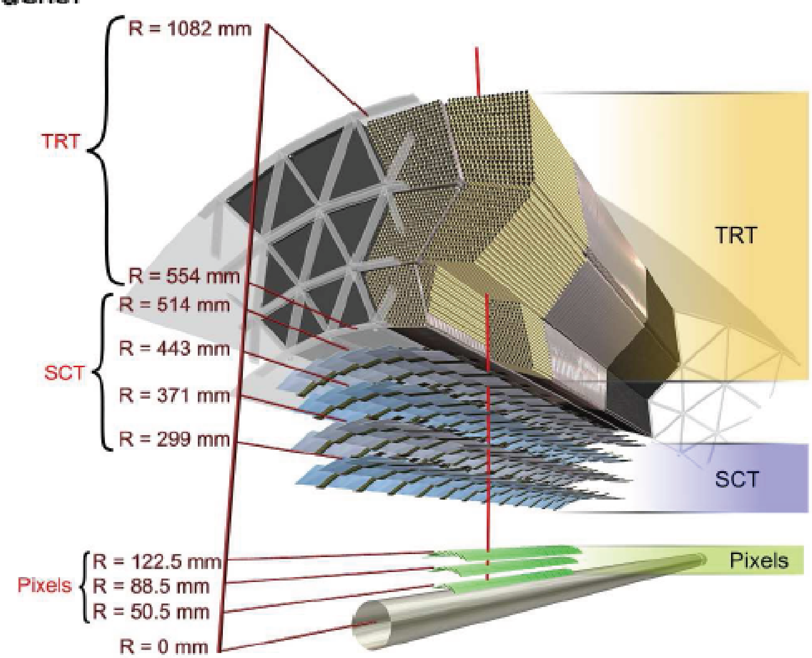
From the beam pipe outwards:

Silicon pixel detector (Pixels)

Silicon microstrip detector (SCT)

Straw drift tube tracker (TRT)

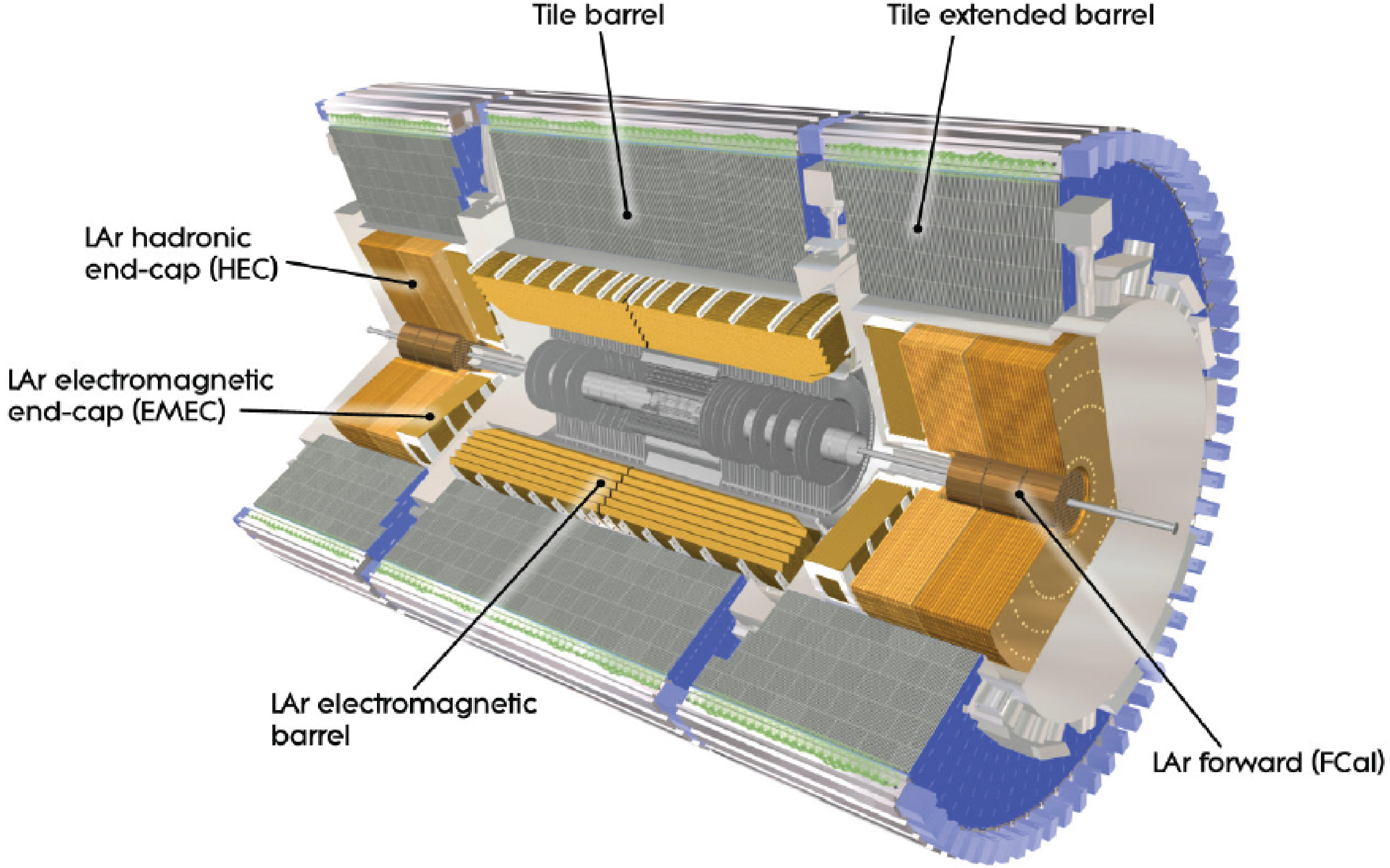




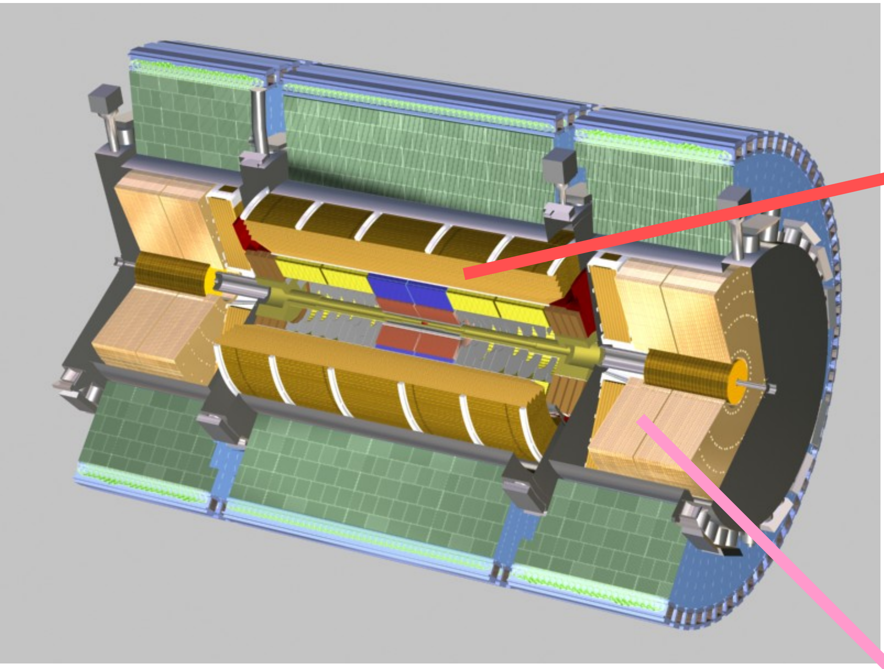
ATLAS Calorimeter System

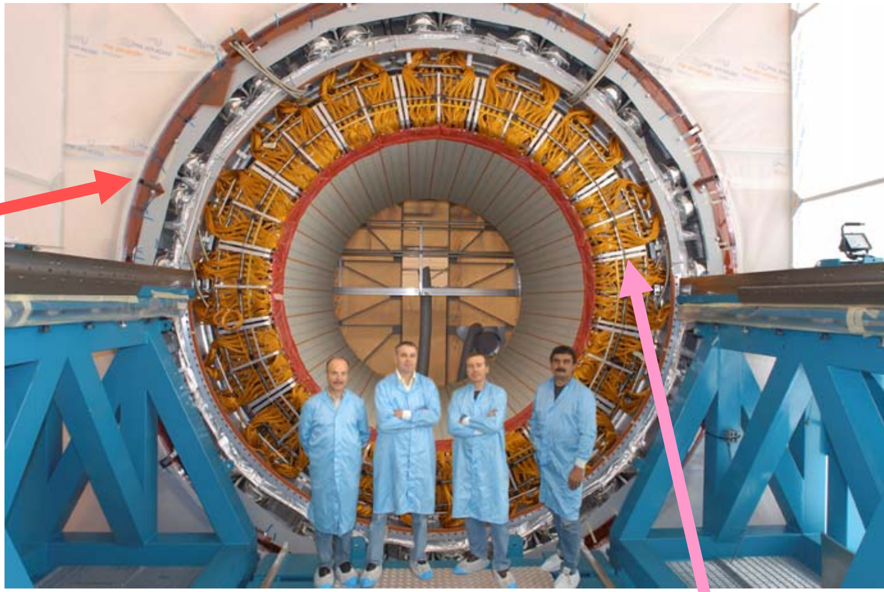
Electromagnetic calorimeter: liquid argon (active)-copper (absorber) sampling.

Hadron calorimeters: scintillating tile (active)-steel (absorber) and LAr-copper/ tungesten sampling

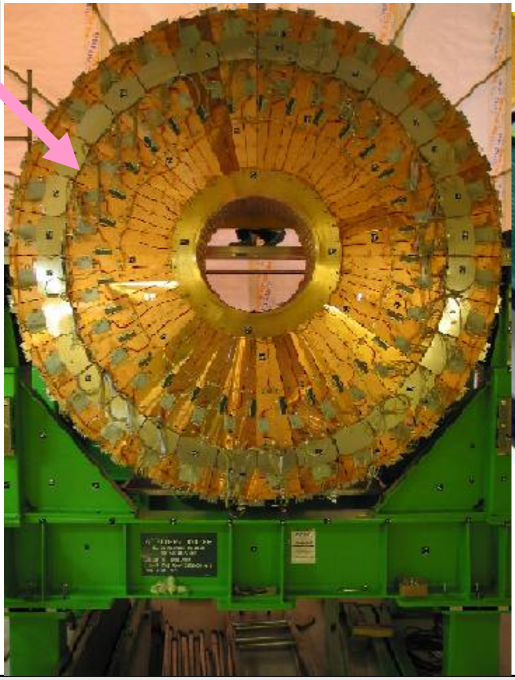


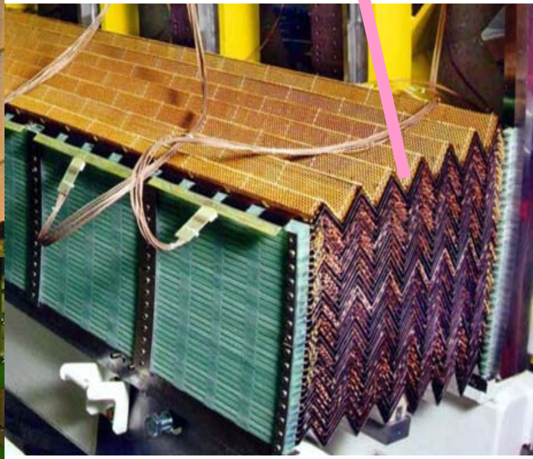
ATLAS Calorimeter System





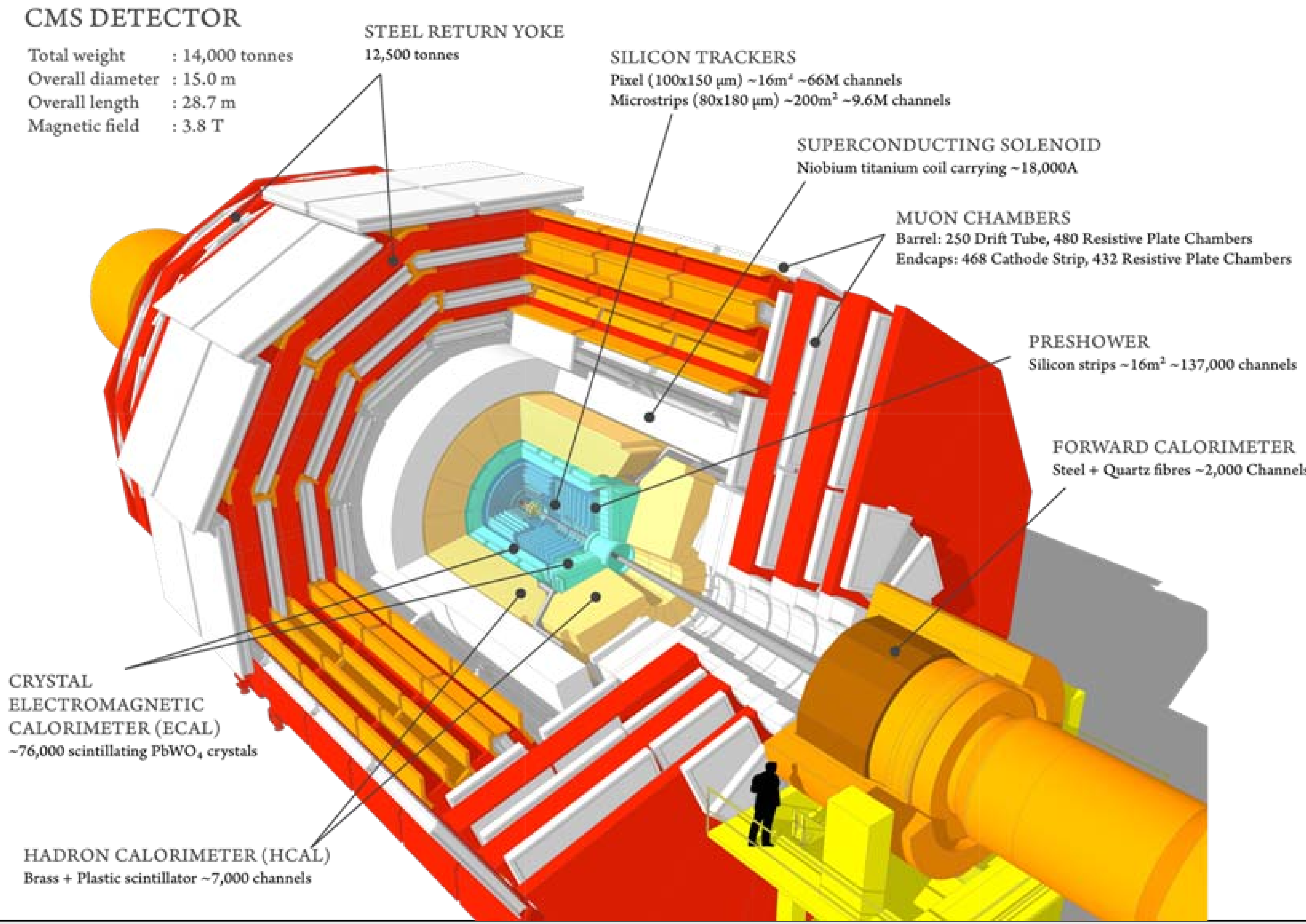
- Electromagnetic liquid-argon (LAr) sampling calorimeter.
- Fine segmentation in η-φ and also in depth.
- Large solid angle coverage.
- Hadron calorimeters: absorb all remaining particles except muons





Accordeon shaped interleaved absorber plates and readout boards in liquid argon

The CMS Detector at the LHC



Challenges for LHC Detectors

Highest beam energy and highest luminosity in proton collisions:

- Proton bunch crossings every 25 ns

  ⇒ very fast detectors and readout electronics.

- High proton density per bunch:

  - More than 20 pp reactions per bunch crossing (event pile-up).
  - $\mathcal{O}(1000)$ particles produced per crossing.

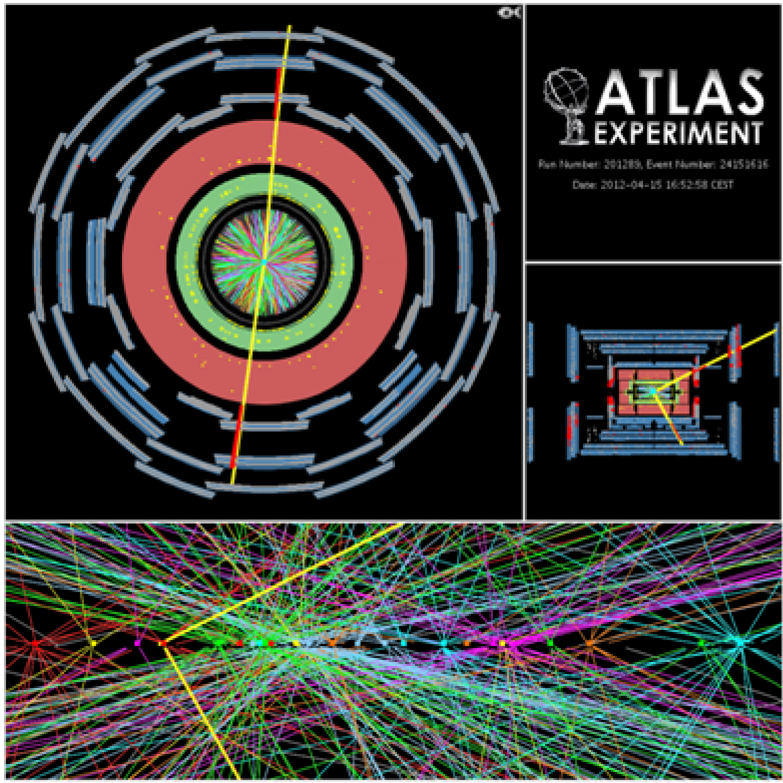
  ⇒ high detector granularity.

- Unprecedented irradiation doses from interaction of collision products with detector, shielding, cavern walls:

  - Inner tracking detectors $> 10^{14}$ protons/cm^2
  - Outer muon detectors $> 10^{11}$ neutrons and γ-rays/cm^2

  ⇒ radiation hard detectors and electronics.

- Very high data rates > 300 Mbyte/s.



Z→μμ event with 25 reconstructed interaction vertices already in Run 1

Required dedicated R&D program over many years. Challenge 10 x higher for HL-LHC!

Previous Hadron Colliders and Experiments:

Highest center-of-mass energies for discoveries:

ISR pp, $p\bar{p}$ at CERN (1971-84): first hadron collider, max. E_{cms} = 62 GeV, still non-hermetic detectors.

SppS $p\bar{p}$ at CERN (1981-93): UA1 and UA2 experiments, E_{cms} = 630−900 GeV, discovery of the W and Z bosons.

Tevatron $p\bar{p}$ at FNAL (1983-2011): CDF and D0 experiments, E_{cms} = 1.8−1.96 TeV, discovery of the top quark 1995, superconducting dipole magnets.

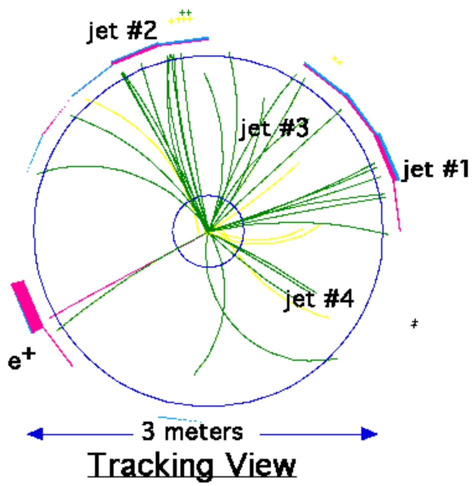
RHIC at BNL (since 2000): Au-Au collisions, STAR and PHENIX experiments.

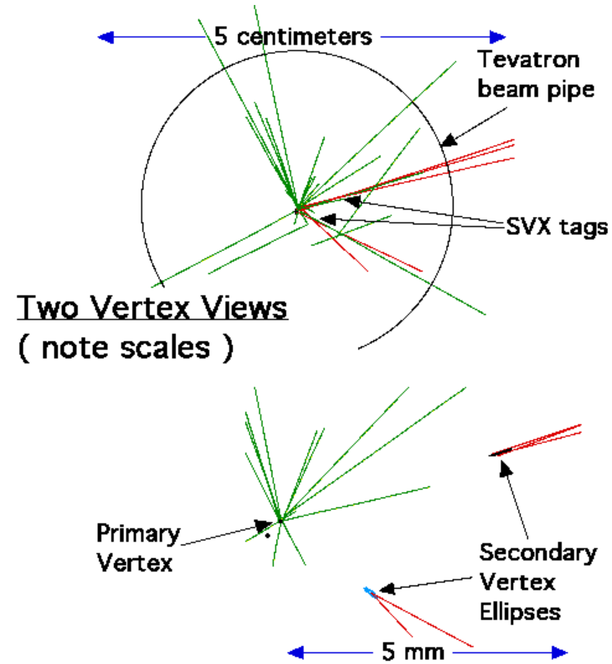
Charged Particle Tracking Detectors

- Track reconstruction and charged particle identification close to the interaction point ("Inner Detector").
- Inside (homogeneous solenoidal) magnetic field for track curvature and momentum measurement.

  $\rightarrow$ Minimum scattering material in tracker.
- Reconstruction of primary interaction point(s) (up to ~60 at LHC!).
- Reconstruction of displaced decay vertices.
- Jet and b quark jet identification.

Top quark pair event in the CDF tracking detector with top decays into b jets containing long-lived B mesons and $W \rightarrow l\nu$ and qq





Types of Tracking Detectors

Gaseous detectors:

Energy deposition of charged particles by ionisation of gas atoms.

Evolution with increasing granularity and intrinsic resolution:

- Multi-wire proportional detectors
- Multi-wire drift chambers
- Micro-pattern gas detectors: GEM, Micromega detectors

Solid state detectors:

Energy deposition by creation of electron-hole pairs in the crystal

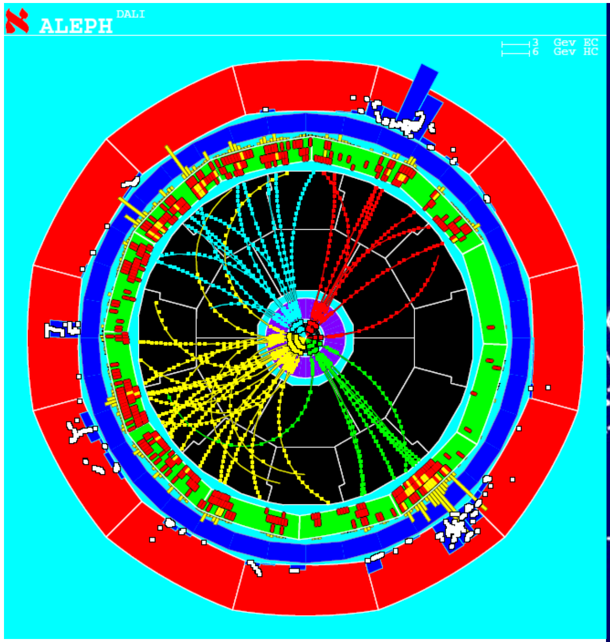
- Silicon micro-strip detectors
- Silicon pixel detectors

Large areas vs. high granularity (no. of electronics channels),

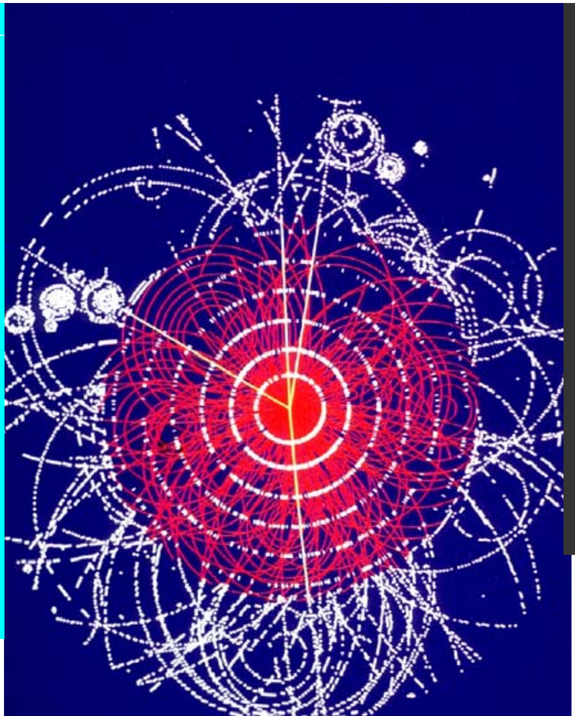
radiation resistance and rate capability

Gaseous Central Tracking Detectors

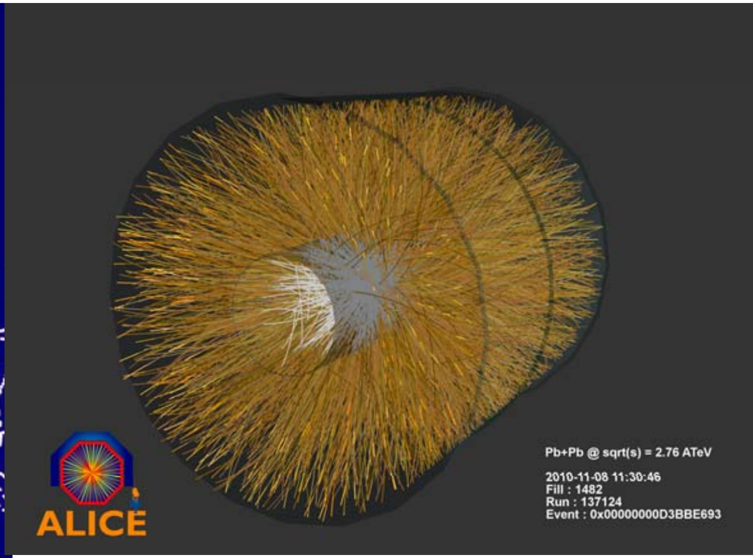
- Track pattern recognition in multi-particle/ multi-jet final states.
- Precise track and momentum measurement in (solenoidal) magnetic field.
- Low-mass detectors, minimise multiple scattering.



ALEPH TPC/ LEP e^+e^-



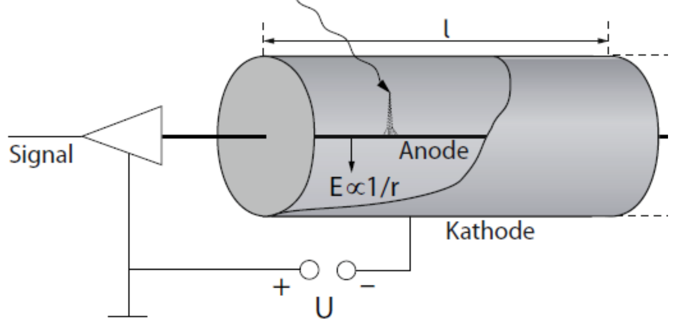
ATLAS tracker/ LHC pp

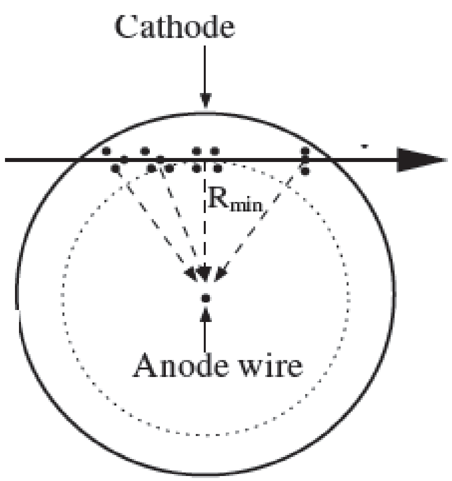


ALICE TPC/ LHC Pb-Pb

Wire Tracking Detectors

- **Detection principle:** ionisation of gas atoms by charged particles along the track.
- **Argon:** low ionisation energy and relatively cheap, most frequently used as ionisable medium (also Xenon, Krypton) together with other admixtures.
- Apply electric field to collect primary ionisation electrons on anode sense wires while positively charged argon ions drift more slowly to the cathode: **wire chambers.**
- High electric field near the wires ~ 1/r accelerates the drifting electrons leading to avalanche of secondary ionisation of the argon atoms by the electrons: **gas amplification** (in proportional mode ~ primary ionisation).
- Charge signal at the wire en electronically amplified.



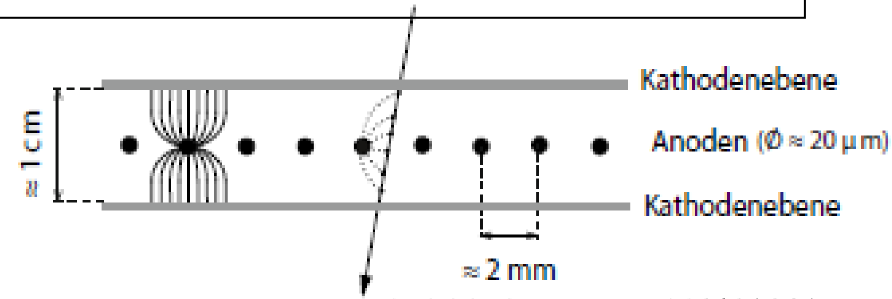


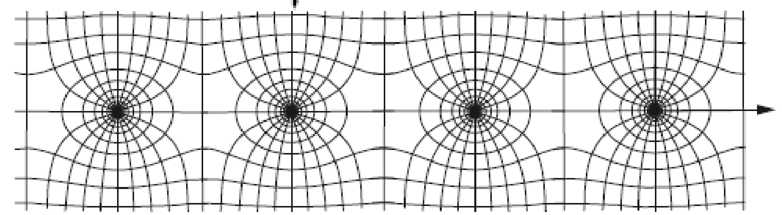
Multi-Wire Drift Chambers

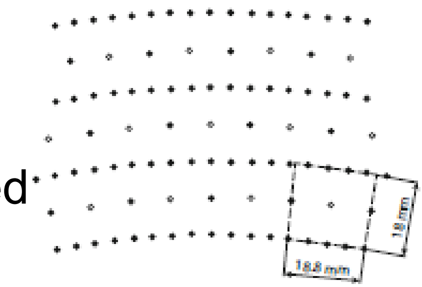
- Track position detection by closest wire in **multi-wire gas detectors (MWPC).**
- Higher precision with fewer wires (and electronics channels) by measuring the drift time of the primary ionisation electrons to the anode wires: **drift chambers.**
- The drift time is converted into the closest distance of the wire to the track via the calibrated **space-to-drift time (r-t) relation.**

  Drift velocity v depends on the gas mixture and operating parameters.

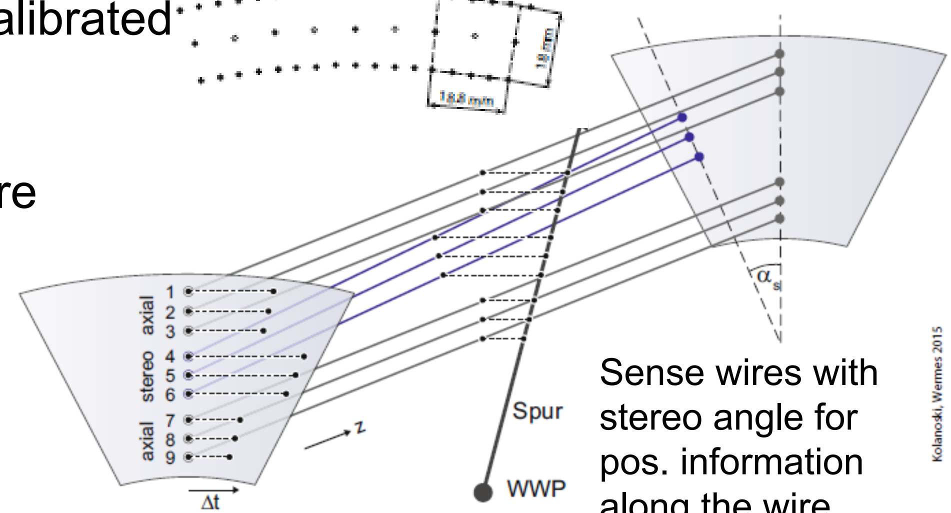
  Non-linear r-t relation if v is dependent on the local electric drift field strength.





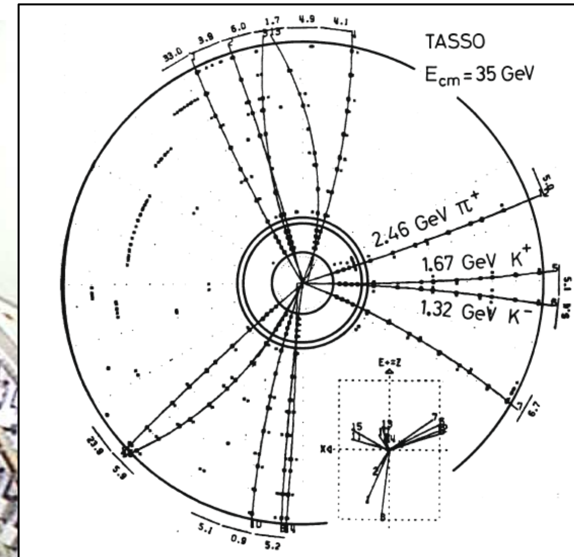


2D drift cell structure defined by cathode field wires

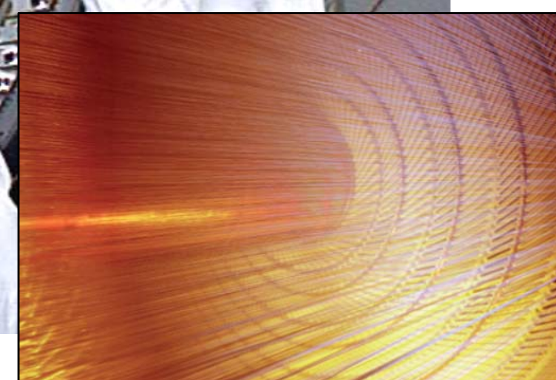


Sense wires with stereo angle for pos. information along the wire.

Large cylindrical multi-wire drift chambers for central tracking of collider detectors



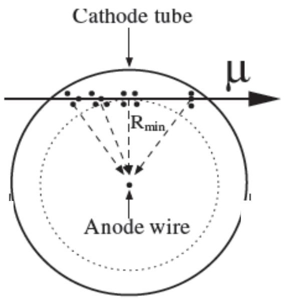
CDF Central Tracking Chamber, 3m ∅

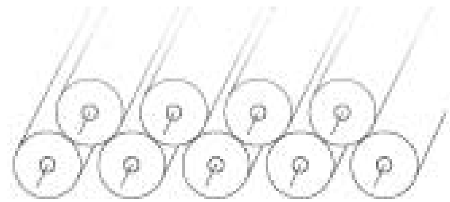


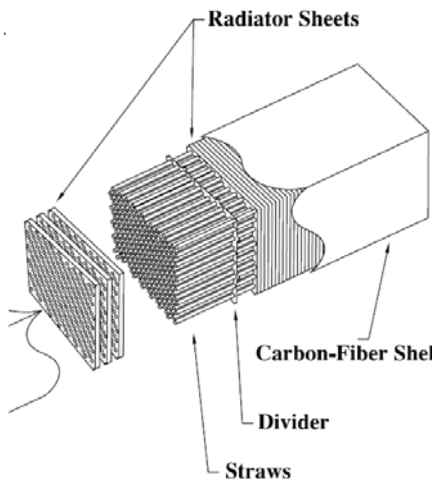
Drift Tube Detectors

ATLAS "Straw" Drift Tube Tracker, TRT:

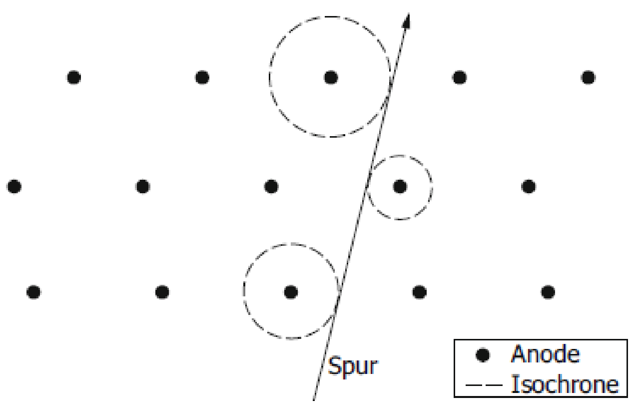
- 50000 kapton drift tubes of 4 mm ∅ and 0.7 m wire length in 35 cylindrical layers
- $Xe:CO_2:O_2$ (70:27:3) gas mixture (prevent aging!)
- Occupancy above 30% at LHC design luminosity

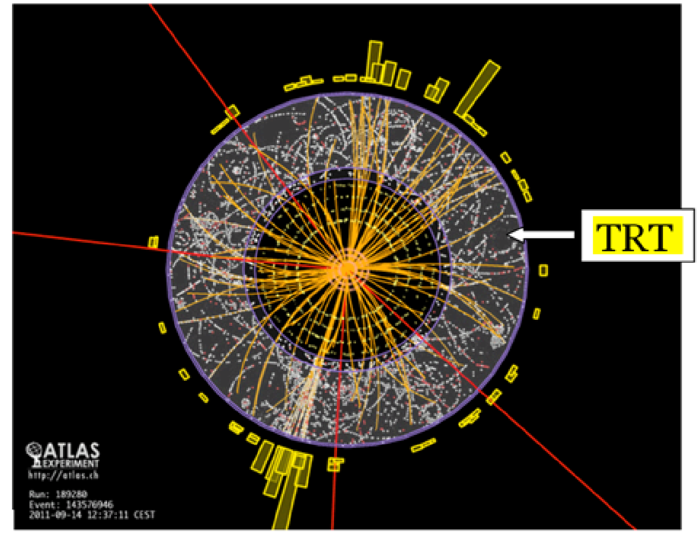


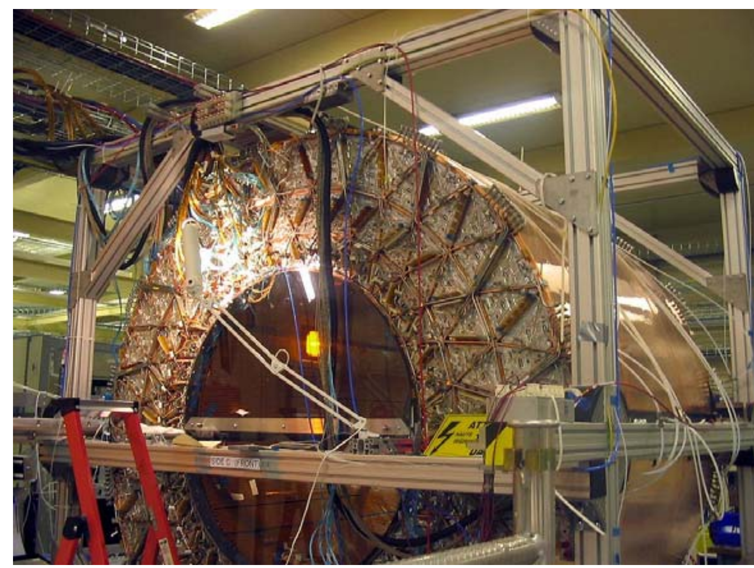




Track reconstruction



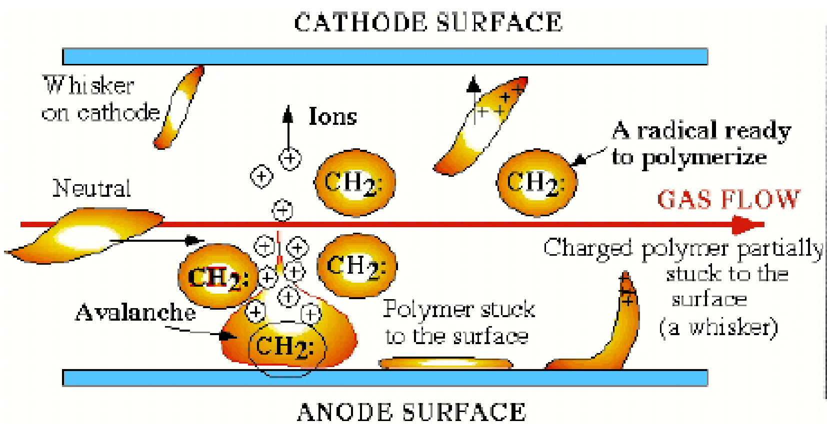


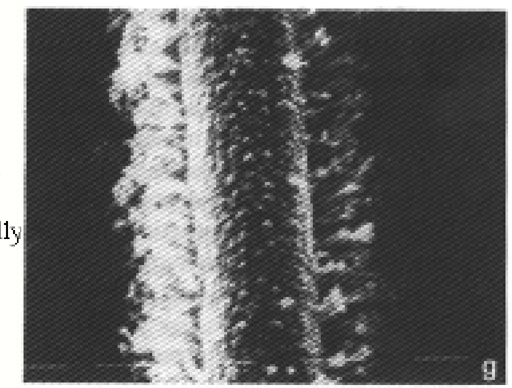


Wire Chamber Aging

Phenomenon of wire chambers under irradiation:

- Hydro-carbon and silicate radicals of drift gas molecules or contaminants created in the plasma of the avalanche near the wire polymerise (plasma chemistry) and form deposits on the sense wire which eventually make it inefficient.





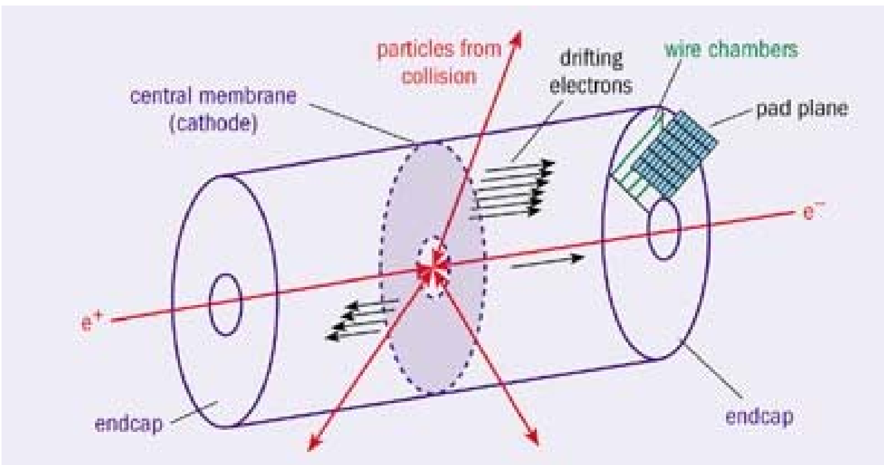
- In particular at very high irradiation rates like at LHC: avoid hydro-carbons and any contamination in the gas to prevent aging, even in the outer muon detectors.

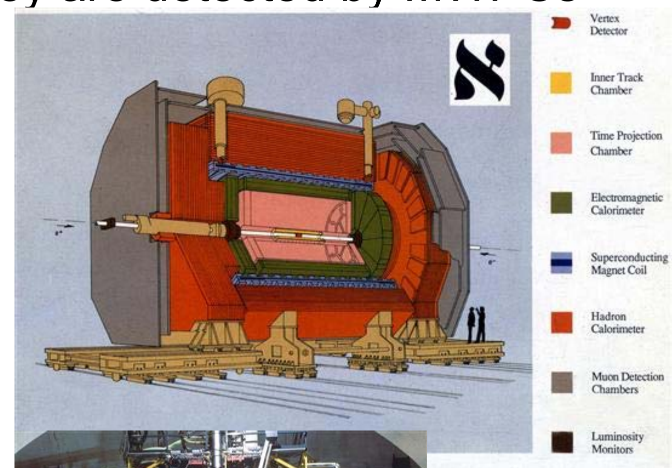
  "Standard gases" now: Ar(Xe):CO_2 (CO_2 admixture for quenching of avalanches).

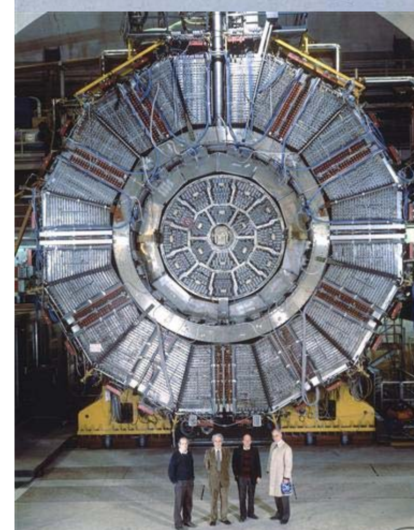
  So far successful at LHC.

Drift detectors without wires: Time Projection Chambers (TPC)

Large drift volume with electric field parallel the solenoidal magnet field.
Ionisation electrons drift towards the endplates where they are detected by MWPCs (and nowadays GEM and Micromegas detectors).

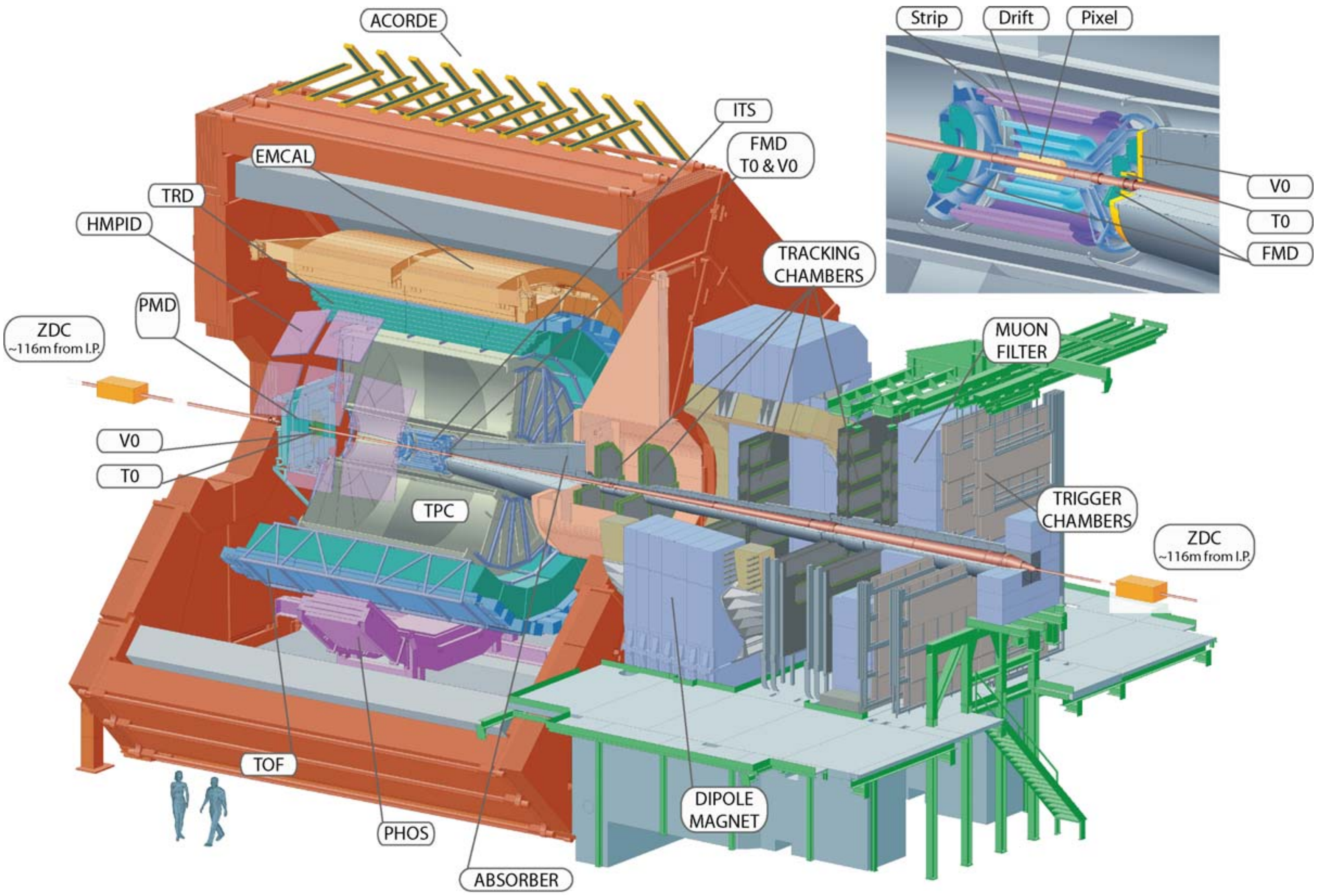






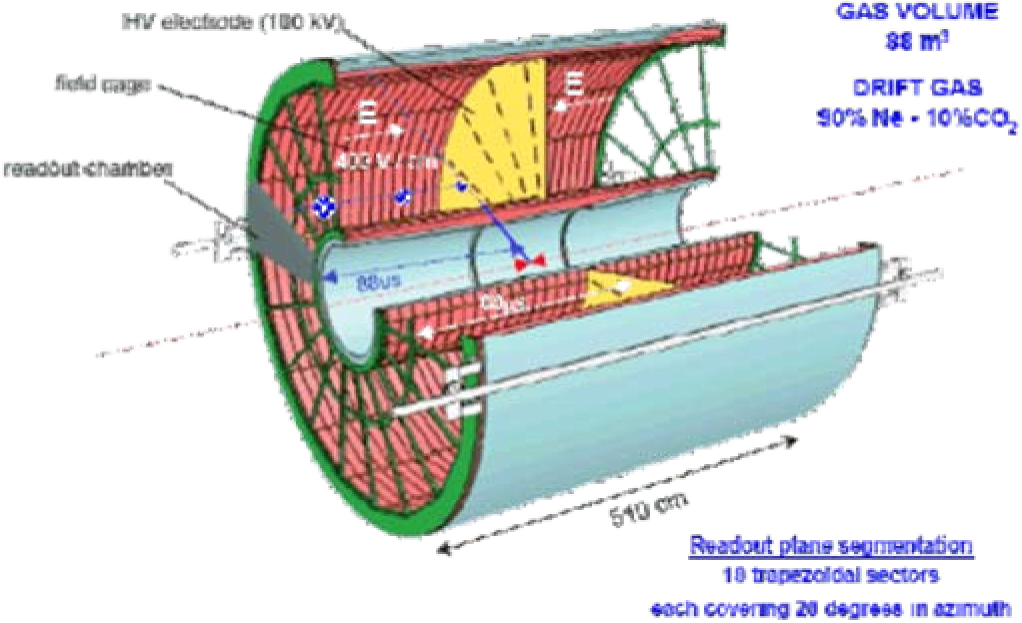
- First employed in the PEP-4 experiment at SLAC.
- Used by the LEP detectors ALEPH and DELPHI.
- Now used in heavy ion collision experiments with very high track densities like STAR at RHIC and ALICE at LHC, and proposed for detectors at future high-energy e^+e^- colliders like ILC.

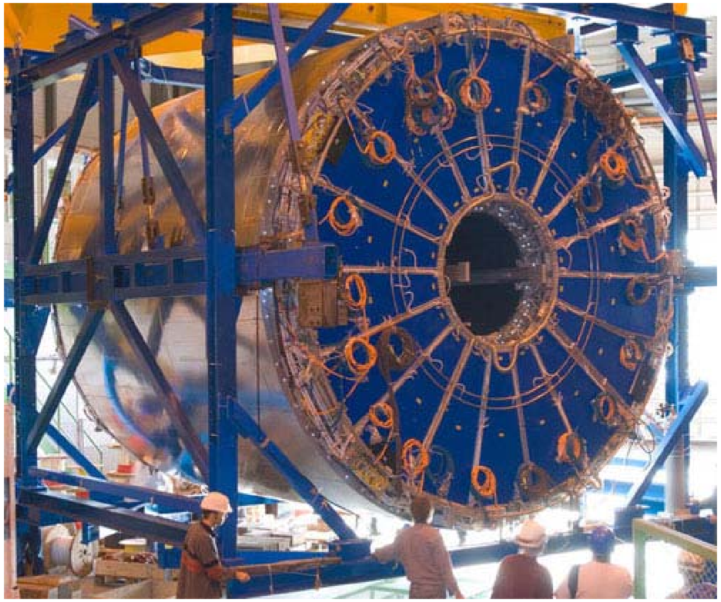
ALICE detector for study of heavy ion collisions at the LHC

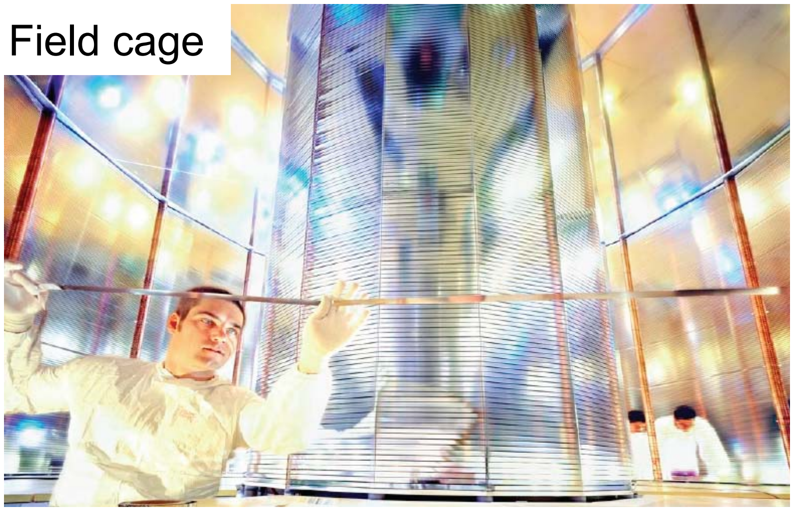


The TPC of the ALICE detector at the LHC

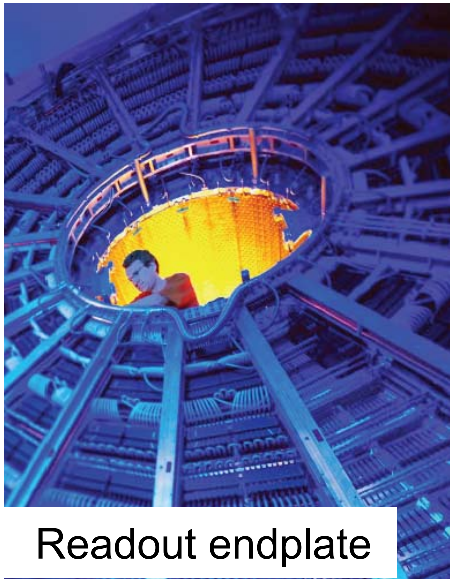
The largest TPC so far







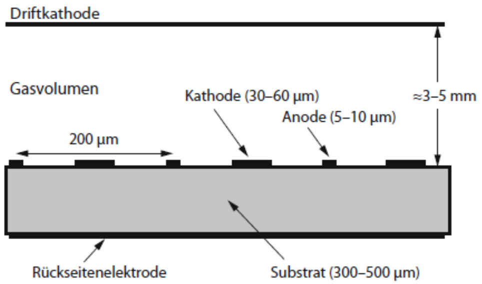
Field cage



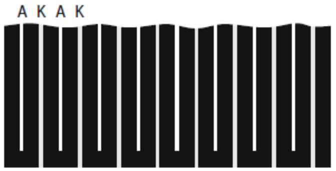
Readout endplate

New Trend: Micro-Pattern Gas Detectors

- Development started in the late 1980s with **Micro-strip Gas Chambers (MSGCs).**
- Thin (few mm) planar detectors using printed circuit boards (PCB) with alternating cathode and anode strips.
- High granularity and spatial resolution. Electronics/cost similar to silicon detectors.
- Far higher rate capability (> 1 MHz/cm^2) than MWPC. Short drift distances.
- 2D position information (crossed strip planes or pad readout).
- Plagued by discharges and gain instabilities due to high field strengths and high gas gain.
- Single detector area limited by PCB manufacturing capabilities.

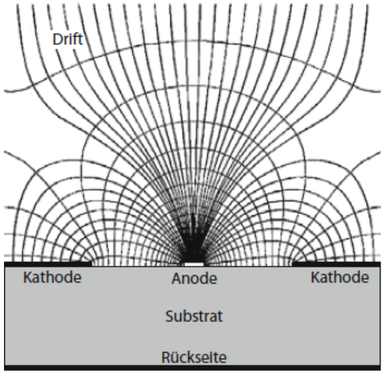


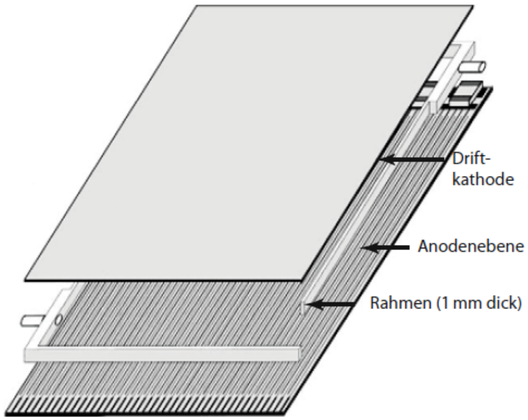
(a) Querschnitt



MSGC layout

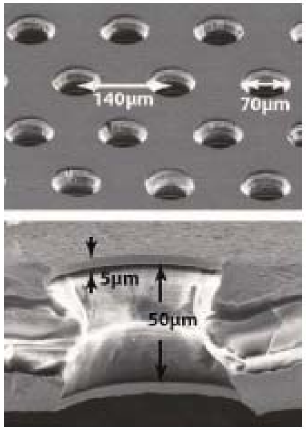
(b) Elektrodenanordnung

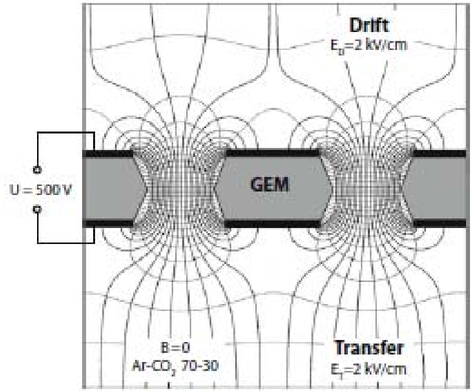


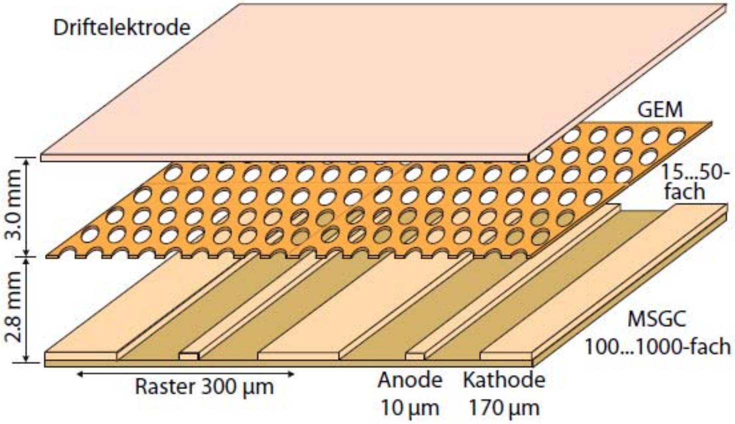


Gas Electron Multiplier (GEM) Detectors

Ionisation charge amplification in high fields in holes of GEM foil (made mostly in the CERN PCB workshop) allows for reduction of gas gain near readout electrodes and of risk of discharges (F. Sauli 1997).







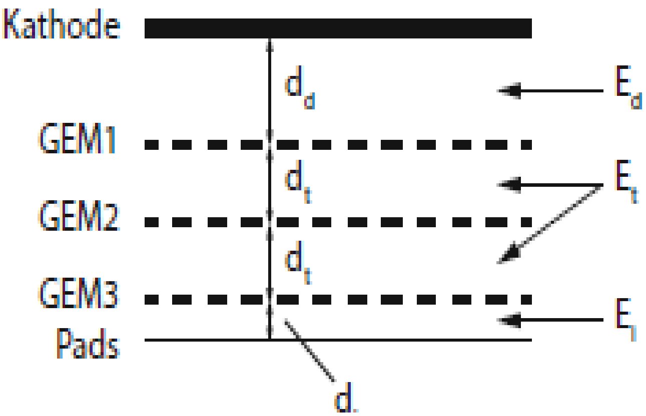
Standard today: several GEM foils, allow for optimisation of all operating parameters.

Such detectors presently used for

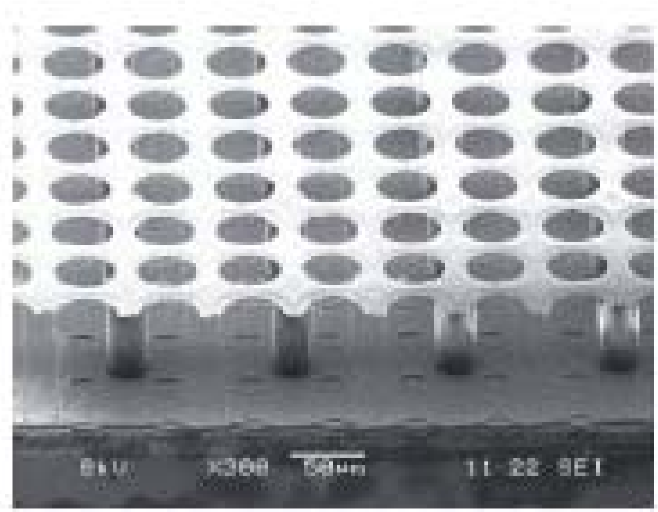
- fixed target tracking detectors (e.g. COMPASS),
- readout chambers of modern TPCs (ALICE, ILC),

  prevent ion backflow into drift volume,
- muon detectors for high rates (ATLAS, CMS),

  challenge: large detection areas (RD51 collaboration at CERN).



Micro-mesh Gas Detectors (Micromegas)



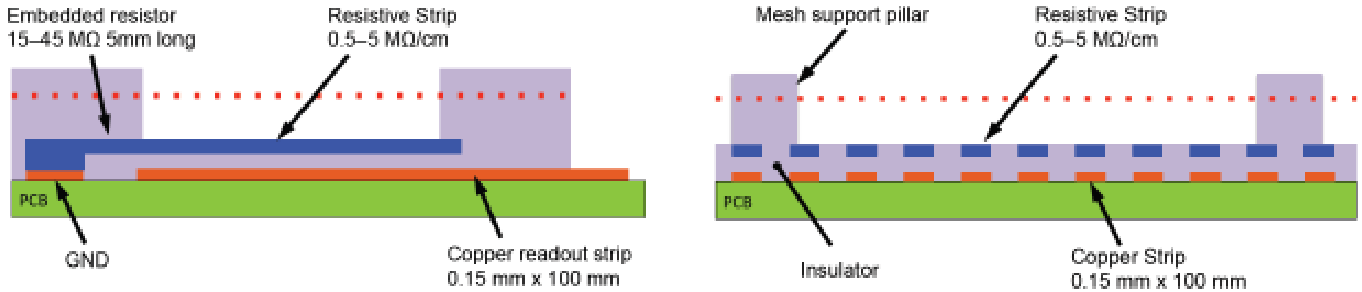
Similar principle as GEM detectors.

Industrially manufactured micro-mesh stretched and mounted on insulating pillars close to the readout board.
Separates thin amplification volume from drift region.

Highest rate capability.

Intermittend sparking occurs,
esp. at the passage of strongly ionising particles.

Effects of sparks on lifetime and efficiency moderated by use of resistive readout strip coating developed for ATLAS muon tracking detectors in the inner endcap layer of the muon spectrometer

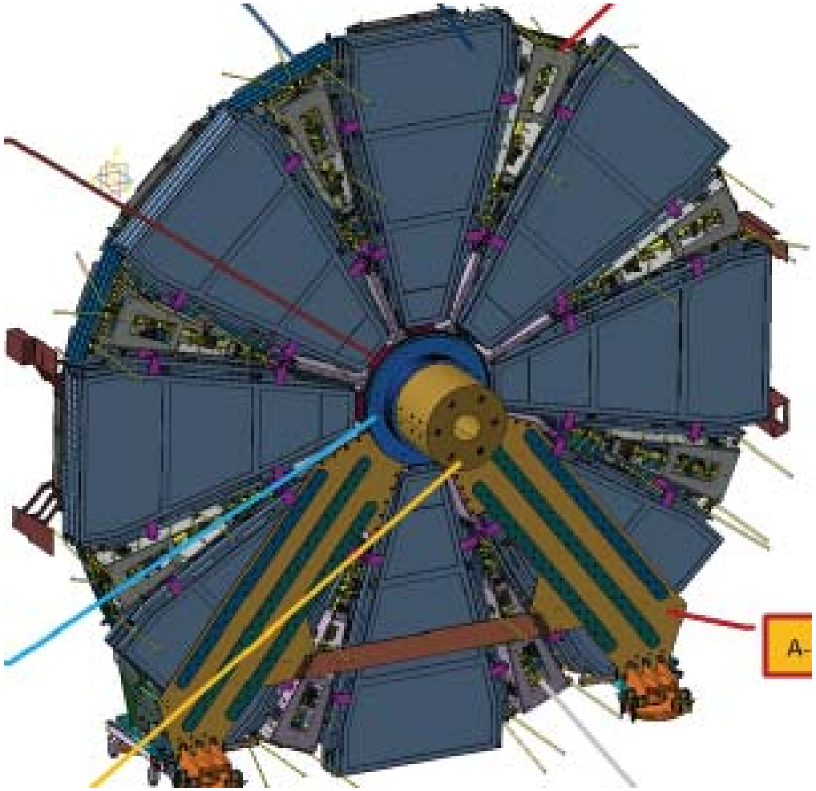


ATLAS Inner Endcap Wheel of the Muon Spectrometer

First large-scale application of large-area (up to ~2 m^2) Micromegas detectors.

Very high background rates of neutrons and γ-rays make replacement of current muon drift-tube (MDT) chambers necessary at high LHC luminosity.

Installation in long LHC shutdown 2019/20.



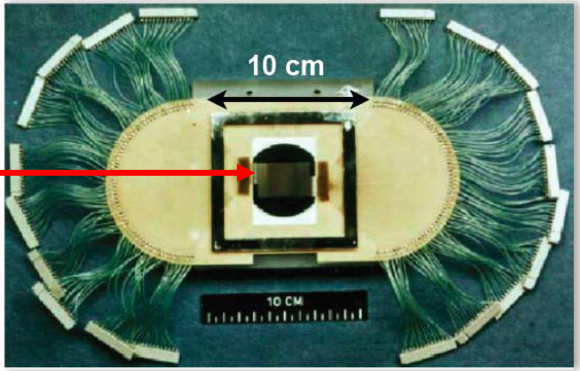
Stretching of Micromega mesh for a large detector

Silicon Tracking Detectors

- Position sensitive silicon micro-strip detectors first developed in the 1980s based on photo-lithographic surface structuring and ion implantation techniqes for VLSI chips from the micro-electronics industry (J. Kemmer, TU Munich, 1979).

  → Advantage of silicon detector technology until today.

- First application in particle physics for charm quark lifetime measurement in the NA11-NA32 fixed target experiments at the SPS at CERN (1981-94).



- Use in larger scale for vertex detectors (SiVTX) in e+e– collider experiments, first **MARKII** at PEP (1990), **LEP detectors** (1991-2000), and **B factories** (1999-…), then HERA ep collider experiments **H1** and **ZEUS** at DESY (1992-2007) Finally at the Tevatron pp collider experiments **CDF** and **D0** (1992/99-2012).

  → B meson decay vertex reconstruction and b-jet tagging.

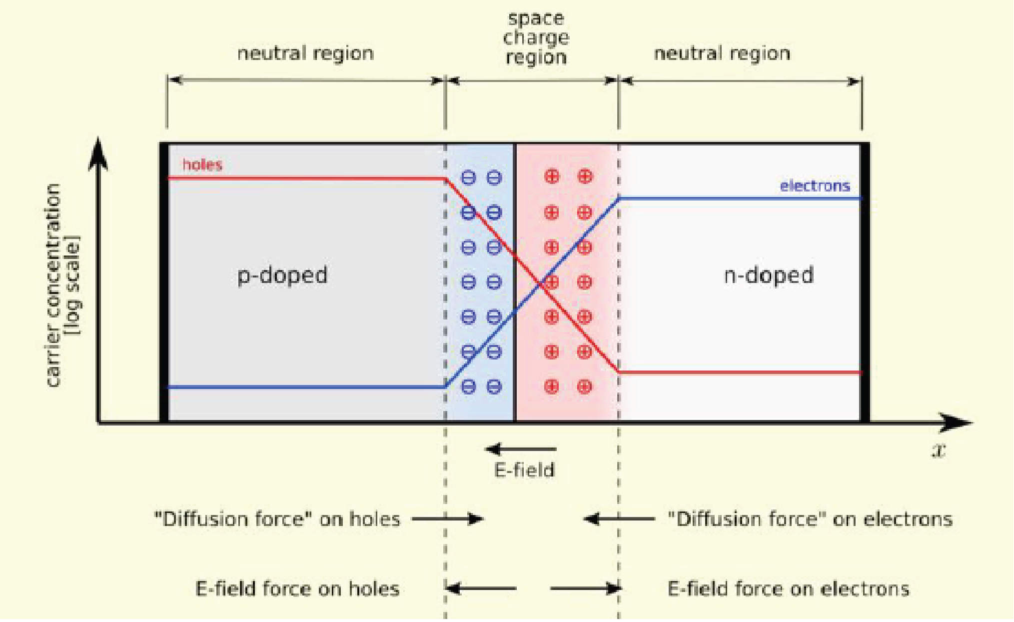
  Discoveries of t-dependent BB oscillations, top quark and CP violation in B decays.

- Revolution for radiation hard tracking detectors at hadron colliders.

  First silicon central tracking detectors in **ATLAS, CMS, ALICE, (LHCb)** at the LHC.

Silicon Position Detector Principle

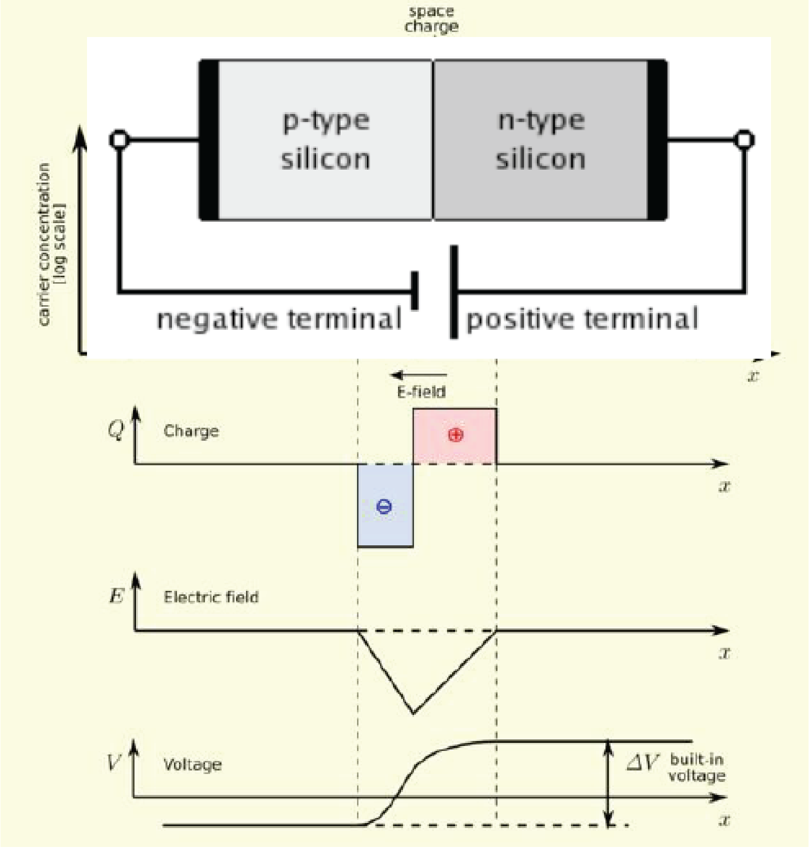
Principle: p-i-n transitions as in photodiodes.



p-i-n transition with no external voltage applied.

Space charge region of fixed ions depleted of charge carriers (electrons, holes).

Intrinsic electric field removes charge carriers.



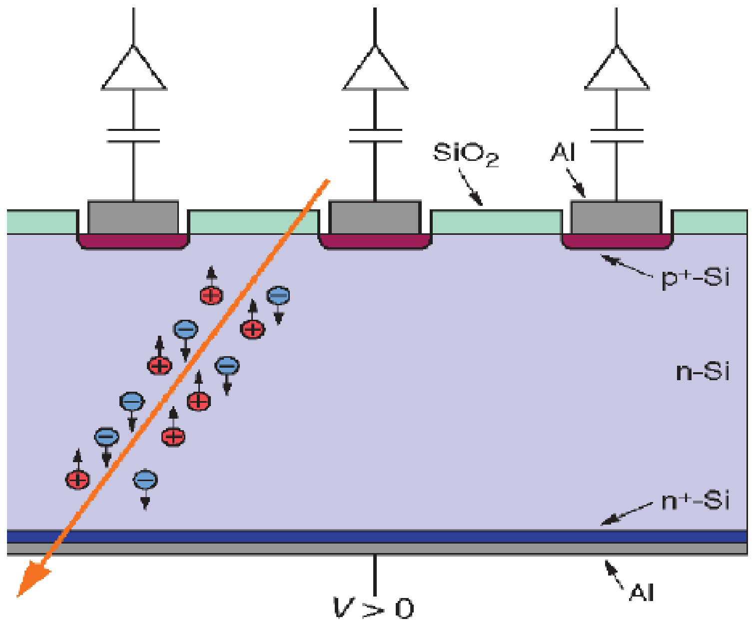
External voltage increases depletion region sensitive for collection of electrons and holes created in pairs by ionising radiation.

Silicon Strip Detector Principle

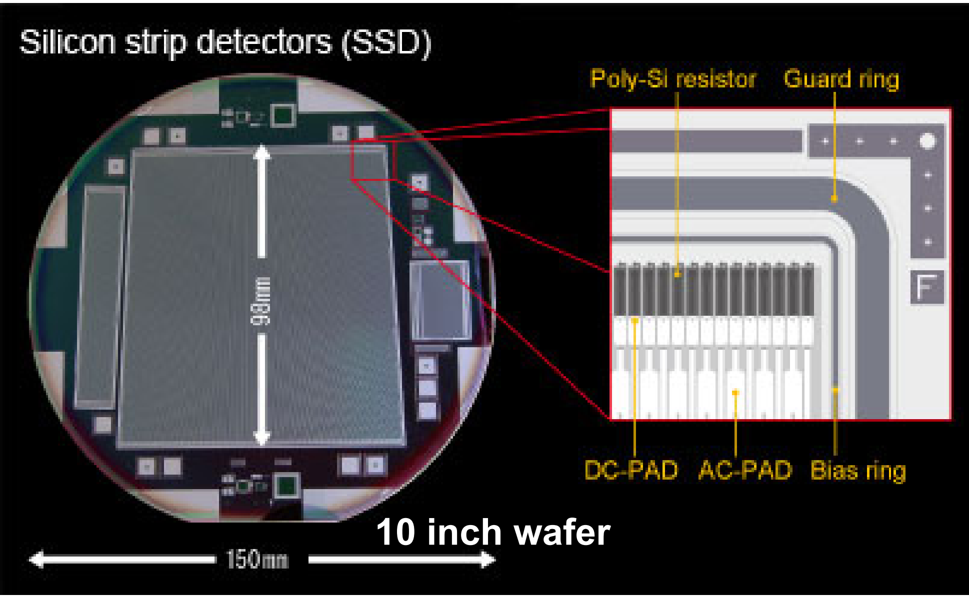
Many strip-like diodes implanted on the surface of thin silicon wafers,
e.g. most common ly p^+ doped strips in n doped bulk material.

Bulk material fully depleted by external voltage between strips
and back-side electrode to maximise the sensitivity to traversing charged particles.

Electron-hole pairs created along particle track are separated in the electric field
in the depleted bulk.
Holes are collected on the p^+ strips.

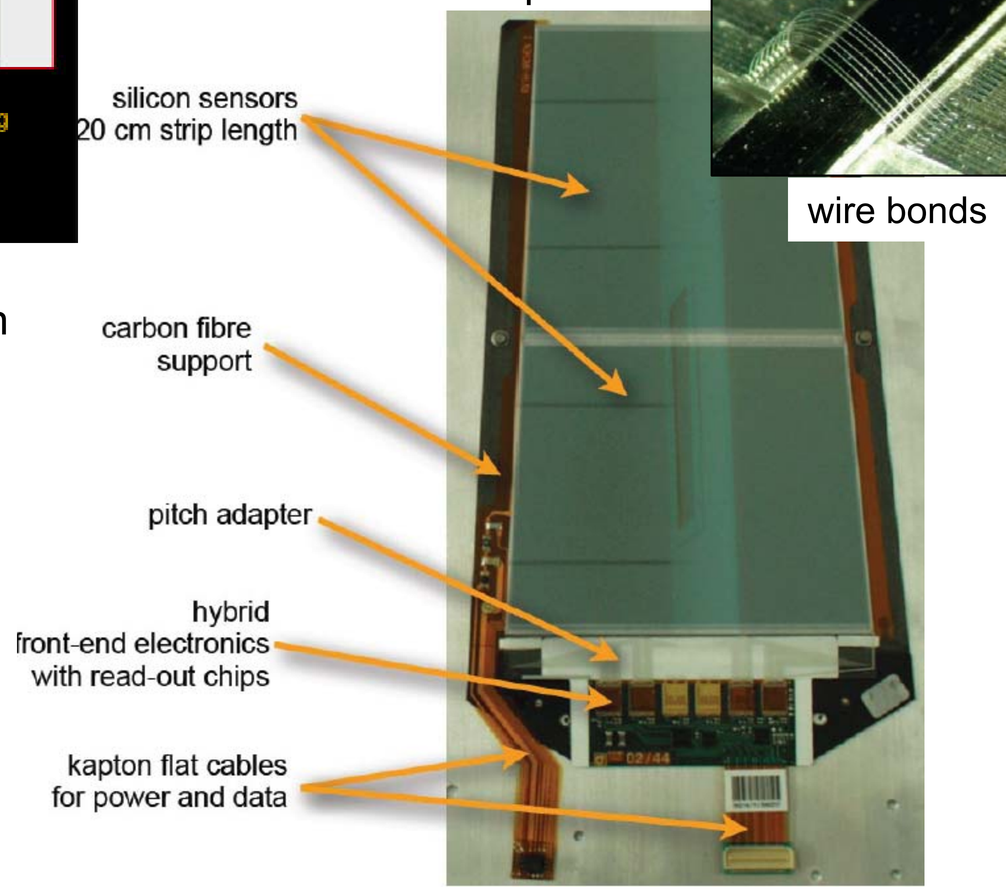


Silicon Detector Modules



Several strip sensors ganged together along the strips (limitation: detector capacitance and assoc. noise) and glued back to back under stereo angle to provide 2D position information.

Strips connected at the ends to integrated readout electronics chips:

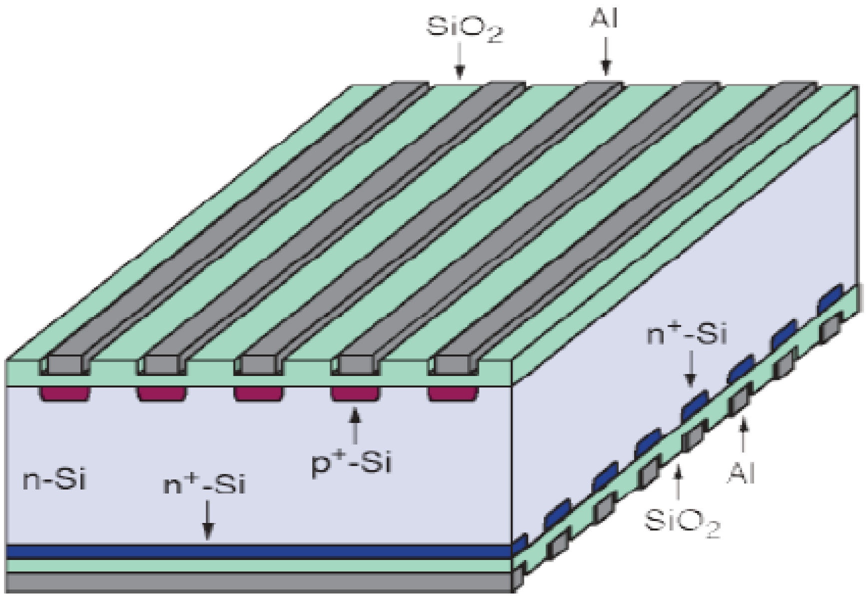


About 1200 strips with typically 50μm pitch on a single sensor occupying a full 10 x 10 cm^2 silicon wafer.

Today larger wafers are industry standard.

High density of strips and readout channels requires use of ASIC readout chips to be developed together with the sensors.

Double-Sided Silicon Strip Sensors



- More compact design, saves material
- n^+ strips in n bulk would be shorted due electron accumulation underneath positively charged silicon oxide layer. Insulation with additional p implants necessary.
- Double sided processing more expensive.
- Used in LEP and B factory detectors, also in the ALICE experiment at LHC.

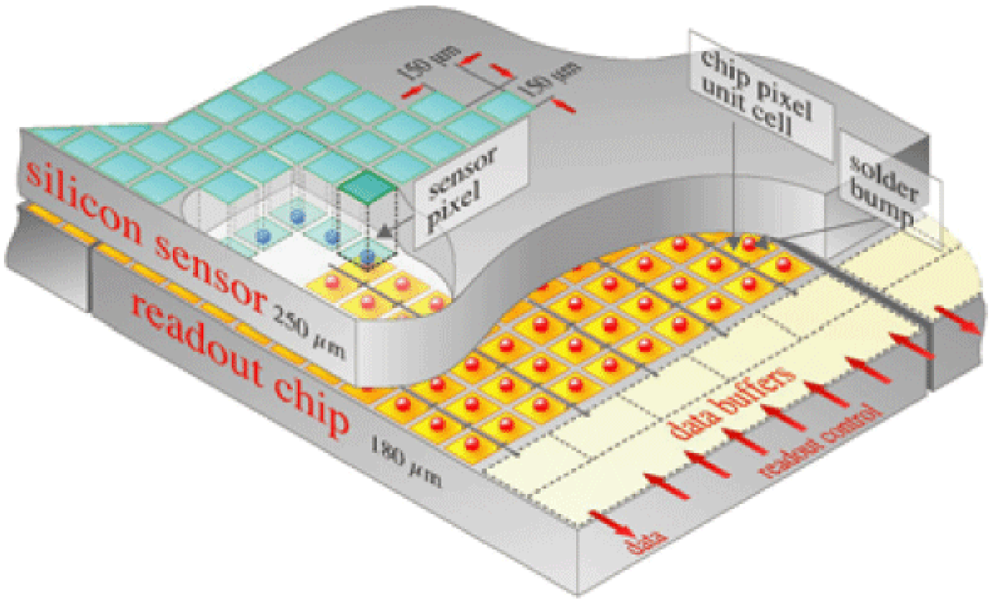
Silicon Pixel Detectors

- Highest granularity and 2D spatial resolution closest to the interaction region.

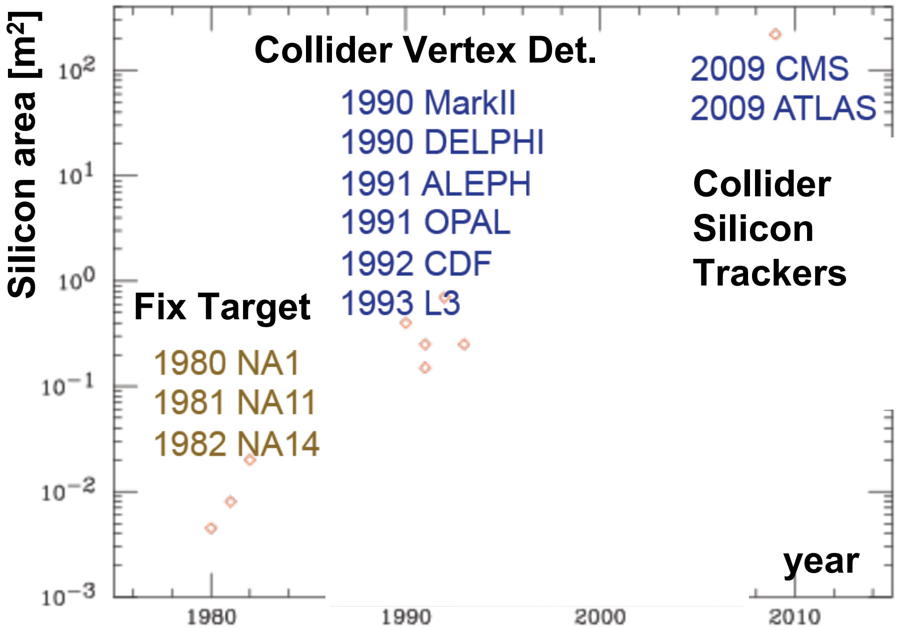
  → Inner part of the silicon tracking detectors of the LHC experiments.

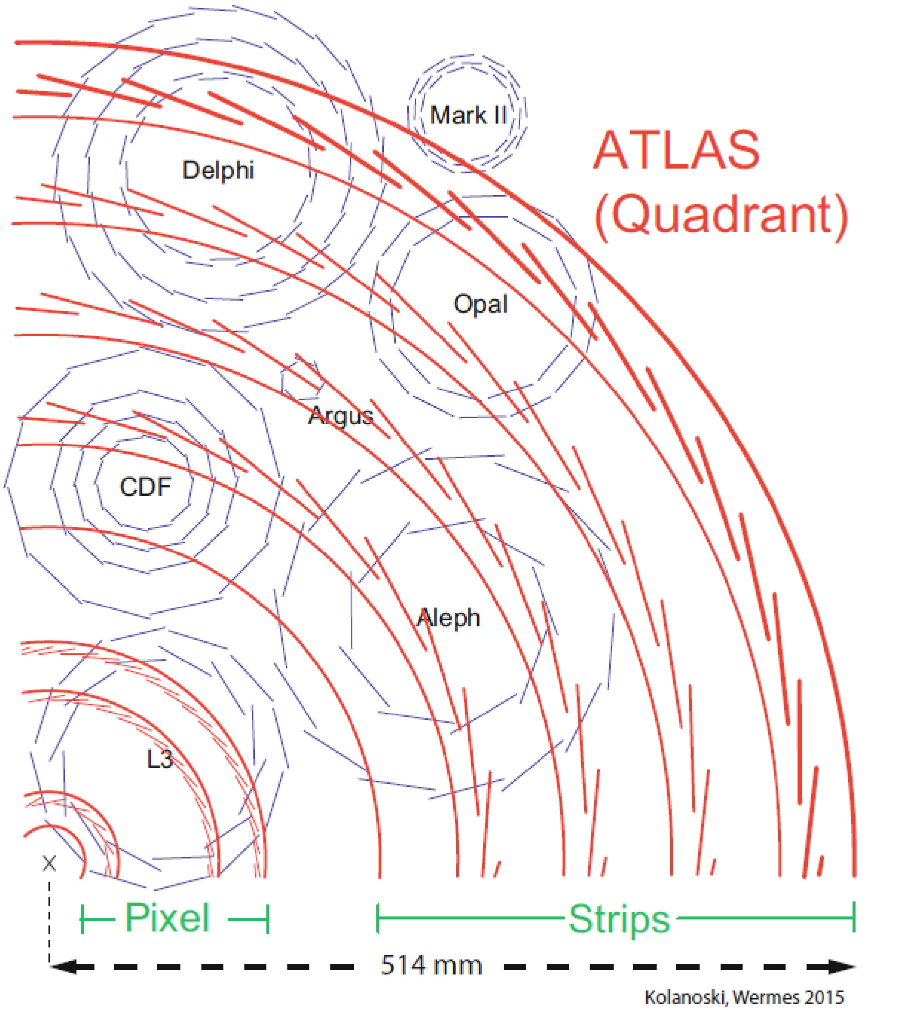
  Highest radiation hardness required.
- Pixel density i.g. not as high as in digital cameras, but much faster readout.
- Hybrid pixel sensors for the LHC era:

  bump bonding of readout chips to sensors pixel by pixel.



Silicon Detectors at Colliders

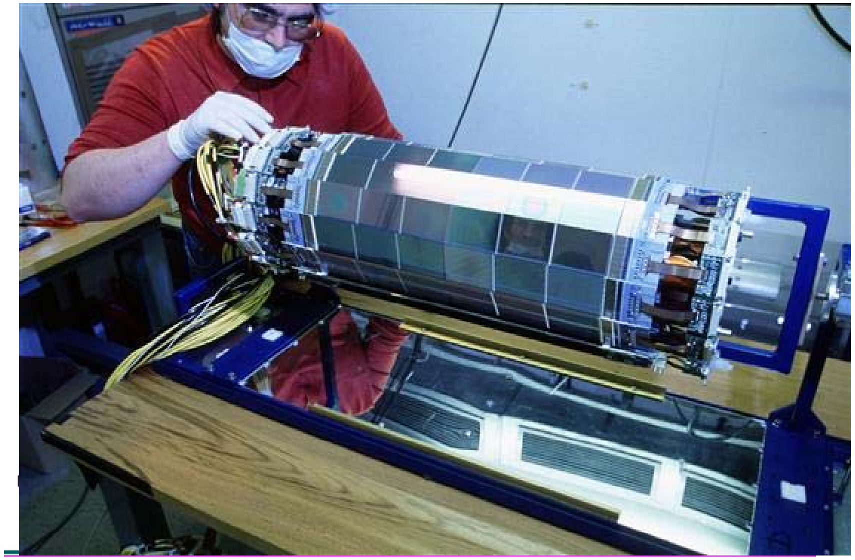


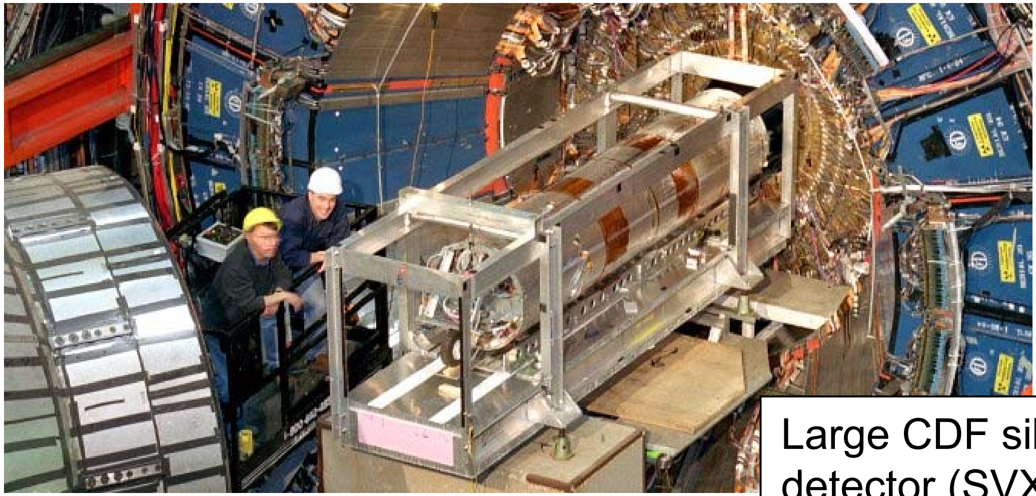


Silicon Vertex Detectors

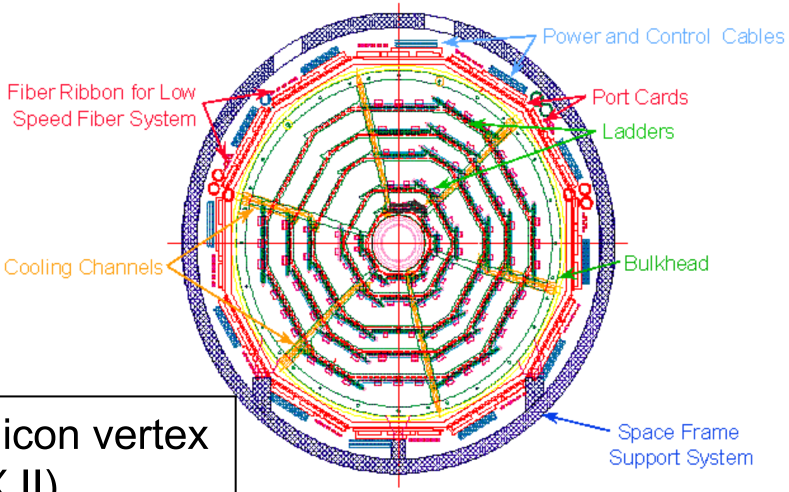
The first silicon strip vertex detector at the MARK II experiment at SLAC

The first silicon strip vertex detector at LEP in the ALEPH experiment.
Also the first double-sided strip sensors.





Large CDF silicon vertex detector (SVX II)



Silicon Central Tracking Detectors

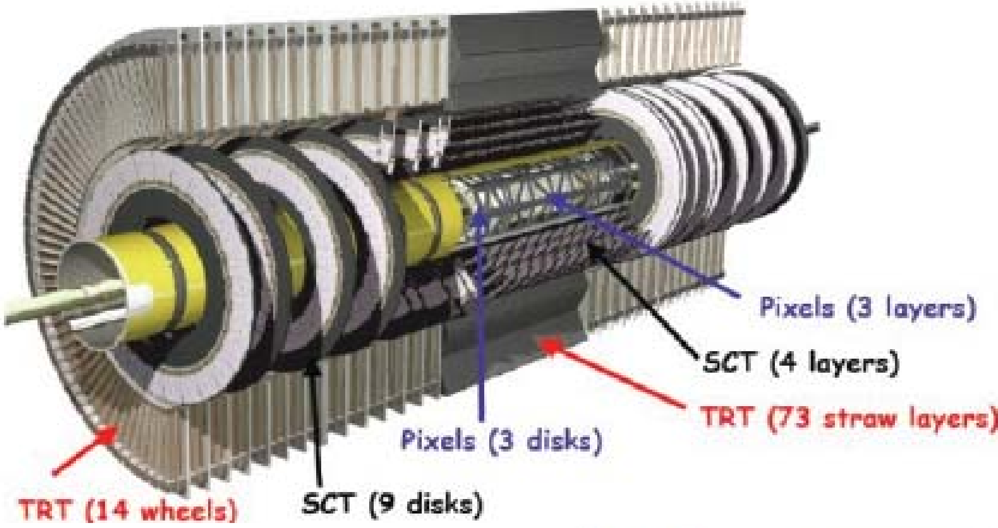
ATLAS:

60 m^2 strip sensors, 1 m^2 pixel sensors,

1750 pixel sensors,

4100 strip modules with 16400 sensors, single-sided, glued back-to back with stereo angle,

6 million strips, 80 million pixels

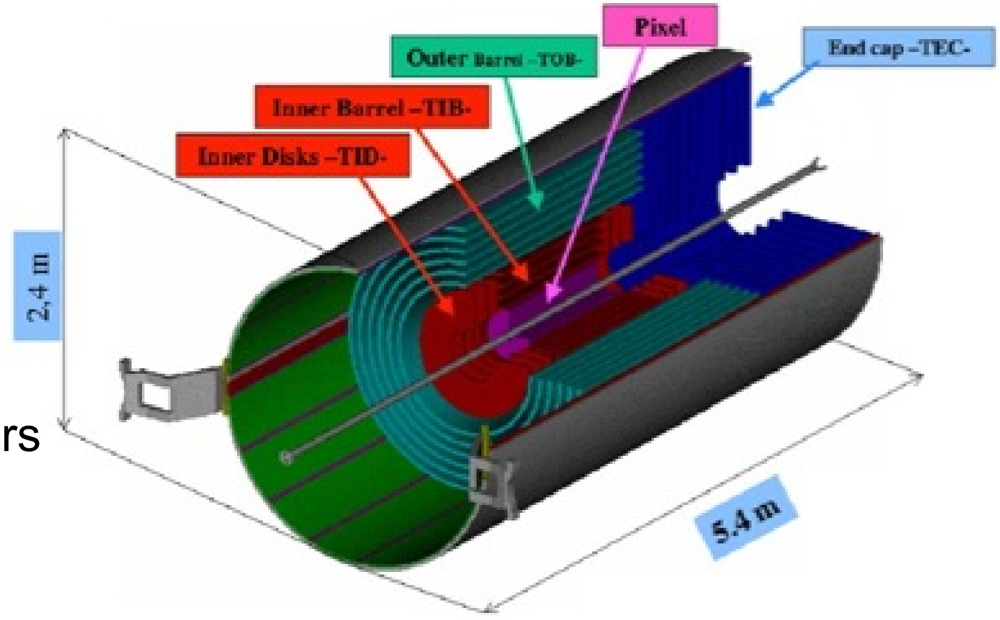


CMS:

The first and only all-silicon
collider central tracker,
and the world's largest silicon detector

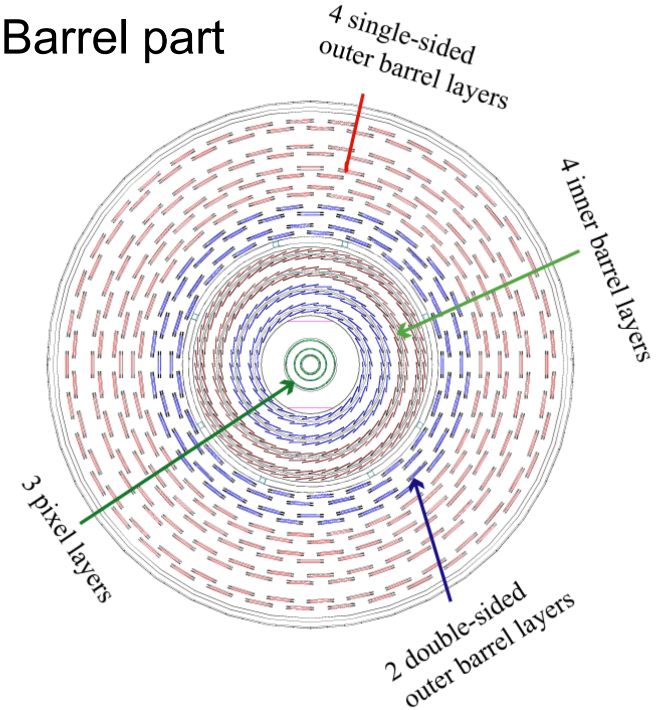
200 m^2 silicon sensors, 1 m^2 pixel sensors

11 million strips, 60 million pixels

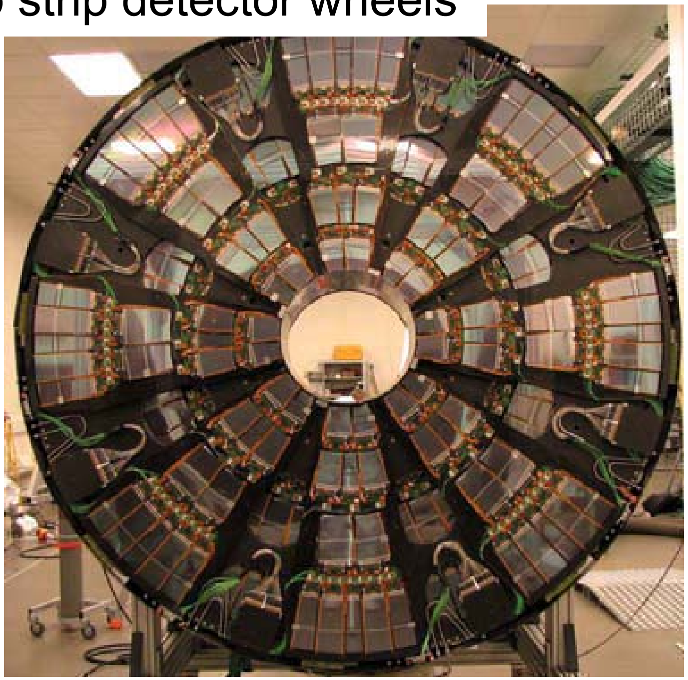


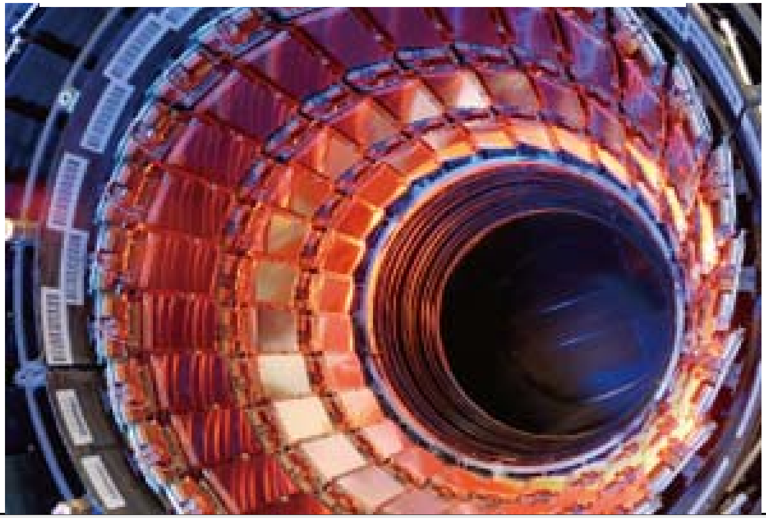
The CMS Silicon Inner Tracker

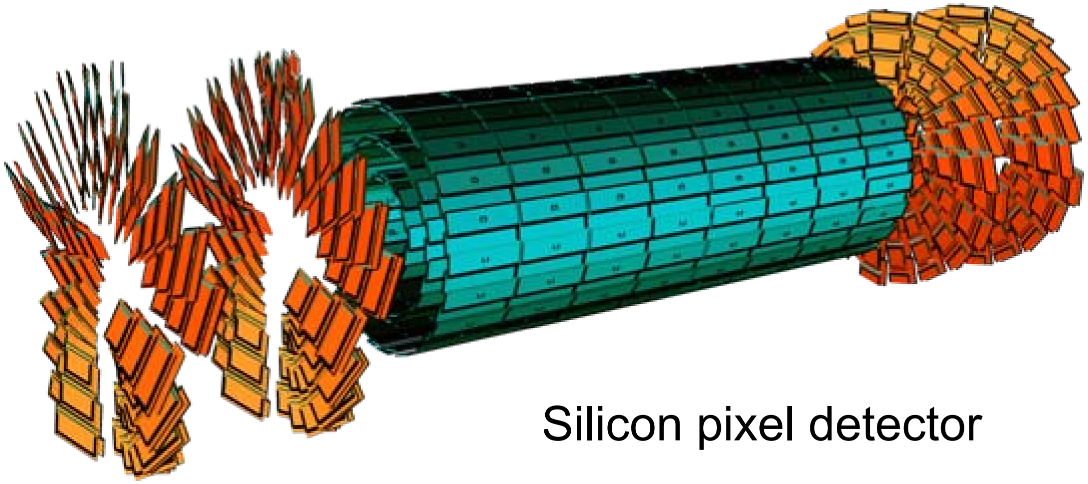
Barrel part



Endcap strip detector wheels

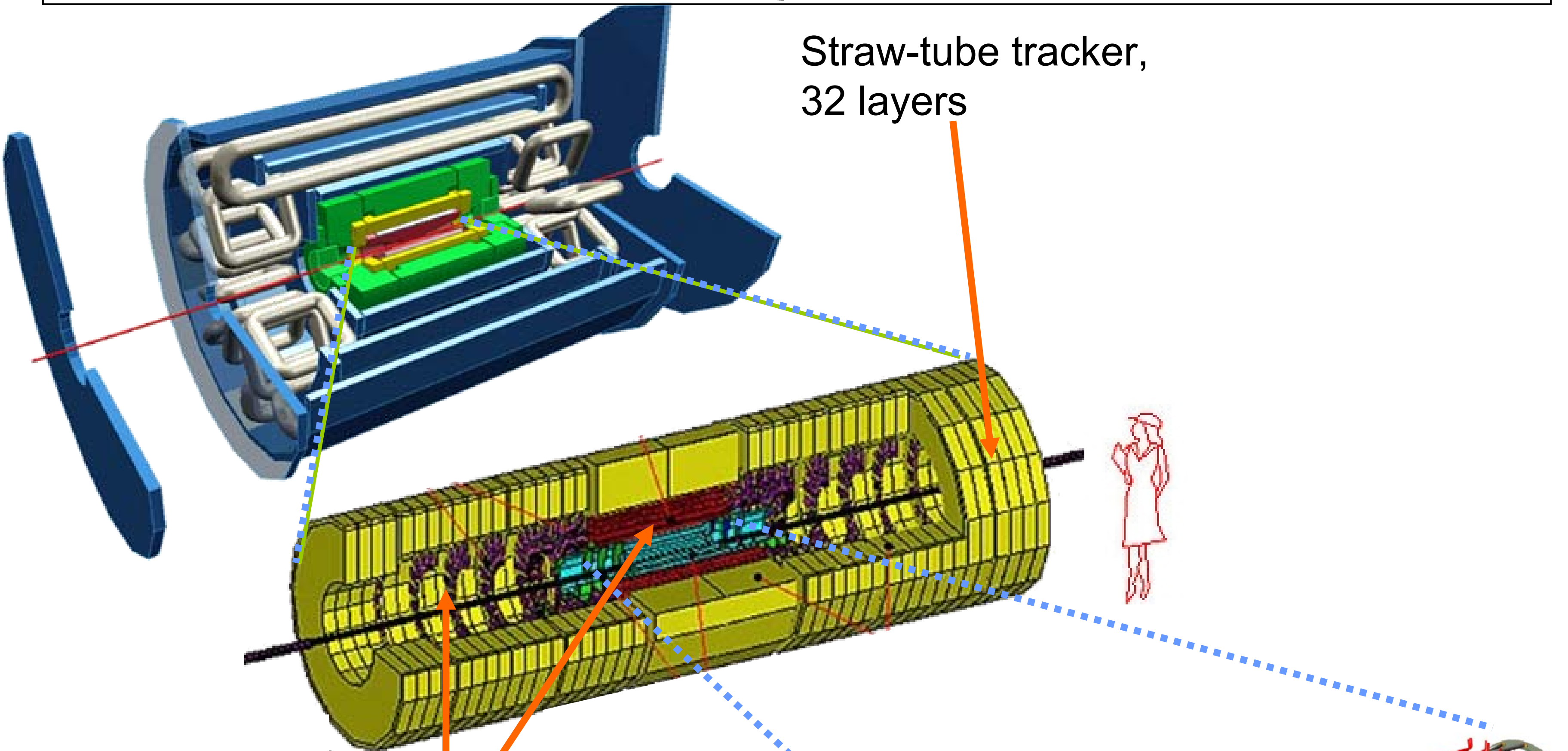




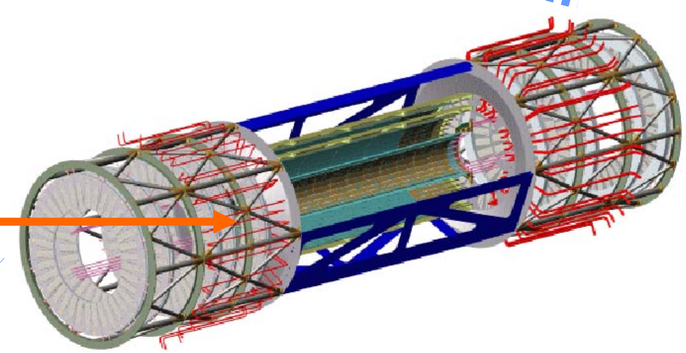


Silicon pixel detector

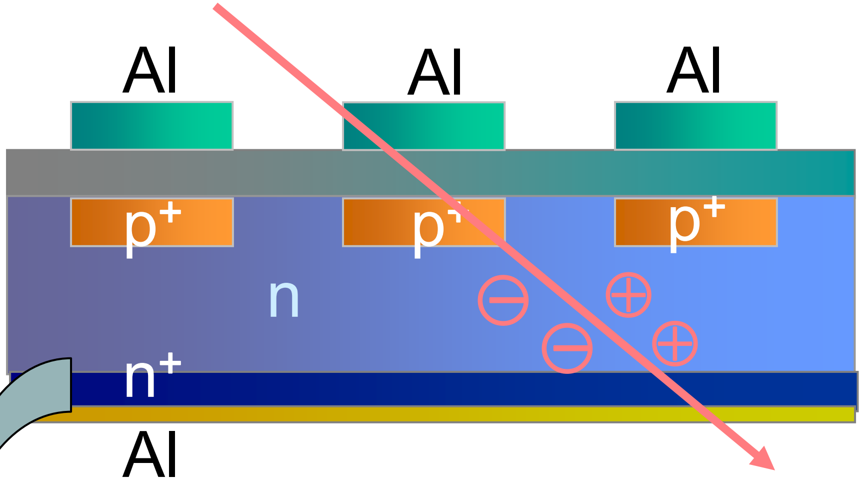
The ATLAS Inner Tracking Detector

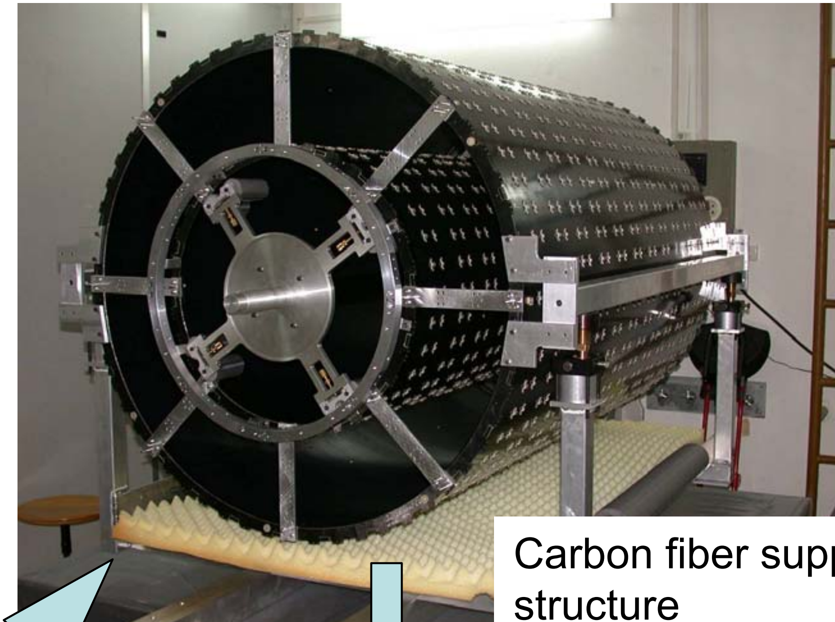


- 60 m² silicon detectors
- 6 million strips, 80 million pixels



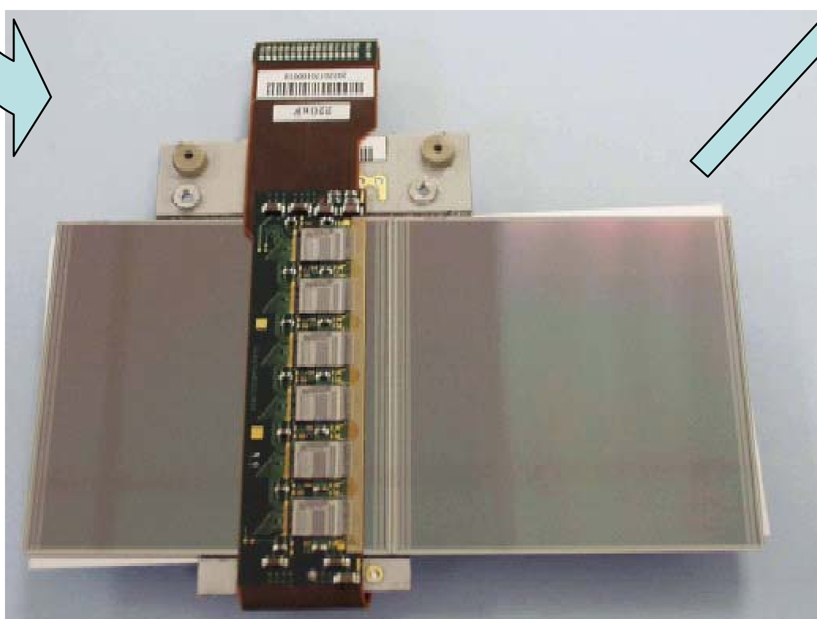
ATLAS Silicon Strip Tracker

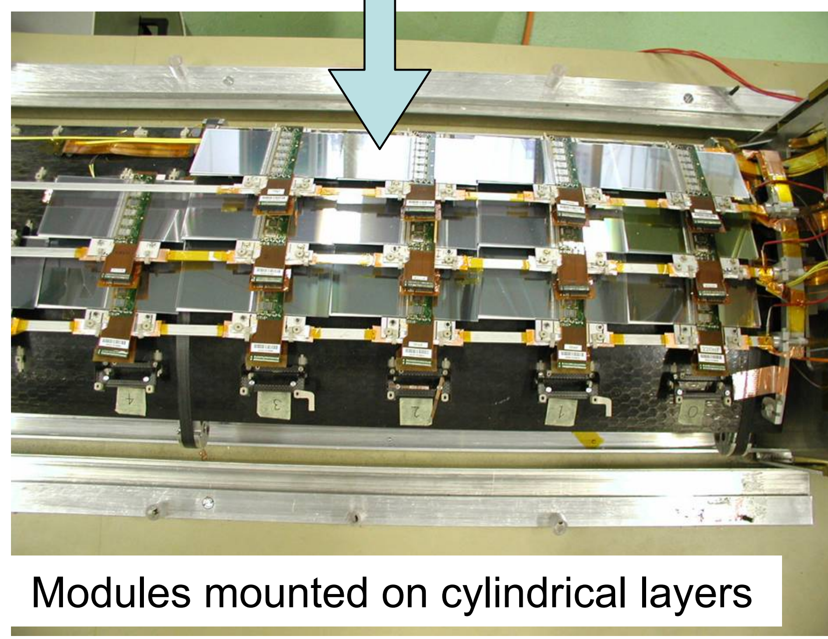




Carbon fiber support structure

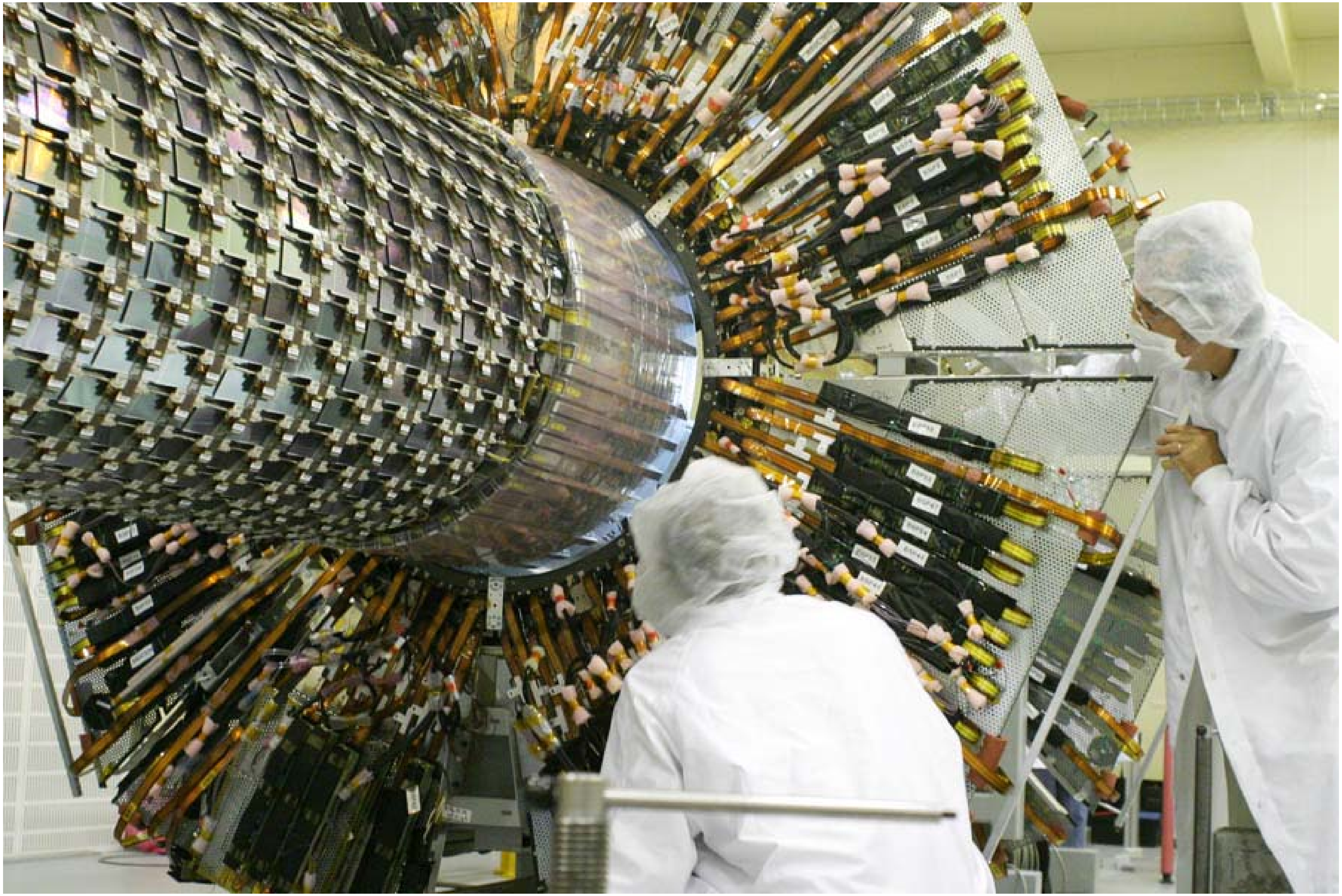
Strip detector module consisting of 4 sensors



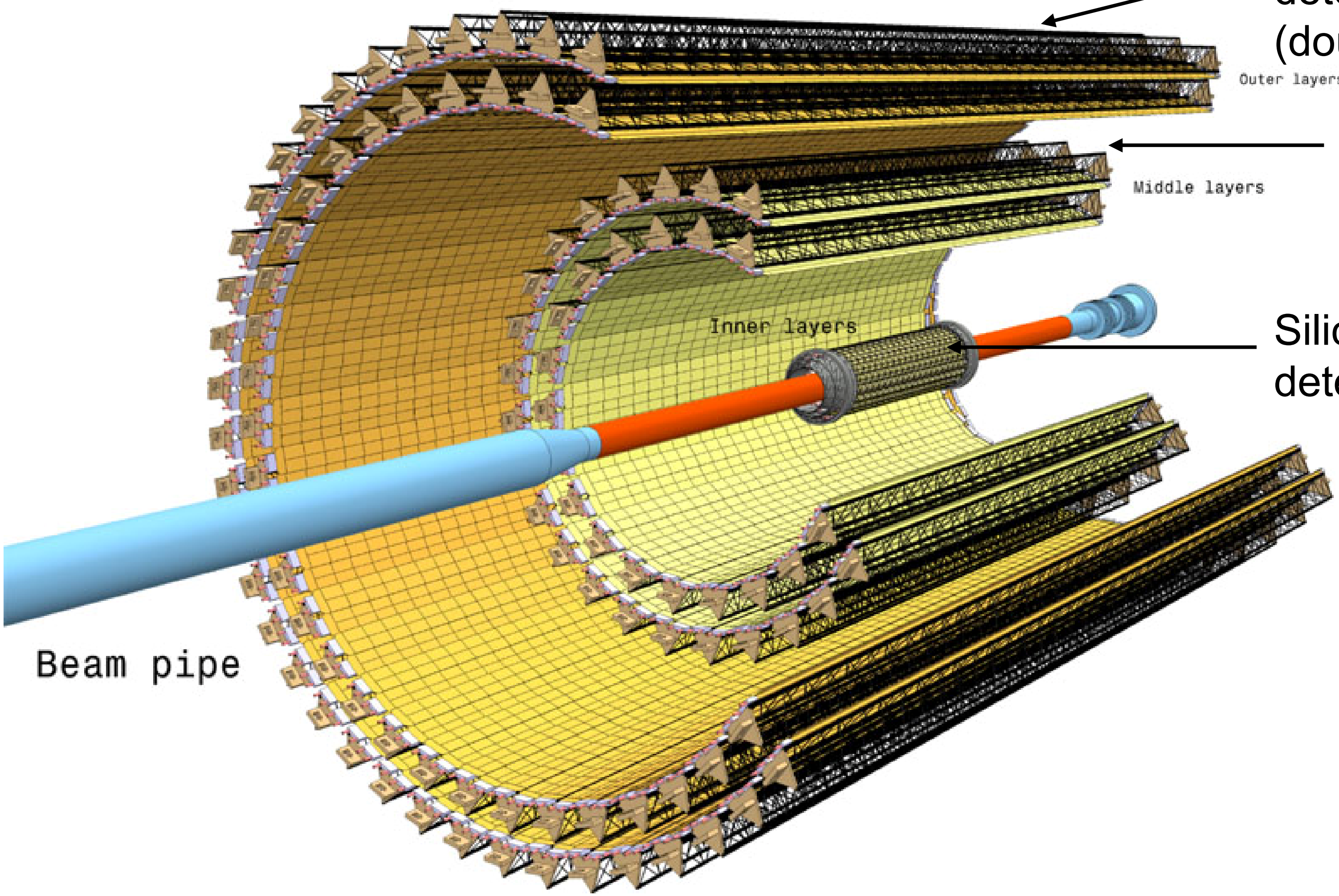


Modules mounted on cylindrical layers

ATLAS Barrel Silicon Strip Tracker Readout cable fan-out at the ends



ALICE Inner Silicon Tracker

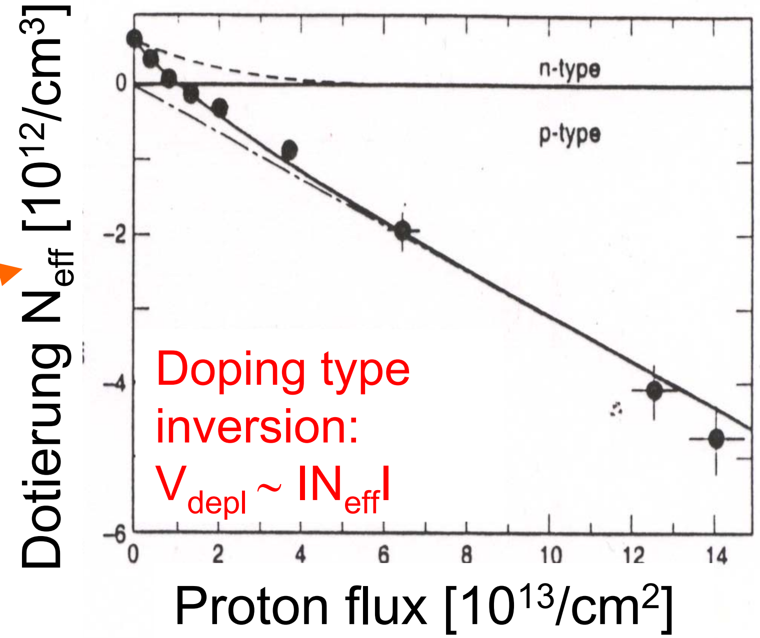


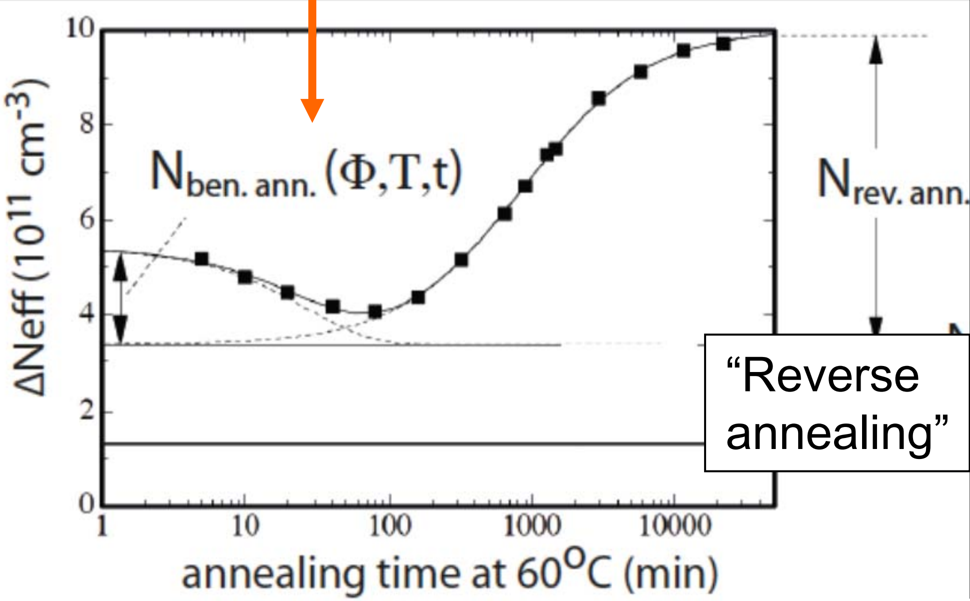
Radiation Hardness of Tracking Detectors

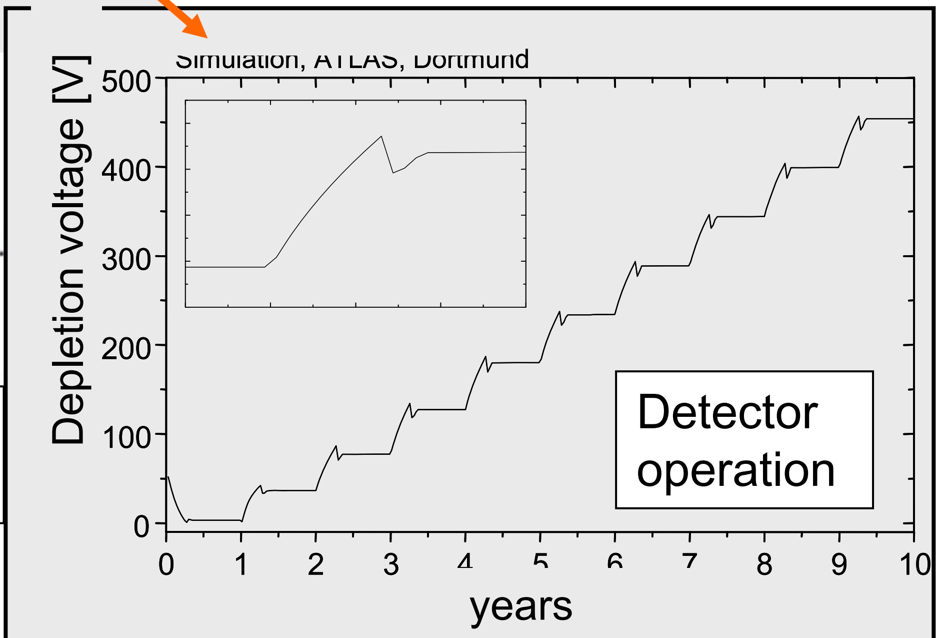
- Radiation hardness of silicon sensors and their readout ASIC chips became a serious issue first for the LHC experiments.
  → Silicon sensors are the only technology which can cope on a large scale with the high radiation levels at LHC. Intense dedicated R&D program in the 1990s.
- Radiation hardness is still more critical for the new all-silicon central detectors of ATLAS and CMS at high-luminosity LHC (HL-LHC).
  → More refined silicon sensor design and material selection, thinned sensors,… R&D started before LHC data taking.
- At e+e– colliders less critical, although non negligible.
- New damage of crystal lattice by hadron irradiation (non-ionising energy loss NIEL).
- Ionising energy loss affects sensors and electronics (Si SiO_2 interface=.
- Radiation hard integrated electronics processes from military applications for LHC.
- Increased ASIC radiation hardness is now a by-product of ever smaller feature sizes of modern chip technologies.

Radiation Hardness of Silicon Sensors

- Irradiation dose in 10 years of LHC operation at design luminosity:
  >10 MRad und > 10^{14} protons/cm^2
- Bulk radiation damage of crystalline silicon lattice: effective change of the doping concentration with n → p transition (depletion from backside n^+ electrode).
  → increase depletion voltage $|N_{eff}| \sim V_{depletion}$
- Effect enhanced by higher temperatures in the long run: defects activated.
  Detector operation at < 0° C in dry N_2 atm.







Radiation Hardness of Silicon Sensors – Further Developments

- Even more radiation hardness needed for silicon sensors at HL-LHC:

  10^{15} protons/cm^2 for strip sensors, 10^{16} protons/cm^2 for pixel sensors (advantage: smaller pixels)
- **Thin planar sensors:** increased charge collection efficiency (CCE) at high damage.

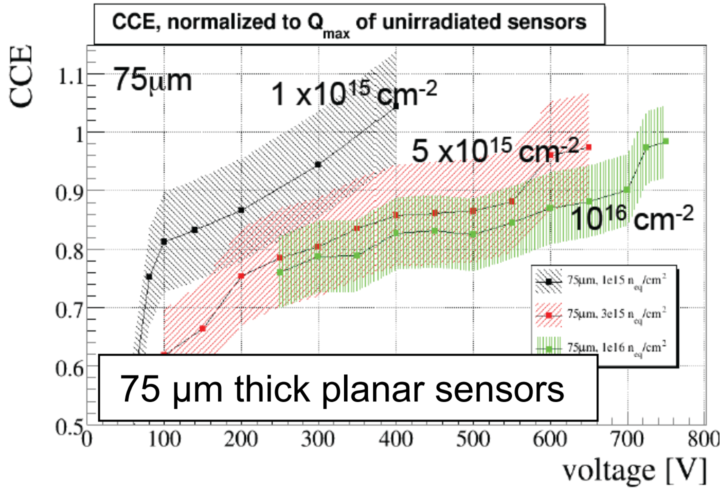
  Short distances, high depl. Voltage. Thinning by etching of back-side of wafer.

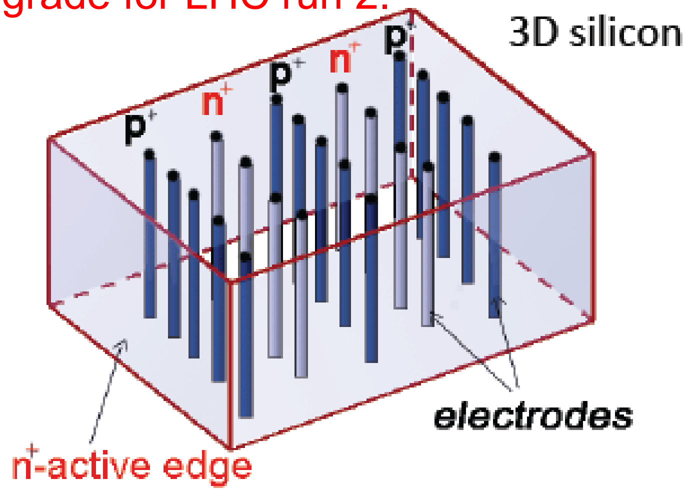
  Also: less scattering material (esp. for future e^+e^- collider detectors).
- **n^+ pixels in p or n bulk:** still work without complete depletion from n^+ pixel side.

  LHC pixel sensors n^+-in-n, HL-LHC strip and pixel sensors n+-in-p (or n+-in-n).
- **3D pixel sensors:** p^+ and n^+ doped holes etched into n doped bulk (50 μm pitch).

  → Sidewards depletion and charge collection over short distances: much improved.

  Industrial production. Used in ATLAS inner pixel layer upgrade for LHC run 2.

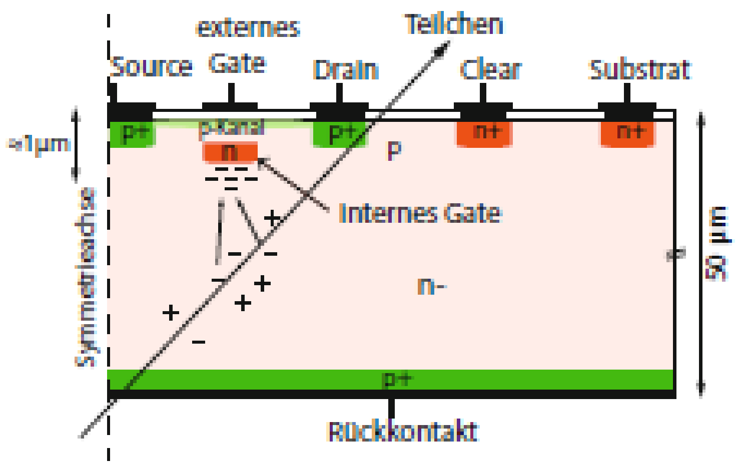


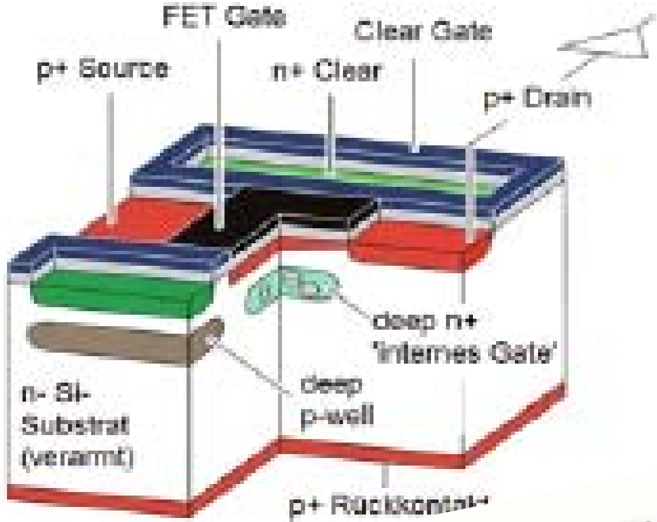


Silicon Pixel Sensors for Future Collider Experiments

DEPFET Pixel Sensors:

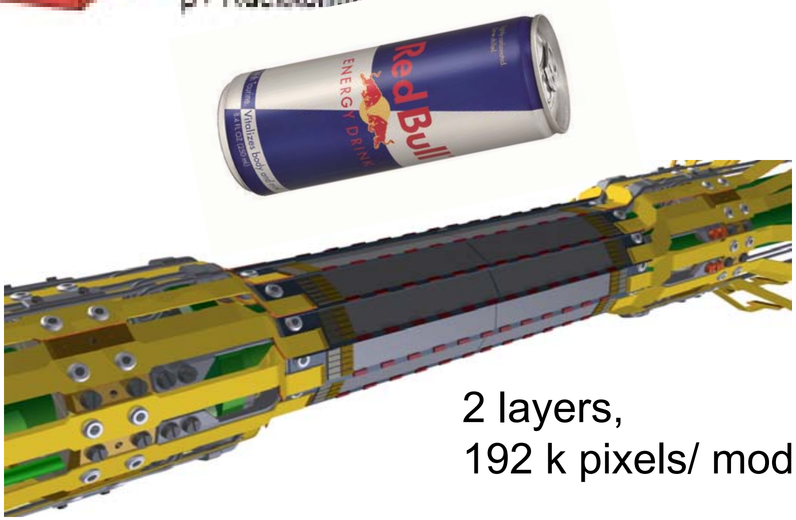
Fully depleted active pixels consisting of FETs for amplification of collected ionisation electrons. Limited radiation hardness.





Can currently only be fabricated at the MPI Semiconductor Laboratory where they have been invented.

Sensors thinned to 75 µm will be used for the pixel vertex detector of the Belle II experiment.



2 layers,
192 k pixels/ module

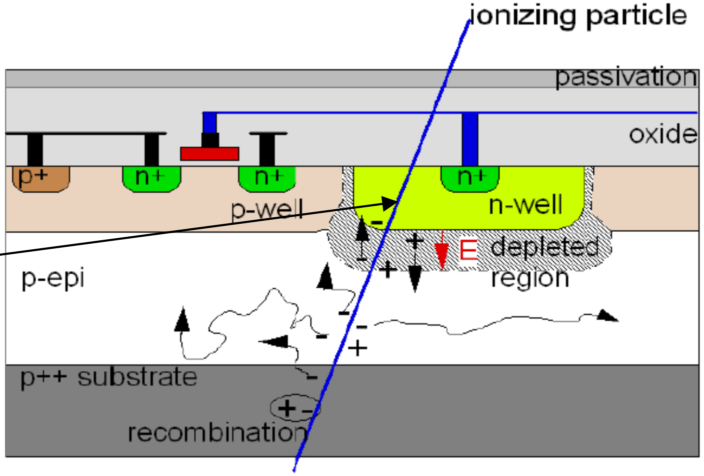
Silicon Pixel Sensors for Future Collider Experiments

Monolithic active pixel sensors (MAPS) with integrated readout electronics using standard CMOS process (like for digital cameras), very small pixels.

Thin active layer near surface, not fully depleted:

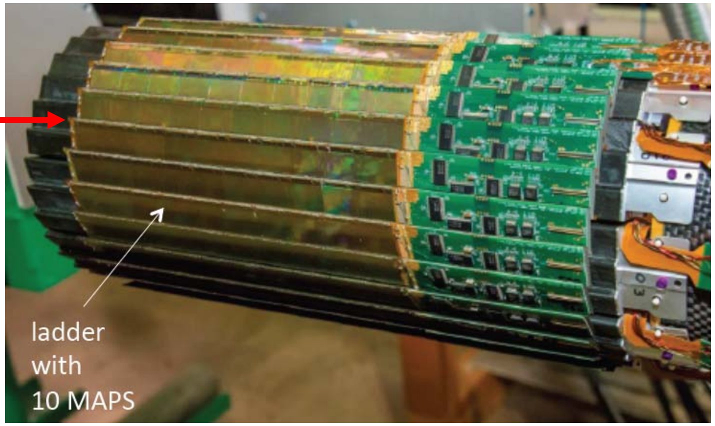
Can be thinned.
Limited radiation hardness.
Slow charge collection.

Charge collection and amplification (n^+ in p)



→ Developed for future e+e– colliders like ILC.

→ Used in the STAR experiment at RHIC since 2014.



→ Planned for new ALICE inner tracker after 2019/20 LHC shutdown: 10 m^2.

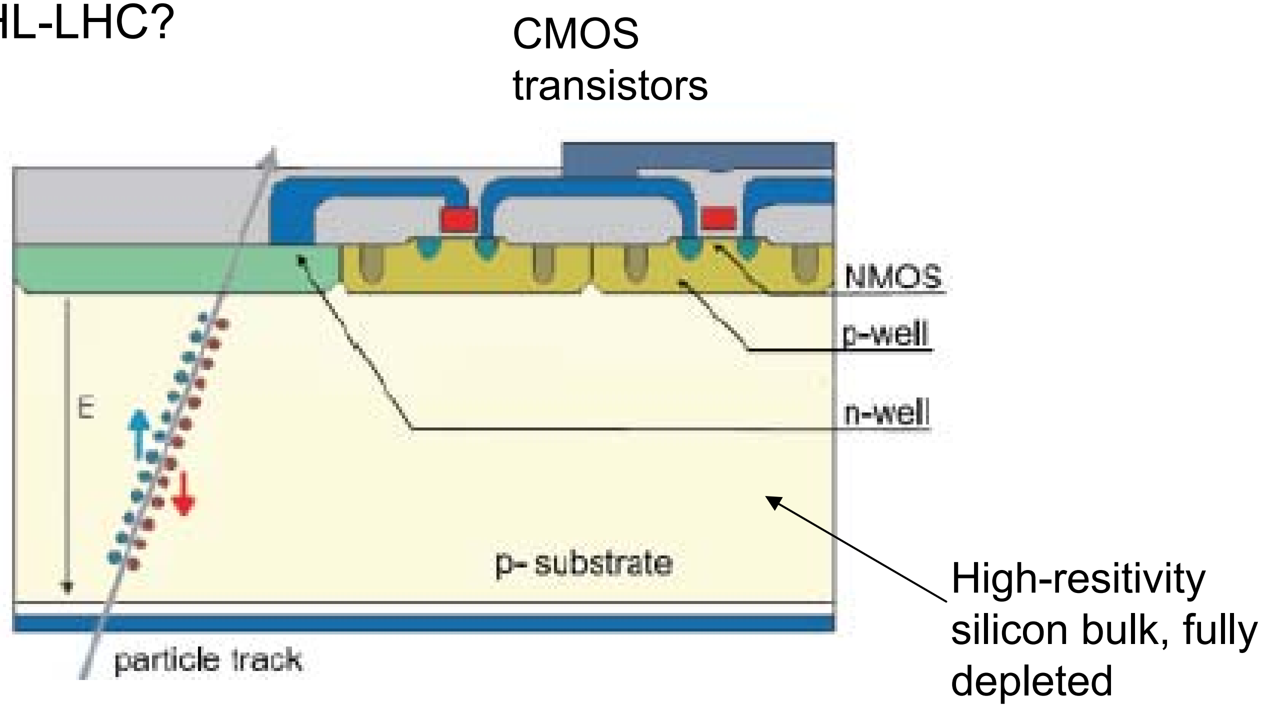
Silicon Pixel Sensors for Future Collider Experiments

Recent (common) developments for ATLAS and CMS trackers at HL-LHC:

Depleted HR/ HV-CMOS MAPS:
hope for a low cost and low material solution for large areas.

Radiation hardness to be verified.

For outer pixel layers at HL-LHC?



Muon Detectors

- The outermost detectors.
  All other particles than muons are absorbed in the calorimeters.

  $\rightarrow$ Large detection areas.
  $\rightarrow$ Gas detectors.

Tasks:

- Muon identification.
- Fast muon trigger detectors for first-level muon trigger and bunch crossing identification.
- Muon track reconstruction and momentum measurement in a magnetic field.

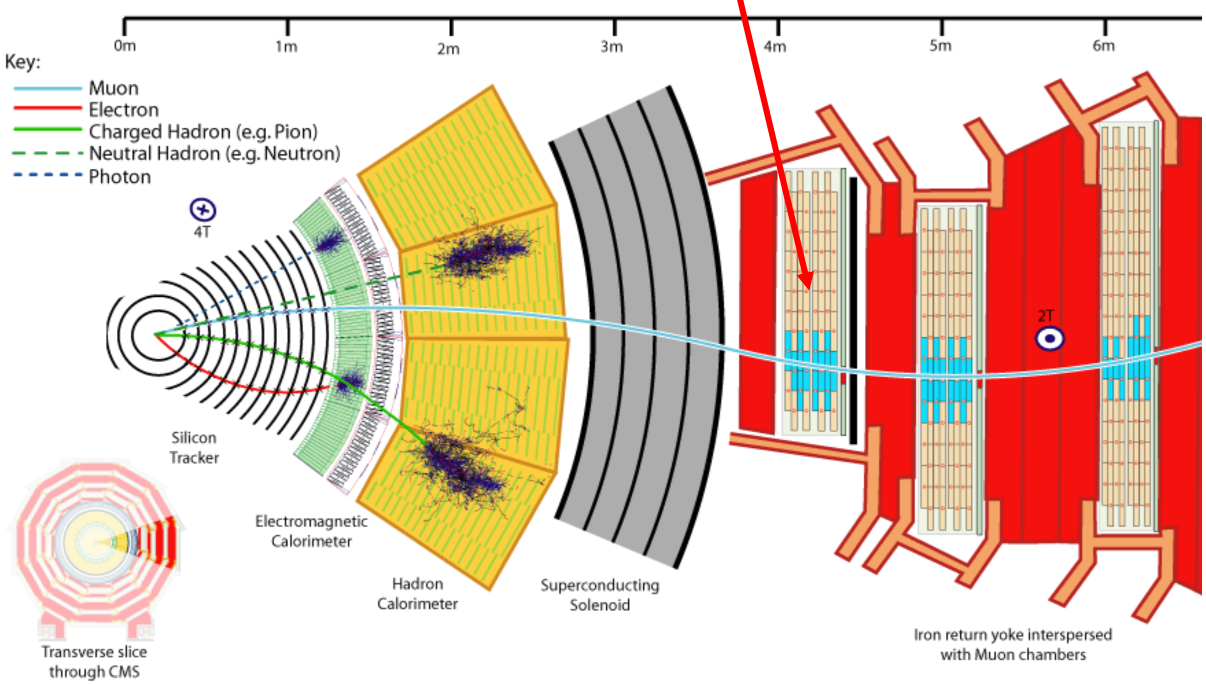
- Most challenging muon detector: **the ATLAS Muon Spectrometer**

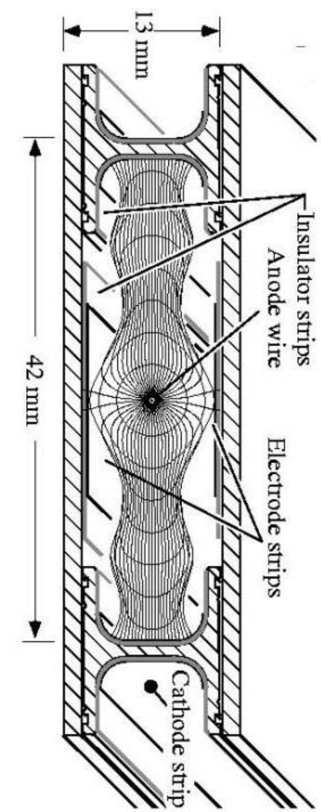
Normally, muon chambers embedded in iron absorber,
the magnetic flux return yoke of the inner detector solenoidal magnetic field, like in the **CMS Detector at the LHC.**

Spatial resolution limited by multiple scattering in the iron.
Drift chambers with few hundred micron resolution sufficient for muon identification.

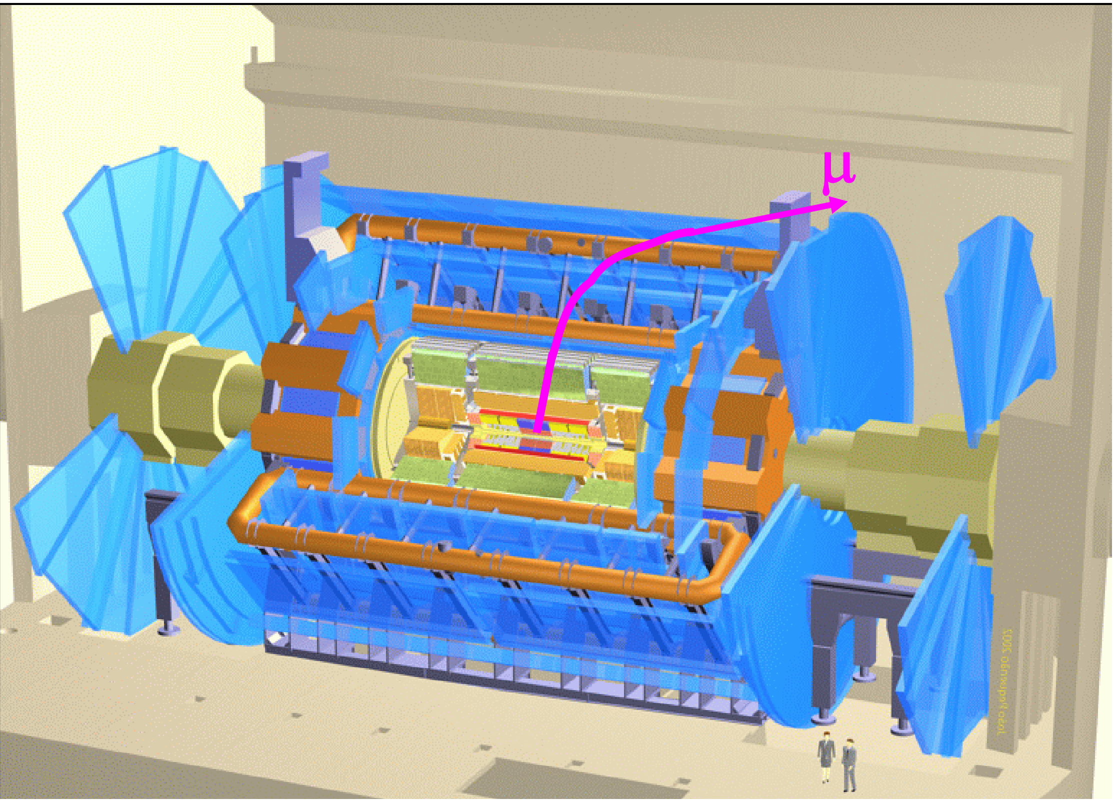
Precise momentum measurement in combination with the inner tracker.

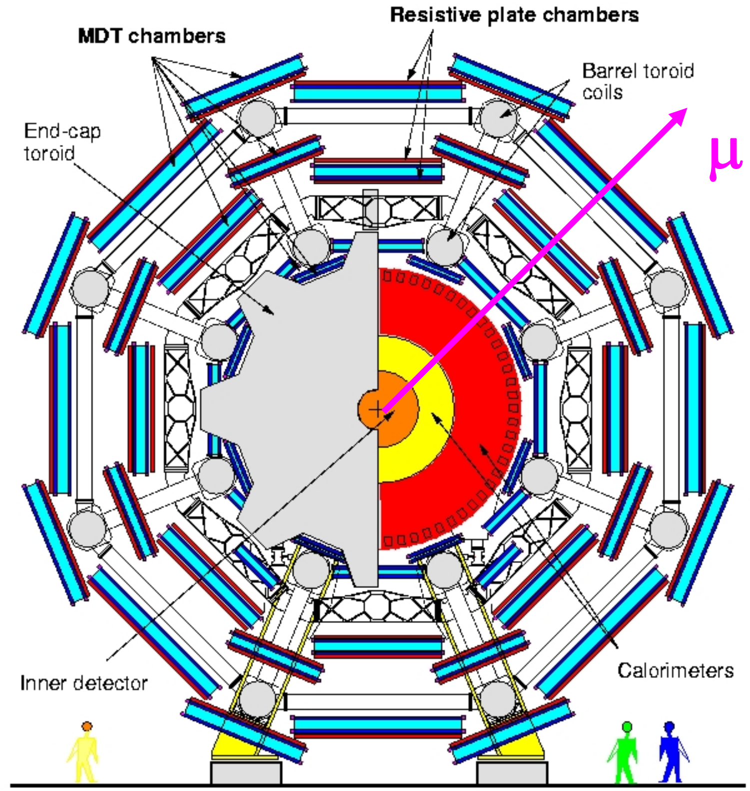
Many layers of crossed drift tube detectors for 2D track reconstruction





ATLAS Muon Spectrometer





- Toroidal magnetic field of superconducting air-core magnet coils, the world's largest:

  multiple scattering minimised!

- Stand-alone momentum resolution of 3-10 % for muon momenta of 10-1000 GeV.

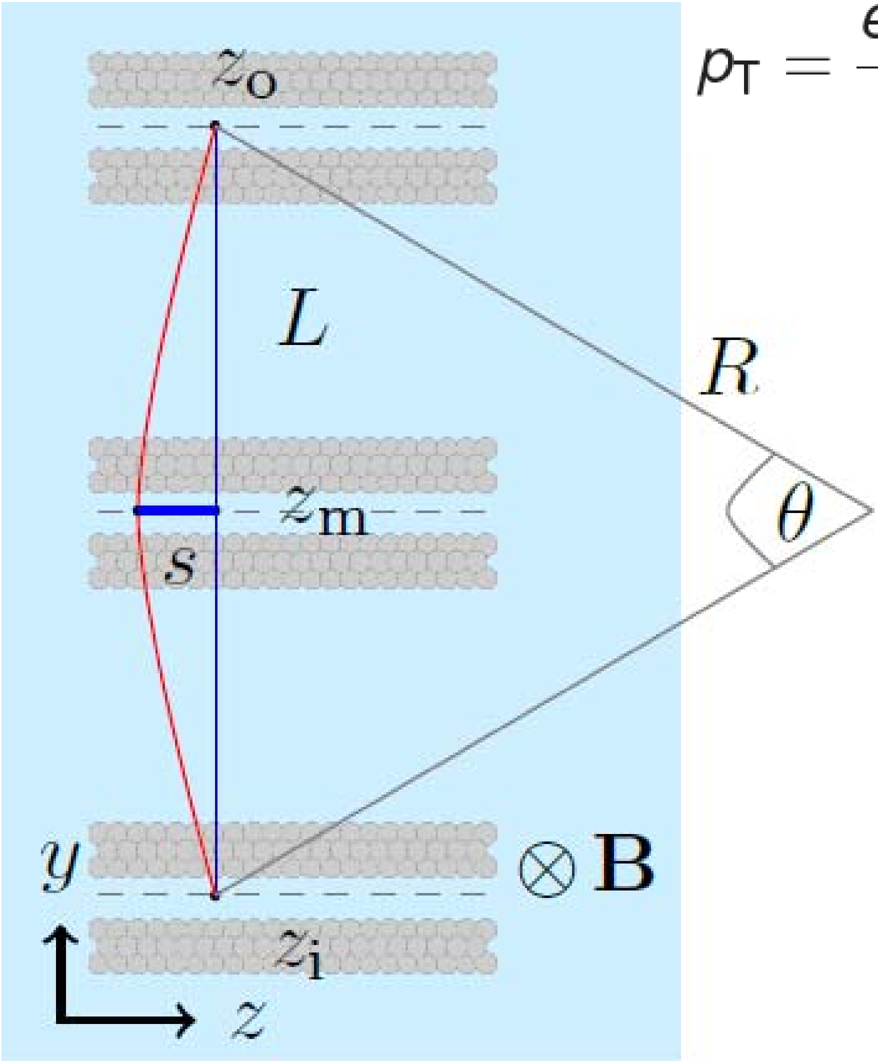
- High-precision muon tracking detectors, unprecedented in a collider experiment.

- Optical alignment monitoring system.

Momentum determination with 3-point track-sagitta measurement

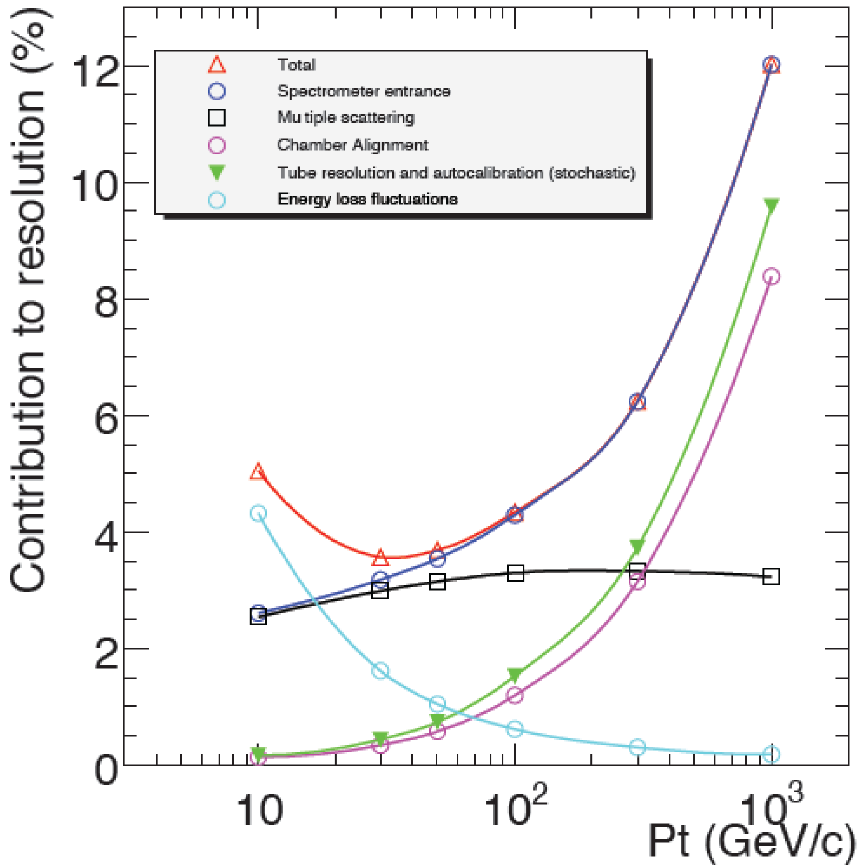
- Track sagitta of 1 TeV muon is 0.5 mm. Multiple scattering uncertainty small.

  ⇒ Sagitta has to be measured with 50 μm accuracy for 10% momentum resol.

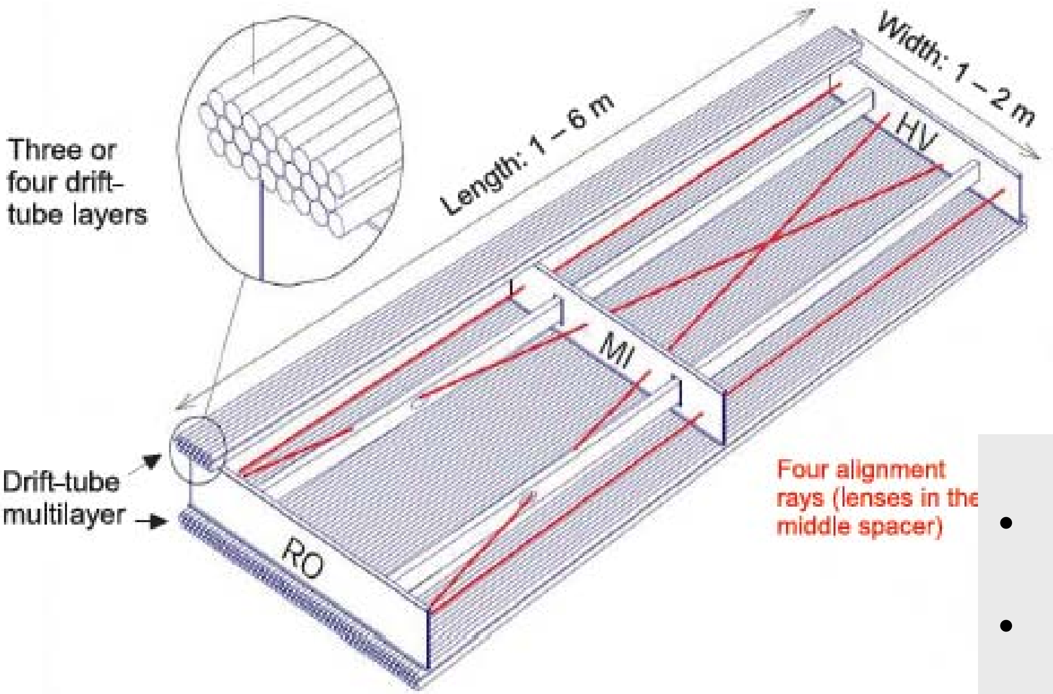


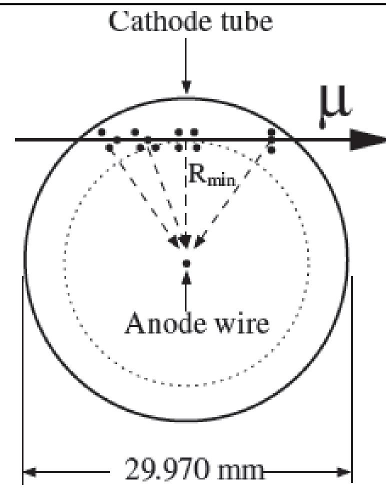
$$p_T = \frac{eL^2 \cdot B(\phi, \eta)}{8s}$$

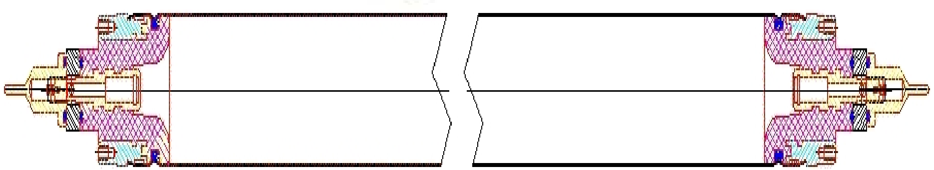
in the bending plane perpedicular to the B field



Precision Muon Tracking Detectors: the Monitored Drift-Tube (MDT) Chambers







Anode wire precisely centered in the endplugs

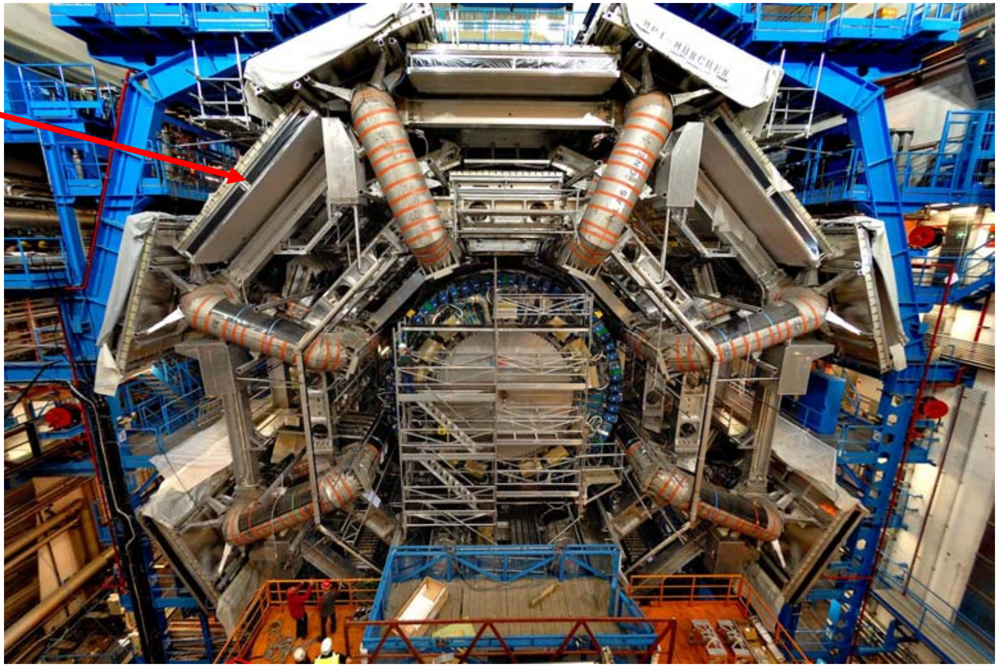
- 6-8 layers of 30 mm ∅ aluminum drift tubes with 400 μm wall thickness
- filled with $Ar:CO_2$ (93:7) gas at 3 bar pressure
- Tube spatial resolution 80 μm
- Sense wire pos. accuracy 20 μm
- Chamber spatial resolution 35 μm
- Maximum drift time 700 ns

1200 chambers with 370000 drift tubes (1000 km total length), 5000 m^2 detector area

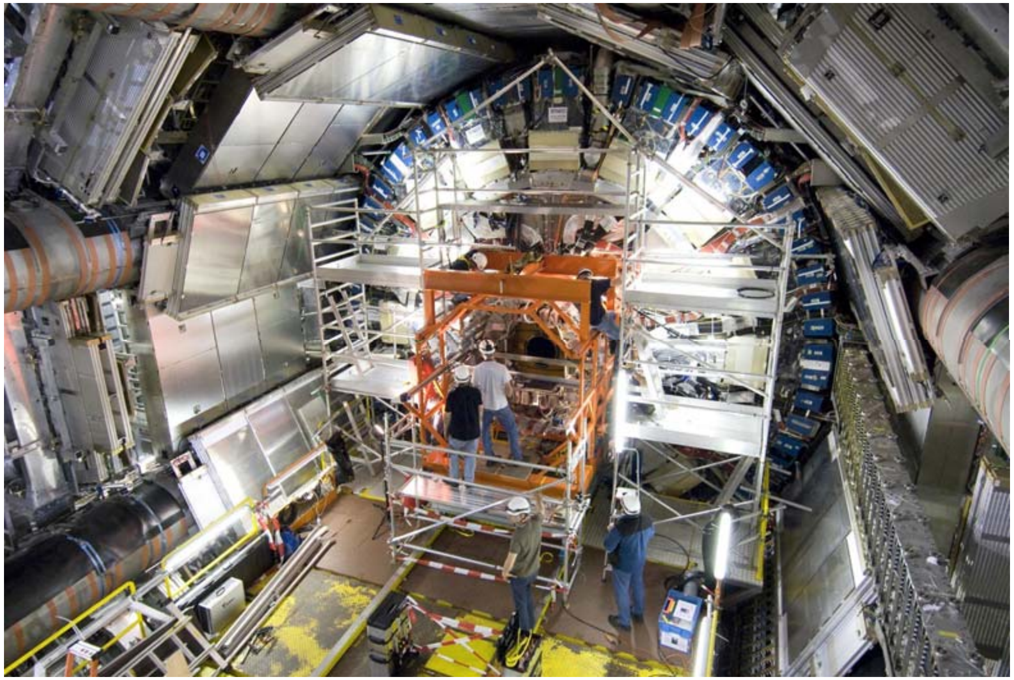
MDT Precision Tracking Chambers

430 drift tubes per chamber,

up to 6 m long



MDT Precision Tracking Chambers in ATLAS

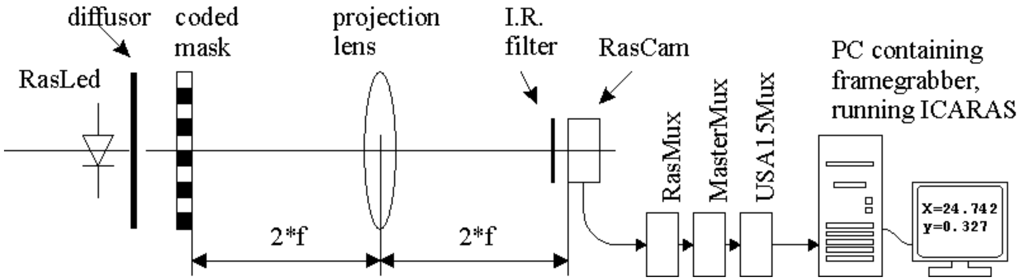


Precision Optical Alignment Monitoring System

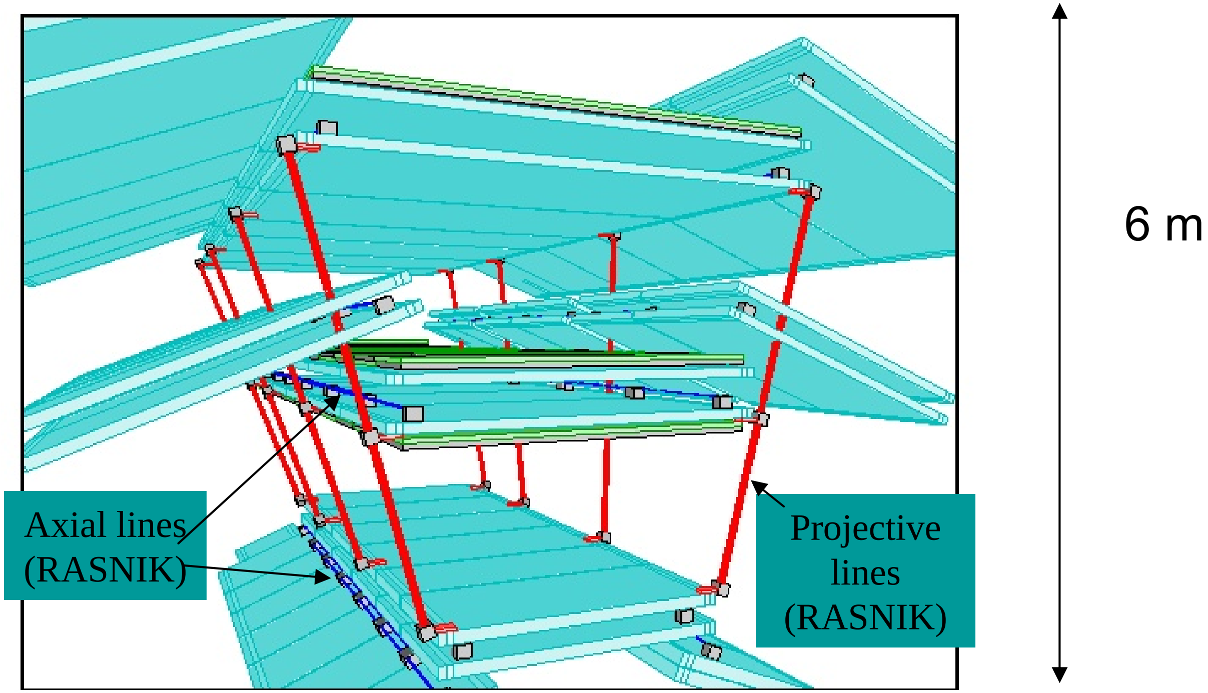
Continuous monitoring of the relative chamber positions

with few micron precision using optical straightness sensors (RASNIK).

→ Corrections on the track sagitta with 30 μm accuracy.



Upgraded system from the one used in the L3 muon detector at LEP



Muon Trigger Detectors

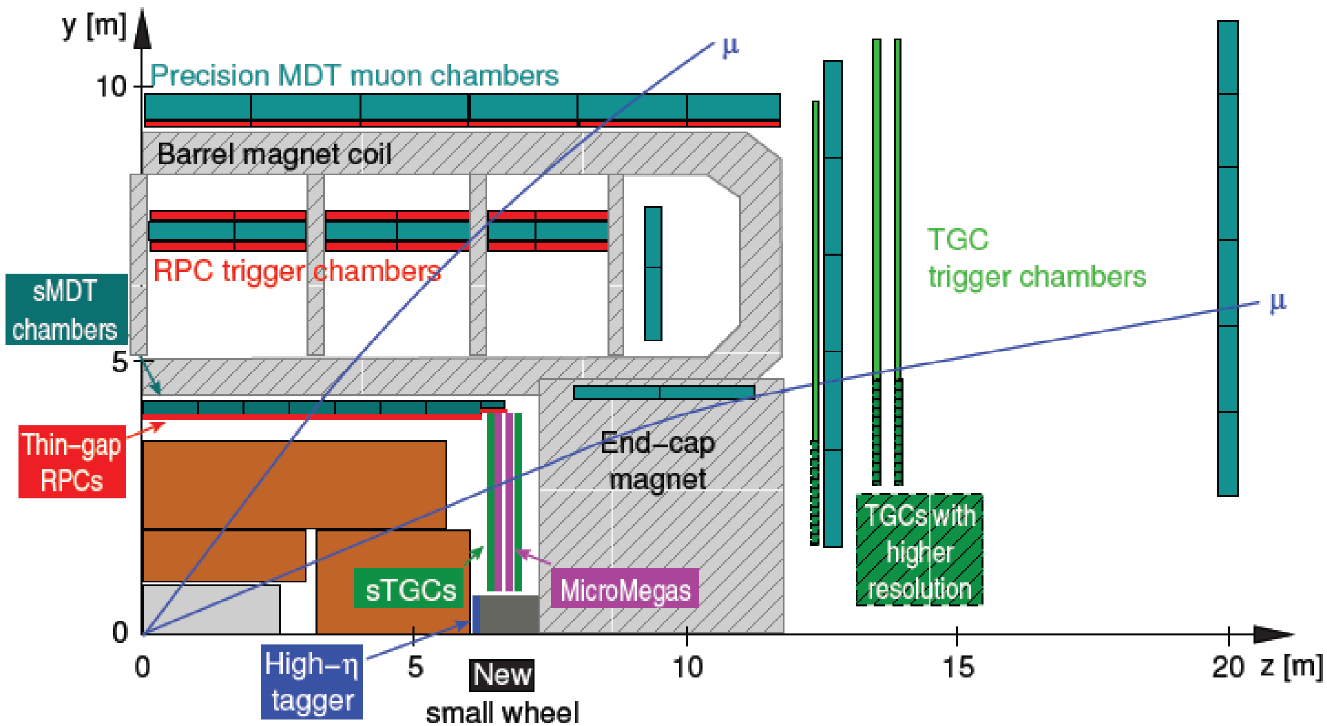
- First-level muon trigger crucial for collider, especially hadron collider experiments
- **Dedicated fast muon trigger detectors in ATLAS and CMS**

  with few ns time resolution for LHC p bunch crossing identification and

  for less precise 2nd coordinate information along the drift tubes:

  Resistive Plate chambers (RPC) and **Thin Gap MWPC (TGC)** in present detectors

  (also large-area GEM detectors (CMS) and Micromegas (ATLAS) for future upgrades)



Quadrant of ATLAS muon spectrometer

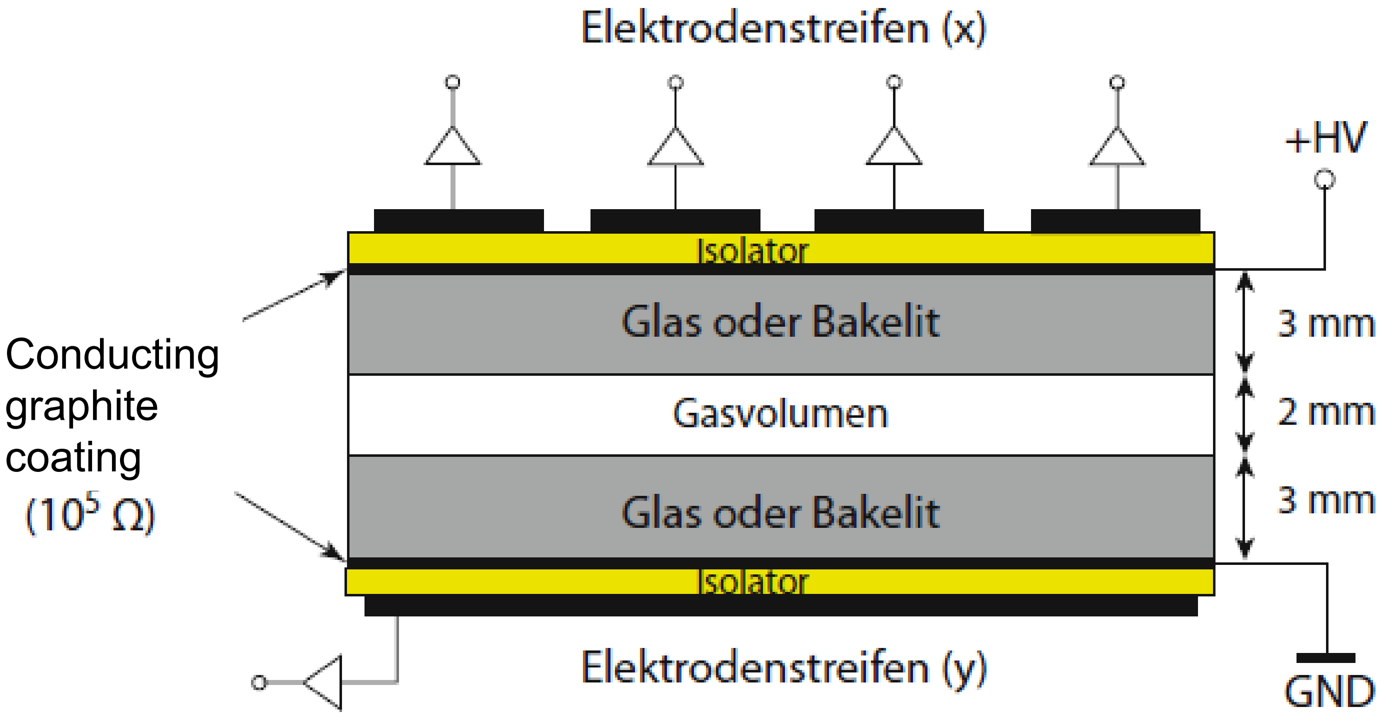
Resistive Plate Chambers (RPC)

Gas chambers without sense wires. Technology for large areas.

High voltage of ~14 kV applied between bakelite or glass panels over thin gas gap.

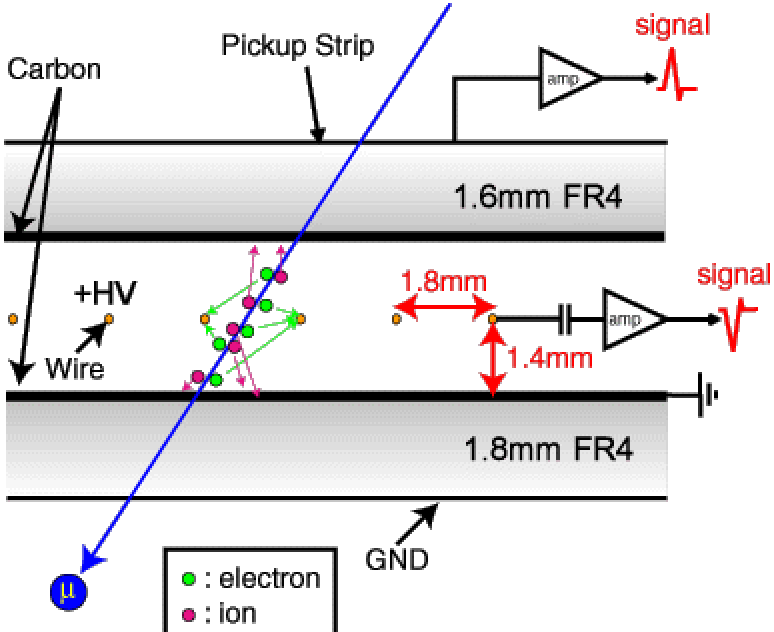
Ionisation by traversing charged particles causes localised sparks which create signals in crossed pick-up electrodes for 2D position information.

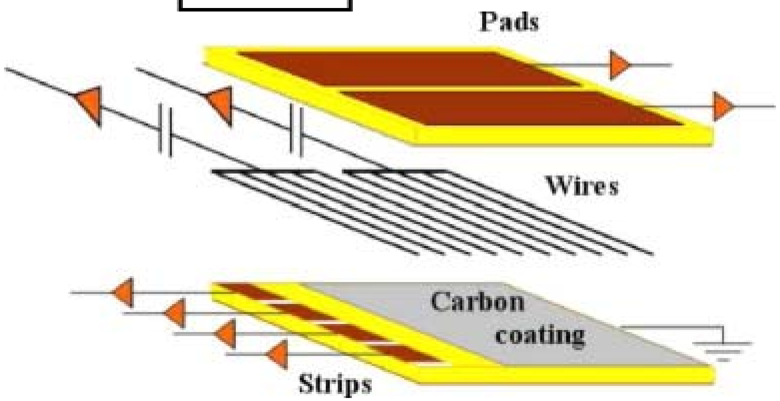
Rate capability and time resolution depend on the conductivity of the panels and their graphite coating.

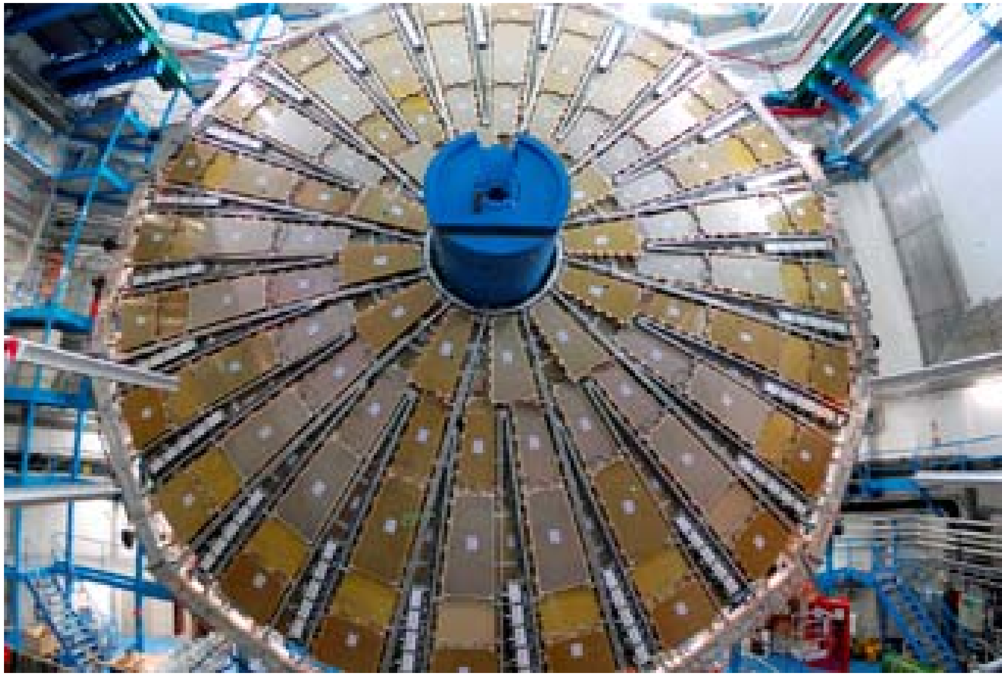


Thin Gap Chambers (TGC)

MWPC with single thin gas gap for fast response
and with signal pick-up strips and/or pads for 2D position information.







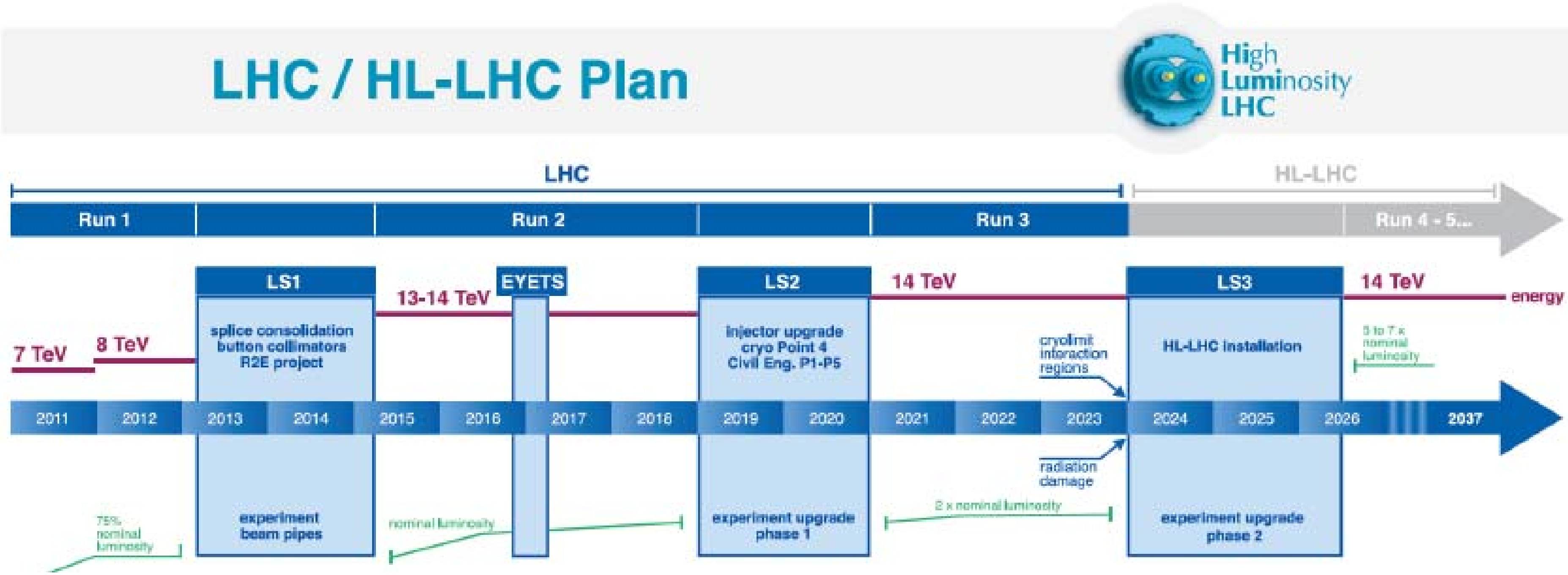
ATLAS big endcap muon detector wheel

Challenges at Future Colliders

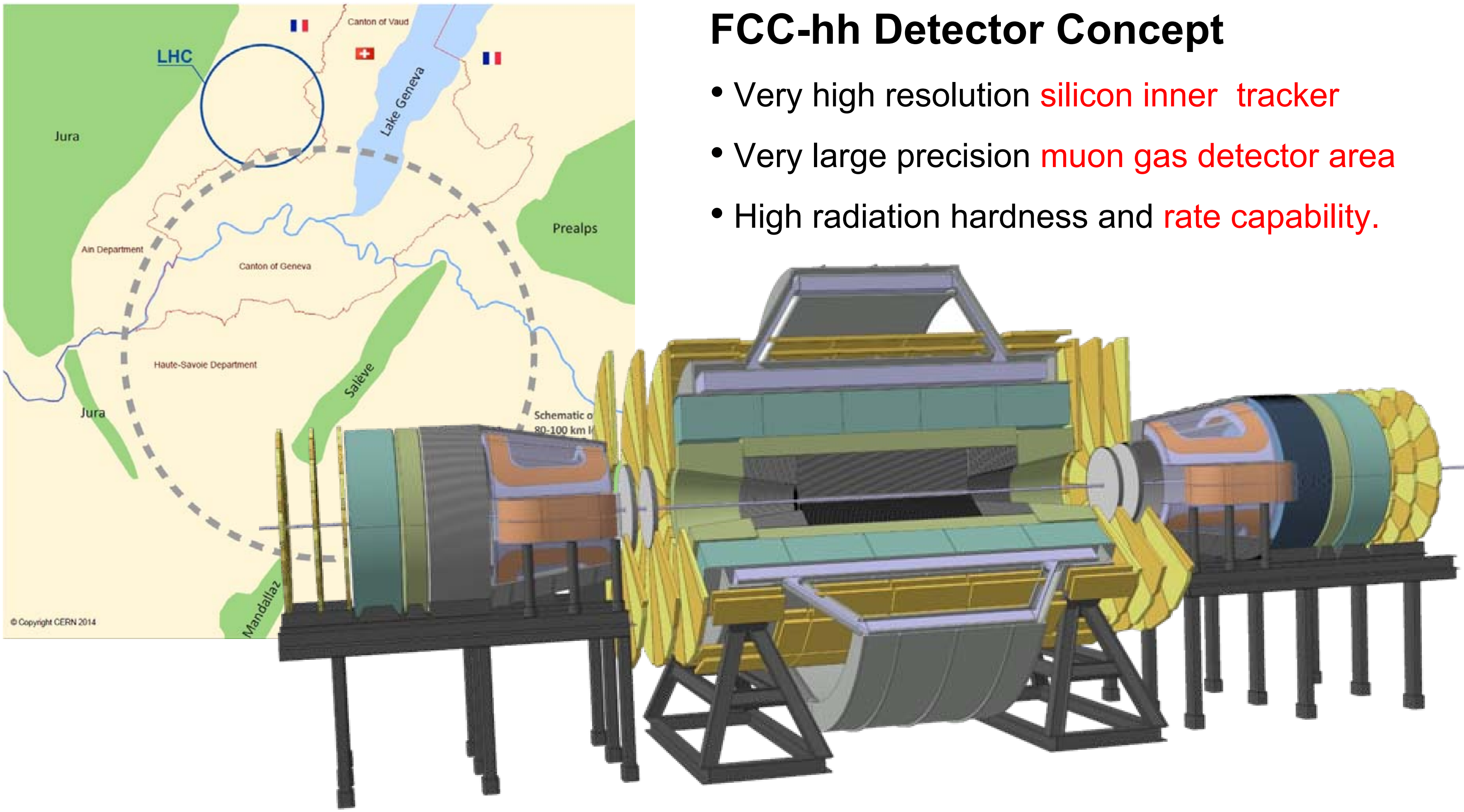
Next highest energy hadron collider: **HL-LHC with 7.5 x LHC design luminosity** (just reached in run 2 at 13 TeV this year).

This means ~10 x higher radiation doses in the inner tracker and the calorimeters, average number of pile-up events 170 at 25 ns bunch crossing interval,
10 x higher neutron and γ-ray background rates in the muon chambers.

Unprecedentedly high background counting rates up to 2 kHz/cm^2 already in the present ATLAS and CMS muon detectors.



At a **Future Circular 100 TeV Hadron Collider (FCC-hh)**
with ~80 km circumference and 30 x LHC design luminosity:
4 x higher background expected than at HL-LHC.
Pile-up up to 1000 (200) events at 25 (5) ns bunch crossing interval.



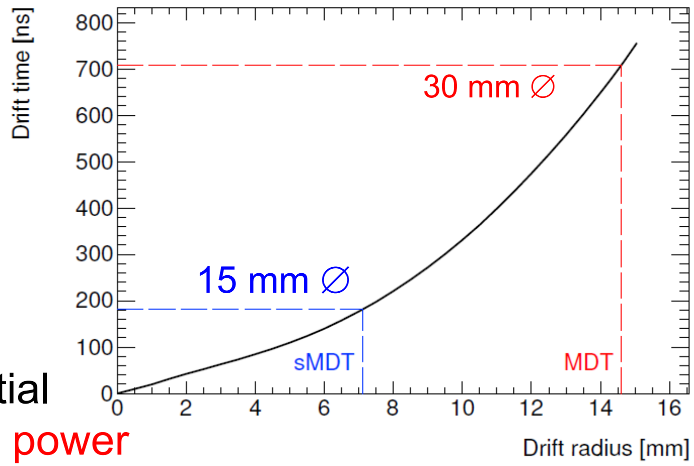
FCC-hh Detector Concept

- Very high resolution silicon inner tracker
- Very large precision muon gas detector area
- High radiation hardness and rate capability.

High Rate Effects in Drift (Tube) Chambers

Spatial resolution deteriorated by

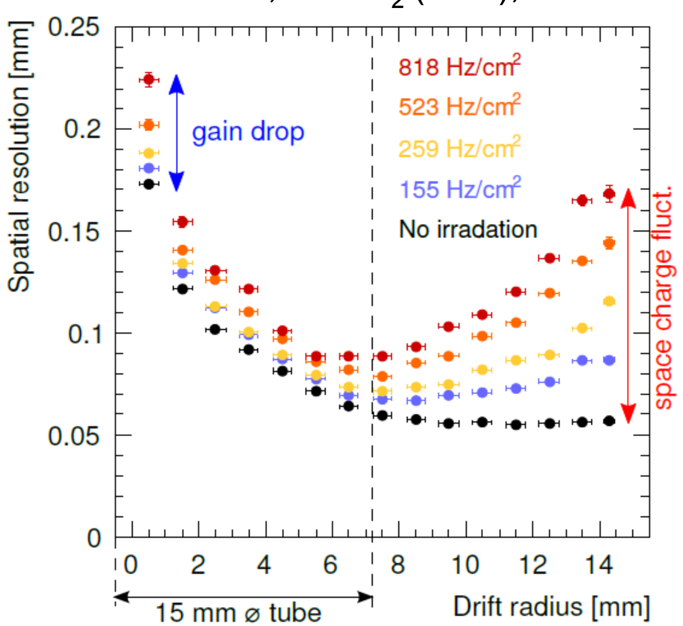
- Fluctuations of the space charge of slowly drifting ions caused by the ionising radiation and, therefore, of the drift field and the drift velocity of the electrons in the $Ar:CO_2$ gas which has good aging properties but non-linear r-t relation.



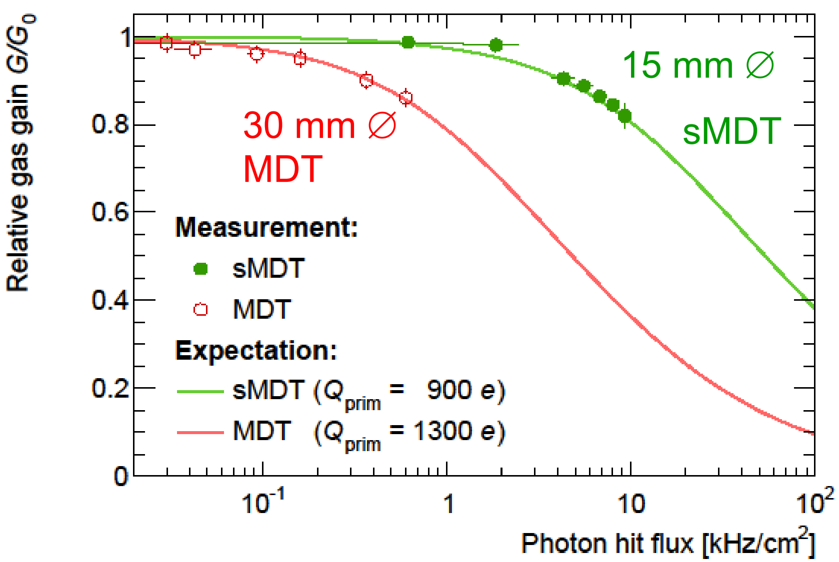
- Loss in gas amplification due to shielding of the wire potential by space charge proportional to drift tube diameter to the 3rd power

⇒ reduce the tube diameter: small-diameter MDT (sMDT) chambers

MDT drift tubes, $Ar:CO_2$ (93:7), 30 mm ∅



Gas gain prediction by Diethorn's formula



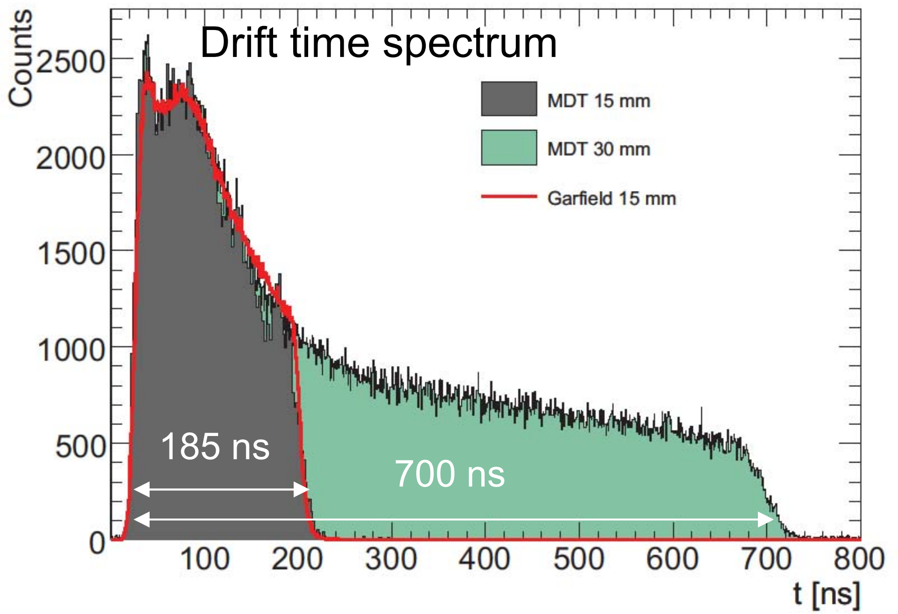
Small-diameter Muon Drift Tube (sMDT) Chambers

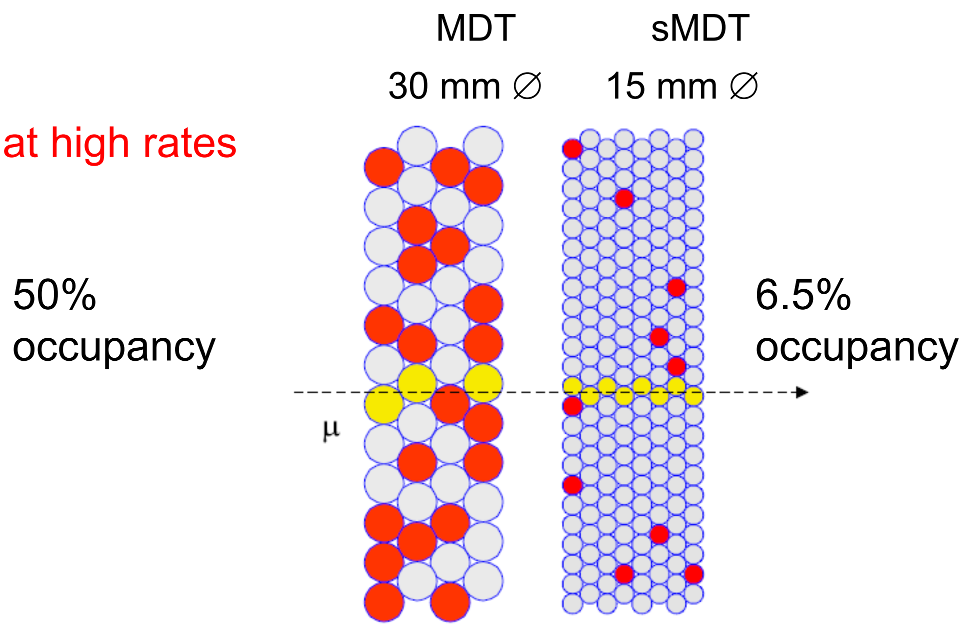
By reducing the drift tube diameter
from 30 mm (MDT) to 15 mm (sMDT)
at otherwise the unchanged operating conditions:

- 8 x lower background occupancy
(4 x shorter maximum drift time, 2 x smaller tube cross section exposed to radiation).

- Electronics deadtime can be reduced.

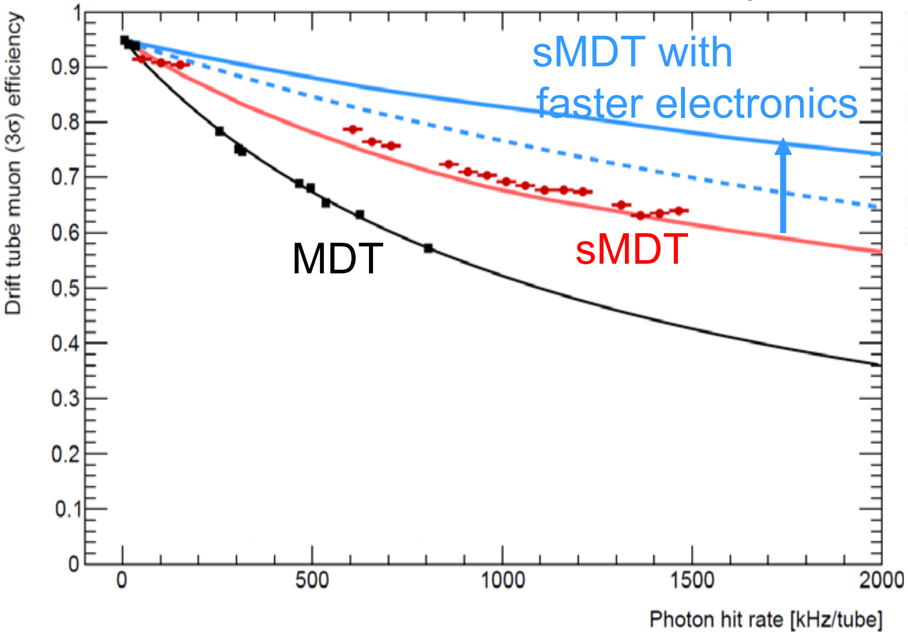
⇒ increased drift tube and tracking efficiency at high rates



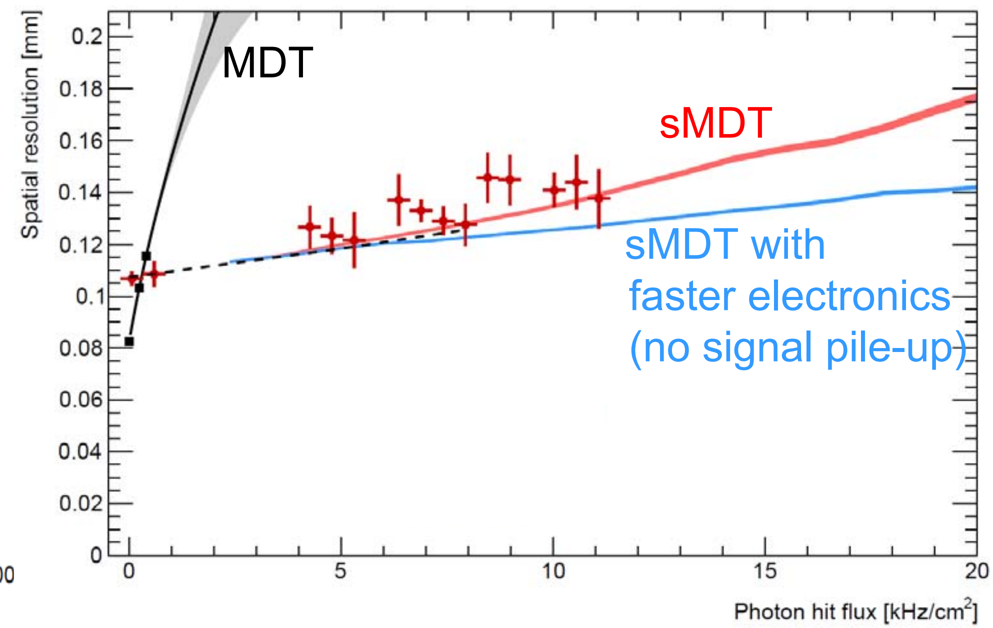


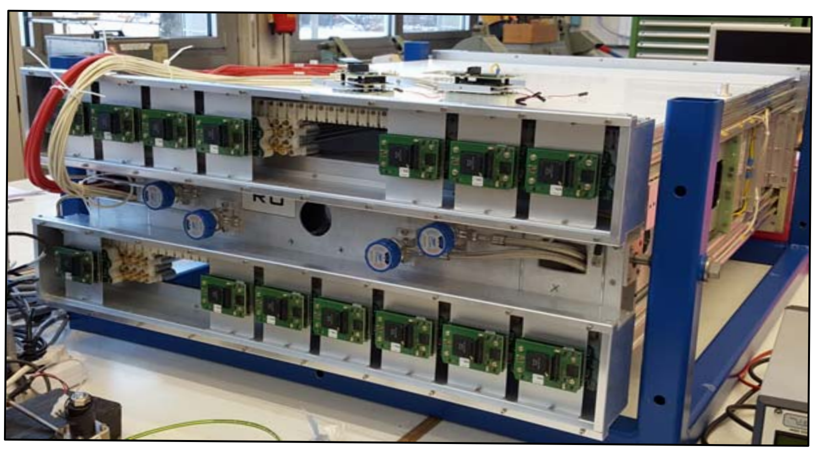
High-Rate Performance of Drift Tubes

Drift tube muon detection efficiency



Drift tube spatial resolution



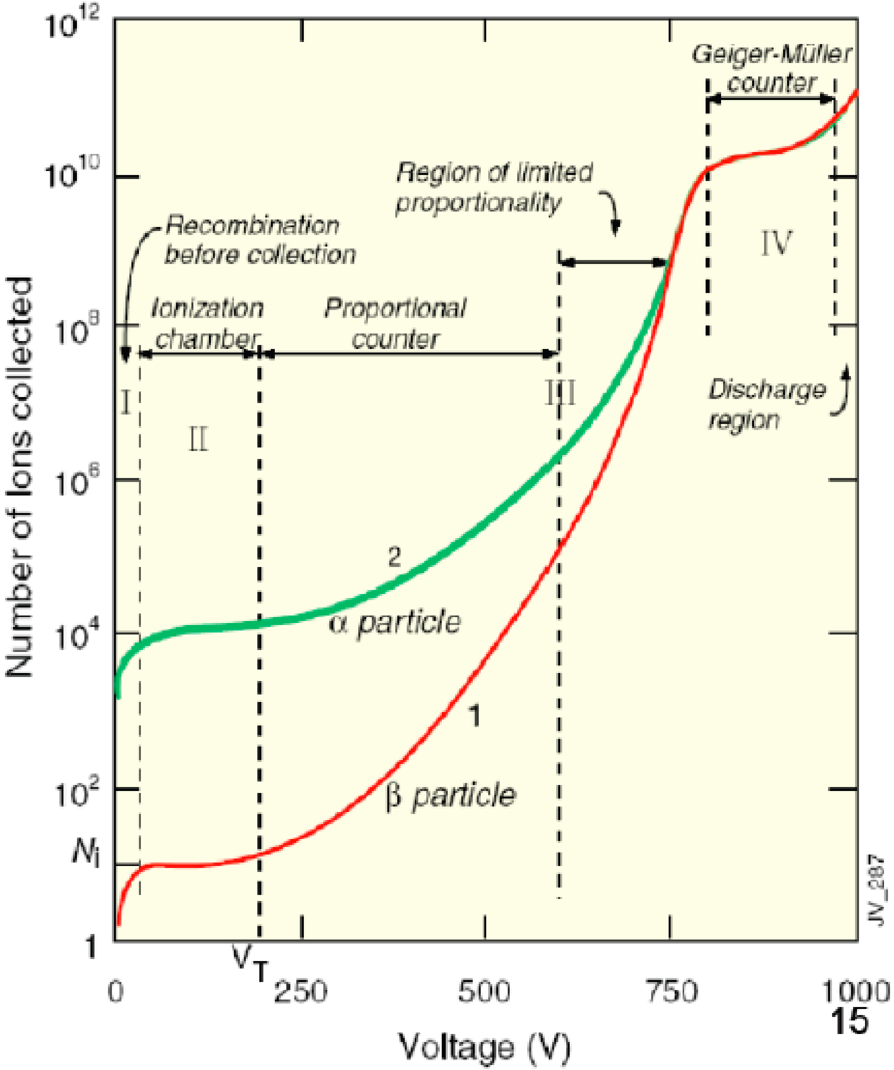


sMDT, thin-gap RPC and sTGC chambers used for ATLAS muon spectrometer upgrades for high luminosities at LHC.

Also suitable detectors for future even higher-energy hadron colliders.

The End

Multi-wire gas detectors



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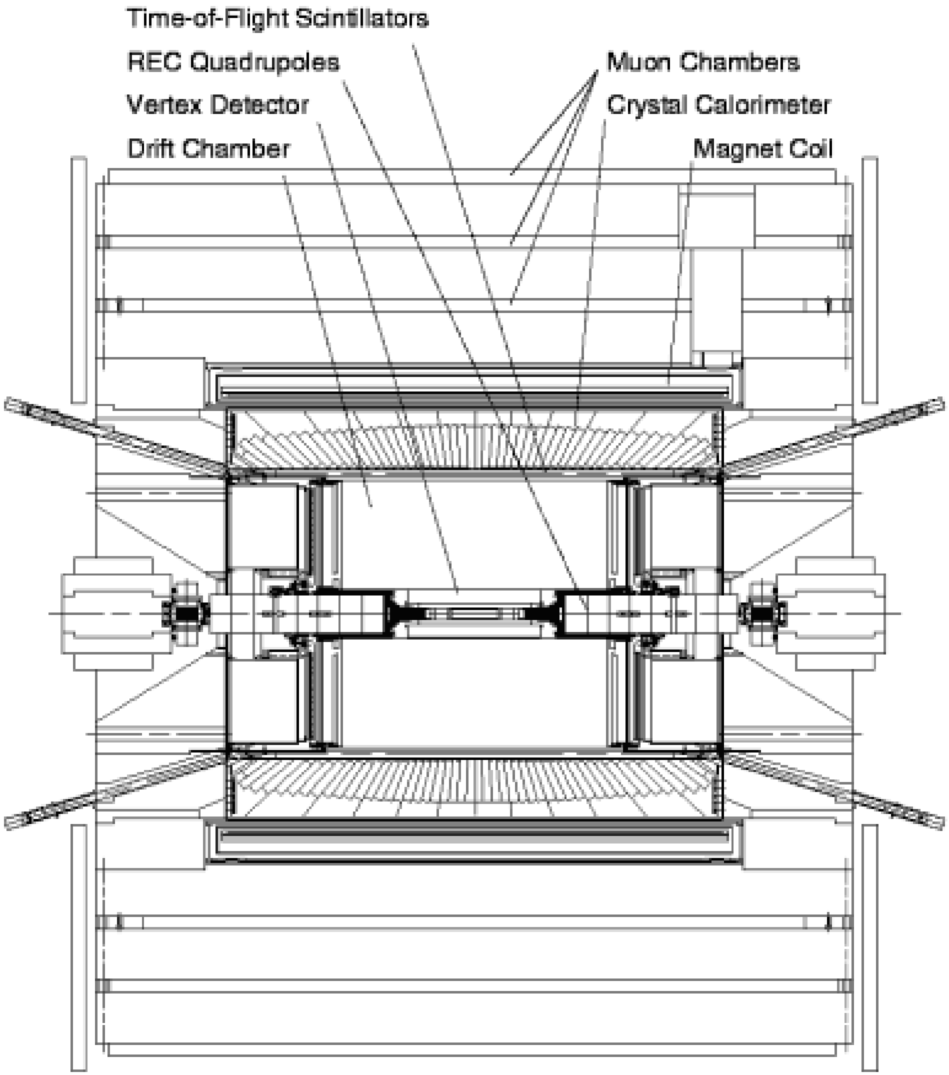
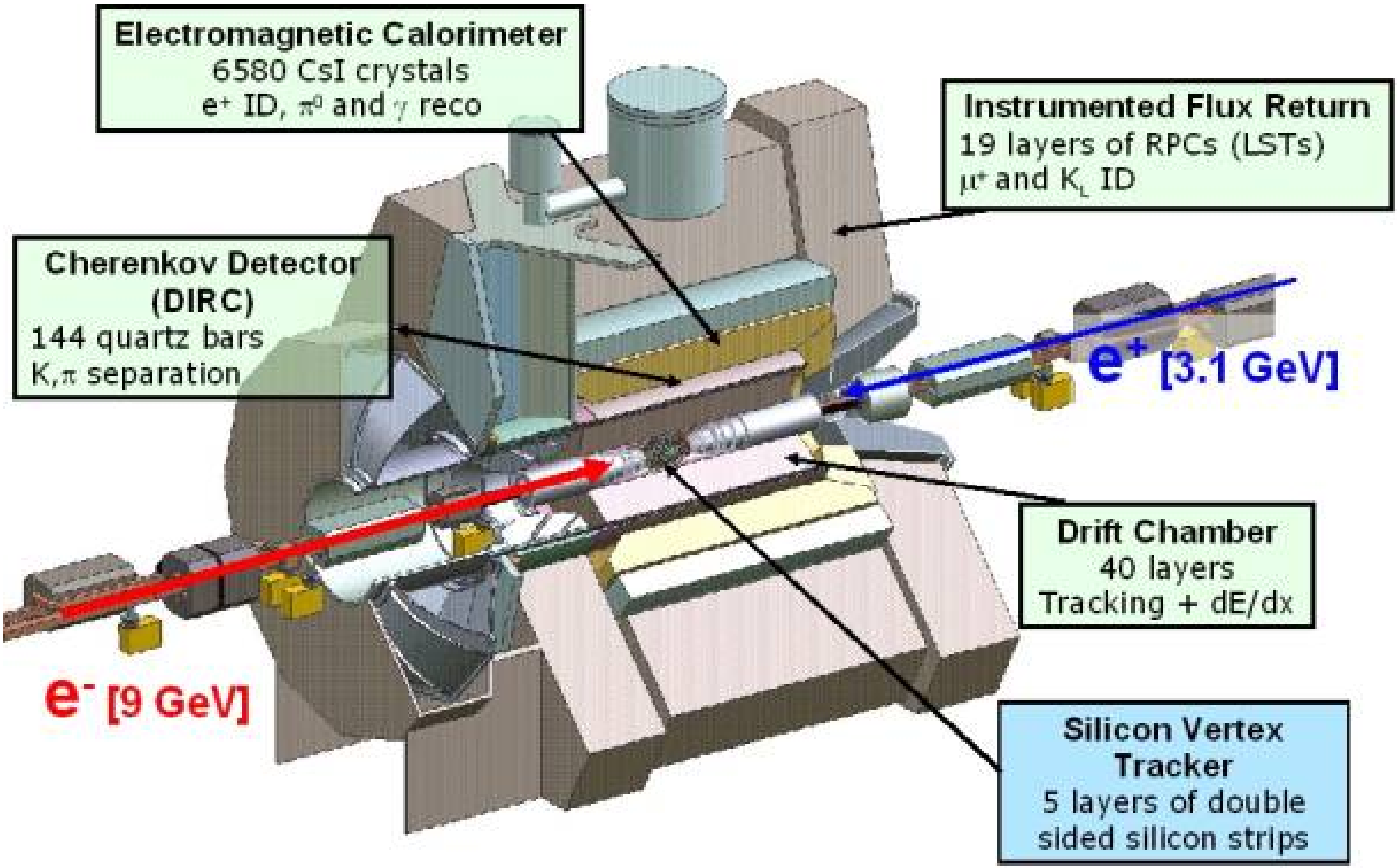
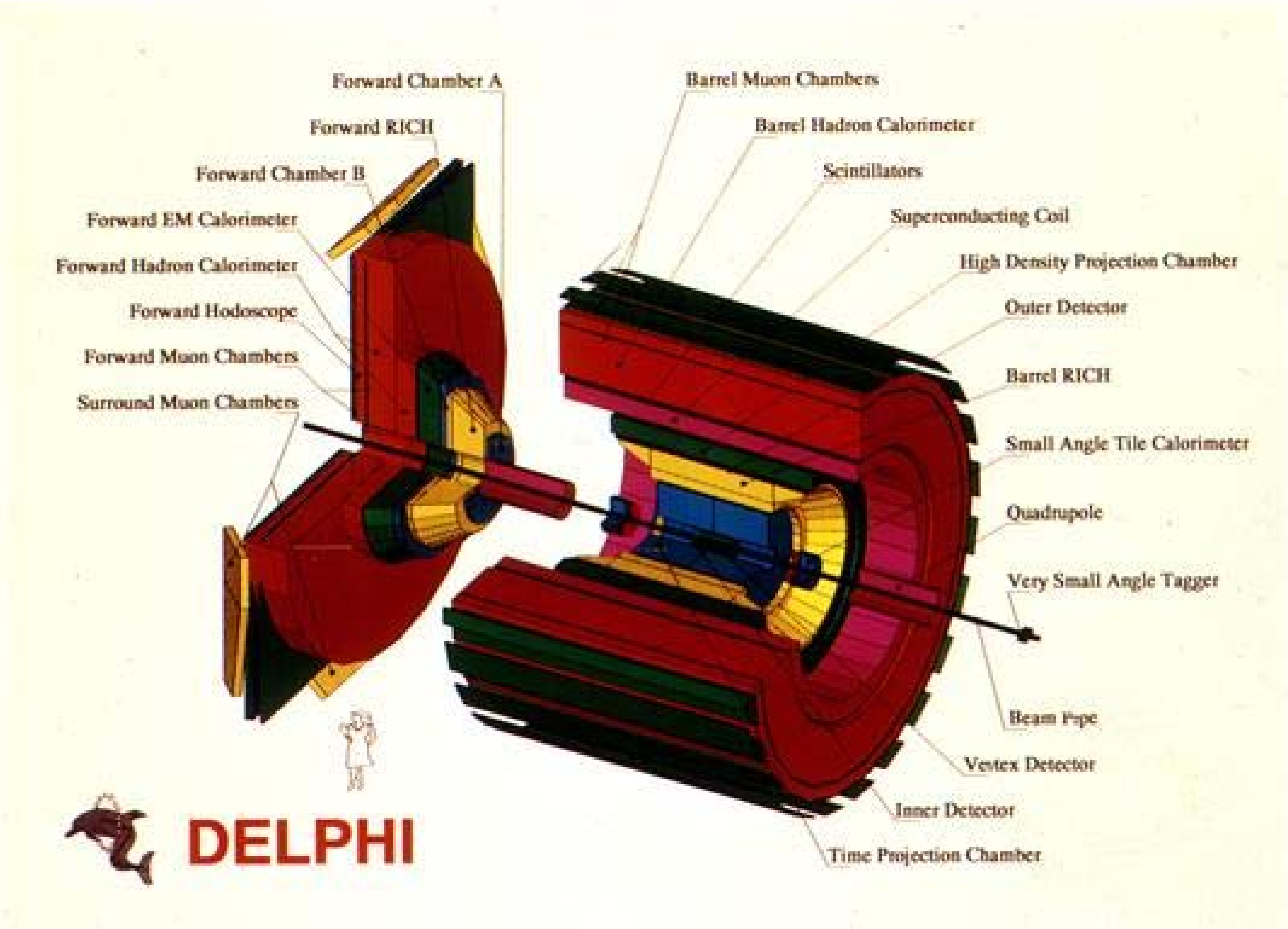
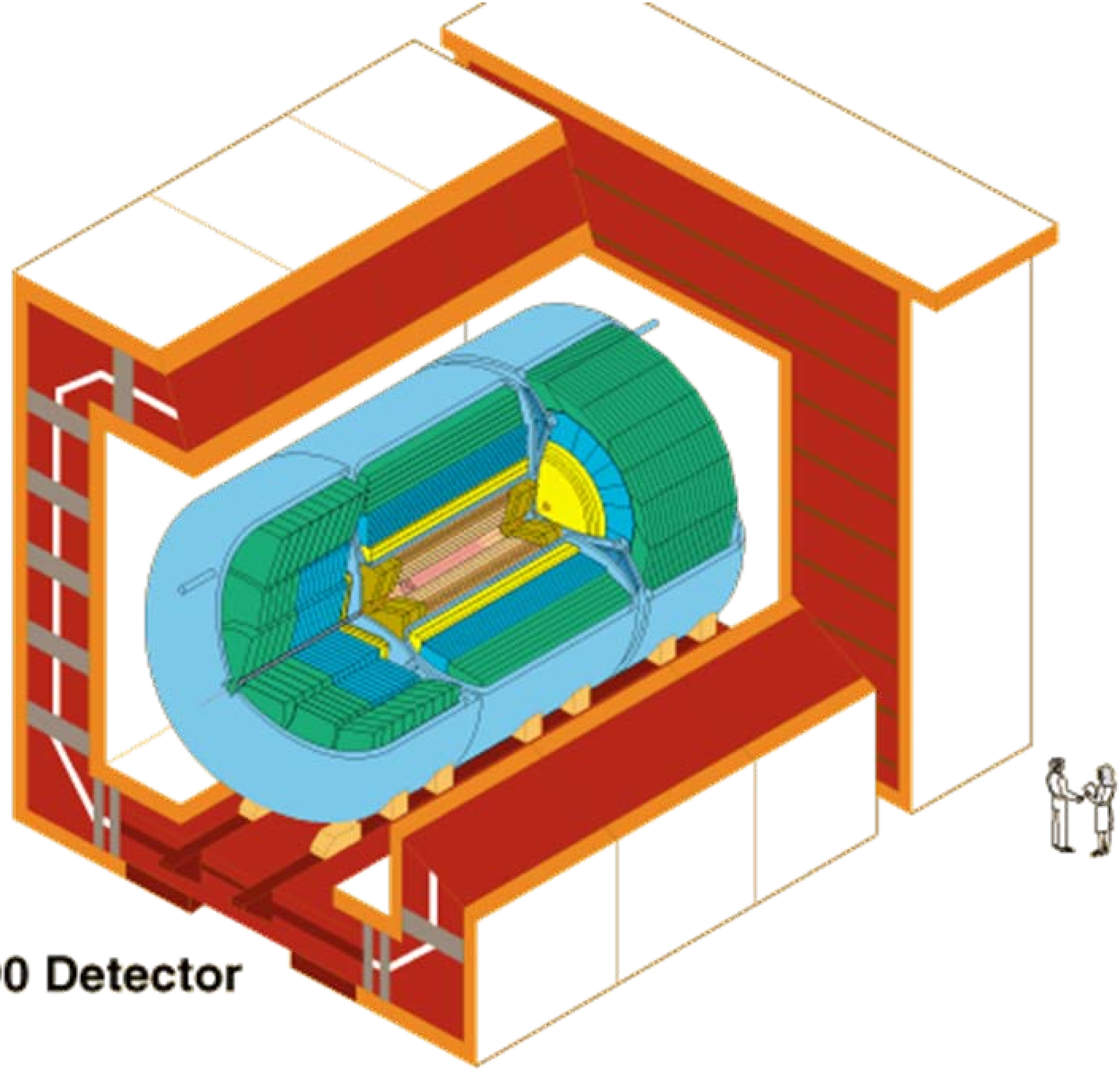
CLEO II Detector



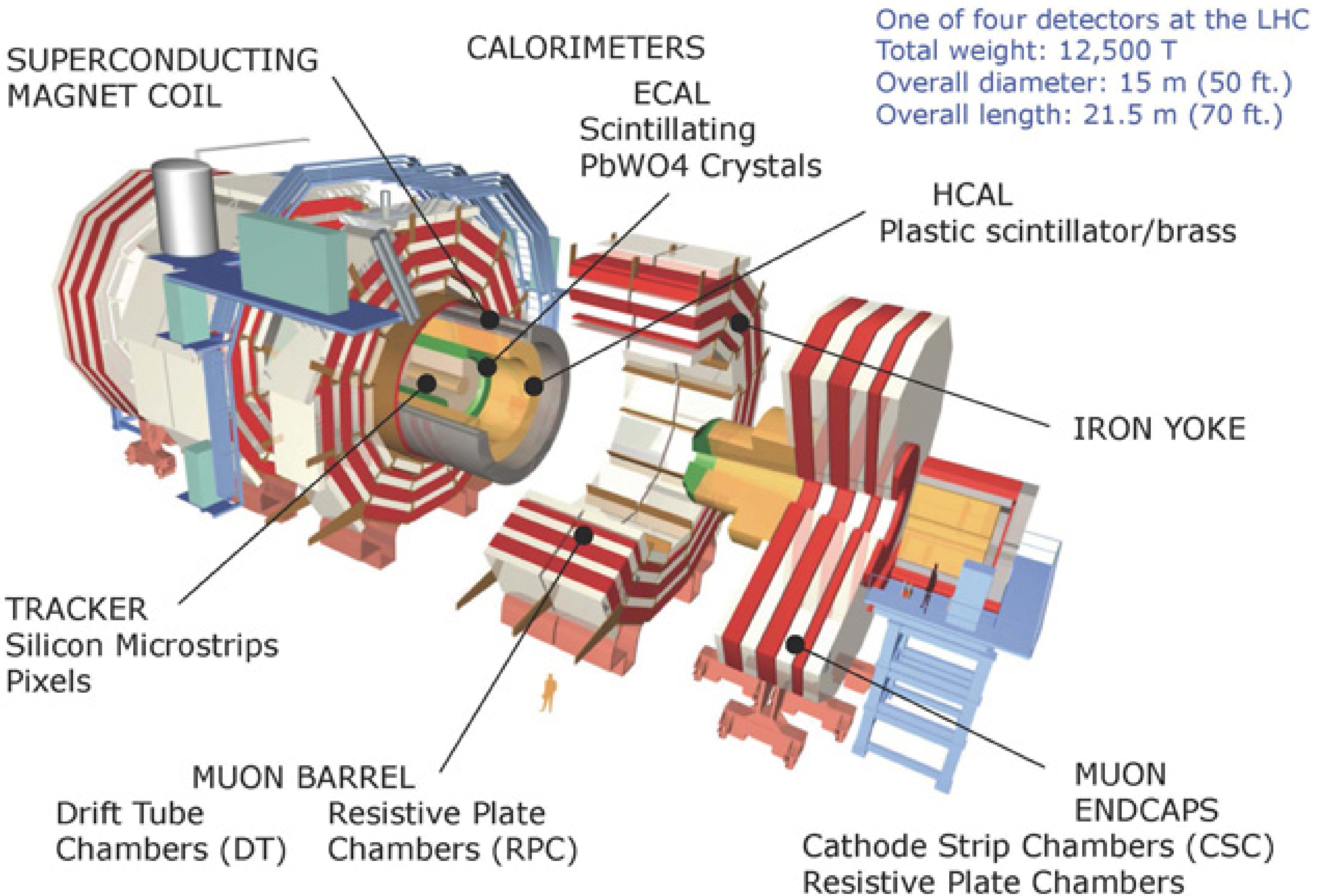


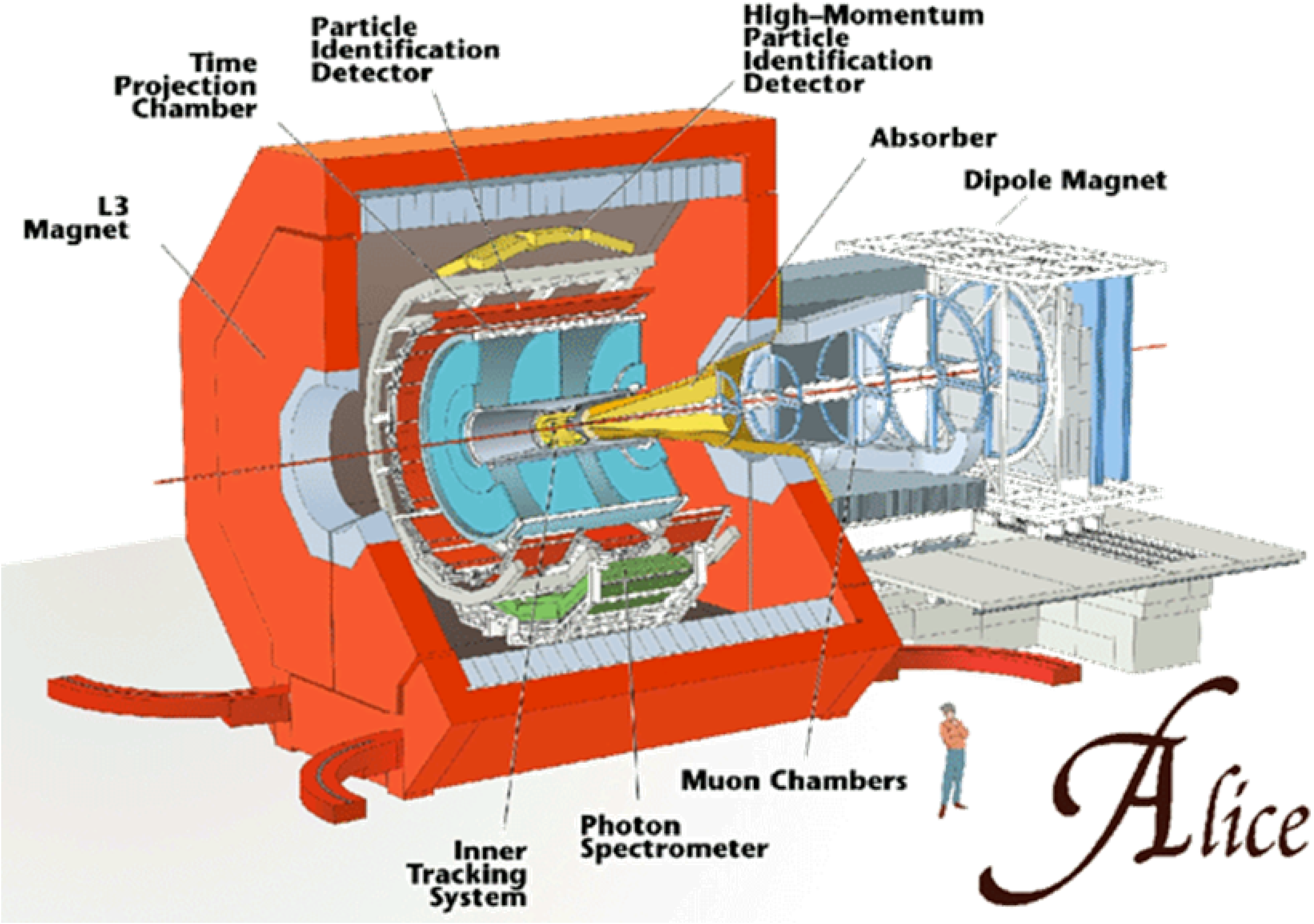
Electromagnetic Calorimeter
6580 CsI crystals
e+ ID, π0 and γ reco
Instrumented Flux Return
19 layers of RPCs (LSTs)
μ+ and K_L ID
Cherenkov Detector
(DIRC)
144 quartz bars
K,π separation
e+ [3.1 GeV]
Drift Chamber
40 layers
Tracking + dE/dx
e- [9 GeV]
Silicon Vertex
Tracker
5 layers of double
sided silicon strips


Forward Chamber A
Forward RICH
Forward Chamber B
Forward EM Calorimeter
Forward Hadron Calorimeter
Forward Hodoscope
Forward Muon Chambers
Surround Muon Chambers
Barrel Muon Chambers
Barrel Hadron Calorimeter
Scintillators
Superconducting Coil
High Density Projection Chamber
Outer Detector
Barrel RICH
Small Angle Tile Calorimeter
Quadrupole
Very Small Angle Tagger
Beam Pipe
Vertex Detector
Inner Detector
Time Projection Chamber
DELPHI



D0 Detector


One of four detectors at the LHC
Total weight: 12,500 T
Overall diameter: 15 m (50 ft.)
Overall length: 21.5 m (70 ft.)
SUPERCONDUCTING
MAGNET COIL
CALORIMETERS
ECAL
Scintillating
PbWO4 Crystals
HCAL
Plastic scintillator/brass
IRON YOKE
TRACKER
Silicon Microstrips
Pixels
MUON BARREL
Drift Tube
Chambers (DT)
Resistive Plate
Chambers (RPC)
MUON
ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers


Time
Projection
Chamber
Particle
Identification
Detector
High–Momentum
Particle
Identification
Detector
Absorber
Dipole Magnet
L3
Magnet
Muon Chambers
Photon
Spectrometer
Inner
Tracking
System
Alice