LHC machine and detectors

An Introduction

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Introductory School to Terascale Physics
DESY, Hamburg, 21. Feb 2011

Outline

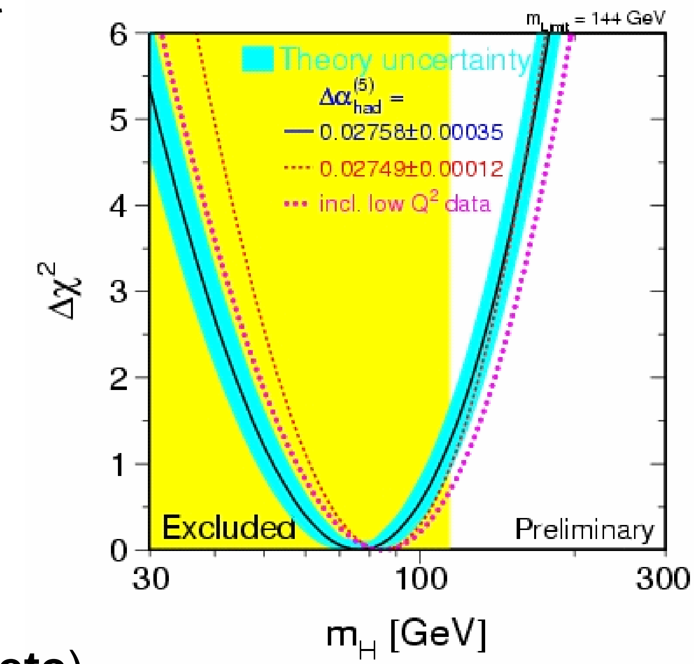
- LHC : Why and What is it ?
- LHC operation, luminosity
- Particle detectors

  Examples : ATLAS & CMS
- Into the future

  ILD & SiD at ILC or CLIC

Why the LHC

- The Standard Model is in impressive agreement with basically all measurements. Still it…
- **will diverge at ~ 1TeV** without the Higgs
  - But no sign of the Higgs or any other extension yet
- The Standard Model **has many parameters**
  - Masses, couplings, mixing angles,…
  - Maybe there is something more simple and beautiful ?
- There is no gauge-coupling **unification**!
  - The three SM couplings do not unify at highest energies!
- Cosmology tells us there is more (**dark matter, etc**)
  - No dark matter candidate in the SM
- And even more **fundamental questions**…
  - Gravity? Gauge structure? Why 3 generations ?
    Hierarchy / fine-tuning problem? Baryon asymmetry? …



Higgs search :
EW fit : M_H < 155GeV (CL 95%)
direct searches : M_H > 114.5 GeV

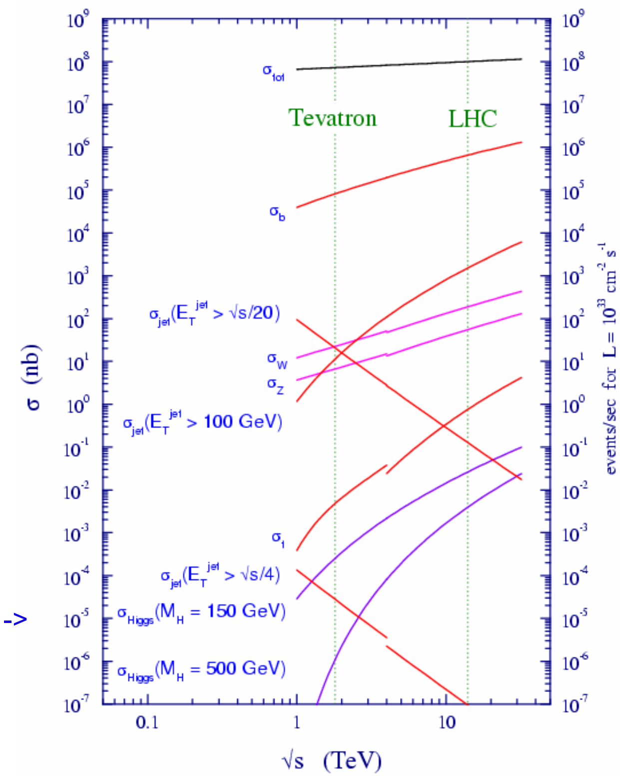
Why the LHC II

- New physics expected @ ~1TeV
  - Electroweak symmetry breaking O(1TeV)
  - Dark matter candidates may show up at O(1TeV)
  - Many extensions of the SM predict 'new particles' at ~ O(1TeV)

- Want to study decays of W,Z,t,H,…
  - Decays in quark (QCD background!) or leptons
  - Cross sections x branching ratio in the order of a few fb

- Want to get sufficient statistical significance
  - to get a few 100 'events' per year we need ~ $100 fb^{-1}/y$
  - With 3×10^7 s/y and 30% duty cycle we need $L = 10^{34} /cm^2 s$

10fb ->



Why the LHC III

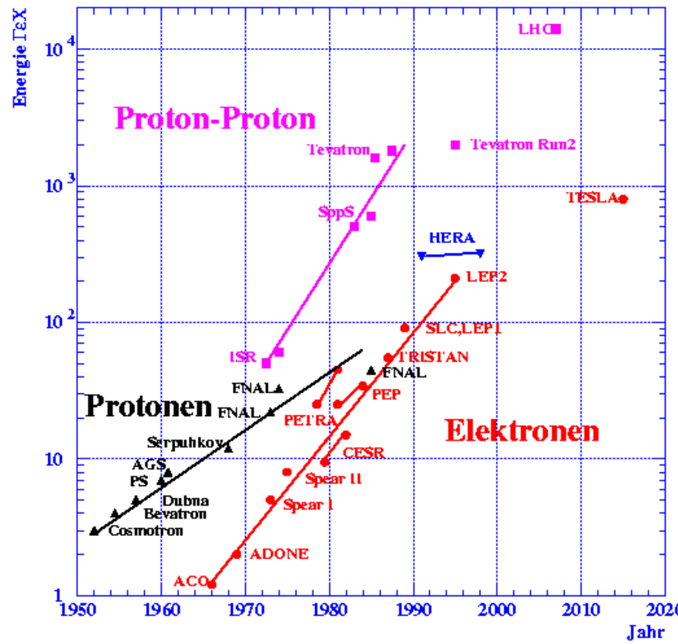
- Collider vs fixed target
  - $\text{collider}: E_{cm} = 2E_{beam} \quad \text{vs} \quad \text{fixed target}: E_{cm} \sim \sqrt{mE_{beam}}$
- pp vs ee
  - pp for discovery, but

    complex initial state (q,g, QCD processes dominates)

    no well defined energy (only unknown fraction x)
  - ee for precision

    well defined energy (neglecting initial state radiation)

    well defined initial state (e, γ, electro-week process)



- Circular vs linear
  - Linear

    no repetition, need high gradient or long accelerator (ILC ~ 30km for O(1TeV))

    no loss due to synchrotron radiation
  - Circular

    reuse beam and acceleration structures many times

    loss due to synchrotron radiation $\Delta E \sim \frac{E^4}{m^4 R}$ need large radius and massive particle (proton)

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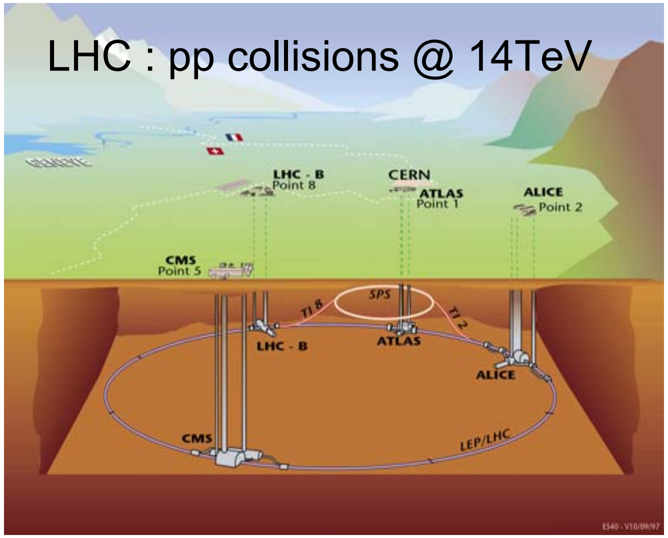

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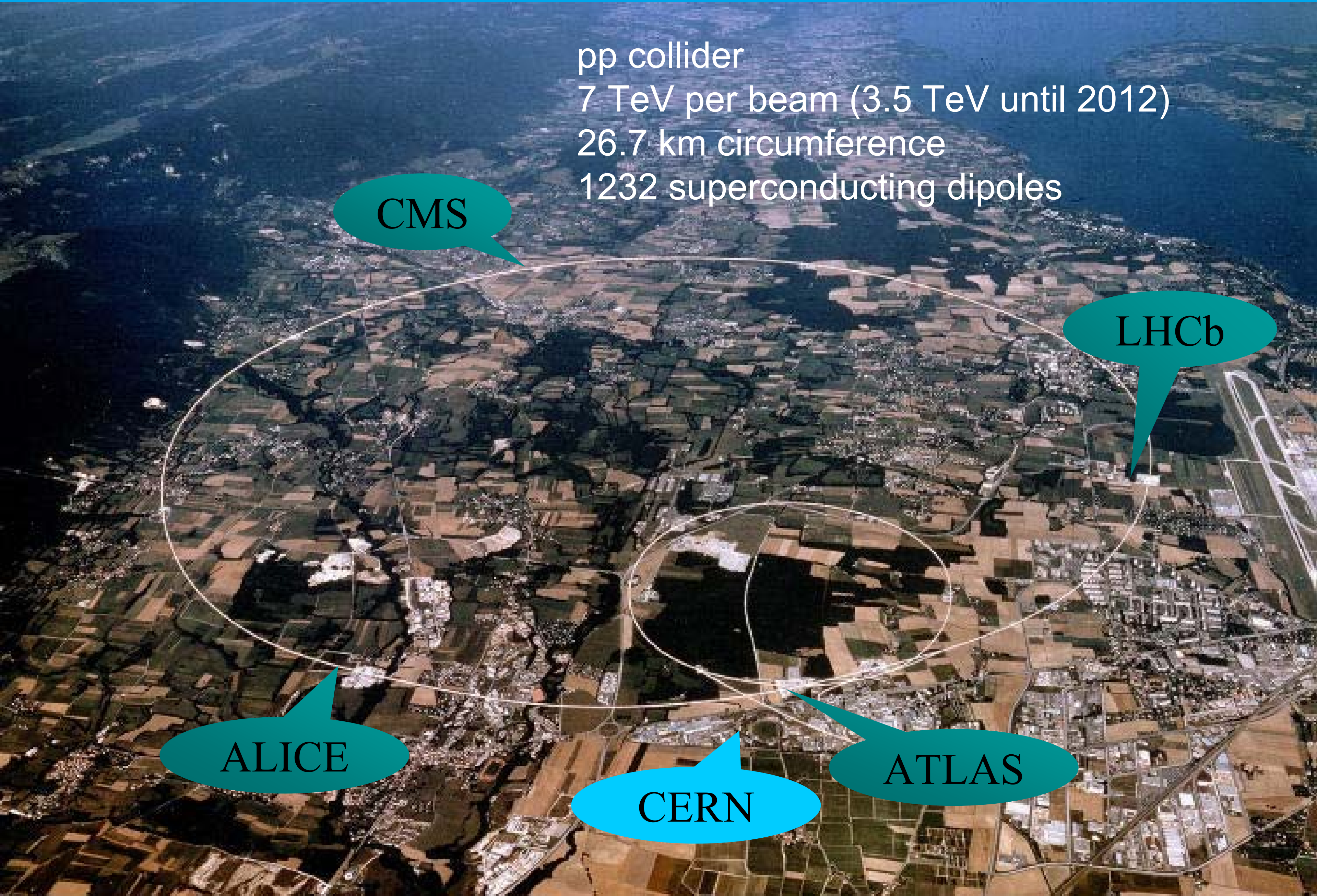
The LHC

pp collider
7 TeV per beam (3.5 TeV until 2012)
26.7 km circumference
1232 superconducting dipoles



The LHC – some more numbers

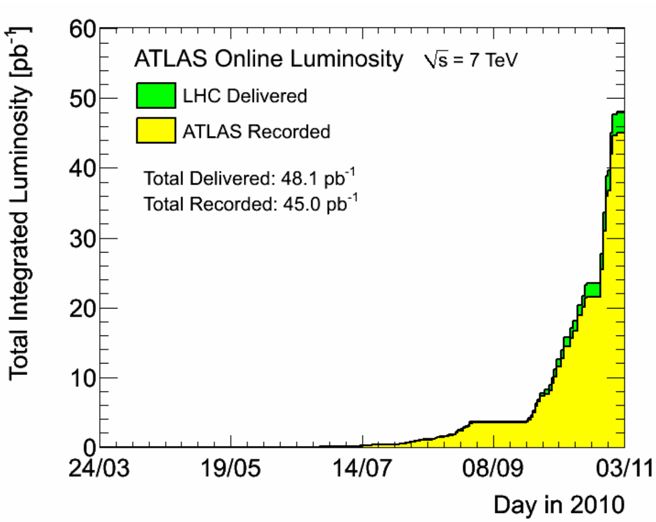
Circumference	26.7 km	100-150 m underground
Number of SC dipoles	1232	Cable Nb-Ti, cold mass 37 kt
Dipole length	14.3 m	
Dipole field strength	8.4 T	High beam momentum
Operating temperature	1.9 K	Super-fluid helium, “largest refrigerator in the world”
Current in SC coils	13 kA	1 ppm resolution
Beam intensity	0.5 A	
Beam stored energy	362 MJ	1 MJ melts 1.5 kg of copper
Magnet stored energy	1100 MJ (*8)	

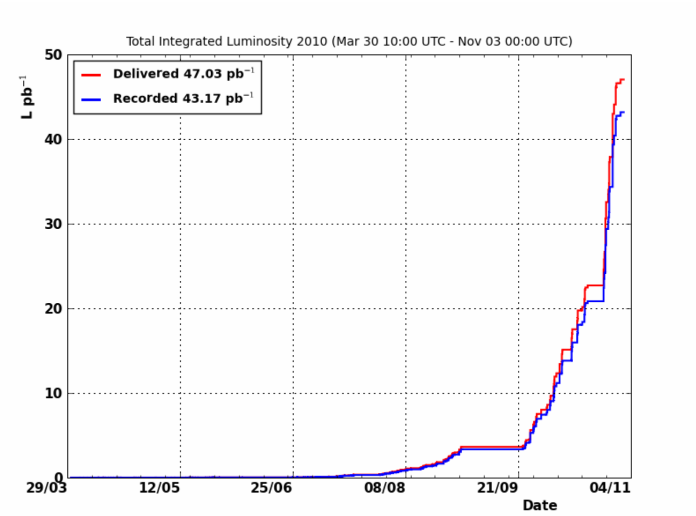
The LHC – a bit of history

- 10 September 2008: first beams around the ring.
- 19 September 2008: the “incident”.
- 2008-2009: 14 months of repairs and consolidation.
- 20 November 2009: First beams round again.
- 14 December 2009: Collisions with E_{beam} = 1.18 TeV ! world record
- 30 March 2010: Collisions at E_{beam} = 3.5 TeV !
- 4 November 2010 Heavy Ions (Pb) with E_{beam} = 3.5 ZxTeV (Z = 82)
- 6 December 2010 – 21 February 2011 : Technical stop

  (maintenance & minor repair for LHC & detectors)
- Last weekend : restart beam operation (machine studies)

The LHC – 2010 Run





pp collisions

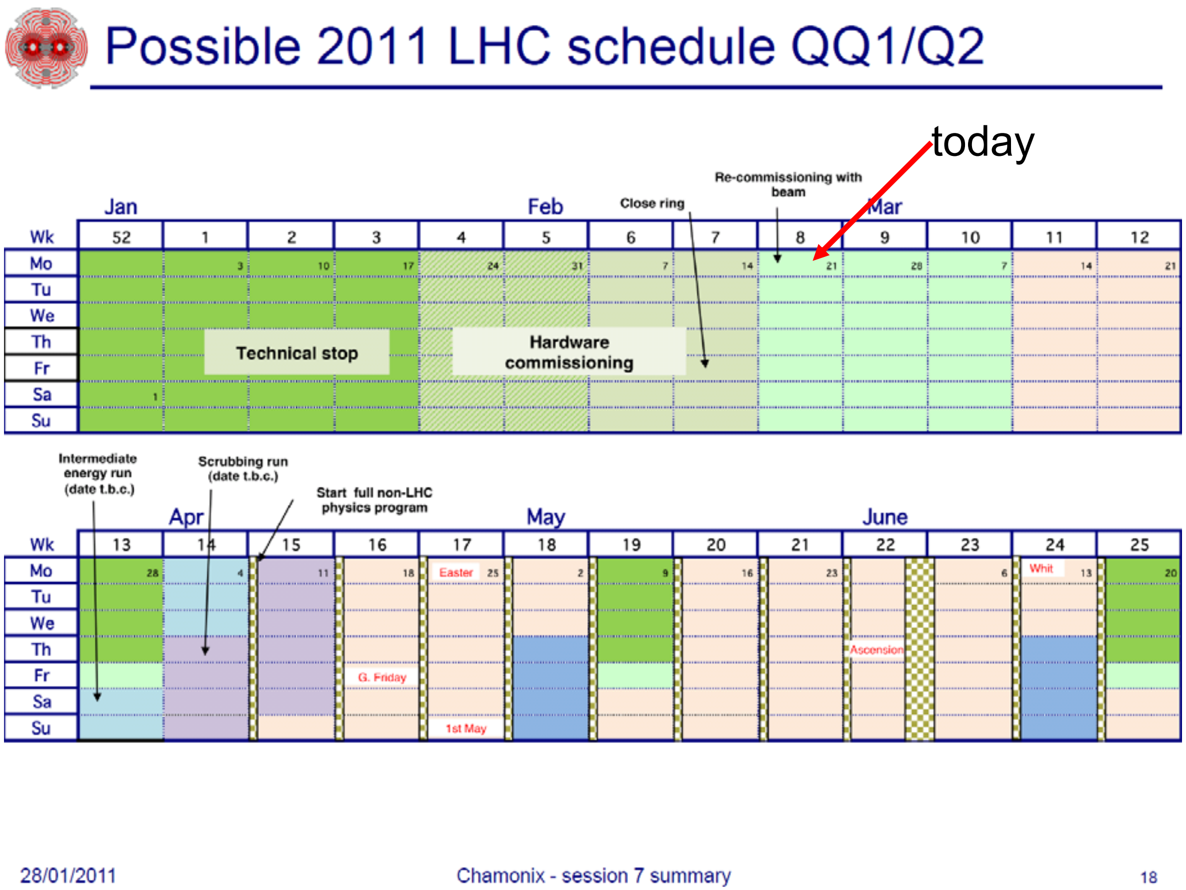
- from Mar. 30th to Oct. 31st
- Energy : 3.5 TeV per beam
- Bunch intensity : 1.2×10^{11} p/bunch
- Number of bunches : up to 348 (colliding)

- **ATLAS : 45.0 pb^{-1}, L_{max}=2.1×10^{32} $cm^{-2}s^{-1}$**
- **CMS : 43.2 pb^{-1}, L_{max}=2.0×10^{32} $cm^{-2}s^{-1}$**

Heavy Ion (lead-lead)

- Energy : 3.5 zTeV per beam
- from Nov. 8th to Dec. 6th
- CMS : 8.5 μb^{-1} , ATLAS : 9.2 μb^{-1}

The LHC – 2011 Schedule



Estimates for 2011 :

Energy : 3.5 TeV
1.2×10^{11} p/bunch
Bunch spacing 75 ns
(~ 930 bunches)
L_{peak} : 1.3 – 1,8 x 10^{33}

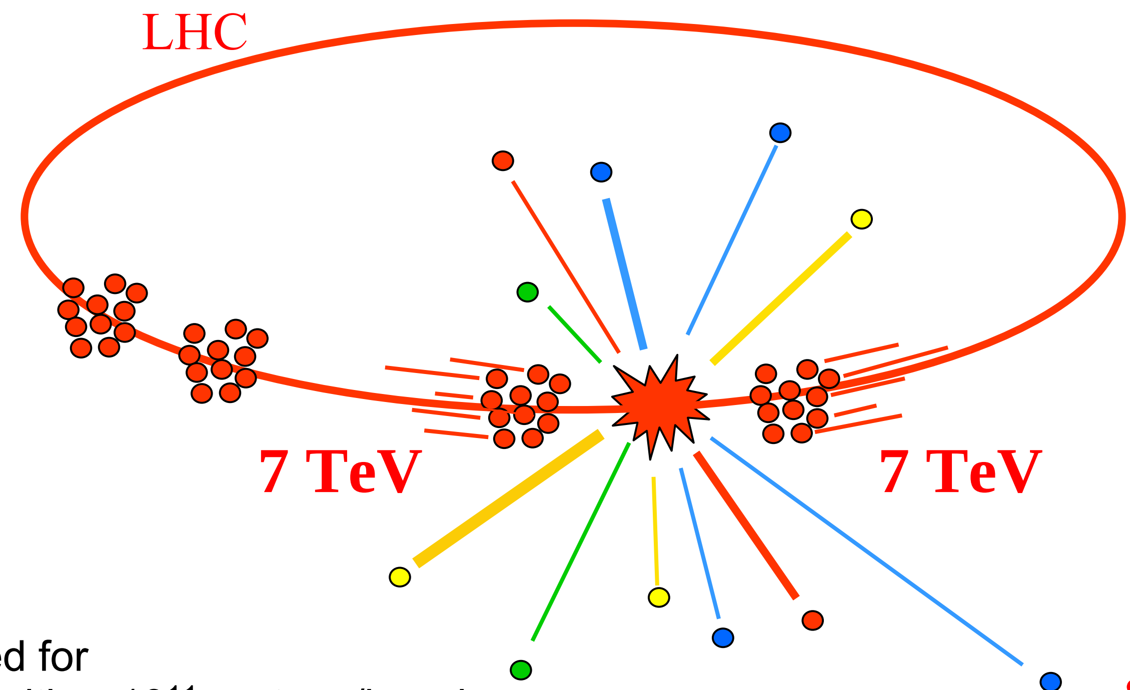
~ 135 days at L_{peak}

$L_{int} = 2 - 3\ fb^{-1}$ in 2011
(official goal : $L_{int} \sim 1 fb^{-1}$)

LHC will continue in 2012

Goal : $L_{int} \sim 10 fb^{-1}$

We need to measure the products of pp collisions…



LHC is designed for
3300 bunches with ~ 10^{11} protons/bunch
bunch to bunch spacing : 7.5m
collision occur every 25 ns (in 2011 : 75ns)
20 pp interactions at the same time.
(mostly producing low energy secondary particles)

Some energy is converted into secondary particles at large angles.

How do we measure these particles ?

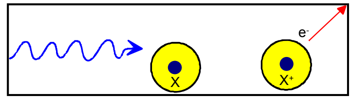
We can only 'see' particles through their interaction with matter :

particle	interaction
neutrinos	none, (weak interaction only)
electrons	electromagnetic
muons	electromagnetic
p, K, π	electromagnetic, hadronic
photons	electromagnetic
neutrons, K^0_L	hadronic
B, D	weak decay
J/ψ, Υ, W, Z, H, t	prompt decay

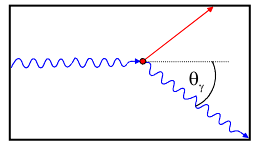
Electromagnetic interactions with matter

- **Photons** :

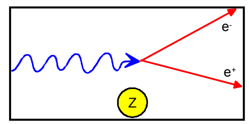
Photoelectric effect < 100keV

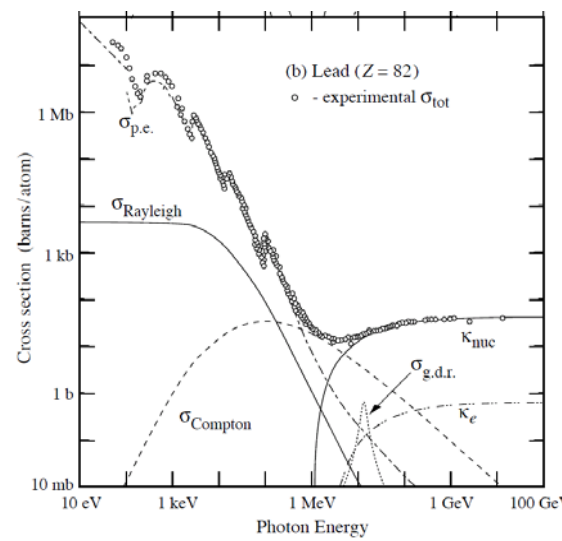


Raleigh scattering < 100keV
Compton scattering 10keV – 2 MeV



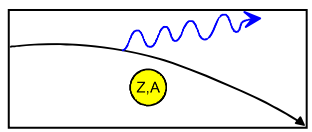
Pair production > 1 MeV
(dominates > 4MeV)





- **Charged particles :**

Ionization
Bremsstrahlung



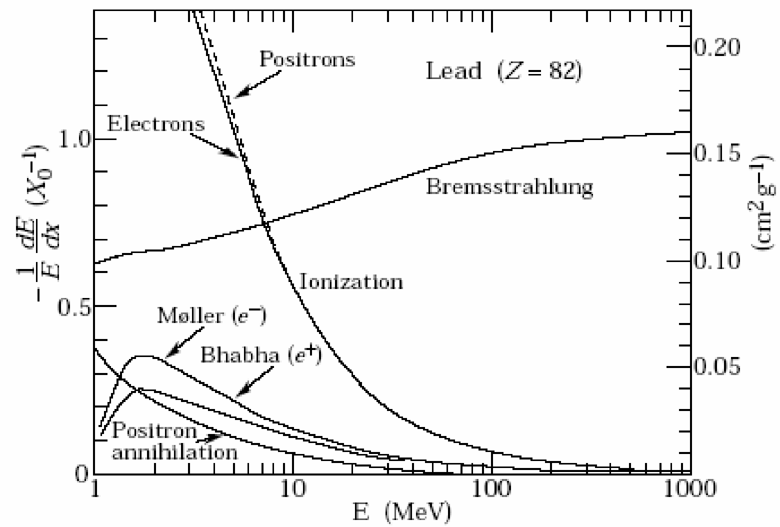
Cherenkov emission (v above c/√ε)
Transition radiation (traversing different ε)

X_0 = radiation length

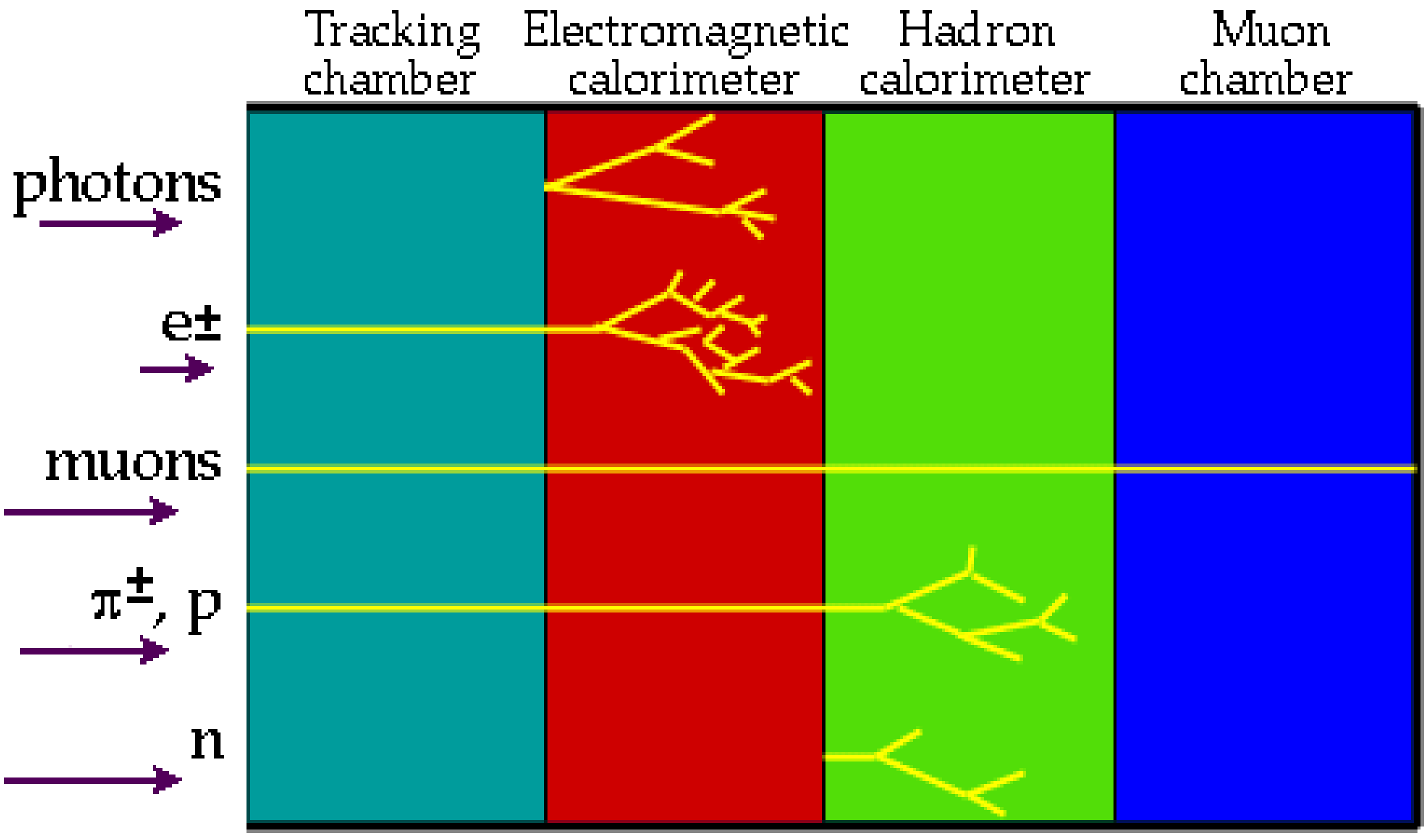
$$\langle E \rangle = E_0 \, e^{\frac{-X}{X_0}}$$

Critical energy E_c (dE/dx : Ionization = Bremsstahlung)

E_c ~ 580 MeV/Z



Symbolic detector layout



non-destructive measurement

destructive measurements

tail catcher

Particle signatures in a detector

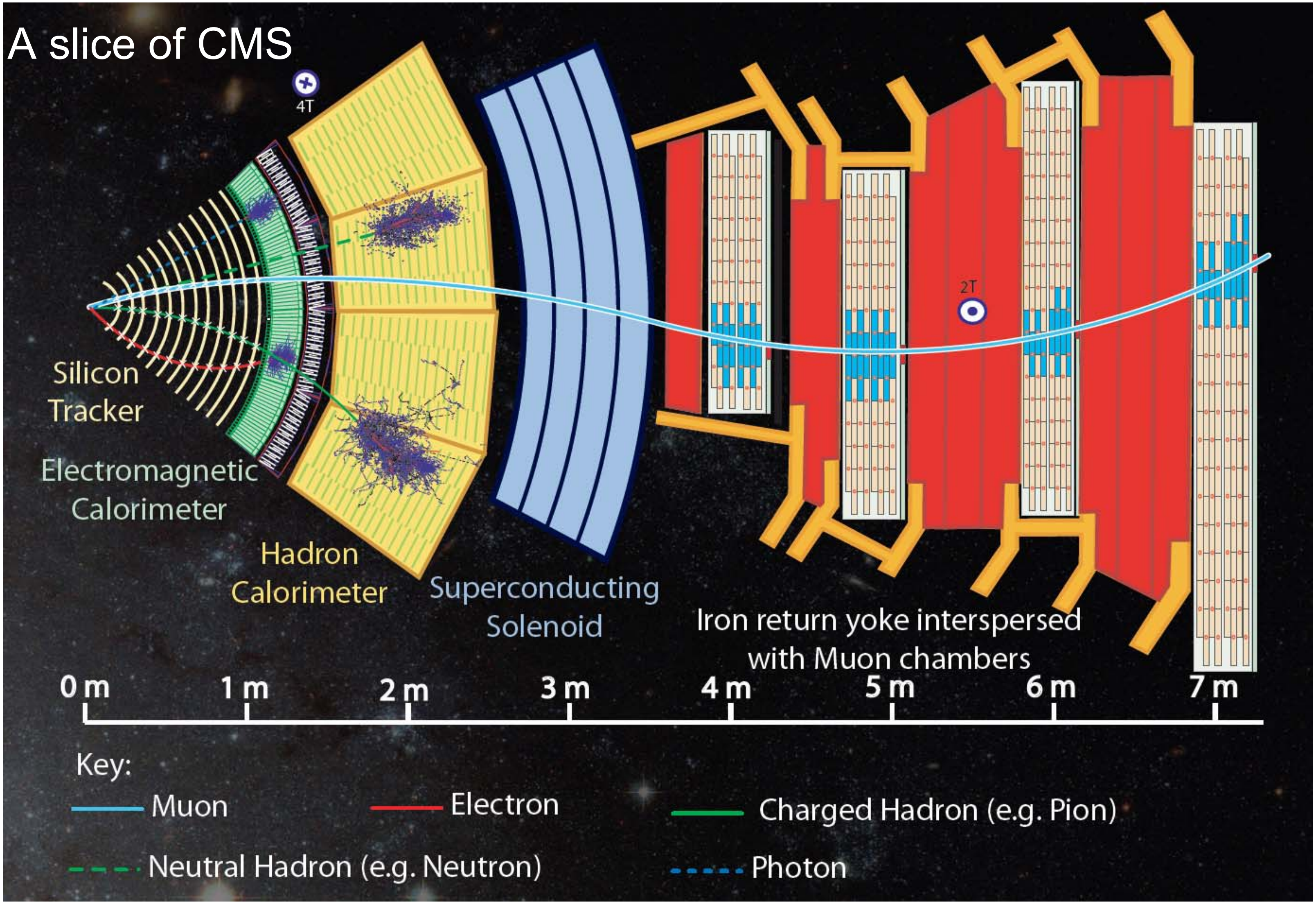
What we can measure is the charge deposit in different materials

neutrinos	none, (weak interaction only)	missing energy
electrons	electromagnetic	track and EM shower
muons	electromagnetic (ionisation)	penetrating track
p, K, π	electromagnetic (ionisation) hadronic	track and hadron shower
photons	electromagnetic	EM shower
neutrons, K^0_L	hadronic	hadron shower
B, D	weak decay	secondary vertex
J/ψ, Υ, W, Z, H, t	prompt decay	invariant mass

Design criteria for an ideal detector

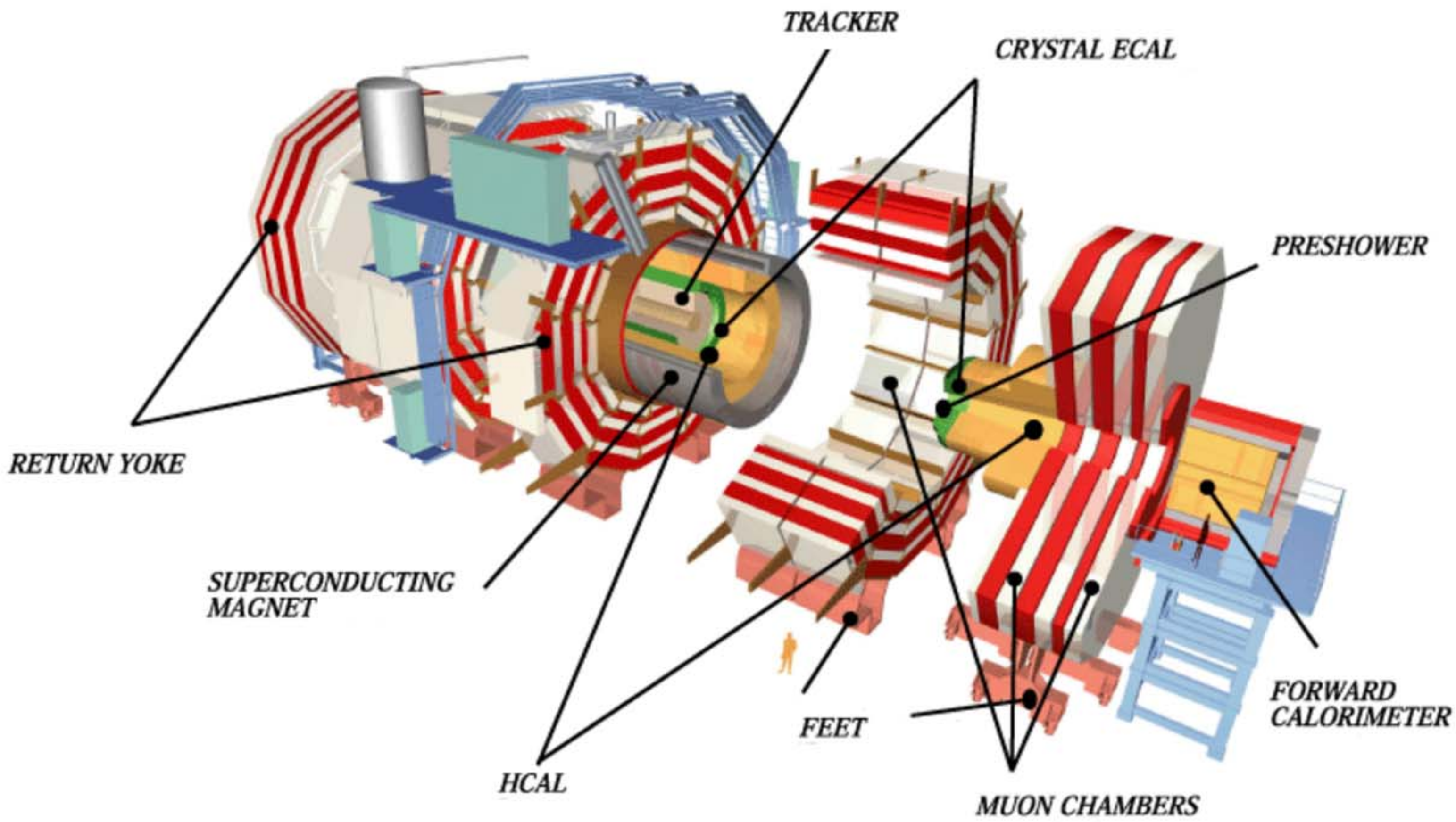
- We want to capture all particles :
  - Surround the interaction region as hermitic as possible (but let the beams pass)
  - No holes, no cracks, no insensitive regions
  - At the LHC we get finally get ~ 20 interactions every 25ns – be fast
- We want to measure as accurate as possible :
  - Resolve all particles (high granularity, many channels)
  - Measure energies and directions with high precision
  - As little influence to the measured particles as possible (except for the calorimeters)
- There are unfortunately some boundary conditions :
  - Cost and available technology
  - Beam pipe and accelerator components
  - Mechanics, power and signal cables, cooling
  - Radiation

For a real collider detector (here CMS) it looks like this

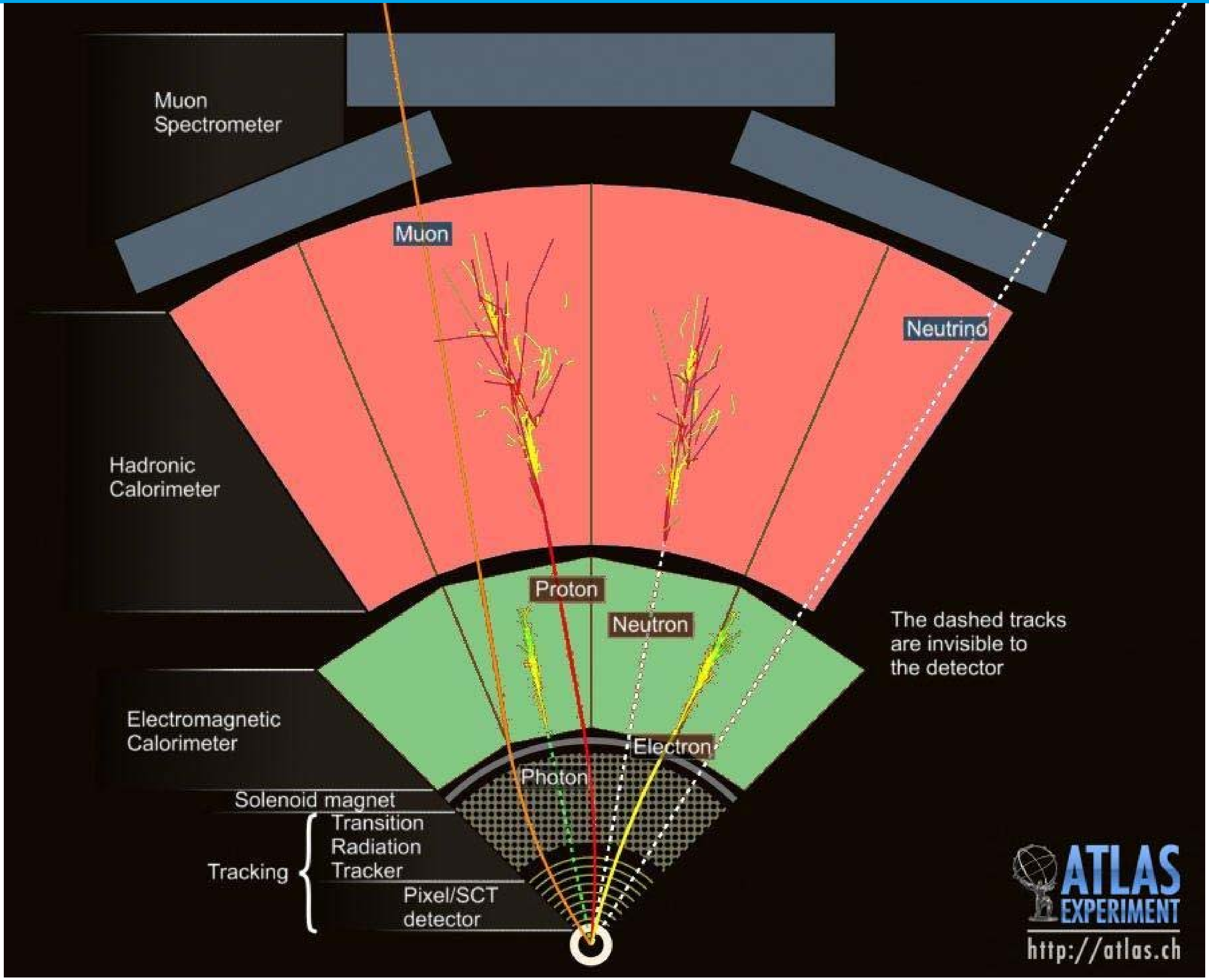


The CMS detector

diameter : 15 m, length : 22 m, total weight : 12500 tons, 4 tesla solenoid,



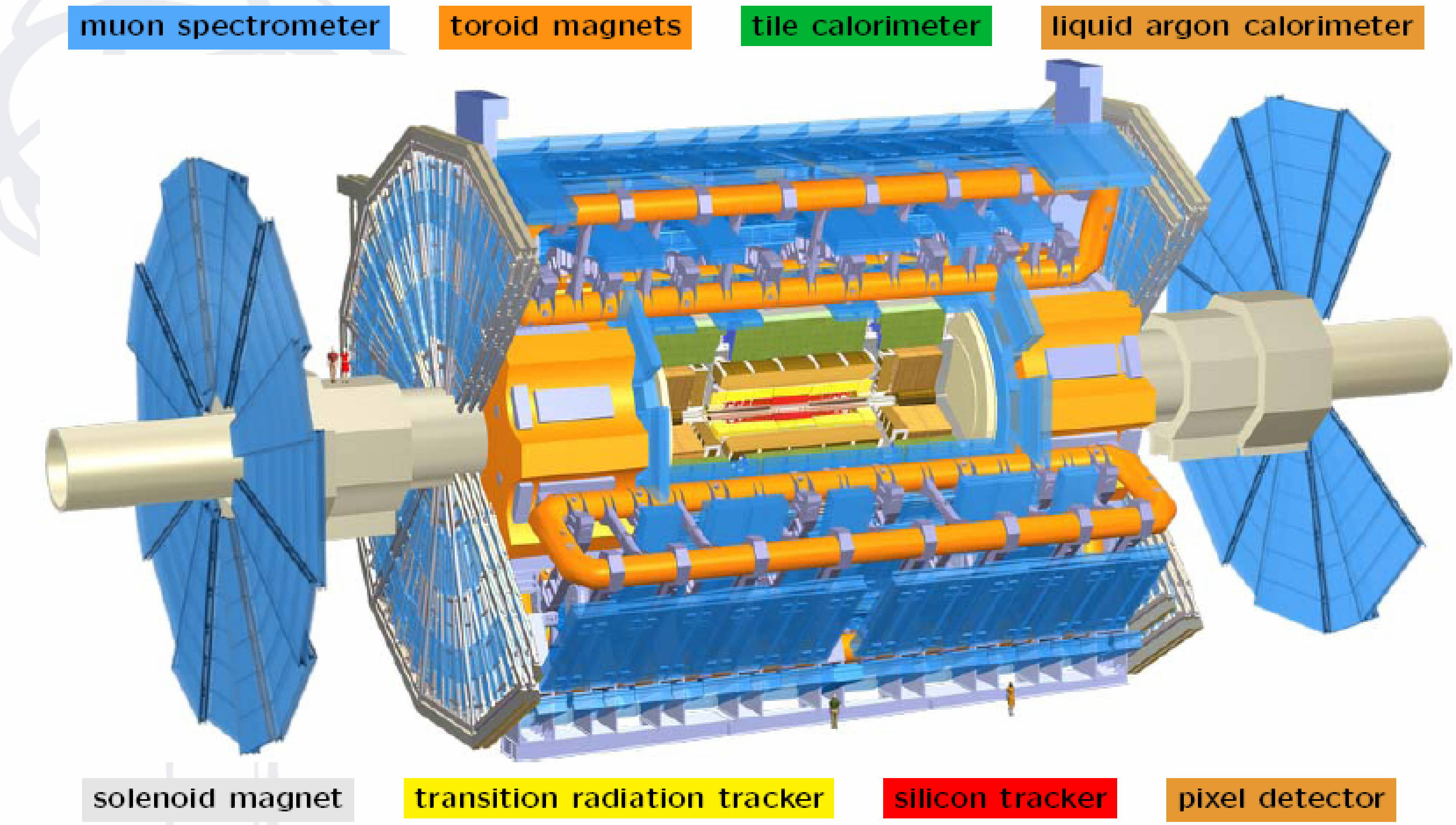
A slice of ATLAS



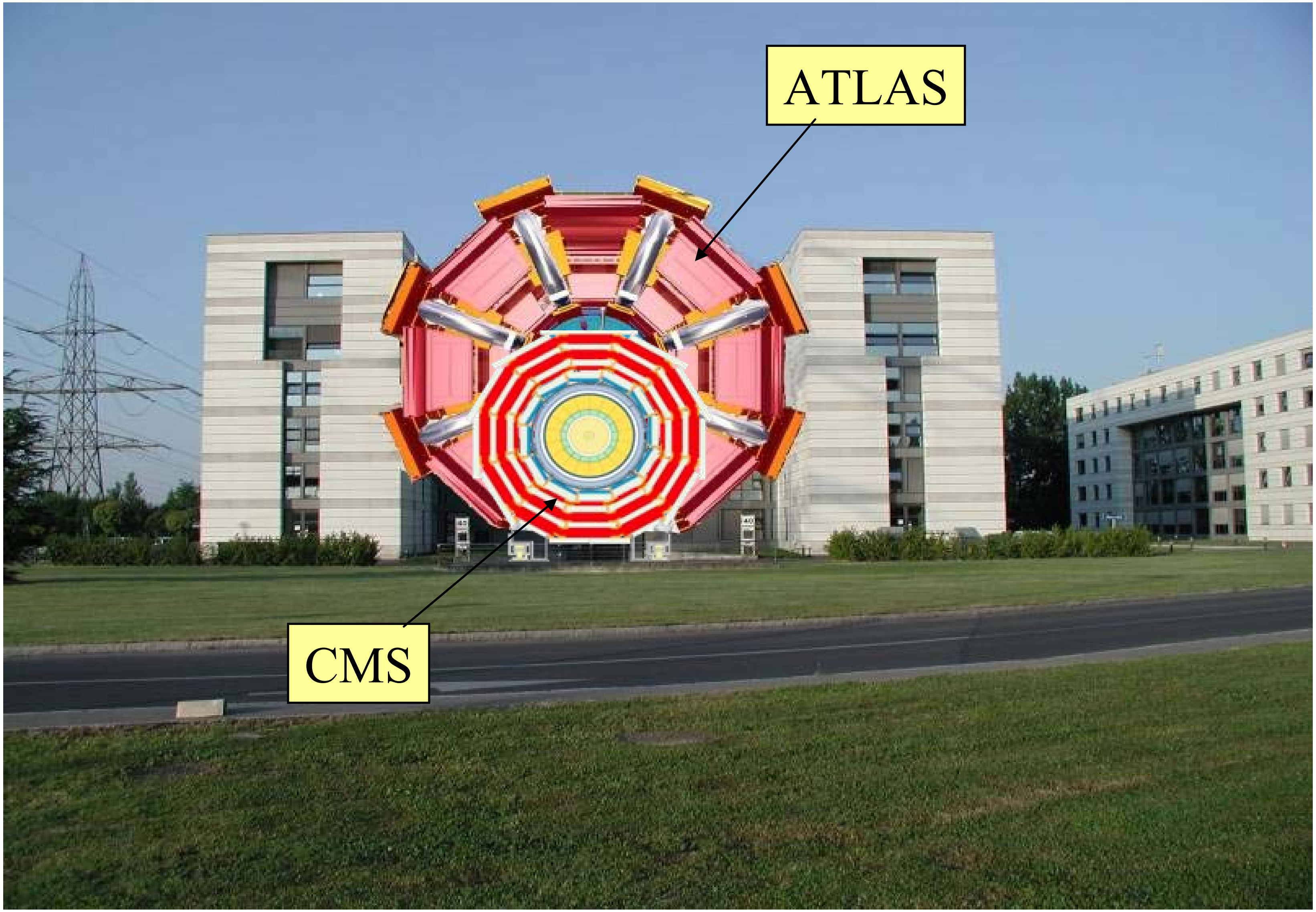
The ATLAS detector

- **ATLAS detector:**

  diameter 25 m, length 46 m, mass 7,000 tons, 10^8 channels, 3,000 km cables



ATLAS, CMS and building 40 at CERN



Charged particles

- Measurement
  - Track (Origin & Direction), energy loss and with B-Field : momentum and sign of charge
  - Photons from Cherenkov light or transition radiation for particle identification
  - Should be non destructive (no scattering and not too much energy loss)

- Examples of tracking detectors with different media :
  - Gaseous detectors

    mainly operated in the proportional scheme

    Drift chambers (planar, radial, cylindrical, jet chamber)

    Time projection chamber (TPC)

    Micro strip gas chambers (MSGC)

    Cathode strips chambers

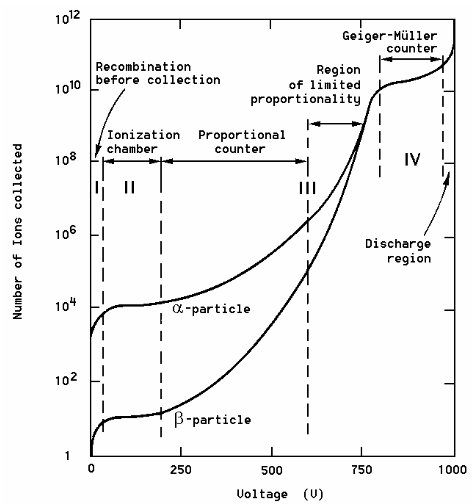
    Straw tubes, drift tubes

    Resistive plates chambers

  - Semiconductor (mainly silicon but also germanium and diamond)

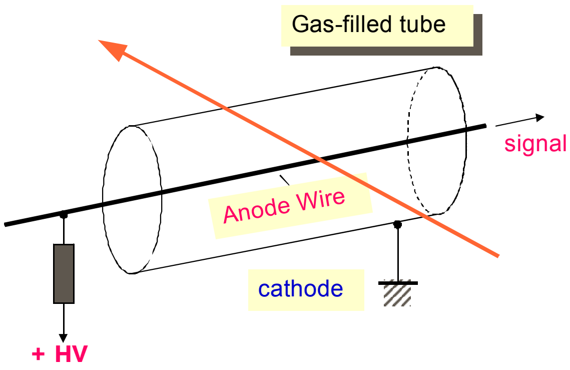
    Strip detectors

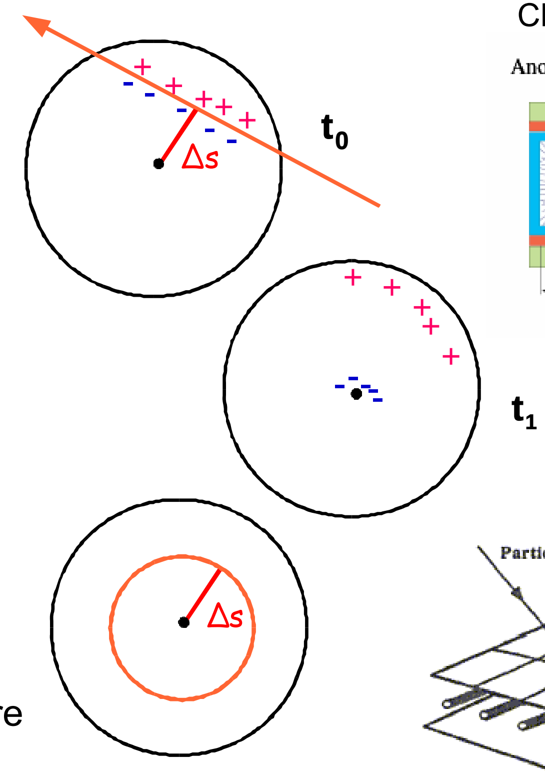
    Pixel detectors



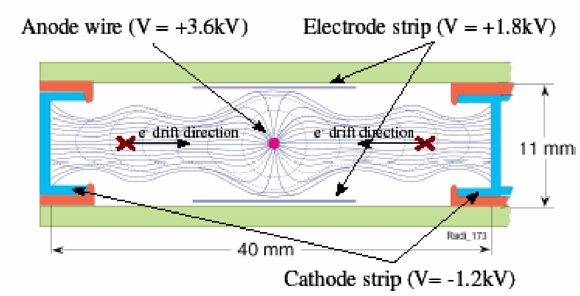
Number of electron-ion pairs of a charged particle traversing a gas detector vs the voltage applied
Note : At very high gain independent of particle type

Example 1 : Gaseous detectors



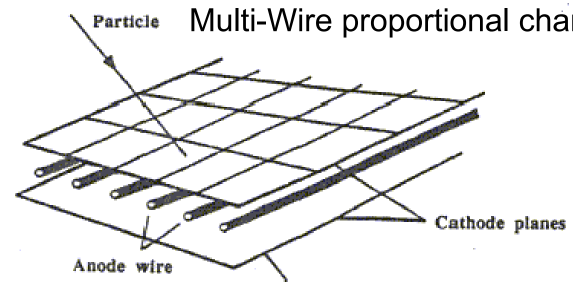


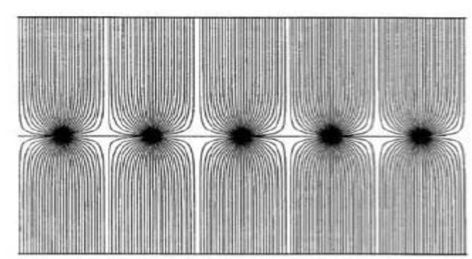
CMS muon barrel drift chambers



- particle ionises gas atoms along track
- electrons drift towards anode: v_d
- E-Field ~1/r - gas amplification near wire
- Measure drift time : $\Delta t = t1 - t0$
- Reconstruct radius : $\Delta s = v_d \, \Delta t$
- V_d depends on gas, voltage, pressure, temperature, field : → need to calibrate

Multi-Wire proportional chamber





Example 2 : Silicon strip detector

- Planar sensor from a high-purity silicon wafer (here *n*-type).
- Segmented into strips by implants forming *pn* junctions.
- Strip pitch 20 to 200 μm, high precision photolithography (expensive).
- Bulk is fully depleted by a reverse bias voltage (25-500V).
- Ionizing particle creates electron-hole pairs (25k in 300 μm).

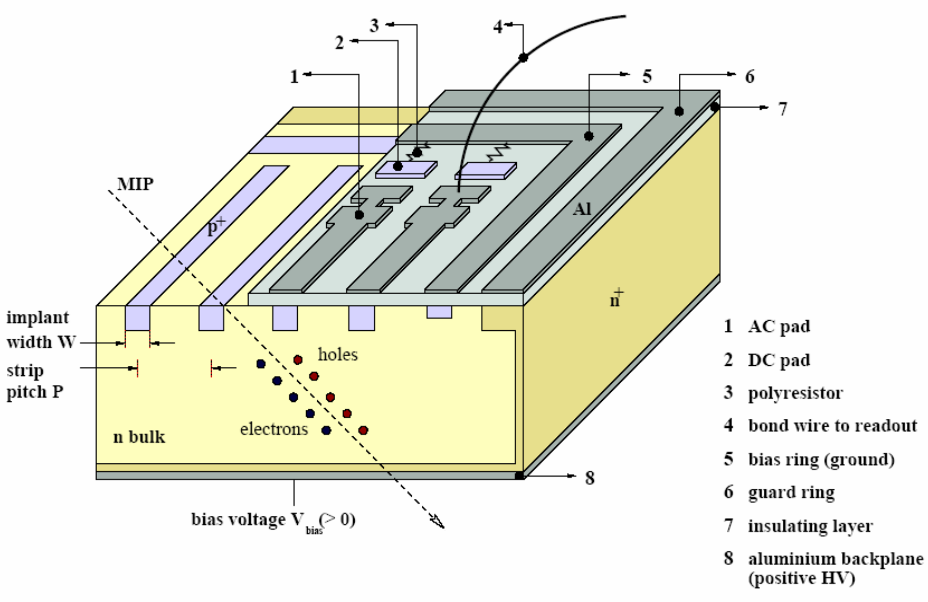
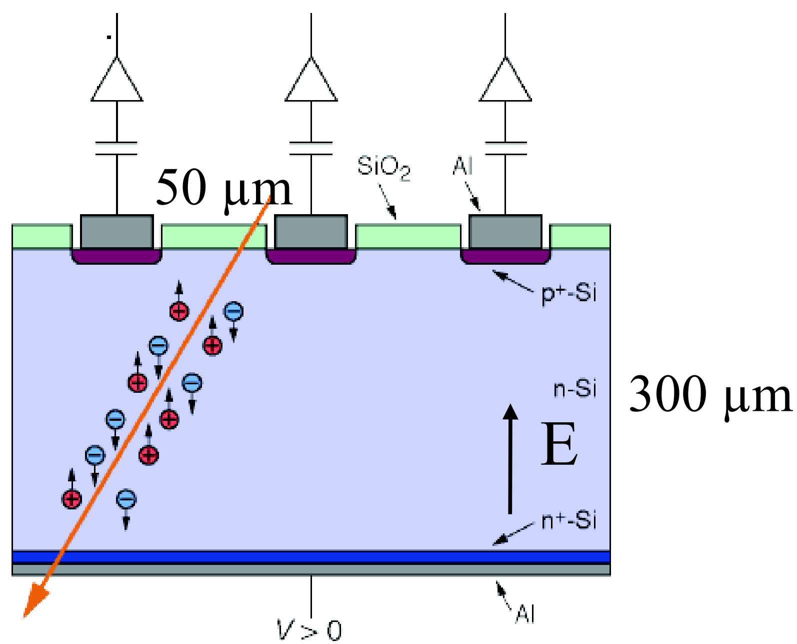
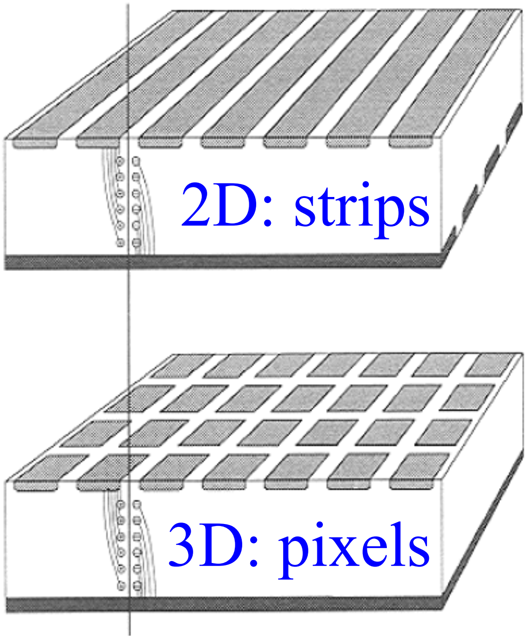


Figure 2.8: Schematic structure of a CMS silicon microstrip sensor.

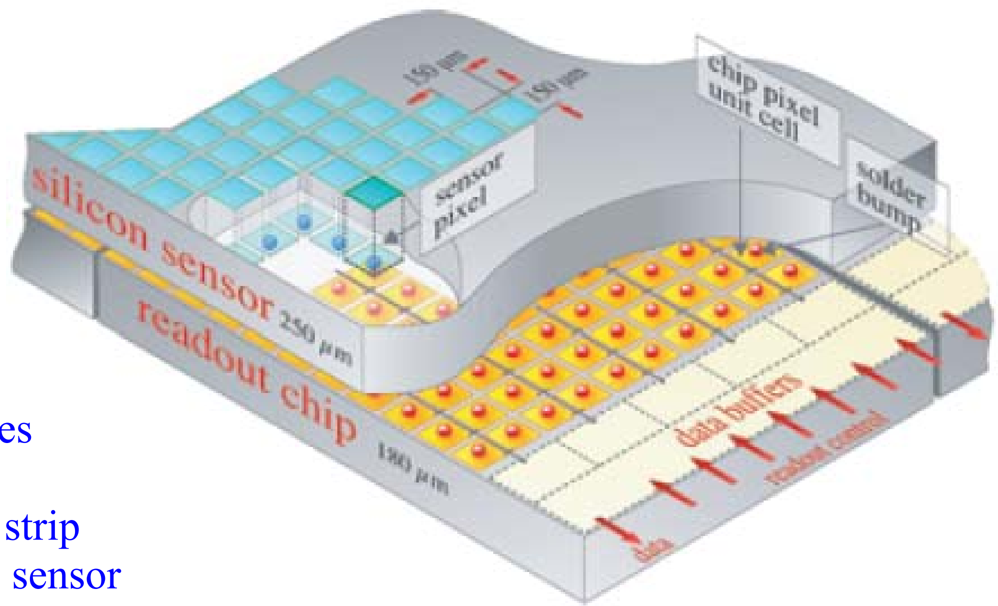


Example 3 : Silicon pixel detectors



Strip detectors have good resolution transverse to strip
Less good along the strip
At lower radius high particle density results in too many (irresolvable) hits on a strip detectors

Divide strips into smaller parts -> pixel
ATLAS : 50 x 300 μm^2
CMS : 100 x 150 μm^2

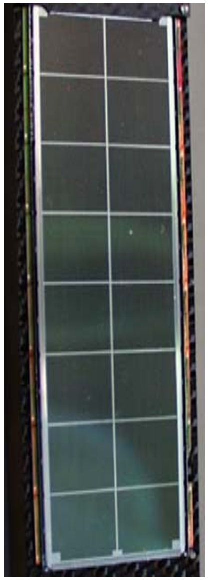


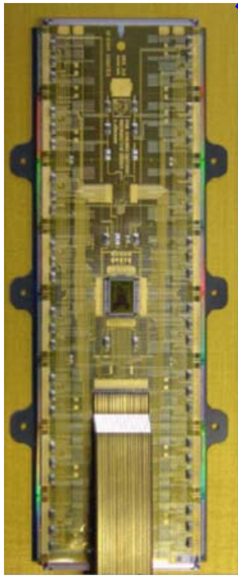
Pixels have much more channels
hence less occupancy but more readout lines

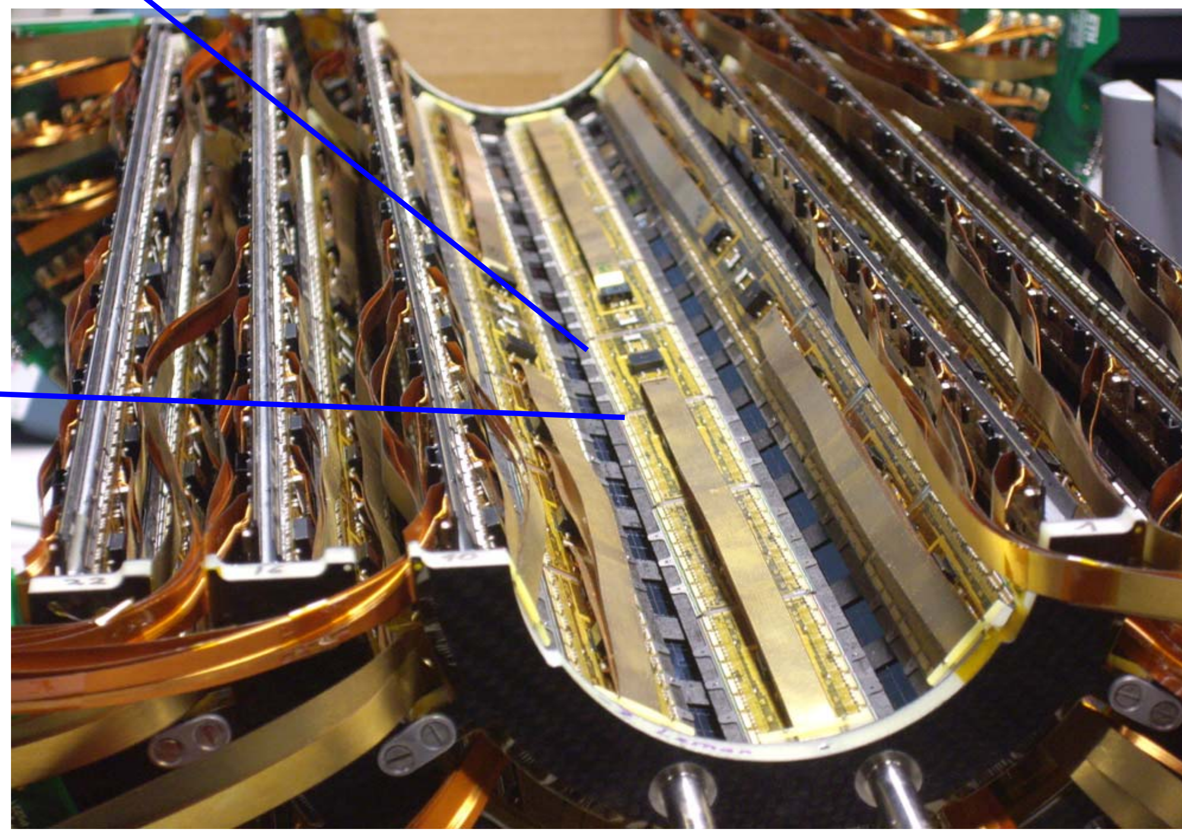
Readout lines cannot be attached at end of strip
Requires readout chip bump-bonded to the sensor

CMS pixel detectors

3 cylinders of silicon pixel sensors





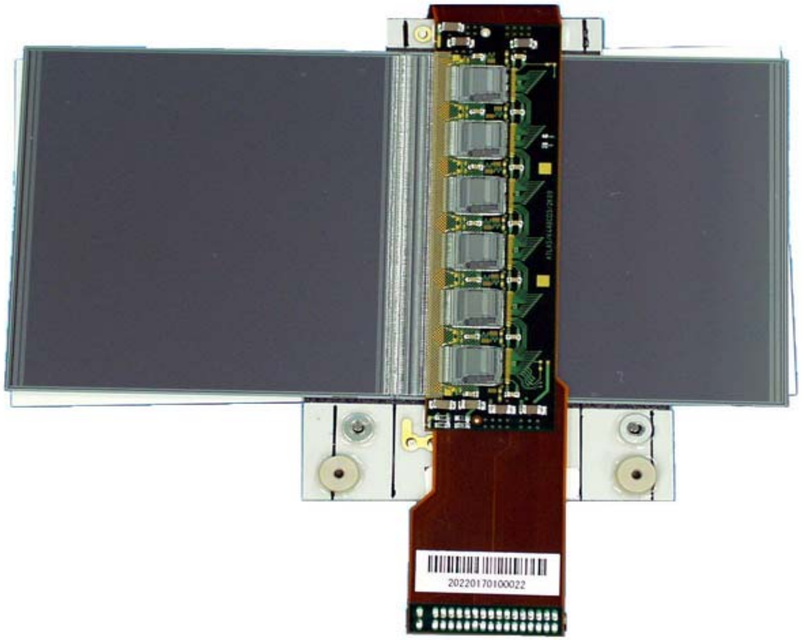


Left :
Bare module with 16 sensors
module size ~ 16x62 mm^2
4160 pixels per sensor

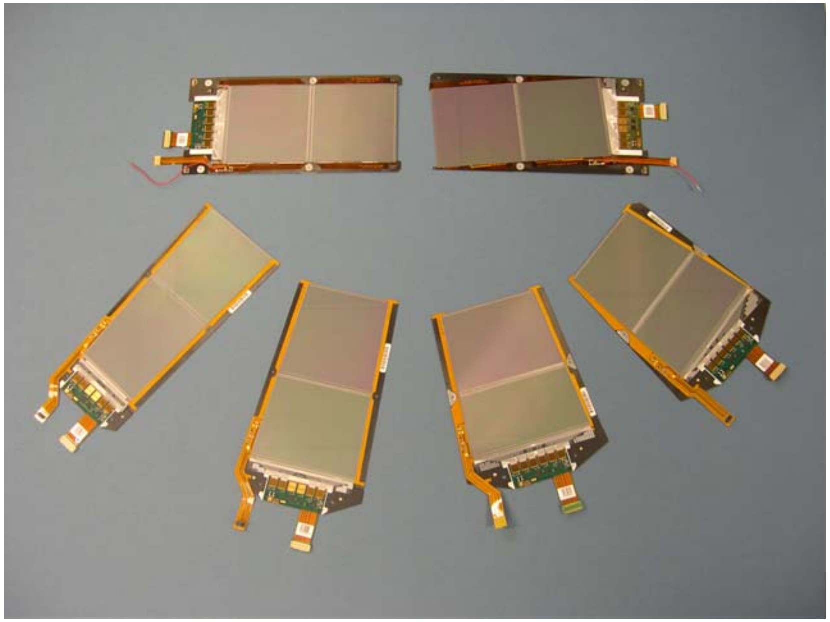
Right :
Full module with HDI and cable

Barrel : 3 layers, 48Mpixel total
End caps : 2x2 disks, 18Mpixel total

Examples of silicon strip sensor modules



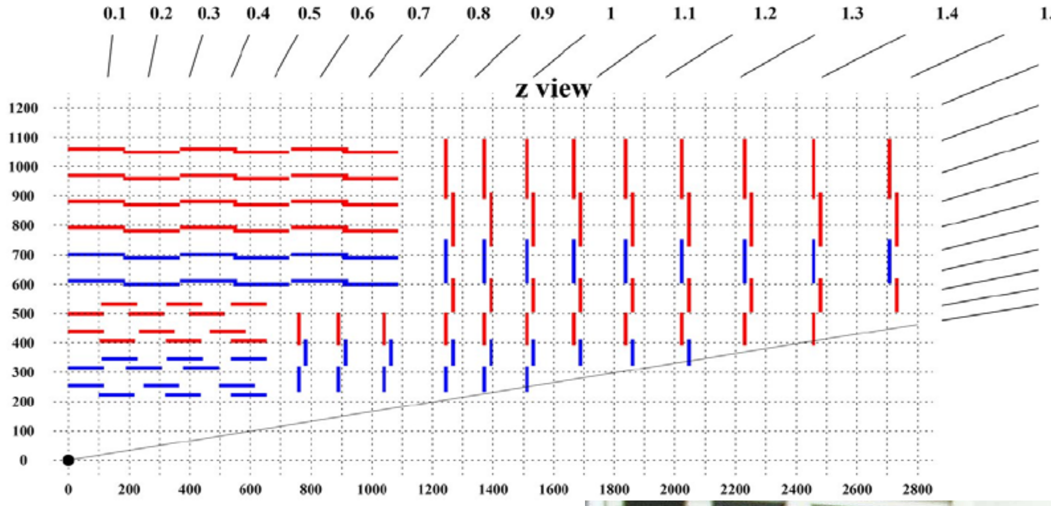
ATLAS
silicon tracker module
2 sensors connected (2 x 6,4 x 6,4 cm^2)
738 strips 12 cm long with 80µm pitch
two modules mounted back to back
with 40 mrad stereo angle



CMS
strip sensors modules of
outer barrel and end cap
single and double layers

double layers with 2 modules mounted
back to back with with 100mrad stereo angle

CMS – Silicon strip tracking



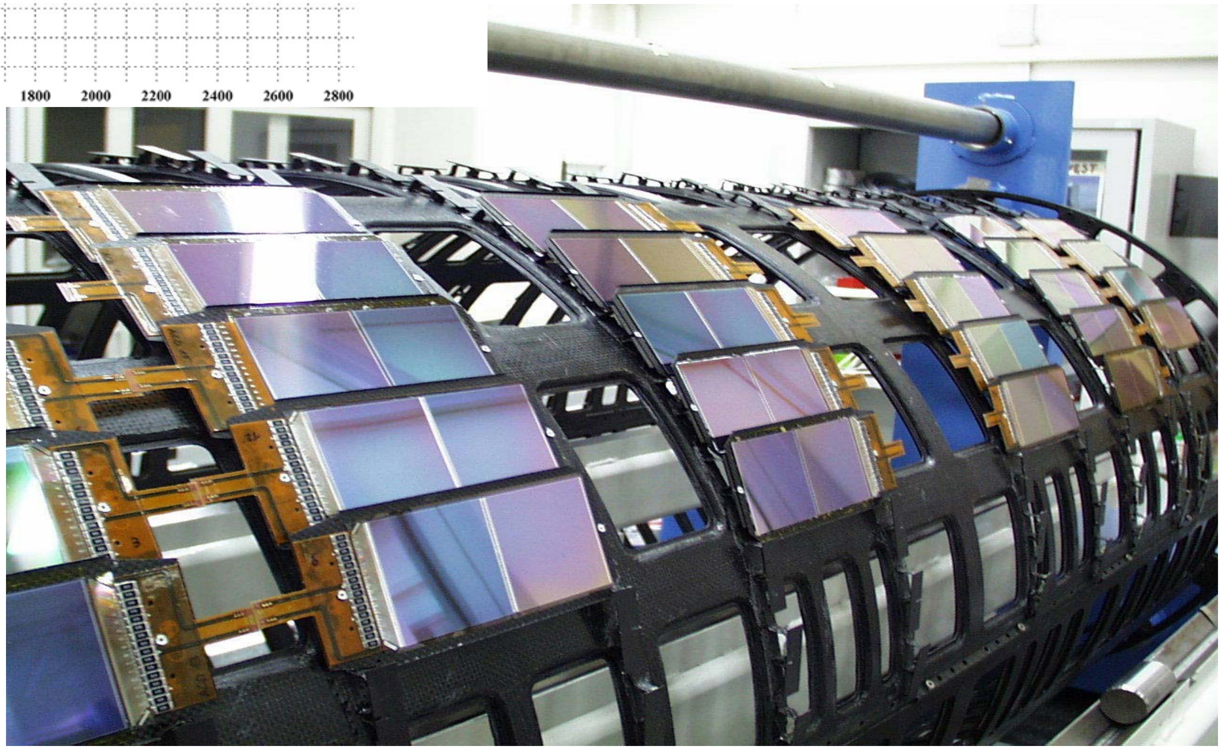
CMS strip tracker :
Inner & outer barrel and end caps

10^7 channels
~ 200 m^2

barrel :
10 cylindrical layers

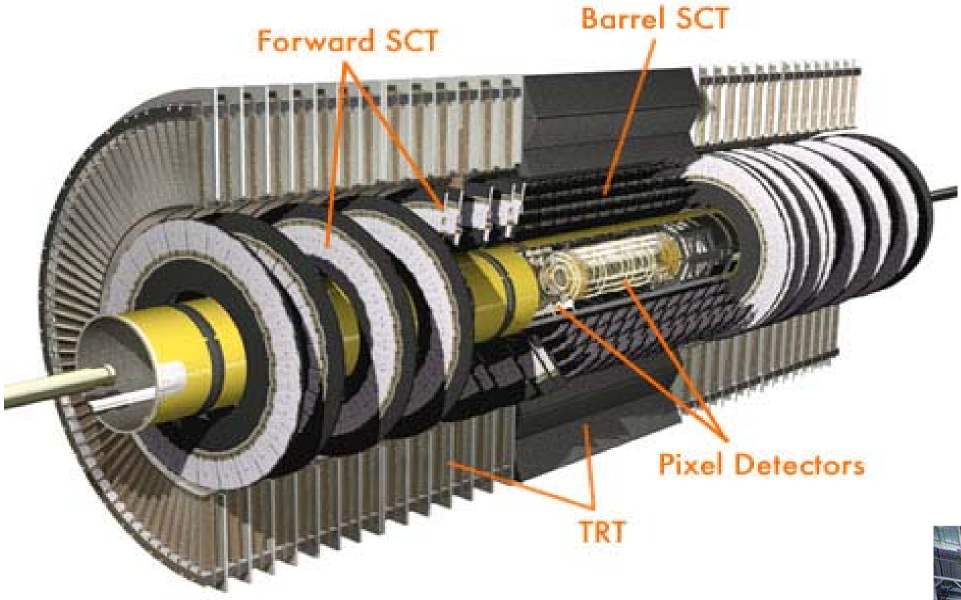
end caps :
12 disks

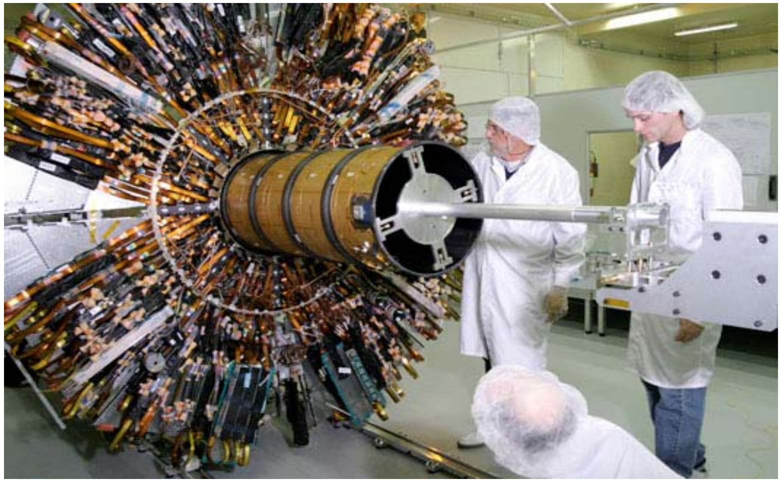
double sided layers in blue

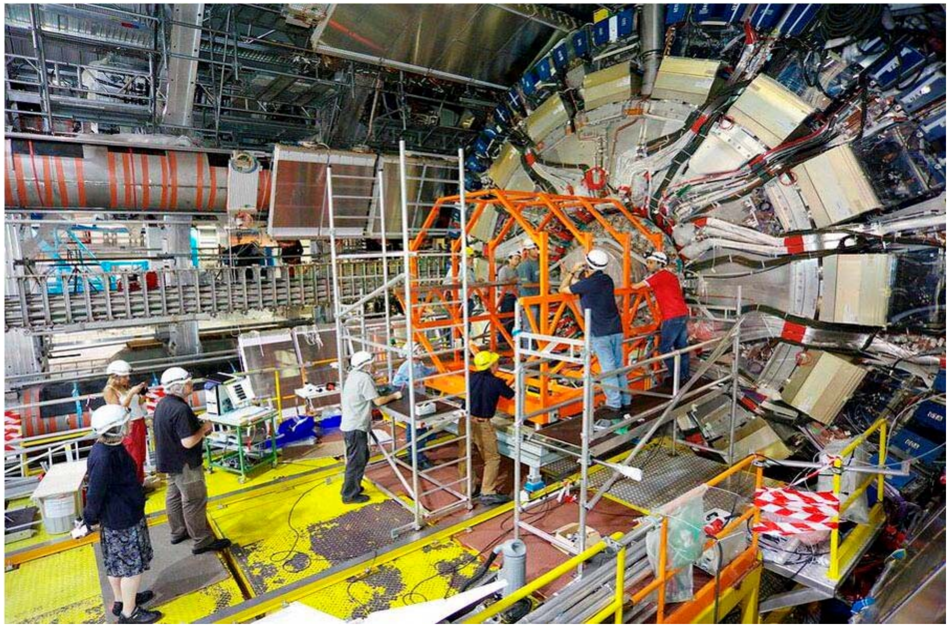


A layer of the
outer barrel

ATLAS inner tracker







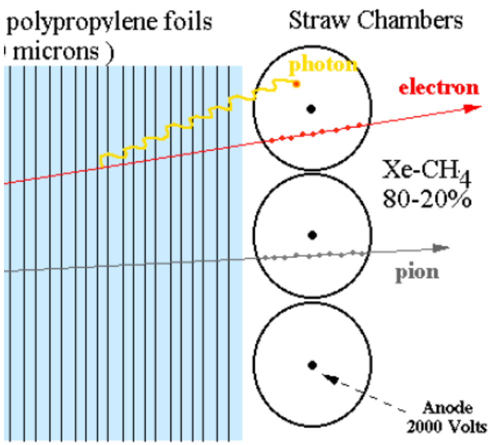
Pixel detector
- 3 cylindrical layers silicon pixel
- 3 disks per end cap

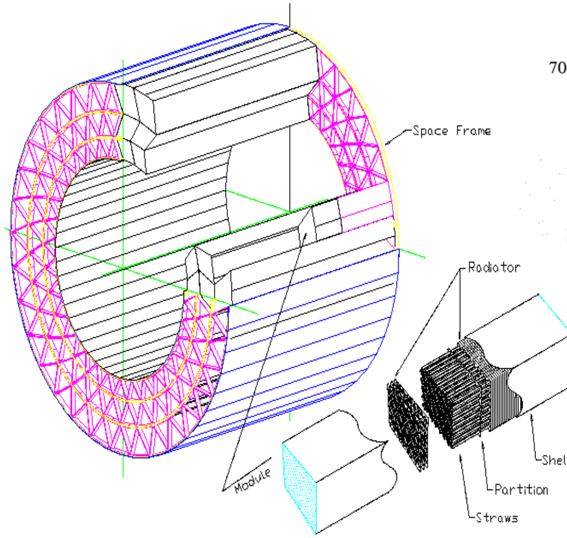
SCT - Semiconductor tracker
- 4 double layers silicon strip
- 9 disks per end cap

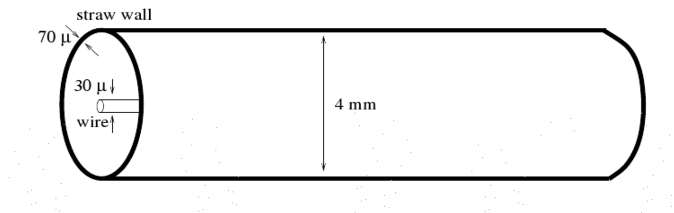
TRT - Transition radiation tracker
- ~36 layers of straw tubes (4mm)
- 12+8 planes in 2 wheels per end cap

Example 4 : transition radiation detector

- Relativistic particles emitting photons if passing material with changing ε





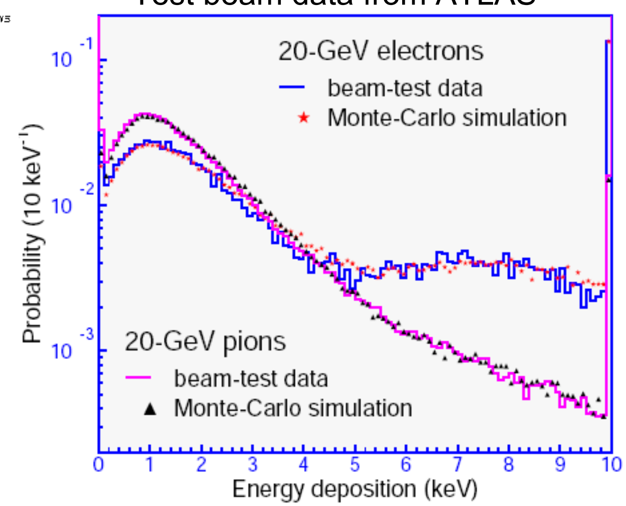


1% probability per foil

straw tube with Xe gas for high x-ray absorption
Straw tubes are interleaved with radiator foils

Transition radiation depends on particle mass :
Energy loss ~ $1/\gamma$ ($\gamma = E/mc^2$)
allows separation of e / π

Test beam data from ATLAS

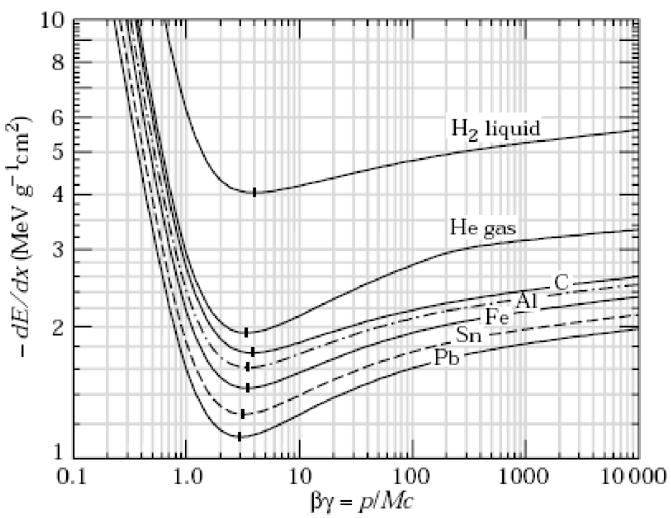


Energy loss allows particle identification

- At lower momentum the energy loss allows particle identification
  - The energy loss due to ionization is given by (Bethe-Bloch) :

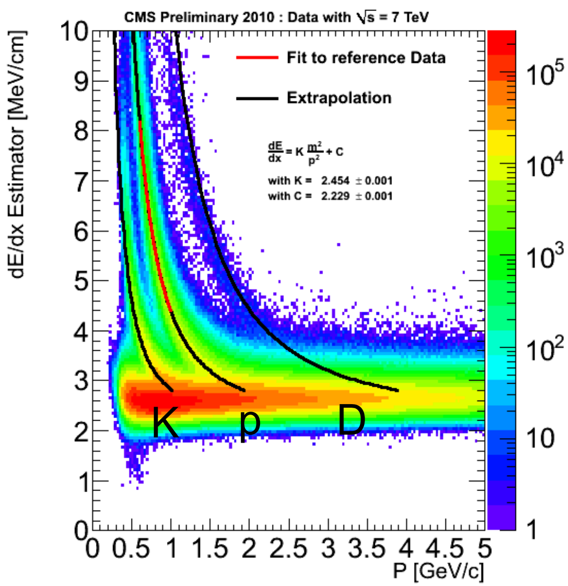
$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi N_A r_e^2 m_e c^2 \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2}{\langle I \rangle}\right) - \beta^2 - \frac{\delta}{2}\right]$$

  - with $\beta = v/c$, $\gamma = E/mc^2$



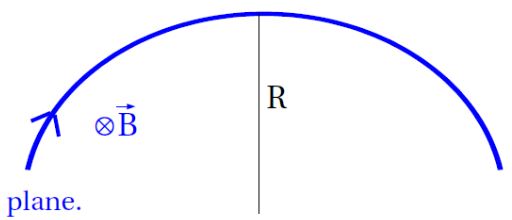
~1/β²   relativistic rise ~ ln γ

CMS tracker data



The momentum of a particle – using a magnet

- A charged particle in a magnetic field will be bent
  - The force on a traveling particle with charge q and velocity v in a magnetic field B is
    - $F_B = q\ v_t\ B$ (with v_t being the velocity component transverse to the B-Field)
  - balancing by the centrifugal force of a particle on a circular track with radius R
    - $F_R = m\ v_t^2 / R$
  - the transverse momentum p_t is given by
    - $p_t = m\ v_t = q\ R\ B$



  - We only measure point ('hits') on a curved track with some precision σ_x
    - the relative error on the momentum increases with the momentum : $\sigma(p_t)/p_t \sim p_t$
    - and depends on hit resolution : $\sigma(p_t)/p_t \sim \sigma_x / BL^2$ (L = length of the measured track)

Tracking summary

- We use mainly ionization, bremsstrahlung and pair production to
  - Detect particles
  - Measure their momentum (curvature in a magnetic field)
    - relatice error increases with momentum : $\sigma(p_t)/p_t \sim p_t$
    - large magnets help : $\sigma(p_t)/p_t \sim \sigma_x / BL^2$
  - Measure the energy loss (dE/dx) to identify particles at lower momentum

- We can use Cherenkov emission and transition radiation to
  - Identify particle type (emissions depend on $\gamma \sim E/mc^2$)

- We avoid to disturb the particle as much as possible
  - Energy loss
  - Multiple scattering

Particle energy measurements - calorimeters

- To determine the total energy of a particle :
  - the particle has to loose all its energy in the material
  - all energy deposited in the material should be measured
  - the signal we measure should depend linear on the particles energy
  - different particles should have the same signal dependence to the energy
- Electromagnetic and hadronic energy loss mechanisms require different detectors
  - Different segmentation according to shower profile
  - Electromagnetic : radiation length X_0, hadronic : nuclear interaction length λ
- High material density is required to capture all energy (no leakage)
- The measurement is highly destructive !
  - Except of muons and neutrinos all particles should stop inside the calorimeter volume
- Calorimeters are essential for high-energy particles:
  - calorimeters get better for higher-energy particles !
  - momentum determination is less precise for high momentum tracks (small curvature)

$$\text{Calorimeter}: \frac{\sigma(E)}{E} \sim \frac{1}{\sqrt{E}}$$

$$\text{Tracker}: \frac{\sigma(p)}{p} \sim p$$

$$\text{with } p = rqB \text{ in magnetic field B}$$

Energy resolution of a calorimeter

The relative energy resolution of a calorimeter can be expressed by

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- 1/√E
  - Fluctuations in shower development
  - Fluctuations in sampling
- Constant term
  - Absorption losses
  - Non linearity
  - Calibration
  - Dead material
- 1/E
  - Electronic noise

Typical values for a/√E

- EM :
  - ~ 20% for sampling calorimeters
  - ~ few% for homgenious calorimeters
- Hadronic
  - ~50% for non compensating (response : EM > hadronic)
  - ~35% for compensating calorimeters (response : EM ≈ hadronic)

Examples of calorimeter types

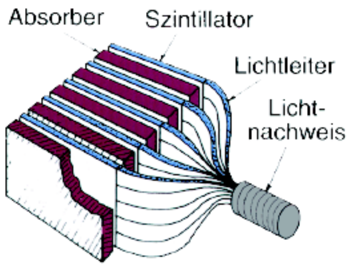
- Calorimeters can be divided in two architectures
  - Sampling calorimeters

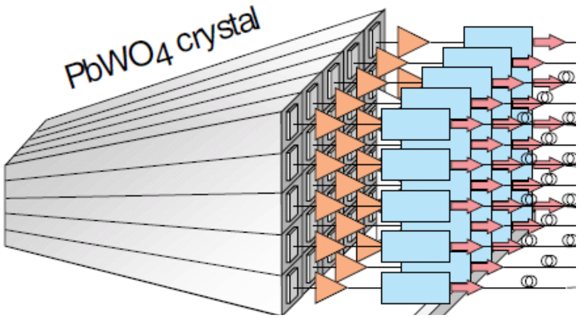
    Separate absorber material and sensitive material

    Material layers usually interleaved

    Examples : Absorber/scintillator sandwich (ZEUS, ATLAS),

    LAr Calorimeters (H1, ATLAS)





  - Homogeneous calorimeters

    Absorber material is sensitive material

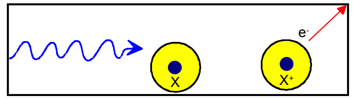
    Example : Lead Crystals (JADE, OPAL, CMS)

- Different types of calorimeters for electromagnetic and hadronic interaction
  - Different absorber/sensitive material
  - Different segmentation according to shower profile

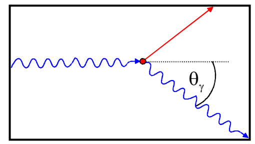
Electromagnetic showers

- **Photons** :

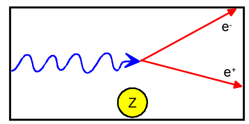
Photoelectric effect < 100keV



Raleigh scattering < 100keV
Compton scattering 10keV – 2 MeV

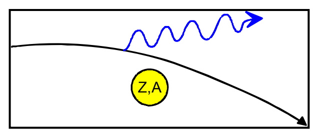


Pair production > 1 MeV
(dominates > 4MeV)



- **Charged particles :**

Ionization
Bremsstrahlung



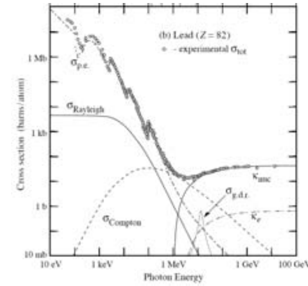
Cherenkov emission (v above c/√ε)
Transition radiation (traversing different ε)

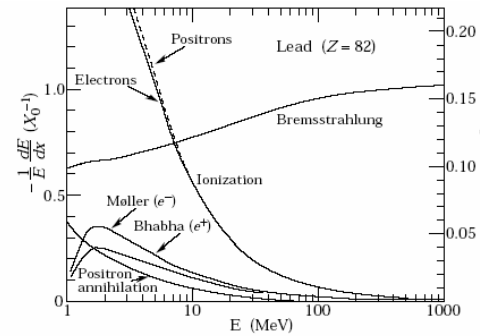
X_0 = radiation length

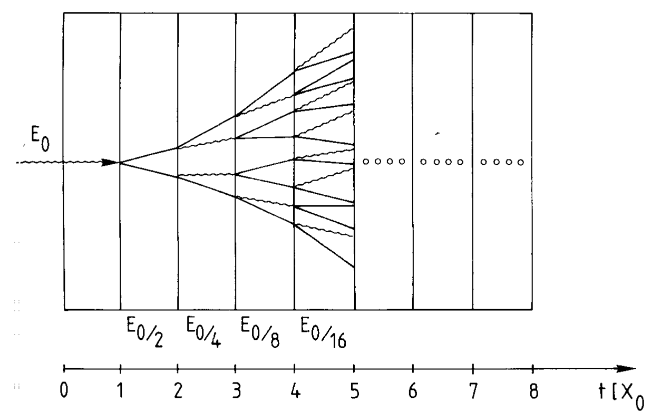
$$\langle E \rangle = E_0 \, e^{\frac{-X}{X_0}}$$

Critical energy E_c (dE/dx : Ionization = Bremsstahlung)

$E_c \sim 580$ MeV/Z







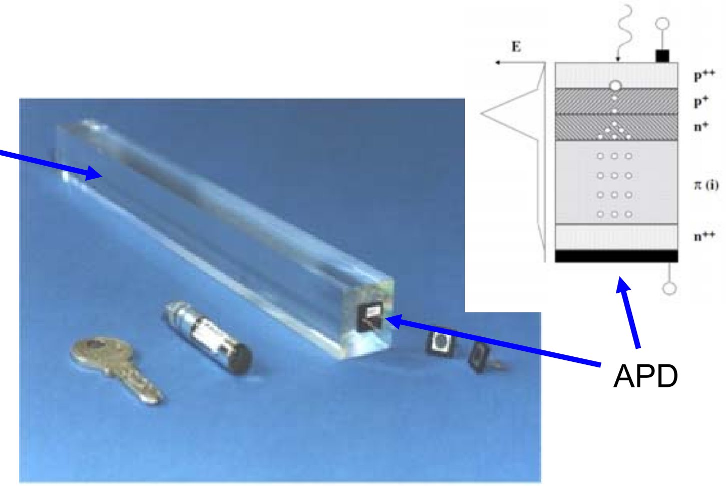
	Scint.	LAr	Fe	Pb	W
X_0(cm)	34	14	1.76	0.56	0.35

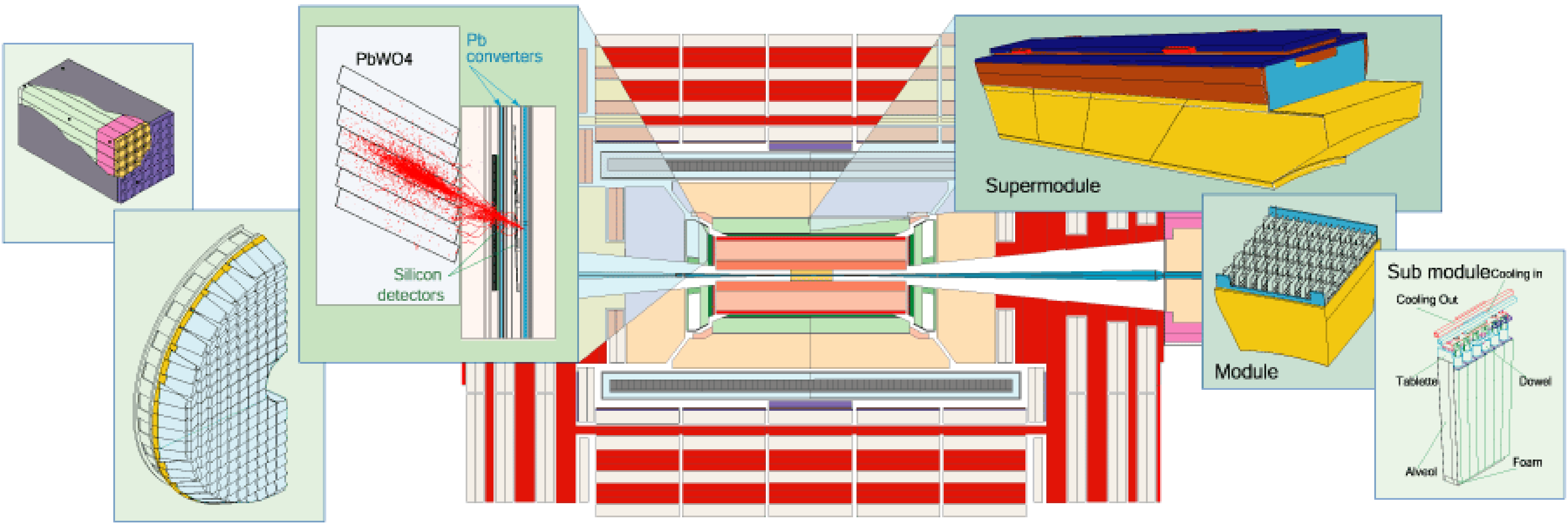
Example : CMS EM Calorimeter

- homogeneous calorimeter
- absorber = active material = $PbWO_4$ crystals
- dimensions of crystal : 2x2x23 cm^3
- radiation length : 23 X_0
- pointing geometry
- energy loss due to Cherenkov emission
- photon detection by APD (barrel) and VPT (end cap)

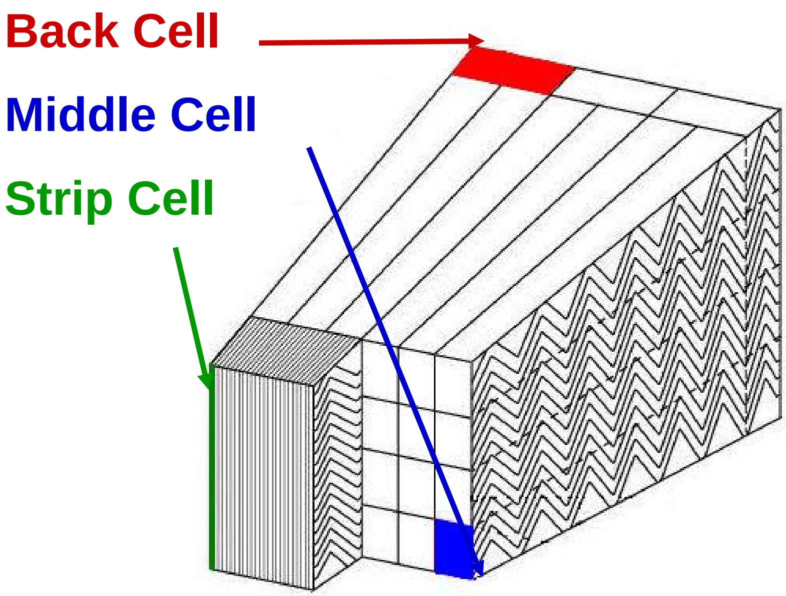
- design resolution :

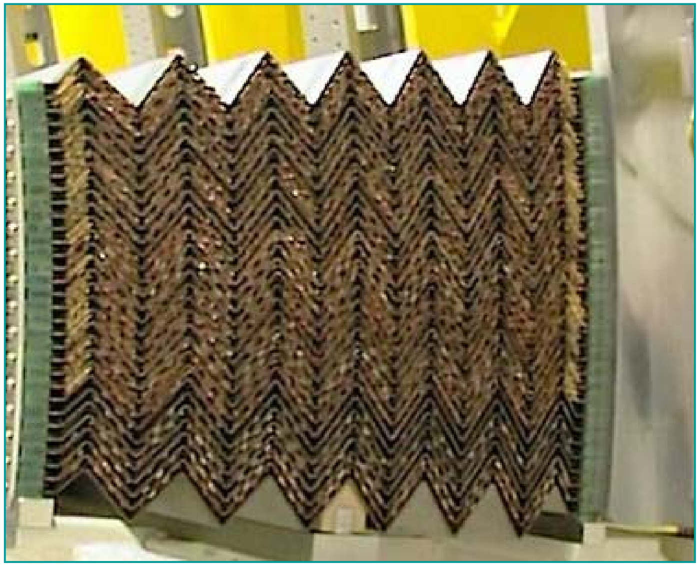
$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} + \frac{155MeV}{E} + 0.55\%$$





Example : ATLAS LAr EM Calorimeter





3 sections:

- strips for position resolution
- middle for energy measurement
- back for leakage control

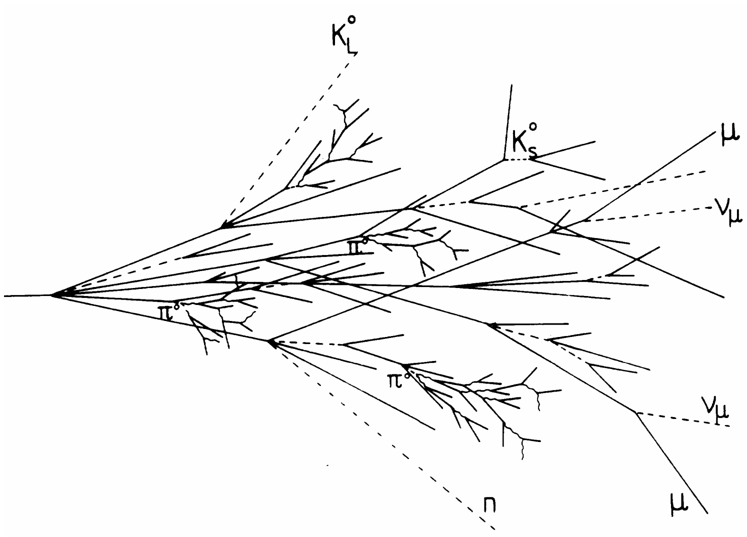
- Pb absorber in LAr
- Accordion geometry for routing of readout signals to the back
- Allows dense packing and fine granularity.

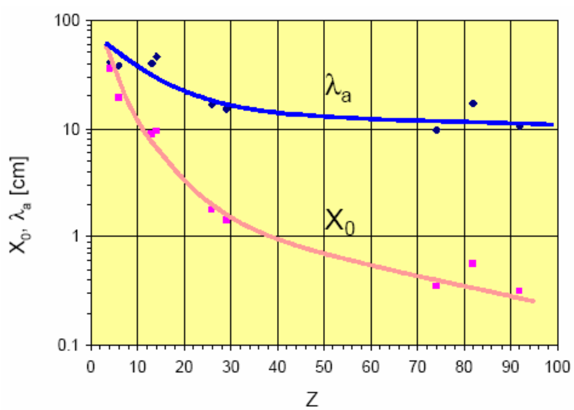
Hadronic showers

- Showers initiated by hadrons are different:
- nuclear reactions (strong interactions) !
  - many different processes
  - probabilities from experimental data
- Production of many secondary particles:
  - EM fraction ($\pi 0 \rightarrow \gamma\gamma$!) increases with energy
  - hadronic contribution: $\pi\pm$, n, p, …
- Nuclear absorption length $\lambda \approx 35 A^{1/3} g.cm^{-2}$

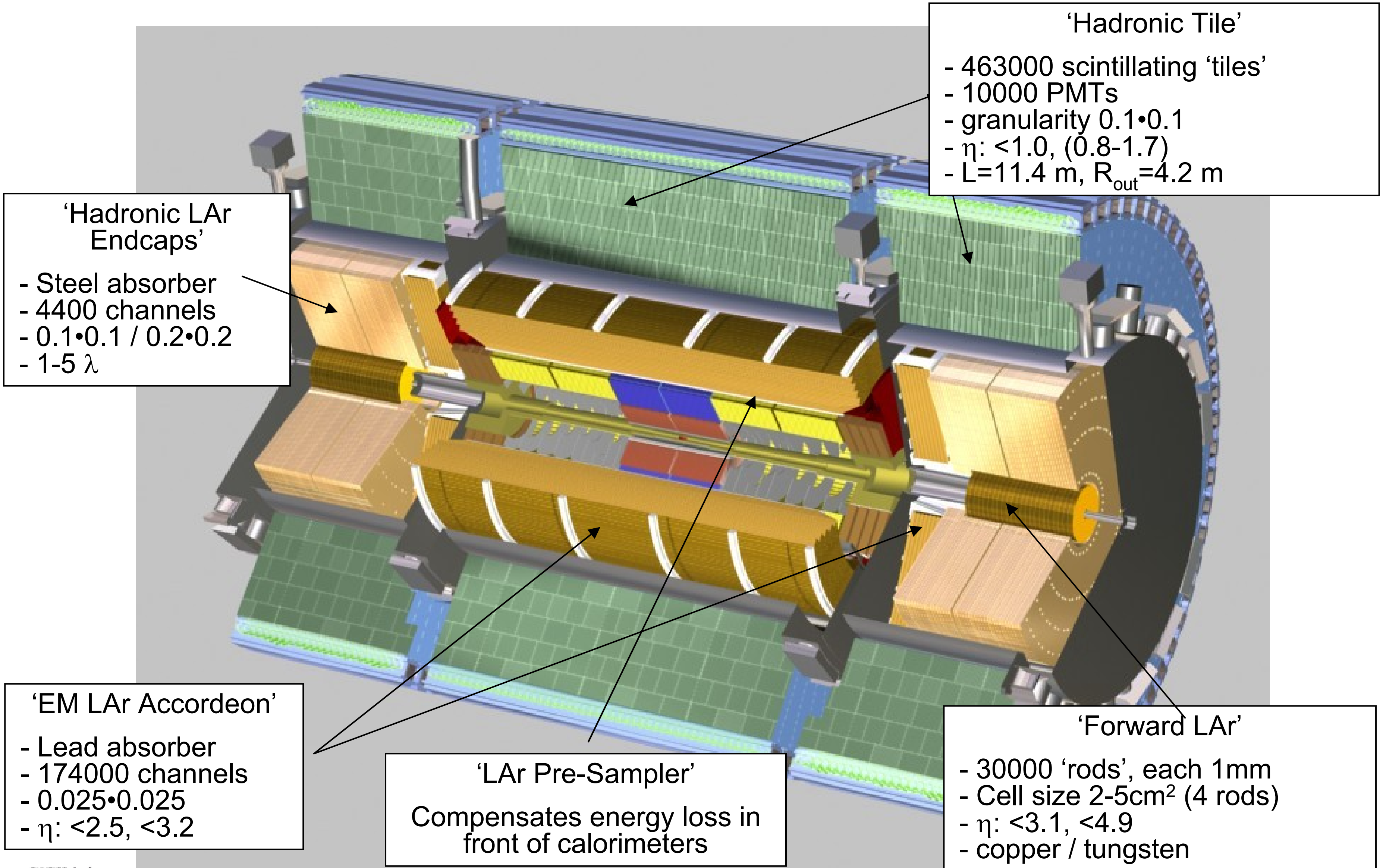
  (equivalent to X0 in EM but larger → need bigger HCAL)
- Particle generation down to π threshold
- Number of secondary hadrons rises with ln(E)
- Hadronic showers are broader than EM showers
- Invisible contribution (excitations of nuclei, fragments, low energy photons, etc)

  → worse energy resolution, response HAD/EM < 1



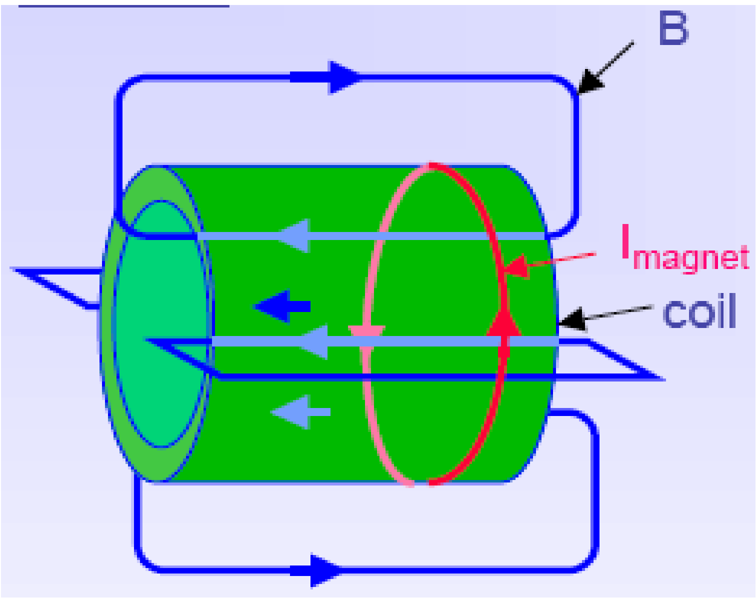


Example : ATLAS Calorimeter



Magnets

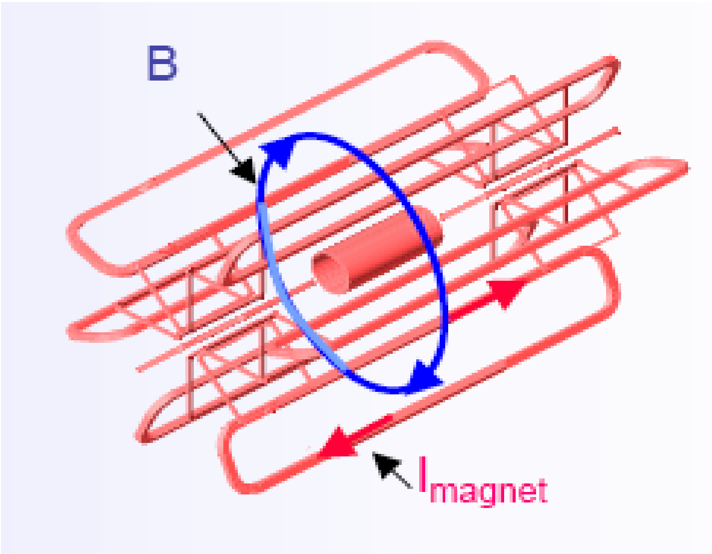
Solenoid



Field direction along beam axis.
Homogenous field inside the coil.
Need surrounding iron structure to capture the 'return field'.

CMS: I = 20 kA, B = 4T.
Superconducting (4K).

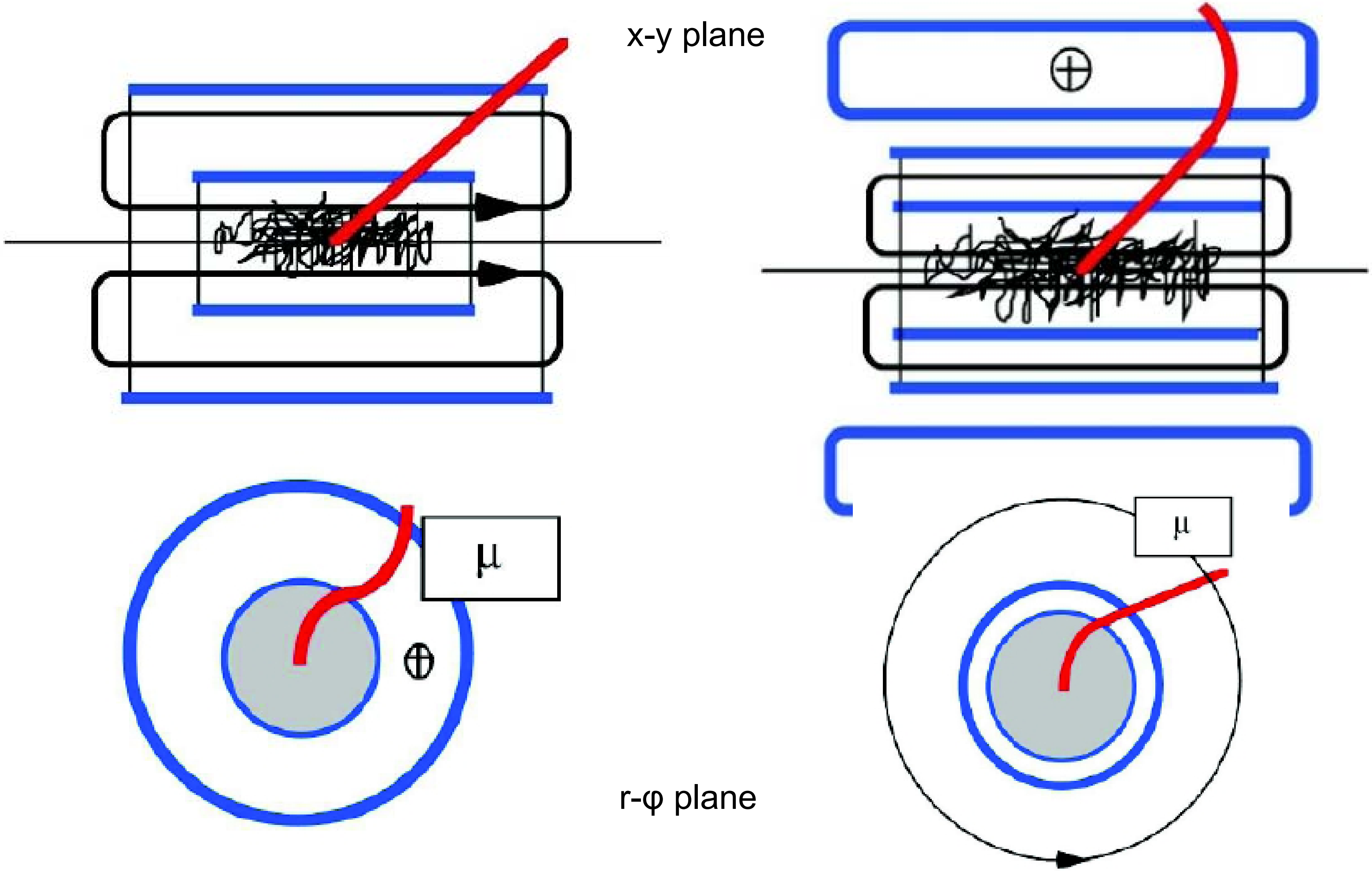
Toroid



Field circles around the detector.
Detailed field map needed.
No iron structure needed.

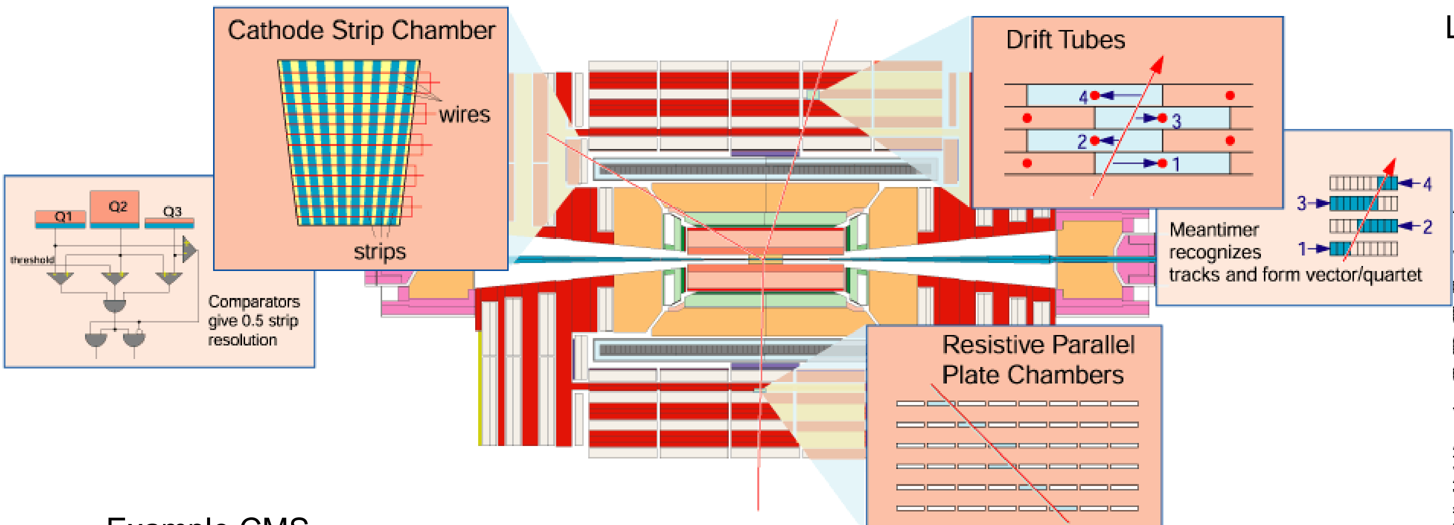
ATLAS: I = 20 kA, B up to 4 T.
Superconducting (4K).

Bending muons : solenoid vs toroid



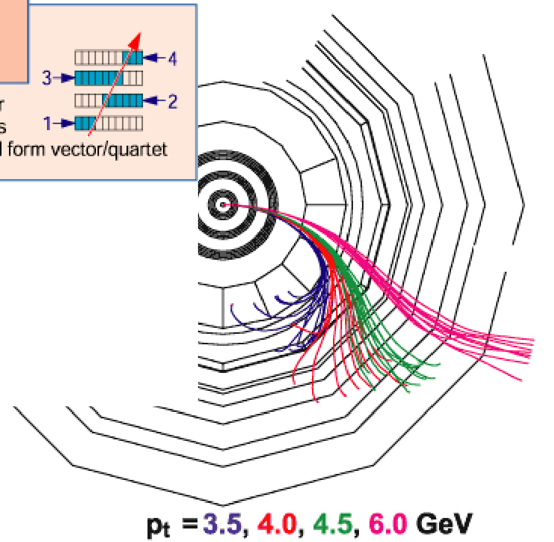
Moun detection

- Mouns may be the key to new and rare physics processes (easy to identify)
- Capability to trigger on moun tracks needed
- Position resolution should match tracking resolution (moun track linking)
- Large range of energy spectrum to be accurately measured (few GeV up to 100 GeV)
- Charge determination at highest energy needed (even above TeV)
- High rate environment in end cap regions need robust detectors
- Use different technologies for the various requirements (RPC, DT, CSC)



Large Magnet is essential !

$\sigma_p/p \sim \sigma_x p/BL^2$



Example CMS
Drift tubes in barrel for high precision
Robust Cathode Strip Chambers in end cap
Fast Resistive Plate Chambers for trigger purpose

Moun detection - ATLAS

Resistive Plate Chambers

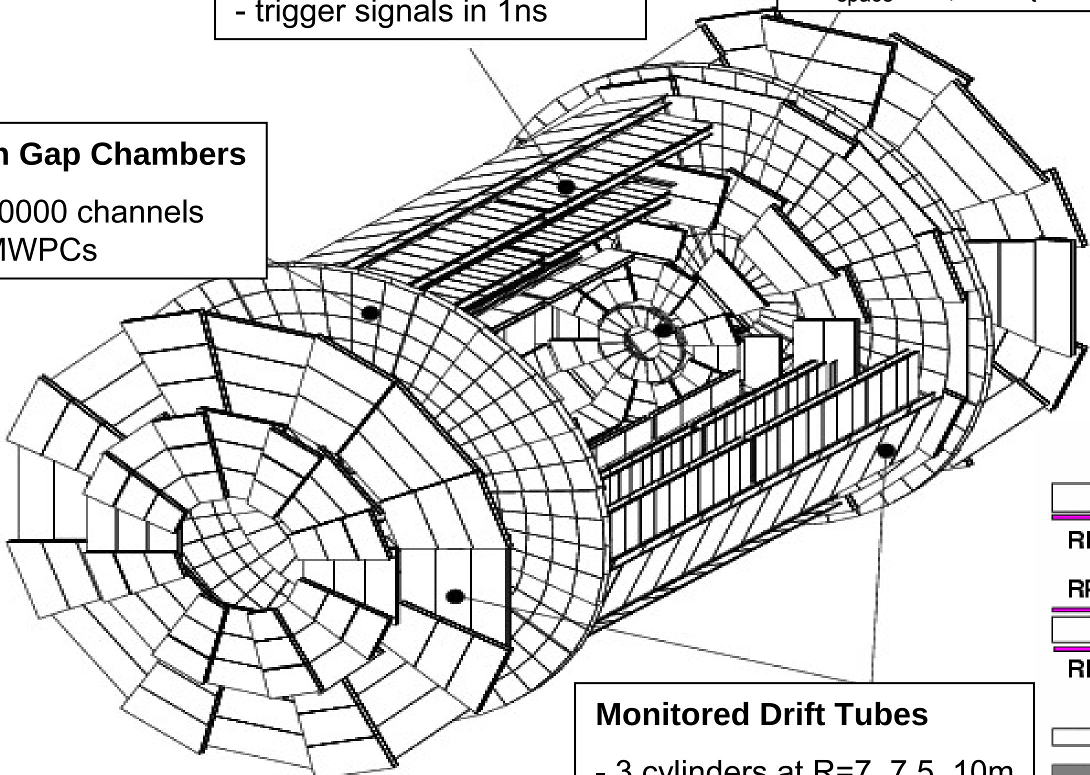
- 354000 channels
- σ_{space}=1cm
- trigger signals in 1ns

Cathode Strip Chambers

- 67000 wires
- only for $|\eta|>2$ in first layer
- σ_{space}=60μm, σ_t=7ns

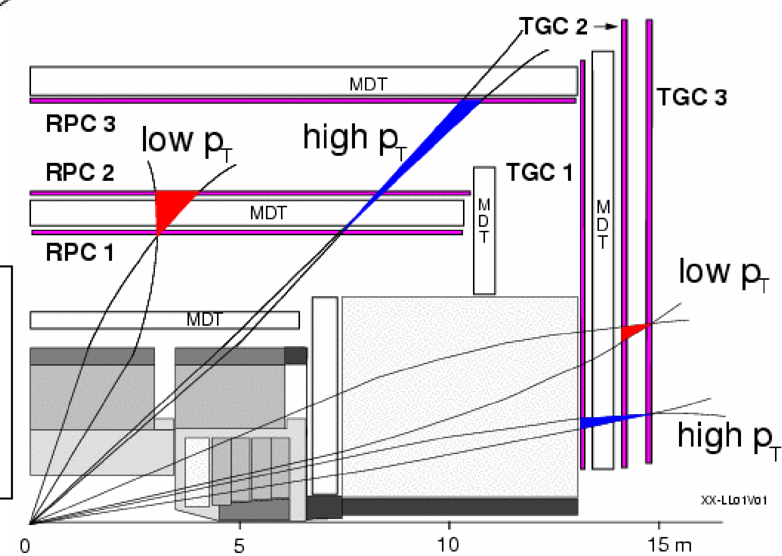
Thin Gap Chambers

- 440000 channels
- ~MWPCs



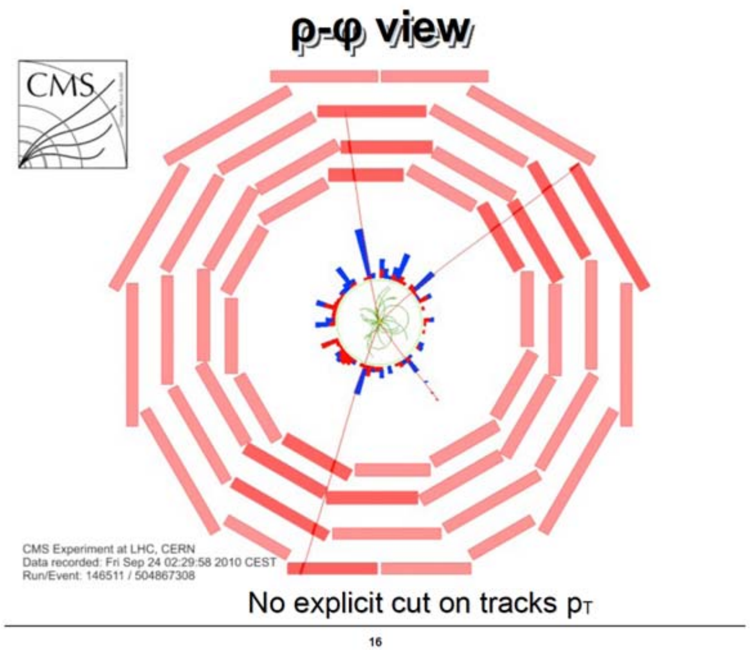
Monitored Drift Tubes

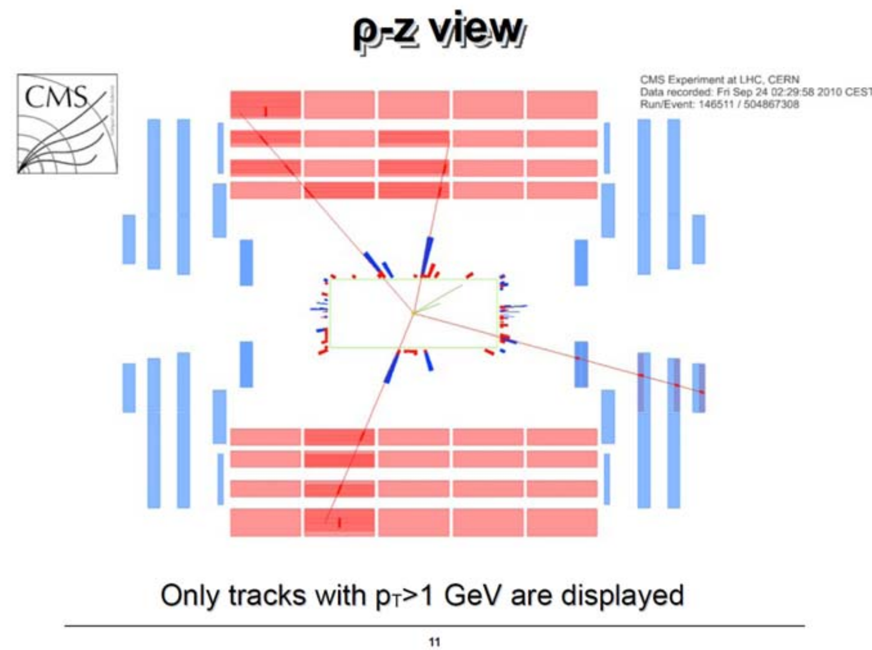
- 3 cylinders at R=7, 7.5, 10m
- 3 layers at z=7, 10, 14 m
- 372000 tubes, 70-630 cm
- σ_{space}=80μm, σ_t=300ps



Moun detection – CMS Event

$$ZZ \rightarrow 4\mu$$





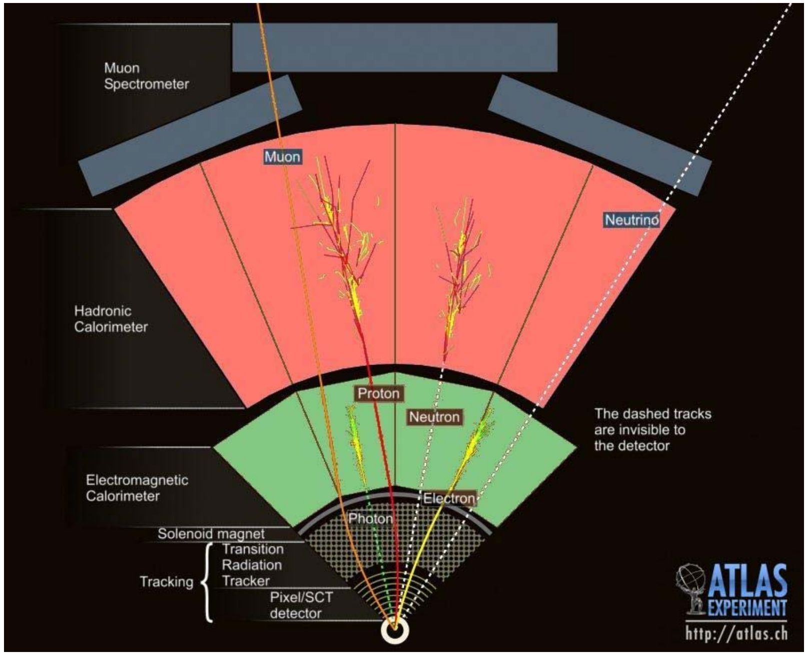
Invariant masses

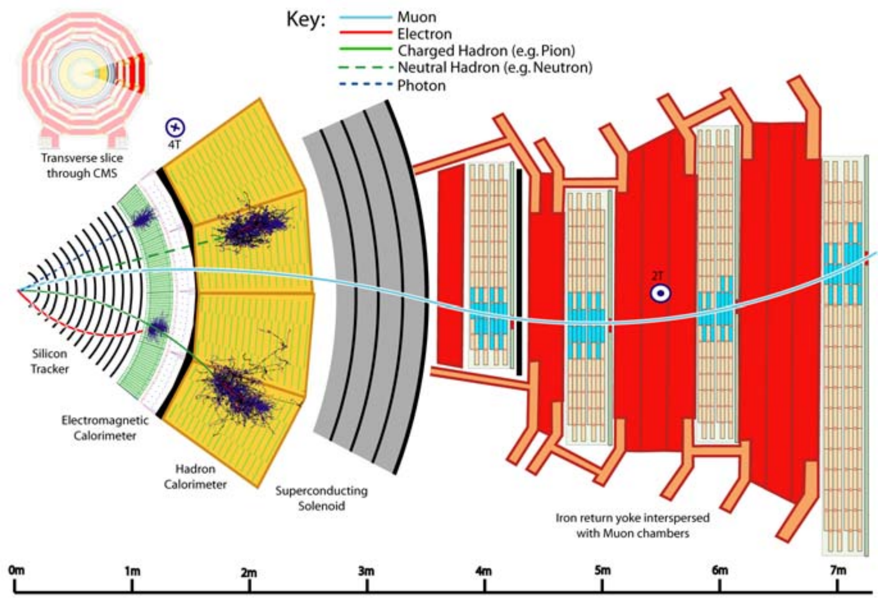
$\mu_0 + \mu_1$: $M_{01} = 92.15$ GeV

$\mu_2 + \mu_3$: $M_{23} = 92.24$ GeV

of all 4 μ : $M_{4\mu} = 201$ GeV

Comparing ATLAS and CMS

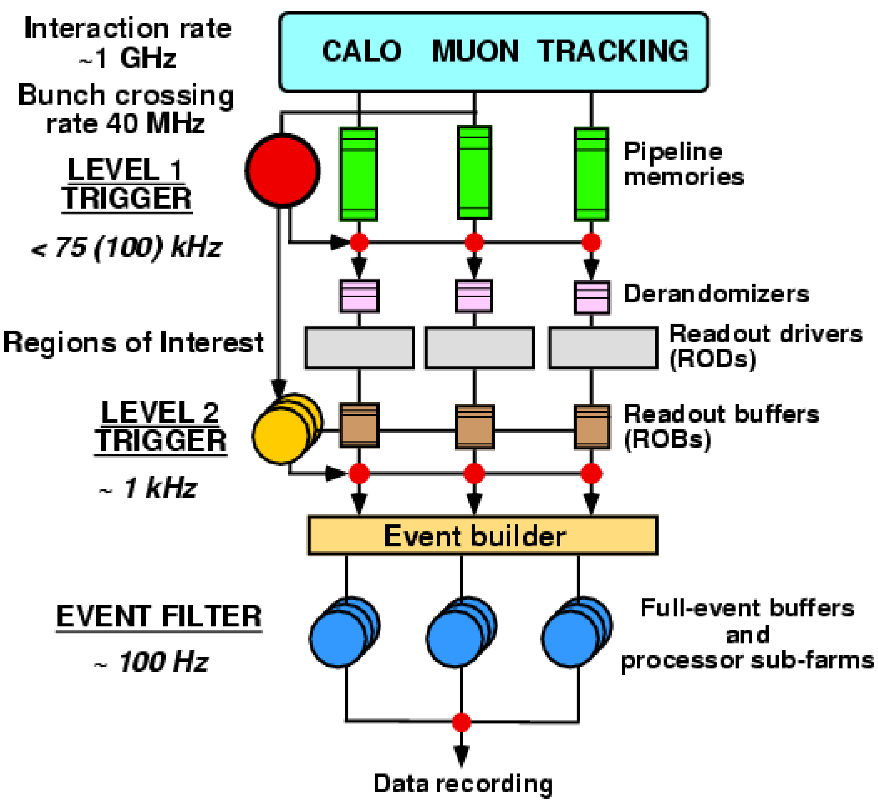




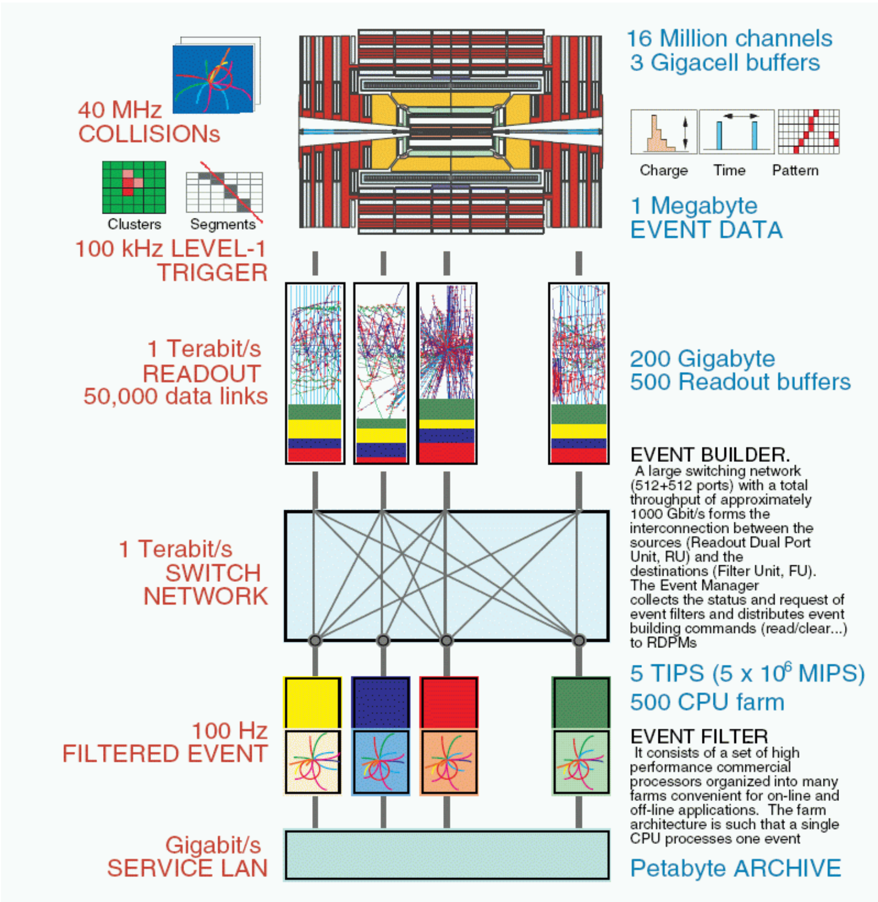
Tracker	Silicon Pixel and Strips, TRD	Silicon Pixel and Strips
Momentum	2 Tesla Solenoid	4 Tesla Solenoid
ECAL	Lead/LAr	Lead-Tungstate crystals
HCAL	Lead/Scintillator (central)	Stainless steel/Scintillaor
	Copper+Tungsten/LAr (forward)	or Copper/Scintillator
Muons	Large Air-core toroid	Instrumented return yoke
	MDT, RPC, CST, TGC	DT, RPC & CST

Trigger & DAQ

ATLAS

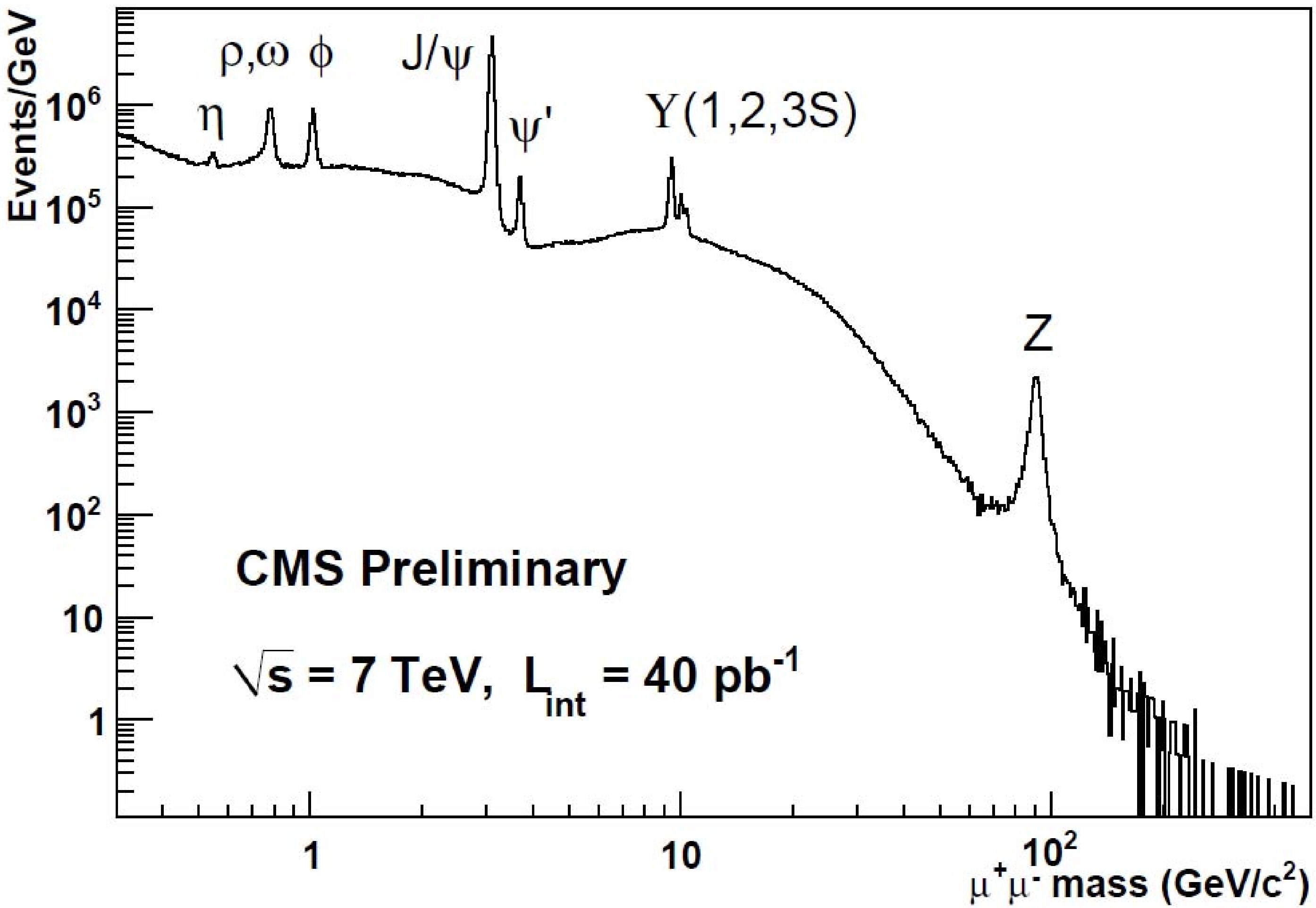


CMS

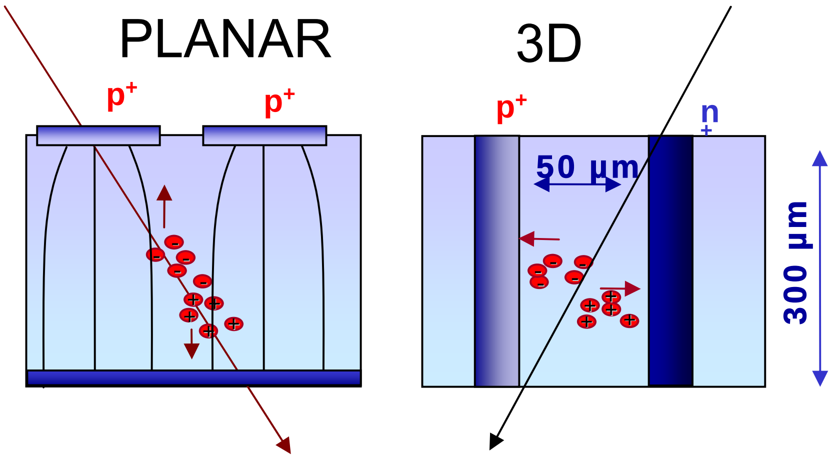


If all works well you finally get things like this …..

Invariant mass of moun pairs measured by CMS data from 2010



Into the future – 3D Silicon Sensors

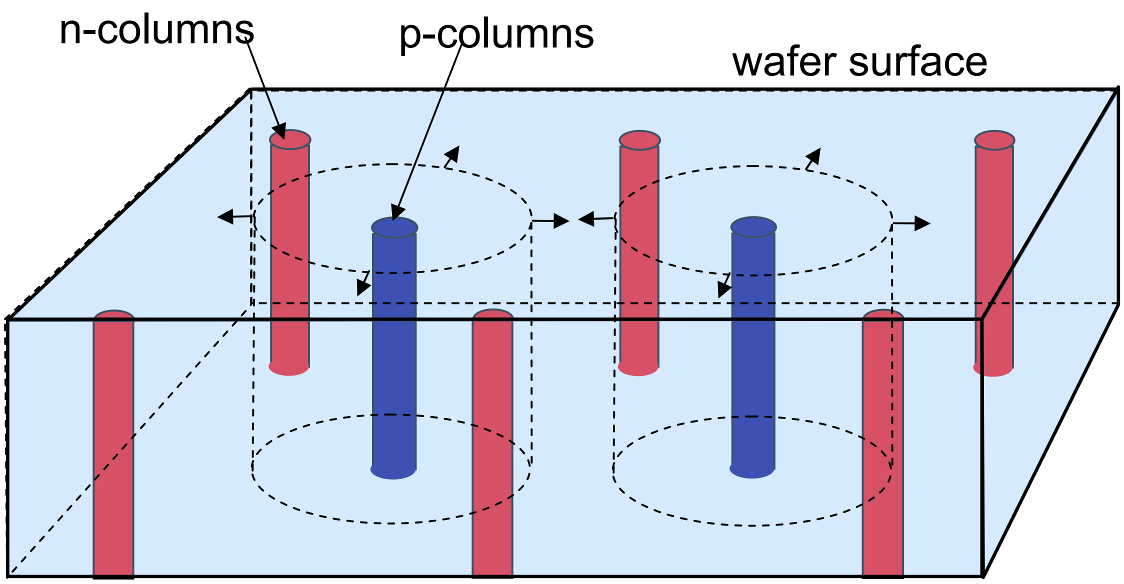


"3D" electrodes:

narrow columns along detector thickness,
diameter: 10 µm,
distance: 50 – 100 µm

Lateral depletion:

lower depletion voltage needed
thicker detectors possible
fast signal
radiation hard

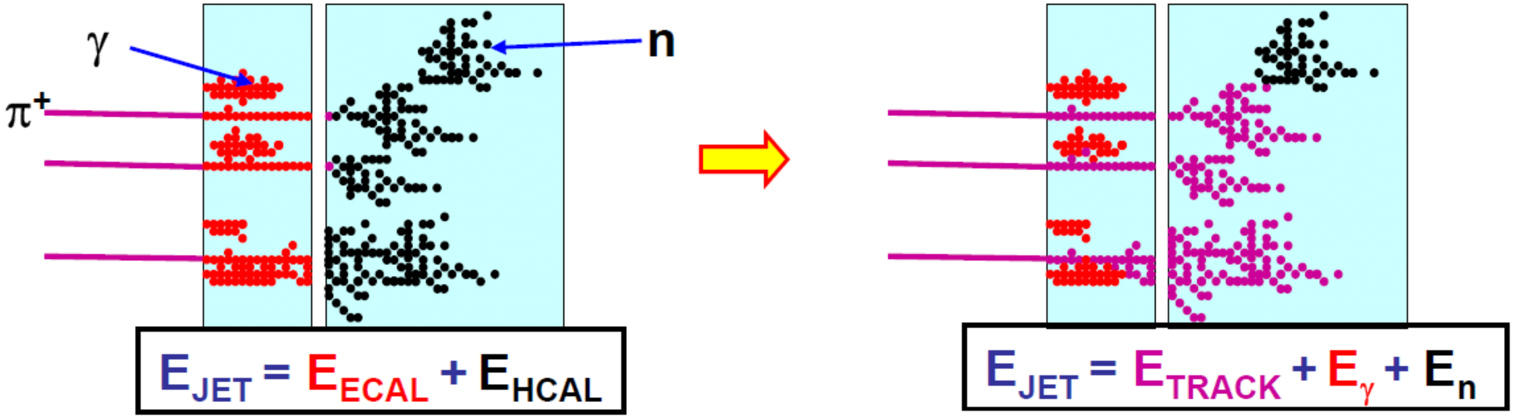


Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

Into the future – Particle Flow

- **In a typical jet :**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)

- **Traditional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL !
  - ~70 % of energy measured in HCAL: $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically “poor” HCAL resolution limits jet energy resolution

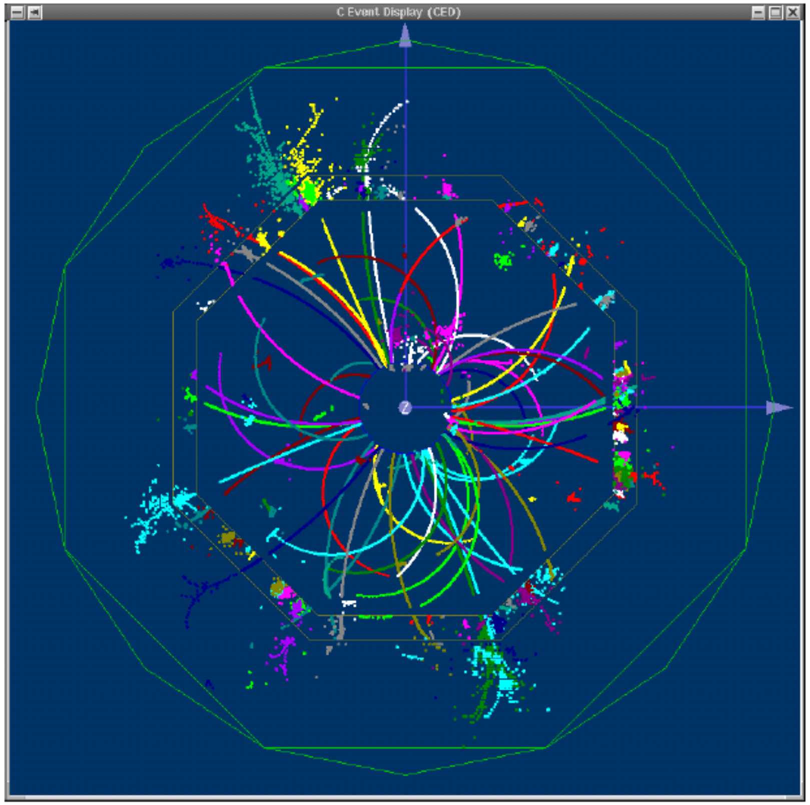


- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⟹ much improved resolution

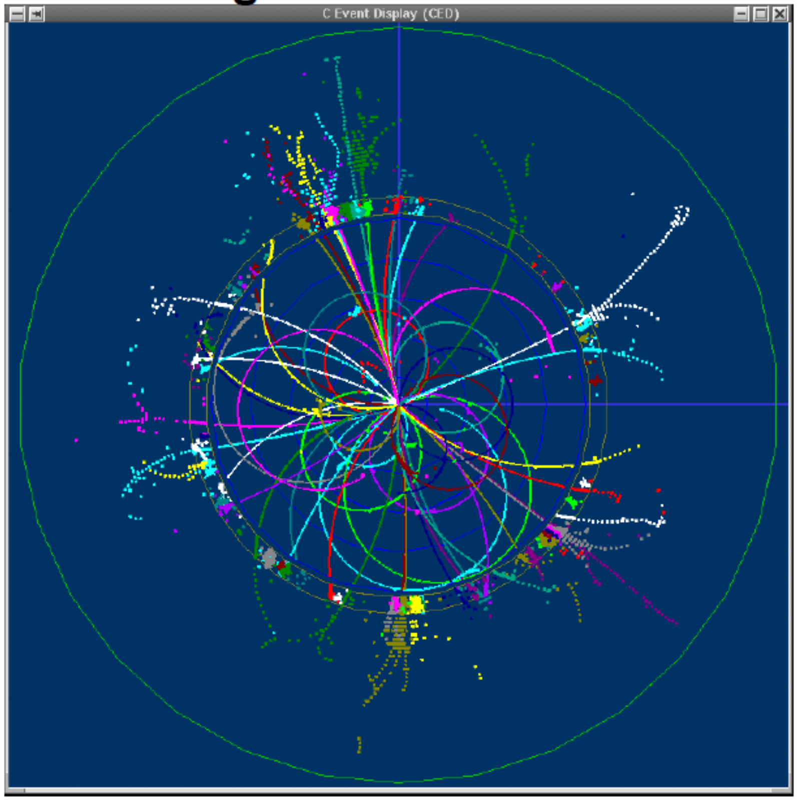
Detectors for particle flow

High granular ECAL and HCAL
Calorimetry inside a large coil
ECAL : SiW, lateral segmentation : $1cm^2$, $24X_0$, $0.9\lambda_{had}$
‘tracking calorimeters’

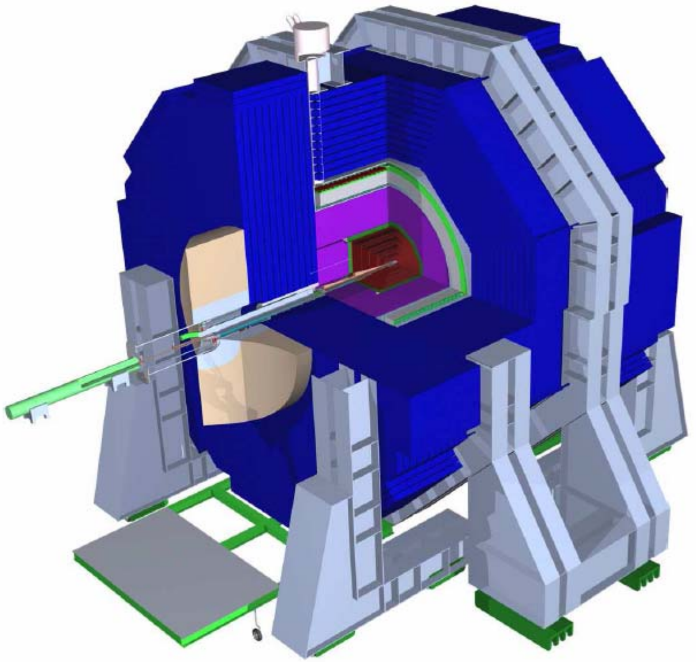
e.g. tt event in LDC



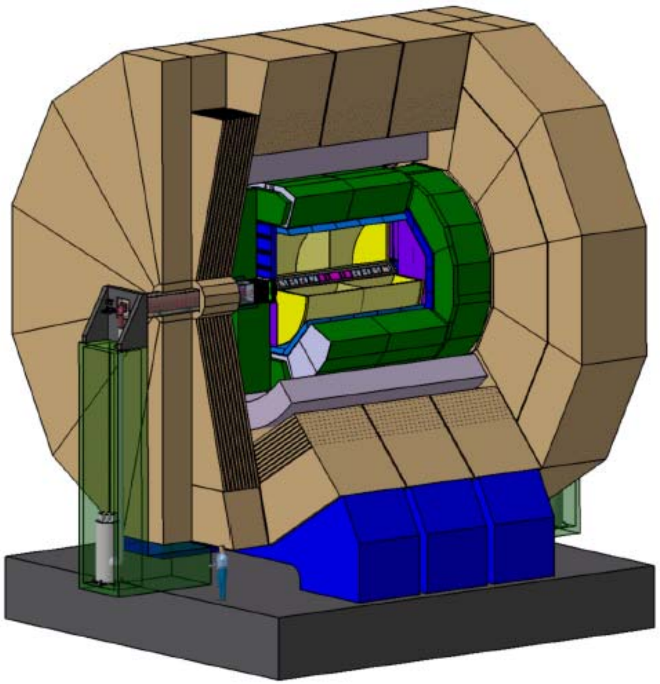
e.g. tt event in SiD

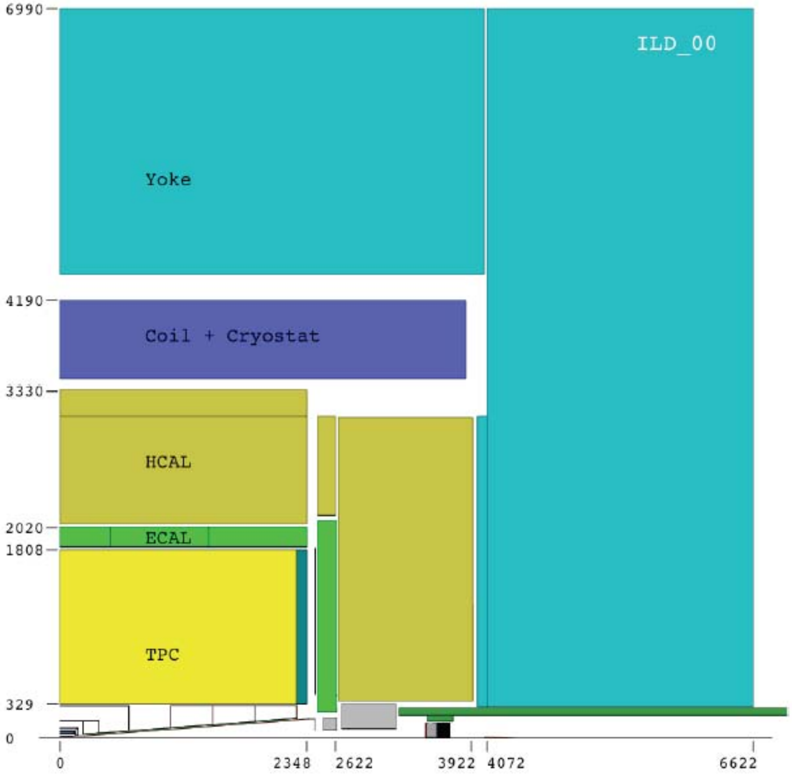


SiD – Detector Design Study for a future Linear Collider



ILD – Detector Design Study for a future Linear Collider





References & Thanks

- books

  - **C.Grupen** *Particle Detectors,* Cambridge UP 22008, 680p
  - **K.Kleinknecht** *Detectors for particle radiation,* Cambridge UP, 21998
  - **D.Green (ed)** *At the leading edge, The ATLAS and CMS LHC Experiments,* World Scientific 2010

- web

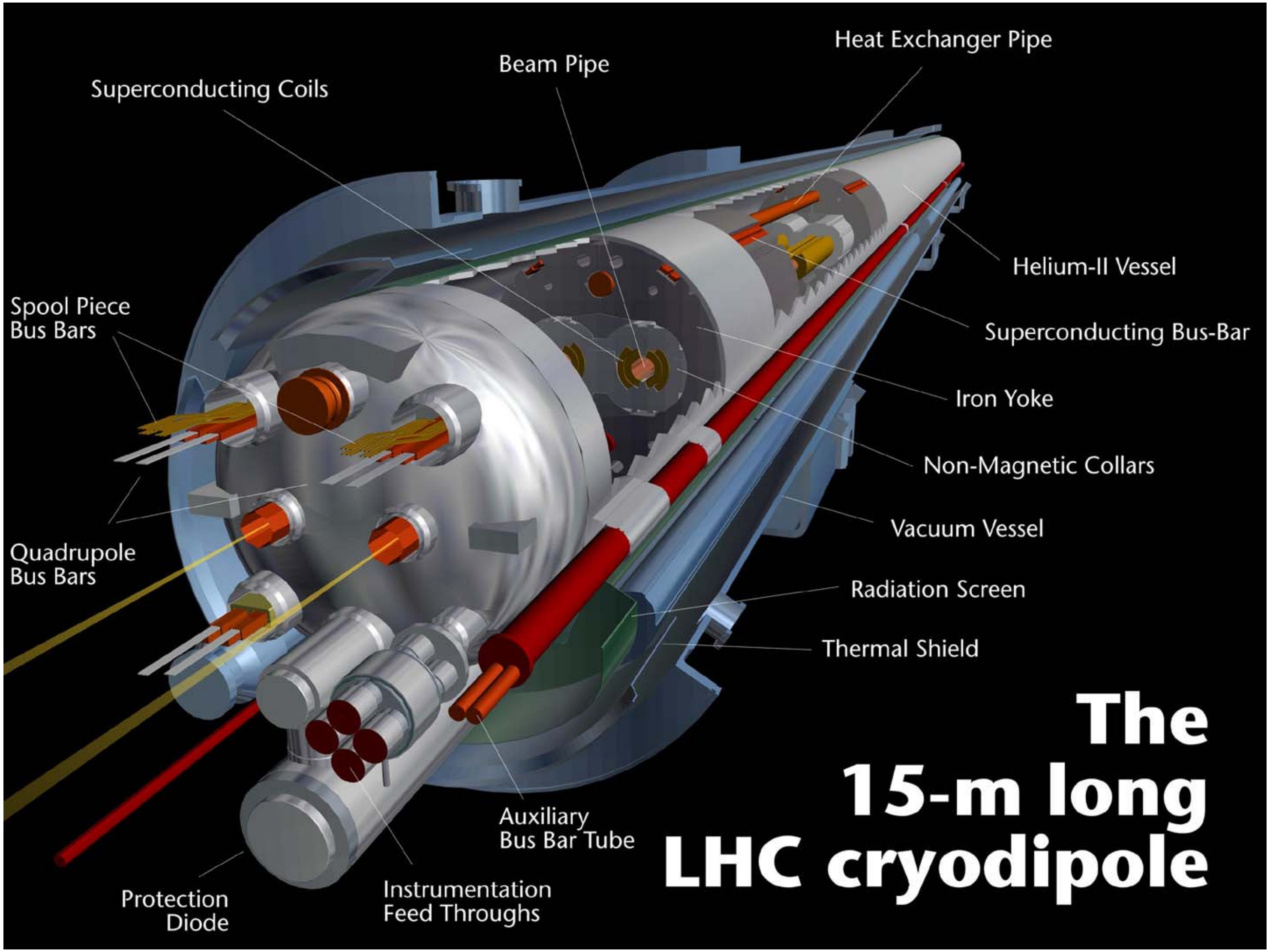
  - **Particle Data Group:** *Review of Particle Properties: pdg.lbl.gov*
  - **ATLAS** ATLAS Detector : atlas.ch/detector.html
  - **CMS** CMS Detector : cms.web.cern.ch/cms/Detector/index.html

- **Thanks for material and ideas from lectures of**

  - **D. Pitzl** Detectors for Particle Physics, DESY Summer students Lecture 2010
  - **T. Schoerner-Sadenius** Physics at the LHC, Graduate School Workshop, Black Forest 2010
  - **M Thomson** Particle Flow Calorimety and PandoraPDF, DESY 2008

Additional material

The LHC – bending 7 TeV protons



1200 dipoles

Avalanche Photodiode

85% quantum efficiency

300-400 V reverse bias:

- photoelectrons create cascade of electron-hole pairs in the bulk.
- Gain ~100 in linear mode.

Low sensitivity to magnetic field.

APD gain decreases by 2.3%/^{O}C.

Crystal light yield decreases by 2.2%/^{O}C

Need temperature stabilization within 0.1^{O}C in the ECAL!

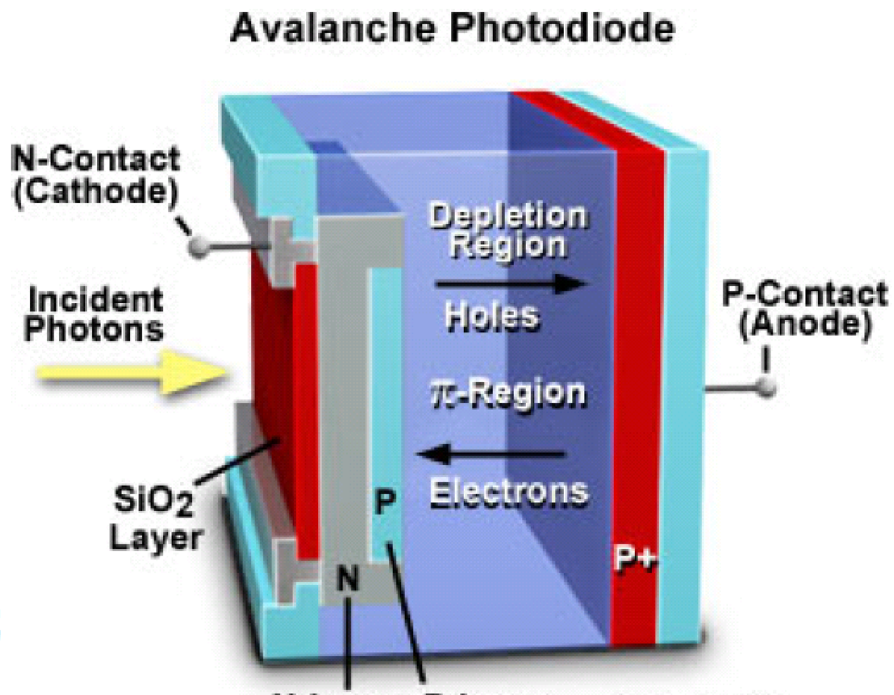
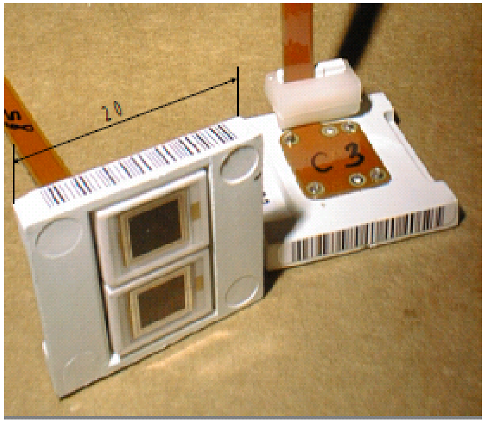


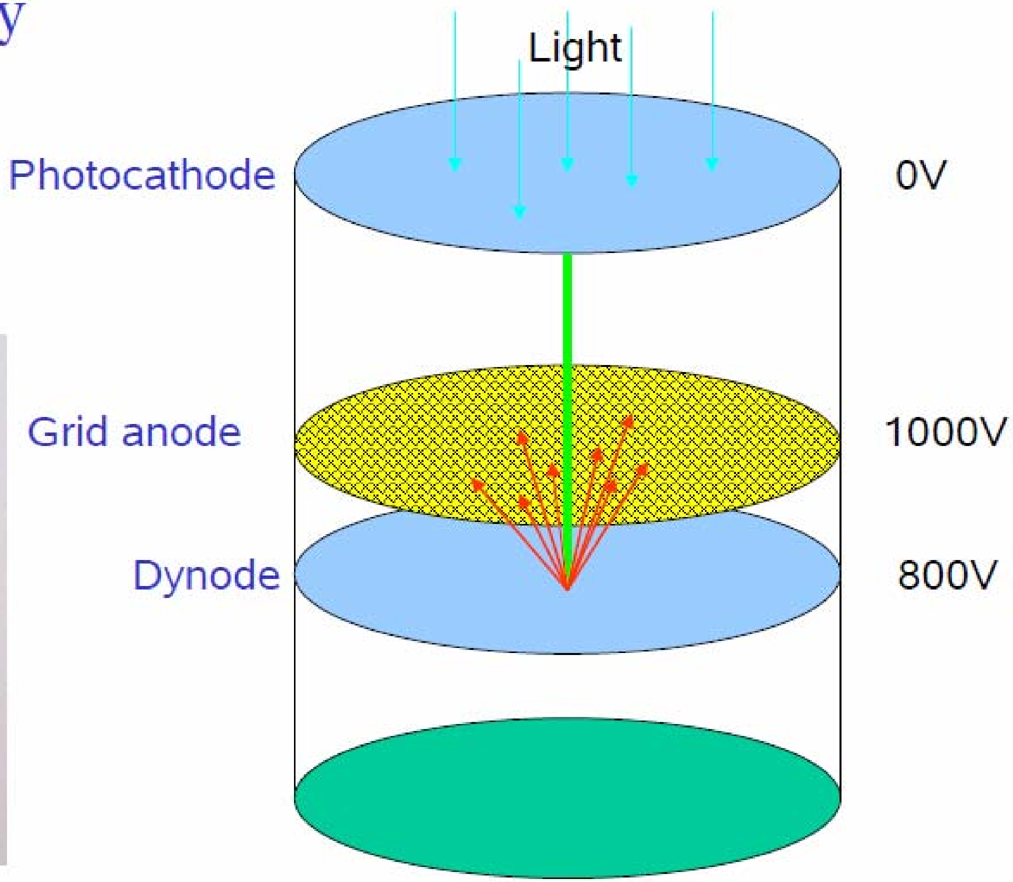
Figure 1

2 avalanche photodiodes per crystal in the barrel:



Vacuum photo-triodes

- ~20% quantum efficiency
- Single-stage photomultiplier
- Gain ~ 10 at B = 4 T



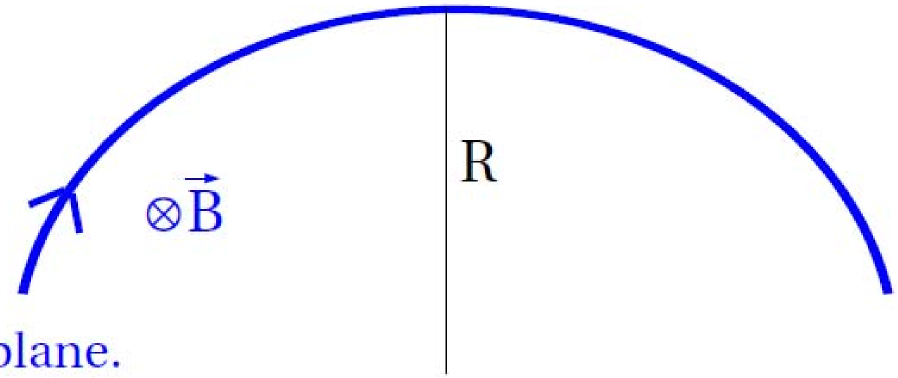
radiation-resistant UV glass window

used in the CMS endcap ECAL.

Charged particles in a magnetic field

Lorentz Force:

$$\vec{F}_L = q\,\vec{v} \times \vec{B}$$



For B = constant:
circular motion in the transverse plane.
Equation of motion:
Lorentz force balanced by centrifugal force: $q\,v_t\,B = m\,v_t^2 / R$

$$p_t = m\,v_t \qquad \Rightarrow \boxed{p_t = qRB}$$

also holds relativistically.

$$\boxed{cp_t\,[GeV] = 0.3\,R\,[m]\,B\,[T]}$$

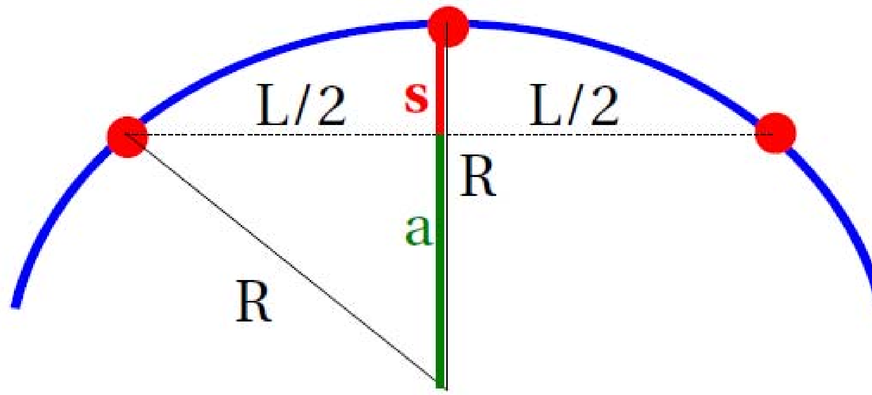
for q = e

CMS: B = 4 T

p_t [GeV/c]	R [m]
100	83.33
10	8.33
1	0.83

Low p_t tracks curl up
inside the tracker: 2R<L

Sagitta measurement



1. Pythagoras: $a^2 + L^2/4 = R^2$

$$\Rightarrow a = R\sqrt{1 - L^2/4R^2}$$

Taylor: $\sqrt{1-x} \approx 1 - x/2$

$$\Rightarrow a \approx R\,(1 - L^2/8R^2)$$

2. Sagitta: $s = R - a$, insert a

$$\Rightarrow \boxed{s = L^2/8R}$$

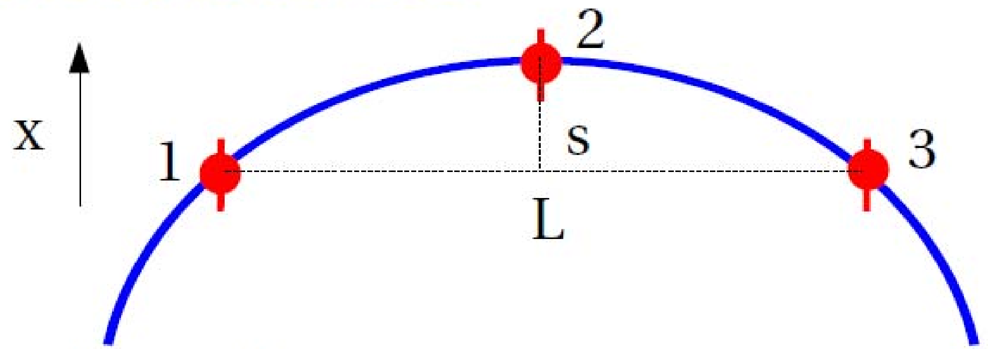
$$\Rightarrow p_t = qBL^2/8s$$

CMS: B = 4 T, L = 1 m

P_t [GeV/c]	s [**cm**]
100	0.15
10	1.50
1	15.00

Momentum resolution

Sagitta: $s = x_2 - \frac{x_1 + x_3}{2}$



Error propagation: $\sigma_s^2 = \sigma_2^2 + \sigma_1^2/4 + \sigma_3^2/4$ (usually Gaussian)

All σ equal: $\sigma_s = \sqrt{3/2}\,\sigma_x$ $\quad p_t = qBL^2/8s$

$\Rightarrow \sigma_{p_t}/p_t = \sigma_s/s = \sqrt{96}\,\sigma_x\,p_t/qBL^2$ (always non-Gaussian)

N equidistant measurements: $\sigma_{p_t}/p_t = \sqrt{720/(N+4)}\,\sigma_x\,p_t/qBL^2$

(Glückstern 1964)

Note: $\sigma_{p_t}/p_t \sim p_t$ worse resolution at high p_t.

$\sigma_{p_t}/p_t \sim \sigma_x/BL^2$ want large, precise tracker, strong field.

Drift and charge collection

Drift in a magnetic field occurs at the Lorentz angle:

Systematic shift of charges must be taken into account.

Position resolution is worse for inclined tracks:

avoid by proper detector design: barrel cylinders and endcap disks.