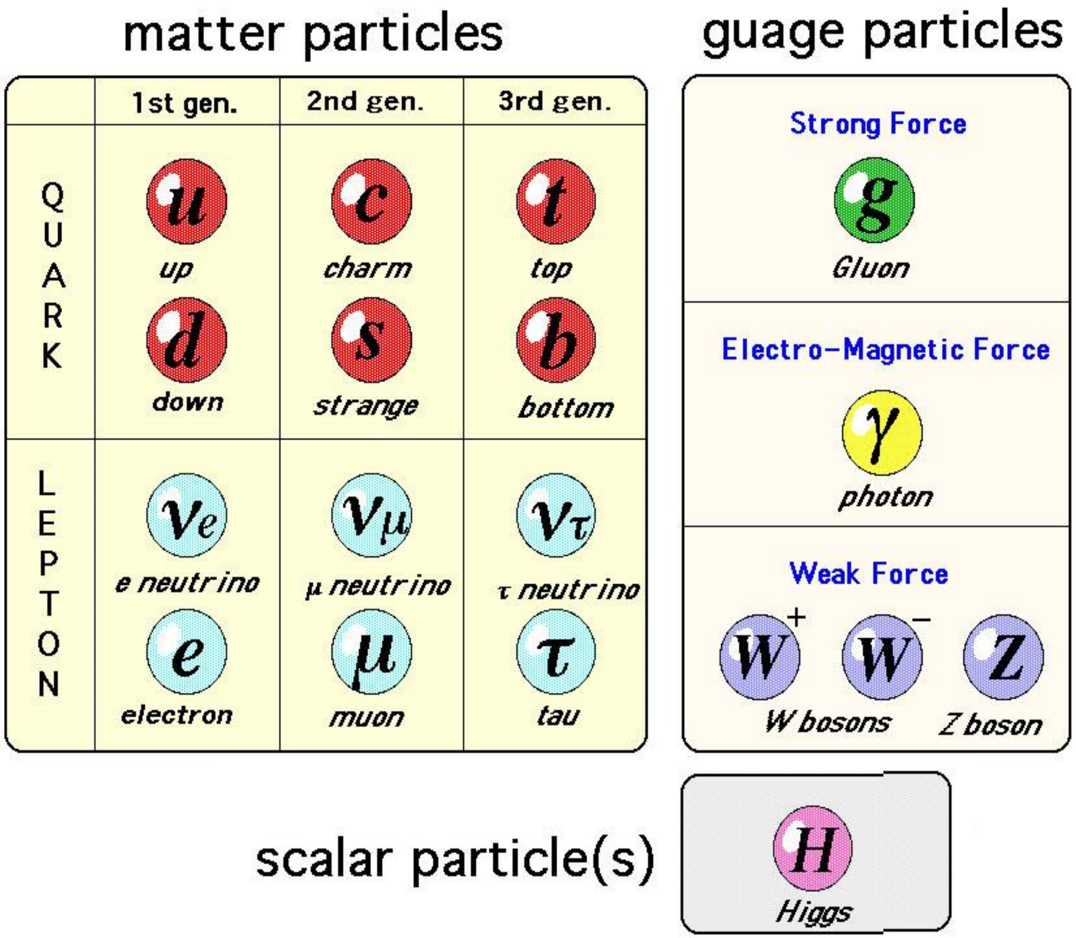
oPAC Workshop

June 26-27 2013, CERN

Trends in Particle Detectors

W. Riegler, CERN

Standardmodel



Quarks are not seen as free particles but they form Mesons and Baryons seen as jets in high energy collisions.

A selection of particles listed by the particle data group.

How can we tell them apart in our detector ?!

http://pdg.lbl.gov ~ 180 Selected Particles

γ, $W^\pm$, Z^0, g, e, μ, τ, ν_e, ν_μ, ν_τ, $\pi^\pm$, π^0, η, $f_0(600)$, $\rho(770)$,
$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,
$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,
$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,
$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,
$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,
$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^\pm$, K^0, K^0_S, K^0_L, $K^*(892)$,
$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,
$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^\pm$, D^0, $D^*(2007)^0$,
$D^*(2010)^\pm$, $D_1(2420)^0$, $D_2^*(2460)^0$, $D_2^*(2460)^\pm$, $D_s^\pm$, $D_s^{*\pm}$,
$D_{s1}(2536)^\pm$, $D_{sJ}(2573)^\pm$, $B^\pm$, B^0, B^*, B_s^0, $B_c^\pm$, $\eta_c(1S)$, $J/\psi(1S)$,
$\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$,
$\psi(4415)$, $\Upsilon(1S)$, $\chi_{b0}(1P)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\Upsilon(2S)$, $\chi_{b0}(2P)$,
$\chi_{b2}(2P)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$, p, n, $N(1440)$,
$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,
$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,
$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,
$\Delta(2420)$, Λ, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$,
$\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$,
$\Lambda(2110)$, $\Lambda(2350)$, Σ^+, Σ^0, Σ^-, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$,
$\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, Ξ^0, Ξ^-,
$\Xi(1530)$, $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$, $\Xi(2030)$, Ω^-, $\Omega(2250)^-$,
Λ_c^+, Λ_c^+, $\Sigma_c(2455)$, $\Sigma_c(2520)$, Ξ_c^+, Ξ_c^0, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2790)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are many more

Out of the hundreds of known particles, these are the only ones that have a lifetime long enough to produce a track of >1um before they decay (at GeV Level).

Some of them decay after flying only a few hundred um.

Others traverse the entire detector.

All Particles with $c\tau > 1\mu m$ @ GeV Level

Particle	Mass (MeV)	Lifetime τ (s)	$c\tau$
γ	0	∞	∞
$\pi^\pm (u\bar{d}, d\bar{u})$	140	$2.6 \cdot 10^{-8}$	7.8 m
$K^\pm (u\bar{s}, \bar{u}s)$	494	$1.2 \cdot 10^{-8}$	3.7 m
$K^0 (d\bar{s}, \bar{d}s)$	497	$5.1 \cdot 10^{-8}$ $8.9 \cdot 10^{-11}$	15.5 m 2.7 cm
$D^\pm (c\bar{d}, \bar{c}d)$	1869	$1.0 \cdot 10^{-12}$	315 μm
$D^0 (c\bar{u}, u\bar{c})$	1864	$4.1 \cdot 10^{-13}$	123 μm
$D_s^\pm (c\bar{s}, \bar{c}s)$	1969	$4.9 \cdot 10^{-13}$	147 μm
$B^\pm (u\bar{b}, \bar{b}u)$	5279	$1.7 \cdot 10^{-12}$	502 μm
$B^0 (b\bar{d}, d\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 μm
$B_s^0 (s\bar{b}, \bar{s}b)$	5370	$1.5 \cdot 10^{-12}$	438 μm
$B_c^\pm (c\bar{b}, \bar{c}b)$	~6400	$\sim 5 \cdot 10^{-13}$	150 μm
$p (uud)$	938.3	$> 10^{33}$ y	∞
$n (udd)$	939.6	885.7 s	$2.655 \cdot 10^8$ km
$\Lambda^0 (uds)$	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm
$\Sigma^+ (uus)$	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm
$\Sigma^- (dds)$	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm
$\Xi^0 (uss)$	1315	$2.9 \cdot 10^{-10}$	8.71 cm
$\Xi^- (dss)$	1321	$1.6 \cdot 10^{-10}$	4.91 cm
$\Omega^- (sss)$	1672	$8.2 \cdot 10^{-11}$	2.461 cm
$\Lambda_c^+ (udc)$	2285	$\sim 2 \cdot 10^{-13}$	60 μm
$\Xi_c^+ (usc)$	2466	$4.4 \cdot 10^{-13}$	132 μm
$\Xi_c^0 (dcs)$	2472	$\sim 1 \cdot 10^{-13}$	29 μm
$\Omega_c^0 (ssc)$	2698	$6.0 \cdot 10^{-14}$	19 μm
$\Lambda_b (udb)$	5620	$1.2 \cdot 10^{-12}$	368 μm

"Secondary Vertices" ($D^\pm$ through $B_c^\pm$)

From the 'hundreds' of Particles listed by the PDG there are only ~27 with a life time $c\tau >\sim 1\mu m$ i.e. they can be seen as 'tracks' in a Detector.

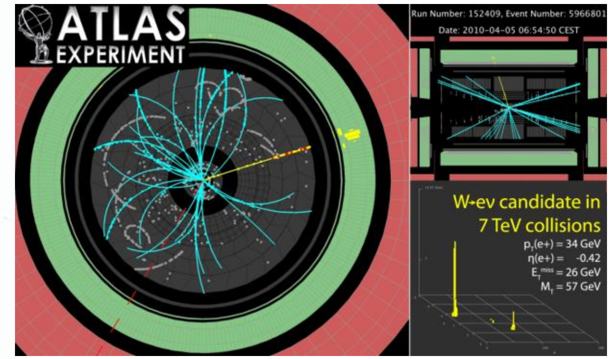
~13 of the 27 have $c\tau < 500\mu m$ i.e. only ~mm range at GeV Energies.
→ "short" tracks measured with Emulsions or Vertex Detectors.

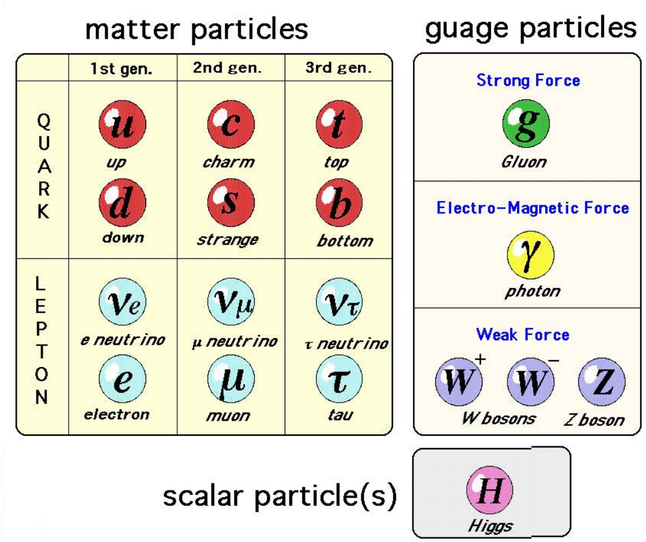
From the ~14 remaining particles

$$e^\pm, \mu^\pm, \gamma, \pi^\pm, K^\pm, K^0, p^\pm, n$$

are by far the most frequent ones

A particle Detector must be able to identify and measure Energy and Momenta of these 8 particles.

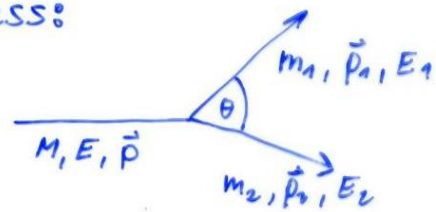




Basics

Invariant Mass:

LAB:



Relativity: $\tilde{a} = \begin{pmatrix} a_0 \\ \vec{a} \end{pmatrix}$ $\tilde{b} = \begin{pmatrix} b_0 \\ \vec{b} \end{pmatrix}$ $\tilde{a}\tilde{b} = a_0 b_0 - \vec{a}\vec{b}$

$$E = mc^2\gamma \ , \ \vec{p} = m\vec{v}\gamma$$

$$\tilde{p} = \begin{pmatrix} \frac{E}{c} \\ \vec{p} \end{pmatrix} , \ \tilde{p}_1 = \begin{pmatrix} \frac{E_1}{c} \\ \vec{p}_1 \end{pmatrix} , \ \tilde{p}_2 = \begin{pmatrix} \frac{E_2}{c} \\ \vec{p}_2 \end{pmatrix}$$

$\tilde{p} = \tilde{p}_1 + \tilde{p}_2$ Energy + Momentum Conservation

$$\tilde{p}^2 = (\tilde{p}_1 + \tilde{p}_2)^2 \rightarrow \tilde{p}\tilde{p} = \tilde{p}_1\tilde{p}_1 + \tilde{p}_2\tilde{p}_2 + 2\tilde{p}_1\tilde{p}_2$$

$$M^2c^2 = m_1^2c^2 + m_2^2c^2 + 2\left(\frac{E_1E_2}{c^2} - p_1p_2\cos\theta\right)$$

- Measuring Momenta and Energies OR
- Measuring Momenta and identifying Particles

gives the Mass of the original Particle

The Mass of the original particle is determined by the decay particle's 4 momenta through relativistic kinematics.

/CERN

Basics

Lorentz Boost:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad \tau = 2.2 \cdot 10^{-6}\,s$$

E.g. Produced by Cosmic Rays (p, He, Li ...) colliding with air in the upper Atmosphere ~10 km

$$s = v \cdot \tau \sim c \cdot \tau = 660\,m$$

But we see Muons here on Earth

$$E_\mu \sim 2\,GeV, \; m_\mu c^2 = 105\,MeV \rightarrow \gamma \sim 19$$

Relativity: $\bar{\tau} = \tau \cdot \gamma$

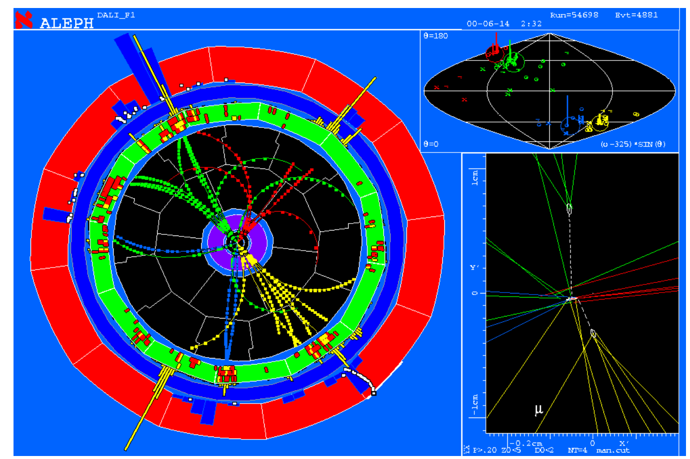
$$s = c \cdot \bar{\tau} = 12.5\,km \rightarrow \text{Earth}$$

Pions: π^+, π^- $\quad \tau \sim 2.6 \cdot 10^{-8}\,s, \; m_\pi c^2 = 135\,MeV$

$$2\,GeV \rightarrow s = 115\,m$$

Pions where discovered in Emulsions exposed to Cosmic Rays on high Mountains.

Displaced vertices from short lived particles like tau, B, D mesons are 'boosted, prolonged' by the particle's Lorentz factor.



Particles 'seen' by a detector:

Particle	Mass		Interaction
$e^{\pm}$	$m_e = 0.511\ \mathrm{MeV}$		EM
$\mu^{\pm}$	$m_\mu = 105.7\ \mathrm{MeV} \sim 200\, m_e$		EM
γ	$m_\gamma = 0$, $Q = 0$		EM
$\pi^{\pm}$	$m_\pi = 139.6\ \mathrm{MeV} \sim 270\, m_e$		EM, Strong
$K^{\pm}$	$m_K = 493.7\ \mathrm{MeV} \sim 1000\, m_e$	$\sim 3.5\, m_\pi$	EM, Strong
$p^{\pm}$	$m_p = 938.3\ \mathrm{MeV} \sim 2000\, m_e$		EM, Strong
K^0	$m_{K^0} = 497.7\ \mathrm{MeV}$	$Q = 0$	Strong
n	$m_n = 939.6\ \mathrm{MeV}$	$Q = 0$	Strong

The Difference in

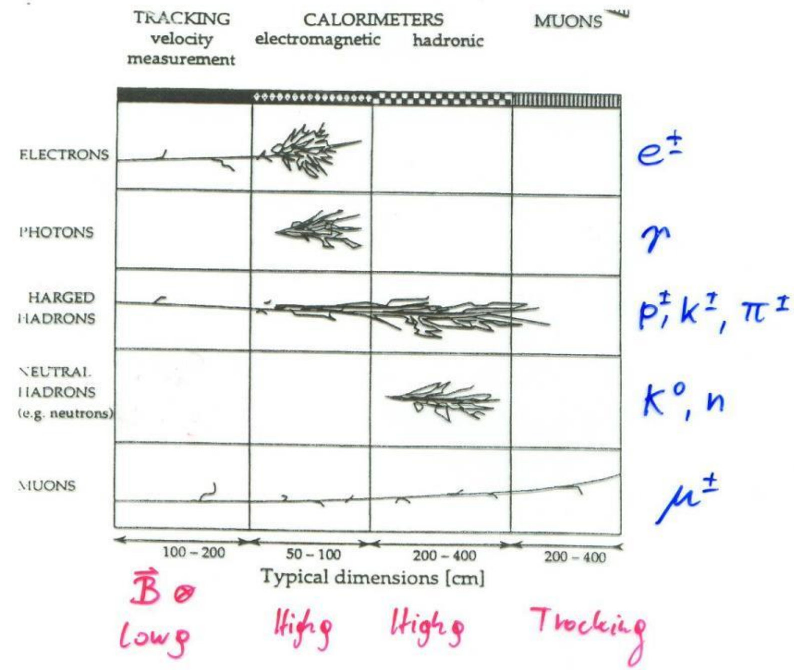
Mass, Charge, Interaction

is the key to the Identification

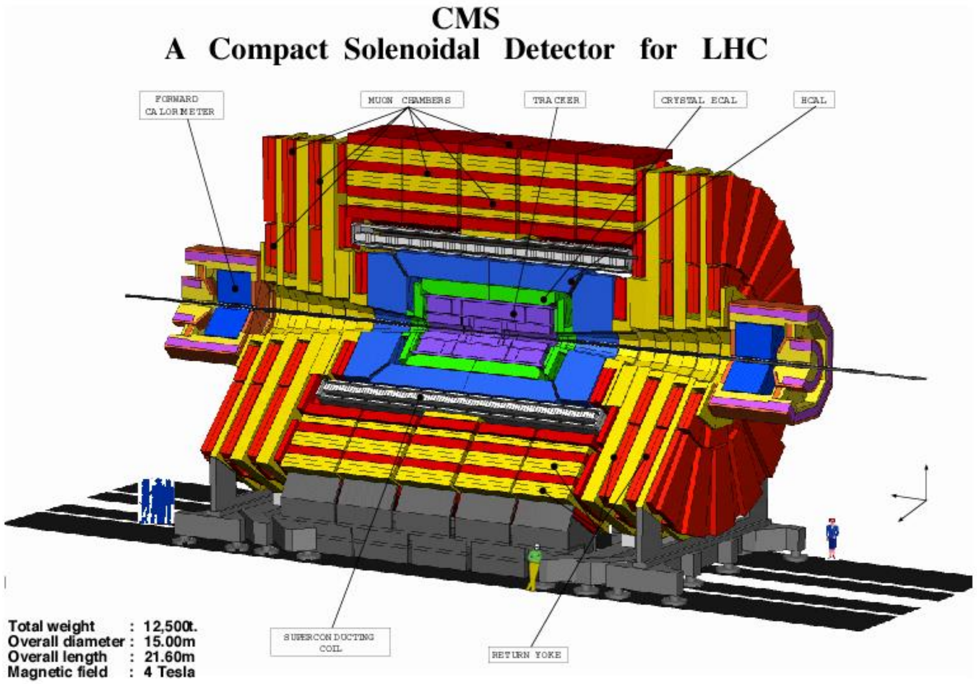
Tracking:
Momentum by bending in the B-field
Secondary vertices

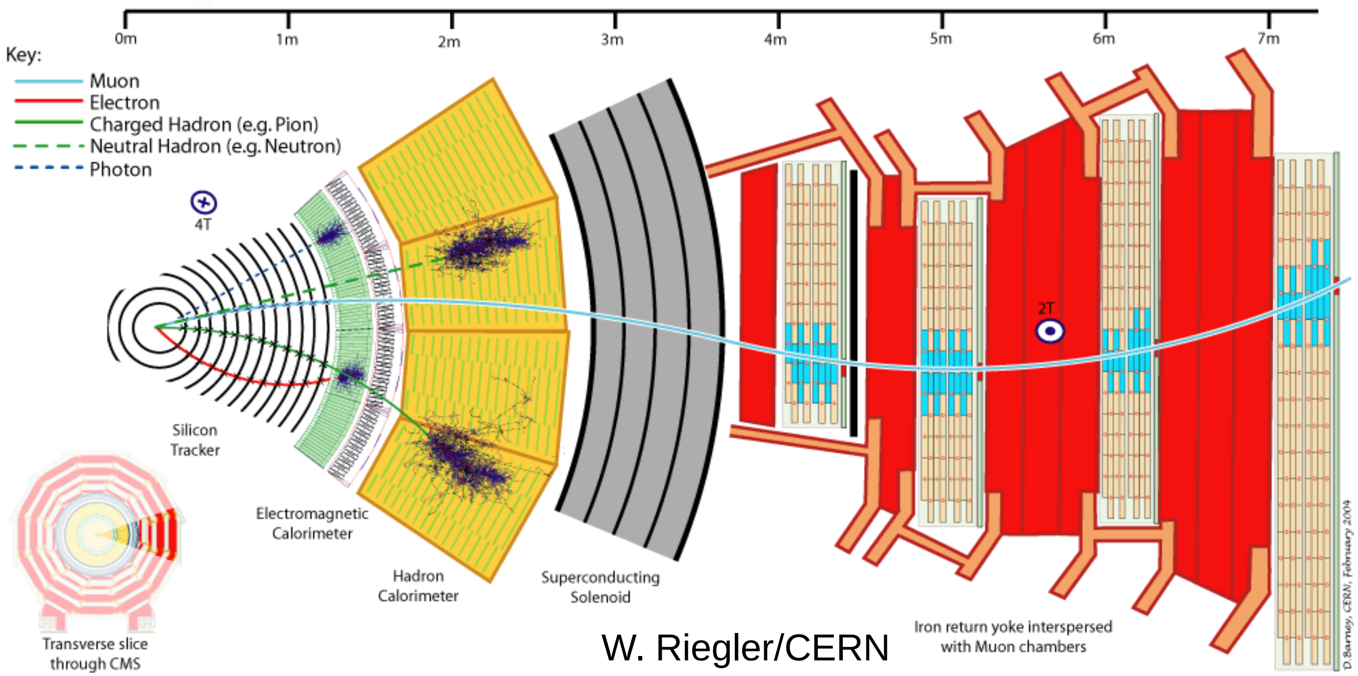
Calorimeter:
Energy by absorption

Muons:
Only particles passing through calorimeters

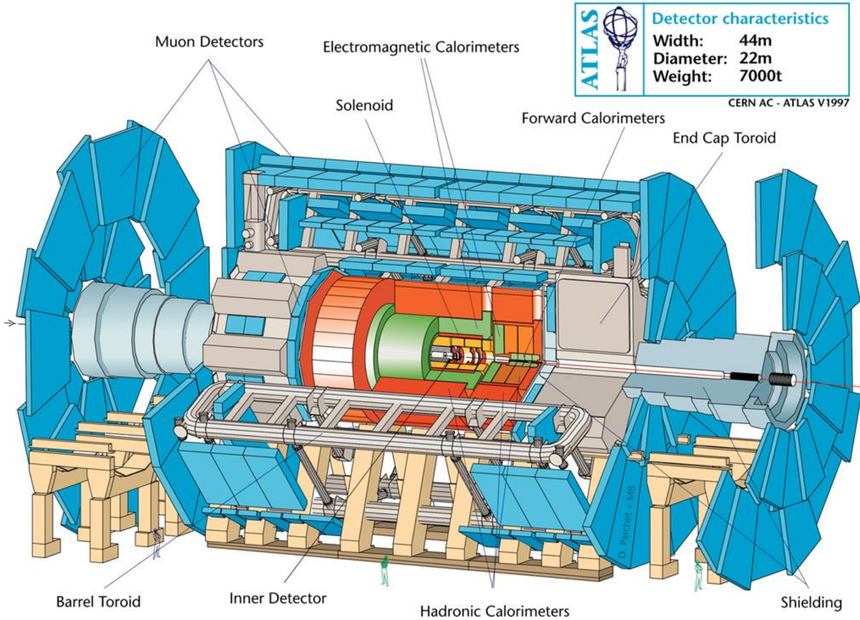


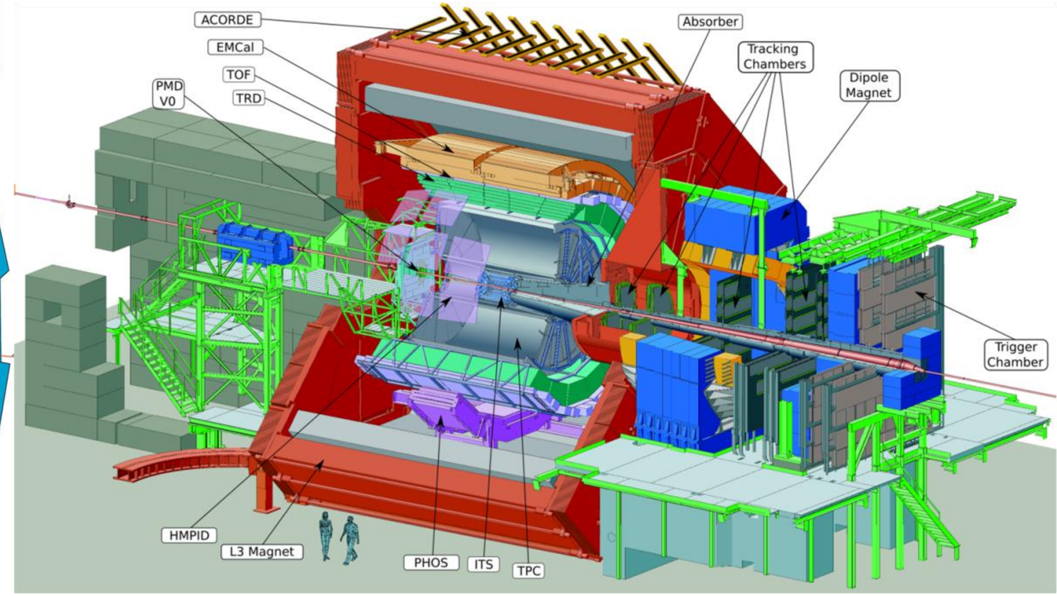
- Electrons ionize and show Bremsstrahlung due to the small mass
- Photons don't ionize but show Pair Production in high Z Material. From then on equal to $e^\pm$
- Charged Hadrons ionize and show Hadron Shower in dense material.
- Neutral Hadrons don't ionize and show Hadron Shower in dense Material
- Myons ionize and don't shower

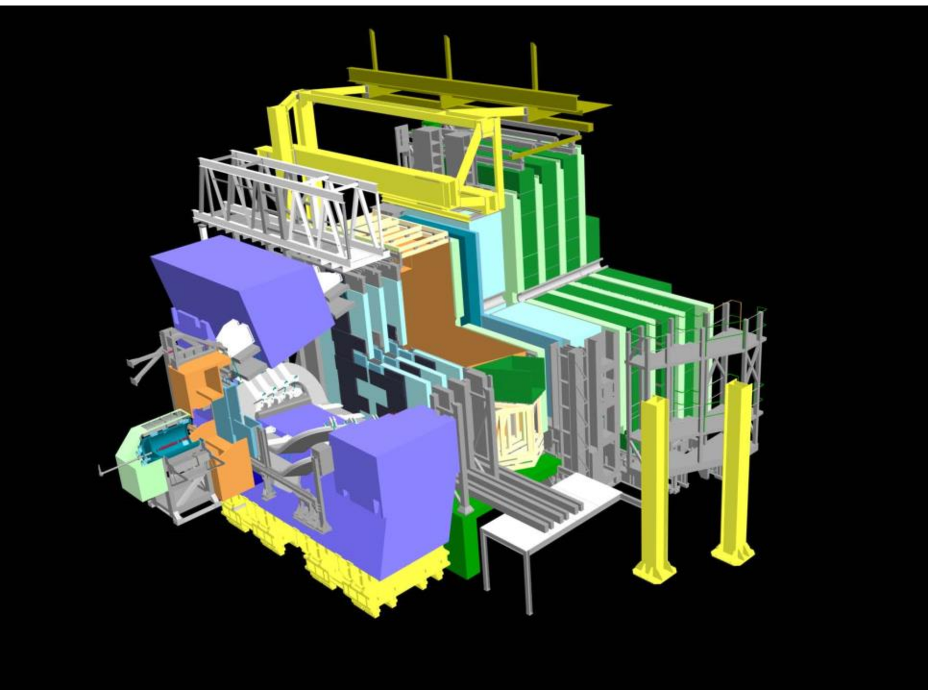


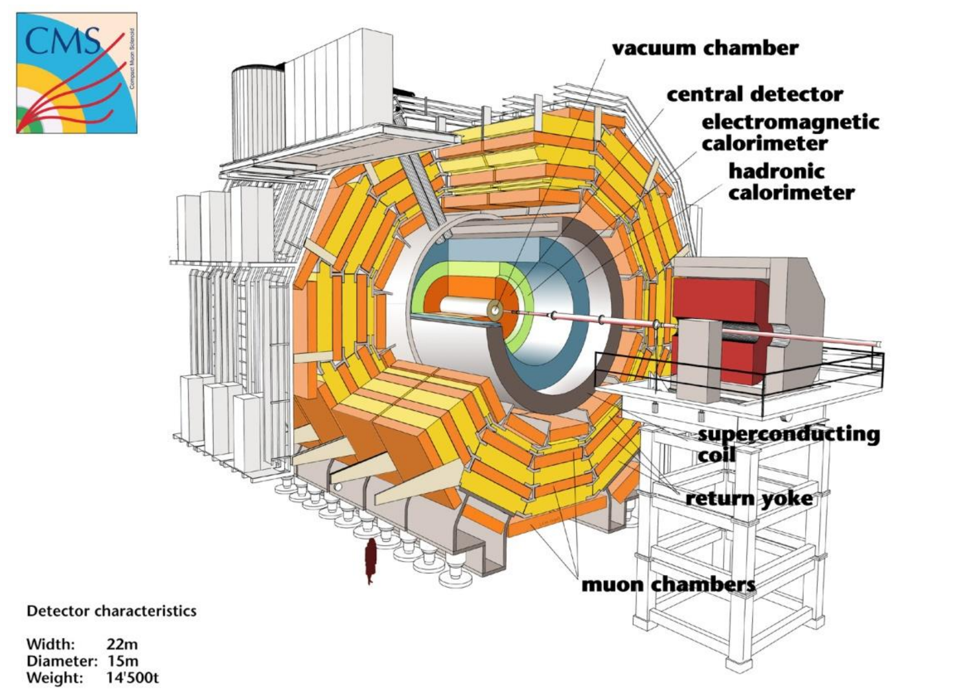


W. Riegler/CERN


Detector characteristics
ATLAS
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

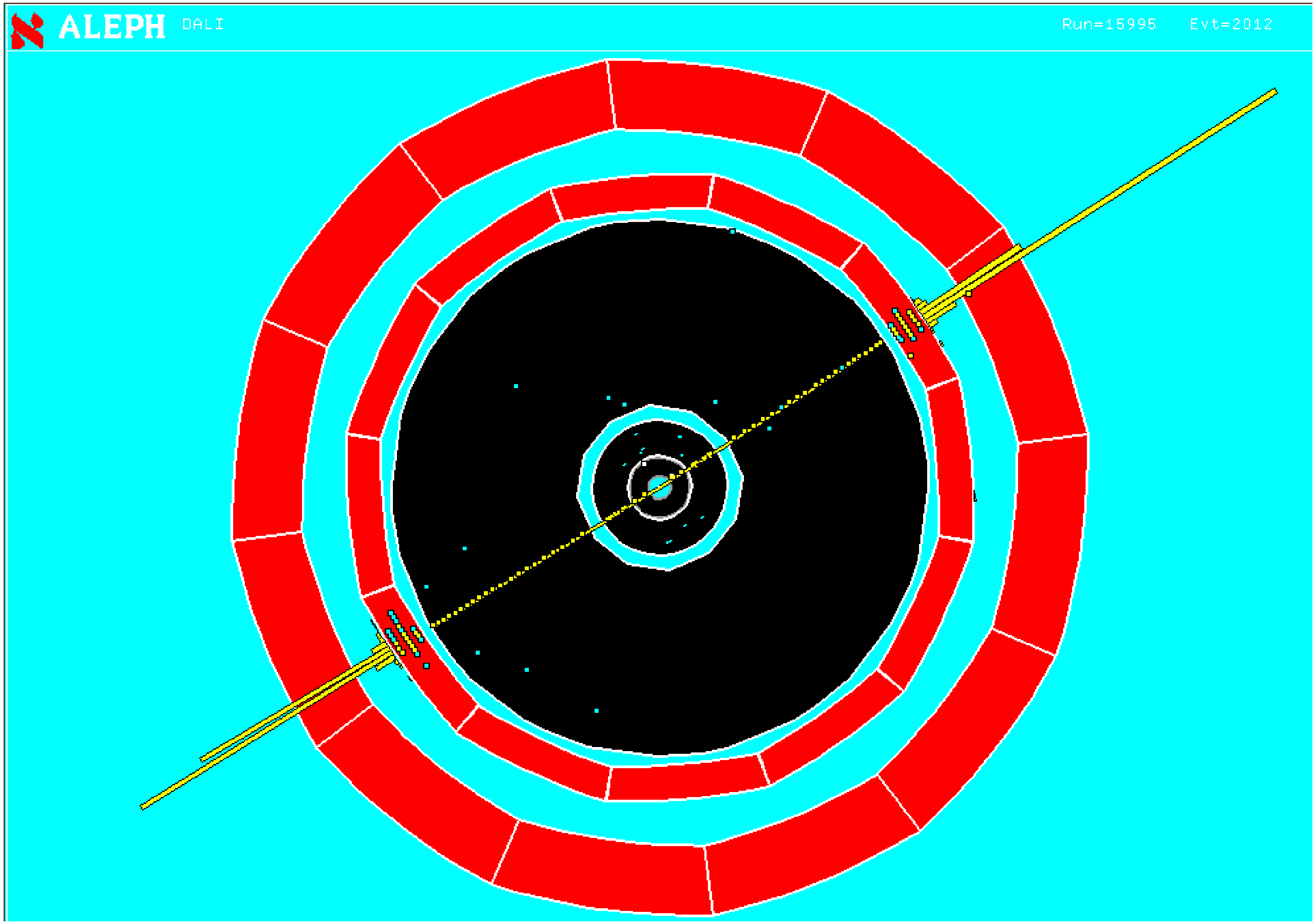

ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC




CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics
Width: 22m
Diameter: 15m
Weight: 14'500t

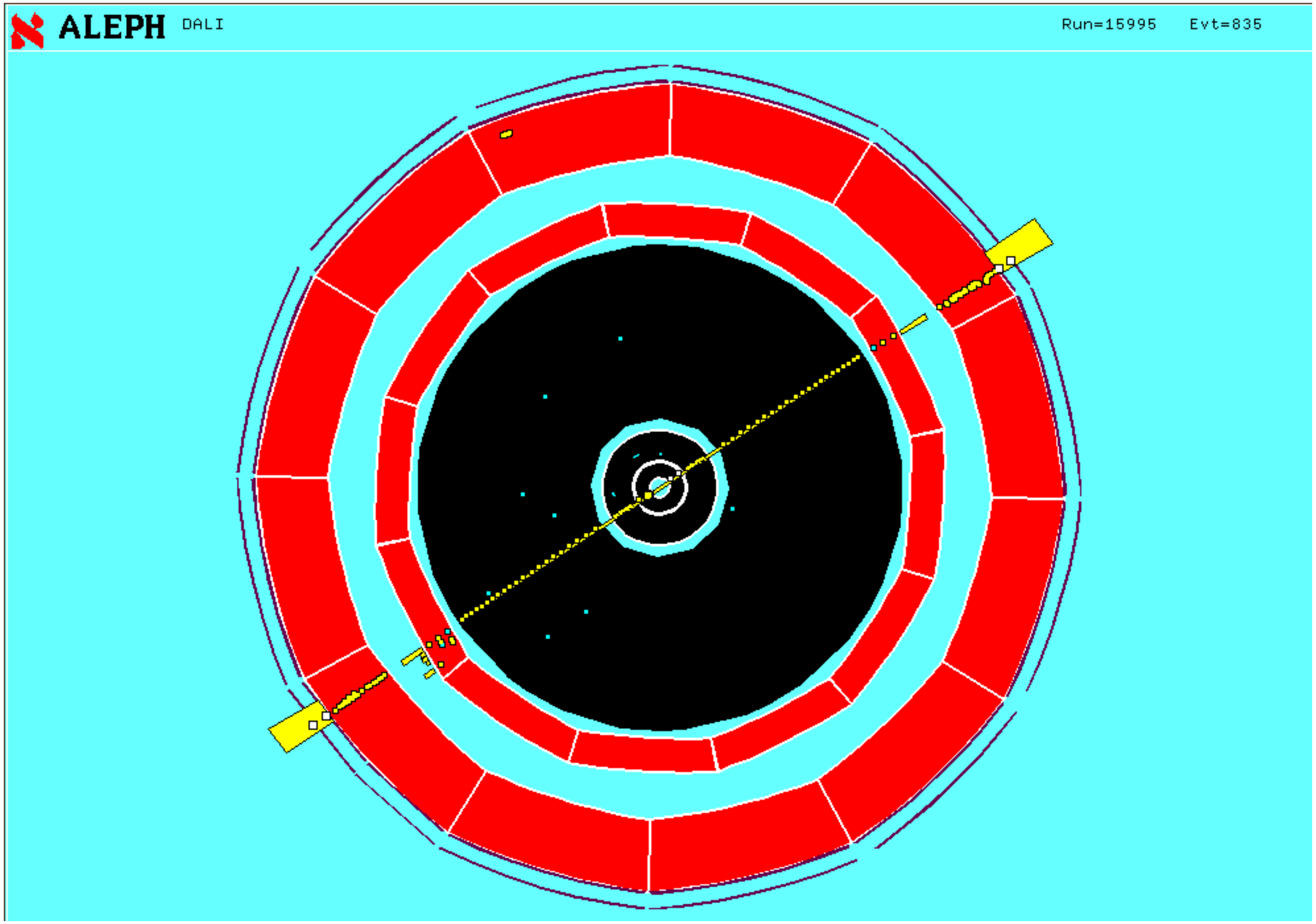
$Z \rightarrow e^+ e^-$

Two high momentum charged particles depositing energy in the Electro Magnetic Calorimeter



$Z \rightarrow \mu^+ \mu^-$

Two high momentum charged particles traversing all calorimeters and leaving a signal in the muon chambers.

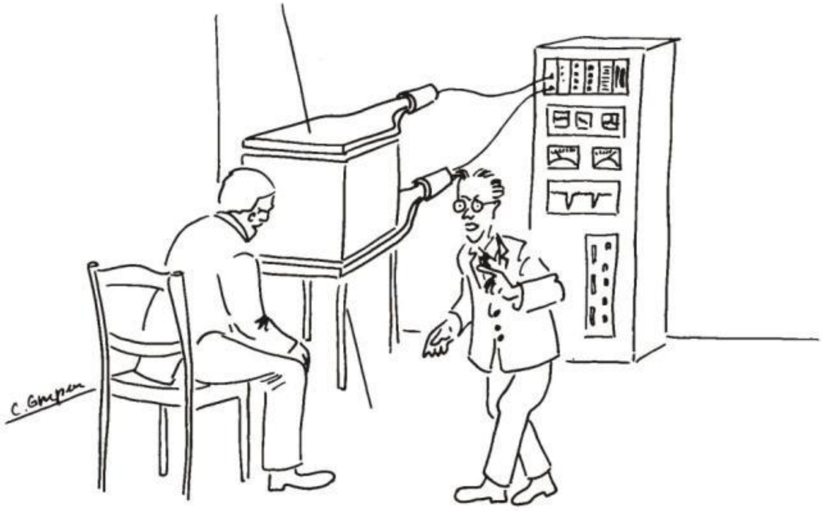


Interaction of Particles with Matter

Any device that is to detect a particle must interact with it in some way → almost …

In many experiments neutrinos are measured by missing transverse momentum.

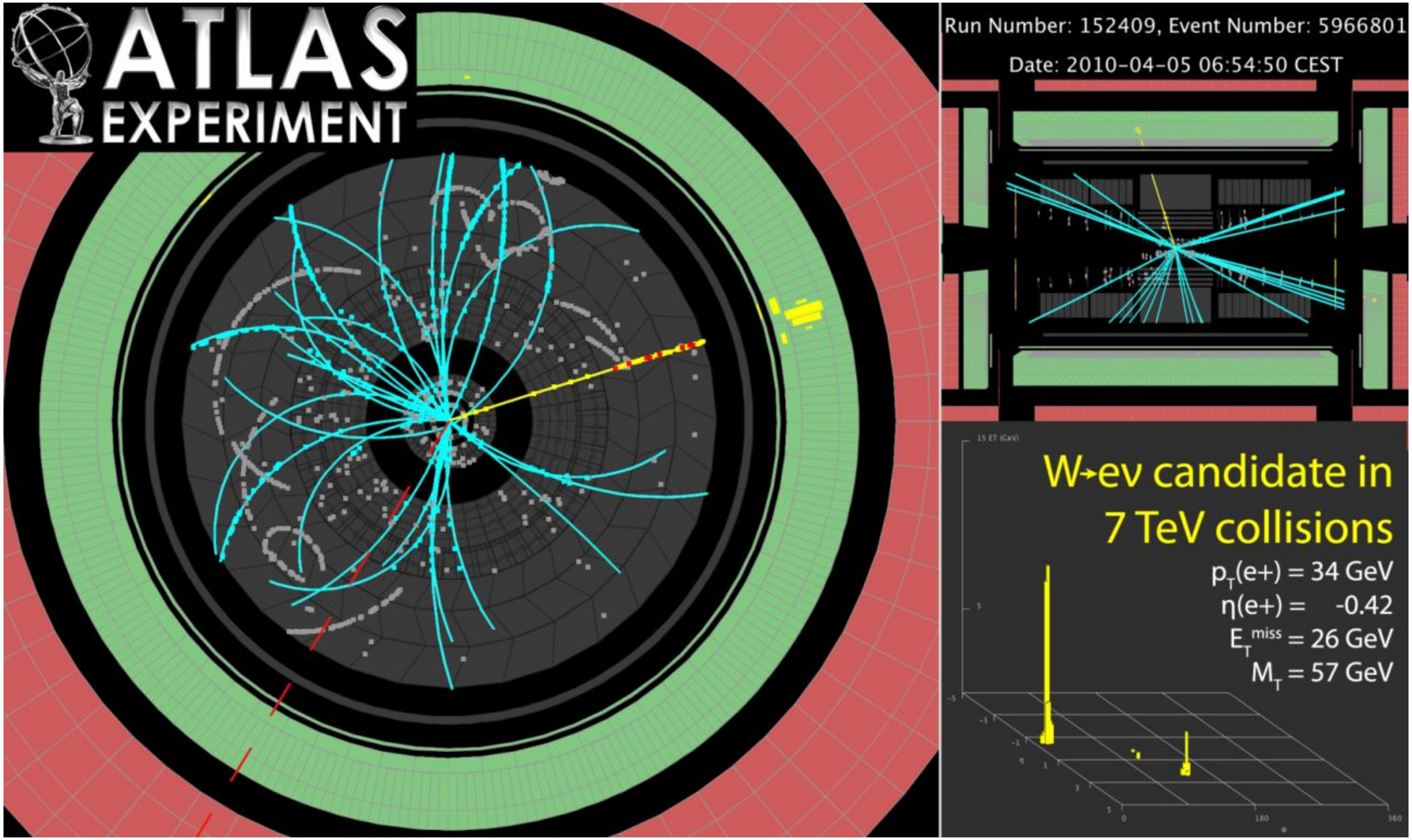
E.g. e^+e^- collider. $P_{tot}=0$,
If the $\Sigma\ p_i$ of all collision products is $\neq 0$ → neutrino escaped.



"Did you see it?"
"No nothing."
"Then it was a neutrino!"

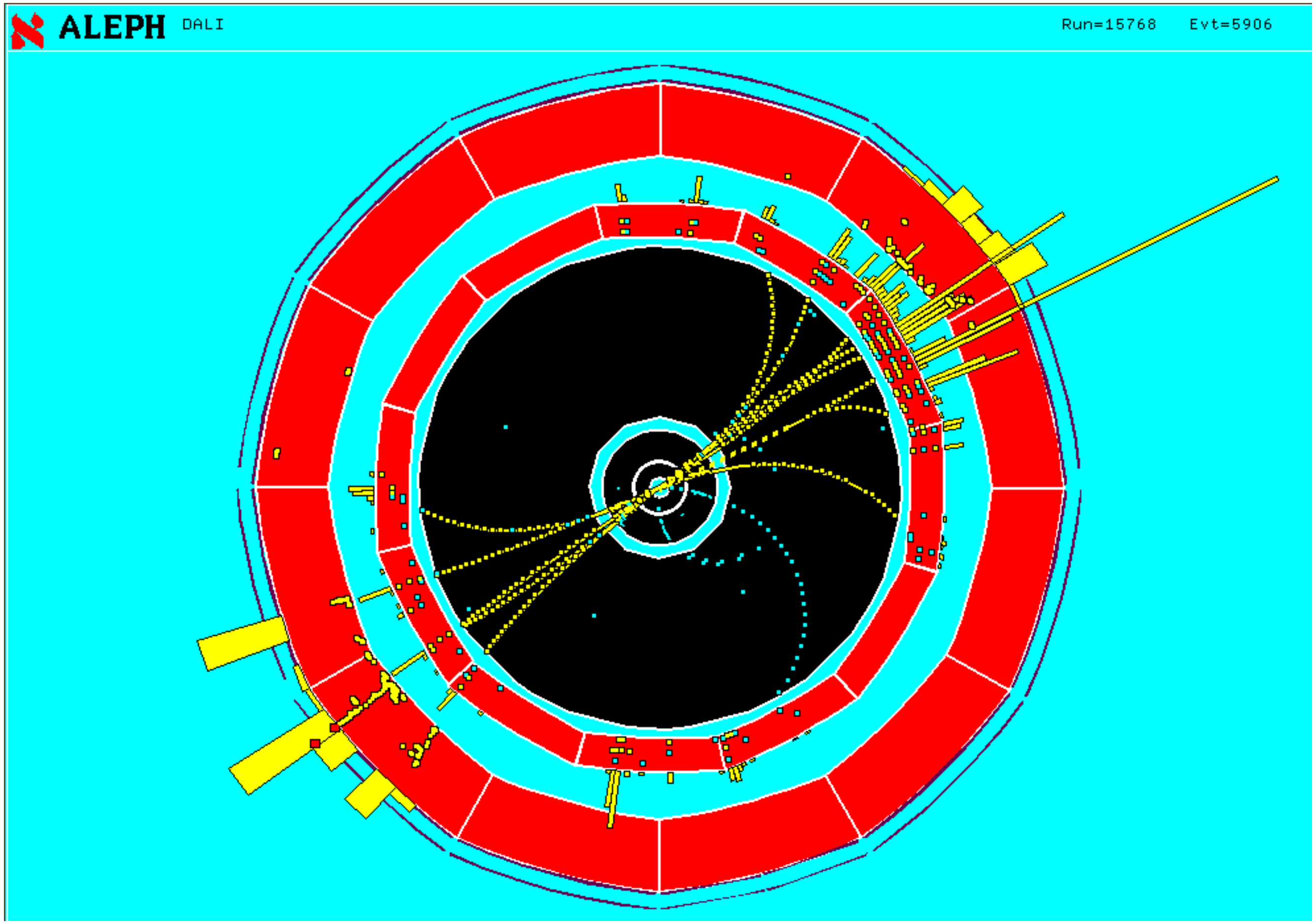
Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

2010 ATLAS W candidate



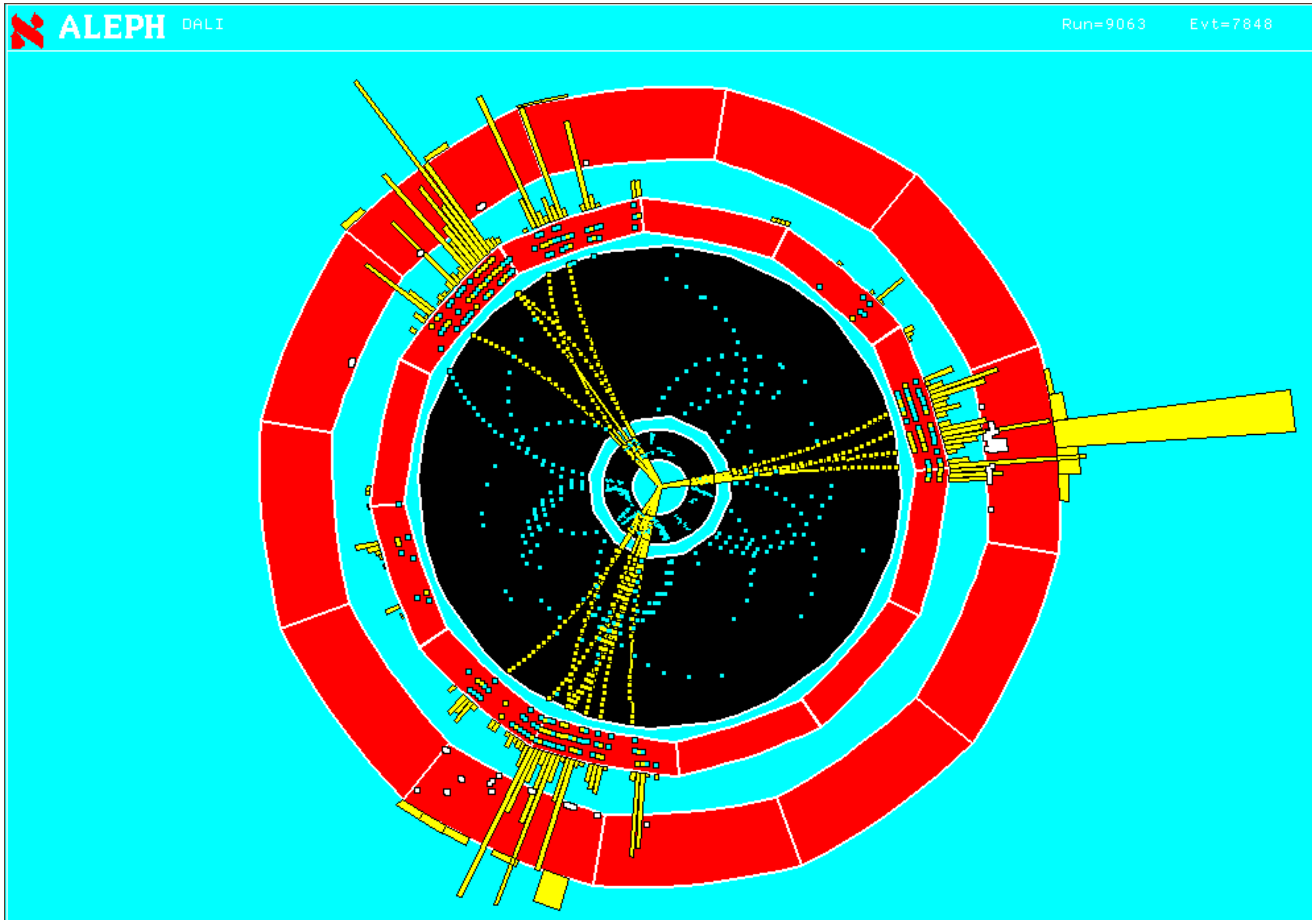
$Z \rightarrow q\bar{q}$

Two jets of particles



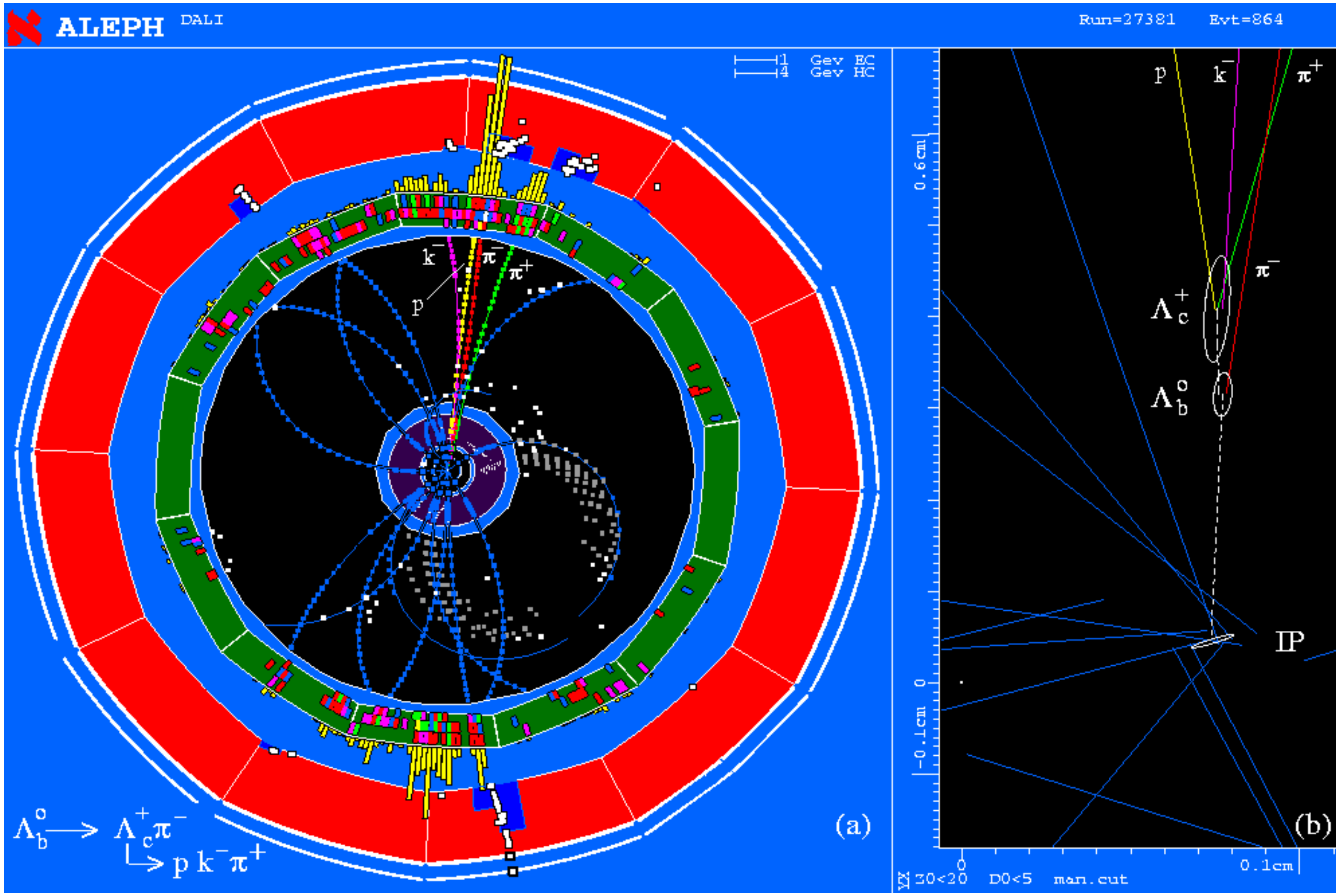
$Z \rightarrow q\,\bar{q}\,g$

Three jets of particles

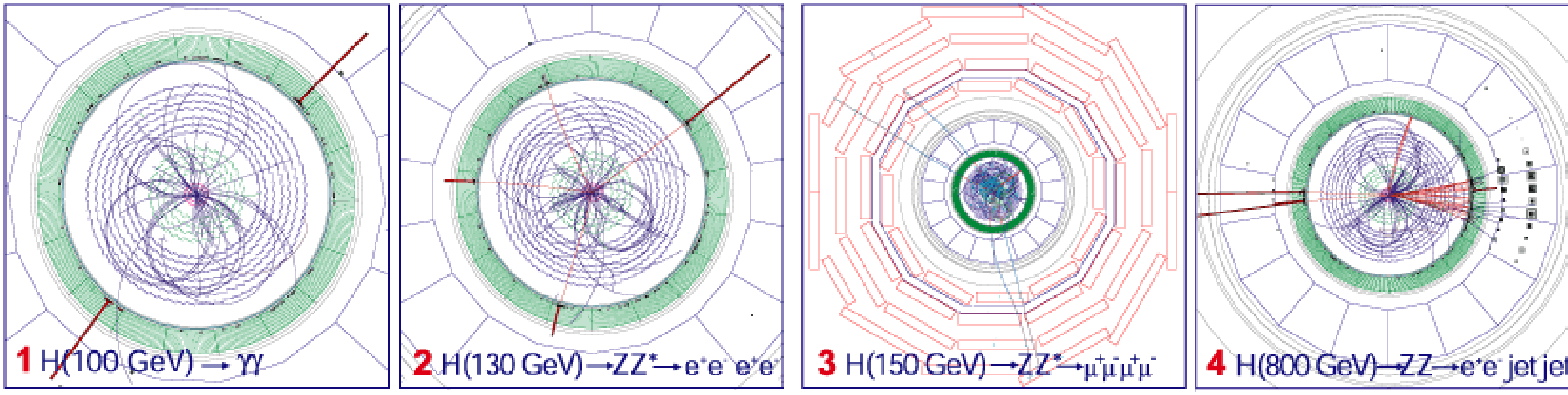


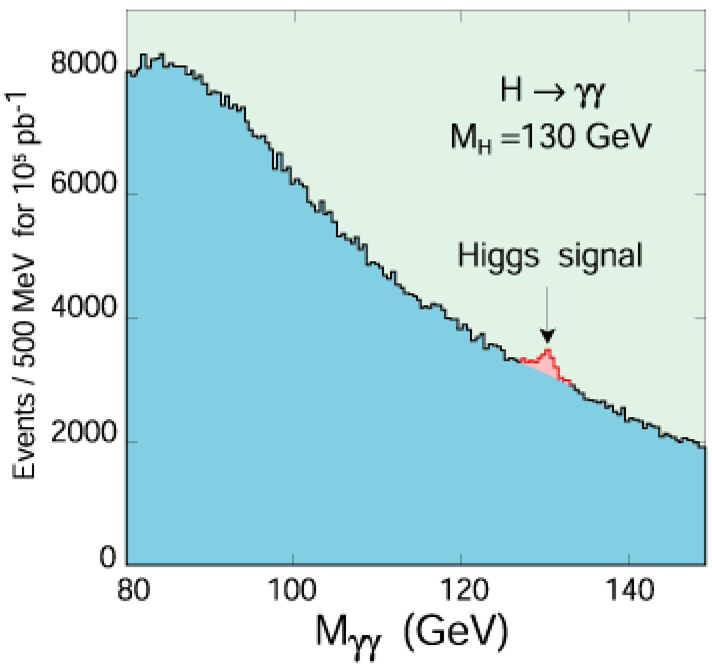
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

A single event tells what is happening. Negligible background.



Simulated Higgs Boson at CMS





Particle seen as an excess of two photon events above the irreducible background.

Principles:

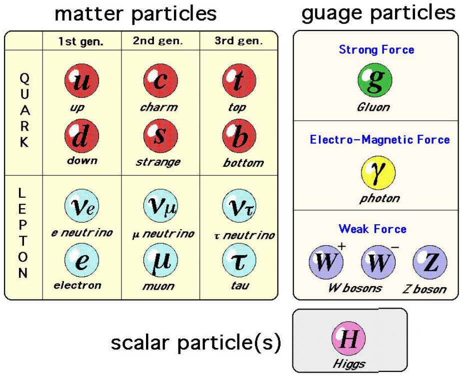
Only a few of the numerous known particles have lifetimes that are long enough to leave tracks in a detector.

Most of the particles are measured though the decay products and their kinematic relations (invariant mass). Most particles are only seen as an excess over an irreducible background.

Some short lived particles (b,c –particles) reach lifetimes in the laboratory system that are sufficient to leave short tracks before decaying → identification by measurement of short tracks.

In addition to this, detectors are built to measure the 8 particles

$$e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, K^{0}, p^{\pm}, n$$



Their difference in mass, charge and interaction is the key to their identification.

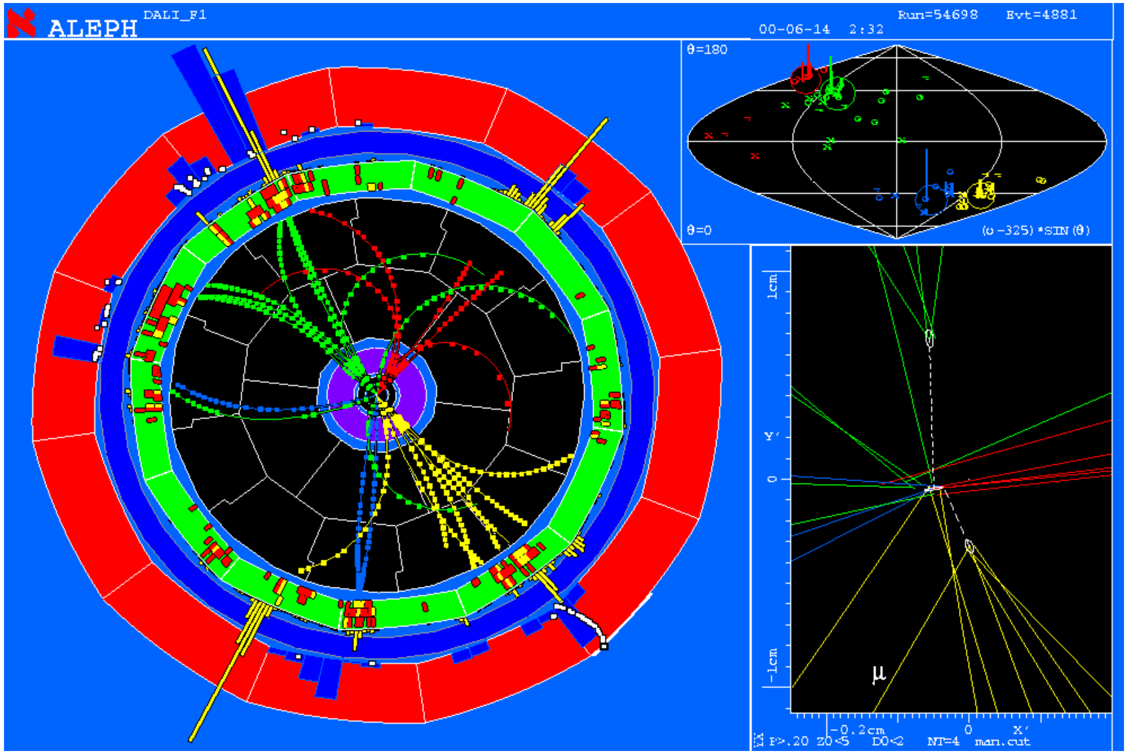
What determines the Size, Material and Geometry of the Detector ?

Impact Parameter Measurement (displaced vertices)

Momentum Measurement (bending of tracks in the B-field)

Energy measurement (absorption of particles in the calorimeters)

Muon measurement (identification)



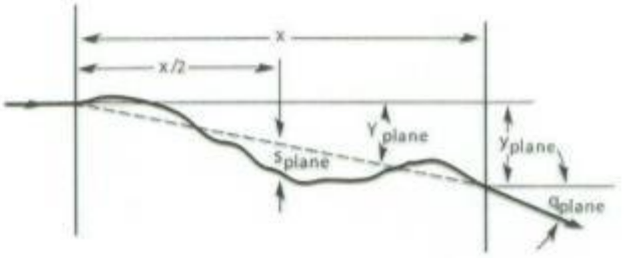
Multiple Scattering

Statistical (quite complex) analysis of multiple coulomb collisions (Rutherford scattering at the nuclei of the detector material) gives:

Probability that a particle is defected by an angle θ after travelling a distance x in the material is given by a Gaussian distribution with sigma of:

$$\Theta_0 = \frac{0.0136}{\beta c p [\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

X_0 ... Radiation length of the material
Z_1 ... Charge of the particle
p ... Momentum of the particle



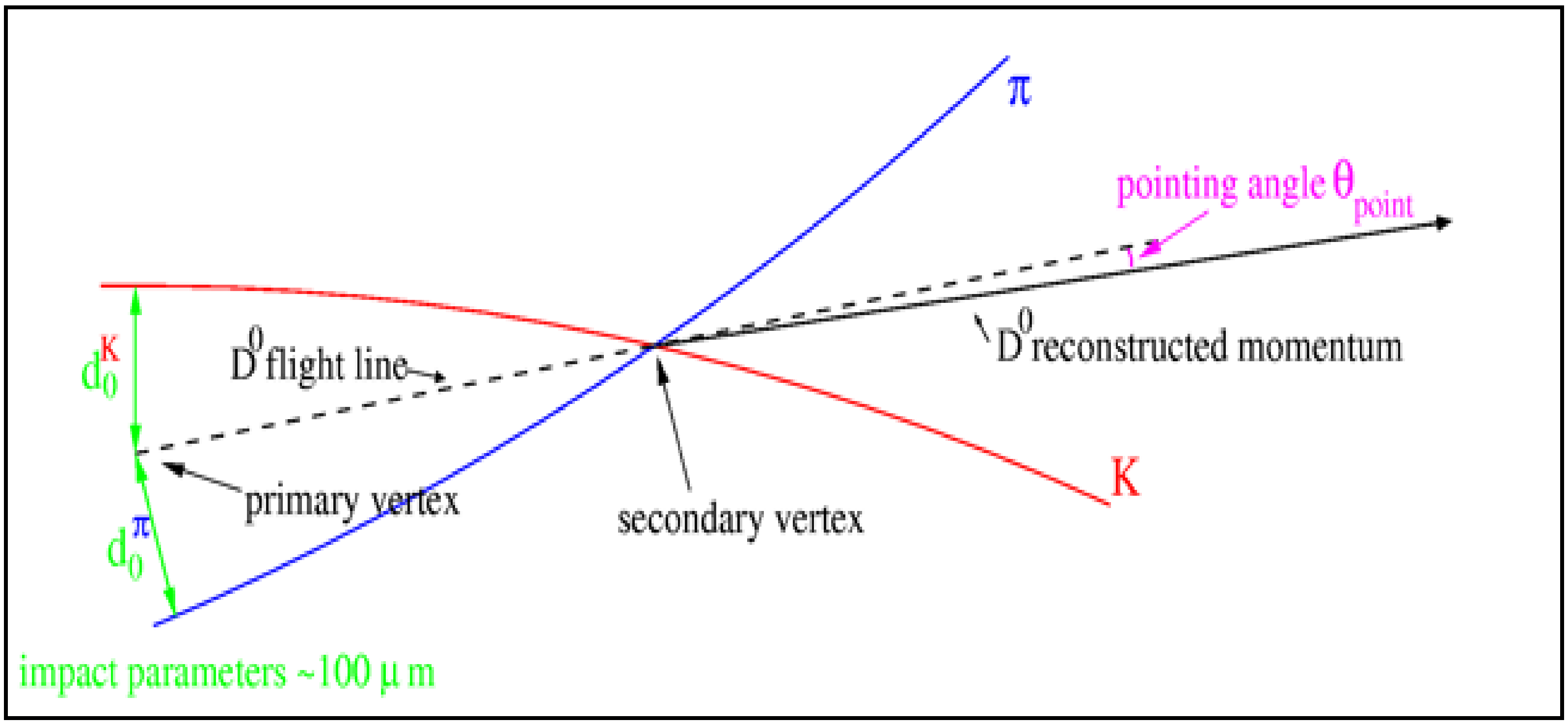
$$E(x) = E_0 e^{-\frac{x}{X_0}} \qquad X_0 = \frac{A}{4\alpha N_A \rho Z^2 \left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 \ln 183 Z^{-\frac{1}{3}}}$$

For small deflection of the particles by our detector we want:
→ Large Radiation length X_0 – i.e. low Z and low density material (Be, C …)
→ Small x i.e. very thin detector elements.

Impact Parameter:

Prolongation of a track to the primary vertex. Distance between primary vertex and prolongation is called impact parameter.

If this number is 'large' the probability is high that the track comes from a secondary vertex.



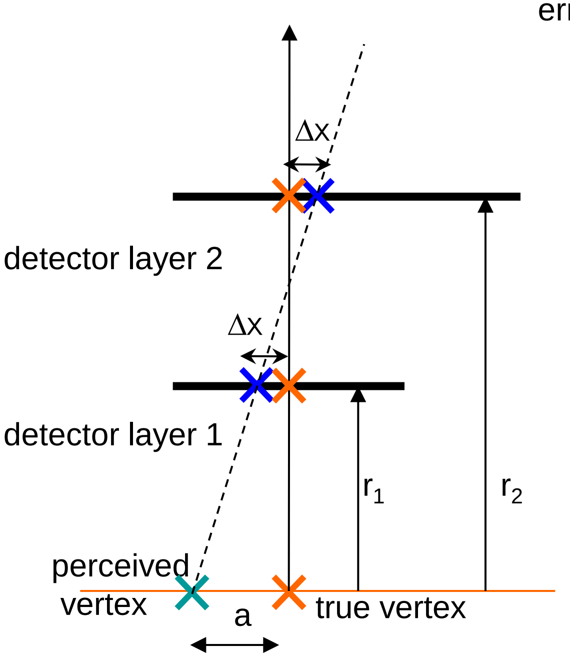
What determines the impact parameter resolution

Vertex projection from two points: a simplified approach (telescope equation)

pointing resolution = (a $\oplus$ b) μm

from detector position error

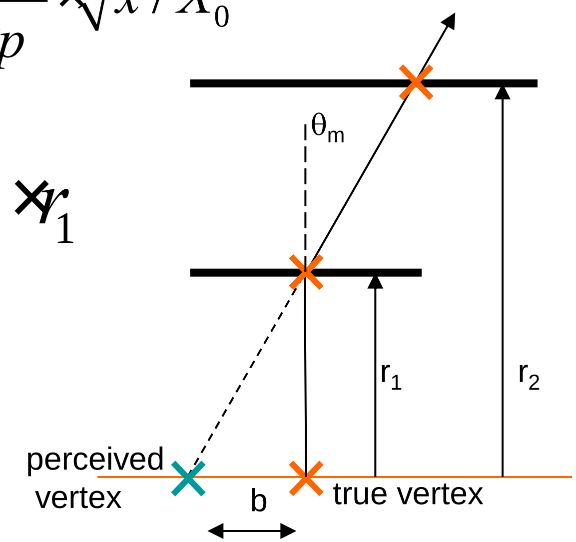
from coulomb scattering



$$a = \Delta x \cdot \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

$$\theta_m = \frac{13.6\,MeV}{\beta \cdot c \cdot p} \cdot \sqrt{x / X_0}$$

$$b = \theta_m \cdot r_1$$



Detector Granularity, minimize Δx:

e.g. 50um pixel and r_2 very large compared to r_1

→ a=Δx=50/√12 = 15um

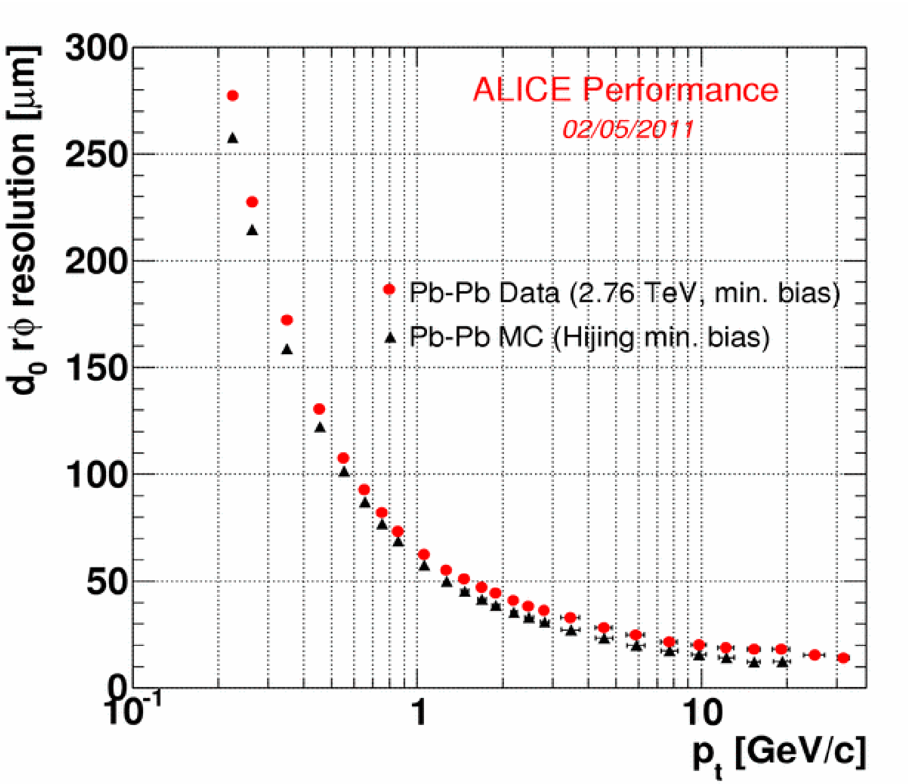
First layer as close as possible to the vertex and First layer with minimal amount of material.

e.g. x/X_0 = 0.0114, r_1= 39mm

→ b= 57um for p=1GeV/c

Example of ALICE Silicon Tracker

Impact parameter resolution



a = 15um
b = 57um for p=1GeV/c

For 'low' particle momenta i.e. p < 10GeV/c the impact parameter resolution is dominated by the material and distance of the first layer.

For high particle momenta the resolution is dominated by the detector granularity.

Alice x/X_0 = 0.014 and r1= 39mm is already very good !

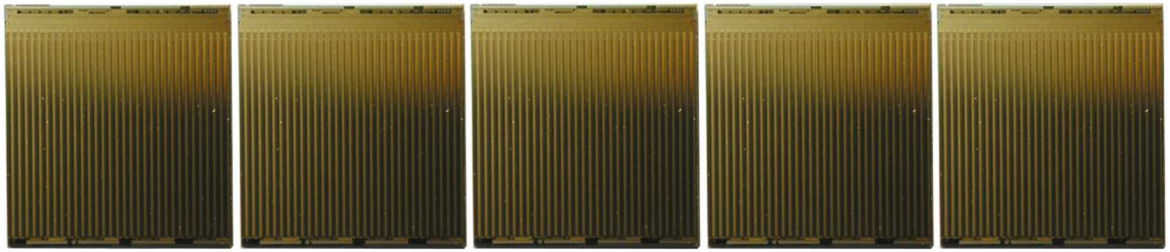
Try to improve for upgrade.

Very ambitious goal x/X_0 = 0.003 and r1= 22mm !

→ Very small beampipe

→ Monolithic silicon sensors <50um
Optimized carbon fiber supports and cooling tubes.

ALICE Silicon Pixel Detector – Sensor and Pixel Chip



5 readout chips/sensor

0.25µm CMOS

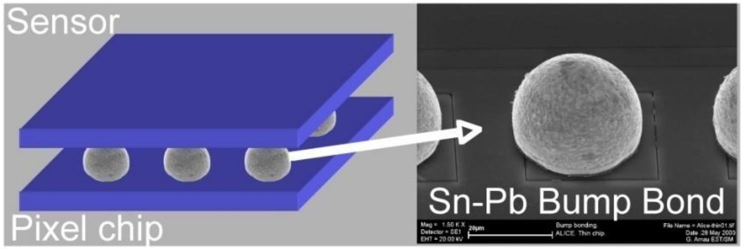
13.68 mm x 15.58 mm

thinned to 150 µm

p-in-n silicon sensor

72.72 mm x 13.92 mm

200 µm thin



40960 bump bonds

~25 µm diameter

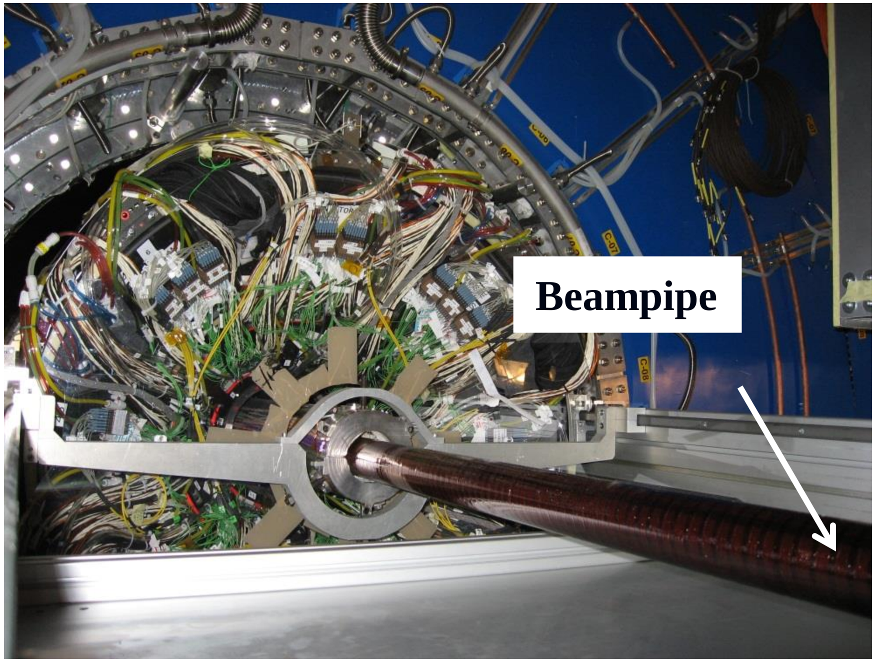
Stand-off:

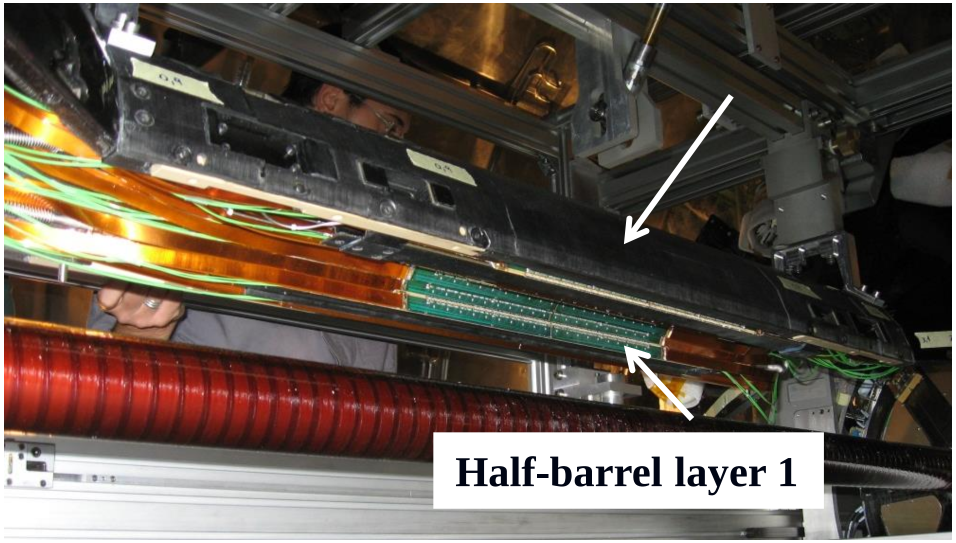
~12 µm (Pb-Sn)

ALICE Pixel Layer

SPD Component	Some details	Thickness (µm)	X/X0 (%)	Contribution to the total X/X0 (%)
Silicon	Sensor + FEE + interconnection	350	0.38	33
Electrical bus	5 Al/polyimide layers + SMD components	280	0.48	42
Mechanical support and cooling	Carbon fiber + tube	200	0.19	17
Others	Glue (assembly / thermal contact) and grounding foil		0.09	8
Total			**1.14**	**100**

ALICE Pixel Detector

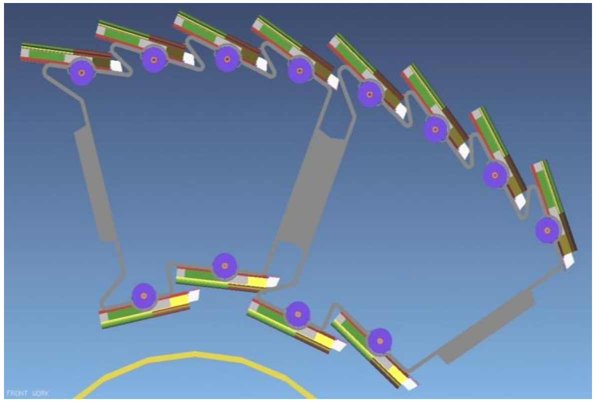




LHC Experiment Beampipe:
As small & thin as possible

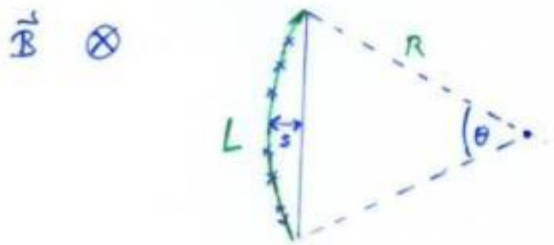
- To be compatible with LHC beam size, orbit offset, mechanical tolerances and movements etc.
- presently 30mm radius
- Beryllium, 0.8mm wall thickness, x/X_0= 0.002

First layer:
Minimum distance from beampipe 5mm, Average radial distance = 39mm



Momentum Measurement

Magnetic Spectrometer: A charged particle describes a circle in a magnetic field:



$$p = q \cdot R \cdot B$$

$$p\left[\frac{GeV}{c}\right] = 0.3\, R[m]\, B[T]$$

$$L = R \cdot \theta$$

$$s = R\left(1-\cos\frac{\theta}{2}\right) \sim R\frac{\theta^2}{8} = \frac{L^2}{8R} \rightarrow R = \frac{L^2}{8s}$$

$$\Delta p = 0.3\, B\, \Delta R = 0.3\, B\, \frac{L^2}{8s^2}\Delta s$$

$$\Delta s = \frac{\sigma_x}{\sqrt{N}} \qquad \sigma_x \ldots \text{point resolution},\ N \ldots \text{Measurement Points}$$

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x[m]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8\, p\left[\frac{GeV}{c}\right]}{B[T] \cdot L^2[m^2]}$$

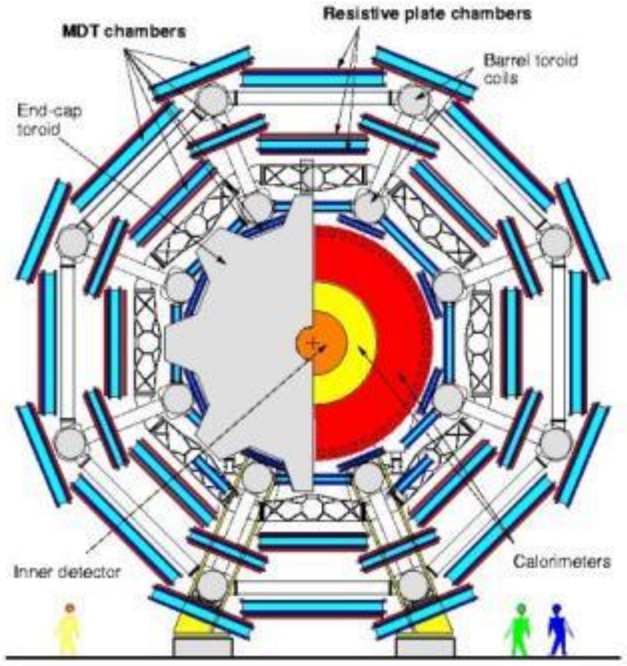
E.g.: $p = 10\,\frac{GeV}{c}$, $B = 1T$, $L = 1m$, $\sigma = 200\mu m$, $N = 25$

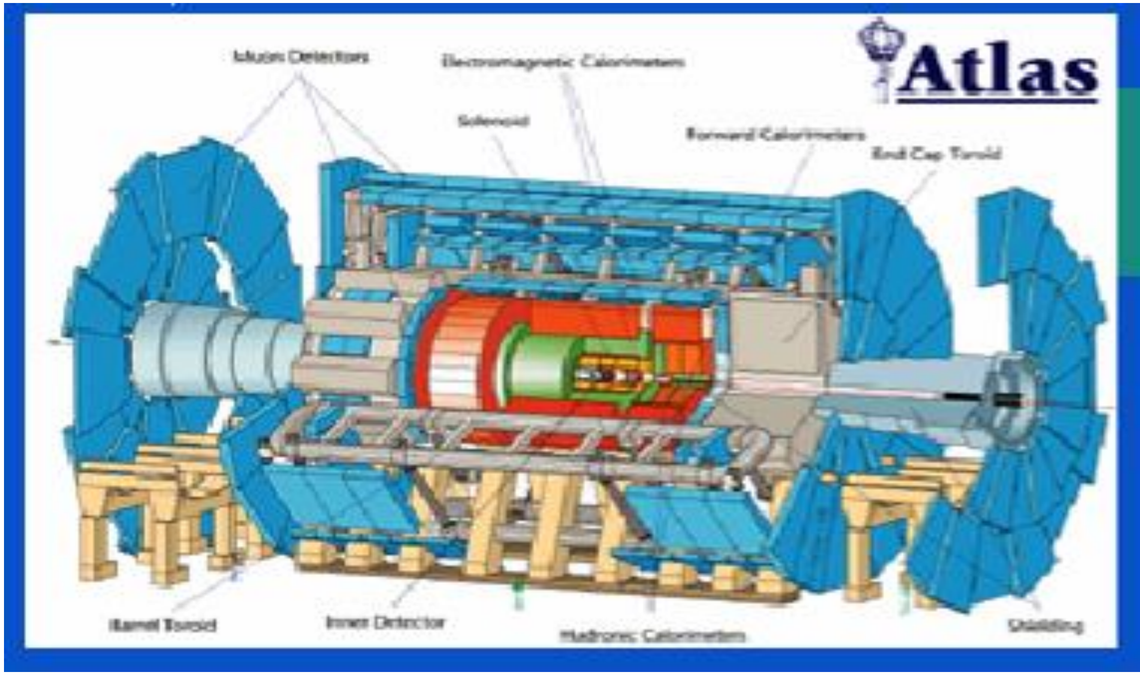
$$\frac{\Delta p}{p} = 0.01 \rightarrow 1\%$$

Example: ATLAS Muon Spectrometer

N=3, σ=50um, p=1TeV,
L=5m, B=0.4T

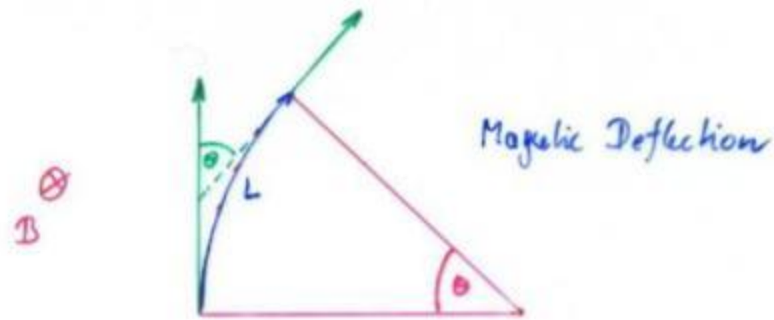
Δp/p ~ 8% for the most energetic muons at LHC





Multiple Scattering

The momentum resolution cannot be improved ad infinitum by larger L and B. Multiple scattering limit for low momenta:



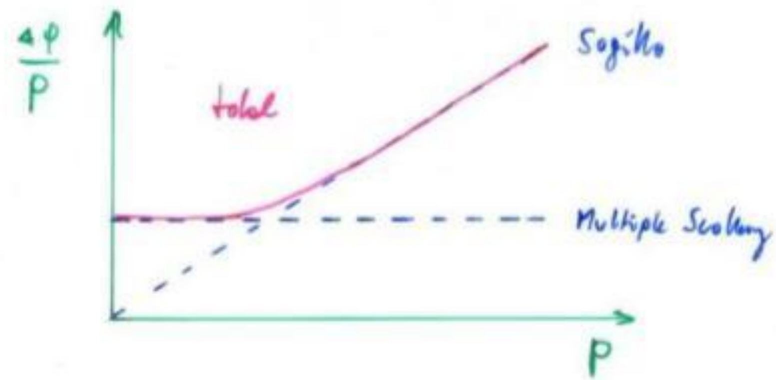
$$p\,[\mathrm{GeV}/c] = 0.3\,R\,[\mathrm{m}]\,B\,[\mathrm{T}]$$

$$\theta = \frac{L}{R} = \frac{L}{p} \cdot 0.3\,B$$

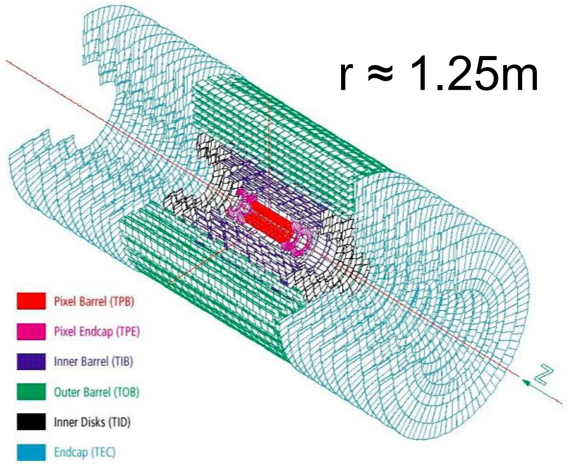
$$\frac{\Delta p}{p} = \frac{\Delta \theta}{\theta} = \frac{\theta_0}{\theta} \sim \frac{0.05}{\beta\, B[\mathrm{T}]\, L[\mathrm{m}]} \sqrt{\frac{L}{X_0}}$$

→ Independent of p

$$\left.\frac{\Delta p}{p}\right|_{tot} = \sqrt{\left(\left.\frac{\Delta p}{p}\right|_{sag}\right)^2 + \left(\left.\frac{\Delta p}{p}\right|_{ms}\right)^2}$$



CMS Tracker: dp/p = 0.65% at 1GeV and 10% at 1000GeV

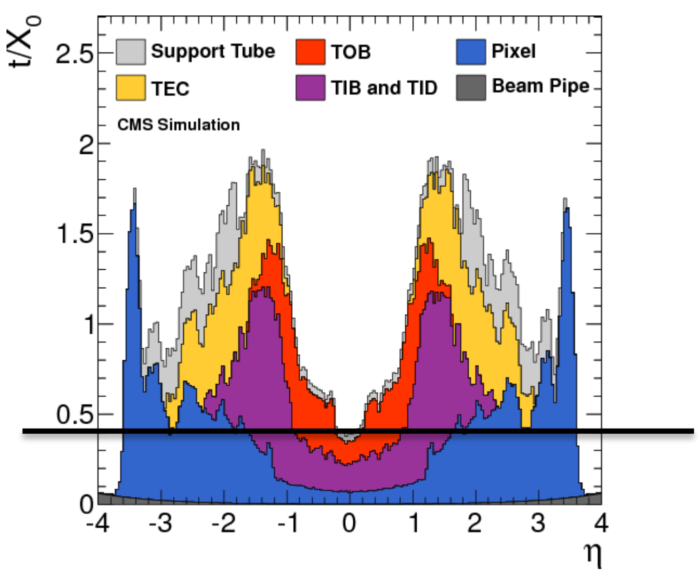


$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x[m]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8 \, p\left[\frac{GeV}{c}\right]}{B[T] \cdot L^2[m^2]}$$

B=3.8T, L=1.25m, average N ≈ 10 layers, Average resolution per layer ≈ 50um, p=1000GeV

→ dp/p = 7% tracking

Material budget



$$\frac{\Delta p}{p} = \frac{\Delta \theta}{\theta} = \frac{\theta_0}{\theta} \sim \frac{0.05}{\beta B[T] L[m]} \sqrt{\frac{L}{X_0}}$$

B=3.8T, L=1.25m, x/X_0 ≈ 0.4 @ eta=0

→ dp/p = 0.7% from multiple scattering

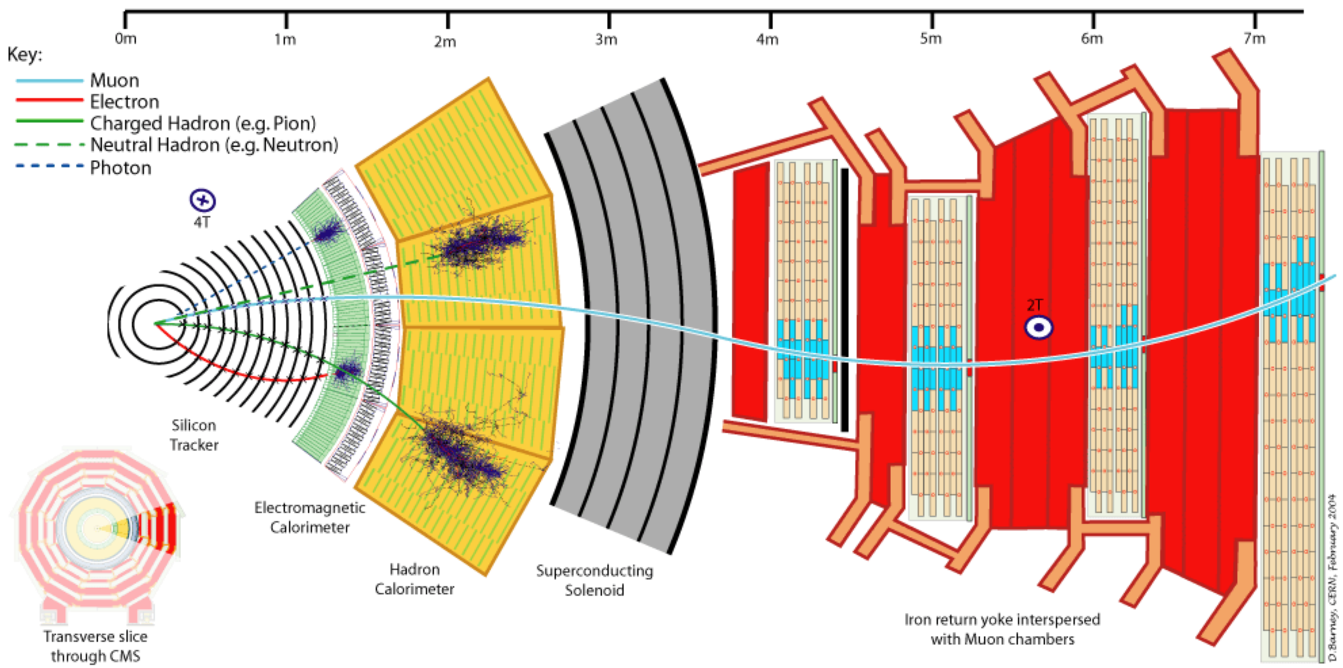
Momentum Measurement

The specified momentum resolution, together with the

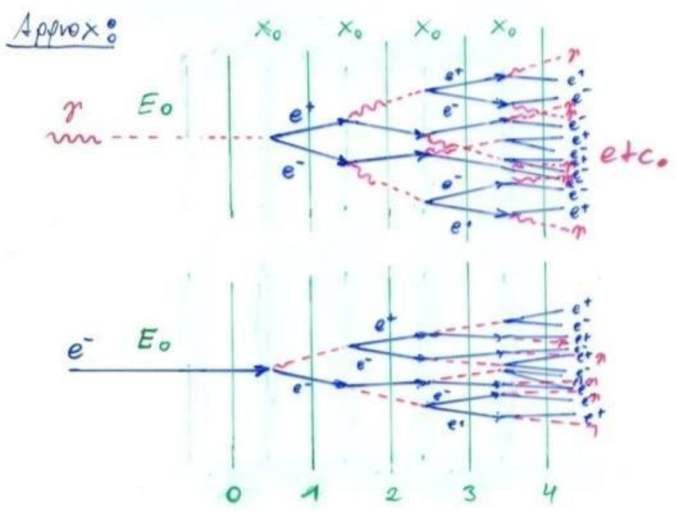
Magnetic field B
Number of tracking layers N
Resolution per layer σ

defines the tracker radius.

Then – EM and Hadron Calorimeter !



Electro Magnetic Calorimetry



Electromagnetic Shower → Em Calorimeter

$$N(n) = 2^n$$ .... Number of particles ($e^\pm$, γ) after $n X_0$

$$E(n) = \frac{E_0}{2^n}$$ ... Average Energy of particles after $n X_0$

Shower stops if $E(n) = E_{critical}$

$$n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}$$ → Shower length rises with $\ln E_0$

Critical Energy E_c = electron energy where energy loss due to Bremsstrahlung equals energy loss due to ionization.

$$X_0 = \frac{A}{4\alpha N_A \rho Z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 \ln 183 Z^{-\frac{1}{3}}}$$

$$E_c \sim \frac{610}{Z+1.24}\,\mathrm{MeV} \sim \frac{610}{Z}\,\mathrm{MeV}$$

For Pb (Z=82) and 1000GeV electrons n_{max}=17

Simulated EM Shower Profiles in $PbWO_4$

Simulation of longitudinal shower profile | **Simulation of transverse shower profile**

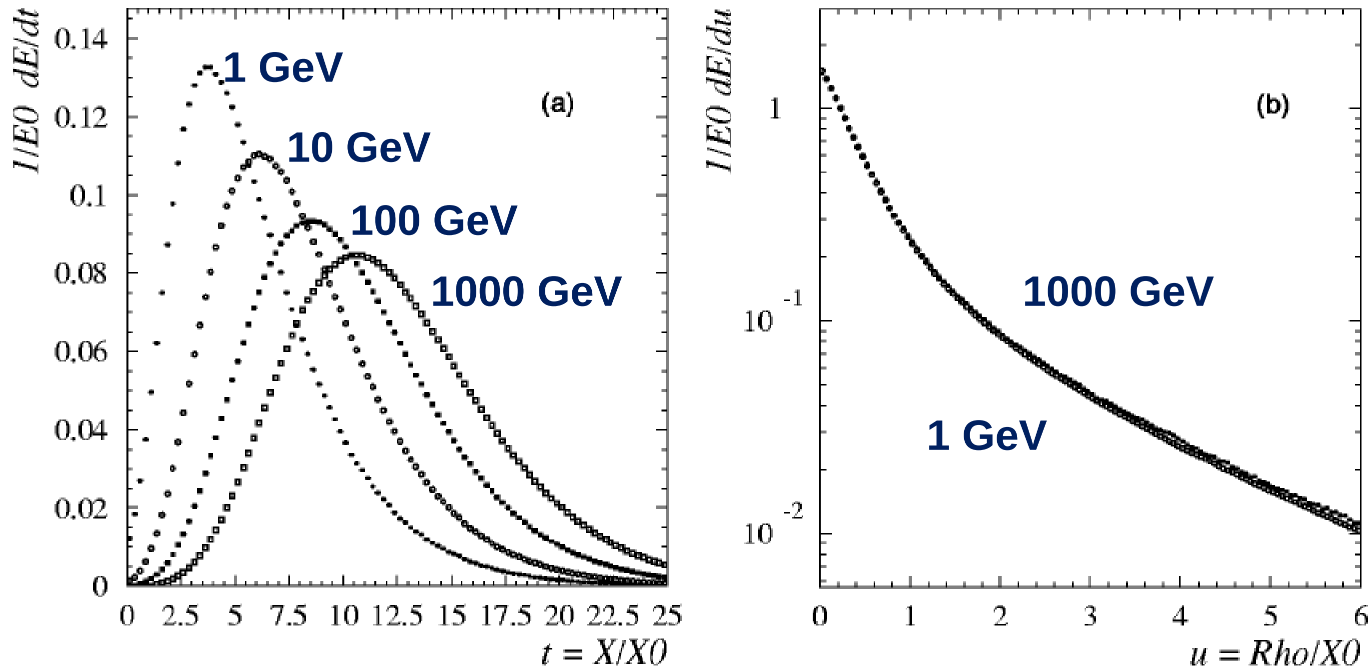


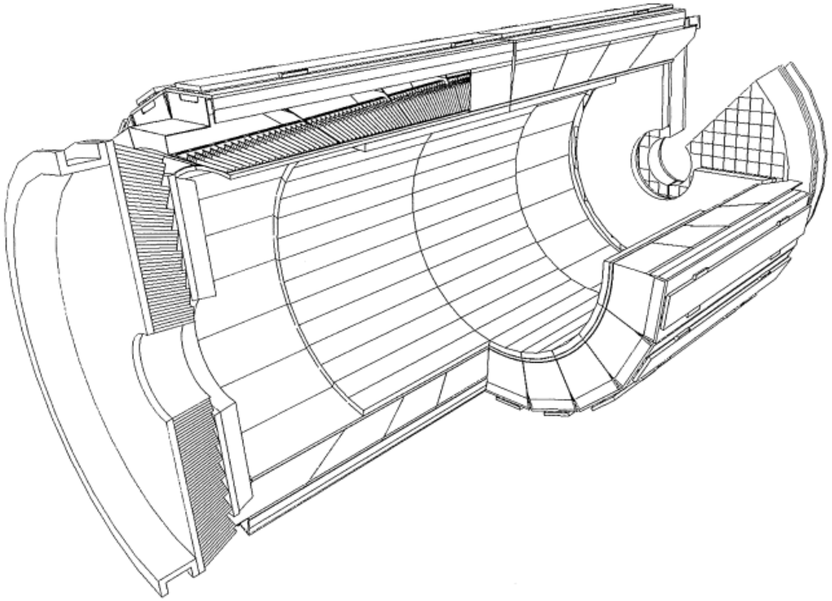
FIG. 2. (a) Simulated shower longitudinal profiles in $PbWO_4$, as a function of the material thickness (expressed in radiation lengths), for incident electrons of energy (from left to right) 1 GeV, 10 GeV, 100 GeV, 1 TeV. (b) Simulated radial shower profiles in $PbWO_4$, as a function of the radial distance from the shower axis (expressed in radiation lengths), for 1 GeV (closed circles) and 1 TeV (open circles) incident electrons. From Maire (2001).

In calorimeters with thickness ~ 25 X_0, the shower leakage beyond the end of the active detector is much less than 1% up to incident electron energies of ~ 300 GeV (LHC energies).

X_0 of Pb = 0.56 cm → $25X_0$=14cm

X_0 of $PbWO_4$ = 0.89cm → $25X_0$=22.5cm

Crystals for Homogeneous EM Calorimetry



Length of Crystal = 23cm

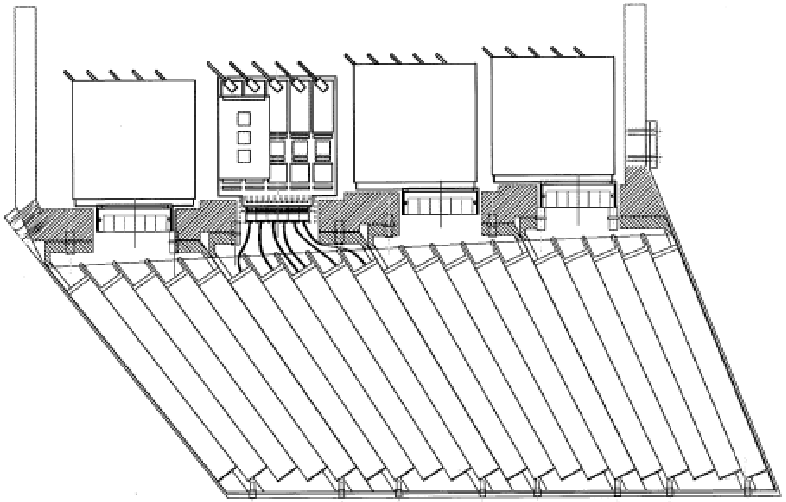


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Hadronic Calorimetry

In Hadron Cascades the Longitudinal Shower is given by the Absorption Length λ_a $I \sim e^{-\frac{x}{\lambda_a}}$

In typical Detector Materials λ_a is much larger than X_0

$$\lambda \sim \frac{1}{\rho} \cdot 35\, A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7.87	1.76 cm	~17 cm
Pb	11.35	0.56 cm	~17 cm

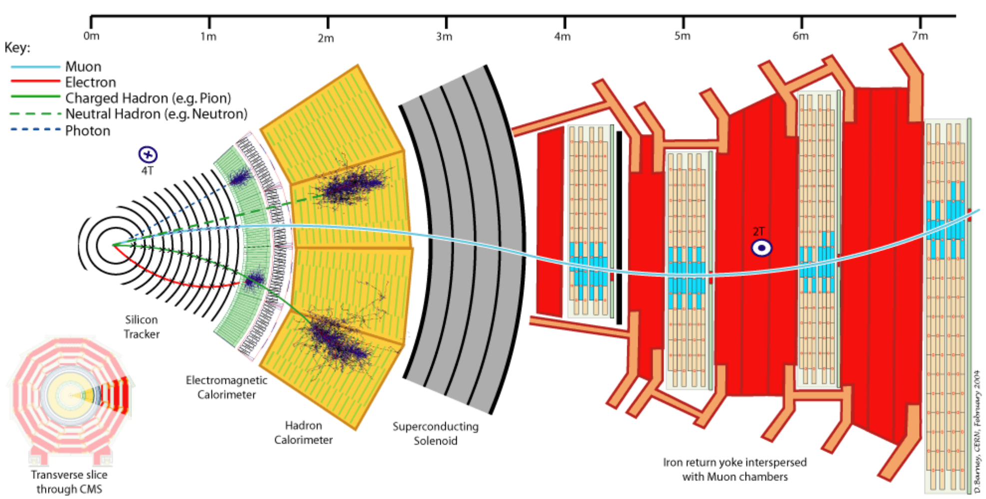
To absorb a hadron shower one typically needs 10-11 interaction lengths.

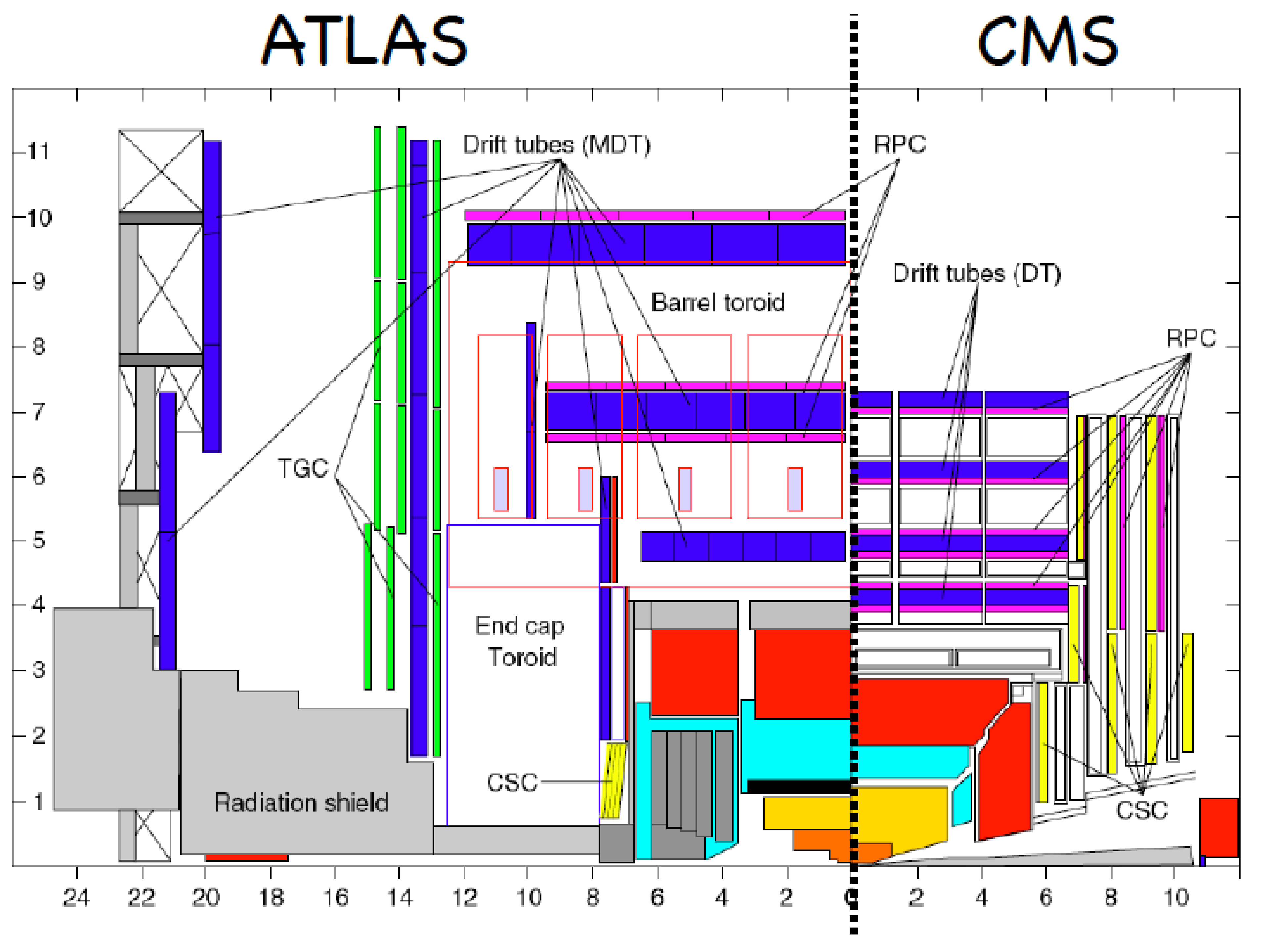
The interaction length is not such a strong function of the material, it should just be very HEAVY ! Cu, Fe, Pb

10 lambda = 170cm of iron.

CMS uses a Cu/Zn mixture with lambda = 16.4cm and a total of 6 interaction lengths + detector = 120cm in order to keep the coil radius small.

To arrive at >10 lambda in total, a ‘tail catcher’ is added outside the coil.





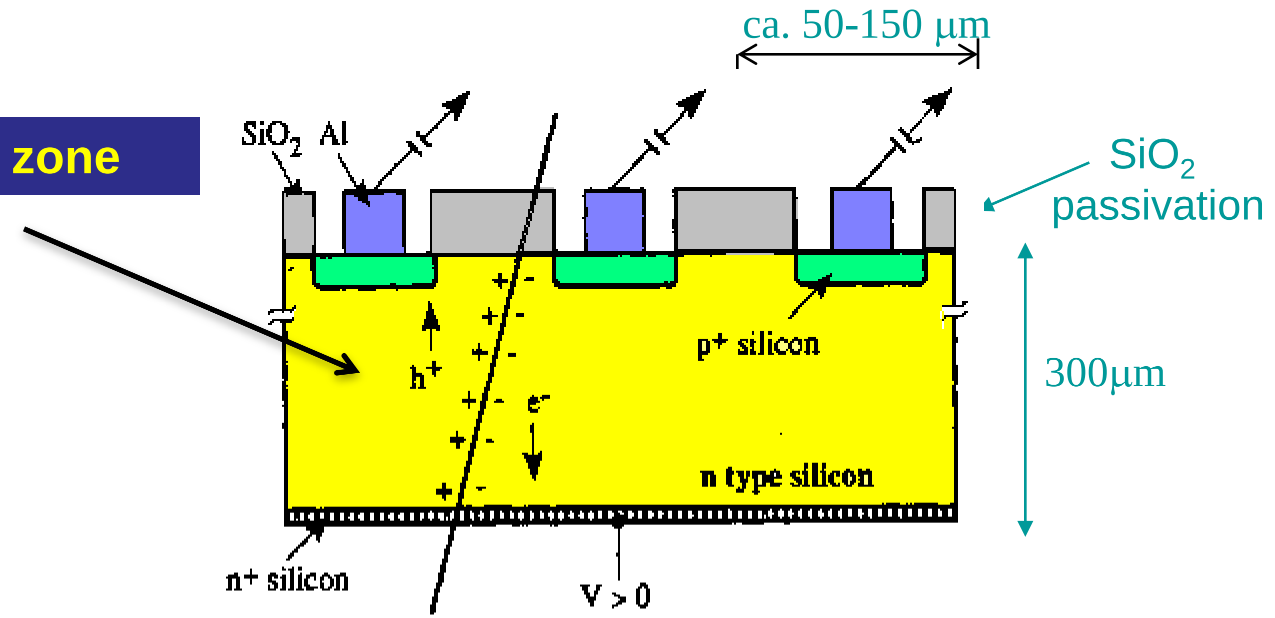
ATLAS
CMS
Drift tubes (MDT)
RPC
Drift tubes (DT)
Barrel toroid
RPC
TGC
End cap
Toroid
CSC
Radiation shield
CSC
24
22
20
18
16
14
12
10
8
6
4
2
0
2
4
6
8
10
11
10
9
8
7
6
5
4
3
2
1

Tracking with Silicon Detectors is one of the major aspects for LHC and HL-LHC.

Thickness, Speed, Radiation Hardness, Granularity

Silicon Detector

Fully depleted zone

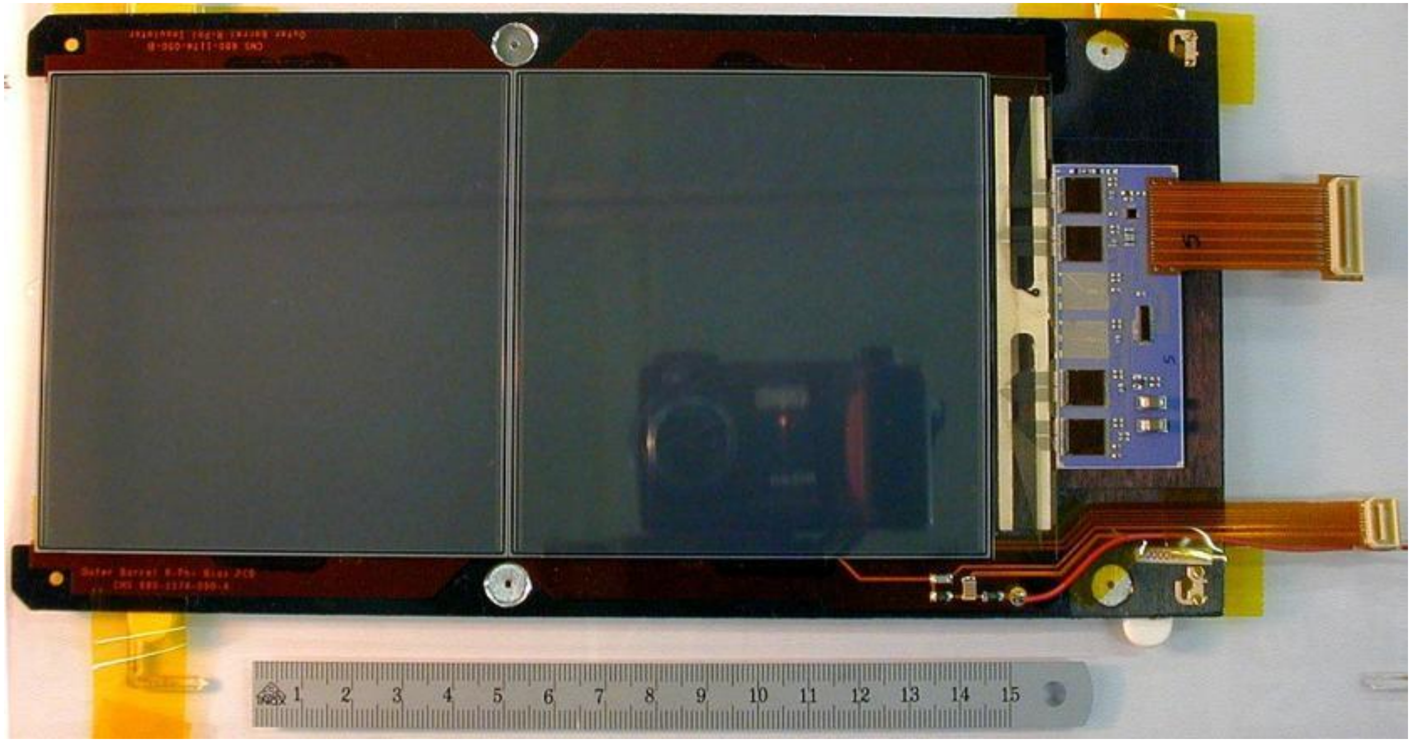


N (e-h) = 11 000/100μm

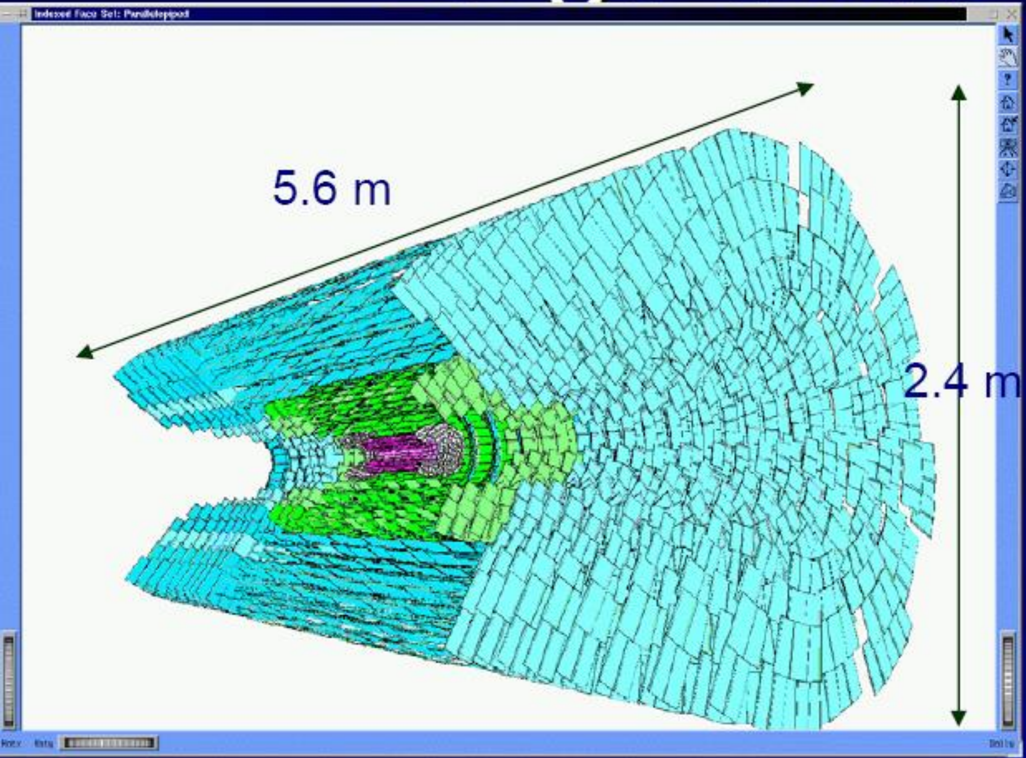
Position Resolution down to ~ 5μm !

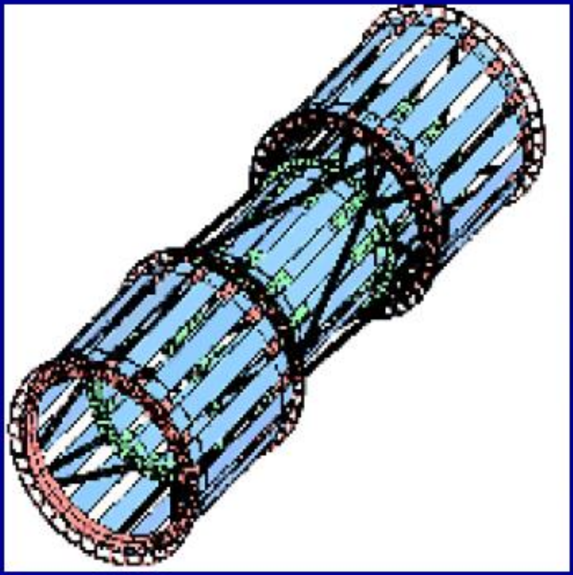
Picture of an CMS Si-Tracker Module

Outer Barrel Module (strips)



Large Silicon Systems





CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

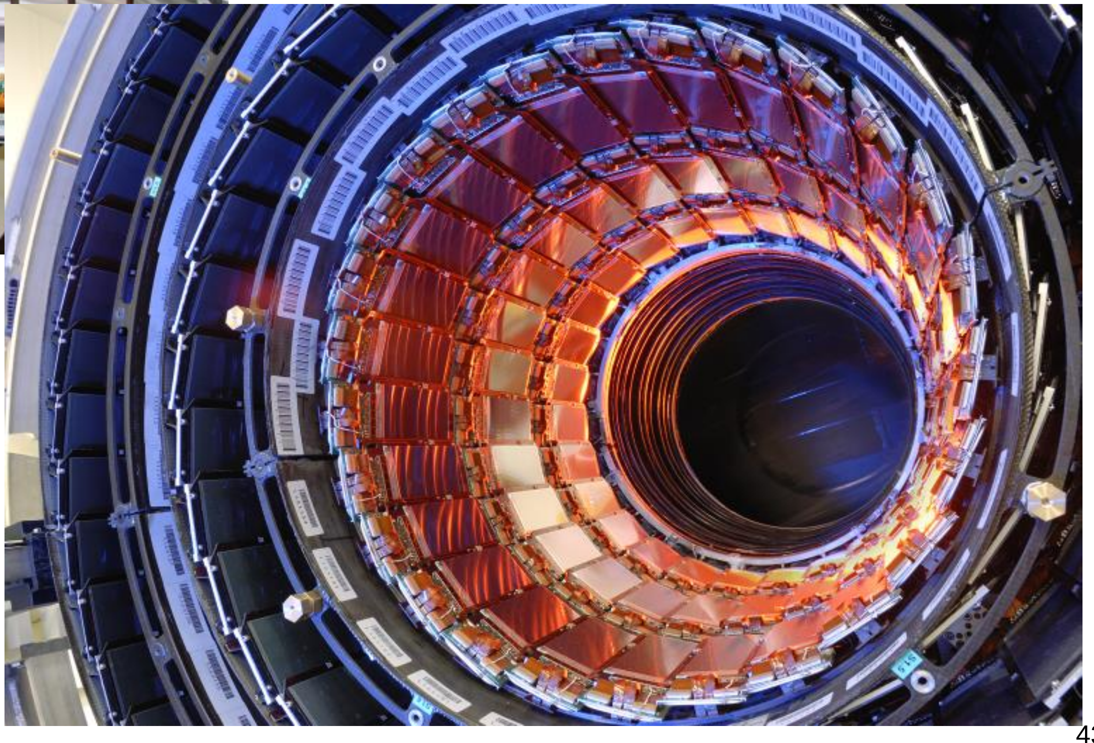
~ 60 M readout channels

CDF SVX IIa (2001-)

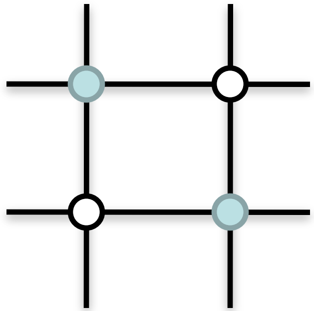
~ 11m^2 silicon area

~ 750 000 readout channels

CMS Tracker



Pixel-Detectors



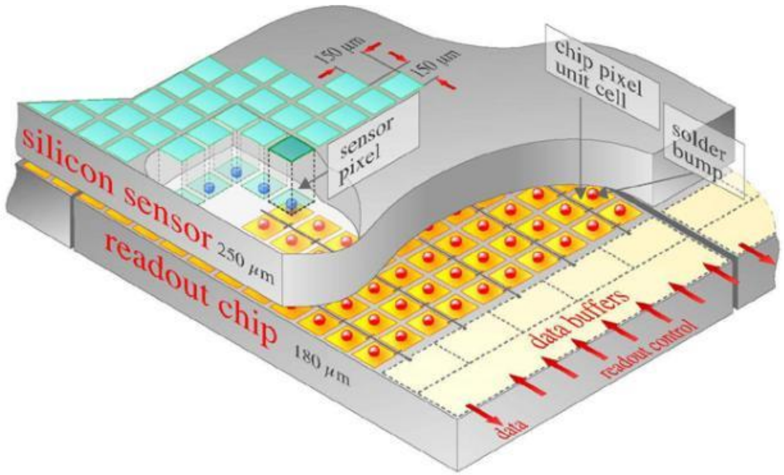
Problem:
2-dimensional readout of strip detectors results in 'Ghost Tracks' at high particle multiplicities i.e. many particles at the same time.

Solution:
Si detectors with 2 dimensional 'chessboard' readout. Typical size 50 x 200 μm.

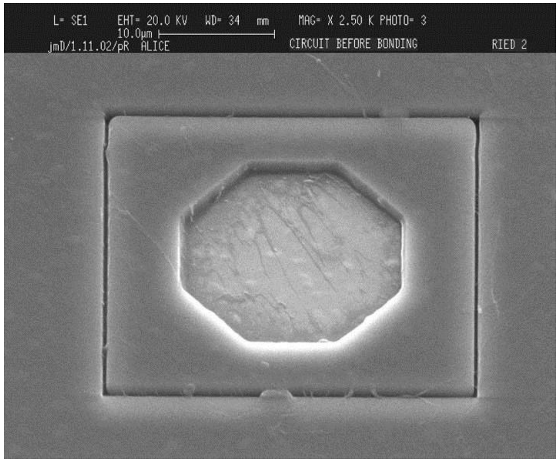
Problem:
Coupling of readout electronics to the detector.

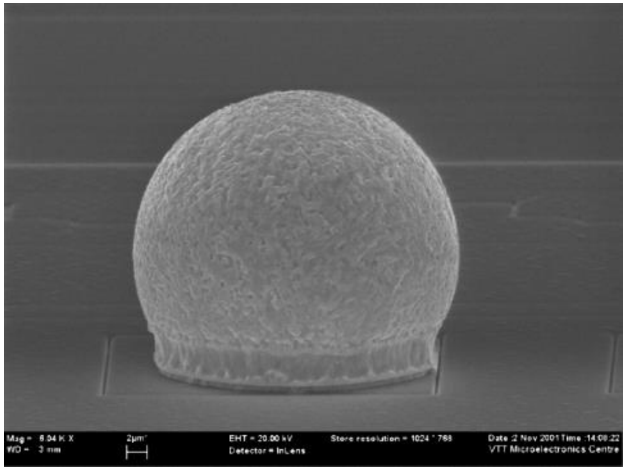
Solution:
Bump bonding.

Bump Bonding of each Pixel Sensor to the Readout Electronics



ATLAS: 1.4×10^8 pixels





Radiation Effects 'Aging'

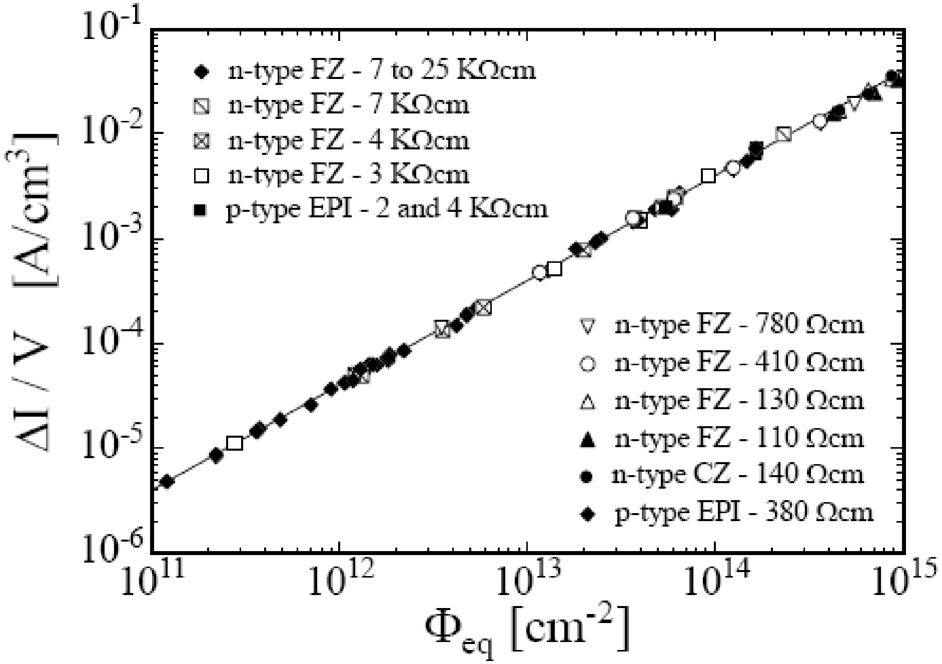
- Two general types of radiation damage
  - "Bulk" damage due to physical impact within the crystal
  - "Surface" damage in the oxide or Si/SiO_2 interface
- Cumulative effects
  - Increased leakage current (increased shot noise)
  - Silicon bulk type inversion (n-type to p-type)
  - Increased depletion voltage
  - Increased capacitance
- Sensors can fail from radiation damage
  - Noise too high to effectively operate
  - Depletion voltage too high to deplete
  - Loss of inter-strip isolation (charge spreading)
- Signal/noise ratio is the quantity to watch

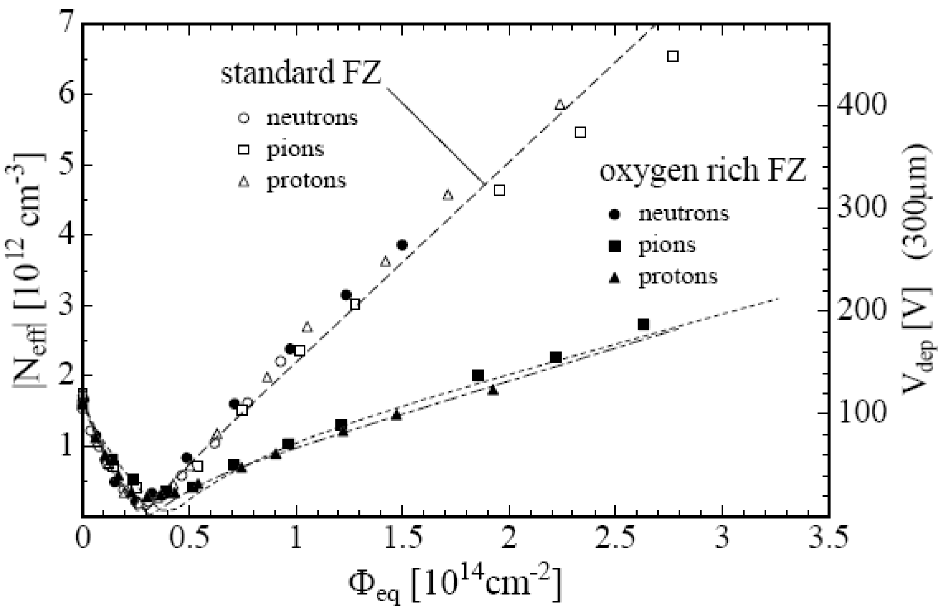
Radiation Effects 'Aging'

Increase in leakage current

Increase in depletion voltage

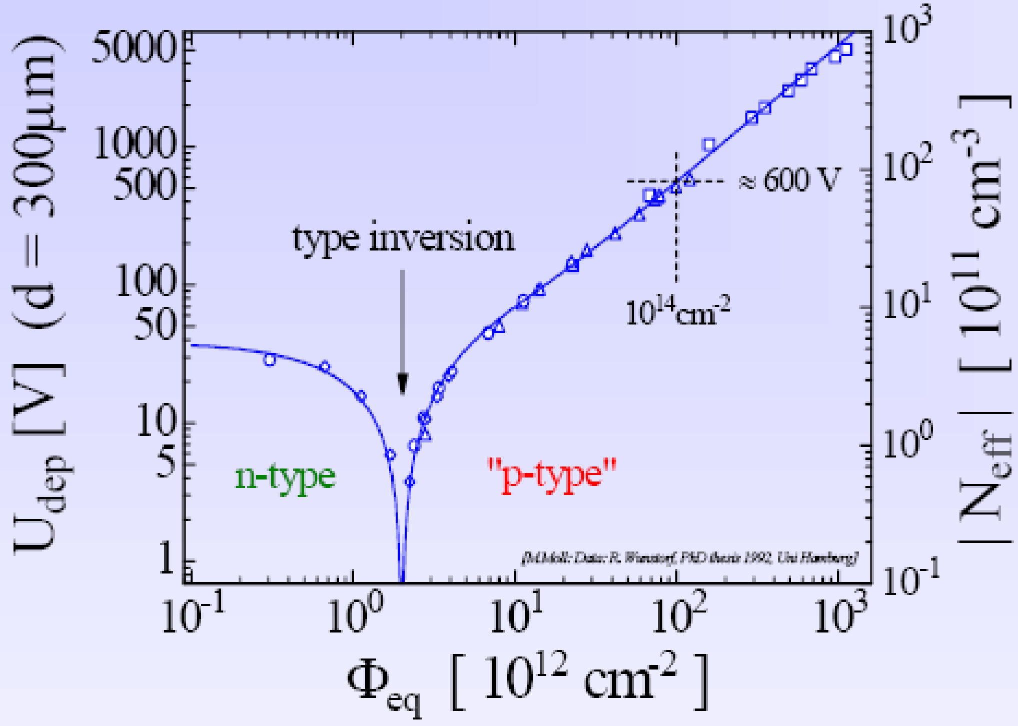
Decrease in charge collection efficiency due to underdepletion and charge trapping.





Radiation Effects 'Aging'

Type inversion ! An n-tyle Si detector becomes a p-type Si detector !



- "Type inversion": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

Silicon Detectors: towards higher Radiation Resistance

Typical limits of Si Detectors are at 10^{14}-10^{15} Hadrons/cm^2

LHC

- We can identify 3 different regions to match radiation damage and occupancy in the current LHC detector

R	Φ	Technology
>50 cm	10^{13}	p-on-n strip 500 µm thick, high resistivity (≈5 KΩ·cm), pitch ~ 200 µm
20-50 cm	10^{14}	p-on-n strips 320 µm thick, low resistivity (≈2 KΩ·cm), pitch ~80 µm
<20 cm	10^{15}	n-on-n pixels 270 µm thick sensors low resistivity (≈2 KΩ·cm) oxygenated

SLHC

- Radiation fluence increases by about a factor of 10 from one region to the other and by a factor of 10 between LHC and SLHC.

R	Φ	CCE	Technology
>50 cm	10^{14}	20ke	Present rad-hard technology (or n-on-p)
20-50 cm	10^{15}	10ke	Present n+-n LHC pixel (or n-on-p)
<20 cm	10^{16}	>5Ke	RD needed

R&D Strategy:

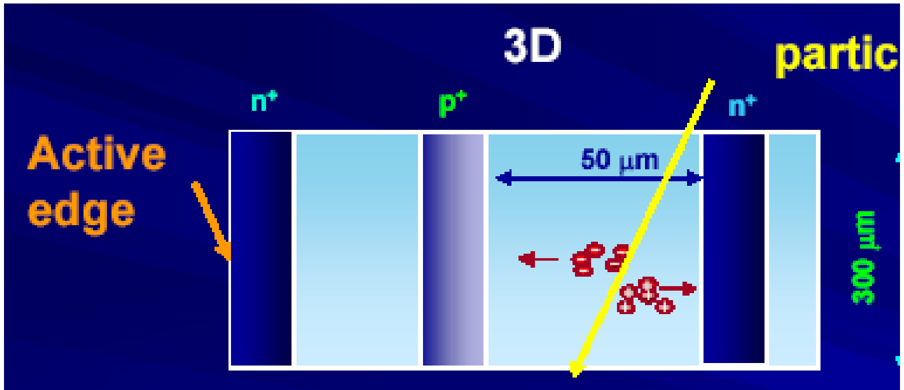
Defect Engineering
- Oxygen enriched Si

New Materials
- Diamonds
- Czochralski Si
- …

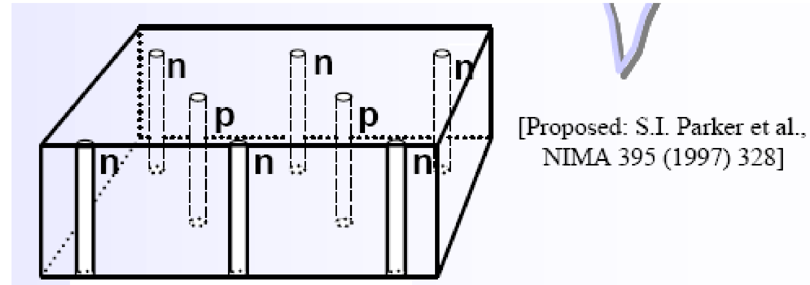
New Geometries

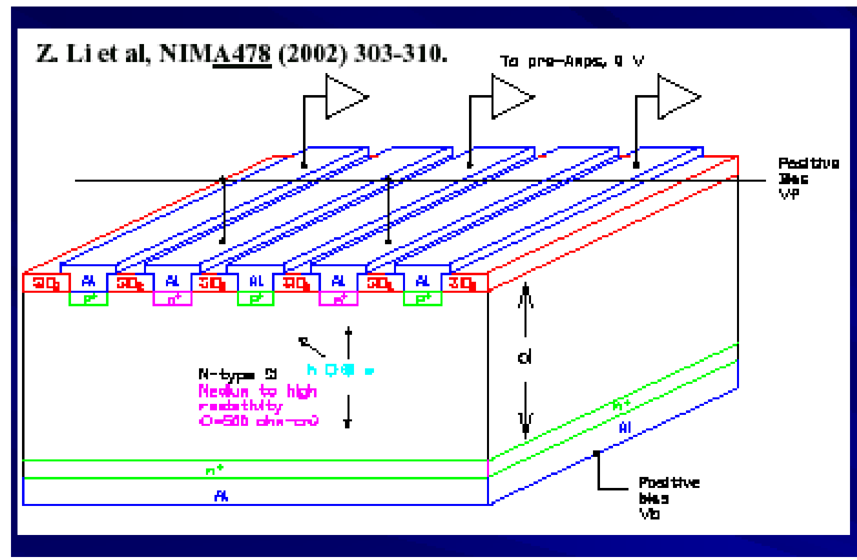
Low Temperature Operation

New Geometries: ‘3D’ Si Detectors



	3D	Planar
Q collection path	50µm	300 µm
$V_{depletion}$	<10V	70 V
Edge sensitivity	10µm	500 µm
Q Collection time	1-2 ns	10-20 ns





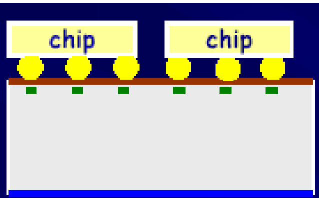
Good Performance after 10^{15} p/cm^2

High Resolution Low Mass Silicon Trackers, Monolithic Detectors

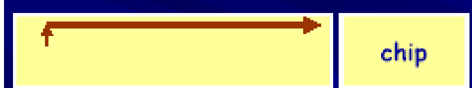
Linear Collider Physics requirement:

$\delta(IP) < 5\ \mu m \oplus 10\ \mu m/(p \sin^{3/2}\theta)$

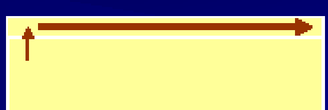
(best SLD $8\ \mu m \oplus 33\ \mu m/(p \sin^{3/2}\theta)$)



Hybrid Active Pixel: Chip bump bonded to sensor
RD: make it thinner (LHC sensors 2% X_0/layer), improve space point resolution with interleaved pixels

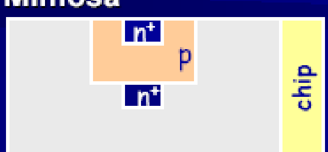


CCD: charge collected in thin layer and transferred through silicon
RD: readout speed, radiation hardness, material support



CMOS sensors (MAPS, FAPS): standard CMOS wafer integrates all functions.
RD: fast readout, non-standard technologies

Poster by Deptuch on Mimosa



DEPFET, CMOS on SOI (talk by Kucewiz) :
Fully depleted sensor with integrated preamp
RD:pixel size, power, thinning, speed

Large variety of monolithic pixel Detectors explored, mostly adapted to low collision rates of LC.

Radiation Hardness up to Approx. 10^{13} hadrons/cm^2

‘Speed’ on the microsecond scale.

Summary on Solid State Detectors

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5um) for vertex measurement and also for momentum spectroscopy over large areas.

Technology is improving rapidly due to rapid silicon development for electronics industry.

Typical number where detectors start to strongly degrade are 10^{14}-10^{15} hadron/cm^2.

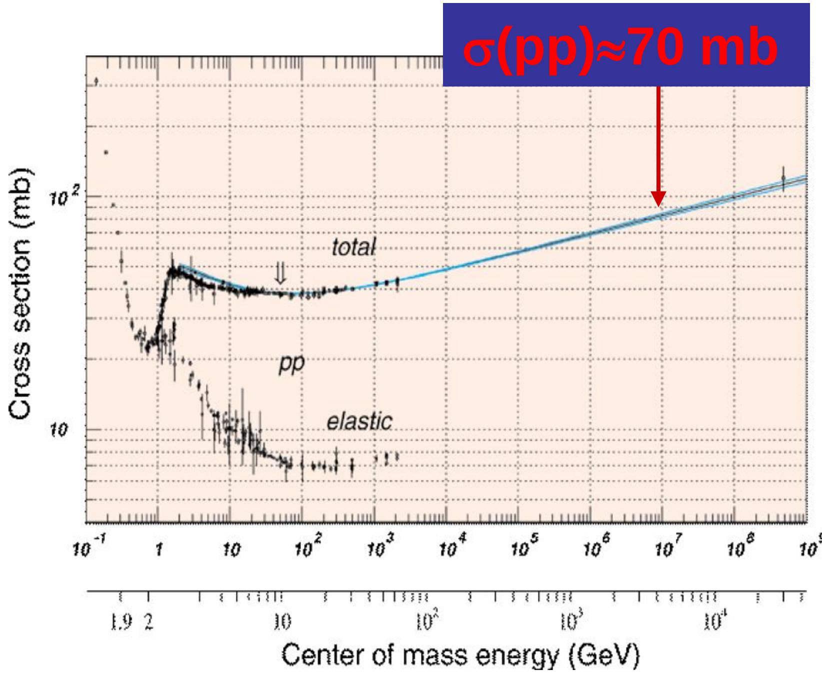
Diamond, engineered Silicon and novel geometries provide higher radiation resistance.

Clearly, monolithic solid state detectors are the ultimate goal. Current developments along these lines are useful for low rate applications.

The Challenge at LHC

– **Interactions/s:**
  - **Lum = 10^{34} $cm^{-2}s^{-1}$ = 10^{7} mb^{-1}Hz**
  - **σ(pp) = 70 mb**
  - **Interaction Rate, R = 7×10^{8} Hz**

– **Events/beam crossing:**
  - **Δt = 25 ns = 2.5×10^{-8} s**
  - **Interactions/crossing=17.5**

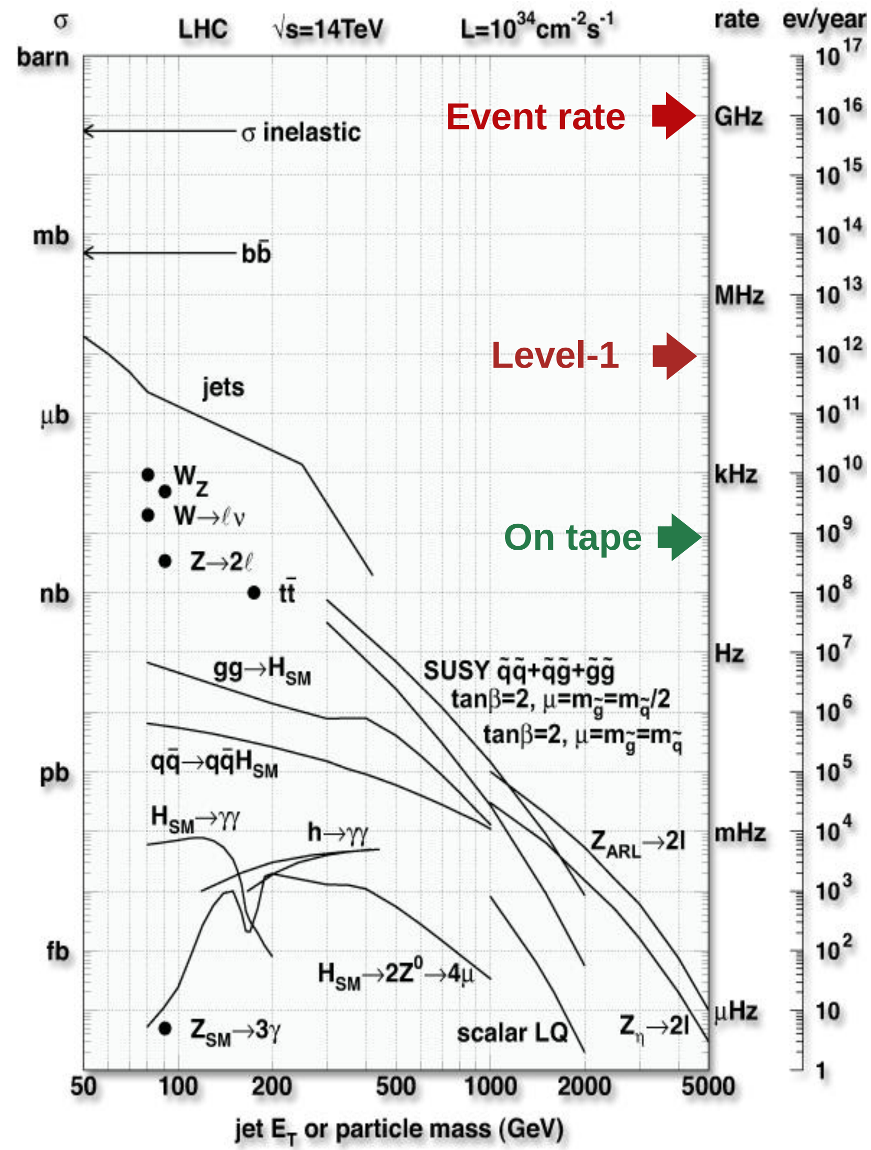


Selectivity: the Physics

- Cross sections of physics processes vary over many orders of magnitude
  - Inelastic: 10^9 Hz
  - $W \to \ell \nu$: 10^2 Hz
  - t t production: 10 Hz
  - Higgs (100 GeV/c^2): 0.1 Hz
  - Higgs (600 GeV/c^2): 10^{-2} Hz

- QCD background
  - Jet E_T ~250 GeV: rate = 1 kHz
  - Jet fluctuations $\to$ electron bkg
  - Decays of K, π, b $\to$ muon bkg

- Selection needed: $1{:}10^{10-11}$
  - Before branching fractions...



P. Sphicas – 2006 CERN summer student lectures

Triggering

Inspect detector information and provide a first decision on whether to keep the event or throw it out.

Detector data not (all) promptly available → Selection function is highly complex and is evaluated by successive approximations, the so called Trigger Levels.

Task at LHC →
Reduce the 40MHz interaction rate to 100Hz data rate on tape.

Even more sophisticated triggering strategies needed for HL-LHC, i.e. possibly track triggering at first trigger level !

The future challenges

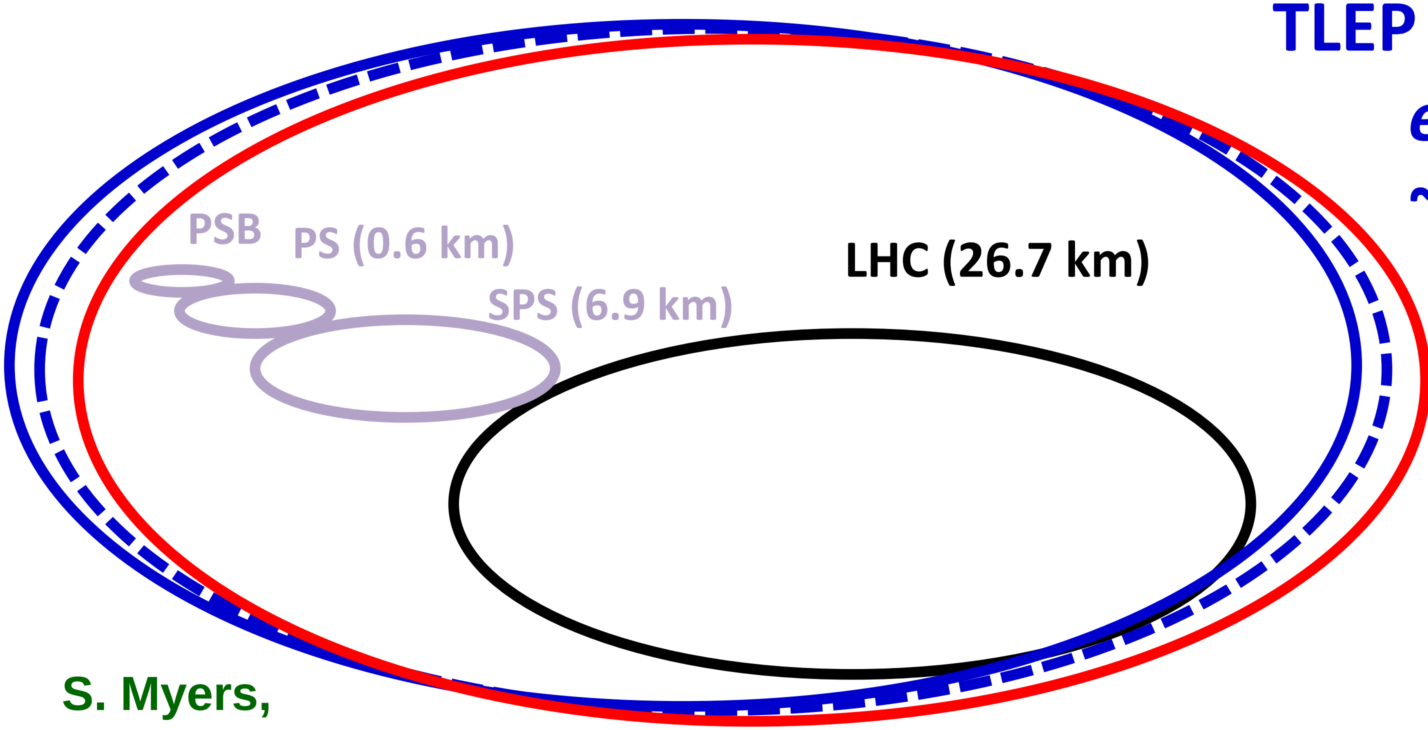
What's Left??

- LHC
  - HL-LHC ✓
  - ~~HE-LHC~~
  - ~~LHeC,~~
  - VHE-LHC
    - TLEP
    - VHE-LHeC
- ILC
- CLIC
- (~~Muon colliders~~)

Personal view of S. Myers, EUCARD meeting June 2013

possible long-term strategy

(CERN implementation)



TLEP (80-100 km, e^+e^-, up to ~350 GeV c.m.)

VHE-LHC (*pp*, up to 100 TeV c.m.)

“same” detectors!?

S. Myers, EUCARD meeting June 2013

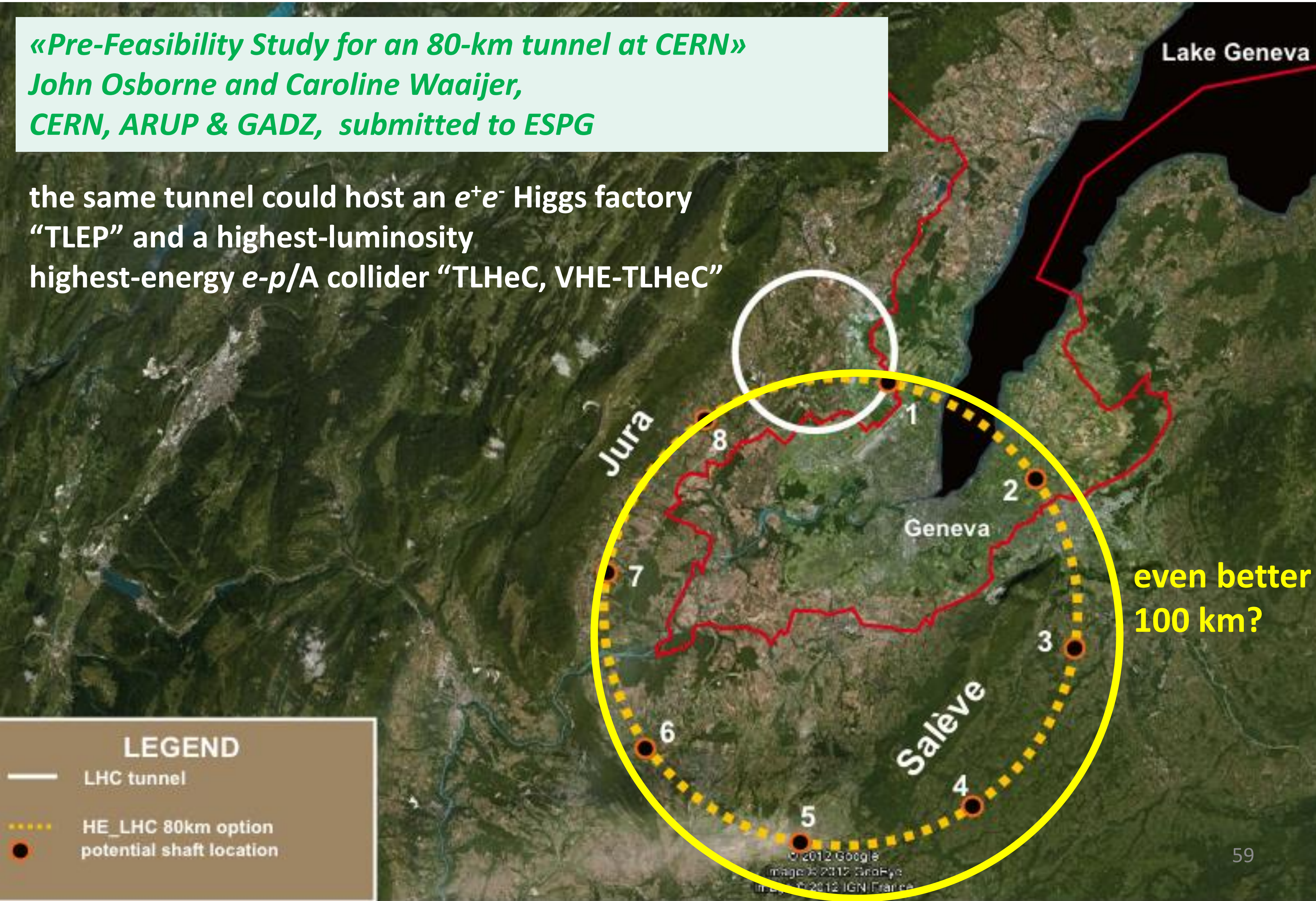
& ***e*$^\pm$ (120 GeV)–*p* (7, 16 & 50 TeV)** collisions **([(V)HE-]TLHeC)**

≥50 years of *e^+e^-*, *pp*, *ep/A* physics at highest energies

80-km tunnel for VHE-LHC – “best” option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG

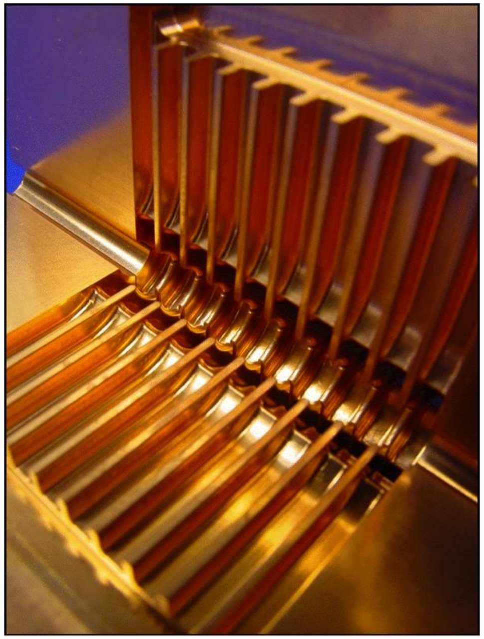
the same tunnel could host an e^+e^- Higgs factory “TLEP” and a highest-luminosity highest-energy *e*-*p*/A collider “TLHeC, VHE-TLHeC”



ILC ad CLIC in just a few words

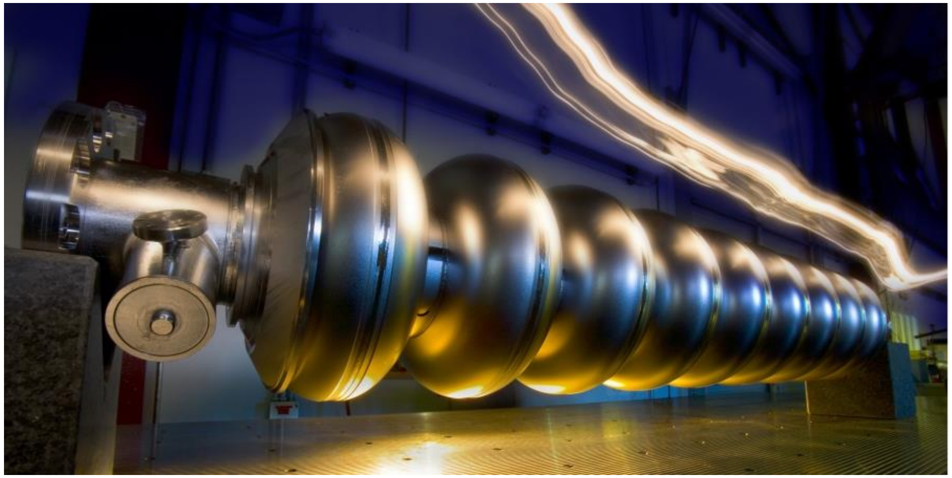
Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

CLIC



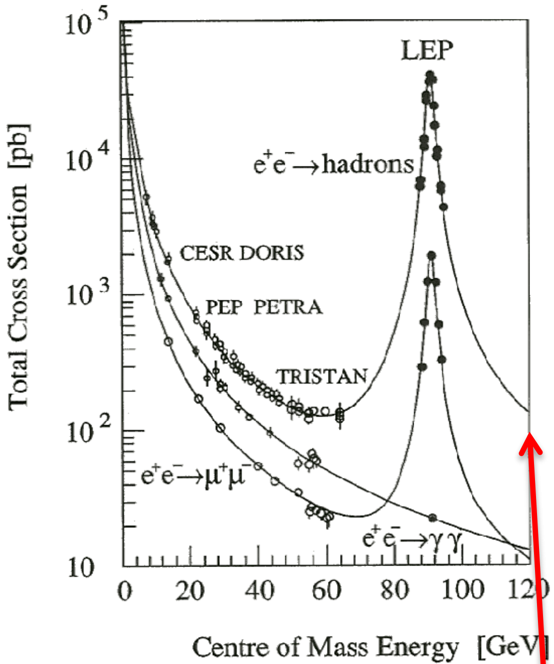
- 2-beam acceleration scheme, at room temperature
- Gradient 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

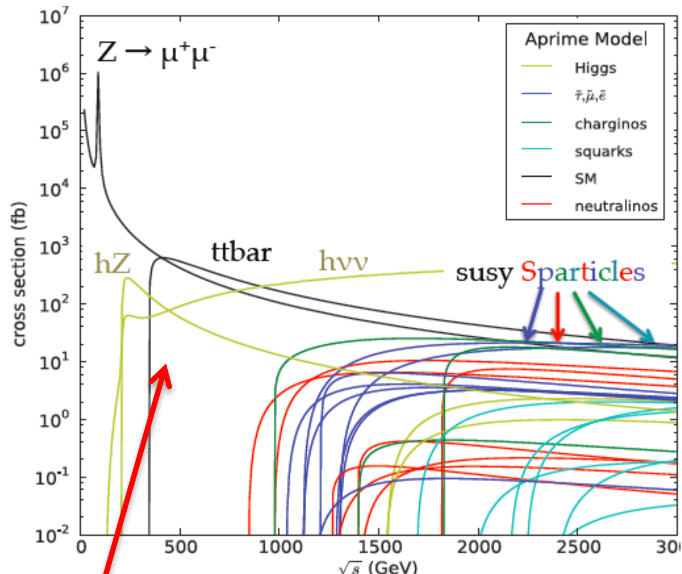
ILC

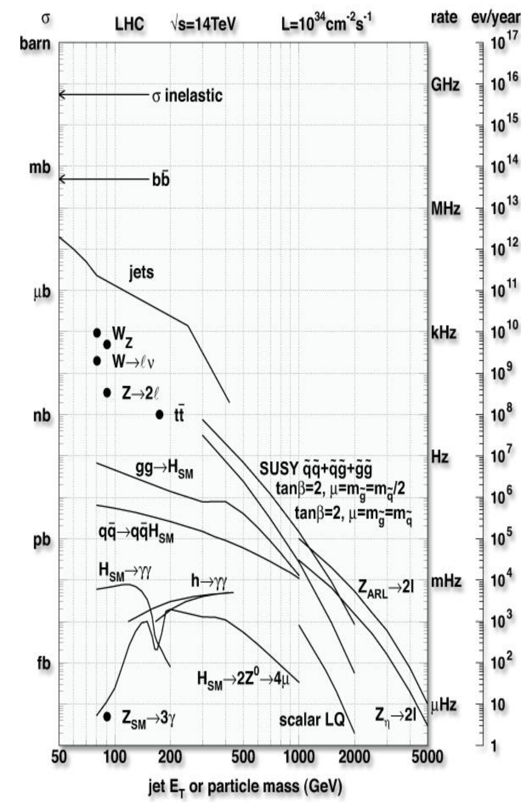


- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, ongoing studies for 1 TeV

Crossections at Lepton Colliders





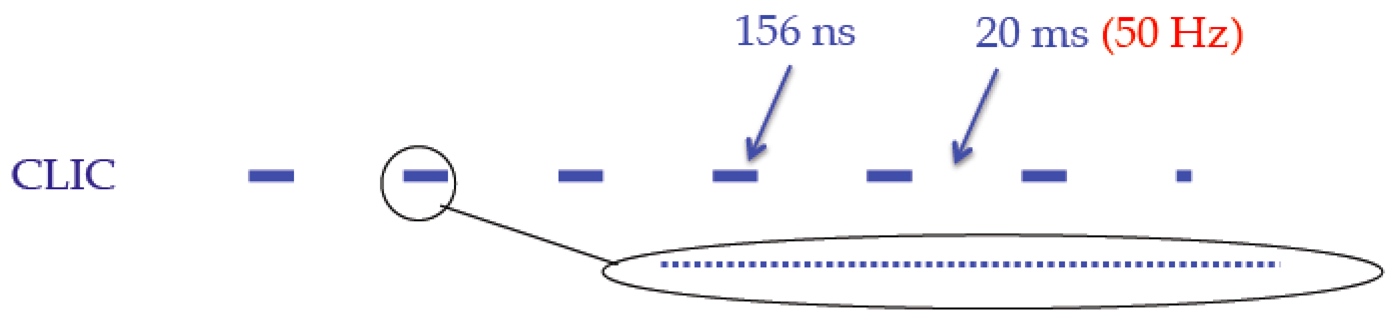


100pb 100fb

Detector at Lepton Colliders have to deal with much less particle rates and radiation loads.

→ Easy (no) Trigger
→ Technology with very low rate capability and radiation tolerance is possible !

Beam structure

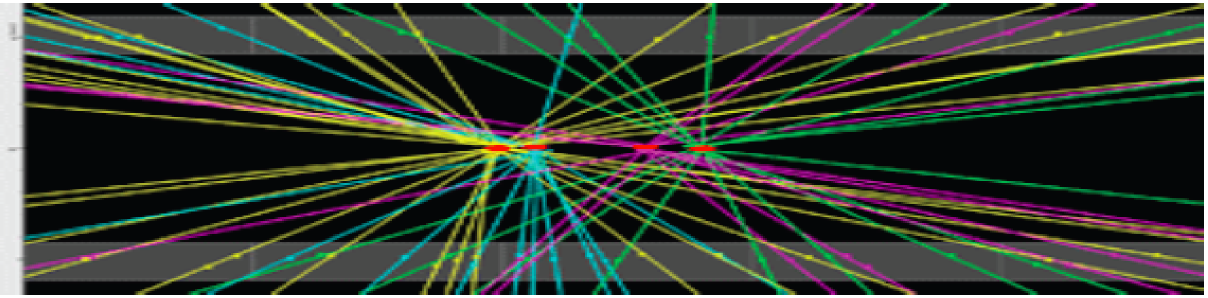


	CLIC 3 TeV	LHC 14 TeV (nominal)
Bunch crossing separation [ns]	0.5	25
Crossing angle	20 mrad	200 μrad
Instantaneous luminosity [$cm^{-2}s^{-1}$]	6×10^{34}	1×10^{34}

Low duty cycle at CLIC:

- 312 BXs per train; all BXs read out in-between bunch trains. No trigger.
- All subdetectors will implement power pulsing schemes at 50 Hz, to reduce needed cooling systems

Pile up at interaction point



ATLAS

	CLIC 3 TeV	LHC 14 TeV (ATLAS)
IP size in x / y / z direction	45 nm / 1 nm / 40 µm	15 µm / 15 µm / ~5 cm

Pile up of:

- LHC: 23 minimum bias over triggered event, each 25 ns.
  - Interaction Points smeared over 5 cm.
- CLIC with 312 BXs / train:
  - Overlapping beam-induced background, *all* at one interaction point.

- At CLIC the IP-spot can be used as constraint in track-reconstruction, at LHC it cannot.

Readout challenge

CLIC frequency of interesting events < ~ 1 / train.

- In high occupancy regions, need multi-hit storage / readout
  With accurate time stamping
- Electronics do not need trigger
- Offline background suppression

	CLIC 3 TeV	LHC 14 TeV (ATLAS)
Trigger [# selected events : # total events]	1 : 1	200 : 10^9
Total data rate after trigger [GBytes/sec]	200	0.3

LHC:

- Major challenge in the (multiple levels of) trigger

CLIC Detector Requirements

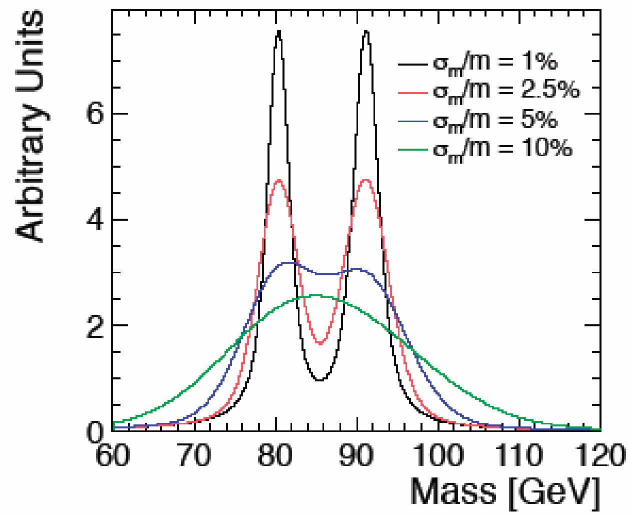
- High-resolution pixel detector for flavor tagging
  p = 1 GeV: σ_{d0}~20 μm (CMS: 90 μm)
  p = 100 GeV: σ_{d0}~5 μm (CMS: ~10μm)

- momentum resolution for high energy lepton final states

  p = 100 GeV: $\sigma(p_T)/p_T = 0.2\%$ (CMS: 1.5%) $\sigma_{pT} / p_T^2 \sim 2{\cdot}10^{-5}\ \mathrm{GeV}^{-1}$

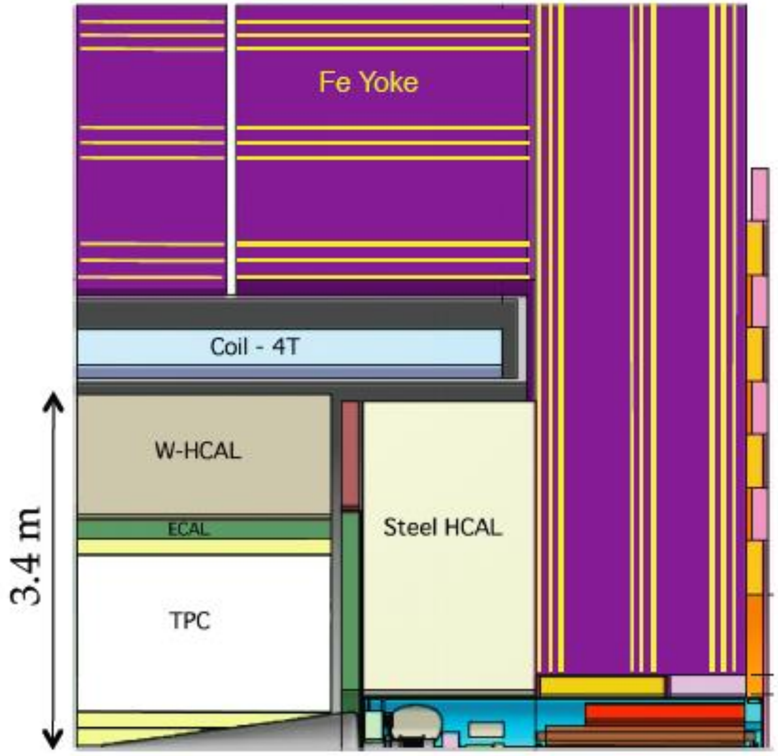
- Need very good jet-energy resolution to distinguish W / Z dijet decays (to be reached with PFA)

E	=	10^2	–	10^3 GeV:
$\sigma(E_j)/E_j$	~	5.0%	–	3.5%
ATLAS	~	8.0%	–	4.0%

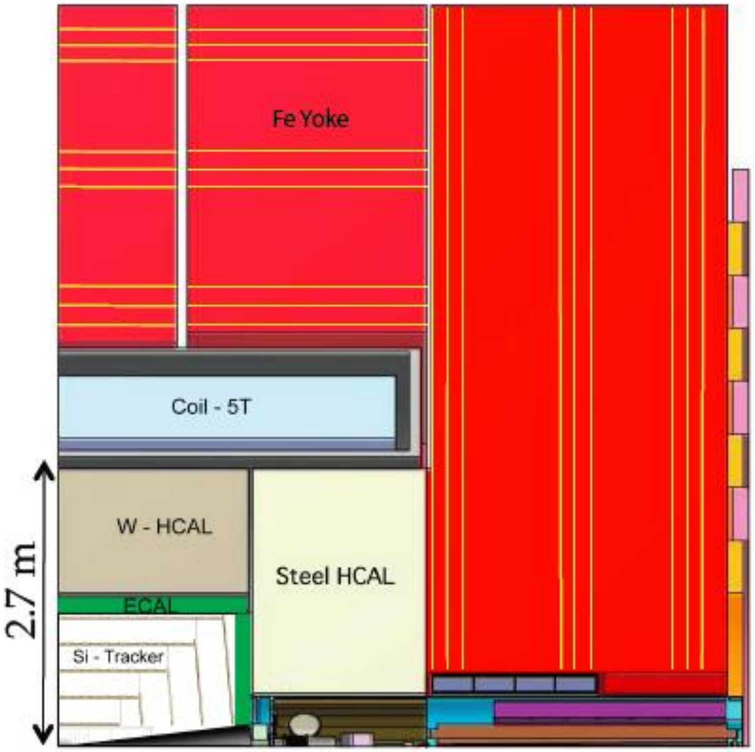


Two general purpose CLIC detector concepts

¼ views: CLIC_ILD

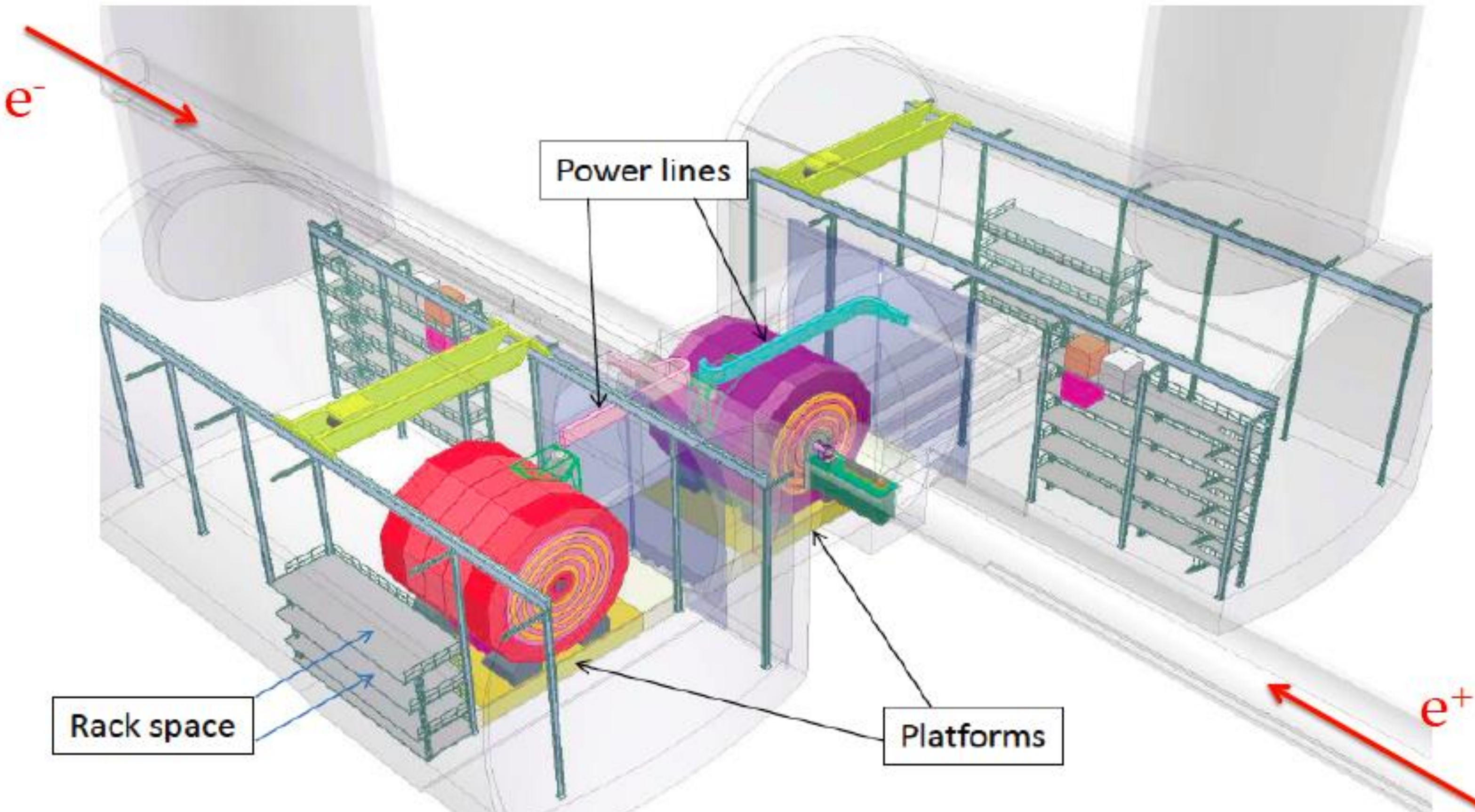


CLIC_SiD



- Difference in tracking systems
- Both have Tungsten in the barrel HCAL, to have a highest possible density and keep the coil radius limited.

Two detectors in Push-Pull



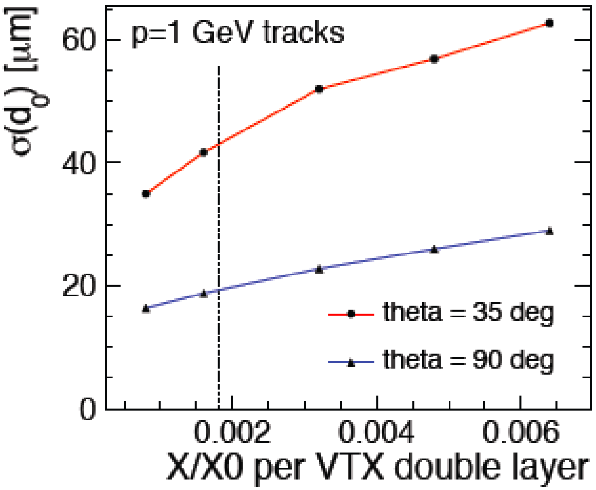
Overall sizes

- For CLIC the design resembles CMS
  - Calorimeters to be placed inside the solenoid for accurate PFA analysis
- CLIC detectors are much shorter than CMS

	CLIC_ILD	CLIC_SiD	CMS	ATLAS
Full detector height & length [m]	H: 14 L: 14	H: 14 L: 14	H: 15 L: 20	H: 22 L: 46
Magnetic field [T]	4	5	3.8	2.0 (solenoid) 0.5 – 1.0 (toroid)
Solenoid inner radius + thickness [m]	3.4 + 0.7	2.7 + 0.8	3.0 + 0.6	1.2 + 0.2
Yoke inner radius + thickness [m]	4.5 + 2.7	3.8 + 2.9	4 + 3	HCAL: 2.3 + 1.6
Yoke mass – Detector mass [10^3 tons]	10 – 12	11 – 12.5	10 – 12.5	4 – 7

Vertex detector

	CLIC	ATLAS	CMS
$\sigma_{r\phi}$ [μm]			
$p_T = 1$ GeV	~20	75	90
$p_T = 1$ TeV	5	11	9



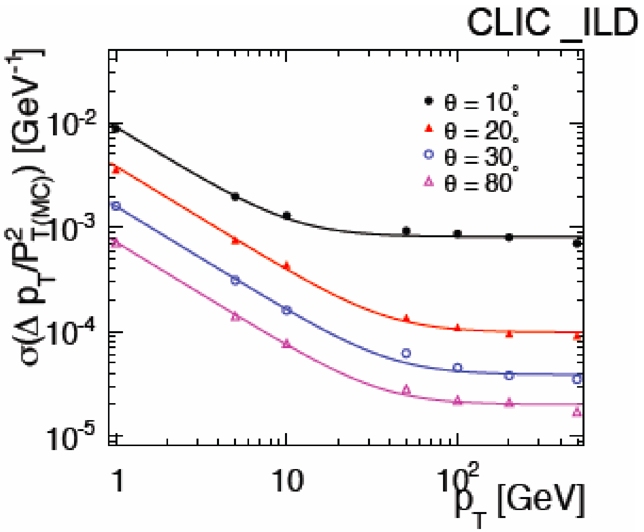
R&D aims at

- Low material budget: $X \lessapprox 0.2\% X_0$ / layer
  - Corresponds to ~200 μm Si, including supports, cables, cooling
- Low-power ASICs (~50 mW / cm^2) + air-flow cooling
- Maintaining high granularity and precise time stamping (~10 ns)

→ See Dominik Dannheim seminar (23 / 11 / '12) for more on VTX

Track momentum resolutions

- CMS tracker, with high point resolution, is very accurate in strong magnetic field
- Large ATLAS air-core muon spectrometer results in better momentum reconstruction in the forward region.
- CLIC muon system is not used for momentum measurement.



		CLIC_ILD	ATLAS	CMS
Inner Detector (at 90°)	**p = 100 GeV**	0.2%	3.8%	1.5%
Incl. muon sys. (at 90°)	**p = 1 TeV**	2%	10.4%	4.5%
Incl. muon sys. (~ θ = 15°)	**p = 1 TeV**	10%	4.4%	7.0%

η ~ 2

Summary of Challenges

Detector for HL-LHC must cope with 5x increased radiation and occupancy requirements as compared to LHC. Clever trigger algorithms have to be employed in order to keep sufficient selectivity for interesting events.

Detectors for ILC and CLIC are of similar size as LHC detectors but have to deal with much lower rates. This allows to use technologies like monolithic silicon detectors or TPCs to arrive at ultimate vertex and tracking resolution.

Detectors for future high energy hadron colliders will operate collision rates similar to HL-LHC but have to scale according to L^2/B in order to measure the 10 times higher particle energies at similar precision.

Rapid silicon technology development is a key factor in achieving improved radiation hardness and performance in the future.