EIROforum 2013
School of Instrumentation

Detector Systems

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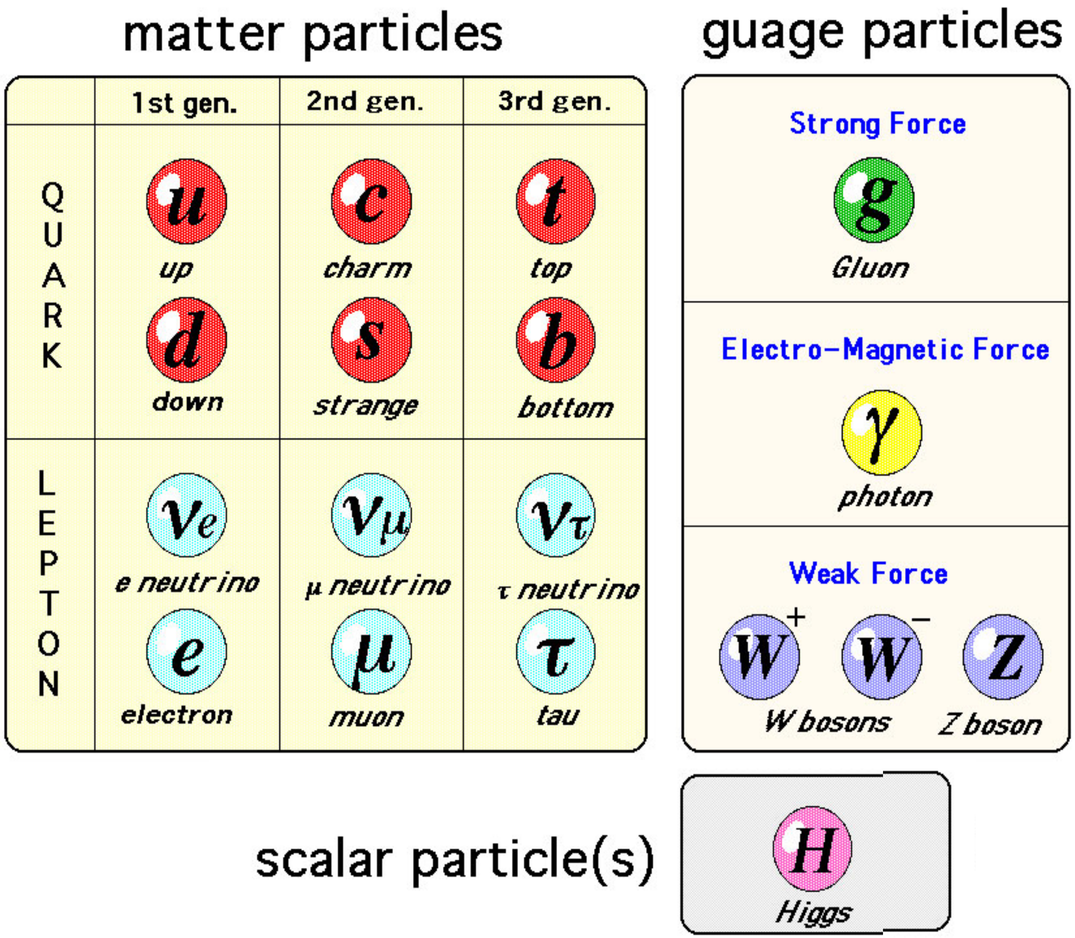
28.5. 2013

Standardmodel



Quarks are not seen as free particles but they form Mesons and Baryons.

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

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

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	"Secondary Vertices"
$B^{0}(b\bar{d}, d\bar{b})$	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	

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.

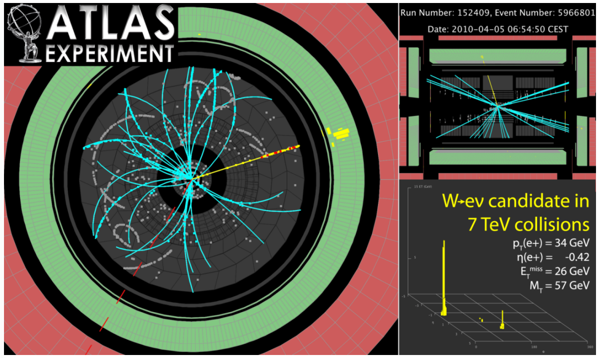
~13 of the 27 have $c\tau < 500\mu m$ i.e. only ~mm range at GeV Energies.
→ "short" tracks measured with Emulsions or Vertex Detectors.

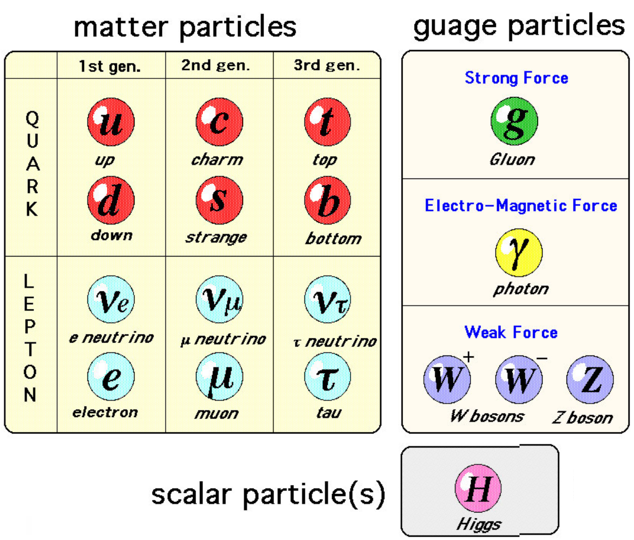
From the ~14 remaining particles

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

are <u>by far</u> the most frequent ones

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

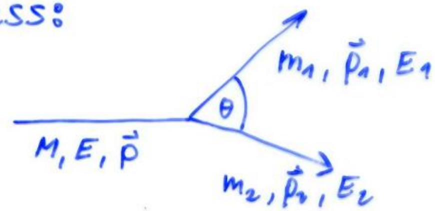




Basics

Invariant Mass:

LAB:



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

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

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

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

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

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

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

gives the Mass of the original Particle

/CERN

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

Basics

Lorentz Boost:

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

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^- $\tau \sim 2.6 \cdot 10^{-8}\, s$, $m_\pi c^2 = 135\, MeV$

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

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:

$$\left.\begin{array}{ll} e^{\pm} & m_e = 0.511\ \mathrm{MeV} \\ \mu^{\pm} & m_\mu = 105.7\ \mathrm{MeV} \sim 200\, m_e \\ \gamma & m_\gamma = 0\ ,\quad Q = 0 \end{array}\right\}\ \mathrm{EM}$$

$$\left.\begin{array}{ll} \pi^{\pm} & m_\pi = 139.6\ \mathrm{MeV} \sim 270\, m_e \\ K^{\pm} & m_K = 493.7\ \mathrm{MeV} \sim 1000\, m_e \\ p^{\pm} & m_p = 938.3\ \mathrm{MeV} \sim 2000\, m_e \end{array}\right\}\ \begin{array}{l} \mathrm{EM,\ Strong} \\ \sim 3.5\, m_\pi \end{array}$$

$$\left.\begin{array}{ll} K^0 & m_{K^0} = 497.7\ \mathrm{MeV} \quad Q = 0 \\ n & m_n = 939.6\ \mathrm{MeV} \quad Q = 0 \end{array}\right\}\ \mathrm{Strong}$$

The Difference in

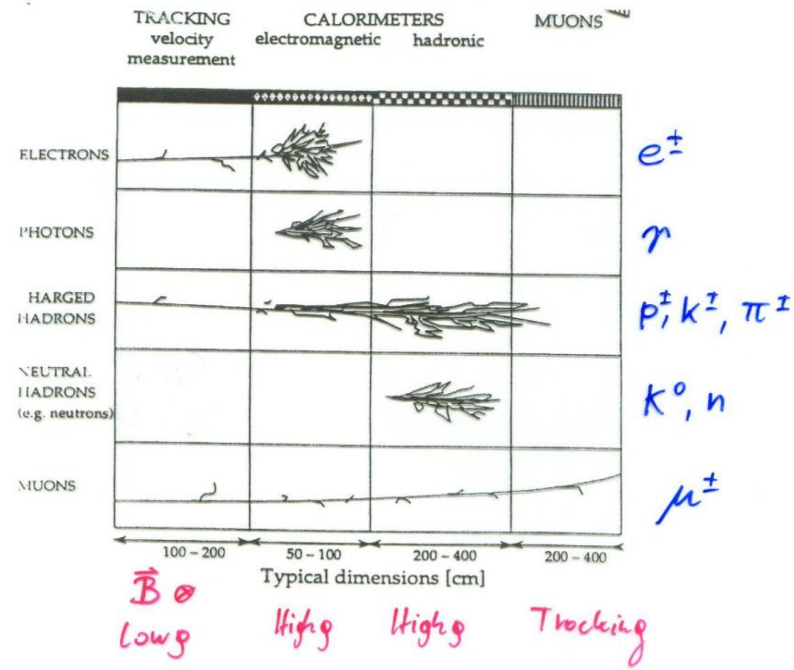
Mass, Charge, Interaction

is the key to the Identification

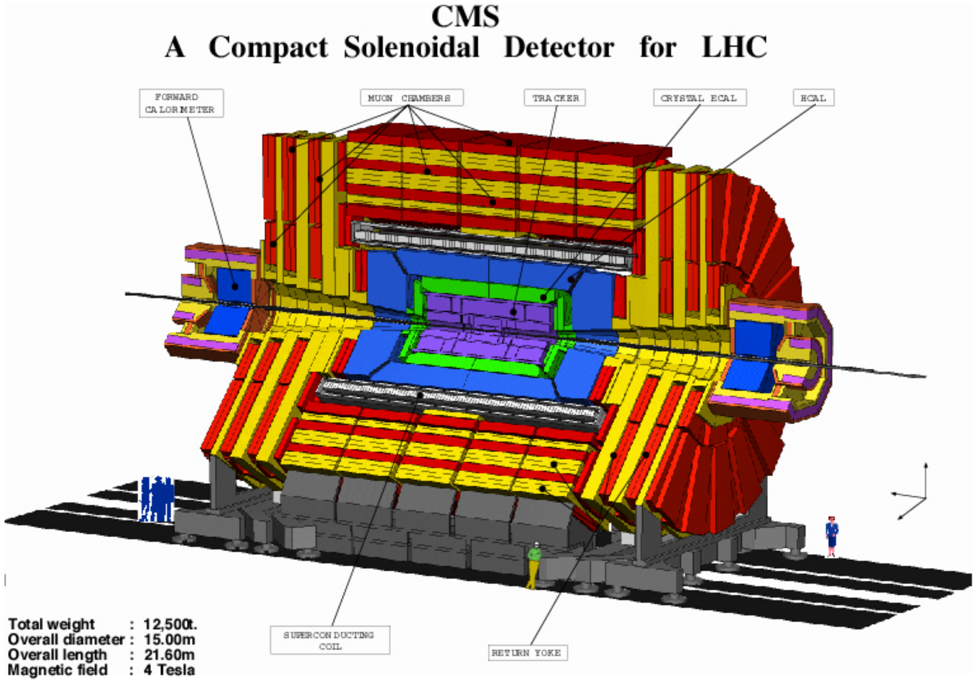
Tracking:
Momentum by bending in the B-field
Secondary vertices

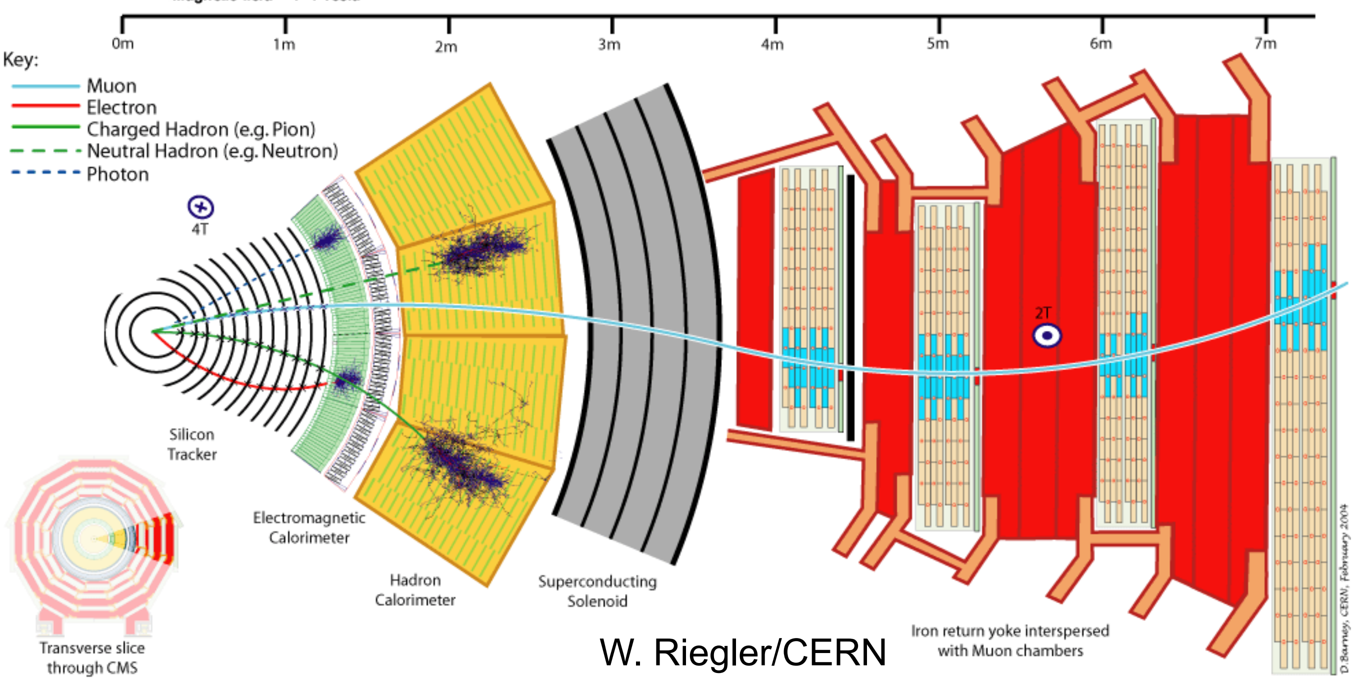
Calorimeter:
Energy by absorption

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
- Muons ionize and don't shower





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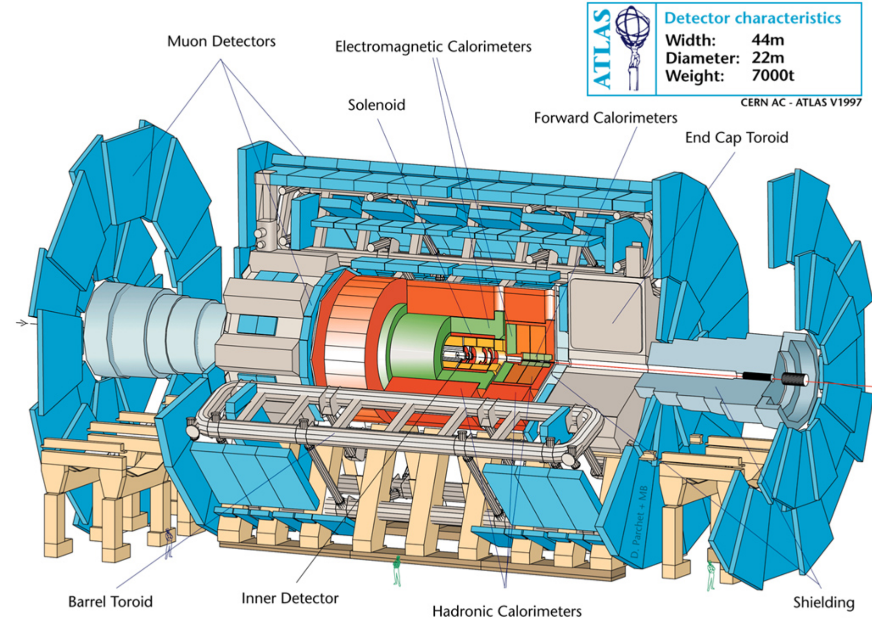
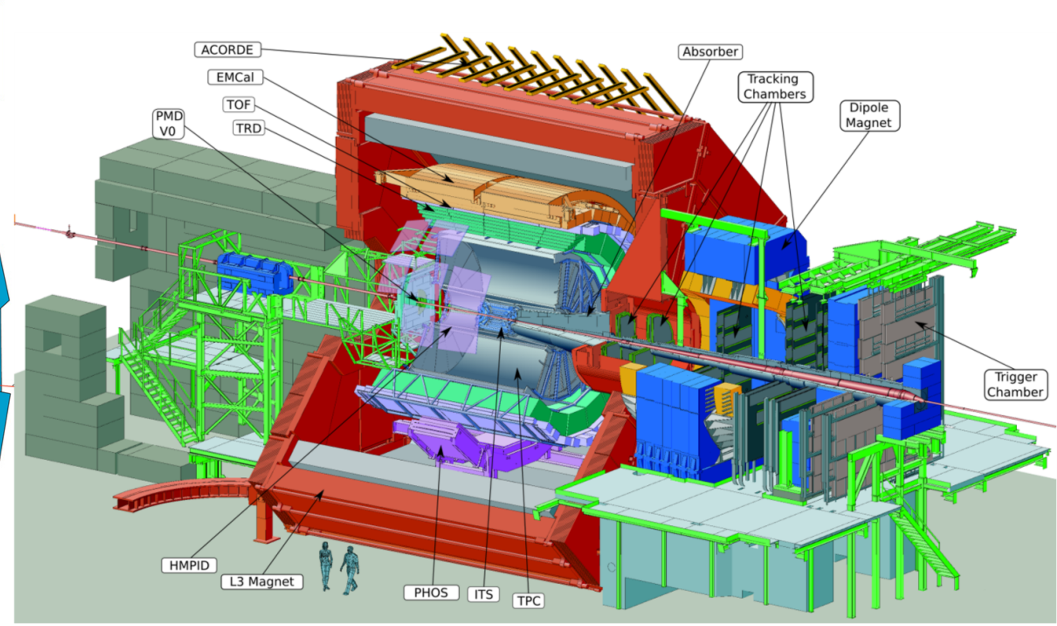
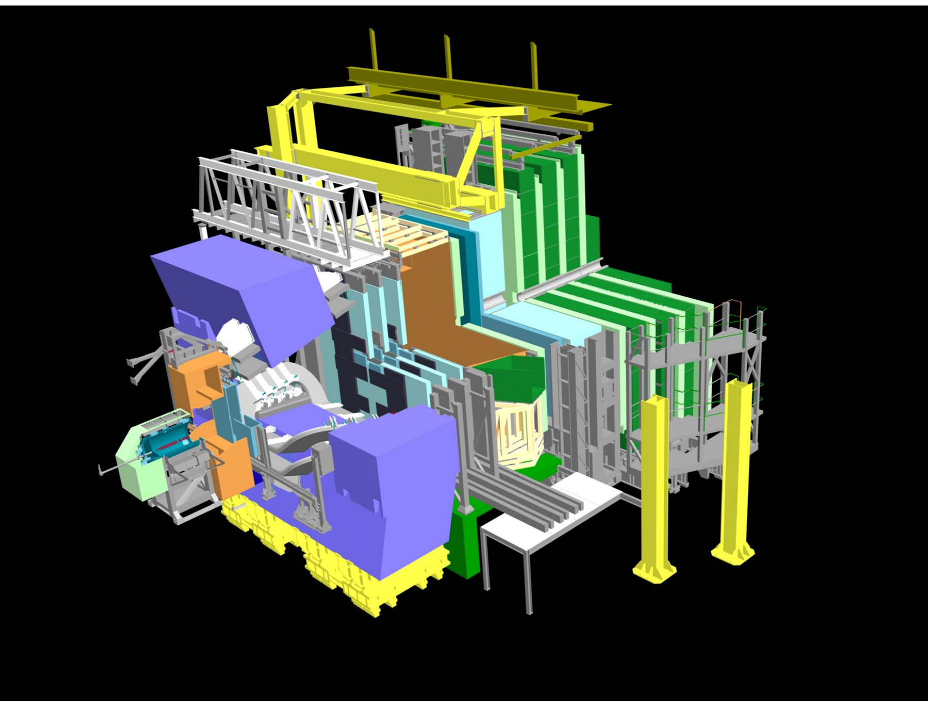
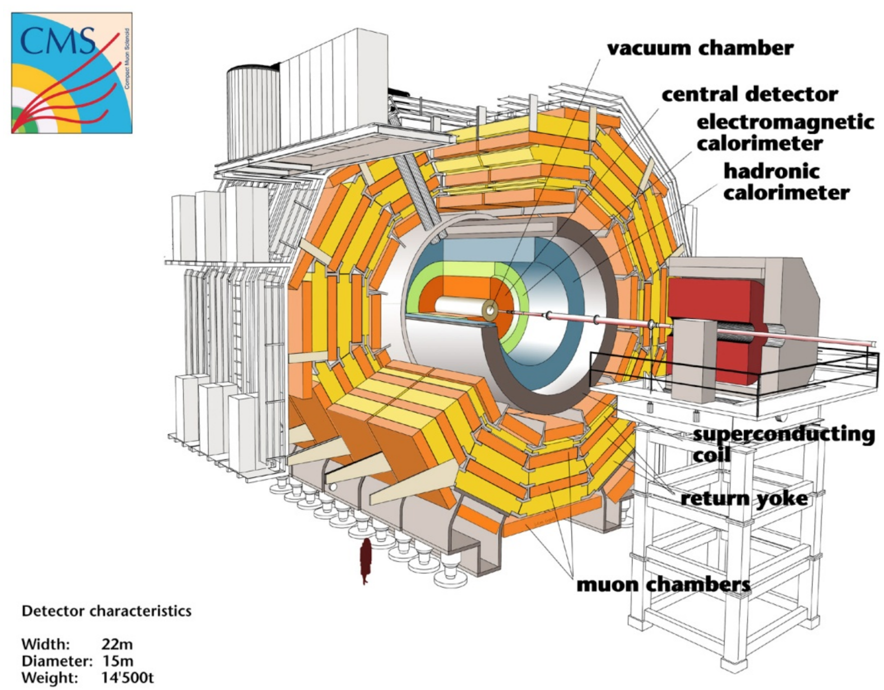

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

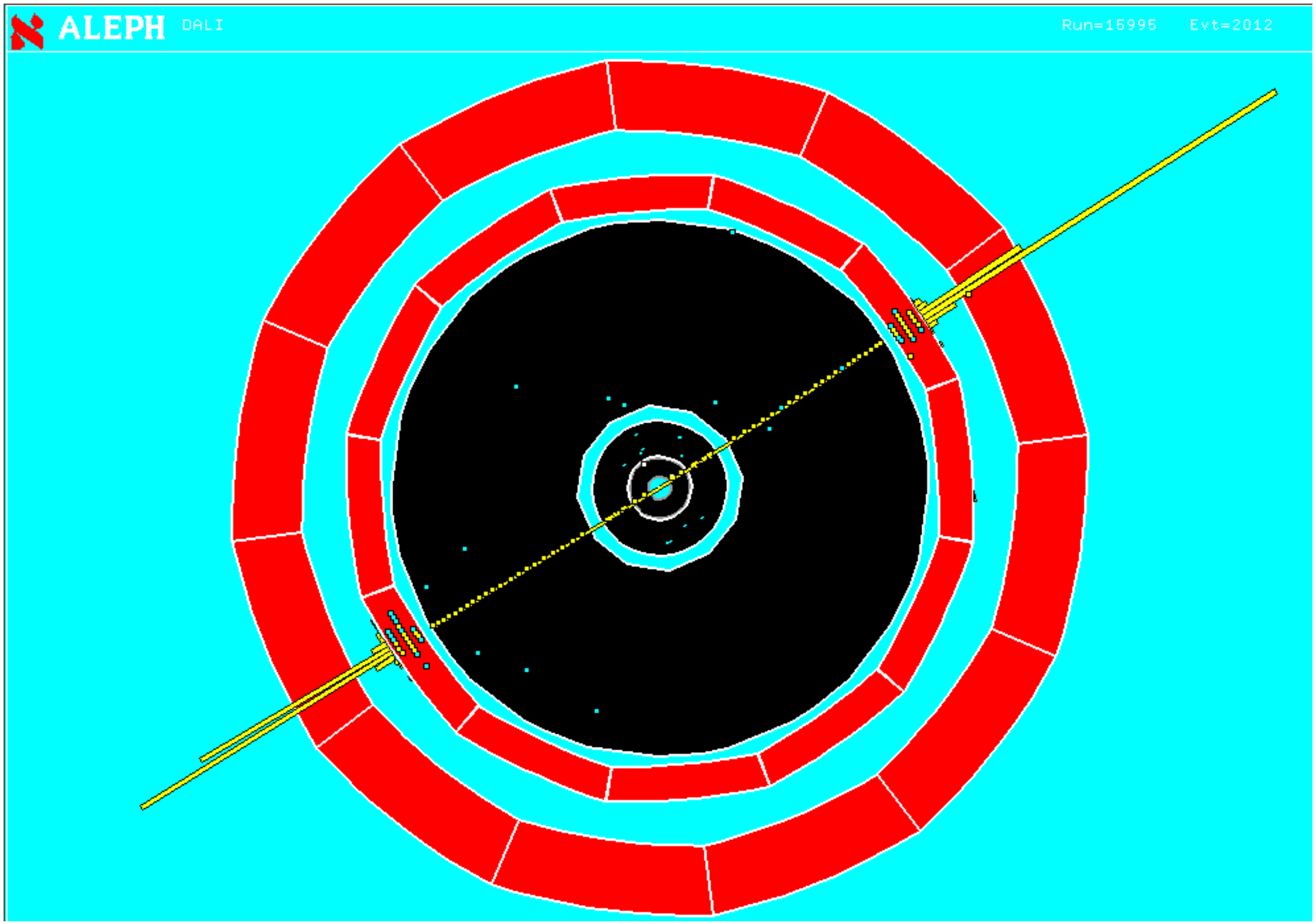

ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC




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

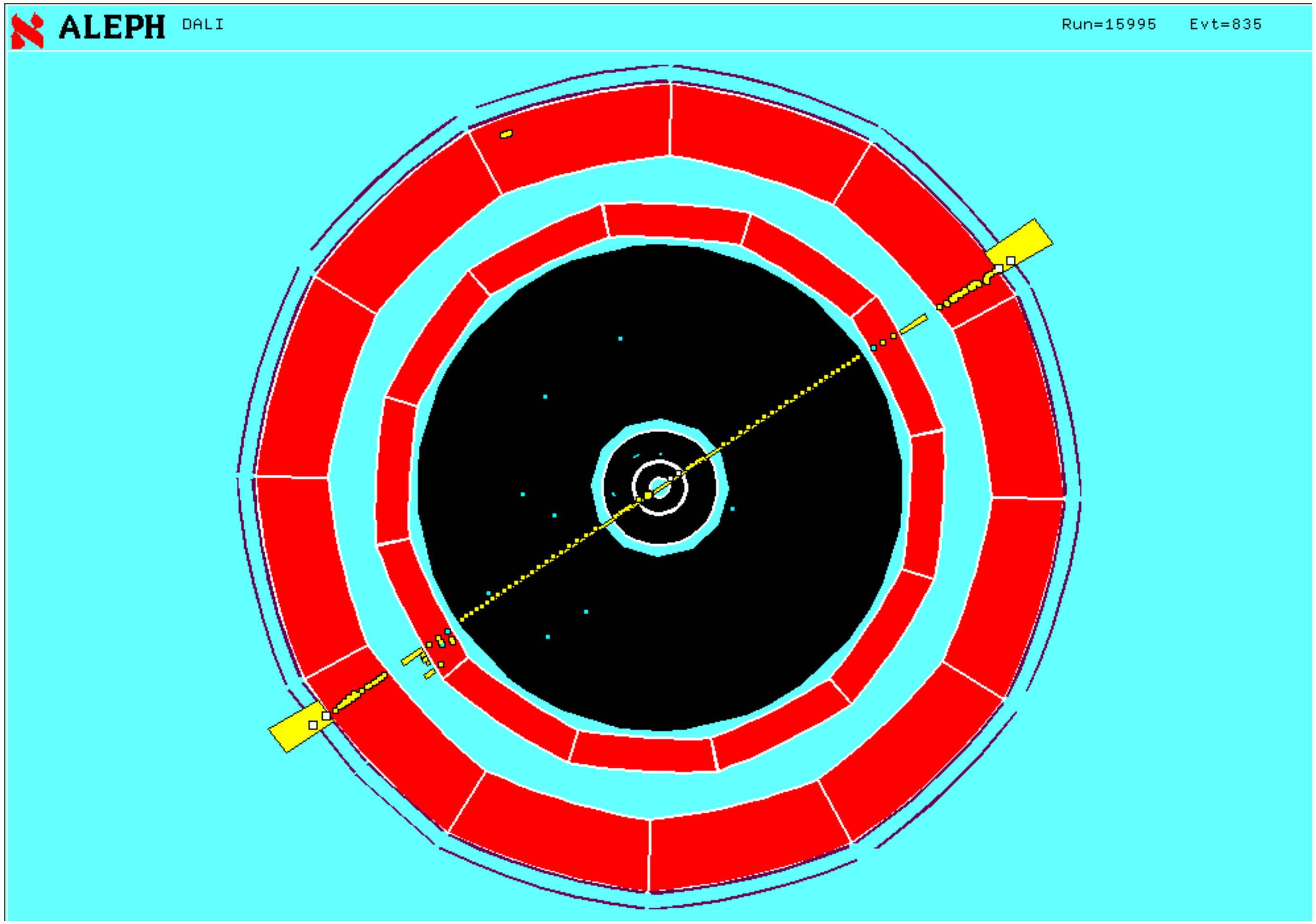
$Z \rightarrow e^+ e^-$

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.

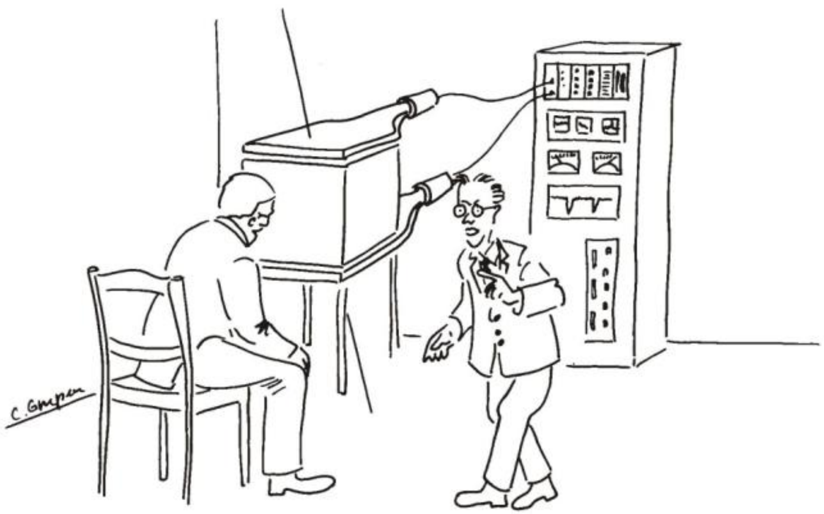


Interaction of Particles with Matter

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.

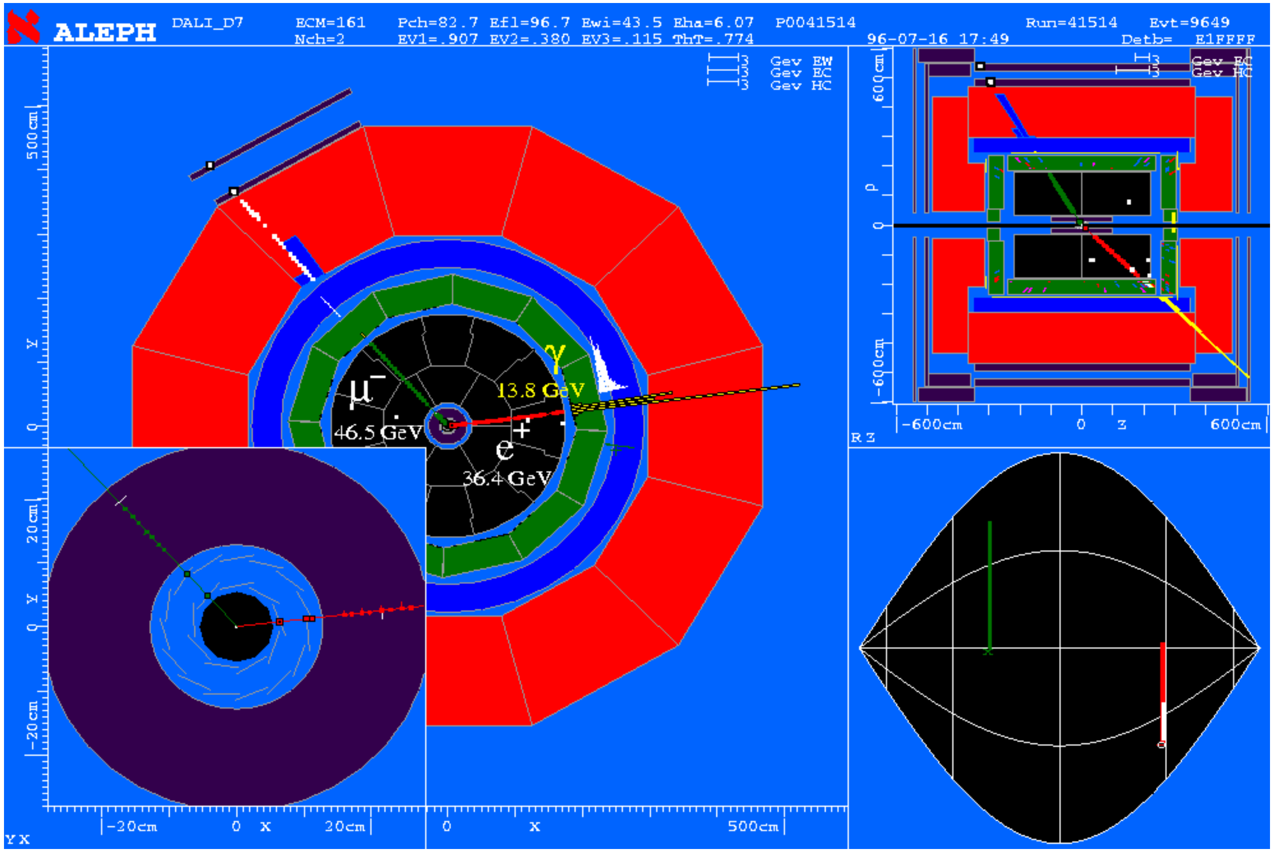


"Did you see it?"
"No nothing."
"Then it was a neutrino!"

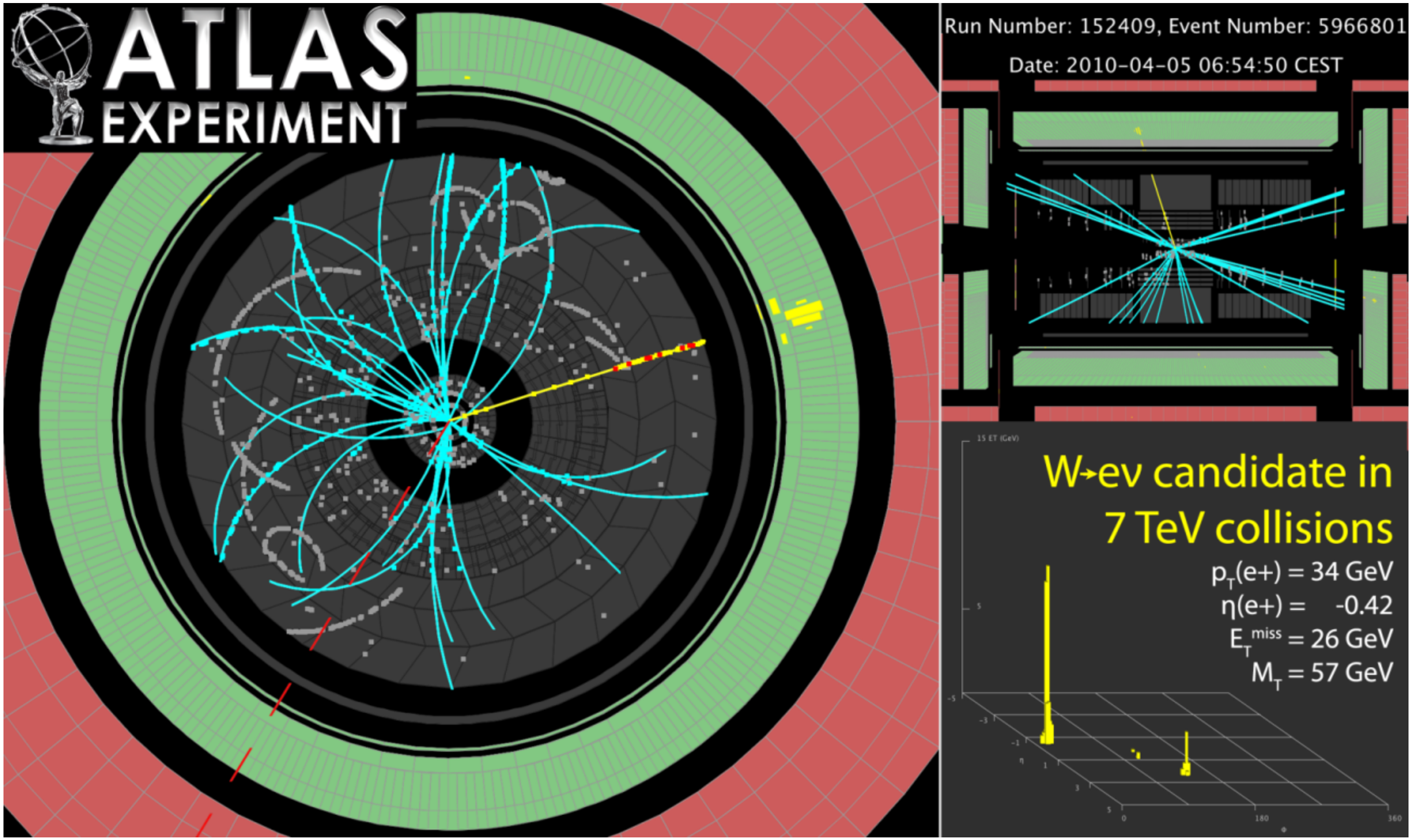
Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

$W^+W^- \rightarrow e + \nu_e + \mu + \nu_\mu$

Single electron, single Muon, Missing Momentum

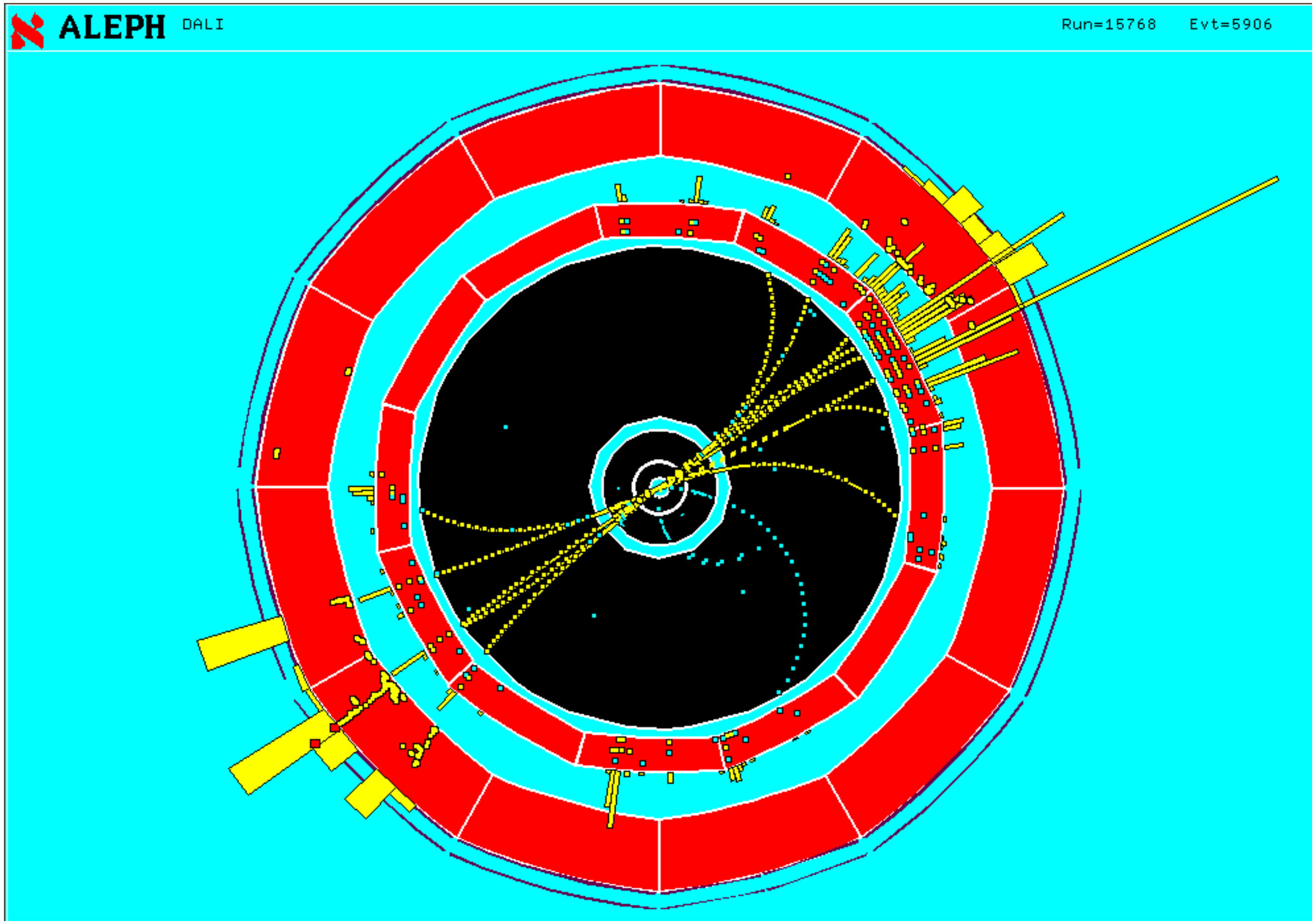


2010 ATLAS W candidate



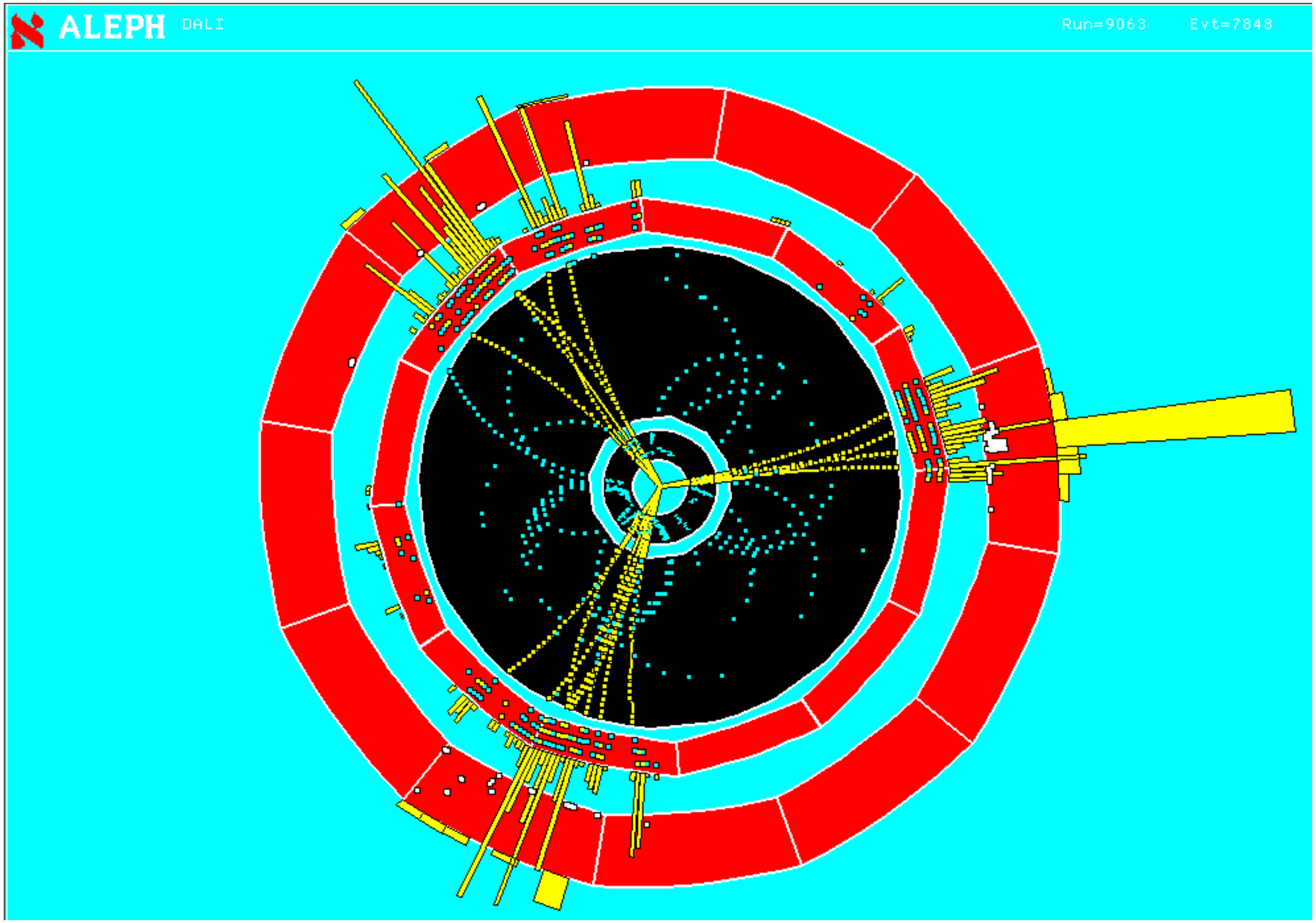
$Z \rightarrow q\bar{q}$

Two jets of particles



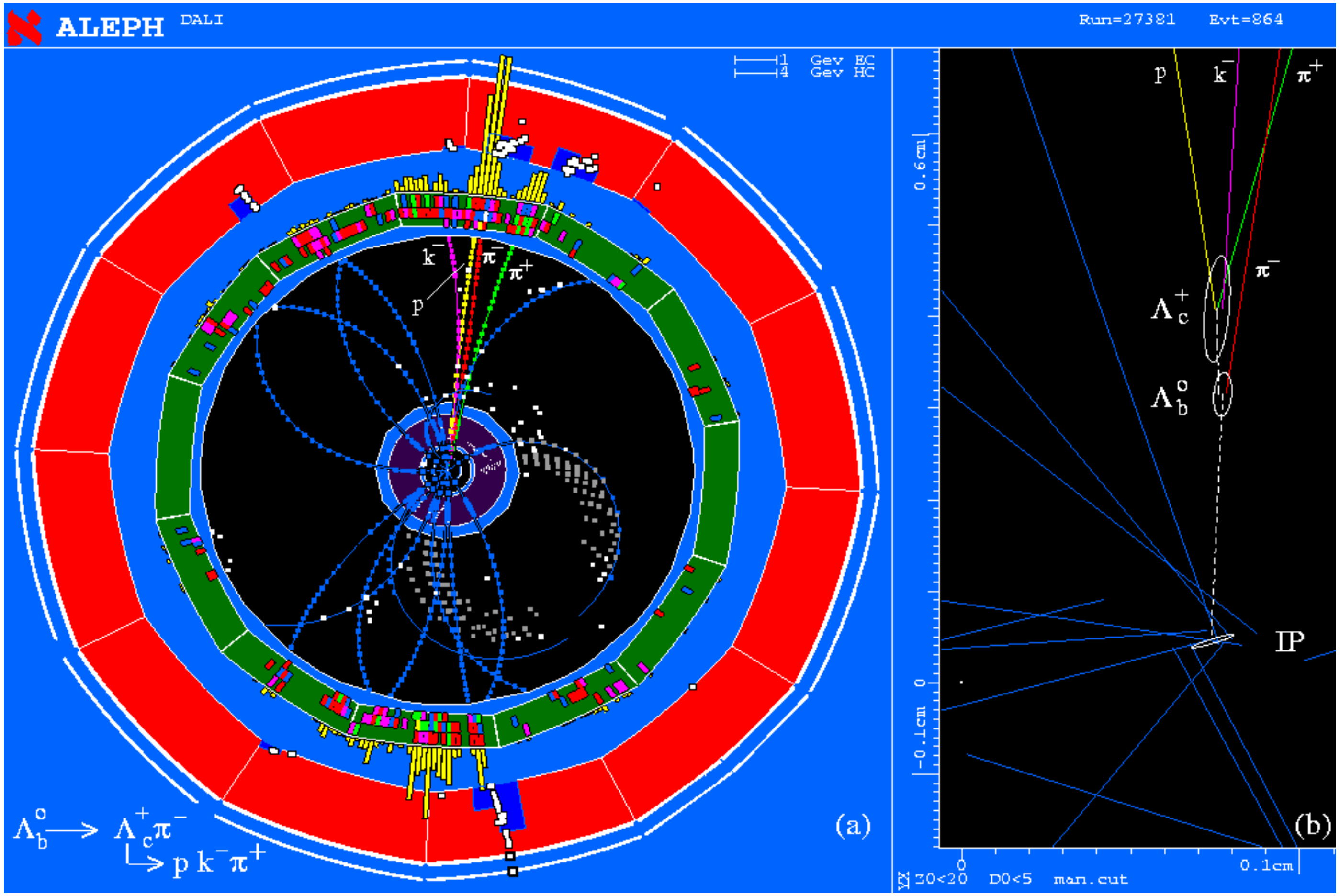
$Z \rightarrow q\bar{q}g$

Three jets of particles

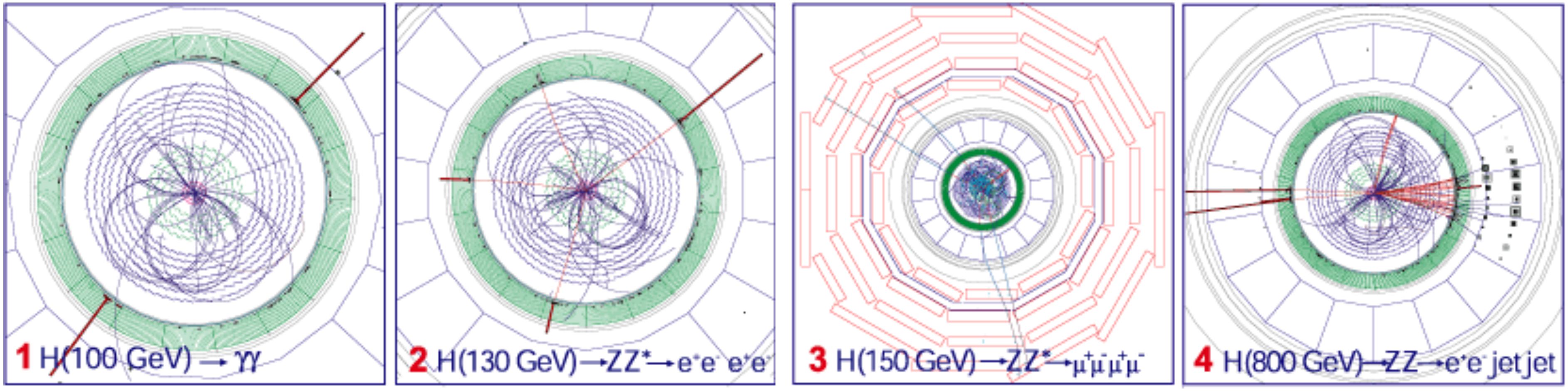


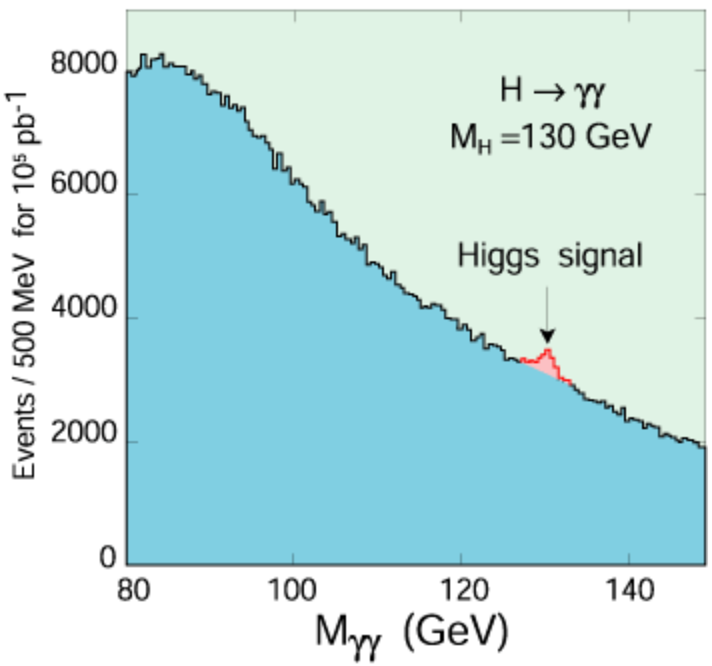
Two secondary vertices with characteristic decay particles giving invariant masses of known particles.

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.

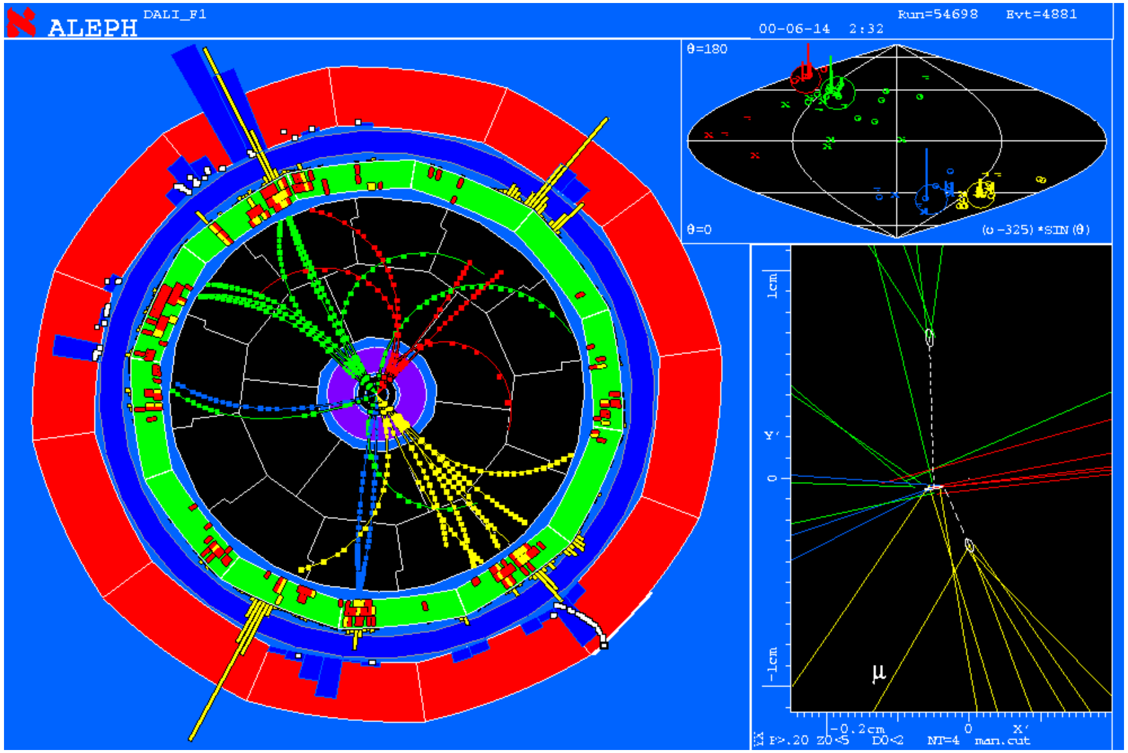
What determines the Size, Material and Geometry of the Detector ?

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)



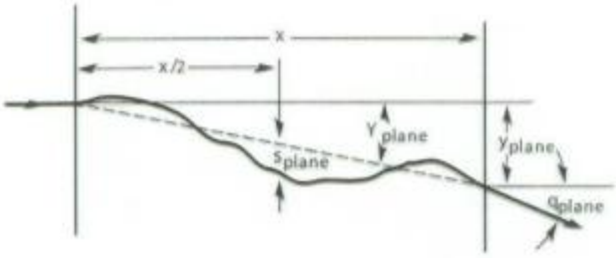
Multiple Scattering

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



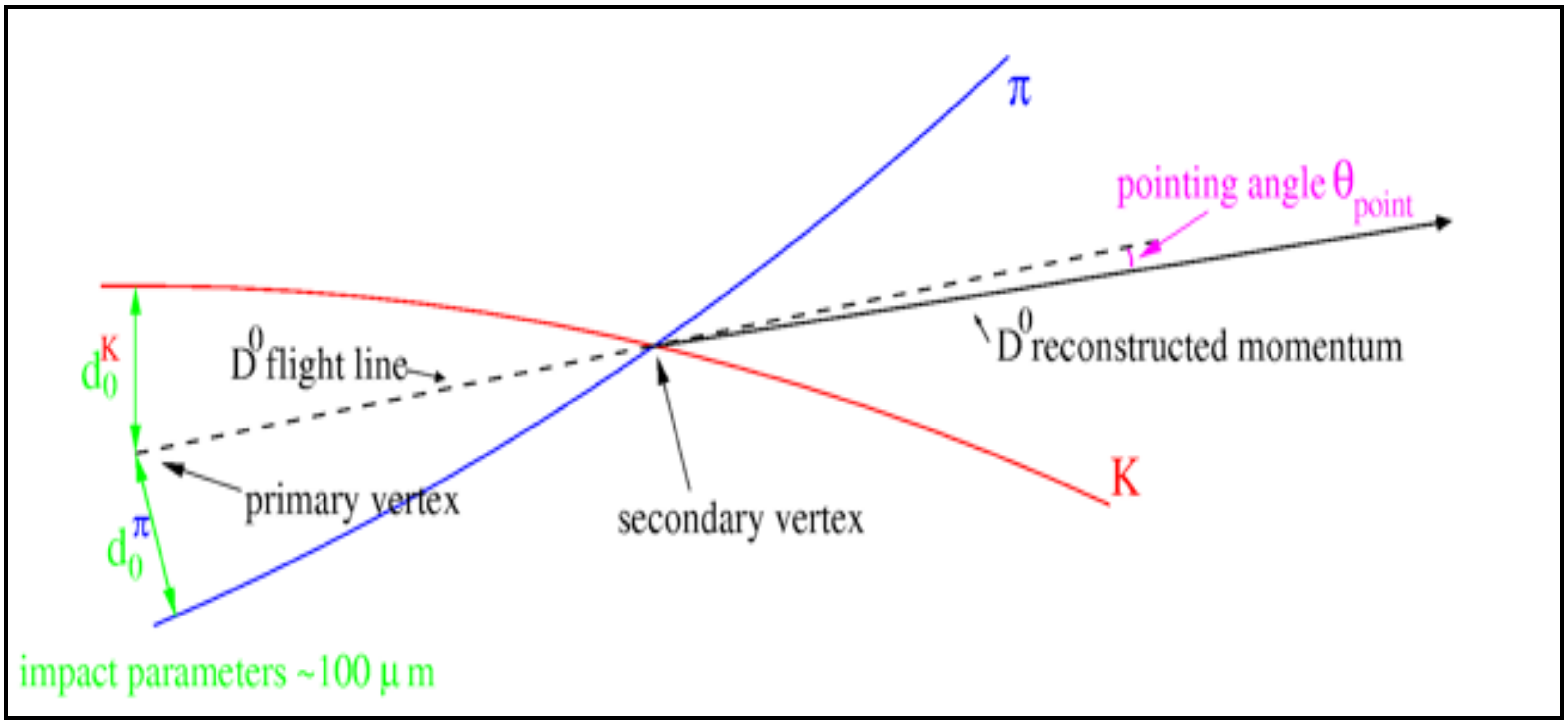
$$E(x) = E_0 e^{-\frac{x}{X_0}} \qquad X_0 = \frac{A}{4\alpha N_A \rho Z^2 \left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 \ln 183 Z^{-\frac{1}{3}}}$$

For small deflection of the particles by our detector we want:
→ Large Radiation length X0 – 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.



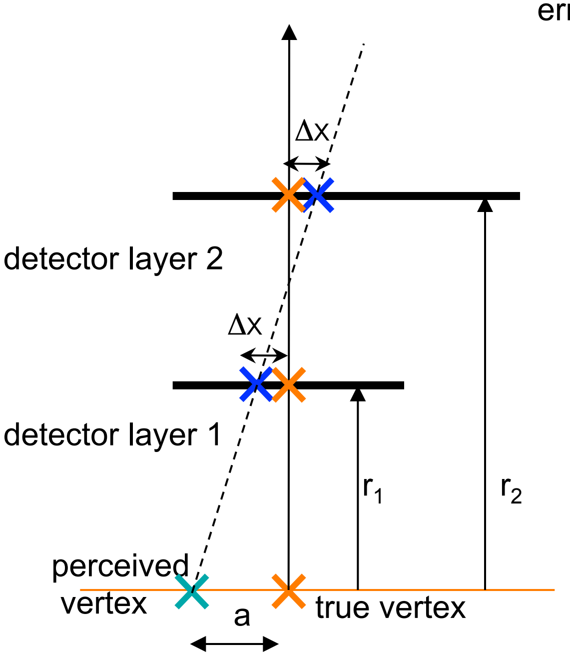
What determines the impact parameter resolution

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

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

from detector position error

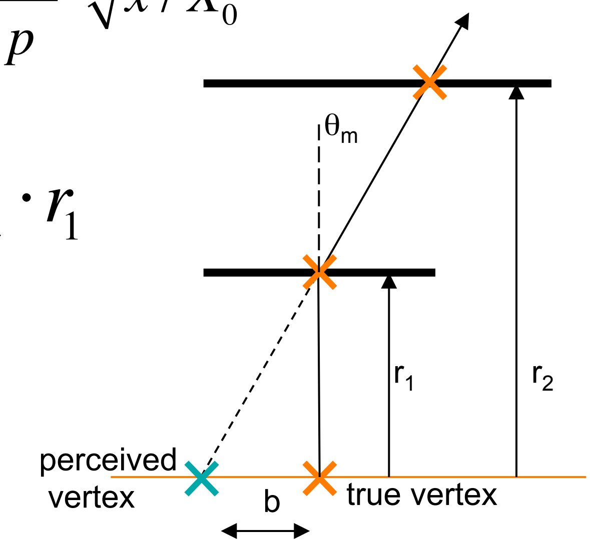
from coulomb scattering



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

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

$$b = \theta_m \cdot r_1$$



Detector Granularity, minimize Δx:

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

→ a=Δx=50/√12 = 15um

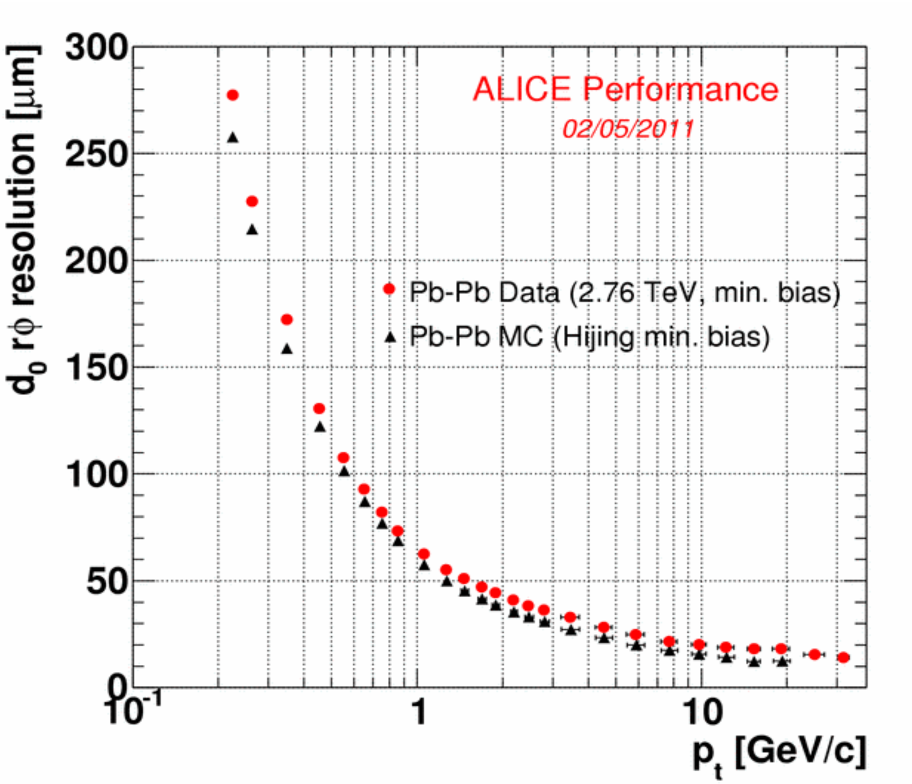
First layer as close as possible to the vertex and
First layer with minimal amount of material.

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 !

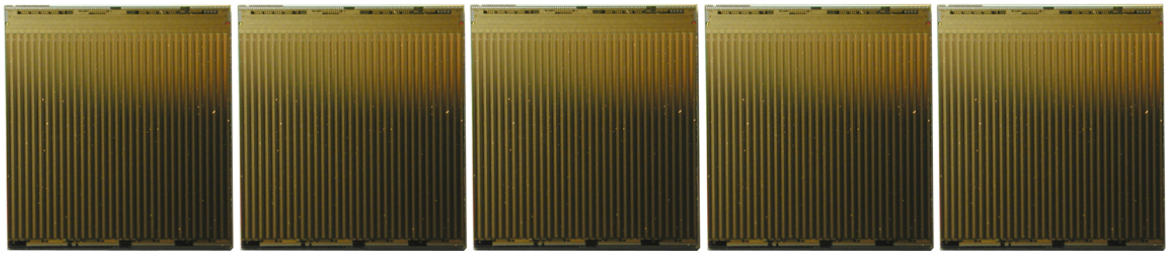
Try to improve for upgrade.

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

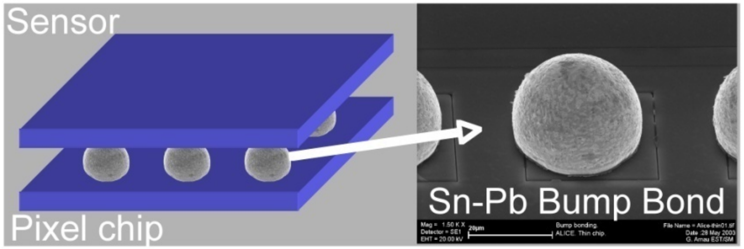
13.68 mm x 15.58 mm

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

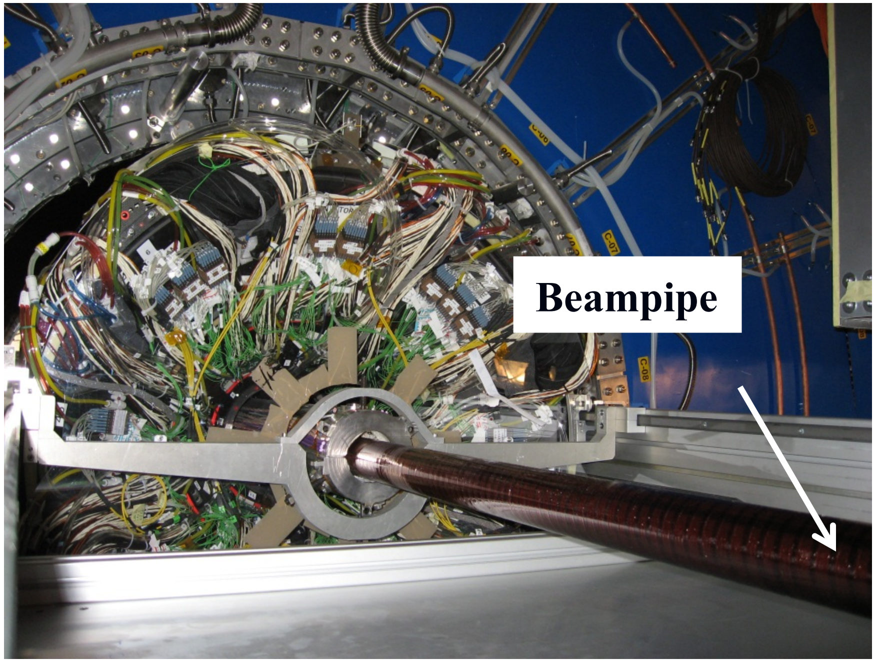
Stand-off:

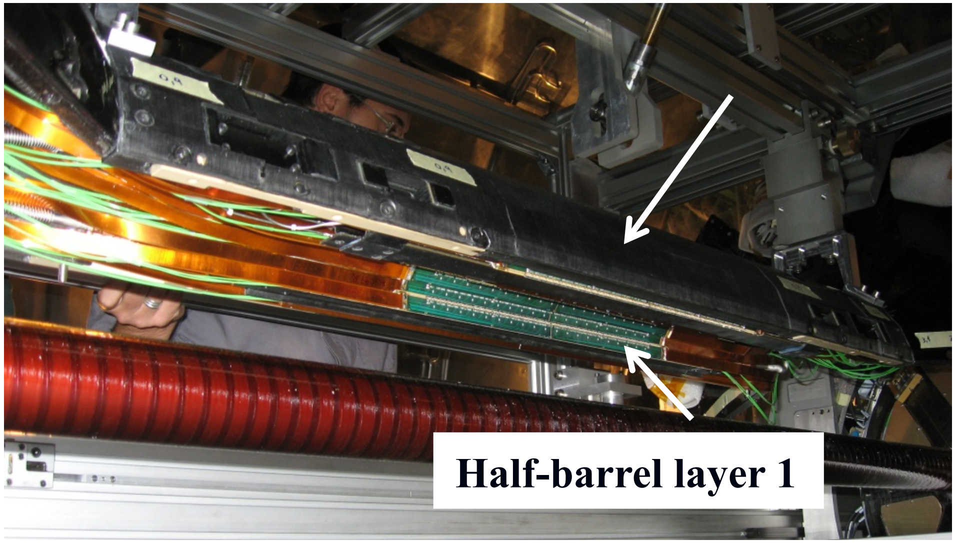
~12 µm (Pb-Sn)

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

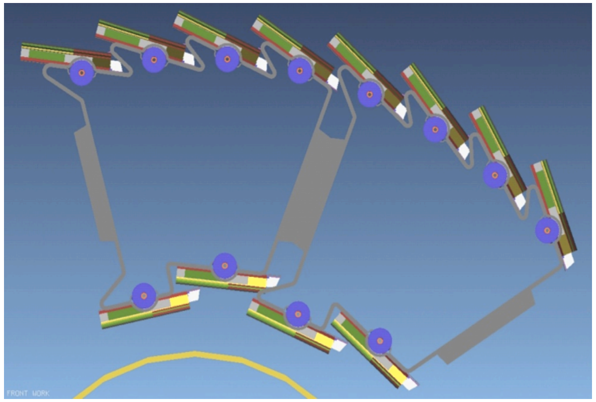




LHC Experiment Beampipe:
As small & thin as possible

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

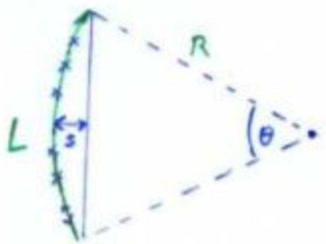
First layer:
Minimum distance from beampipe 5mm, Average radial distance = 39mm



Momentum Measurement

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

$\vec{B} \otimes$



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

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

$$L = R \cdot \theta$$

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

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

$$\Delta s = \frac{\sigma_x}{\sqrt{N}}$$ σ_x ... point resolution, N ... Measurement Points

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

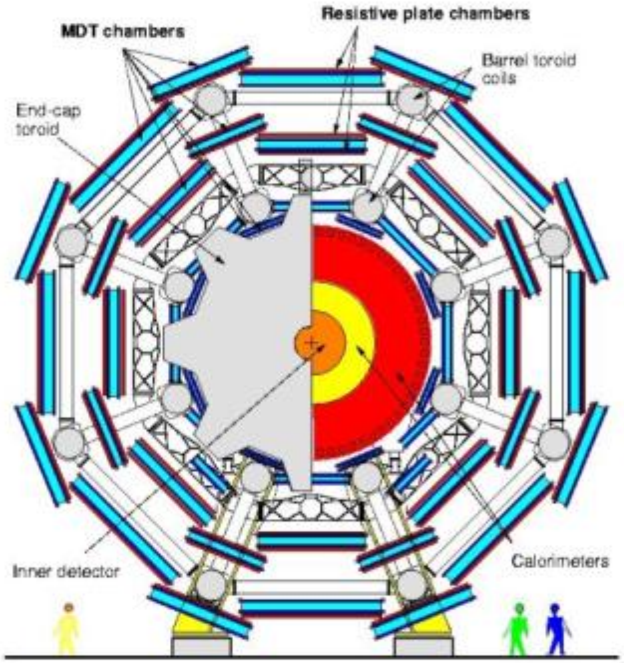
E.g.: $p = 10\,\frac{GeV}{c}$, $B = 1T$, $L = 1m$, $\sigma = 200\mu m$, $N = 25$

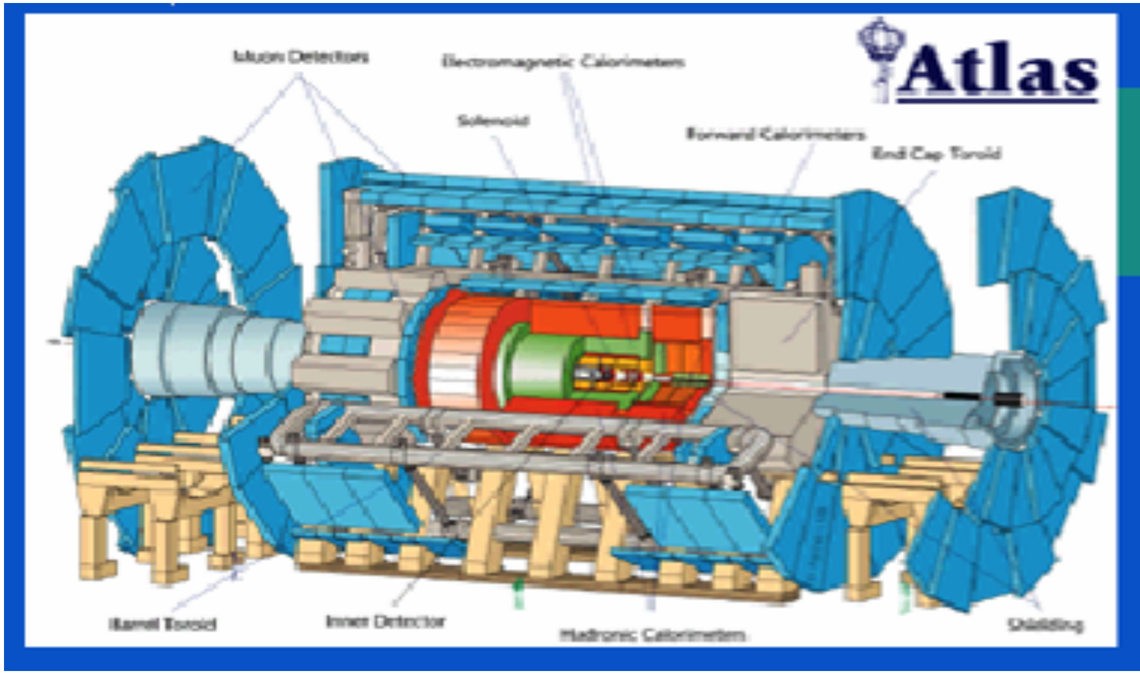
$$\frac{\Delta p}{p} = 0.01 \rightarrow 1\%$$

Example: ATLAS Muon Spectrometer

N=3, σ=50um, p=1TeV,
L=5m, B=0.4T

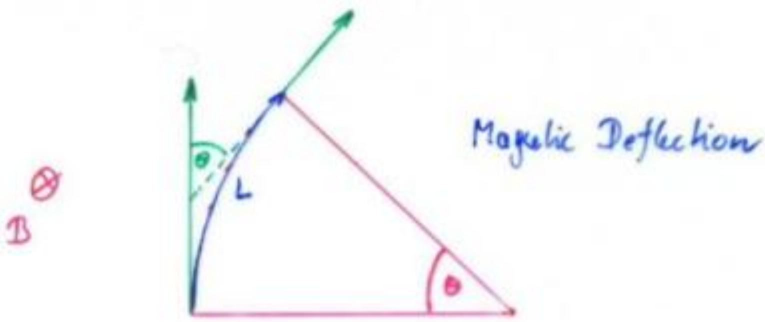
Δp/p ~ 8% for the most energetic muons at LHC





Multiple Scattering

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



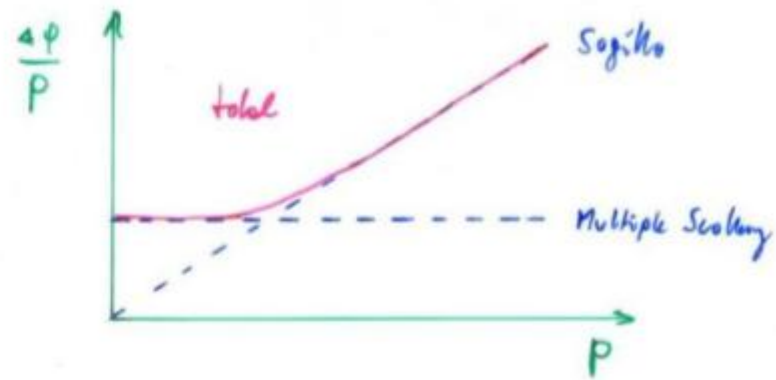
$$p\left[\frac{GeV}{c}\right] = 0.3\, R[m]\, B[T]$$

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

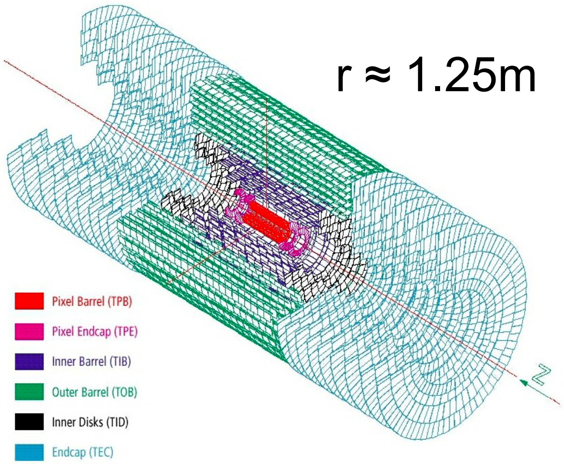
$$\frac{\Delta p}{p} = \frac{\Delta\theta}{\theta} = \frac{\theta_0}{\theta} \sim \frac{0.05}{\beta B[T] L[m]} \cdot \sqrt{\frac{L}{X_0}}$$

→ 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

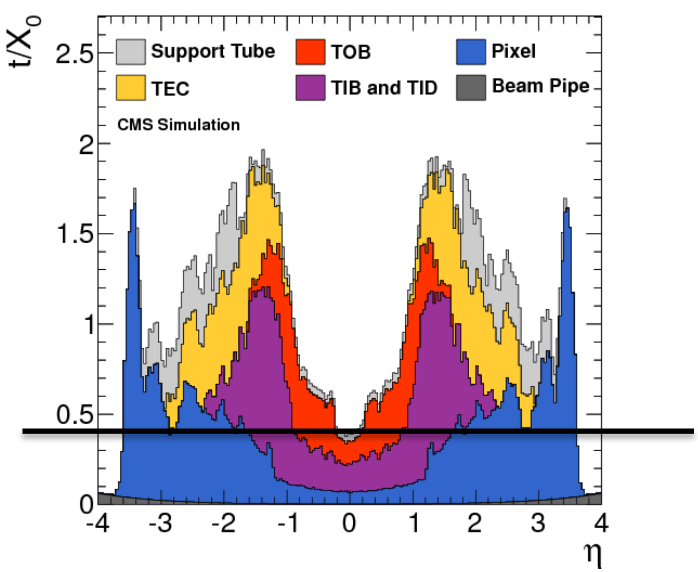


$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x[m]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8\, p\left[\frac{GeV}{c}\right]}{B[T] \cdot L^2[m]}$$

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

→ dp/p = 7% tracking

Material budget



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

B=3.8T, L=1.25m, x/X_0 ≈ 0.4 @ eta=0

→ dp/p = 0.7% from multiple scattering

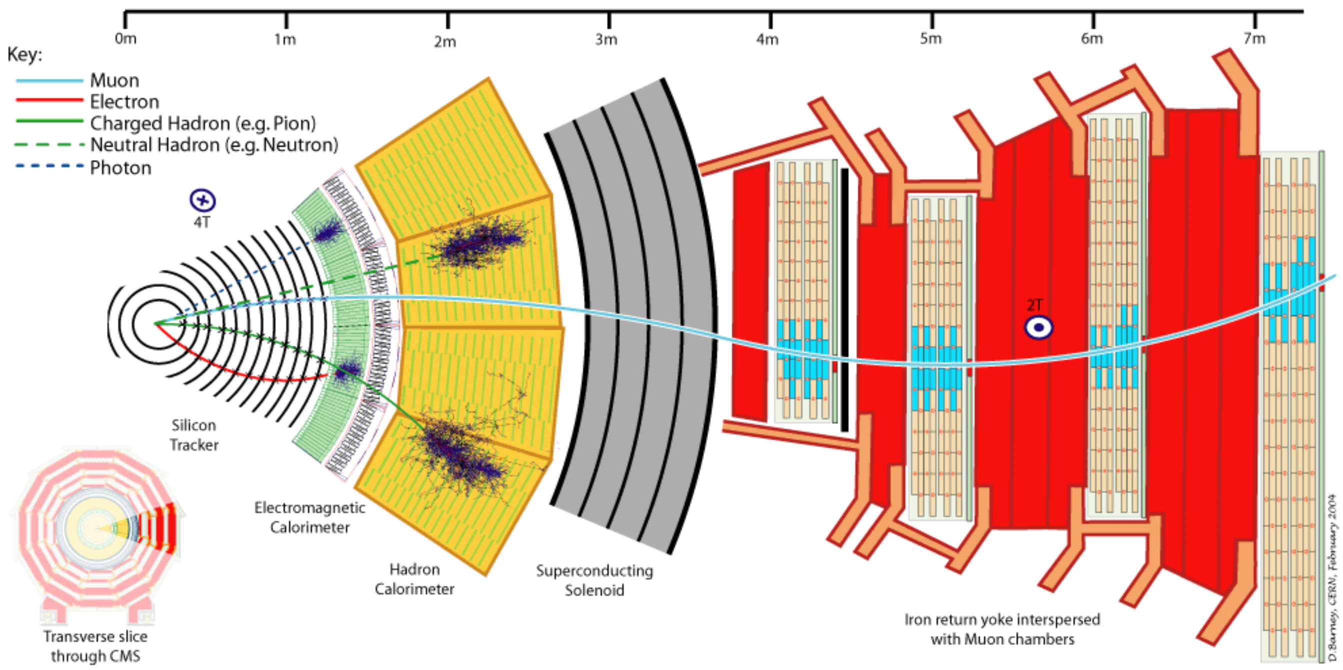
Momentum Measurement

The specified momentum resolution, together with the

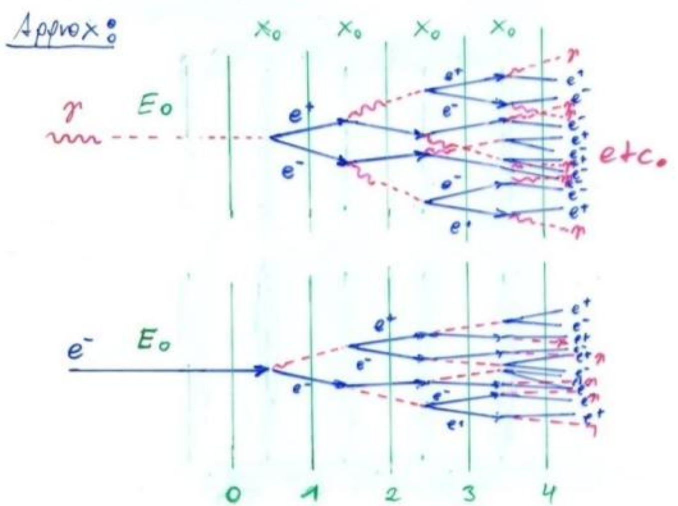
Magnetic field B
Number of tracking layers N
Resolution per layer σ

defines the tracker radius.

Then – EM and Hadron Calorimeter !



Electro Magnetic Calorimetry



Electromagnetic Shower → EM Calorimeter

$$N(n) = 2^n \quad \ldots\ldots \text{ Number of particles } (e^\pm, \gamma) \text{ after } n\, X_0$$

$$E(n) = \frac{E_0}{2^n} \quad \ldots \text{ Average Energy of particles after } n\, X_0$$

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

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

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

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

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

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

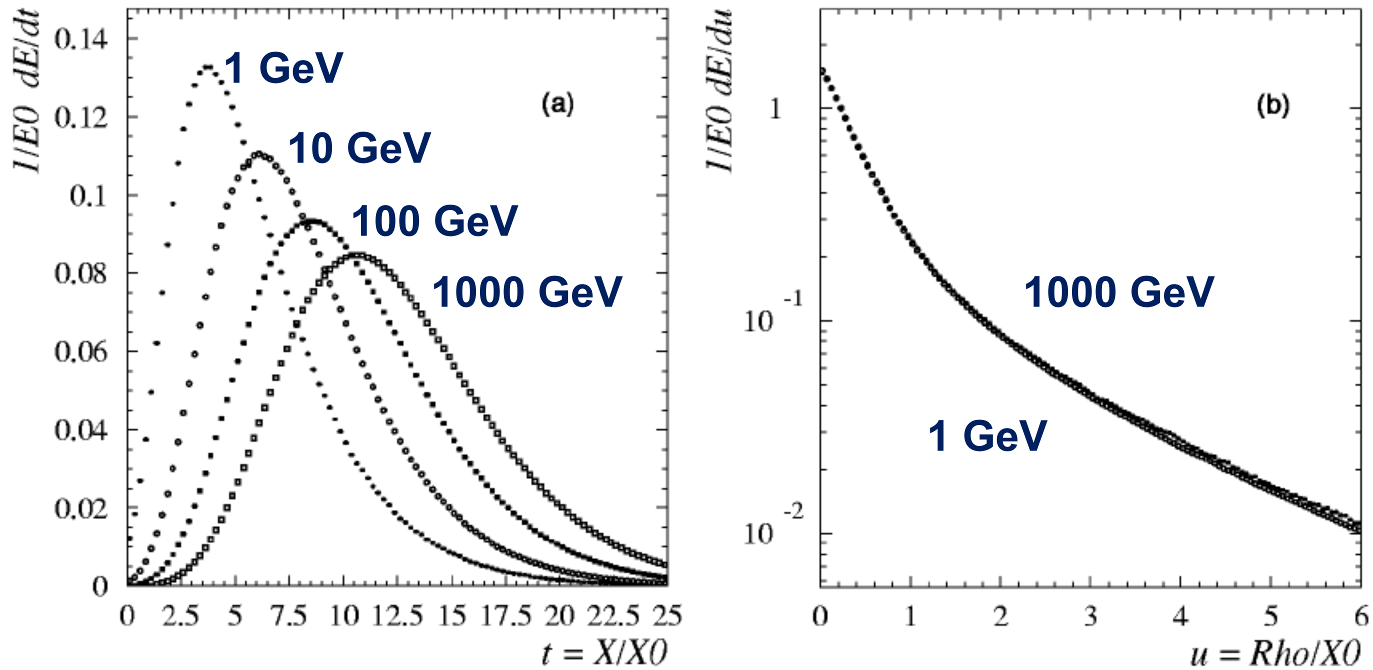
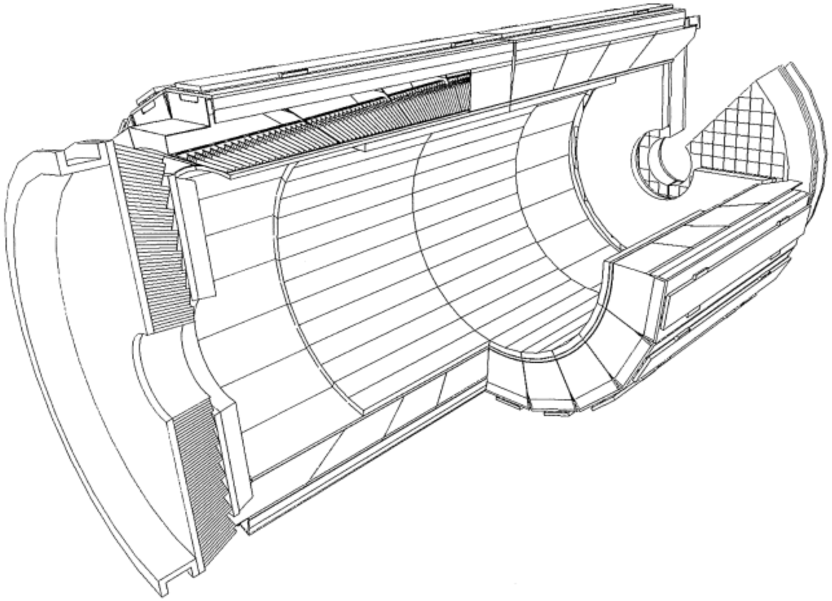


FIG. 2. (a) Simulated shower longitudinal profiles in $PbWO_4$, as a function of the material thickness (expressed in radiation lengths), for incident electrons of energy (from left to right) 1 GeV, 10 GeV, 100 GeV, 1 TeV. (b) Simulated radial shower profiles in $PbWO_4$, as a function of the radial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

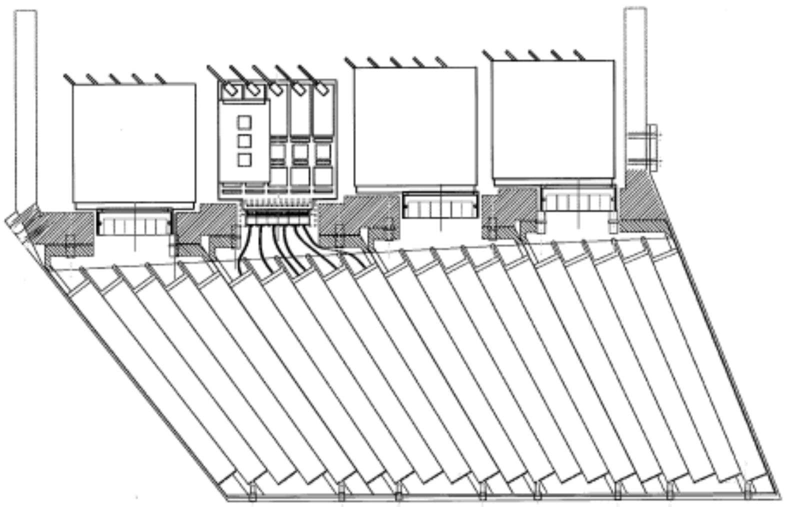


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Hadronic Calorimetry

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

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

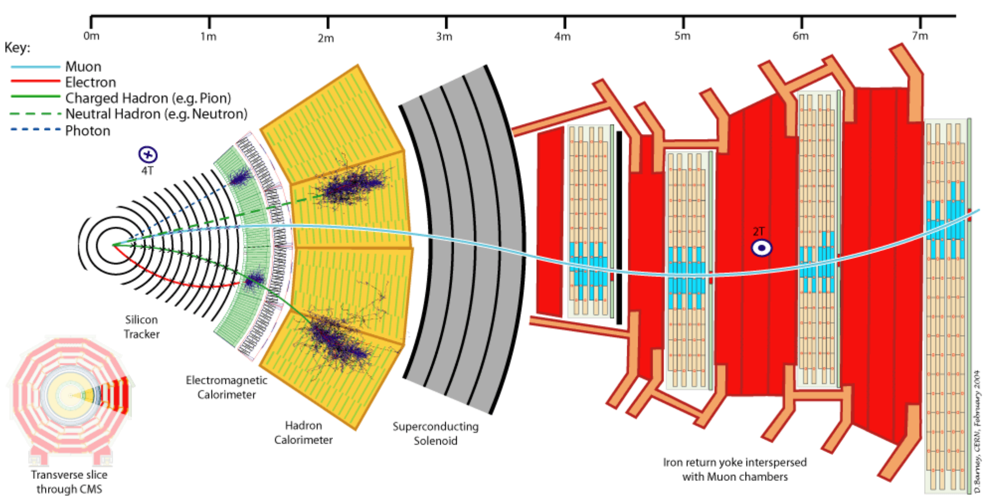
To absorb a hadron shower one typically needs 10-11 interaction lengths.

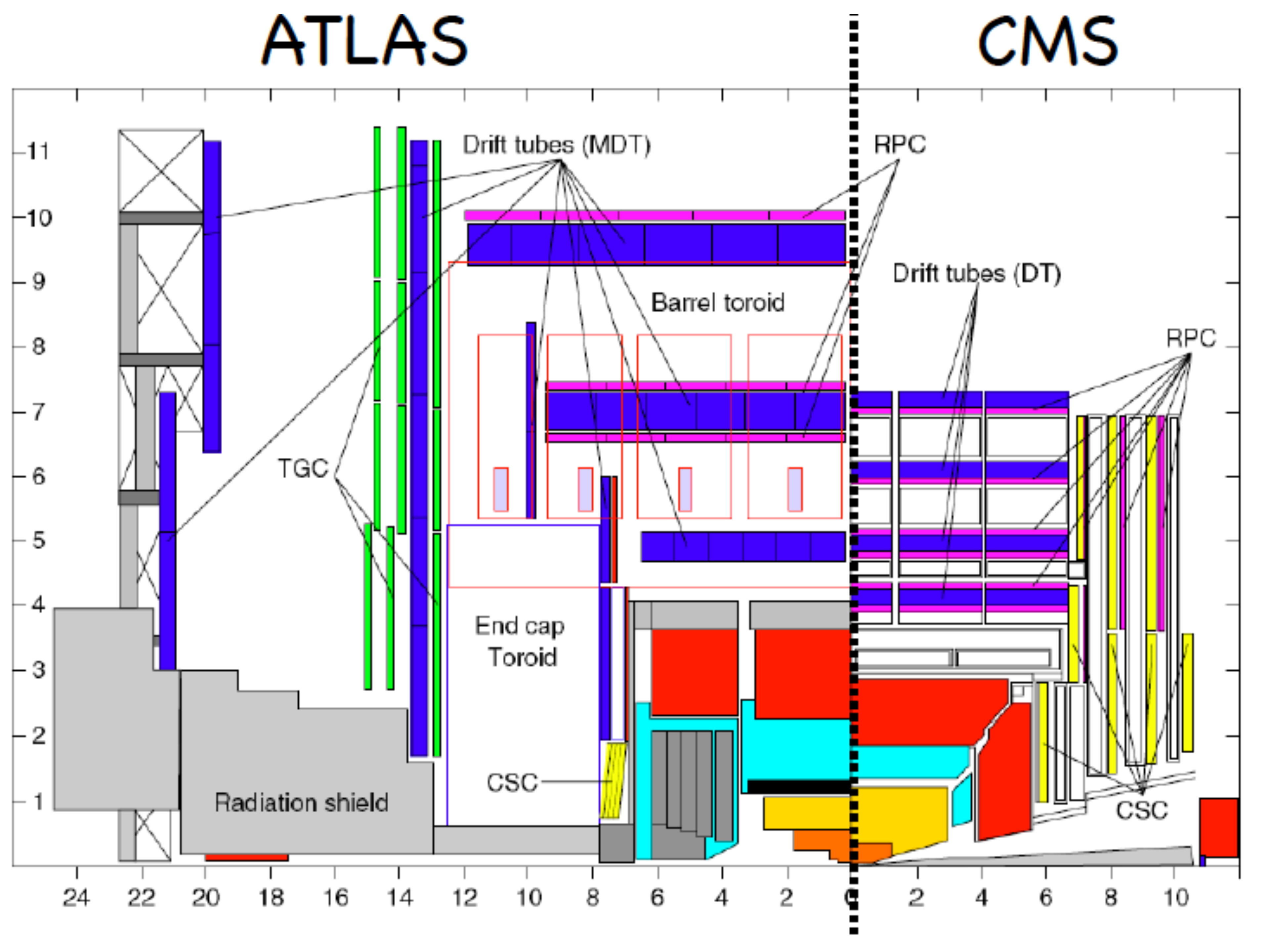
The interaction length is not such a strong function of the material, it should just be very HEAVY ! Cu, Fe, Pb

10 lambda = 170cm of iron.

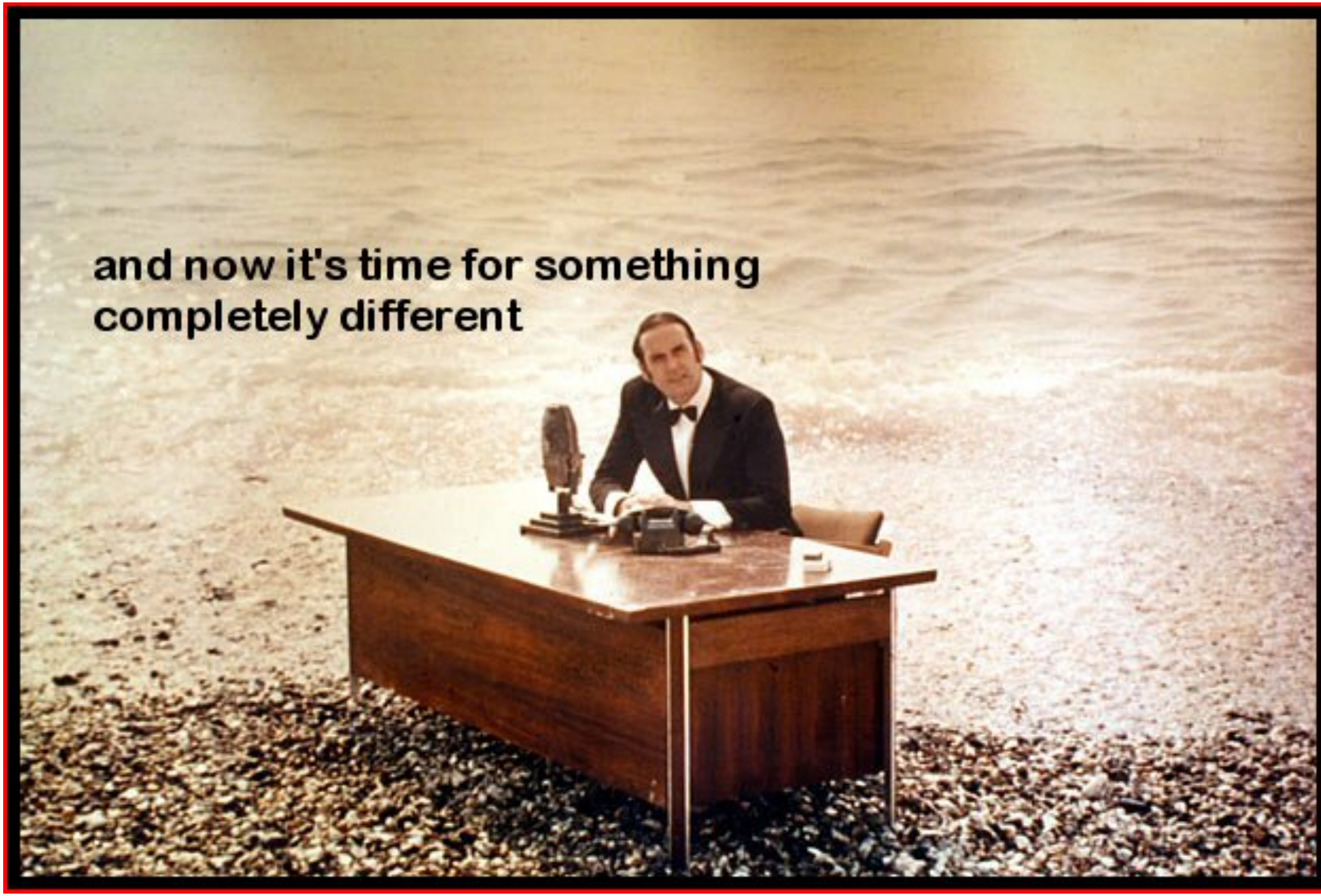
CMS uses a Cu/Zn mixture with lambda = 16.4cm and a total of 6 interaction lengths + detector = 120cm in order to keep the coil radius small.

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

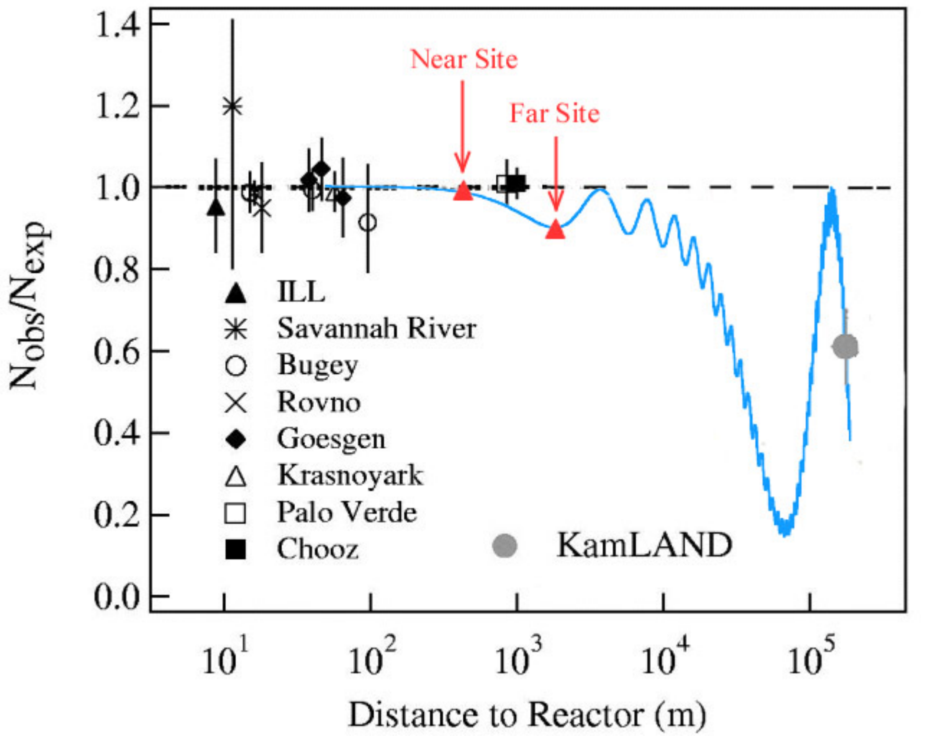


Neutrino Detectors

Antineutrinos from Nuclear Power Plants

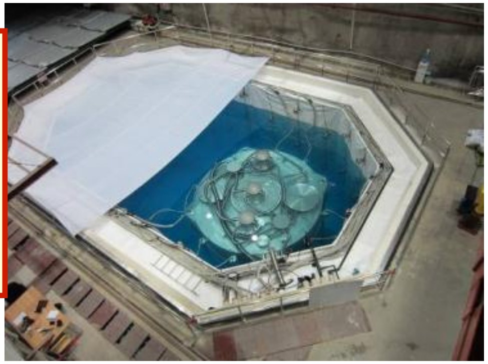
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Disappearance of Antineutrinos:
Measures Antineutrino Flux at different distances from the Reactor



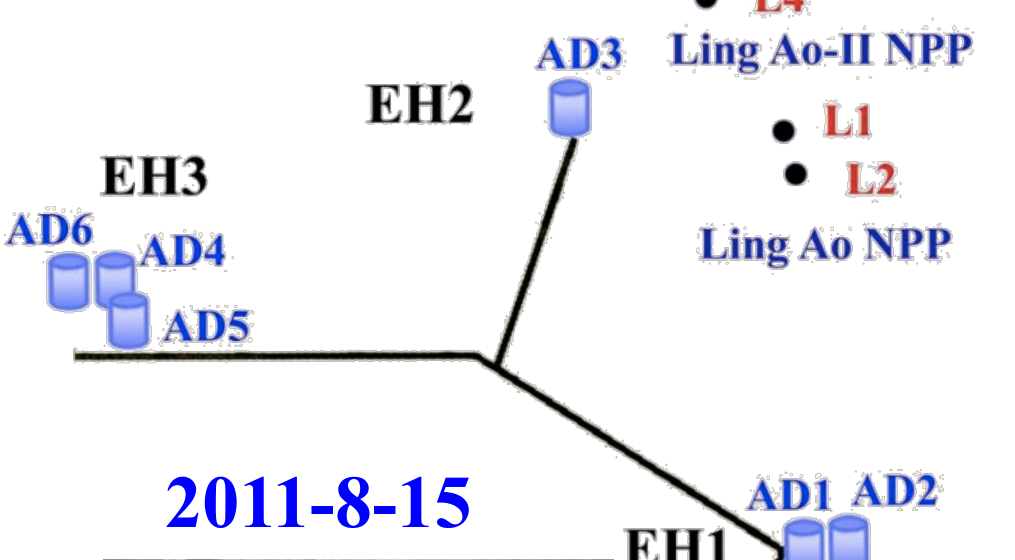
Daya Bay Results

2011-11-5



Mar.8, 2012, with 55 day data
$\sin^2 2\theta_{13}=0.092\pm0.016(\text{stat})\pm0.005(\text{syst})$
5.2 σ for non-zero θ_{13}

2011-12-24



2011-8-15

Jun.4, 2012, with 139 day data
$\sin^2 2\theta_{13}=0.089\pm0.010(\text{stat})\pm0.005(\text{syst})$
7.7 σ for non-zero θ_{13}

Detector Design

Water
- **Shield radioactivity and cosmogenic neutron**
- **Cherekov detector for muon**

RPC or Plastic scintillator
⇨ **muon veto**

Three-zone neutrino detector

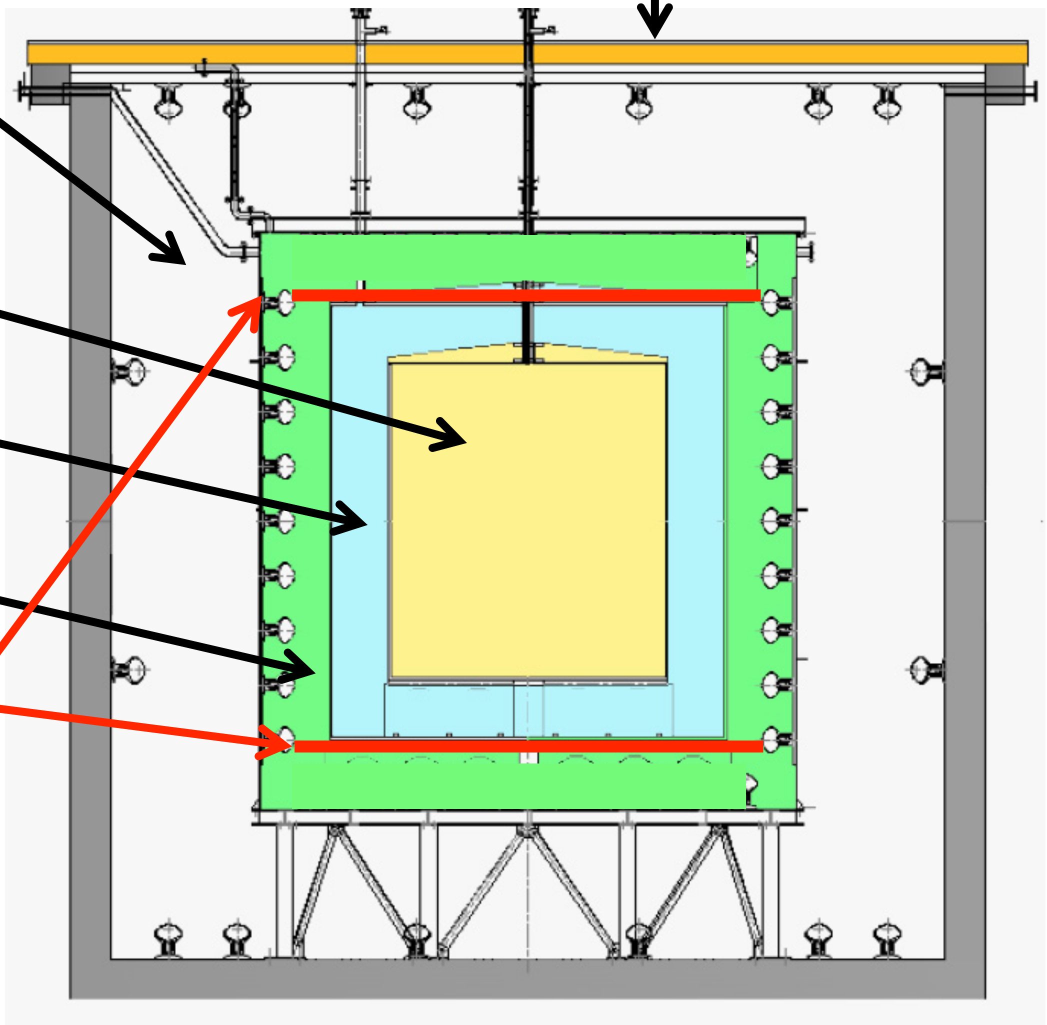
⇨ **Target: Gd-loaded LS**
- **8-20 t for neutrino**

⇨ **γ-catcher: normal LS**
- **20-30 t for energy containment**

⇨ **Buffer shielding: oil**
- **40-90 t for shielding**

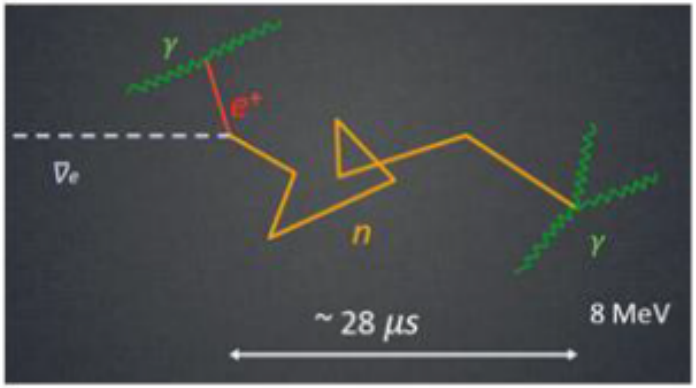
Daya Bay Reflective panels

Reduce PMT numbers to 1/2



Signal Generation

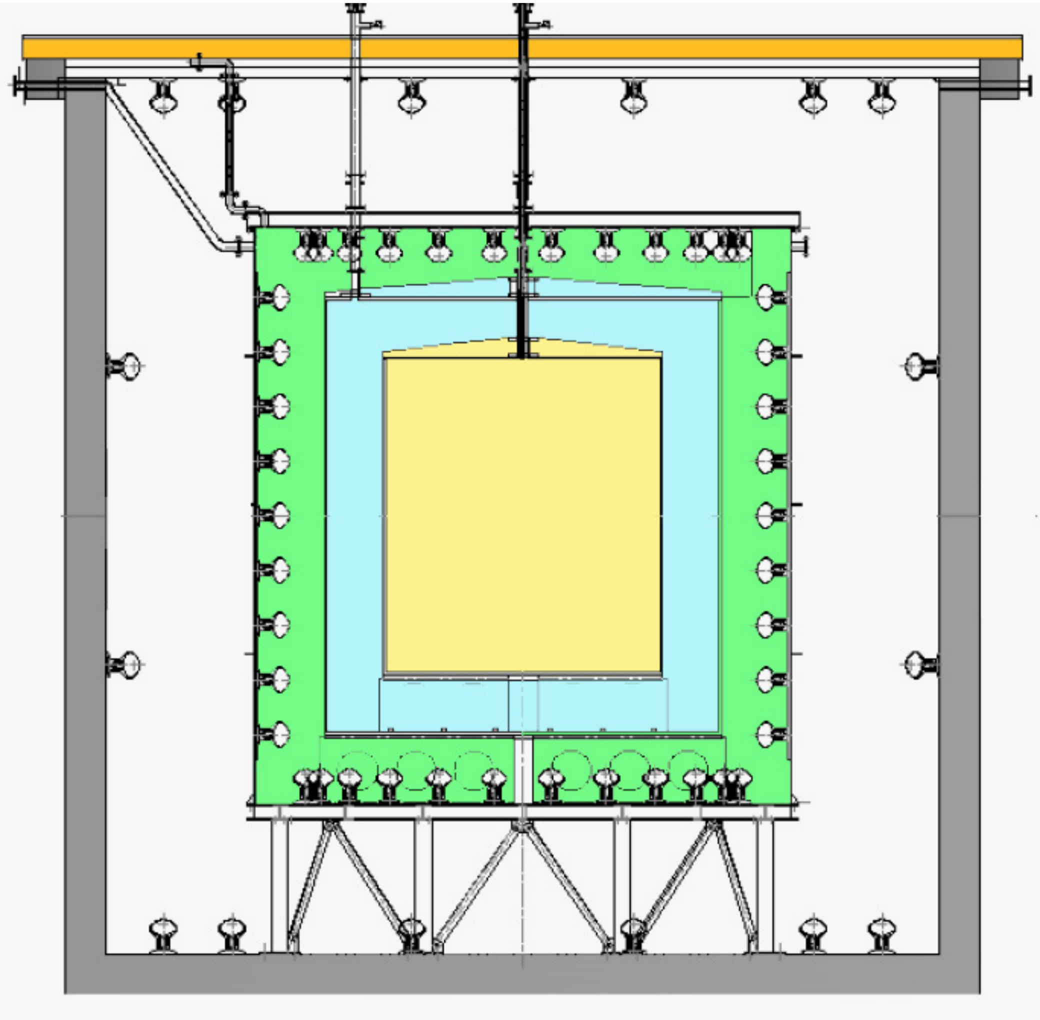
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



$\tau \approx 28\ \mu s (0.1\%\ Gd)$

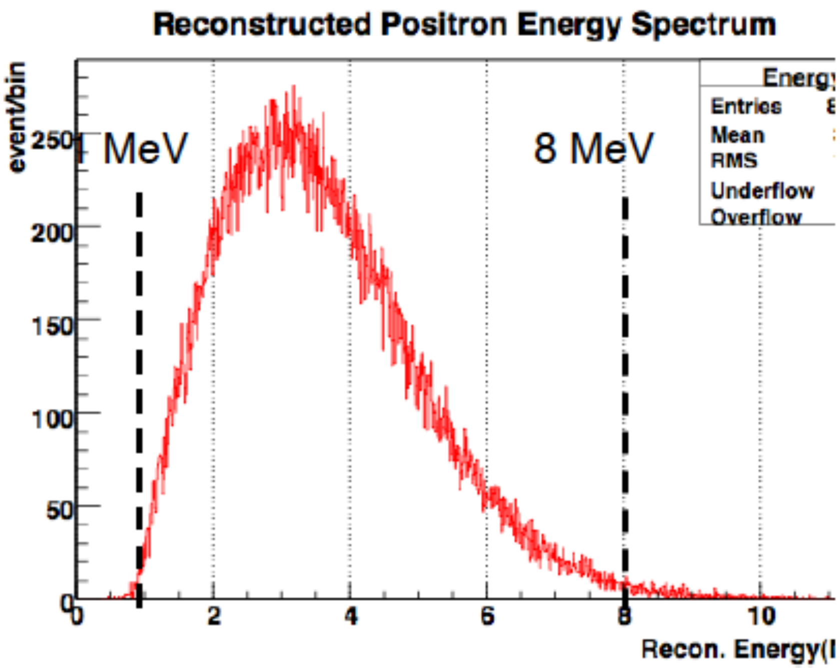
$n + p \rightarrow d + \gamma\ (2.2\ MeV)$

$n + Gd \rightarrow Gd^* + \gamma\ (8\ MeV)$

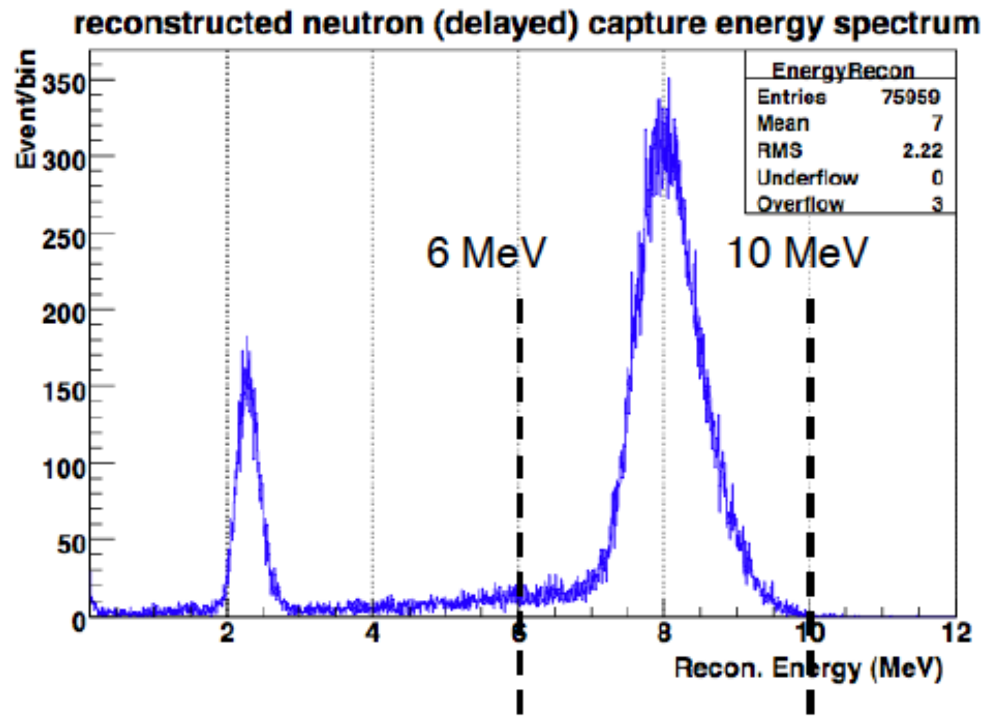


Signal Selection

Prompt Energy Signal

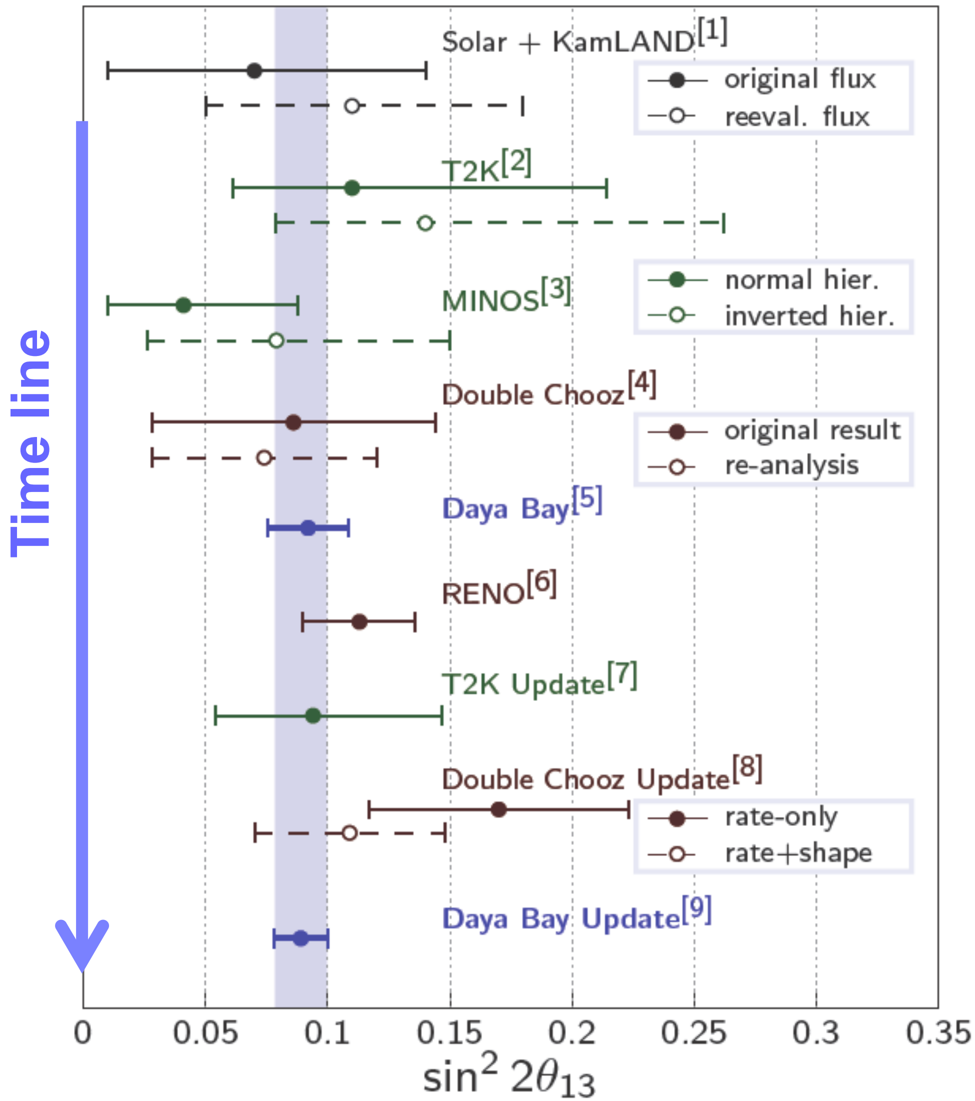


Delayed Energy Signal



positron energy: $0.7\ \text{MeV} < E_{\text{prompt}} < 12.0\ \text{MeV}$;
neutron energy: $6.0\ \text{MeV} < E_{\text{delayed}} < 12.0\ \text{MeV}$;
time coincidence: $1\ \mu\text{s} < \Delta t_{\text{prompt,delayed}} < 200\ \mu\text{s}$;

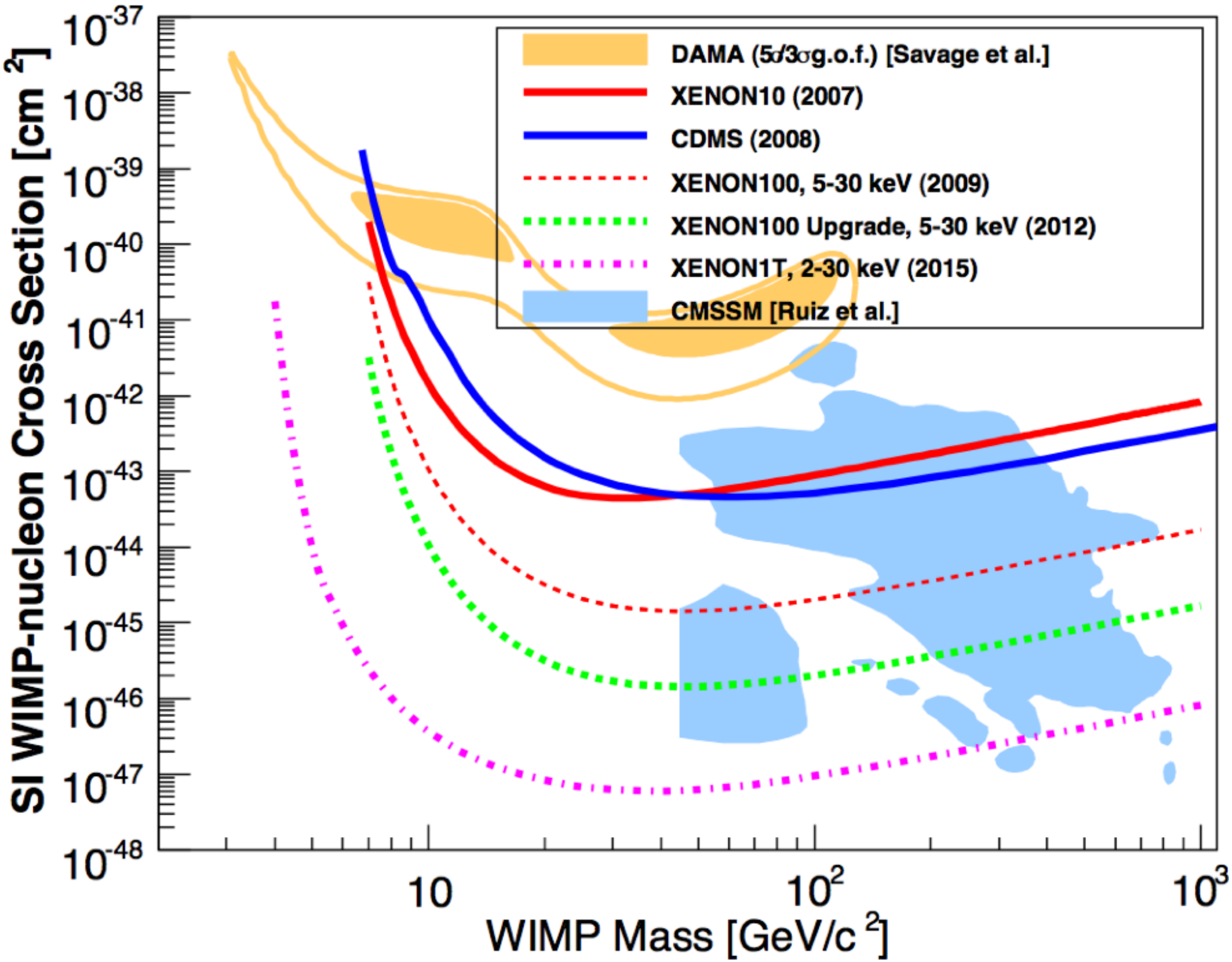
Global Picture of θ_{13} Measurements



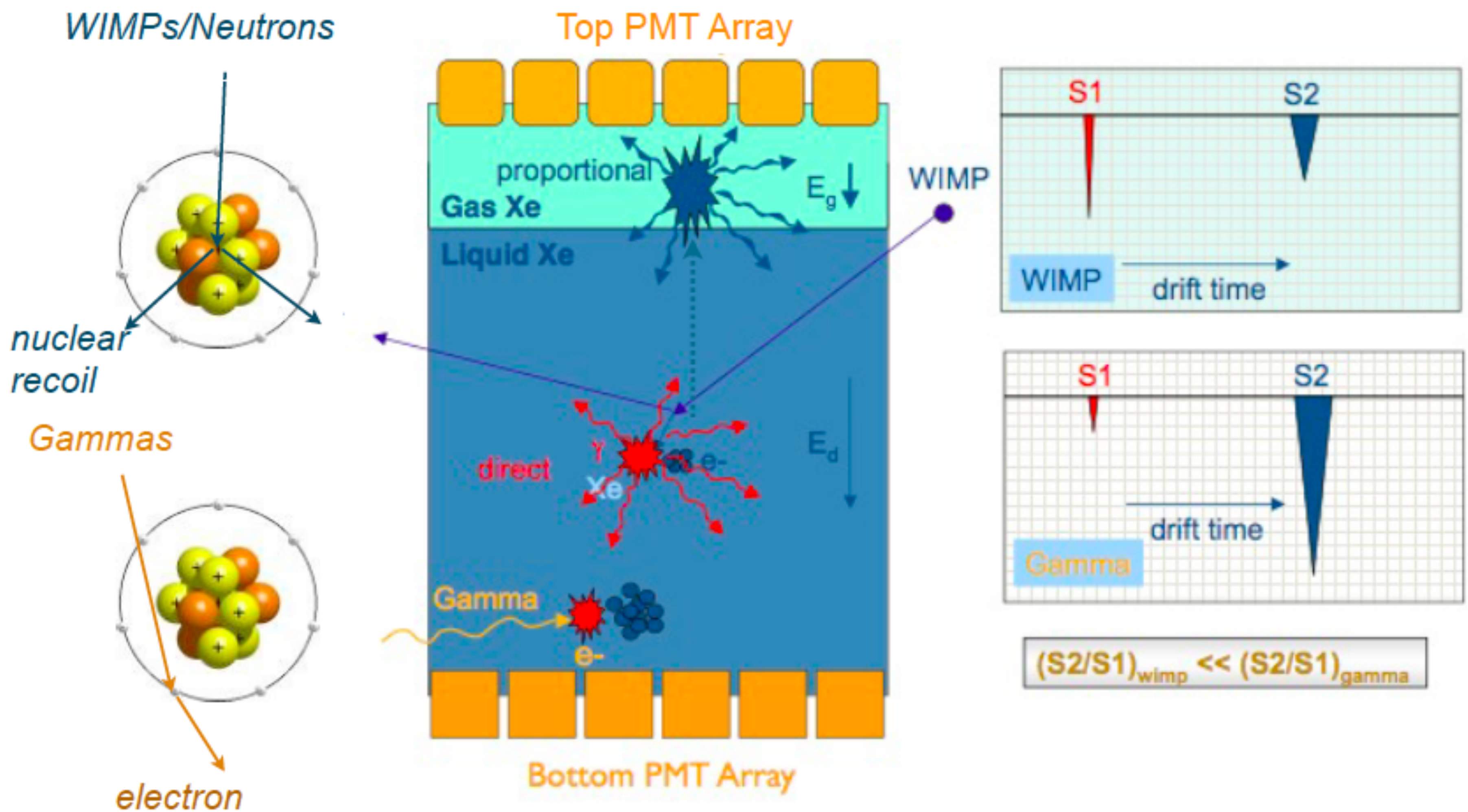
1. G.L. Fogli *et al.*, "Evidence of $\theta_{13} > 0$ from global neutrino data analysis," Phys. Rev. **D 84** (2011) 053007 arXiv:1106.6028
2. K. Abe *et al.*, "Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam," Phys. Rev. Lett. **107** (2011) 041801, arXiv:1106.2822
3. P. Adamson *et al.*, "Improved Search for Muon-Neutrino to Electron-Neutrino Oscillations in MINOS," Phys. Rev. Lett. **107** (2011) 181802, arXiv:1108.0015
4. Y. Abe *et al.*, "Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment," Phys. Rev. Lett. **108** (2012), 131801, arXiv:1112.6353
5. F. P. An *et al.* "Observation of electron-antineutrino disappearance at Daya Bay," Phys. Rev. Lett. **108** (2012), 171803, arXiv:1203.1669
6. J. K. Ahn *et al.* "Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment," Phys. Rev. Lett. **108** (2012) 191802, arXiv:1204.0626
7. K. Sakashita, "Results from T2K," presented at ICHEP 2012 in Melbourne. Available at T2K.org
8. Y. Abe *et al.* "Reactor electron antineutrino disappearance in the Double Chooz experiment," Phys. Rev. **D86** (2012) 052008, arXiv:1207.6632
9. F. P. An *et al.* "Improved measurement of electron antineutrino disappearance at Daya Bay," Chinese Phys. **C37** (2013) 011001 arXiv:1210.6327

Dark Matter Detectors

WIMP Searches

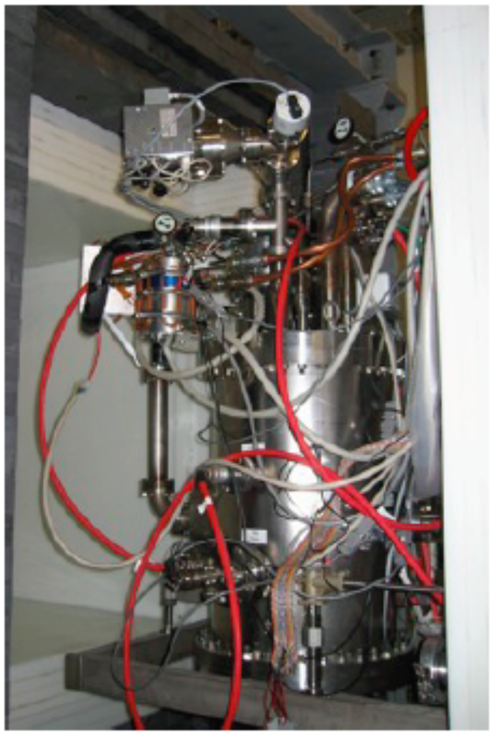


The XENON two-phase TPC



The XENON Roadmap

past (2005 - 2007)	*current* (2008-2010)	*future* (2011- 2015)



XENON10

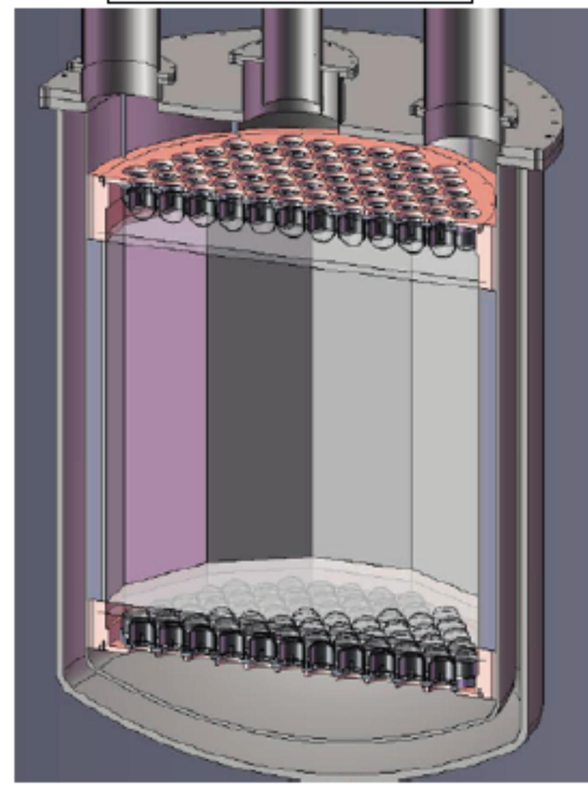
Achieved (2007) σ_{SI}=8.8 x10^{-44} cm^2

Phys. Rev. Lett. ***100****, 021303 (2008)*

Phys. Rev. Lett. ***101****, 091301 (2008*

XENON100

Projected (2010) σ_{SI}~2x10^{-45} cm^2



XENON1T

Goal: σ_{SI} <10^{-46} cm^2

Conclusions:

Particle detectors at accelerator facilities have developed into highly optimized and extremely sophisticated devices.

The driving requirements are:

Impact parameter resolution for secondary vertex measurement
Momentum resolution
EM and Hadronic Energy Resolution
+
efficiencies, multiplicities, particle identification, fake tracks rates, double track resolution, cost, practicability, style, radiation ……..

Neutrino Experiments, Dark Matter Experiments, Cosmic Ray experiments etc. use very ingenious detection tricks

→ It is up to you to develop these ideas further and invent new tricks for further physics reach !