Introduction of CMS Detector

Ijaz Ahmed

National Centre for Physics, Islamabad

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Layout of my Lectures:

1) Introduction of CMS Detector
2) CMS sub-detectors
3) CMS Trigger System

Contents

Background

- LEP closure in 2000
- Tevatron still running
- Questions remain unanswerable
- Lack of evidence of Higgs boson
  - Dark matter
  - Anti matter

The Large Hadron Collider and the associated experiments are designed to address a number of these questions.

CMS……..

Introduction of LHC

Luminosity

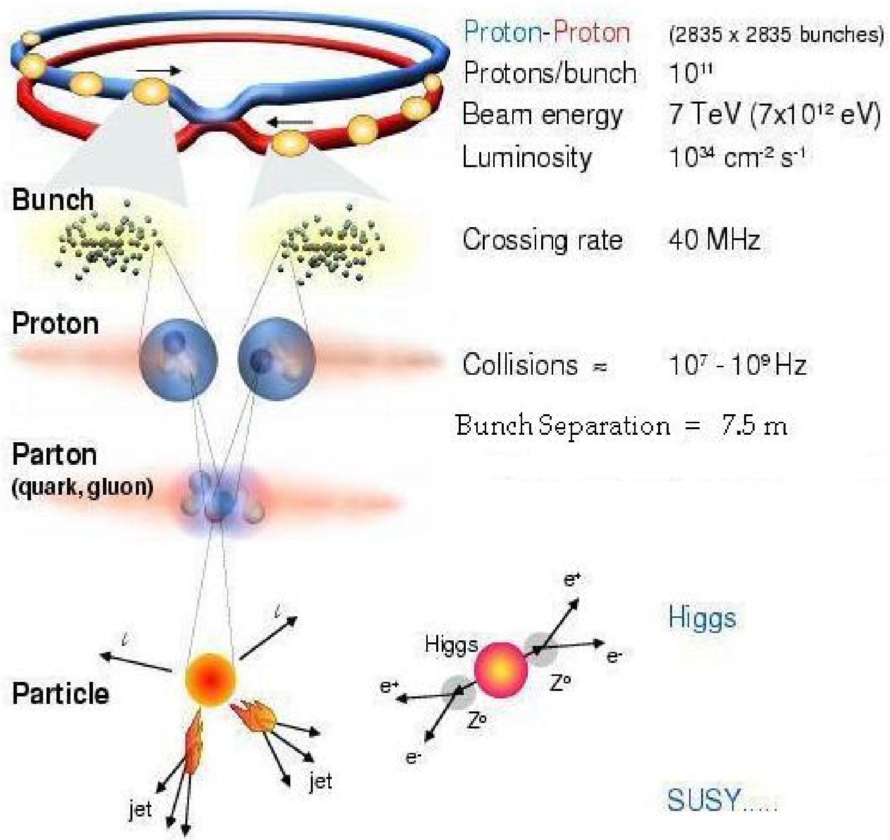
$$L = \frac{\gamma f k_b N_P^2}{4\pi\varepsilon_n \beta^*} F = 10^{34} cm^{-2} s^{-1}$$

Event Rate

$$R = \sigma \times L = 80mb \times 10^{34} cm^{-2} s^{-1} \approx 10^9 / s$$

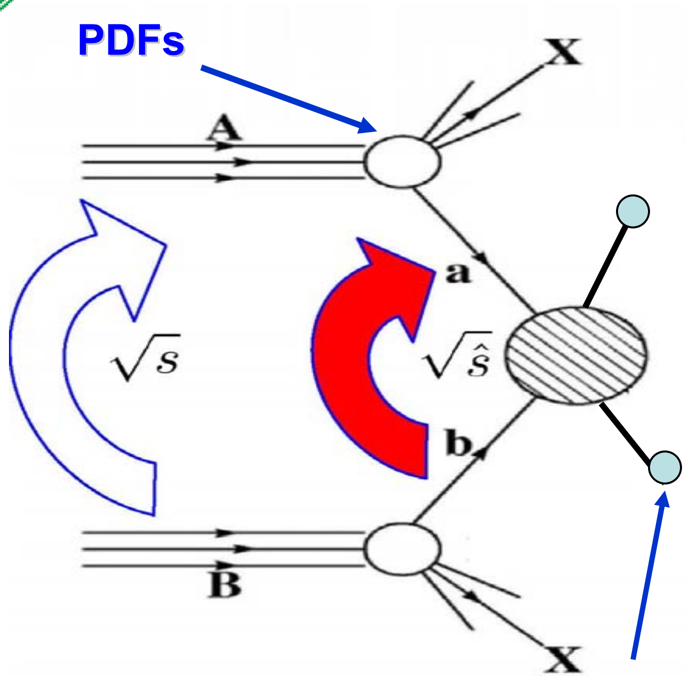
- Large distance collisions
  - o Soft scattering
- Short distance collisions
  - o Hard scattering (rare events)

Collisions at LHC



Selection of 1 in 10,000,000,000,000

PP collisions



Proton momenta $p_A = p_B = p = 7\text{TeV}$
m ometum of partons in proton

$$x_a \cdot p \qquad x_b \cdot p$$

x= longitudinal momentum fraction

center of mass energy

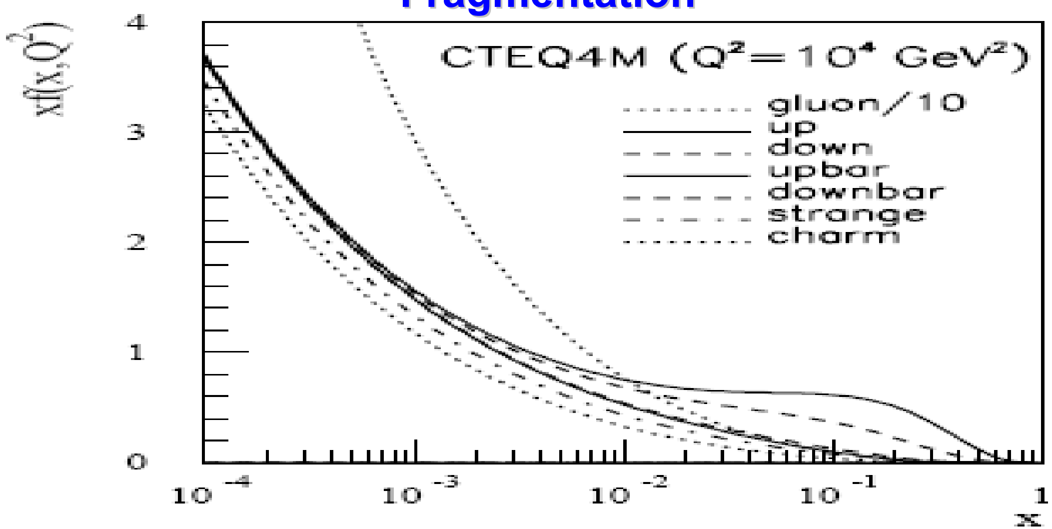
of pp collision: $\sqrt{s} = 2E_{beam}$
of hard subprocess:

$$\hat{s} = x_1 x_2 2 p_A p_B = x_1 x_2 s$$

$$\sqrt{\hat{s}} = < x > \sqrt{s}$$

which x needed to produce masses M ?

M	<x>	LHC	Tevatron
100 GeV		~0.007	~0.05
5 TeV		~0.36	⚡



Minimum-bias Events

Inelastic pp scattering cross section (70 mb = very large)
dominated by

long distance interaction between pp with low momentum transfer

- final state very little pT, very large pL
- pt of charged tracks ~ 500 MeV
- # charged particles dN/dη ~ 7

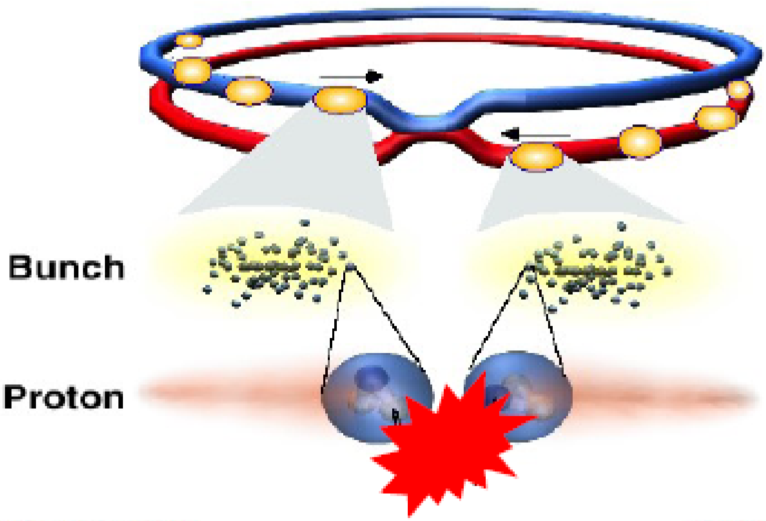
so-called **minimum-bias events**
why this name ? Trigger on... almost nothing = minimum bias

why interesting?
Underlying event = everything but what I'm interested in
e.g. everything except the hard subprocess

min.-bias events = part of underlying event, Lumi dependent pile-up

all interesting events come along with underlying min-bias events!

Pile up of min-bias Events (1/2)

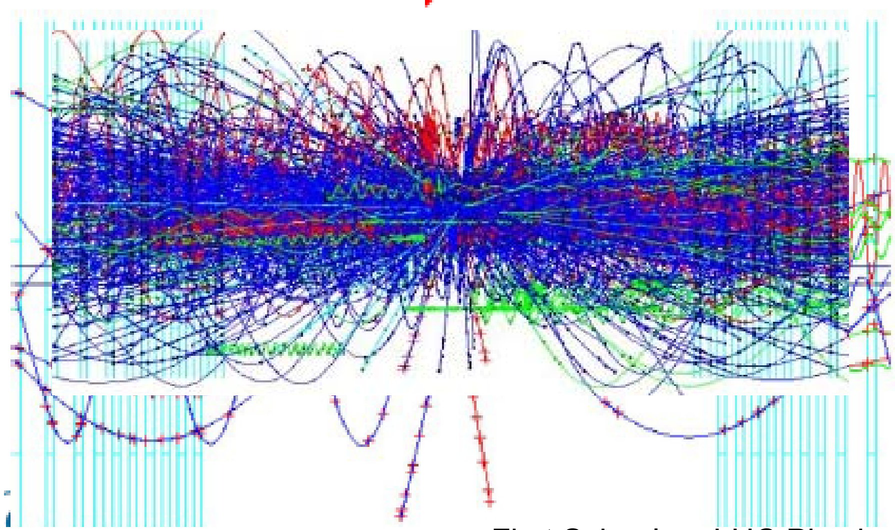


2835x2835 proton bunches
separation 7.5 m (25 ns)
10^{11} protons/bunch

bunch crossing rate: 40 MHz
Lumi (design): $10^{34}\ cm^{-2}\ s^{-1}$

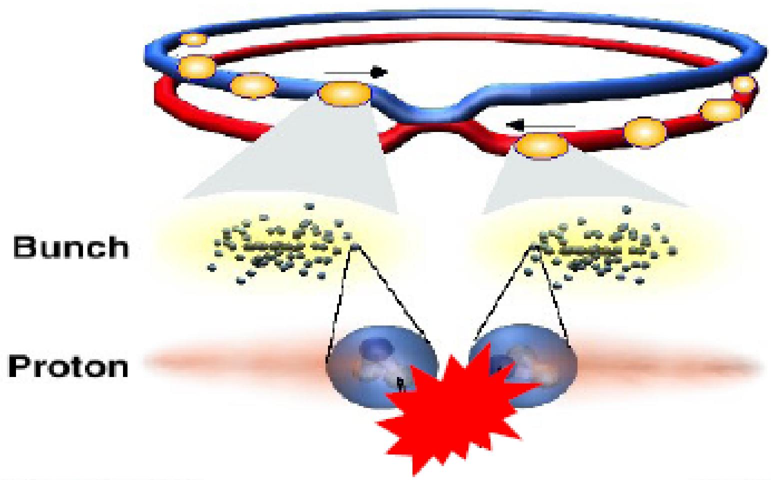
$\sim 10^9$ pp collisions / s and
$10^9 / 40 \cdot 10^6$

~ 25 pp interactions/bc = pile up!



Simulated event in CMS
$h \rightarrow \mu\mu\mu\mu$

Pile up of min-bias Events (2/2)



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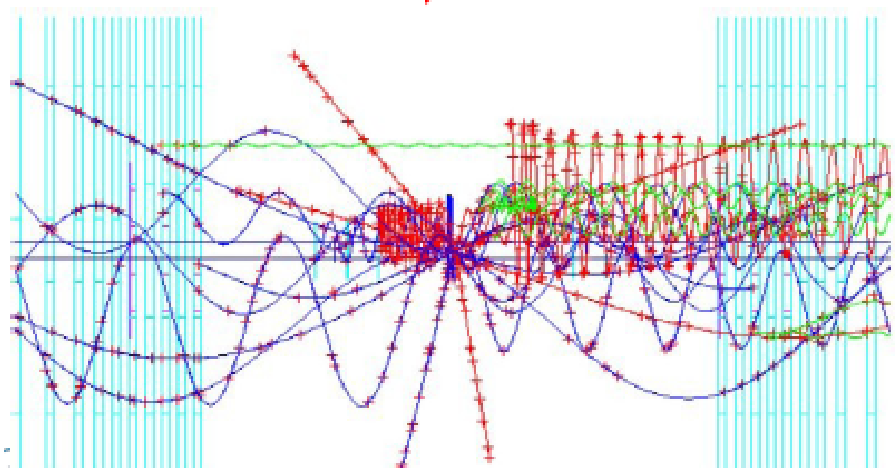
~10^{9} pp collisions / s and
10^{9} / 40 · 10^{6}

~ 25 pp interactions/bc = pile up!



Simulated event in CMS
$h \rightarrow \mu\mu\mu\mu$

The pile-up is one of the most serious difficulties for the experimental operation at the LHC

To confront with Pile-up: detector demands

- ❖ **Fast response time**
- ❖ **High granularity**
- ❖ **Radiation resistant**

Triggering at LHC

Reminder of some numbers …

- LHC bunch crossing interval 25 ns
  event rate of 40 Mhz

in 25 ns particles at the speed of light travel only 7m
next bc while particles still traverse the detector!

- each bunch crossing ~23 piled up events
  leading to an interaction rate of 1 GHz

for triggering BC rate of 40 MHz is of interest

ATLAS has in total 140 mio channels

- size of events e.g. ATLAS : 1-1.5 MB
- affordable mass storage: ~300 MB/s or event rate of 200 Hz

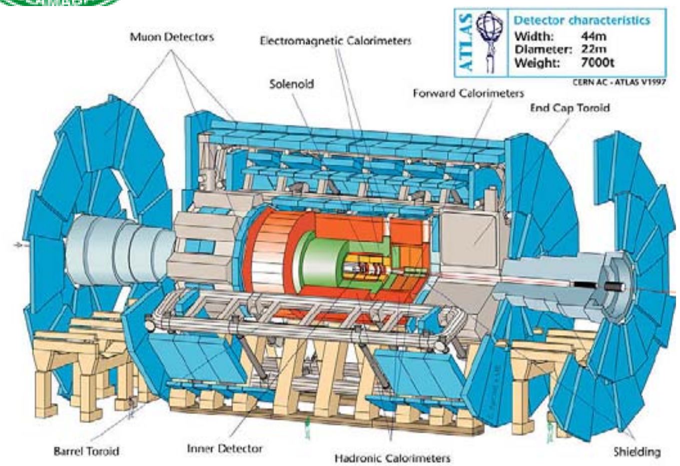
reduction needed 40 MHz down to 200 Hz reject 99.9995 %

interesting rare physics cross section ~10^{-9} and lower w.r.t. Total cross section
but have to identify these events fast!

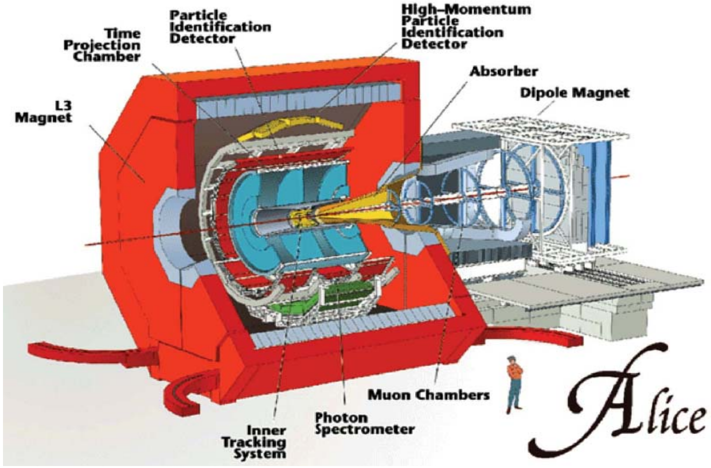
Physics Goals

- To explore physics at the TeV scale
- To discover the Higgs boson
- To look for evidence of physics beyond the standard model, such as supersymmetry, or extra dimensions
- To study aspects of heavy ion collisions

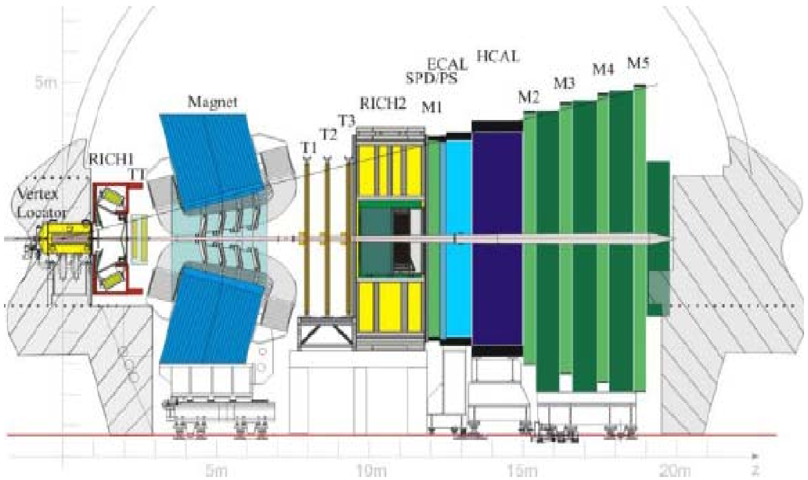
LHC experiments



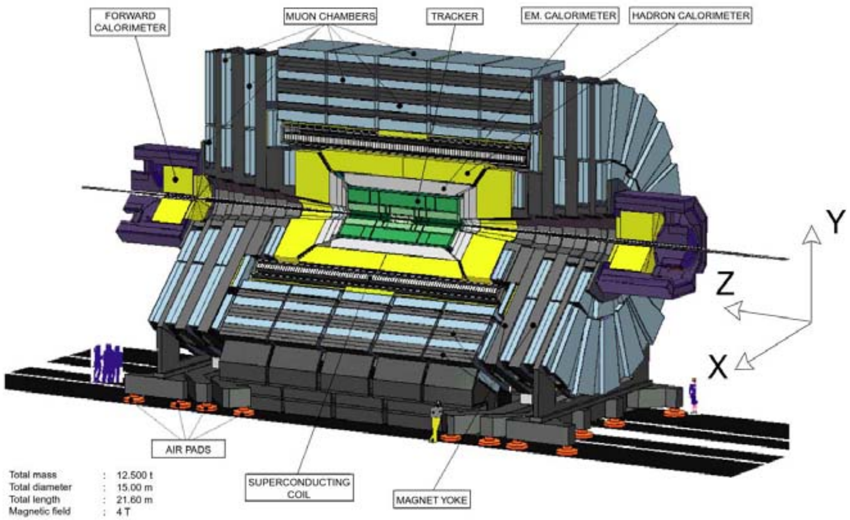
ATLAS



ALICE



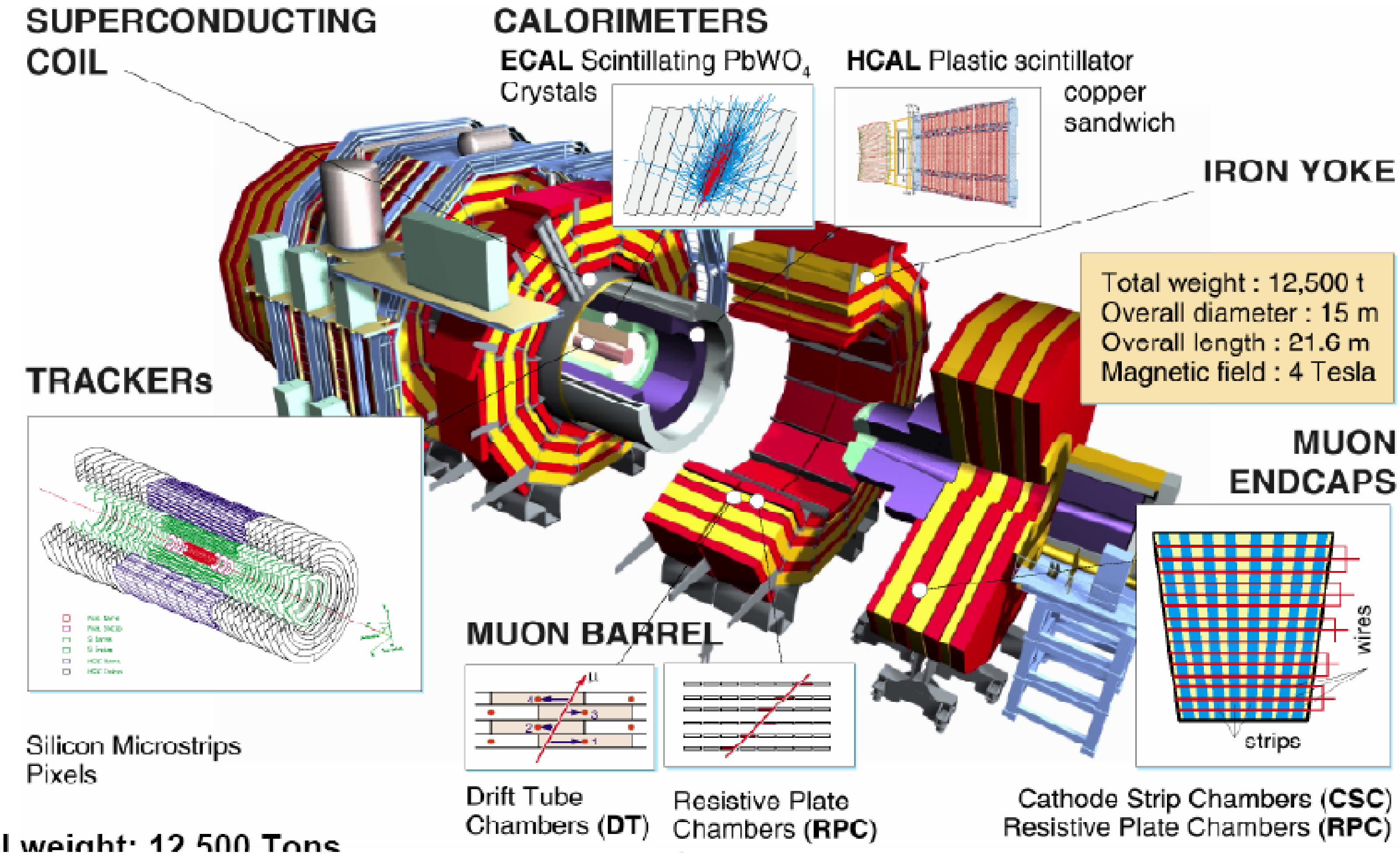
LHC-b



CMS

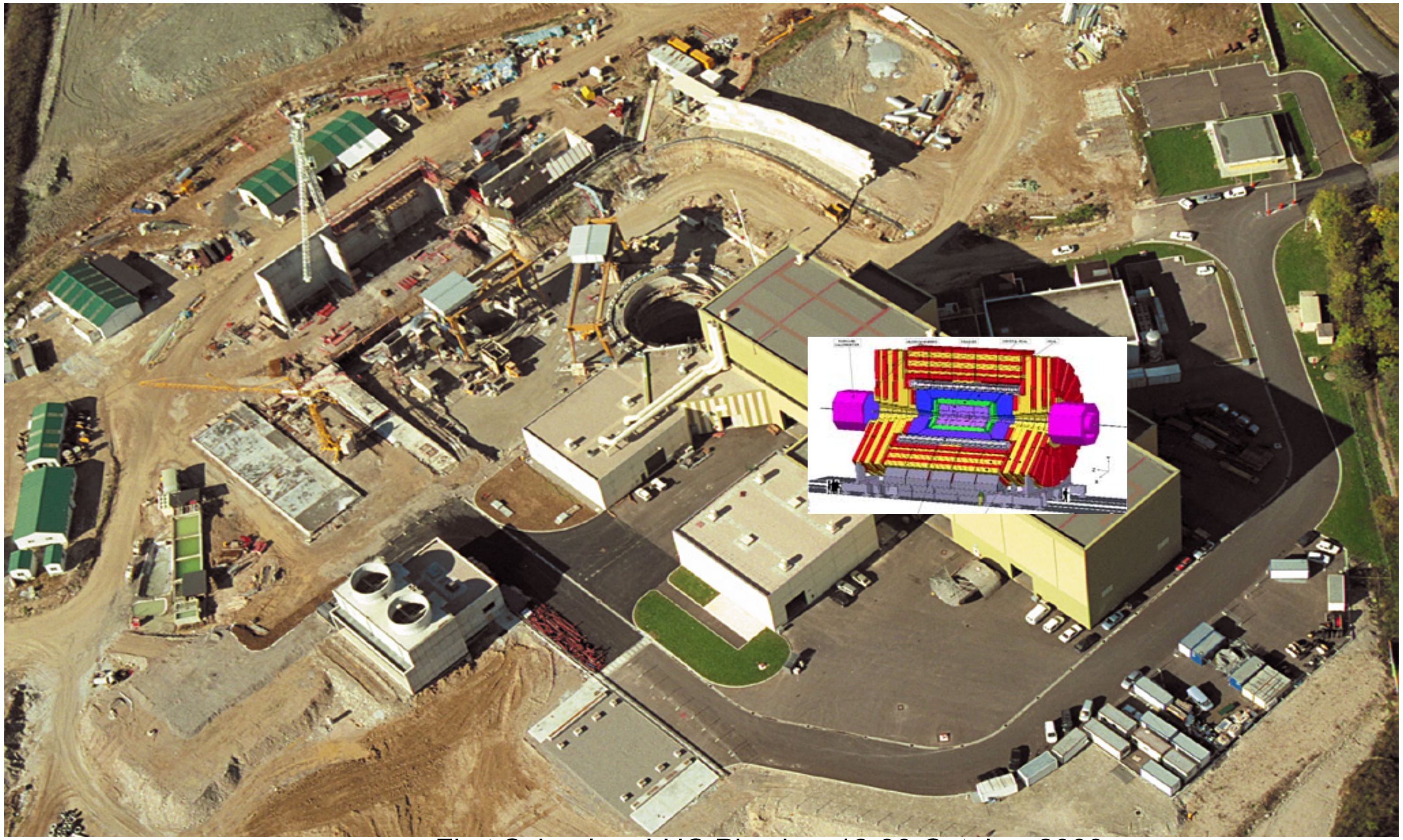
What is CMS

- ✓ CMS-stands for Compact Muon Solenoid
- ✓ General purpose detector
- ✓ Onion shape



How was CMS design

- Lessons learnt from LEP
- Fifteen separate sections lowered into cavern



Typical Signatures

The signatures we look for are characterised by...

- Leptons and photons at high p_T

  initial state pp : no leptons , no p_T

  hight pT leptons in final state :

  decay of heavy particles

  signature of interesting physics

- b quarks, tau leptons from decays

  long lived particles, decay vertex reconstruction

- missing Energy --> $E_T$miss

  Higgs, W decays involve neutrinos

  many SUSY and other BSM scenarios

  missing Energy

  measure missing transverse E

  why not $E_L$miss?

❖ Stable particles

❖ Quasi-stable particle

❖ Vertex tagged particles

❖ Short lived

❖ Missing particles

What we will see in CMS

Leptons	Vetexing	Tracking	ECAL	HCAL	Muon Cham.
$e^{\pm}$	$\times$	$\vec{p}$	E	$\times$	$\times$
$\mu^{\pm}$	$\times$	$\vec{p}$	$\surd$	$\surd$	$\vec{p}$
$\tau^{\pm}$	$\surd\times$	$\surd$	$e^{\pm}$	$h^{\pm}$; $3h^{\pm}$	$\mu^{\pm}$
ν_e, ν_μ, ν_τ	$\times$	$\times$	$\times$	$\times$	$\times$
Quarks					
u, d, s	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$c \to D$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$b \to B$	$\surd$	$\surd$	$e^{\pm}$	h's	$\mu^{\pm}$
$t \to bW^{\pm}$	b	$\surd$	$e^{\pm}$	$b +$ 2 jets	$\mu^{\pm}$
Gauge bosons					
γ	$\times$	$\times$	E	$\times$	$\times$
g	$\times$	$\surd$	$\surd$	$\surd$	$\times$
$W^{\pm} \to \ell^{\pm}\nu$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}'$	$\times$	$\surd$	$\surd$	2 jets	$\times$
$Z^0 \to \ell^+\ell^-$	$\times$	$\vec{p}$	$e^{\pm}$	$\times$	$\mu^{\pm}$
$\to q\bar{q}$	$(b\bar{b})$	$\surd$	$\surd$	2 jets	$\times$

Detector Requirements...

The signatures we look for ...

- Leptons and photons at high p_T
- missing Energy --> E_t^{miss}
- b quarks, tau leptons
- Jets

with high backgrounds and low pT pile up

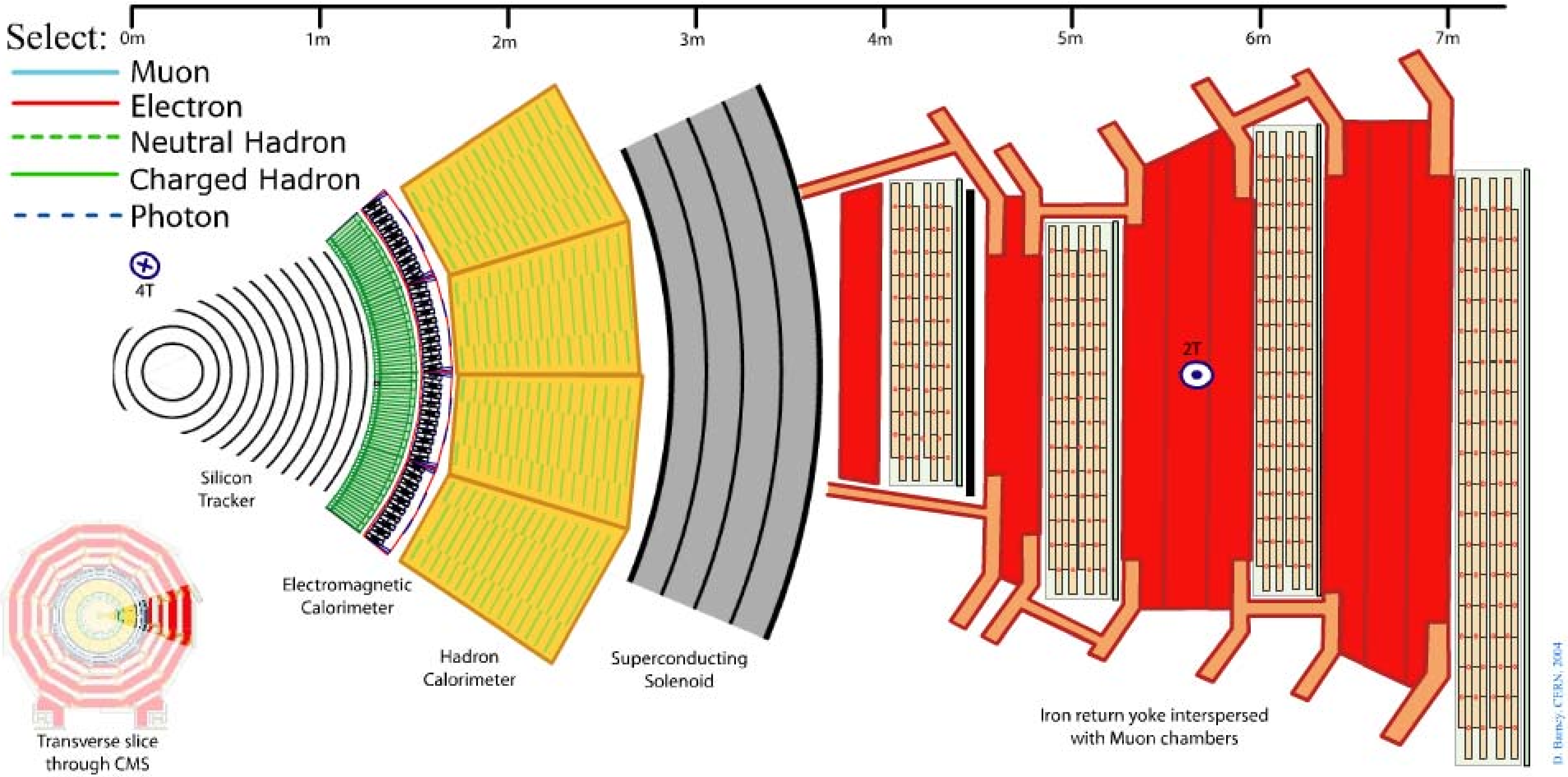
Detector requirements ...

- radiation hardness
- timing 25 ns
- identify and measure leptons, photons at high pT
  lepton ID over huge background e/jet ~ 10^{-5}
- good measurement of missing transverse Energy energy measurement in forward region ($|\eta|<5$)
- b and τ tag (silicon detectors)
- highly selective and fast trigger
  signal xs ~ 10^{-14} of total xs

Specific Design

- A high performance system to detect and measure muons,
- A high resolution method to detect and measure electrons and photons (an electromagnetic calorimeter),
- A high quality central tracking system to give accurate momentum measurements, and
- A “hermetic” hadron calorimeter, designed to entirely surround the collision and prevent particles from escaping

Working Principle



Why is it so Big

- Record the Universe's tiniest
- Possibility of obtaining more accurate measurements
- Need a strong magnetic field to bend the particles trajectories

Total weight: 12,500 Tons
Diameter: 15m
Length: 21 m
Field: 4 Tesla
Readout channels: ~80M

Coordinate conventions

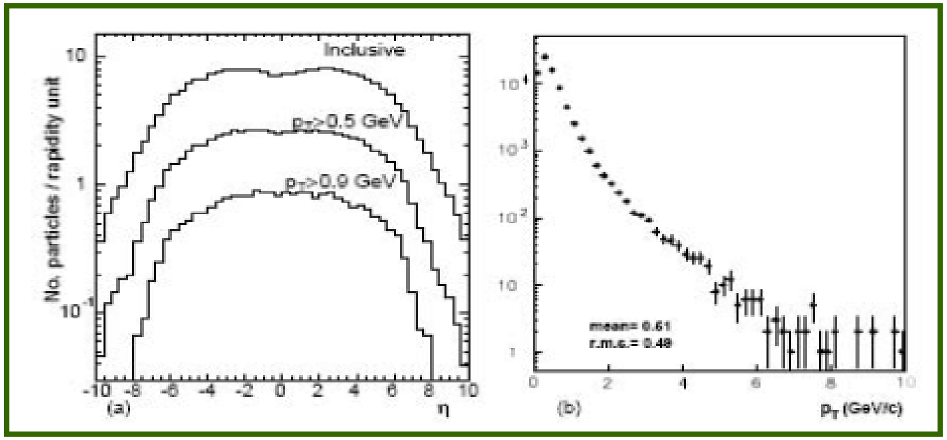
- **transverse momentum p_T:** momentum perpendicular to the beam axis

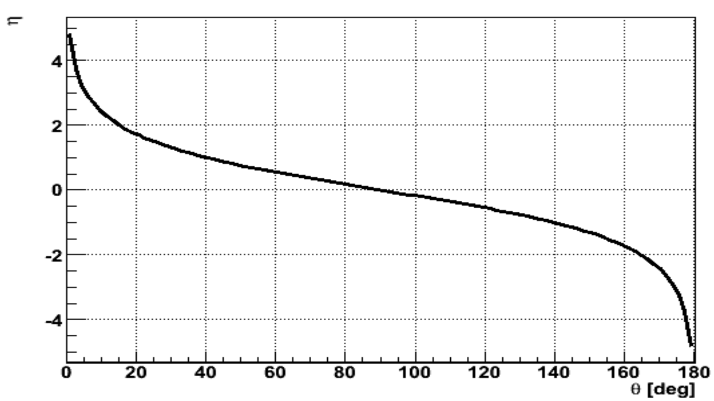
- **pseudorapidity η**

  rapidity $$y = \frac{1}{2}\ln\frac{E+p_L}{E-P_L}$$

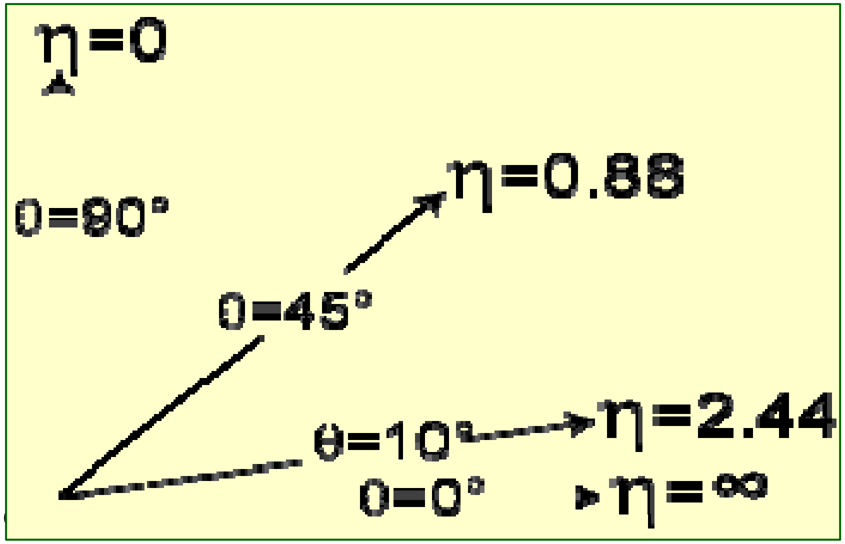
  massless particles (mass unknown) use pseudorapidity instead:

  $$\eta = -\ln\tan\theta/2$$





θ (degrees)	η
0	infinite
5	3.13
10	2.44
20	1.74
30	1.31
45	0.88
60	0.55
80	0.175
90	0

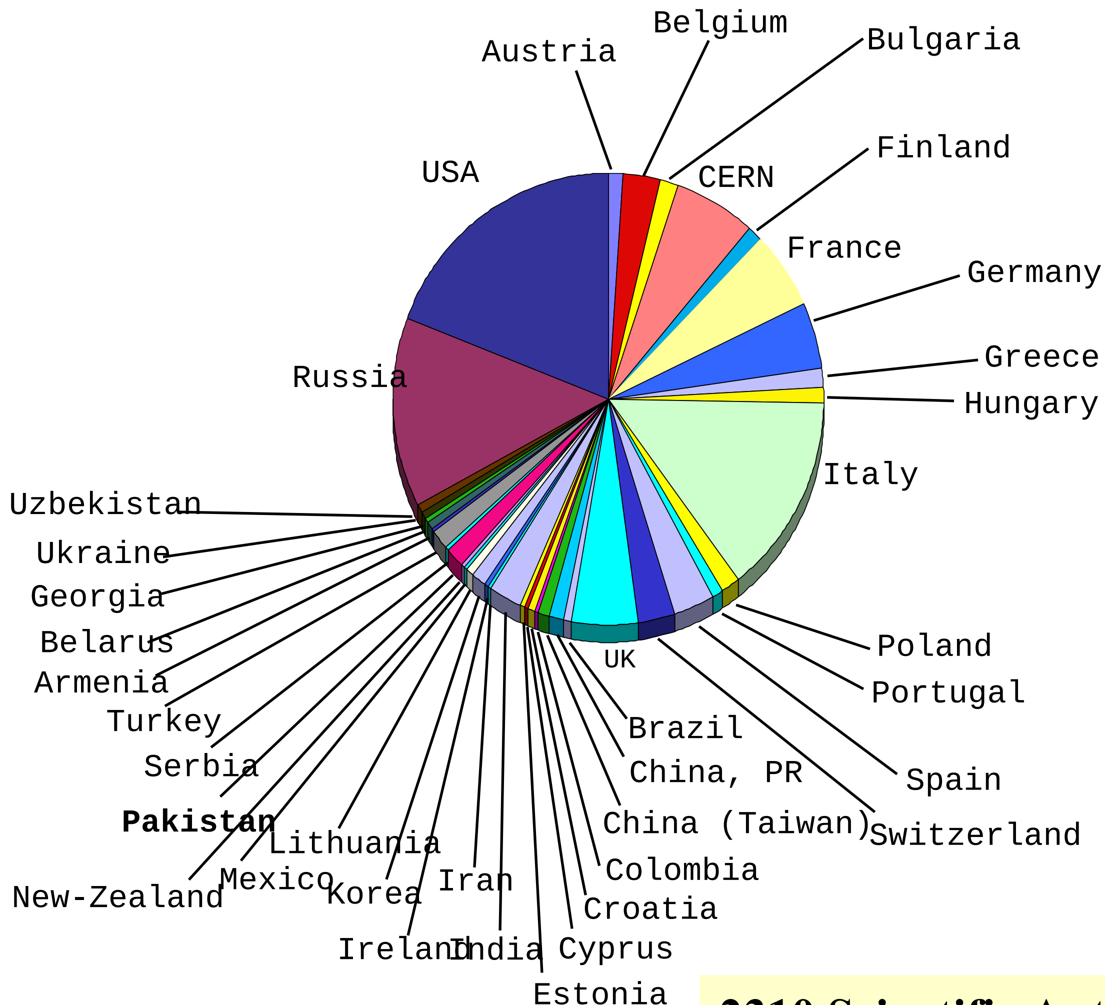


The CMS Collaboration

	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	175

	# Scientific Authors
Member States	1084
Non-Member States	503
USA	723
Total	2310

Associated Institutes	
Number of Scientists	62
Number of Laboratories	9



2310 Scientific Authors
38 Countries
175 Institutions

Oct. 3rd 2007/gm

CMS Design Criteria

- **Very good muon identification and momentum measurement**
  Trigger efficiently and measure sign of TeV muons dp/p < 10%

- **High energy resolution electromagnetic calorimetry**
  ~ 0.5% @ E_T ~ 50 GeV

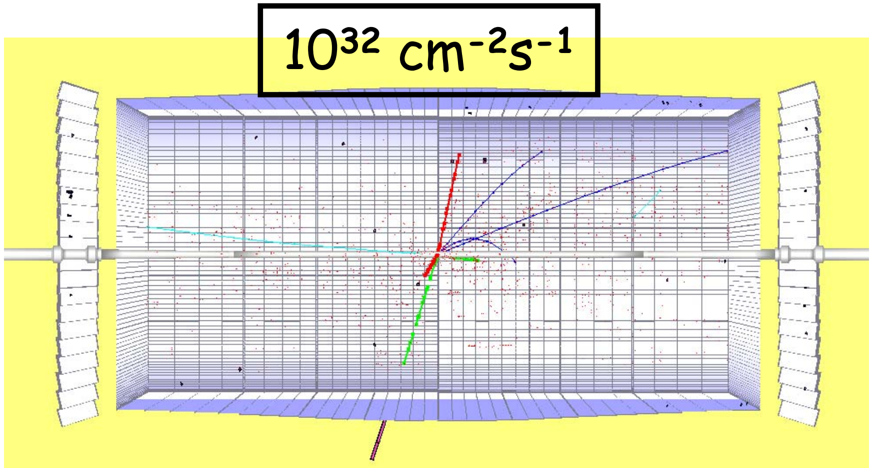
- **Powerful inner tracking systems**
  Momentum resolution a factor 10 better than at LEP

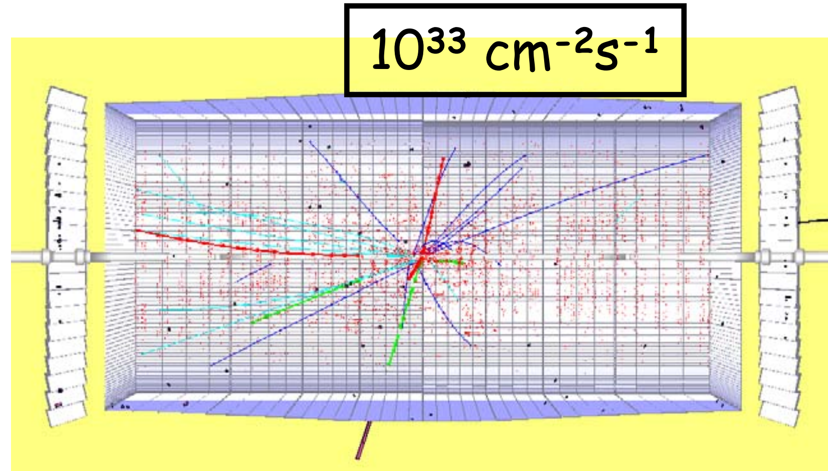
- **Hermetic calorimetry**
  Good missing E_T resolution

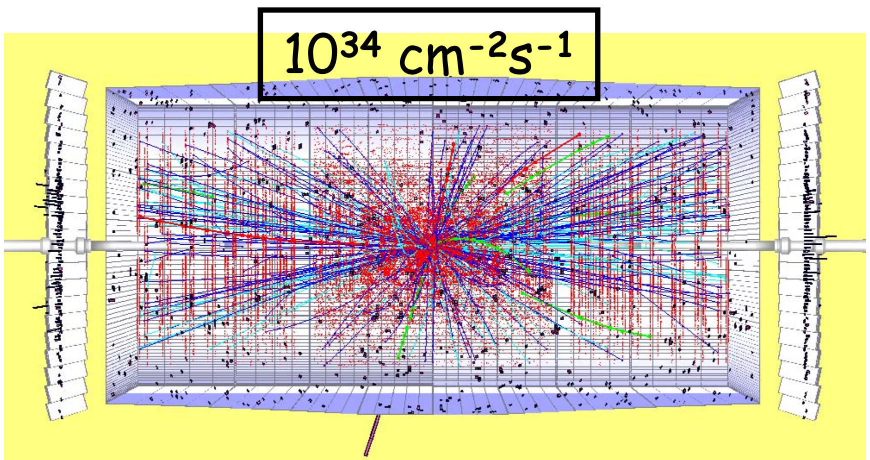
- **(Affordable detector)**

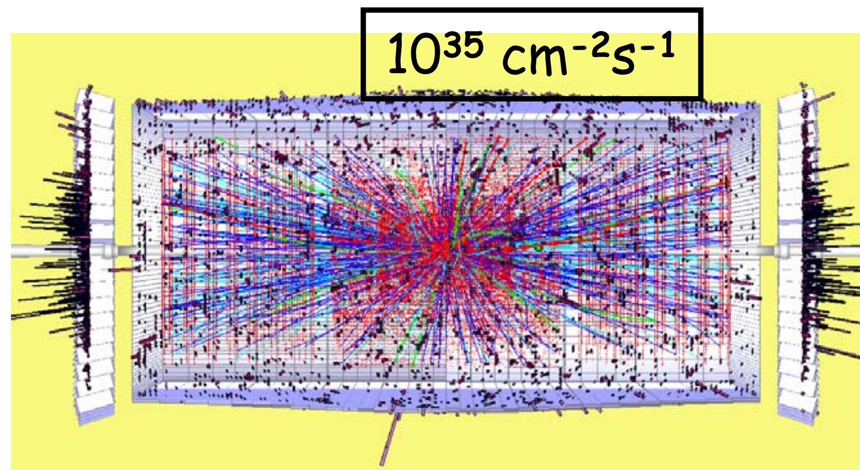
Luminosity Effects

$H \to ZZ \to \mu\mu ee$ event with M_H= 300 GeV for different luminosities



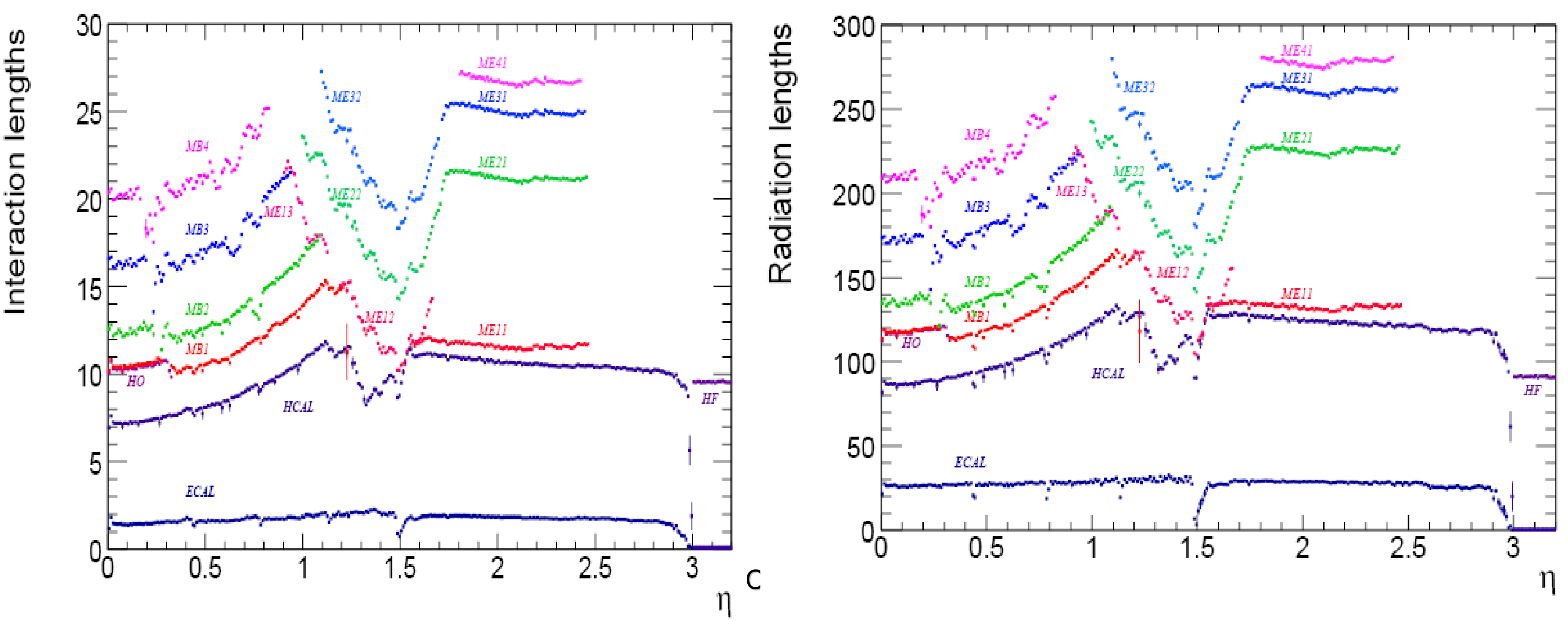






Detector Thickness

Material thickness in terms of radiation length and interaction length



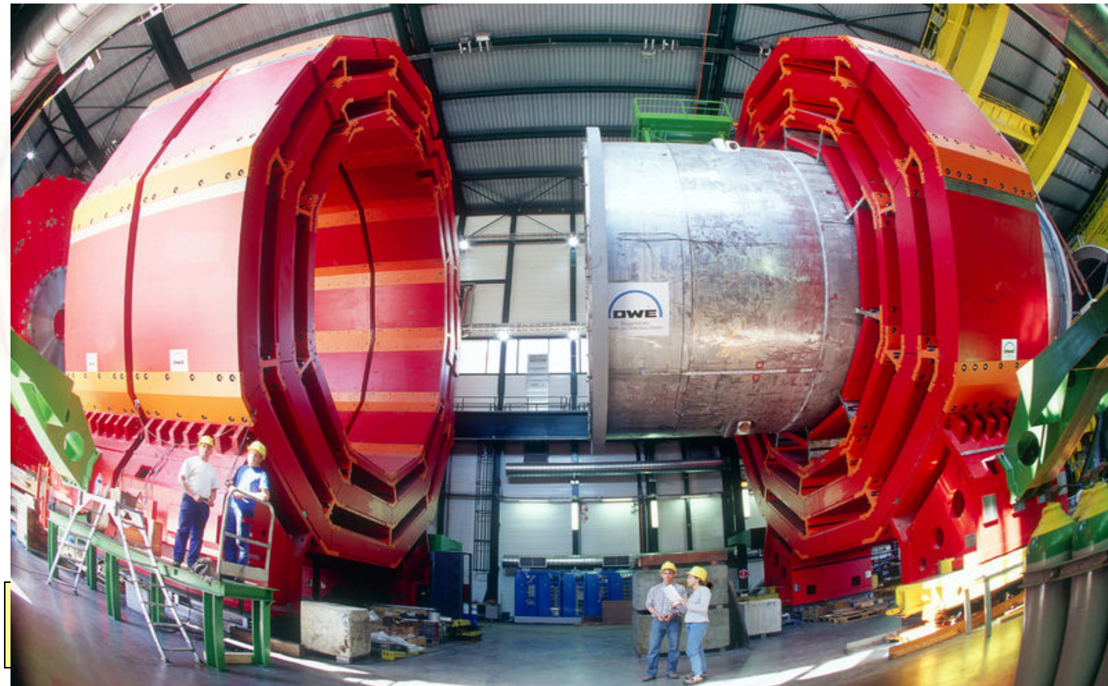
The CMS Solenoid

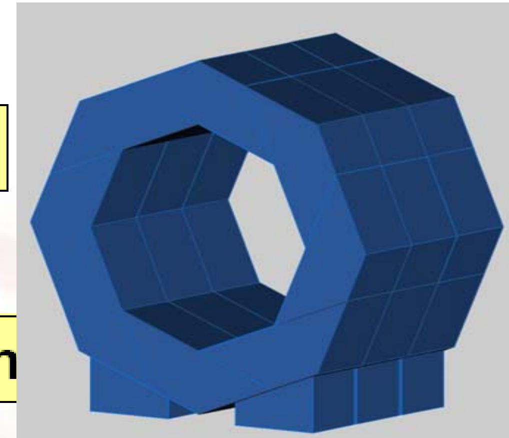
The CMS magnet…

- ❖ is the largest superconducting magnet ever built
- ❖ weighs 12,000 tonnes
- ❖ is cooled to -268.5°C, a degree warmer than outer space
- ❖ is 100,000 times stronger than the Earth's magnetic field
- ❖ stores enough energy to melt 18 tonnes of gold
- ❖ uses almost twice much iron as the Eiffel Tower

A stronger field provides You more precise momentum and energy resolution

The return yoke-parameters





Total weight	12500 tonnes
Diameter	15m
Length	21.6m
Magnetic field	4 Tesla

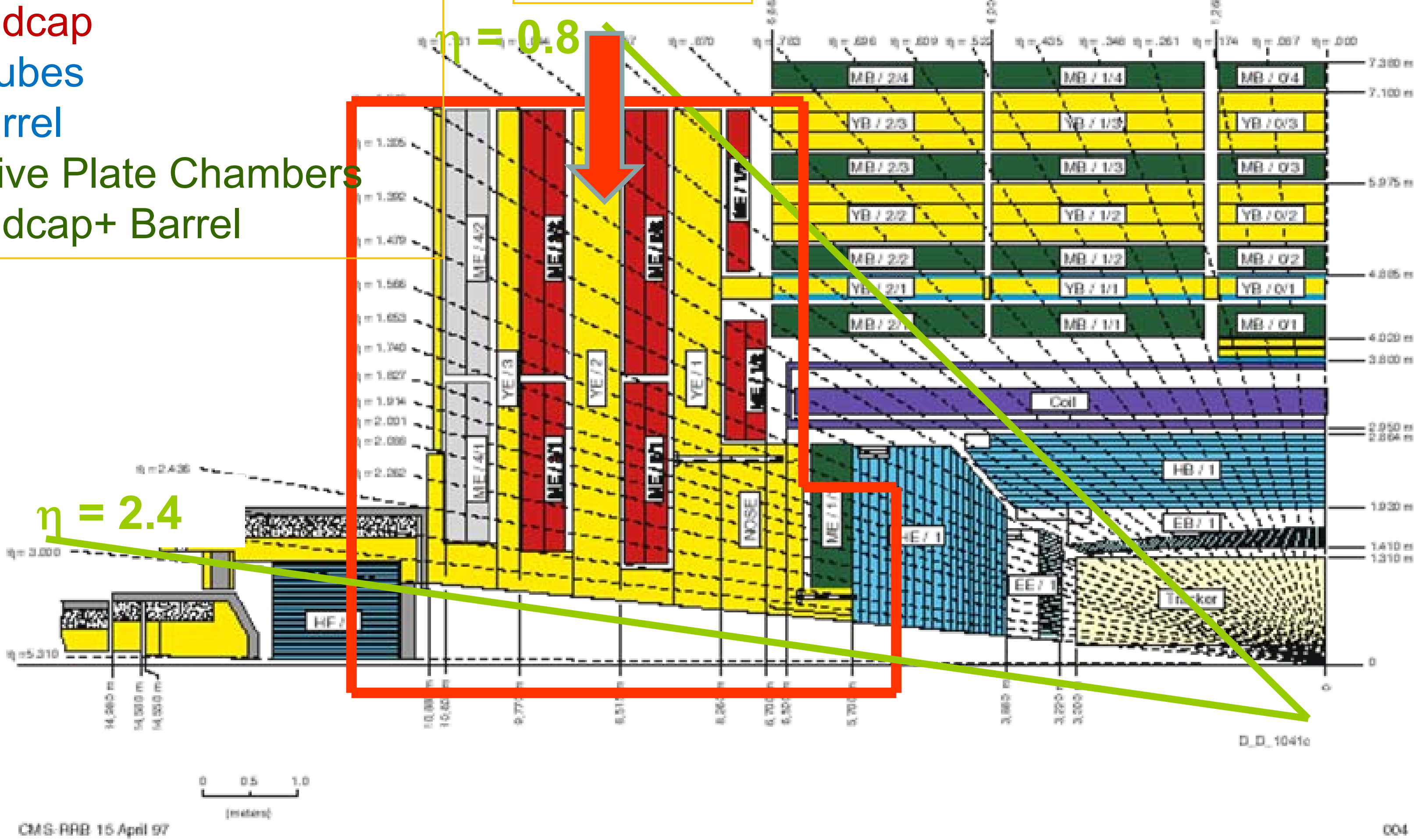
	Central Ring	*Outer Rings*
Barrel ring	1250 tonnes	1174 tonnes
Vacuum vessel	264 tonnes	-
Superconducting coil	234 tonnes	-
Support feet	72 tonnes	66 tonnes
Cabling on vacuum vessel	150 tonnes	-
Support for racks and cables	10 tonnes	10 tonnes
Total	**1980 tonnes**	**1250 tonnes**

Endcap disk 1 (YE1)	~730 (disk) + 90 (cart) tonnes
Endcap disk 2 (YE2)	~730 (disk) + 90 (cart) tonnes
Endcap disk 3 (YE3)	~300 (disk) + 90 (cart) tonnes

Muon System

- ❑ Cathode Strip Chambers
  - o Endcap
- ❑ Drift Tubes
  - o Barrel
- ❑ Resistive Plate Chambers
  - o Endcap+ Barrel

Endcap

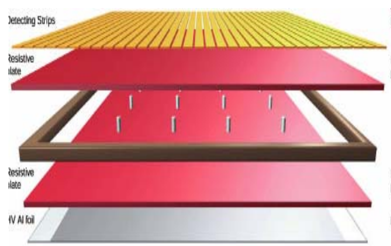


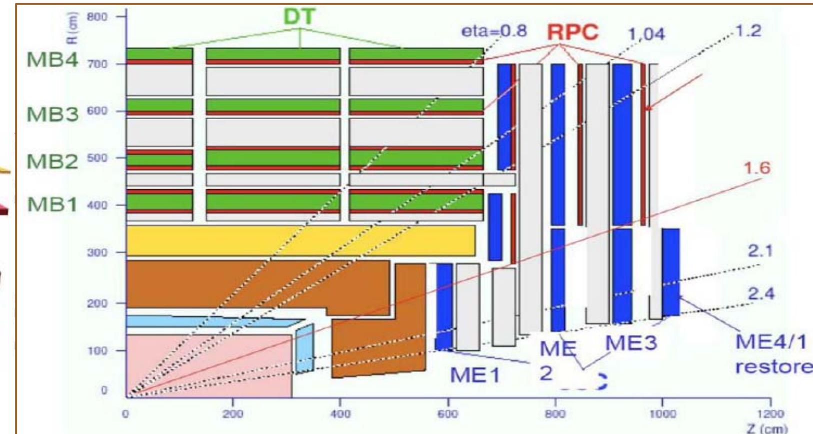
The Muon Chambers

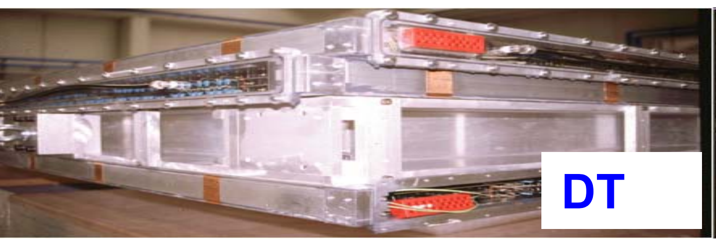
Barrel region:

- ❖ DTs and RPCs
- ❖ Low almost uniform B field
- ❖ Low muon rate ~ 1 Hz/cm^2
- ❖ Negligible neutron induced background

RPC







CSC

➢ Stand alone

dp_t/p_t = 8 - 15% at p_t = 10 GeV

dp_t/p_t = 20 - 40% at p_t = 1 TeV

➢ Global

dp_t/p_t = 1 - 1.5% at p_t = 10 GeV

dp_t/p_t = 6 - 17% at p_t = 1 TeV

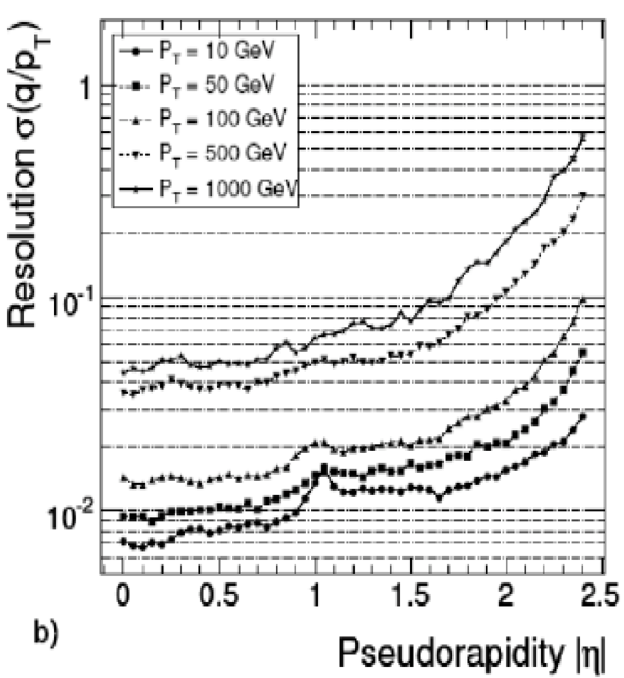
Endcap region:

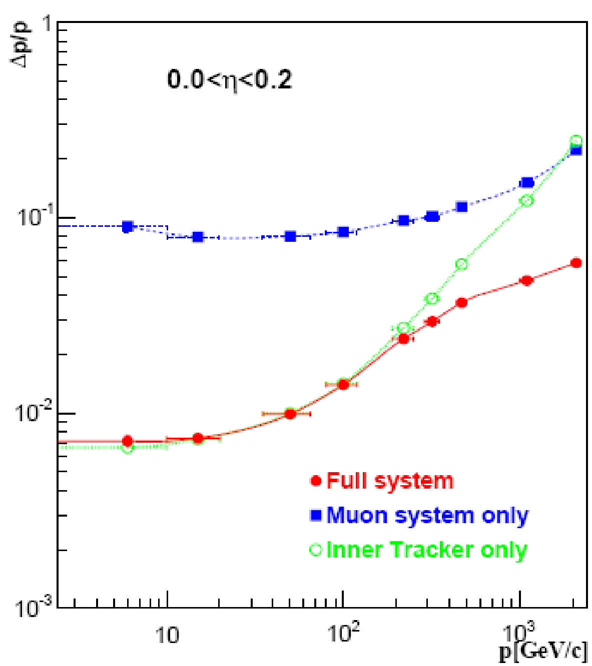
- ❖ CSCs and RPCs
- ❖ Strong non-uniform B-filed (~ 3.5 Tesla)
- ❖ High muon rate ~ 1000 Hz/cm^2
- ❖ γ and neutron induced background are comparable

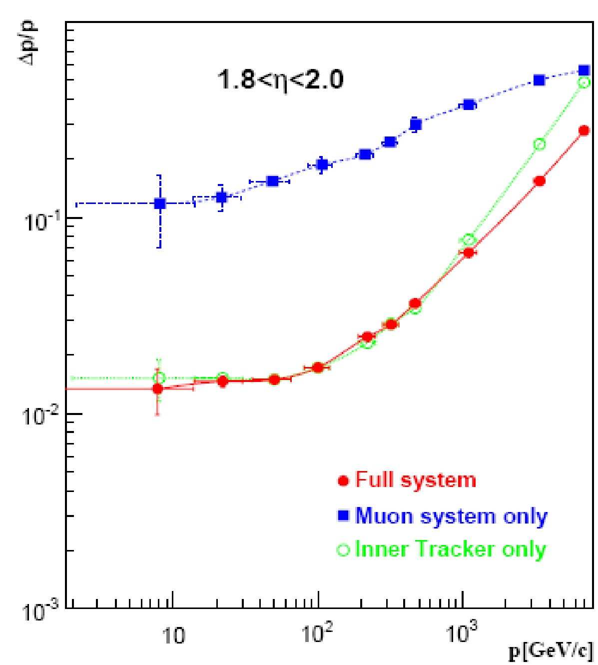
- Geometrical coverage up to η=2.4
- 128 BX Latency = 3.2 μs
- No Dead-time allowed: every BX must be processed
- Output Rate: ~ 30 KHz –> reduction factor > 10^3
- Ghost Rate < 0.5 %
- p_t threshold should be set in the range ~ 4 – 50 GeV

Muon System: Requirements

- Muon Identification
- Muon Trigger
- Standalone Momentum Resolution: from 8 to 15% pT/pT at 10 GeV and 20 to 40% at 1 TeV.
- Global Momentum Resolution.
- CHARGE Assignment.
- Capability of Withstanding.

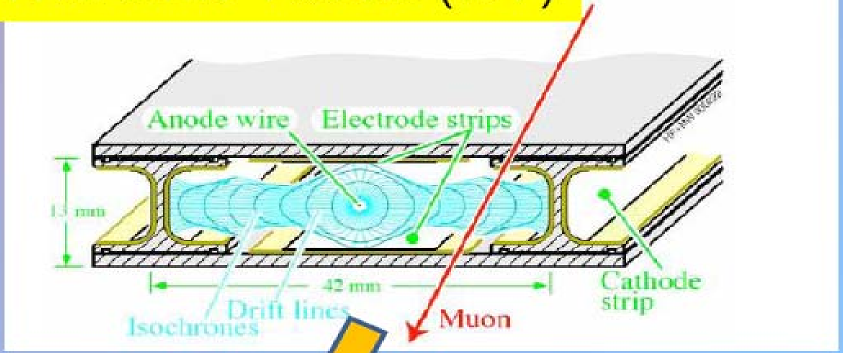






Muon System: DT

The Drift-Tubes (DT)

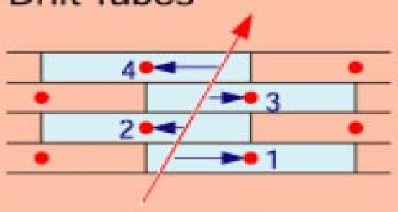


V_{drift} ~ 55 μm/ns -> Max drift time ~380 ns

Single wire resolution ~ 250 μm

Local reconstruction (r-ϕ) ~ 100 μm

Drift Tubes



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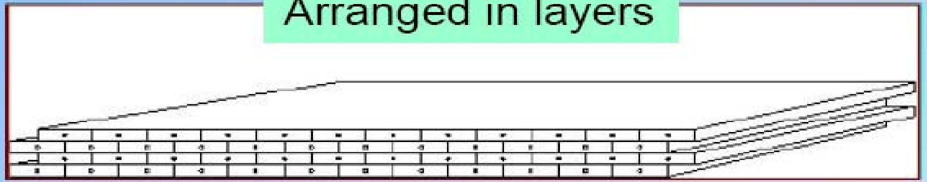
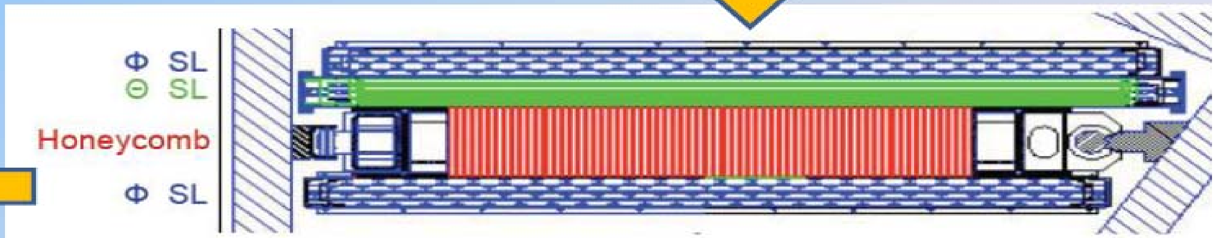




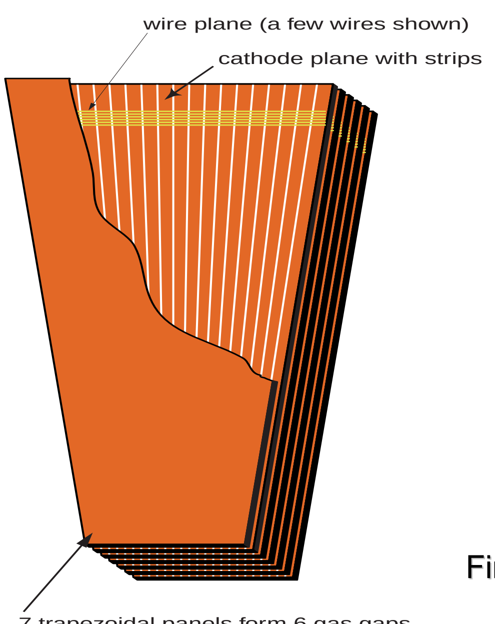
250 **chambers** like this in the barrel

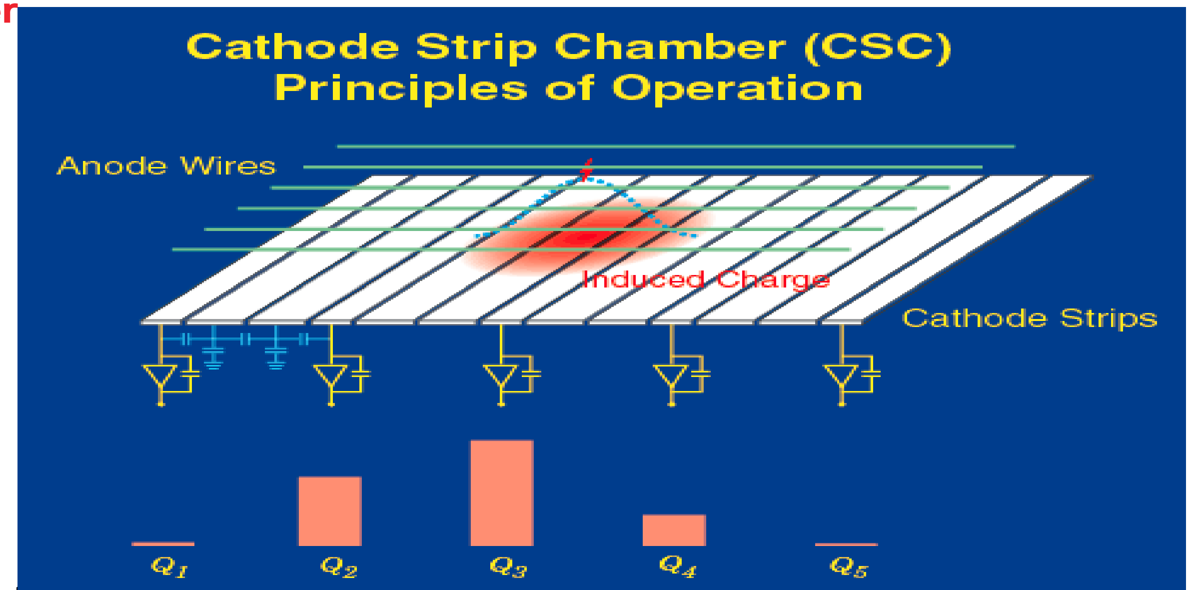
Muon System: CSC

- 6 planes/chamber –540 chambers in total
- ϕ measured from fit to the induced charger r and BX id from the signal on the wire f resolution ~ 100 mm

- 468 CSCs of 7 different types/sizes
- > 2,000,000 wires (50 mm)
- 6,000 m^2 sensitive area
- 1 kHz/cm^2 rates
- 2 mm and 4 ns resolution/CSC (L1-trigger)
- 100 μm resolution/CSC (offline)

EMU Cathode Strip Chamber

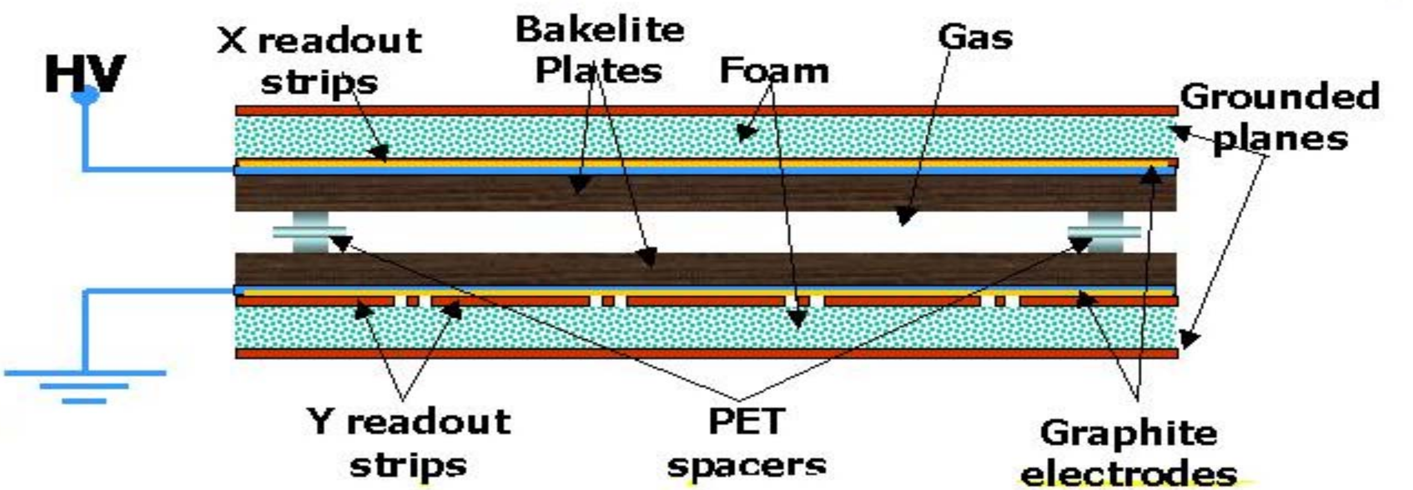


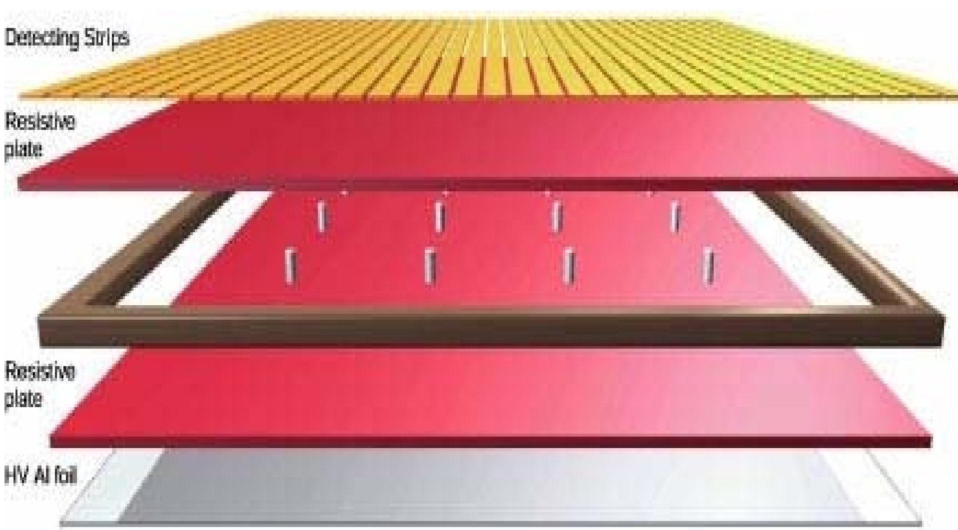


Muon System: RPC

Pakistan

- Intrinsically fast response ~ 3 ns
- Rate handling depends on electrode resistivity





- Bakelite resistivity ~10^{10} Ωcm
- Gap width: 2 mm
- Surface resistivity: 200-300 KW/sq
- HV electrodes : 100 μm graphite layer
- PVC Spacers (tolerance ± 200 μm)
- Gas pressure : ~ 1 Atm
- Gas mixture: 96% Freon, 3.5% Iso-butane, 0.5% SF6
- CMS RPC-trapezoidal in shape, 3 eta segments
- Inter-strip spacing ~ 1.5 mm
- Strip length ~ 1 m, # of strips/chamber = 96
- Strip Width ~ 20-30 mm

Muon System: RPC mode

$$n_i(x) = n_j e^{\eta(x - x_j)}$$

$$Q_e(x) = Q_j e^{\eta(x - x_j)}, Q_j = q_{el} n_j$$

$$Q_i^-(x) \approx \frac{\beta}{\eta} Q_e(x)$$

$$Q_i^+(x) \approx \frac{\alpha}{\eta} Q_e(x)$$

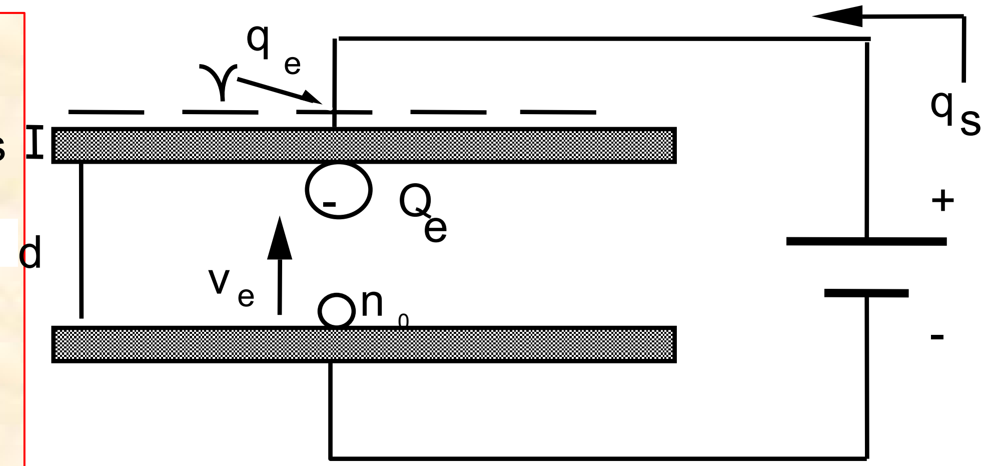
$$P_j(x)dx = \frac{x^{j-1}}{(j-1)!} \lambda^j e^{-\lambda x} dx$$

$$P(n)dn = \frac{\mu^n}{n!} e^{-\mu} dn$$

$$< Q_e(x) >= q_{el} \mu e^{\eta x} \left(\frac{\lambda}{\lambda + \eta}\right)^j$$

$$< Q_i^-(x) >= \frac{\beta}{\eta} < Q_e(x) >$$

$$< Q_i^+(x) >= \frac{\alpha}{\eta} < Q_e(x) >$$



RPC schematic diagram

Avalanche formation
(Raether's condition)

$$\eta = \alpha - \beta$$

$$N = N_0 e^{\eta d}, \frac{N}{N_0} < 10^8, \eta d < 20$$

Muon System: RPC

$$i(t) = -\int_{-\infty}^{t} Q(P(\tau))\Phi_w(P(t-\tau)) \times v_d(P(\tau))\,d\tau$$

$$\Phi_w(t) = -gradV_g = \delta(t)\Phi_w$$

$$\Phi_w = \frac{k}{d}$$

$$k = \frac{C_b}{C_b + 2C_g} = \frac{\varepsilon_r d/s}{\varepsilon_r d/s + 2} = const$$

0.7—S.G

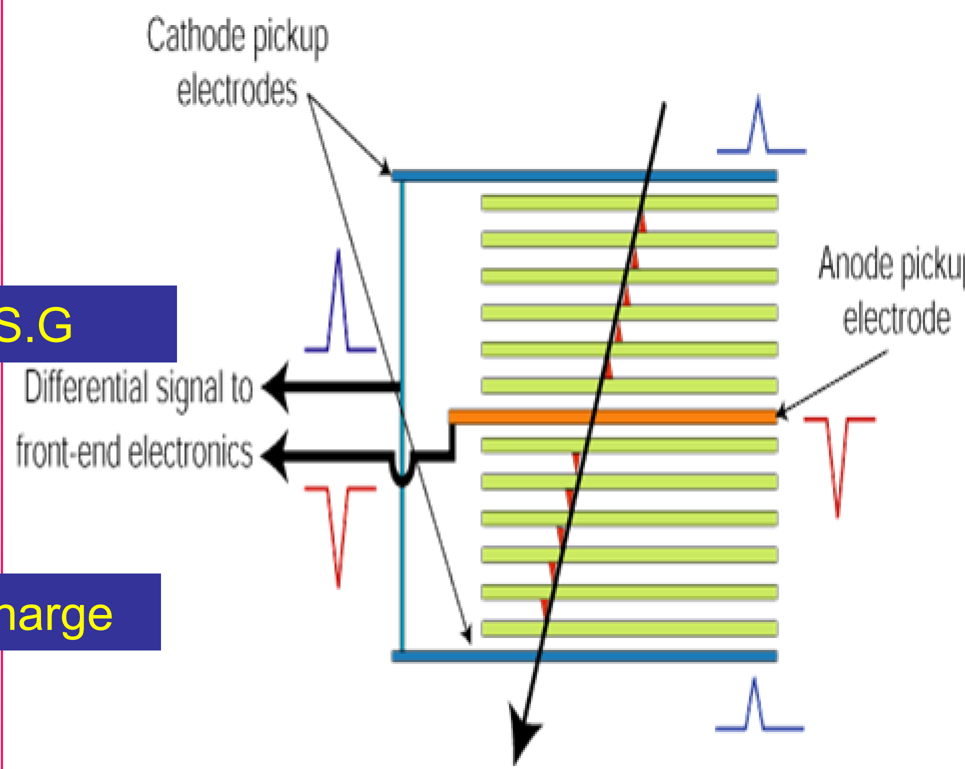
$$i(t) = -Q(x)\Phi_w \times v_d = kQ(x)\frac{v_d}{d}$$

$$q_e \approx \frac{k}{\eta d} < Q_e(d) >$$

Fast charge

$$k = \frac{C_b}{nC_b + (n+1)C_g} = \frac{\varepsilon_r d/s}{n\varepsilon_r d/s + (n+1)}$$

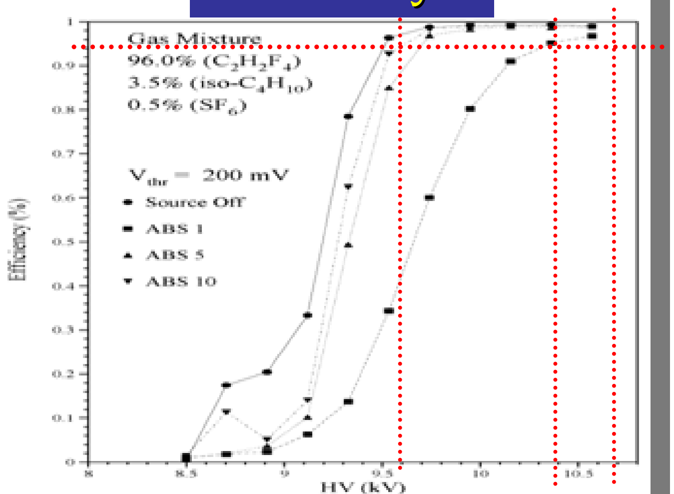
$$\frac{q_e}{q_s} = \frac{k}{\alpha d}$$



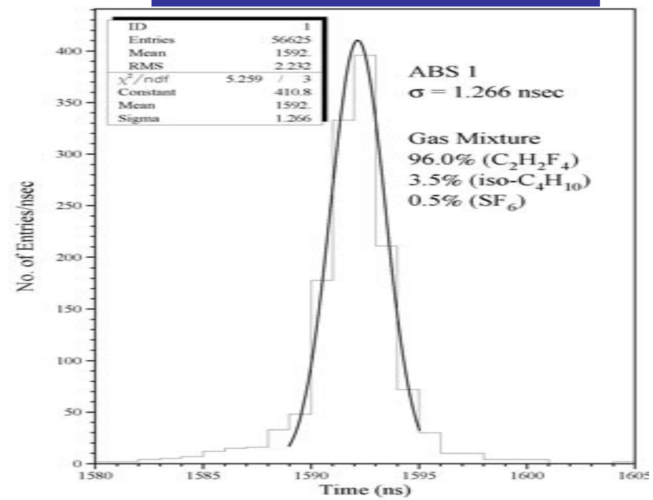
Typically $1/\eta d$ is ~ 5 - 7 %

Muon System: RPC Performance

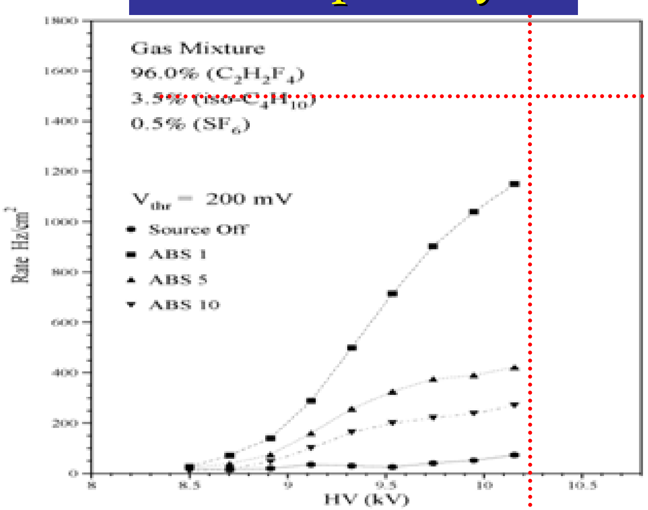
Efficiency



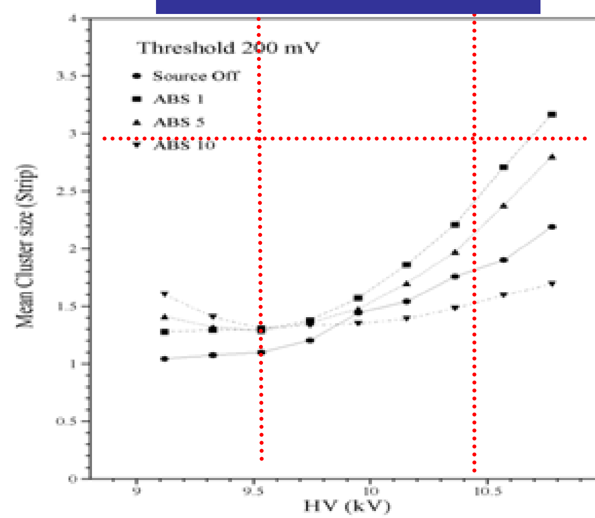
Time Resolution



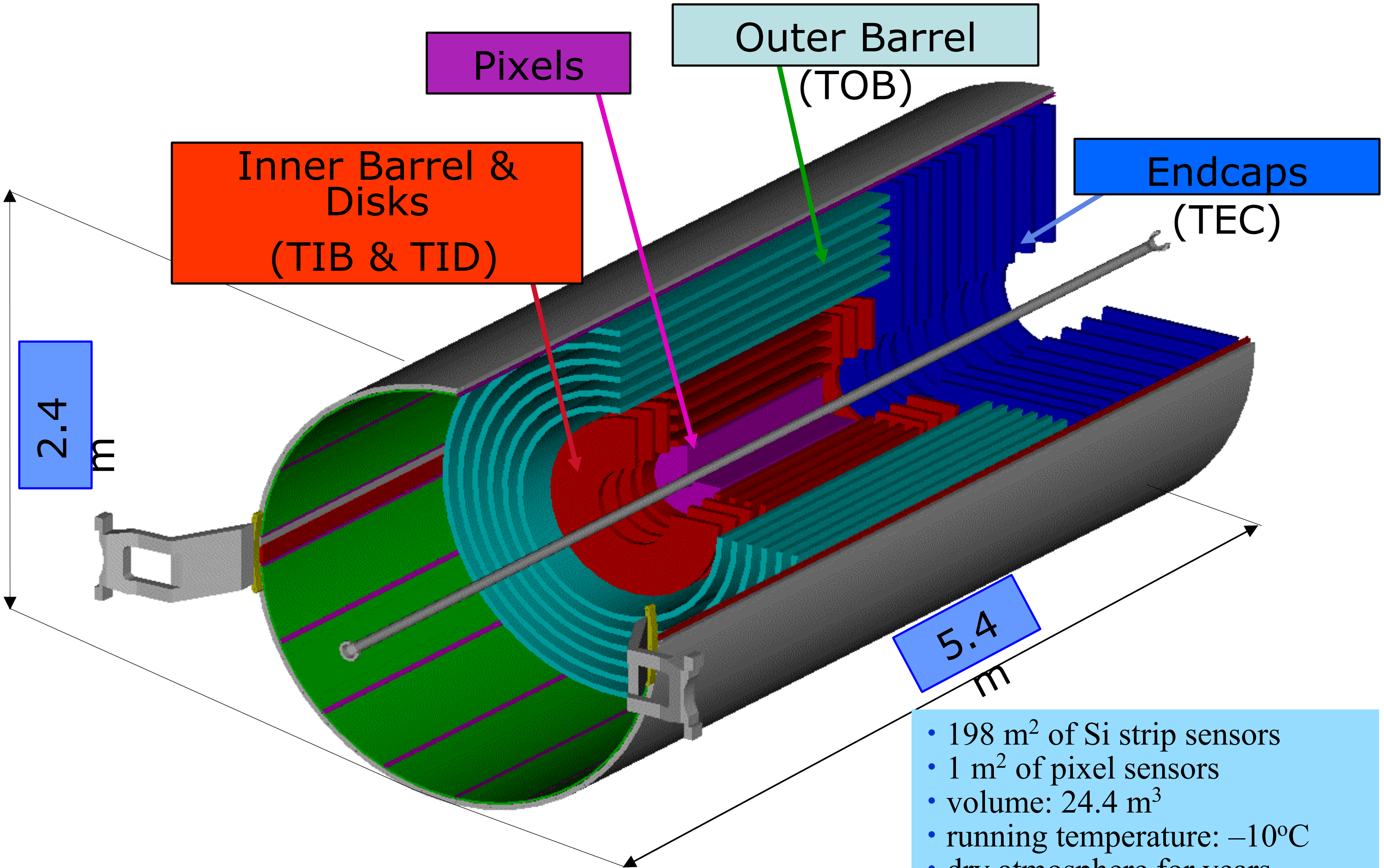
Rate Capability



Cluster Size



Tracker: Overview



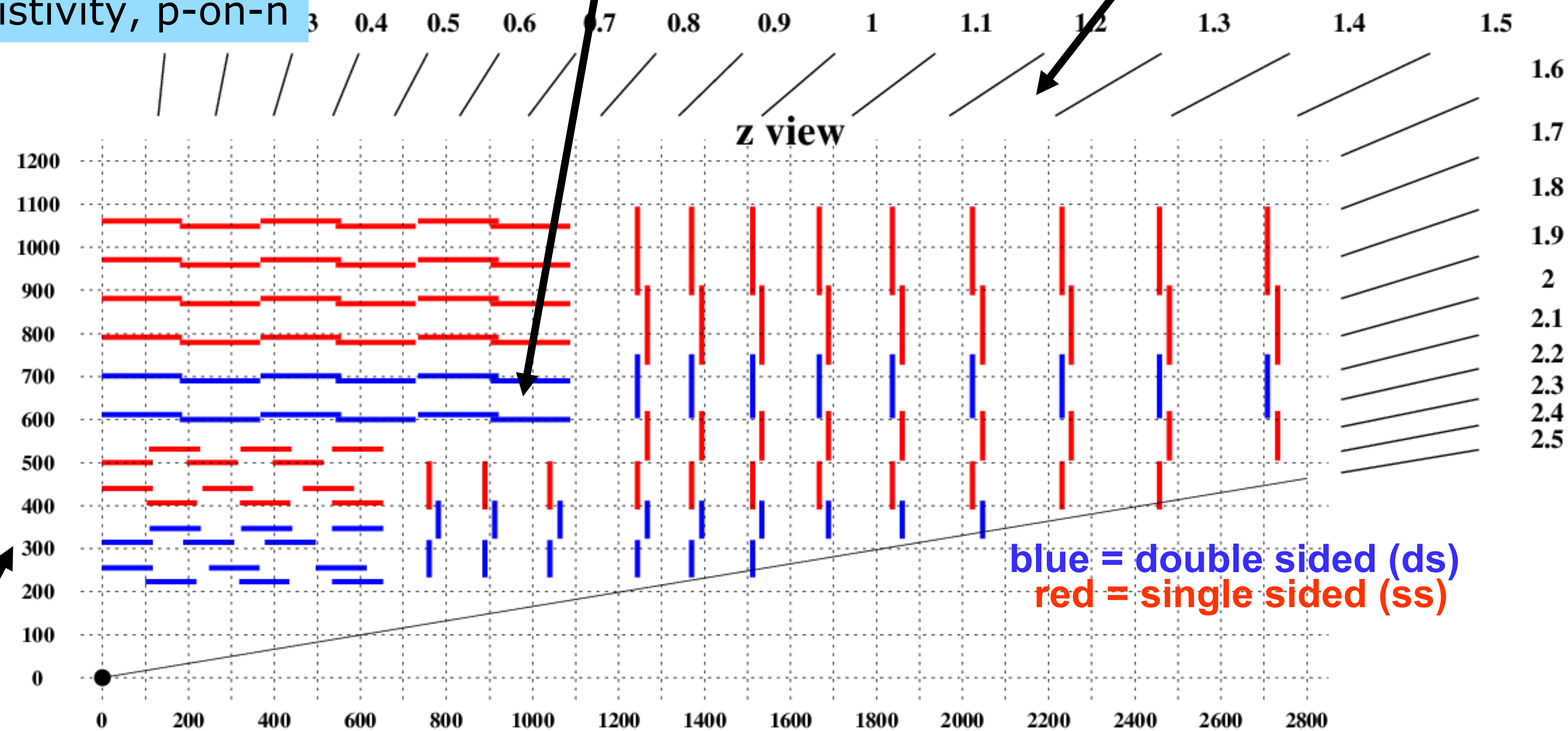
- 198 m^2 of Si strip sensors
- 1 m^2 of pixel sensors
- volume: 24.4 m^3
- running temperature: -10^oC
- dry atmosphere for years

Tracker: layers

Outer barrel
6 layers of 500 μm sensors
high resistivity, p-on-n

Inner disk
3 disks, 3 rings (thin)

Endcap
9 disks, 7 rings (1..4 thin)

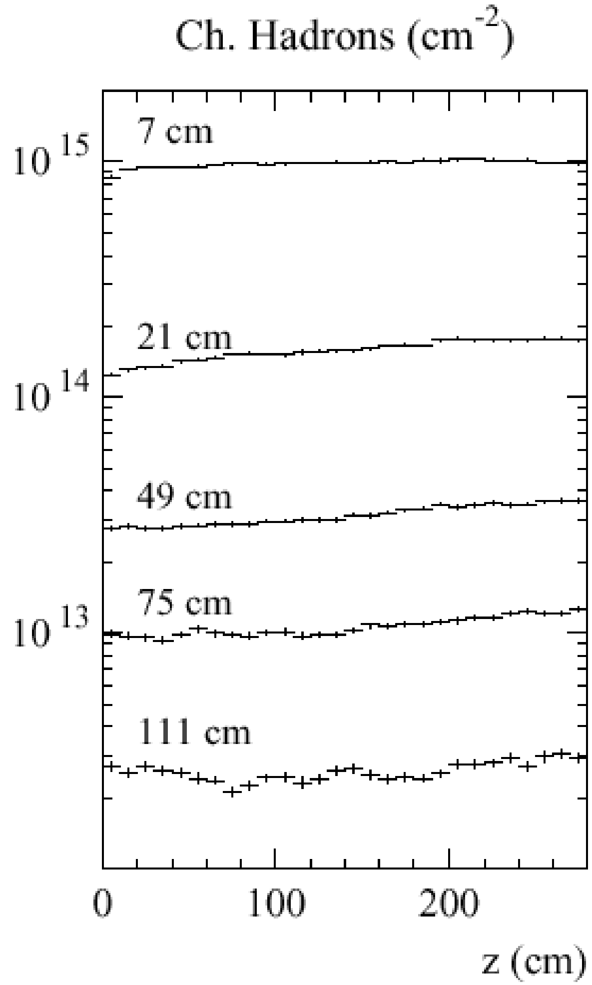


Inner barrel
- 4 layers of 320 μm sensors
- low resistivity, p-on-n

Tracker: Fluence

Need factor 10 better momentum resolution than at LEP
1000 particles emerging every crossing (25ns)

Fluence over 10 years of LHC Operation



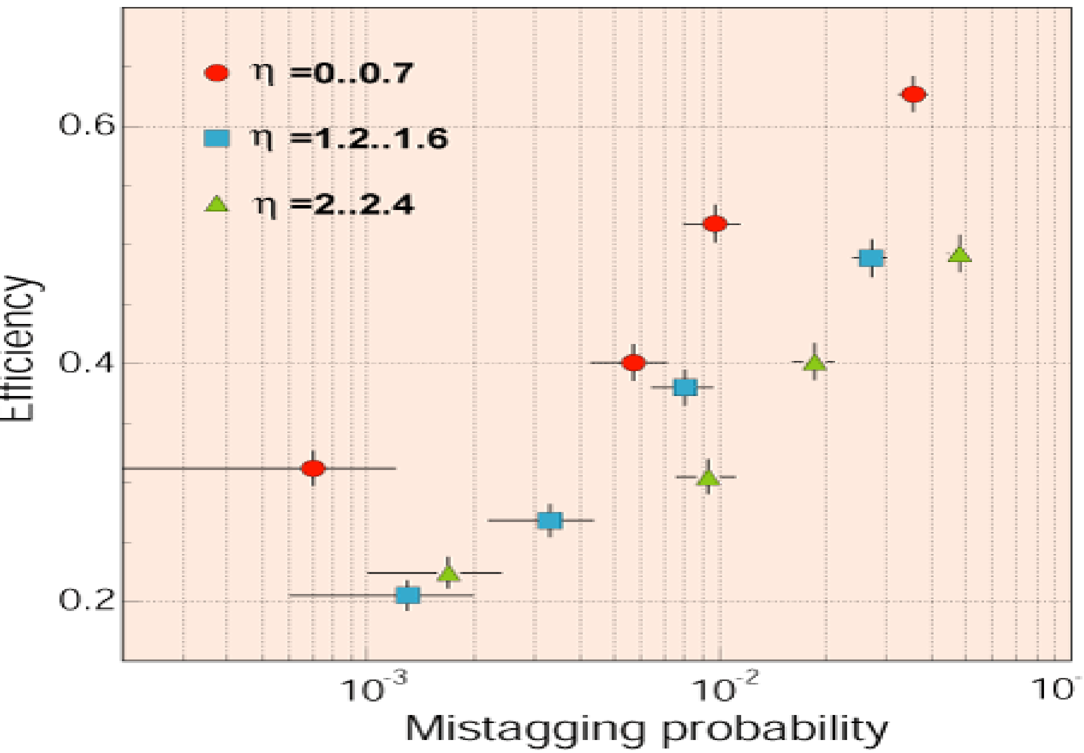
$\leq$ 4.10^7 h$^\pm$/cm^2/s
pixels ($\approx 10^4$ μm^2)
occupancy $\approx 10^{-4}$

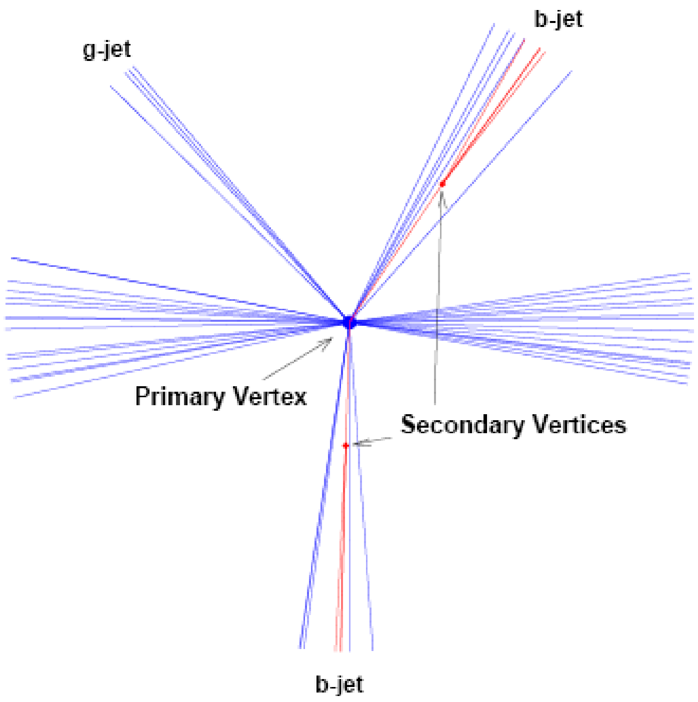
$\leq$ 4.10^6 h$^\pm$/cm^2/s
Si μ-strip det.
($\approx$10 mm^2)
occupancy $\approx$ 1%

$\leq$ 4.10^5 h$^\pm$/cm^2/s
Si or Gas detectors.
($\approx$1 cm^2)
occupancy $\approx$ 1%

Tracker: Vertex Identification

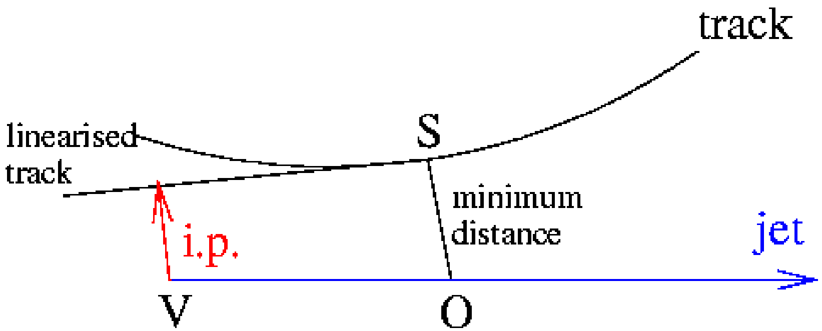
- $\delta pT/pT \approx (15pT+0.5)\%$, with pT in TeV, in the central region $|\eta| \leq 1.6$, gradually degrading to $\delta pT/pT \approx (60pT+0.5)\%$ as $|\eta|$ approaches 2.5.

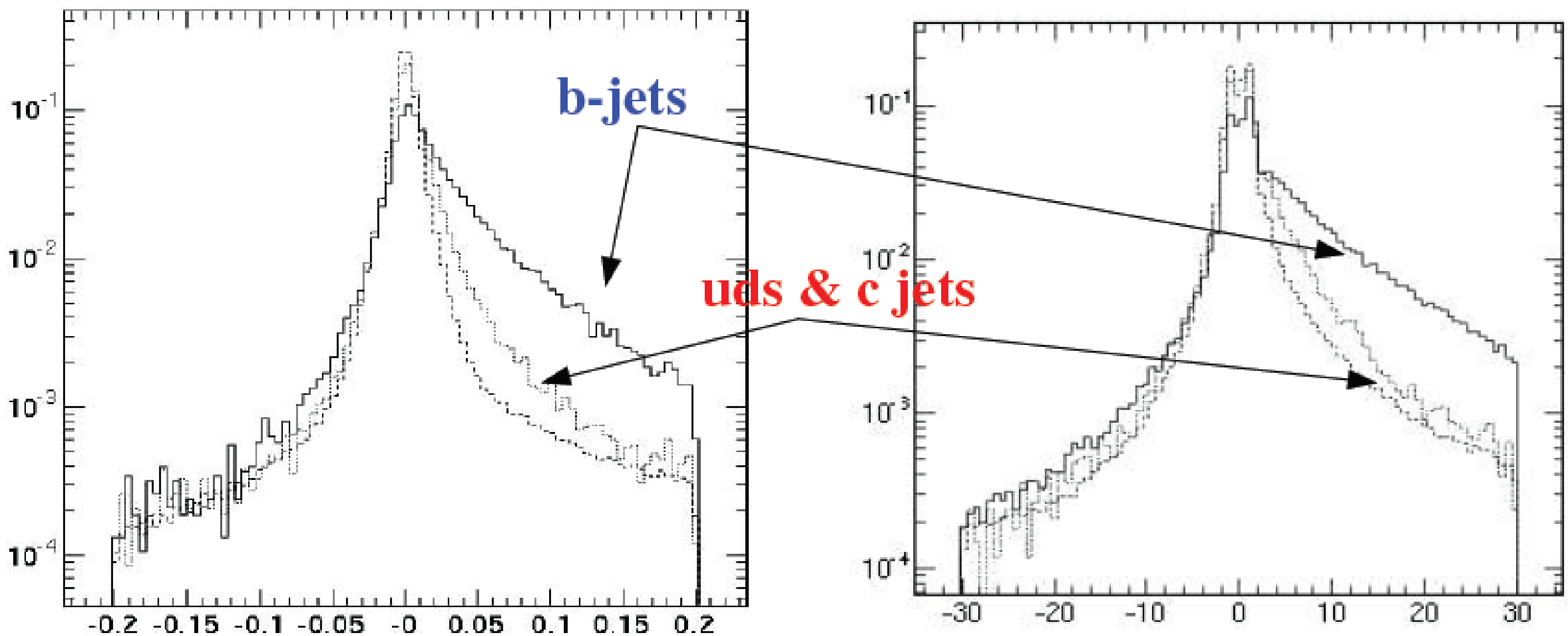




Tracker: b-tagging

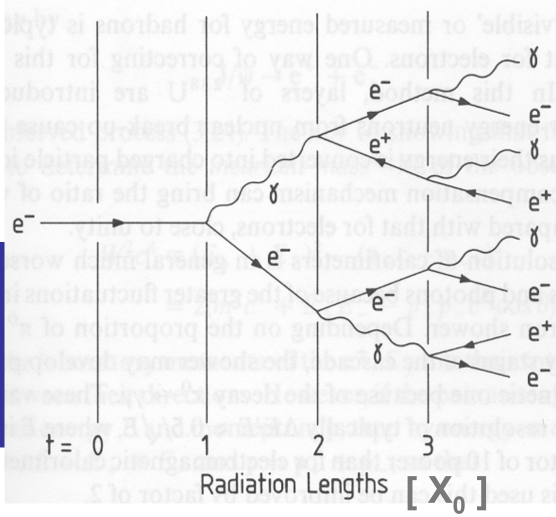
- **b-tagging**
  - impact parameter, secondary vertex finding, soft lepton tag





ECAL: Shower Development

- **Radiation length** $X_0 \approx 180\ A / Z2\ g.cm^{-2}$
- **Mean free path** $L_{pair} = (9/7)\ X_0$
- **Critical energy** $\varepsilon_C \approx 560 / Z\ (MeV)$
- **Moliere radius** $R_M = 21X0 / eC \ \approx 7A / Z\ g.cm^{-2}$



$$t_{\max} = \frac{\ln(E_0 / E_c)}{\ln 2}$$

$$N_{\max} = e^{t_{\max} \ln 2} = E_0 / E_c$$

→ Shower maximum at t_{max}

→ Logarithm growth of t_{max} with E_0

→ N_{max} α energy of the primary particle

$$N_{e^+e^-} = \frac{2}{3} \times 2 \frac{E_0}{E_c} = \frac{4}{3} \frac{E_0}{E_c}$$

→ **Measured energy proportional to E_0**

$$\alpha = \frac{N_{e_+e^-}}{E_0} = \frac{4}{3} \frac{1}{E_c} = \text{constant} \Rightarrow$$

Number of ions per unit of incident energy is a constant → absolute calibration of the calorimeter

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

→ Resolution improves with E (homogenous calorimeter)

→ Longitudinal development scales with X_0

→ Lateral development scales with ρ_M

95% of the shower is contained laterally in a cylinder with radius $2\rho_M$

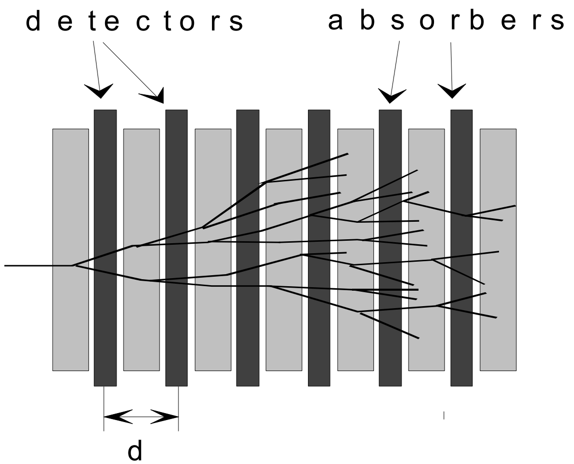
ECAL: Shower Development

Resolution:

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

- $\frac{a}{\sqrt{E}}$: Statistic fluctuations
- b: Constant term (calibration, non-linearity, etc
- $\frac{c}{E}$: Noise, etc

Sampling Calorimeter:



$$N_{sample} \propto \frac{N_{e^+e^-}}{d\,[X_0]}$$

$$\frac{\sigma_{sample}}{E} \propto \frac{1}{\sqrt{N_{sample}}} \propto \frac{\sqrt{d}}{\sqrt{E}}$$

→ The more we sample, the better is the resolution

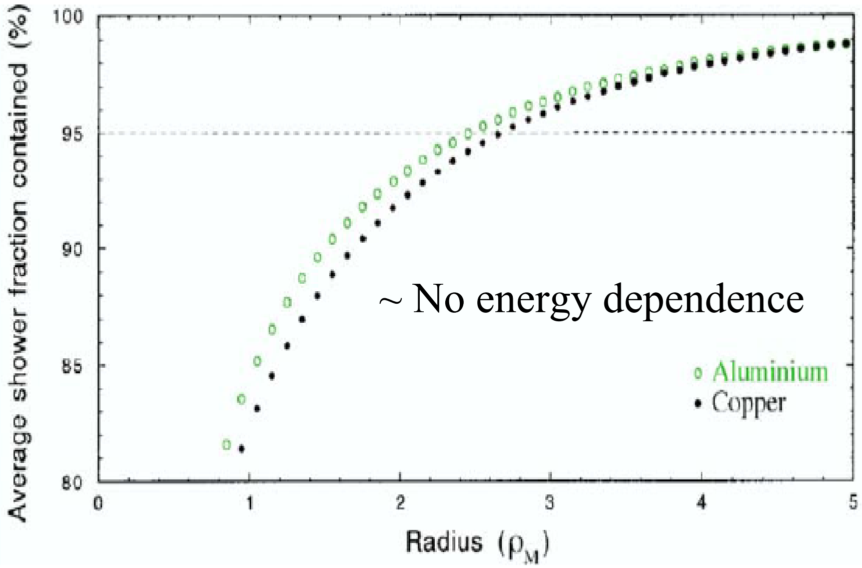
→ Worst resolution than homogenous calorimeter $\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$

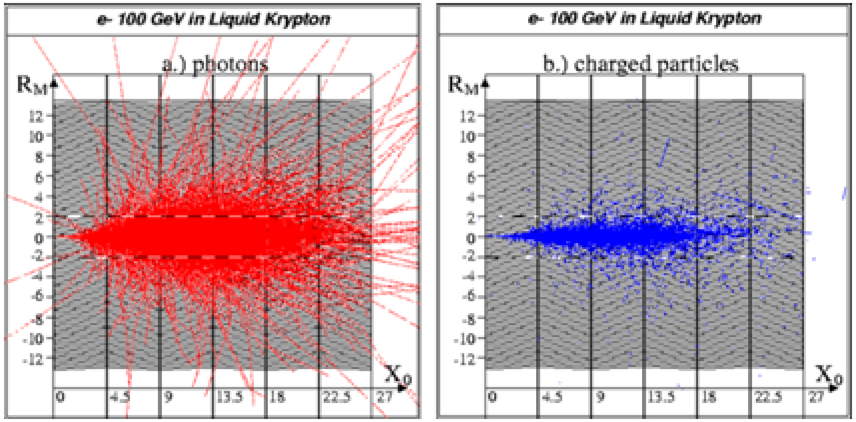
For lead, $\langle \cos(\theta) \rangle \approx 0.57$

$$d_{eff} = \frac{d}{\langle \cos(\theta) \rangle} \Rightarrow \frac{\sigma(E)}{E} \propto \sqrt{\frac{d}{\langle \cos(\theta) \rangle}} \frac{1}{\sqrt{E}}$$

Electromagnetic Shower Development

Lateral leakage

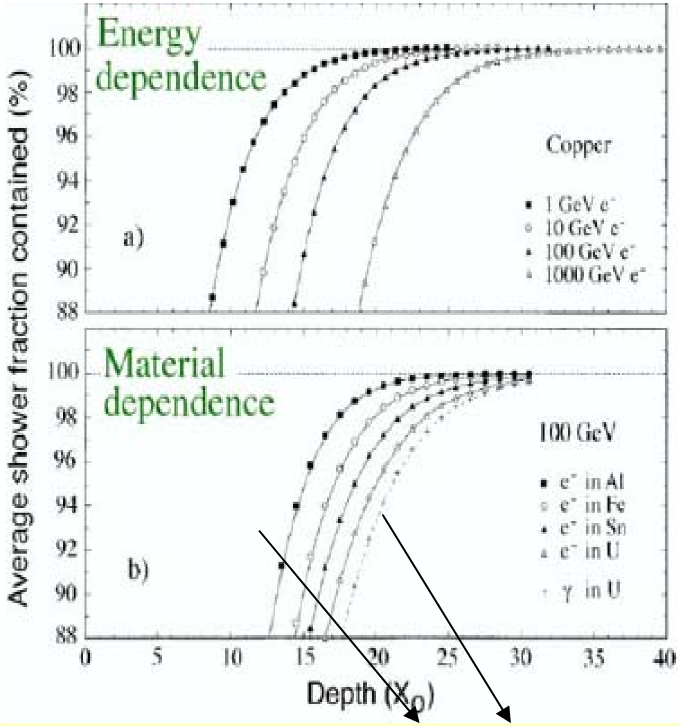




Some considerations on energy resolution

Energy leakage

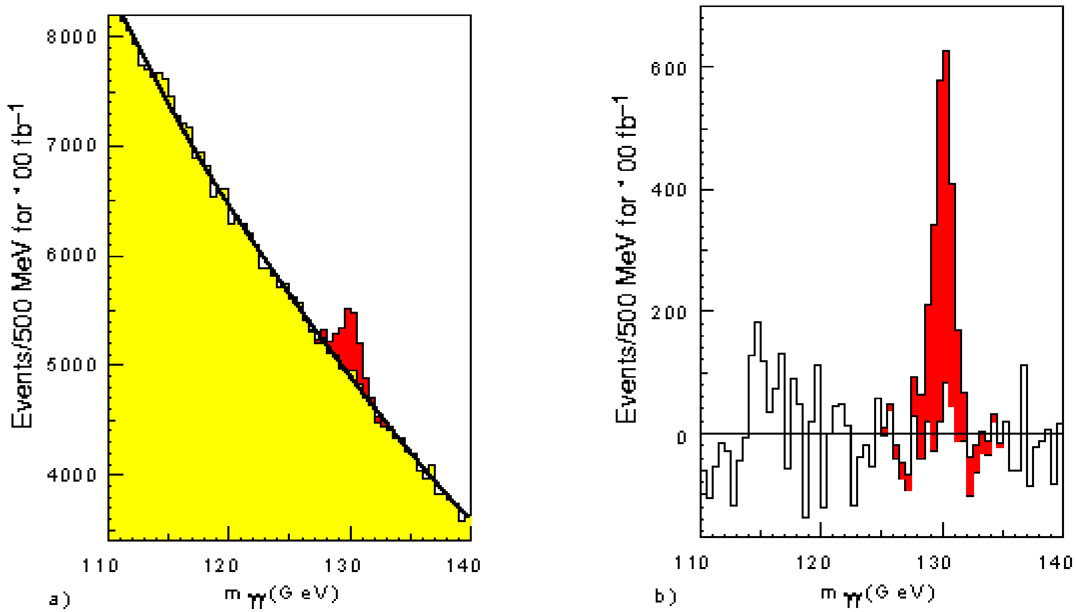
Longitudinal leakage



More X_0 needed to contain γ initiate shower

ECAL: General Purpose

• Need for a high-resolution electromagnetic calorimeter comes from the Higgs decay channel H → 2γ, for Higgs mass 100 < m_H < 140 GeV



ECAL just outside the tracker, in the magnetic field

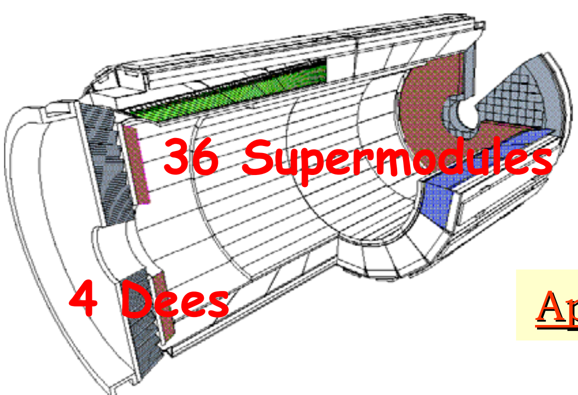
ECAL will operate in a challenging environment of B = 4 T, 25nsec bunch crossings and radiation flux of a few kGy/year

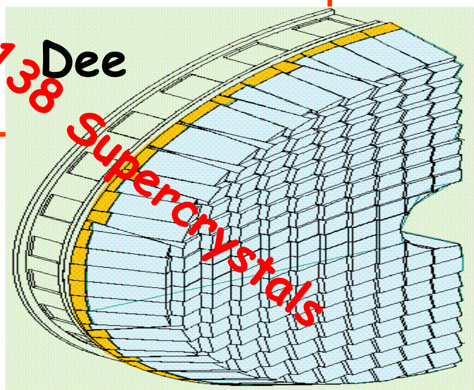
ECAL: Goals

- High Resolution calorimetry:

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

  - Stochastic term 2.7%, Constant term 0.5%, Noise term 150 – 220 MeV.
- Large volume:
  - 75,848 crystals covering $|h| < 2.6$.
  - 90.8 tons of crystals or 10.9 m^3.
- Operated inside a 4T magnetic field.
- In a radiation environment with an integrated dose of:
  - 10^{13} neutrons/cm^2 and 1 kGy at $h = 0$
    to 2×10^{14} neutrons/cm^2 and 50 kGy for $h = 2.6$.
- 40 MHz bunch crossing rate.

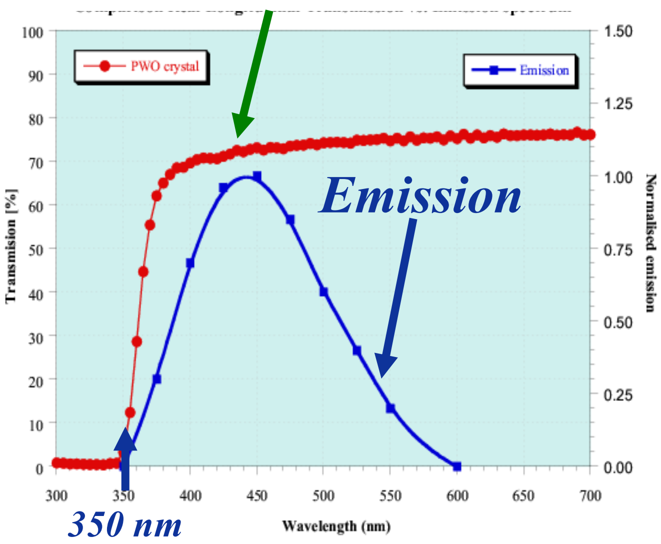




Approximately 80,000 Crystals (22X22 mm^2)

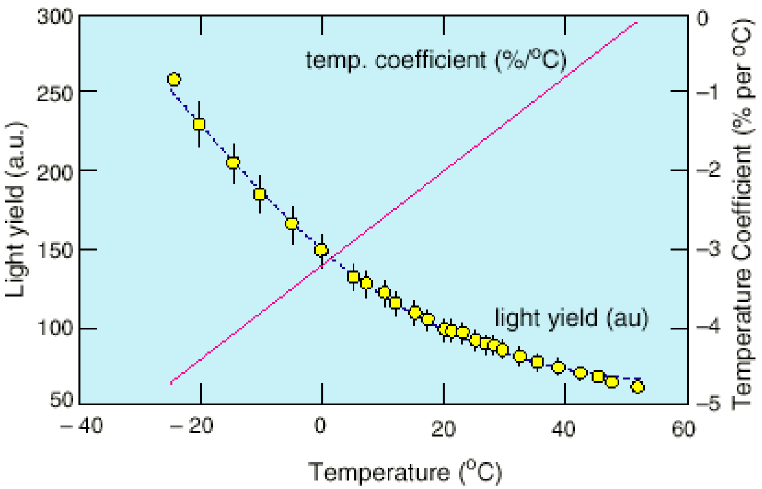
ECAL: Lead Tungstate Crystals

Transmission



- Radiation length – 0.83 cm
- Molière radius – 2.2 cm.
- Fast light output – 80% in 25 nsec.
- Relative Light Yield – 1.3% NaI
- Large radiation hardness

Operate at 18^o C – Temp dependence = -2.2%/^{O}C.

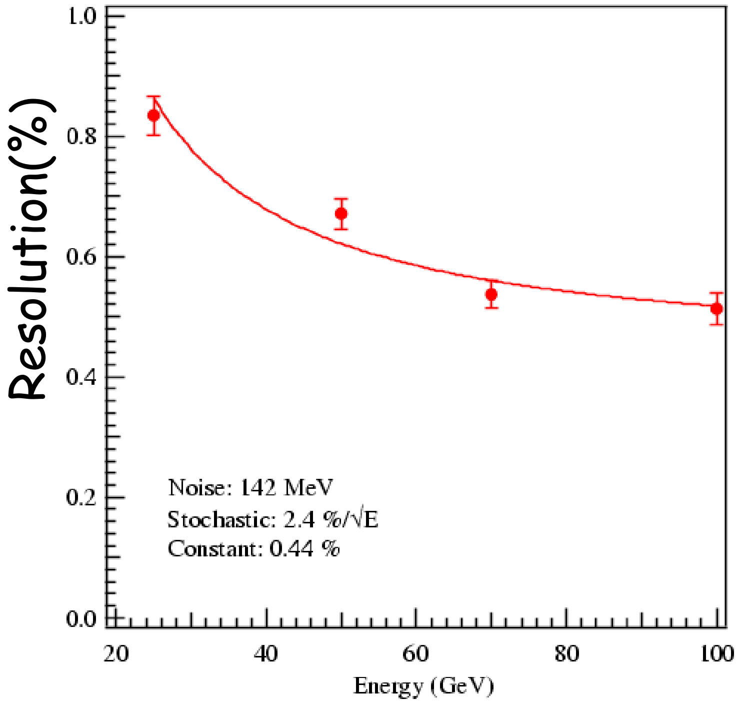


No long-lived radiation damage.

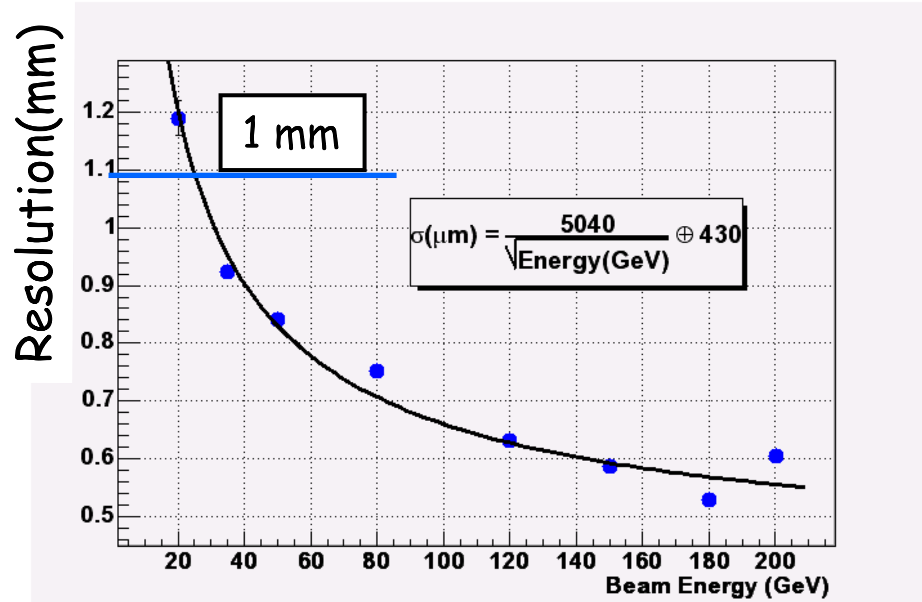
But short-lived metastable color centers created by radiation – careful monitoring

Results from Test beam with final electronics

Energy



Position



$$\frac{\sigma(E)}{E} = \frac{2.4\,\%}{\sqrt{E}} \oplus \frac{142\text{ MeV}}{E} \oplus 0.44\ \%$$

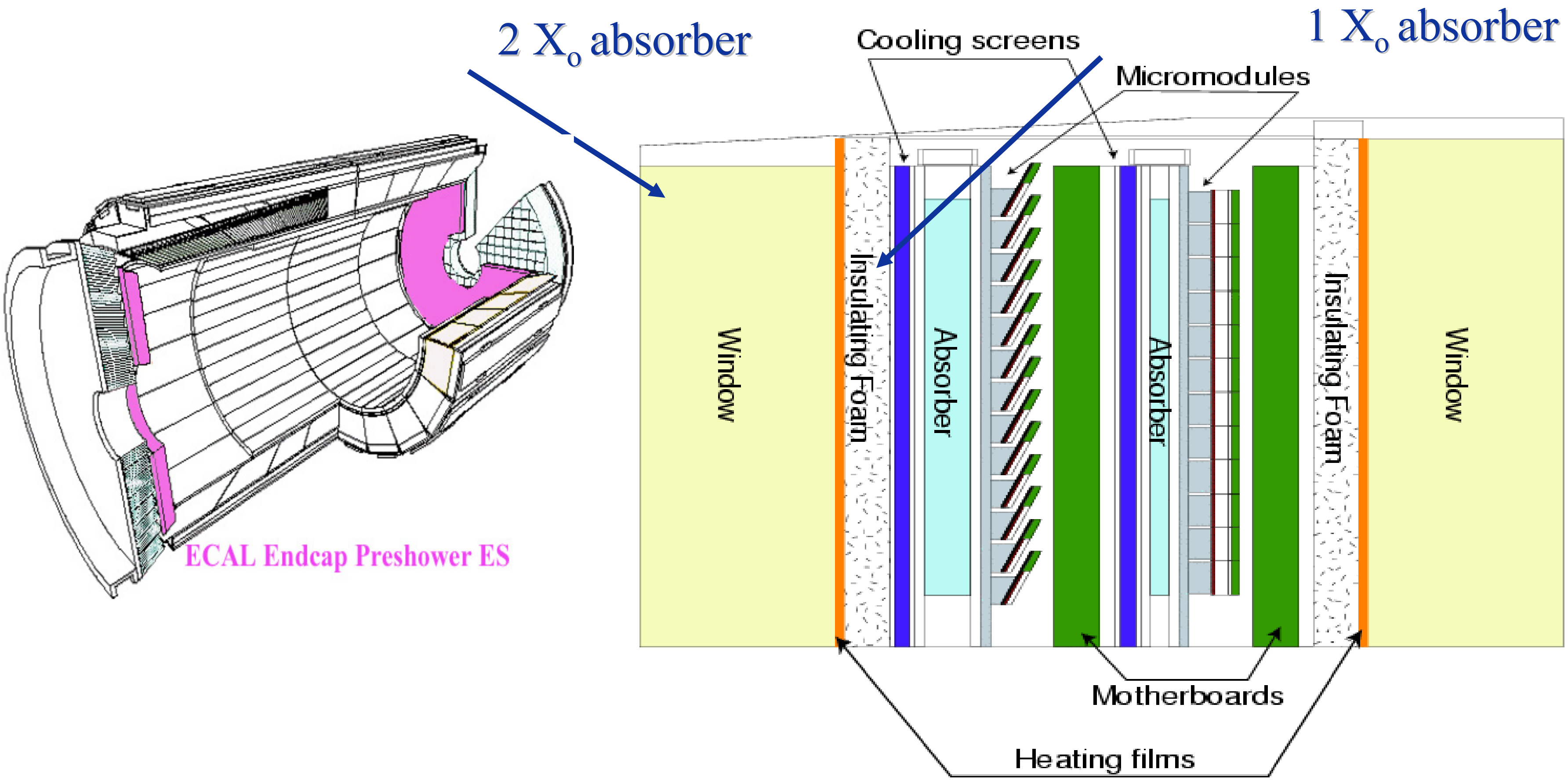
0.6% at 50 GeV.

$$\sigma_Y\,(\mu m) = \frac{5040}{\sqrt{E}} \oplus 430$$

0.85 mm at 50 GeV.

ECAL: Preshower

Two-layer silicon preshower detector placed in front of the endcap calorimeters

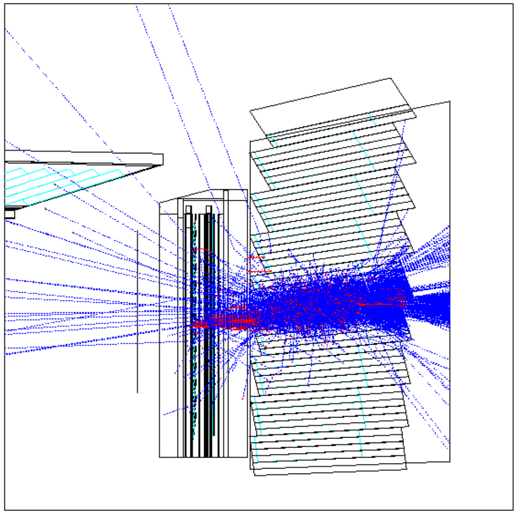


2mm silicon strips to separate γ's from π^o's and for vertex identification.

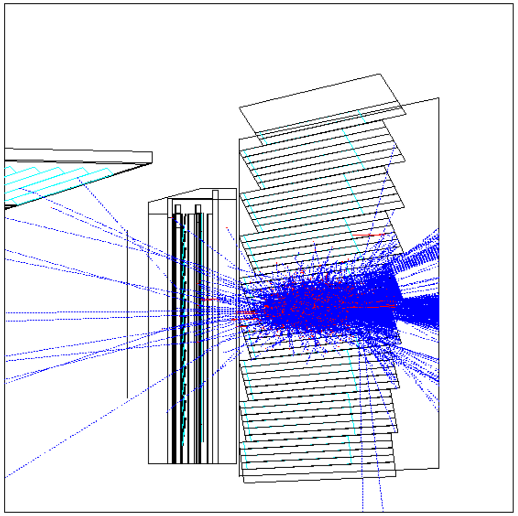
ECAL: Preshower

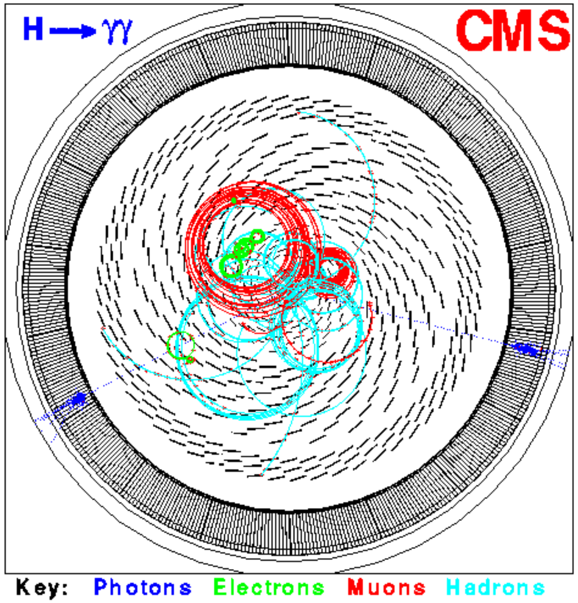
- Purpose
  - Neutral pion rejection from higgs decaying into 2 photons
- Neural Network Technique

$\Pi \rightarrow \gamma\gamma$



Single photon



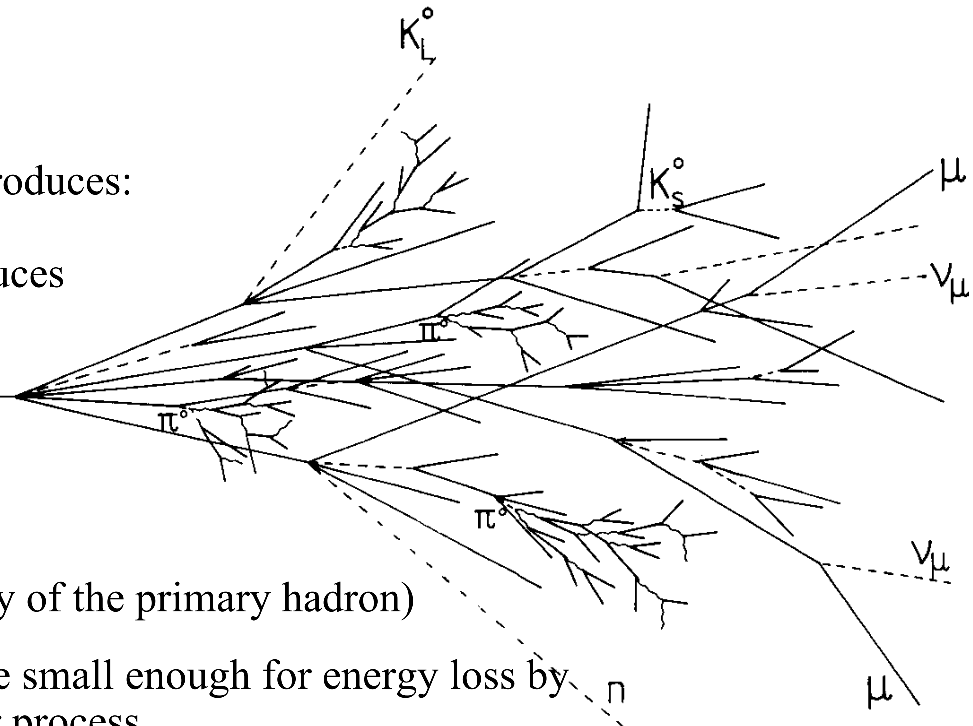


Development of Hadronic Showers

Hadronic shower

→ Process similar to EM shower:

- → Secondary particles interact and produces:
- → tertiary particles
- → tertiary particles interact and produces
- → …… (and so forth)



→ However, processes involved are much more complex

- → Many more particles produced
- → $\text{Multiplicity} \propto \ln(E)$ (E = energy of the primary hadron)

→ Shower ceases when hadron energies are small enough for energy loss by ionization or to be absorbed in a nuclear process.

→ The longitudinal development of the shower scales with the nuclear interaction length, λ_I.

$$\lambda_I = \frac{A}{N_A \sigma_{abs}}$$

→ The secondary particles are produced with large transve[rse momentum]. Consequently, hadronic showers spread more laterally than EM showers.

$$\langle p_T \rangle > 0.35 \text{ GeV/c}$$

Development of Hadronic Showers

Hadronic shower

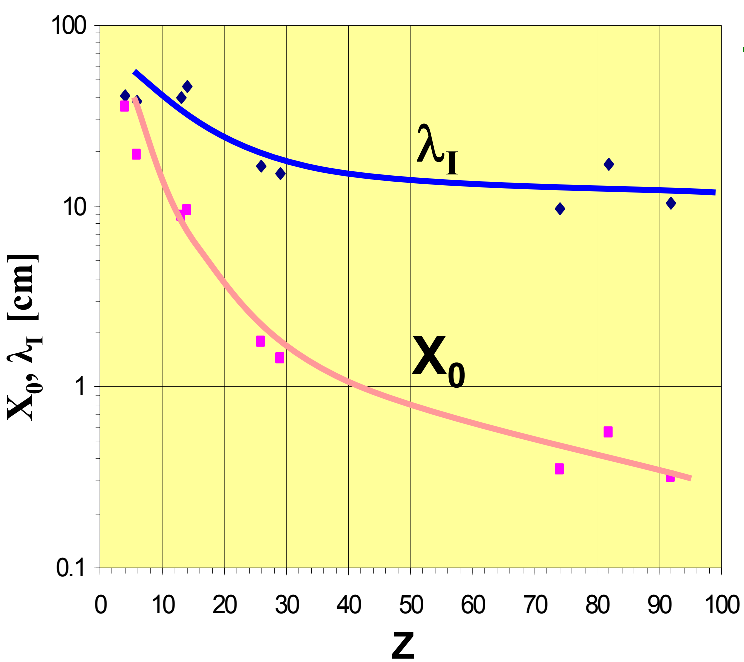
→ At **energies > 1 GeV**, cross-section depends little on energy:

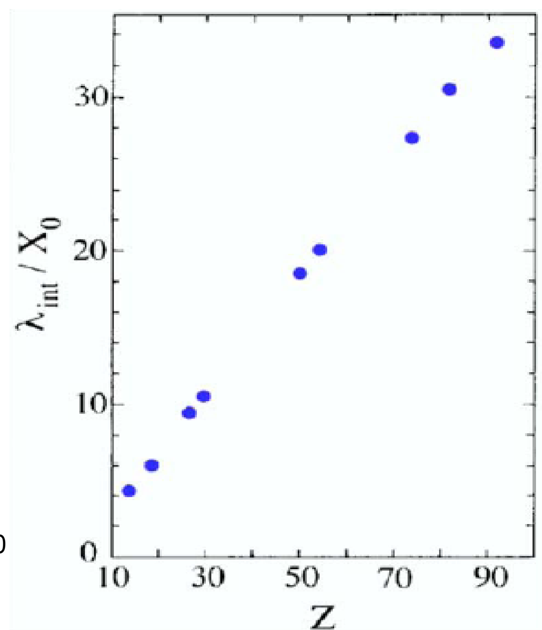
$$\sigma_{abs} \approx \sigma_0 A^{0.7} , \quad \sigma_0 \approx 35\ mb \quad \Rightarrow$$

$$\lambda_I \propto A^{1/3}$$

→ For Z > 6 → $\lambda_I > X_0$

Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_I [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0





Comparing X_0 and λ_I, we understand why Hadronic calorimeters are in general larger than EM calorimeters

Development of Hadronic Showers

Shower profile

→ Longitudinal distribution scales with λ_I

→ Transverse distribution depends on the longitudinal depth

→ Initially the shower is narrow, and spreads laterally with the shower depth

→ As in electromagnetic showers, defines a shower maximum at a position x (in units of λ_I) which also depends logarithmically on energy E of the primary hadron:

→ $$\frac{x}{\lambda_I} \equiv t_{\max}(\lambda_I) \approx 0.2 \ln\left(\frac{E}{1\,GeV}\right) + 0.7$$

$$L_{95\%}(\lambda_I) \approx t_{\max} + 2.5\lambda_{att}$$

$$\lambda_{att} \approx \lambda_I \left(\frac{E}{1\,GeV}\right)^{0.13}$$

is the longitudinal dimension need to contain 95% of the hadronic shower.

λ_{att} = describes the exponential decay of the shower after $t_{\max}$

→ 95% of the shower is contained within a $R < \lambda_I$ cone around the axis of the shower

Development of Hadronic Showers

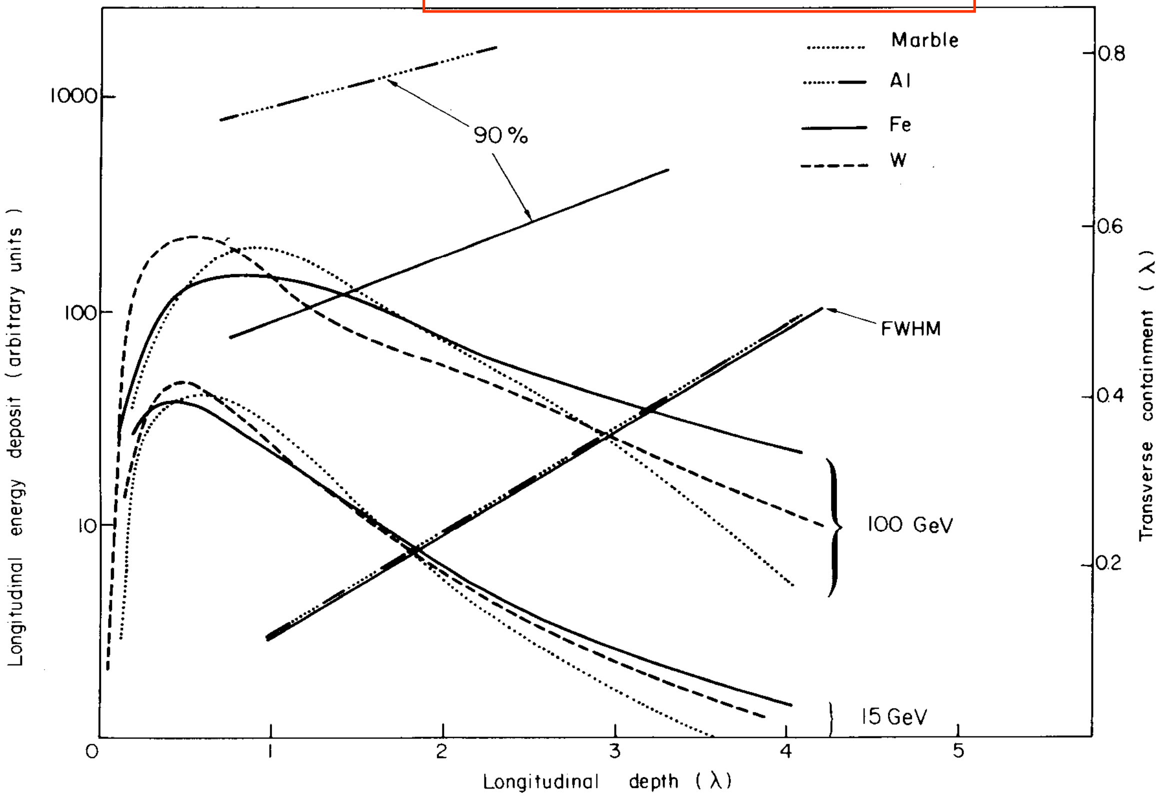
Shower profile

- Hadronic showers much longer than EM shower
- Also broader

↓

Allows e/h separation

C. Fabjan, T. Ludlam, CERN-EP/82-37



Note: $\lambda_I(Al) = 39.4$ cm > $X_0(Al) = 68.9$ cm

Usually, hadronic calorimeters are longer than EM calorimeters

Development of Hadronic Showers

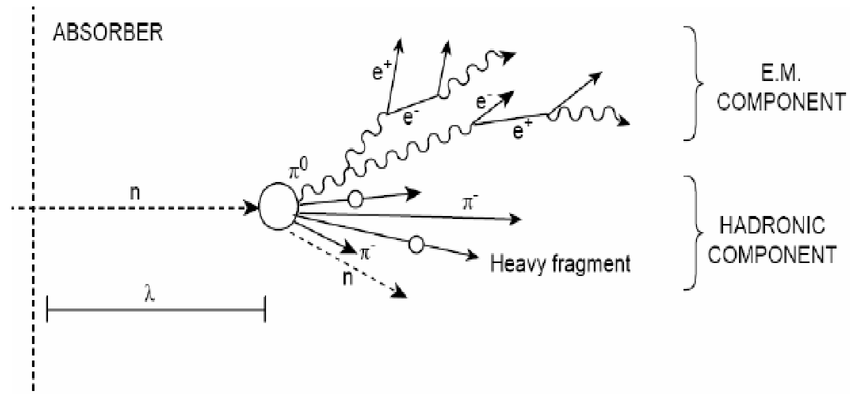
Energy measurement

Energy measurement

→ Based on the same principle as for the electromagnetic shower

→ Shower develops until a E_{min}

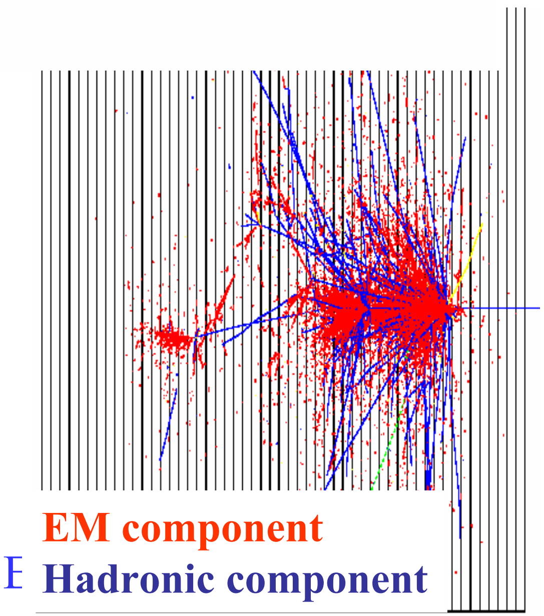
→ Energy deposition by ionization ($\pi^0 \rightarrow \gamma\gamma$ and charged hadrons) and low-energy hadronic activity (fission, neutron elastic scattering off proton, etc)



→ There are two components in the mechanism of energy deposition

→ **Electromagnetic component**, due to $\pi^0 \rightarrow \gamma\gamma$ with subsequent EM photon interactions

→ **Hadronic**



EM component
Hadronic component

→ The end product is sampled and converted into signal.

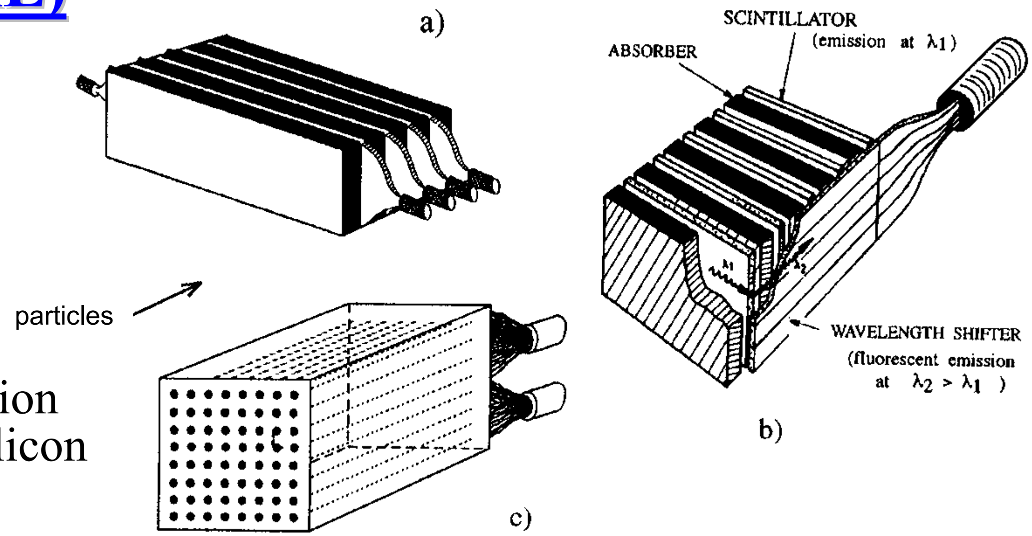
→ The ratio between the efficiency in energy deposition due to E hadronic interaction is given by **e/h**

Hadronic Calorimeter (HCAL)

→ Hadronic calorimeters are usually sampling calorimeters

→ The active medium made of similar material as in EM calorimeters:

→ Scintillator (light), gas (ionization chambers, wired chambers), silicon (solid state detectors), etc



→ The passive medium is made of materials with longer interaction length λ_I

→ Iron, uranium, etc

→ Resolution is worse than in EM calorimeters (discussion in the next slides), usually in the range:

$$\frac{\sigma(E)}{E} \propto \frac{(35\% - 80\%)}{\sqrt{E}}$$

→ Can be even worse depending on the goals of an experiment and compromise with other detector parameters

Forward Detector: VCAL

Performance Requirments

- Missing transverse energy
- Tagging jet for vector boson fusion
- High pt neutrinos or lightest SUSY particles

Description

- ✓ Sampling calorimeter based on PPC
- ✓ Cherenkov light

Design Consideration

- ❖ VF energy resolution are more or less loose
- ❖ Operate reliably at the high LHC luminosity during many years
- ❖ Fast response to minimize pileup of soft hadronic events

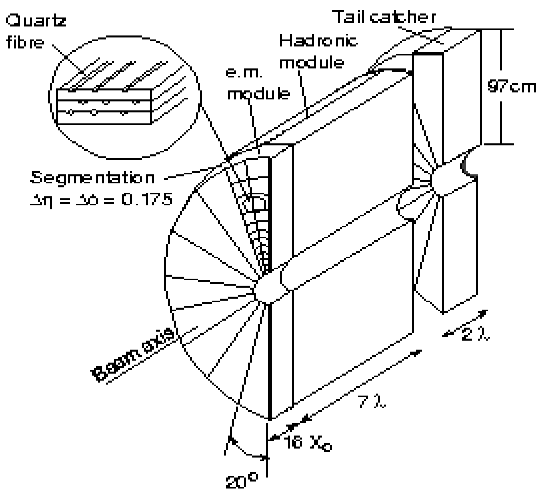
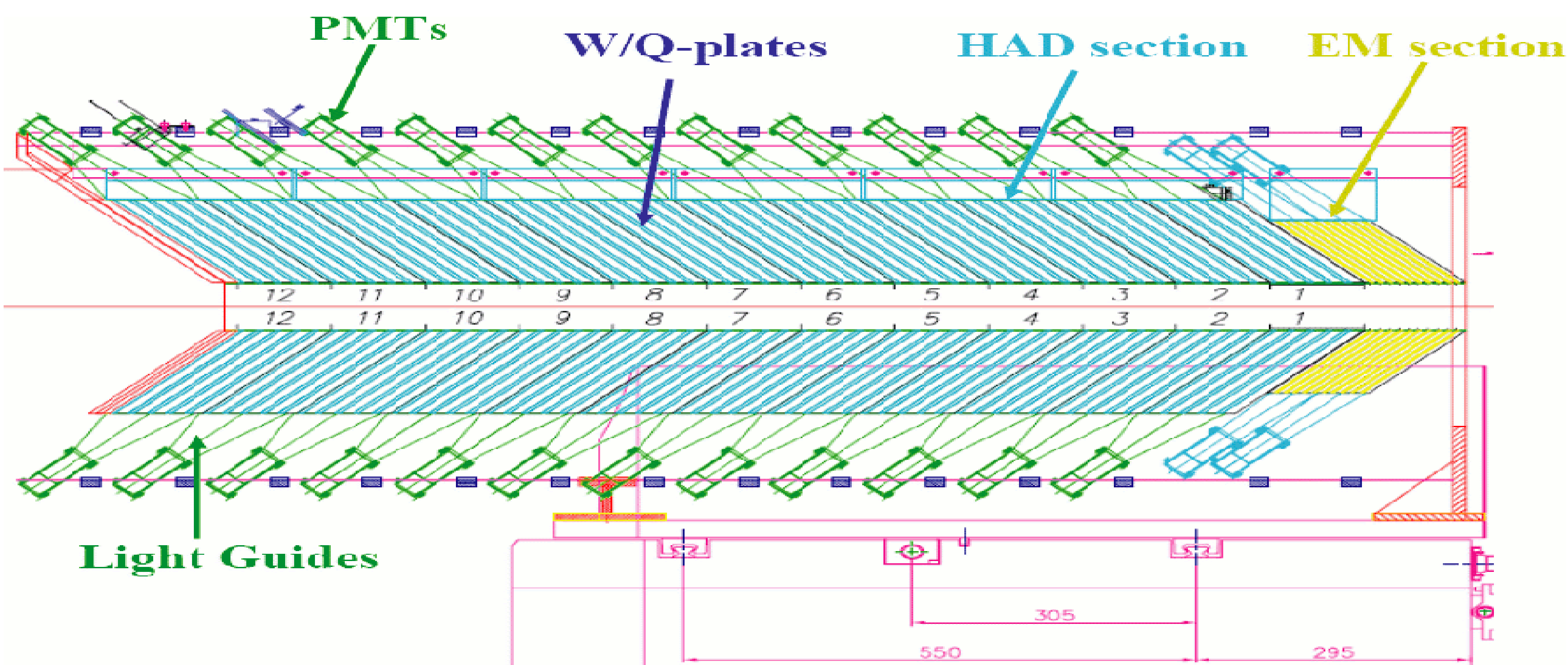


Fig. 52. One half of the quartz fiber VF showing the wedge structure.

Forward Detector: Castor

- Cerenkov detector
- Electromagnetic and hadronic sections
- Strangelets in AA collisions
- Low x QCD
- Multi-parton interactions
- QGP
- Luminosity

- Excellent energy linearity
- Excellent spatial resolution

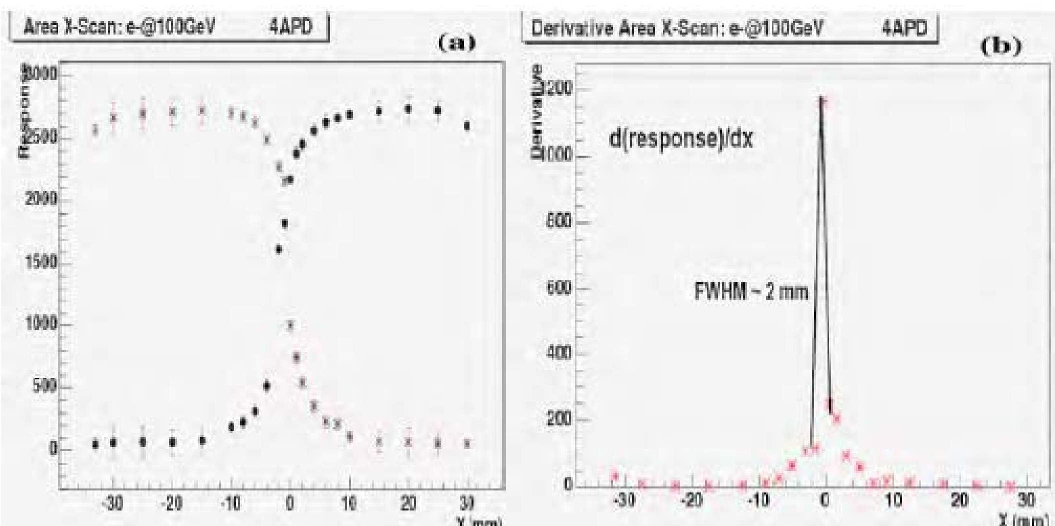


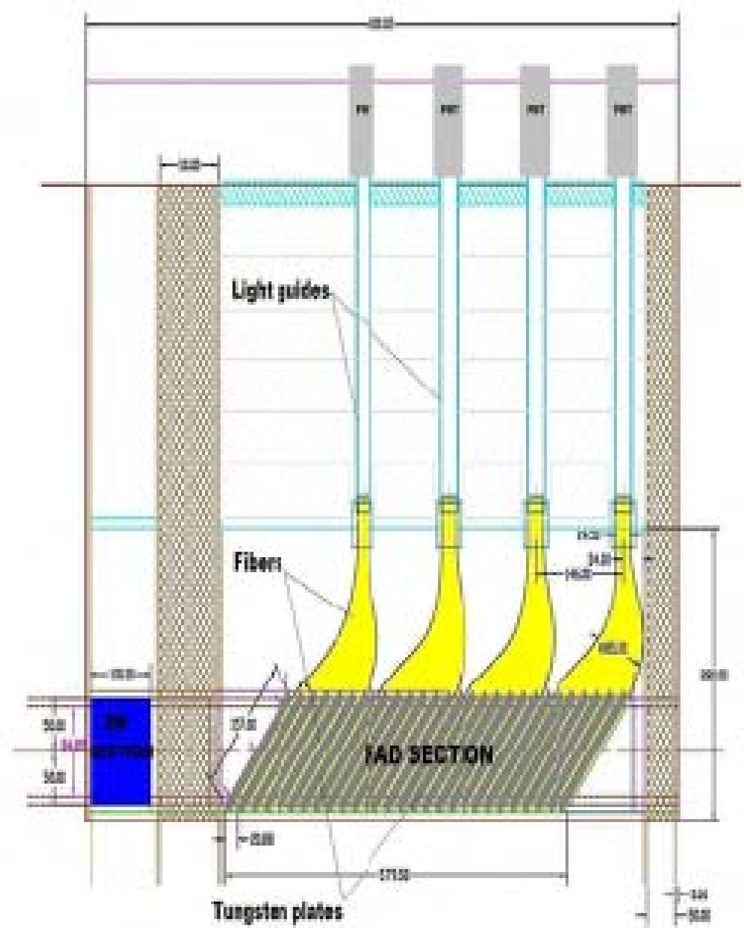
Forward Detector: ZDC

- Cerenkov detector
- Centrality in AA collisions
- Hadronic and electromagnetic sections

Design Requirements

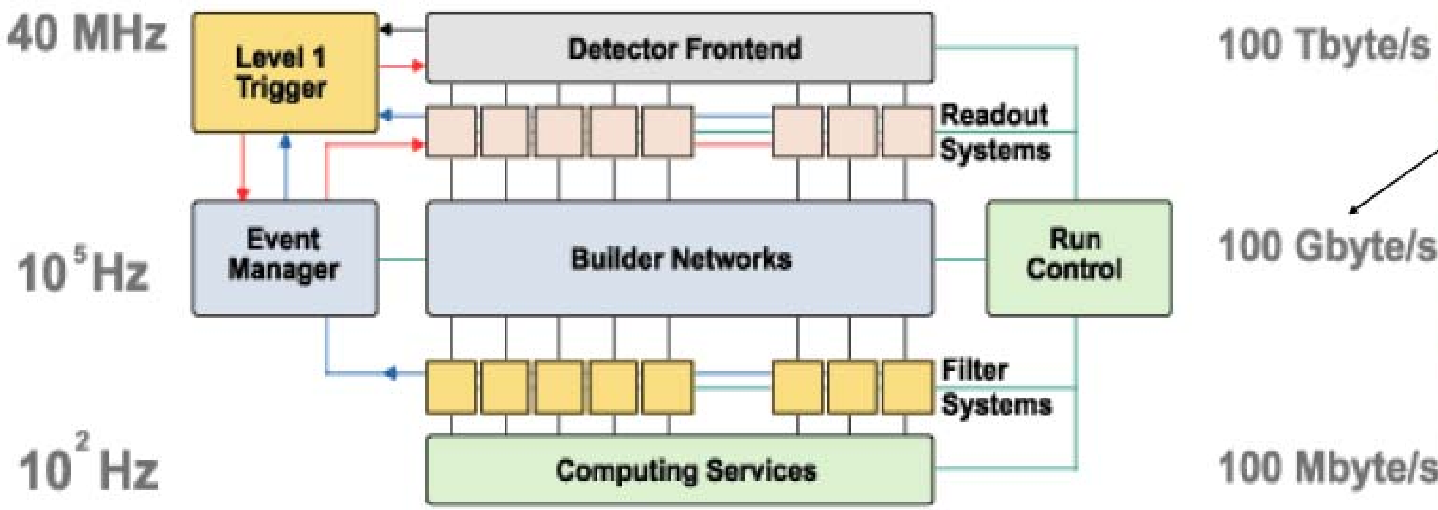
- Width < 9.6 cm, length < 100 cm;
- Energy resolution sufficient to resolve the 1 neutron peak
- Very high radiation tolerance
- Low sensitivity to induced radioactivity
- Rate capability above 50 kHz (for Ar-Ar)
- Vertex resolution through timing of few cm, i.e. t 100 ps.





The Trigger and Data Acquisition System

Data Acquisition Main Parameters	
Collision rate	40 MHz
Level-1 Maximum trigger rate	100 kHz
Average event size	1 Mbyte
No. of electronics boards	10000
No. of readout crates	250
No. of In-Out units (200-5000 byte/event)	1000
Event builder (1000 port switch) bandwidth	1 Terabit/s
Event filter computing power	5 10^6 MIPS
Data production	Tbyte/day

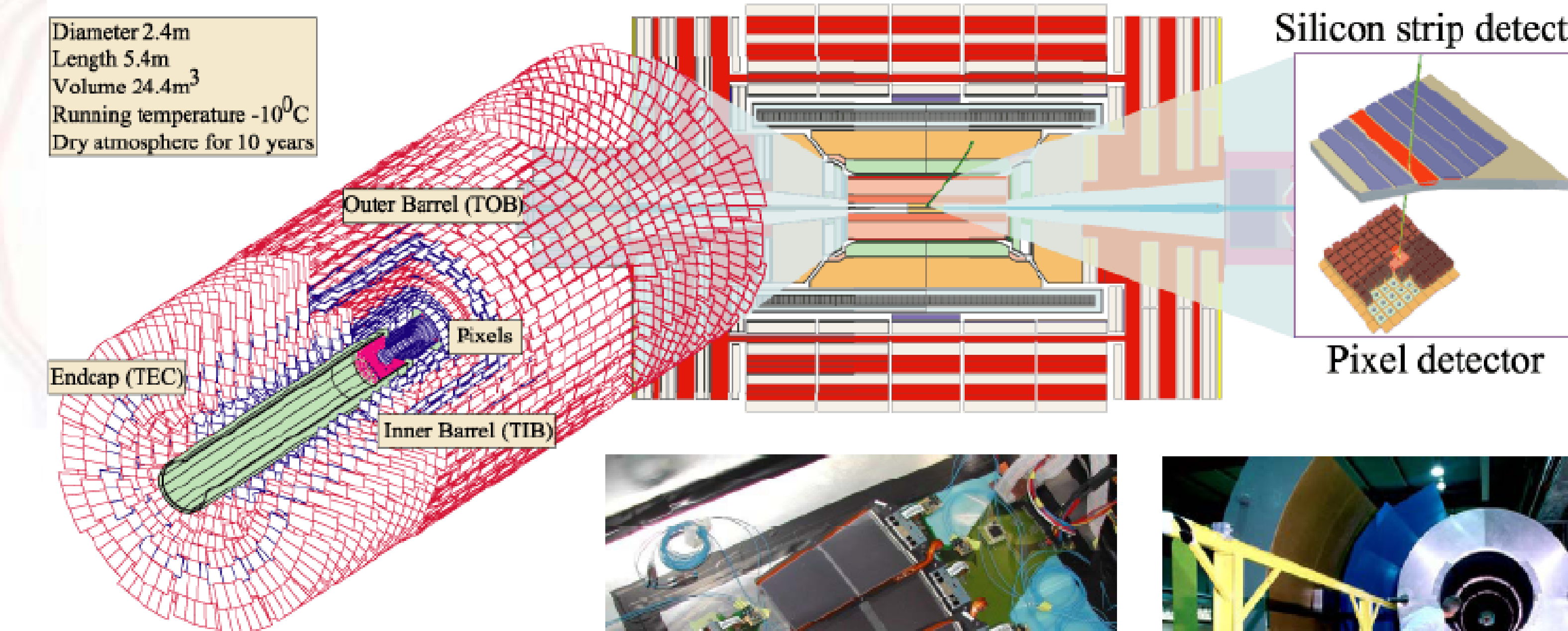


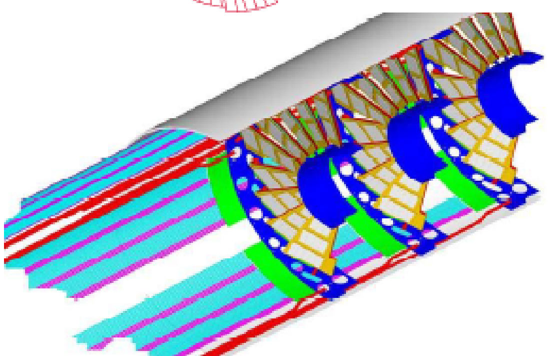
Trigger and Data Acquisition baseline structure

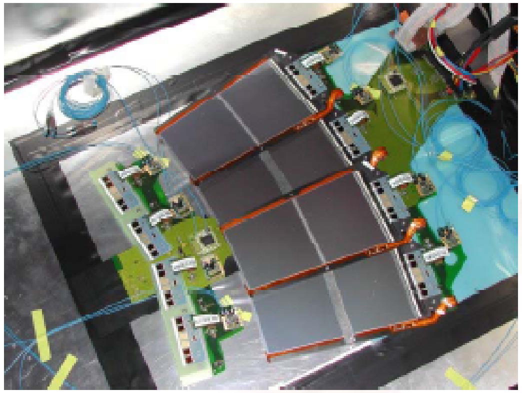
~same as whole world's telecom network!

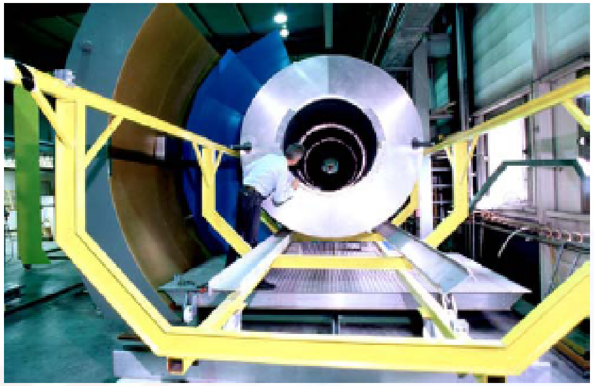
Backup

The Tracking System





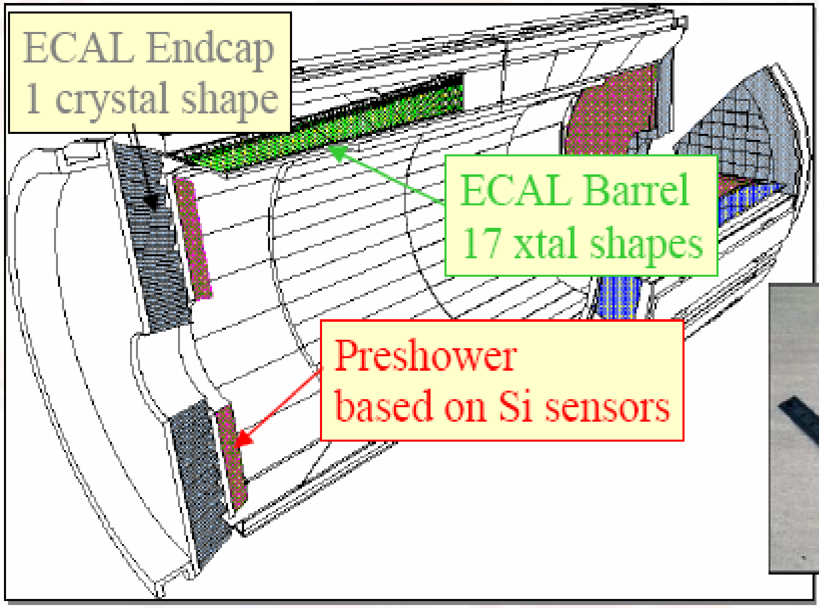




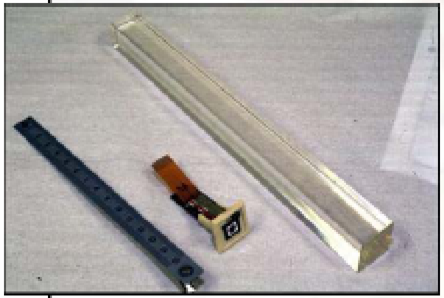
Pixel endcap disks

$214m^2$ of silicon sensors
11.4 million silicon strips
65.9 million pixels in final configuration!

The Electromagnetic Calorimeter- ECAL



Characteristics of $PbWO_4$
X_0 = 0.89cm
ρ = 8.28g/cm^3
R_M (Molière radius) = 2.2cm



Parameter	Barrel	Endcaps
Coverage	$\lvert\eta\rvert<1.48$	$1.48<\lvert\eta\rvert<3.0$
$\Delta\phi$ x $\Delta\eta$	0.0175 x 0.0175	0.0175 x 0.0175 to 0.05 x 0.05
Depth in X_0	25.8	24.7
# of crystals	61200	14648
Volume	8.14m^3	2.7m^3
Xtal mass (t)	67.4	22.0

The Hadron Calorimeter-HCAL

- **CMS HCAL is constructed in 3 parts:**
  - Barrel HCAL (HB)
    - Brass (laiton) plates interleaved with plastic scintillator embedded with wavelength-shifting optical fibres (photo top right)
  - Endcap HCAL (HE)
    - Brass plates interleaved with plastic scintillator
  - Forward HCAL (HF)
    - Steel wedges stuffed with quartz fibres (photo bottom right)
- **~10000 channels total**