3rd WORKSHOP ON PARTICLE PHYSICS

NATIONAL CENTRE FOR PHYSICS
(QUAID-I-AZAM UNIVERSITY)

Detectors for High Energy Physics

Lecture V – Atlas and CMS

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CERN Site

Gig

LHC Layout and Parameters

$$L = \frac{\gamma\, f\, k_b N_p^2}{4\pi \varepsilon_n \beta^*} F$$

- f revolution frequency
- k_b no. of bunches
- N_p no. of protons/bunch
- ε_n norm transverse emittance
- β^* betatron function
- F reduction factor xing angle

Magnetic Field

p (TeV) = 0.3 B(T) R(km)

For p= 7 TeV, R= 4.3 km

⇨ **B = 8.4 T**

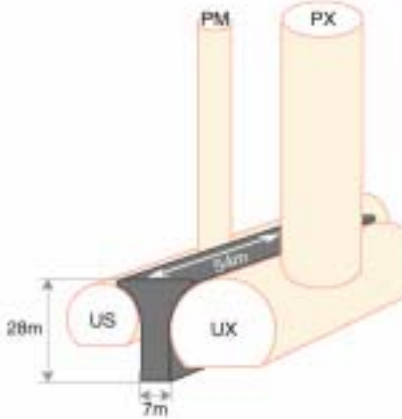
Energy at collision	E	7	TeV
Dipole field at 7 TeV	**B**	**8.33**	**T**
Luminosity	**L**	**10^{34}**	**$cm^{-2}s^{-1}$**
Beam beam parameter	ξ	3.6	10^{-3}
DC beam current	I_{beam}	0.56	A
Bunch separation		24.95	ns
No. of bunches	**k_b**	**2835**	
No. particles per bunch	**N_p**	**1.1**	**10^{11}**
Normalized transverse emittance (r.m.s.)	ε_n	3.75	µm
Collisions			
β-value at IP	β^*	0.5	m
r.m.s. beam radius at IP	**σ^***	**16**	**µm**
Total crossing angle	ϕ	300	µrad
Luminosity lifetime	τ_L	10	h
Number of evts/crossing	**n_c**	**17**	
Energy loss per turn		7	keV
Total radiated power/beam		3.8	kW
Stored energy per beam		**350**	**MJ**

Civil Engineering ATLAS

ATLAS took delivery of Experimental Cavern in June-03

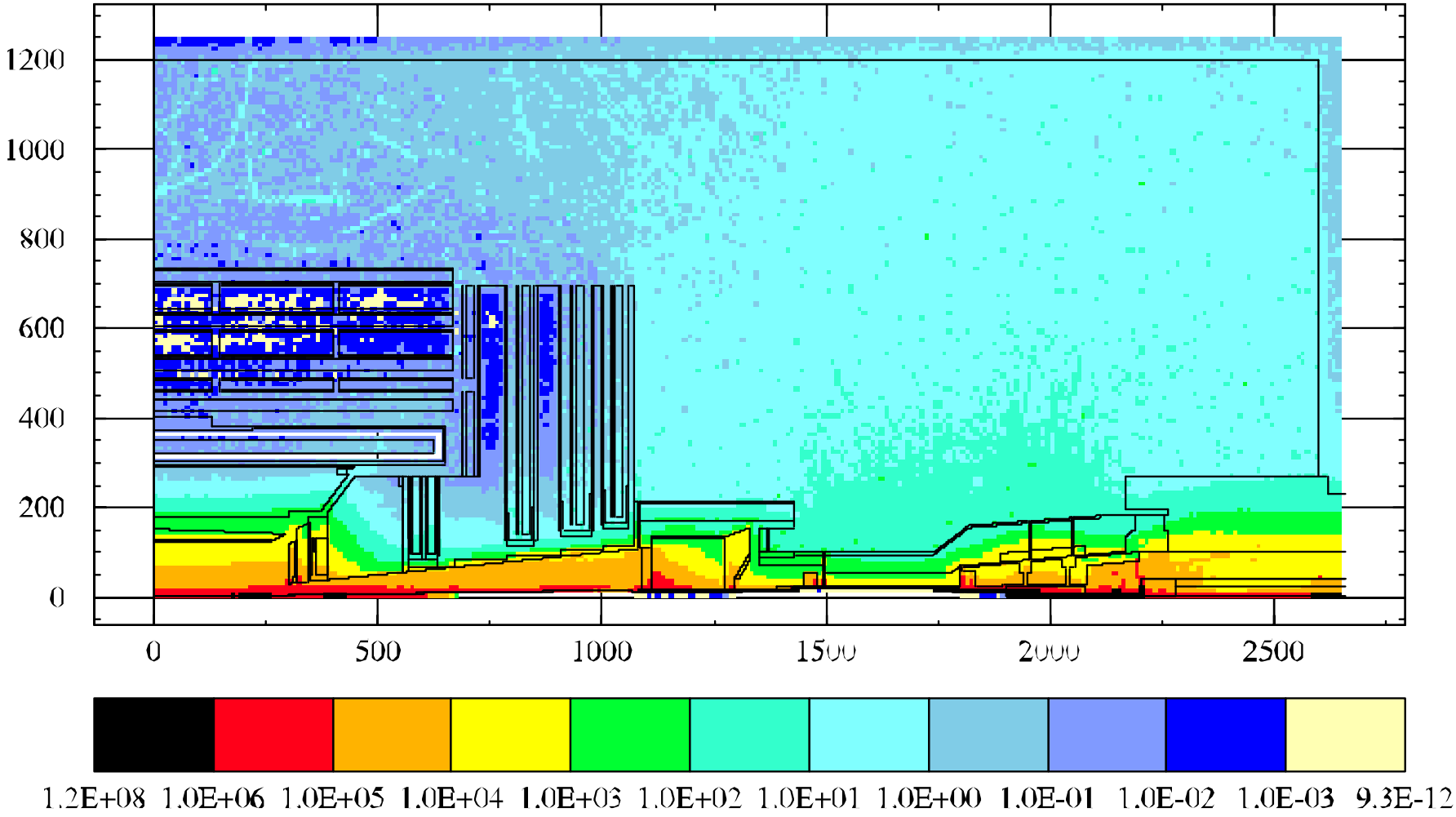
Civil Engineering: CMS

CMS will take delivery of Experimental Cavern in July-04

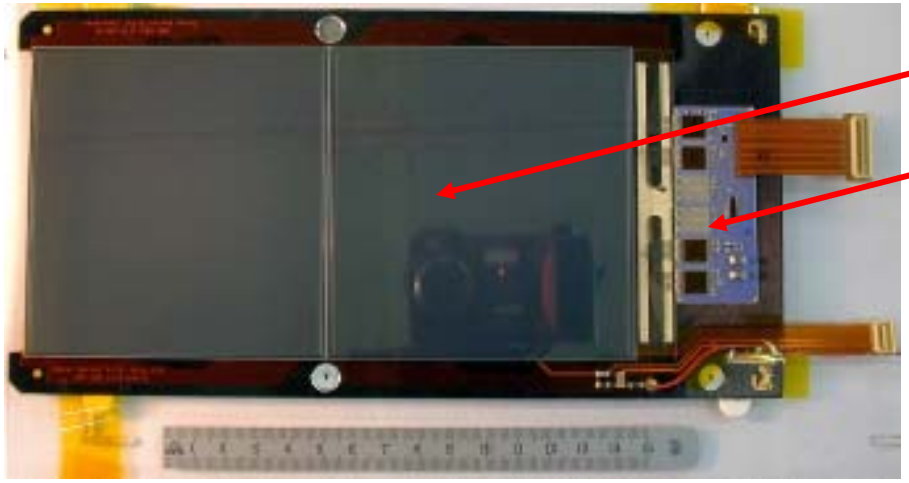


Radiation Levels: Dose

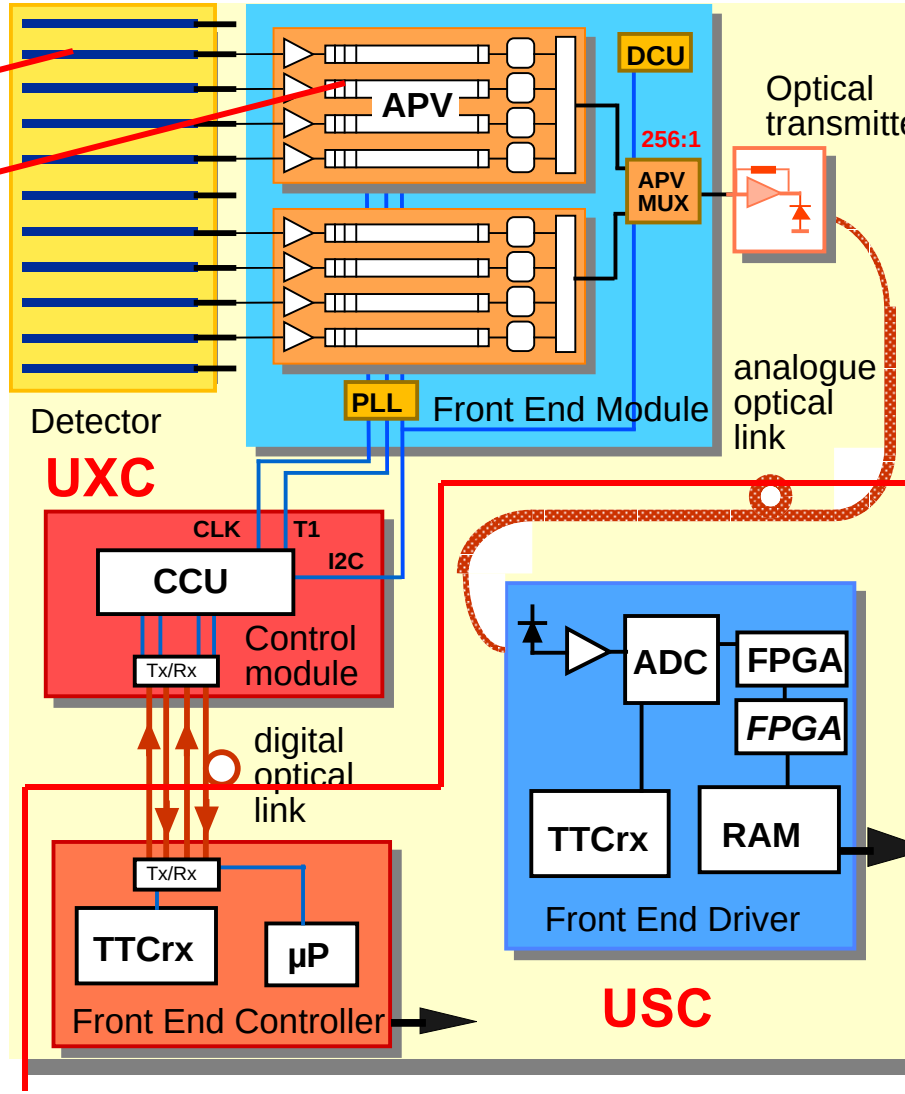
Dose (Gy) in CMS for an integrated luminosity of 5.10^5 pb^{-1} (~ 10 years)



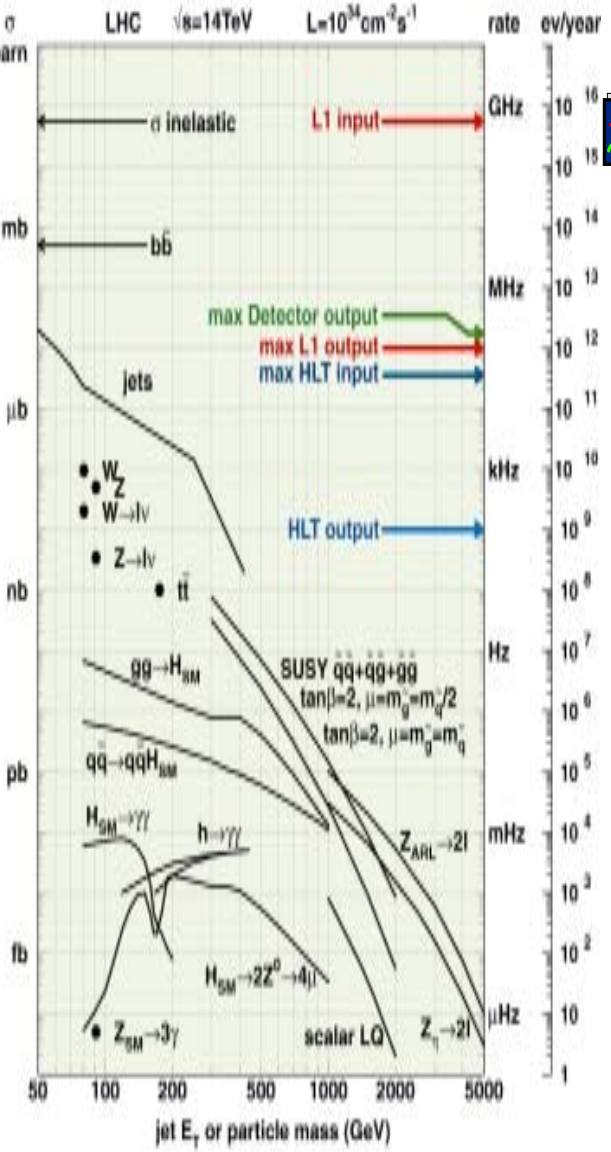
Challenges: Front-end Electronics

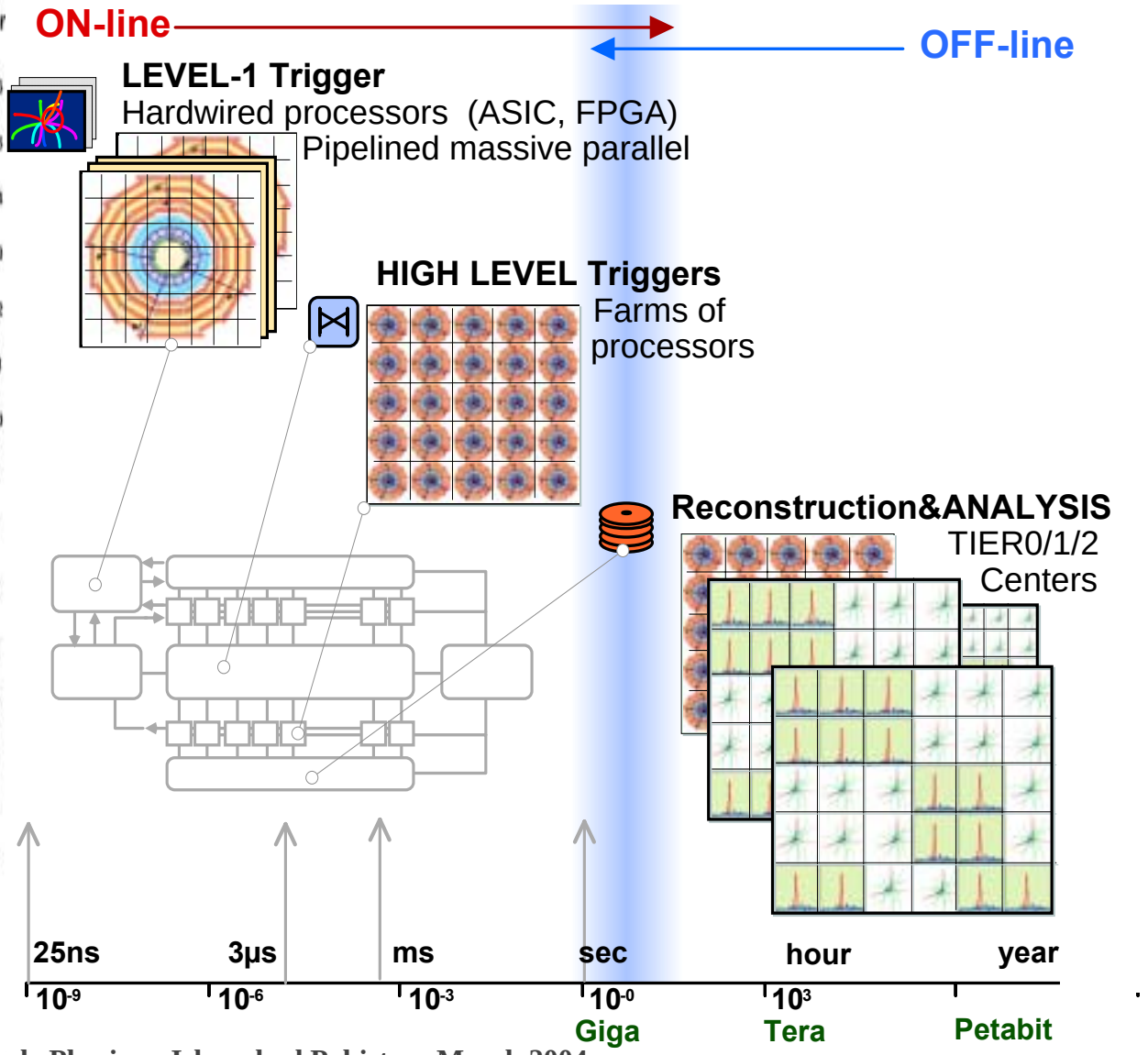


Each microstrip is read out by a charge sensitive amplifier with τ= 50 ns.
The o/p voltage is sampled at the beam crossing rate of 40 MHz.
Samples are stored in analog pipeline for up to Level-1 latency (3.2 μs)
Following a trigger form a weighted sum of 3 samples in analog circuit
This confines signal to single bx and gives pulse height
Buffered pulse height data multiplexed out on optical fibres
Output of laser modulated by the pulse height for each strip

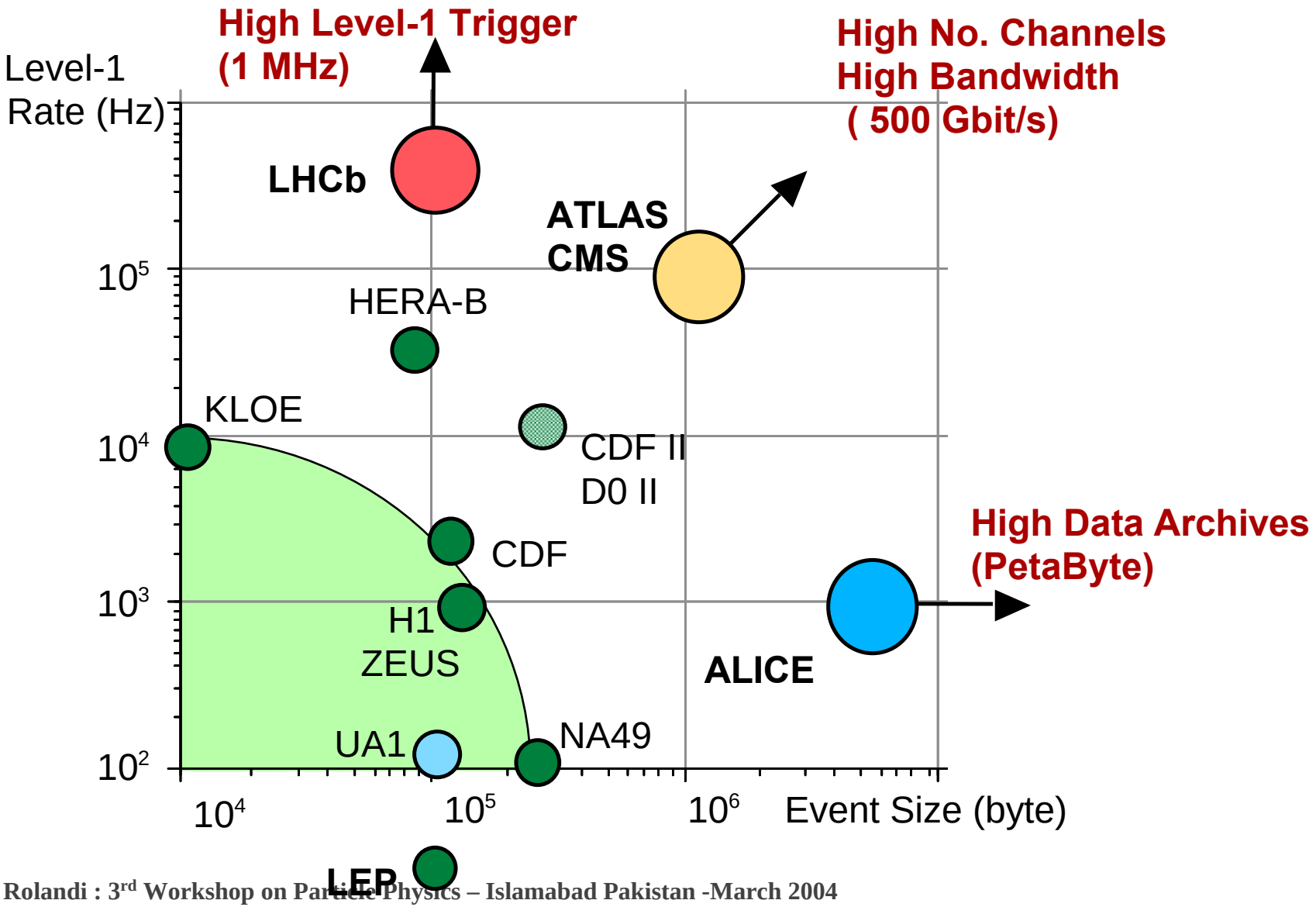


Challenges: Event Selection

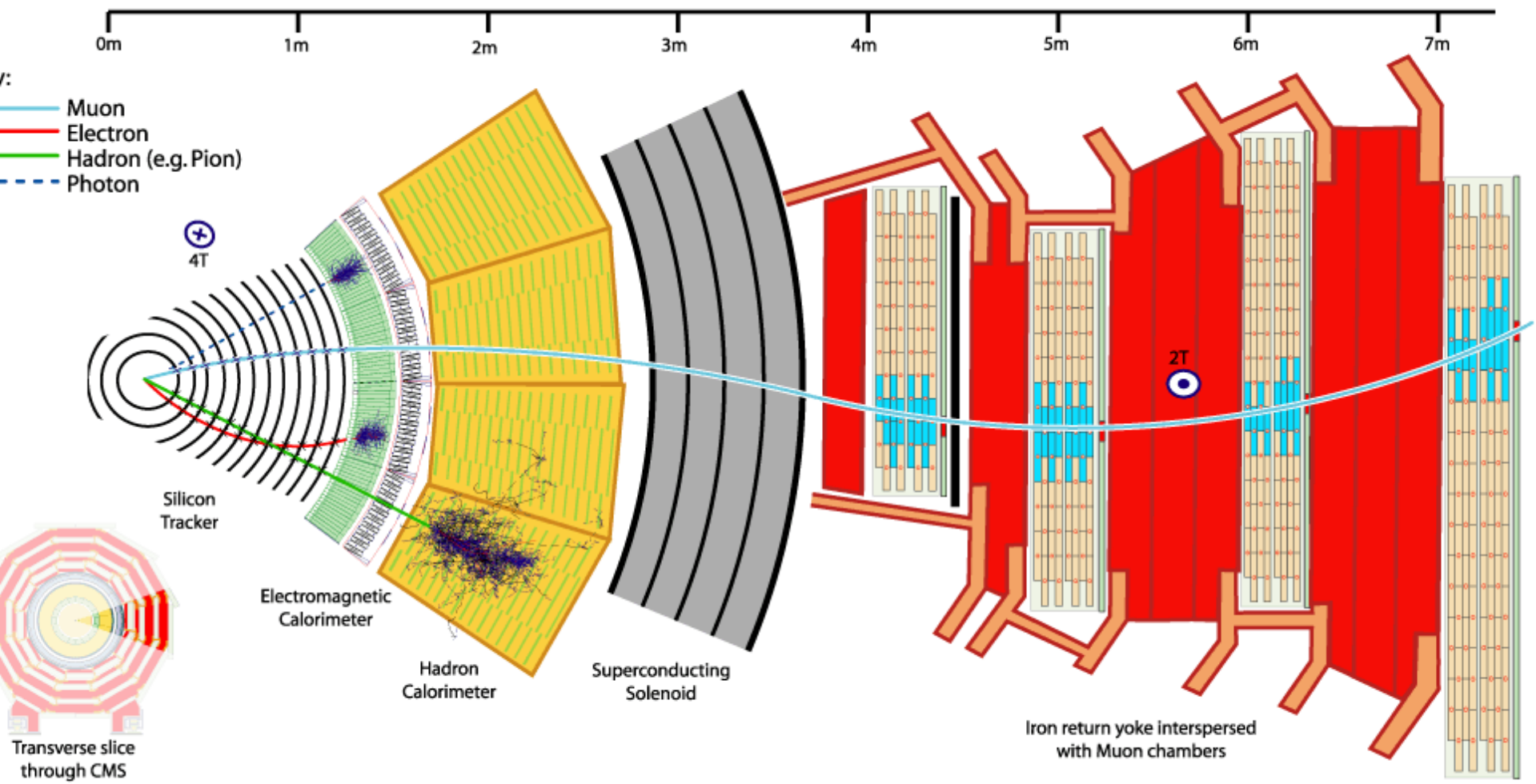




Challenges Data Acquisition

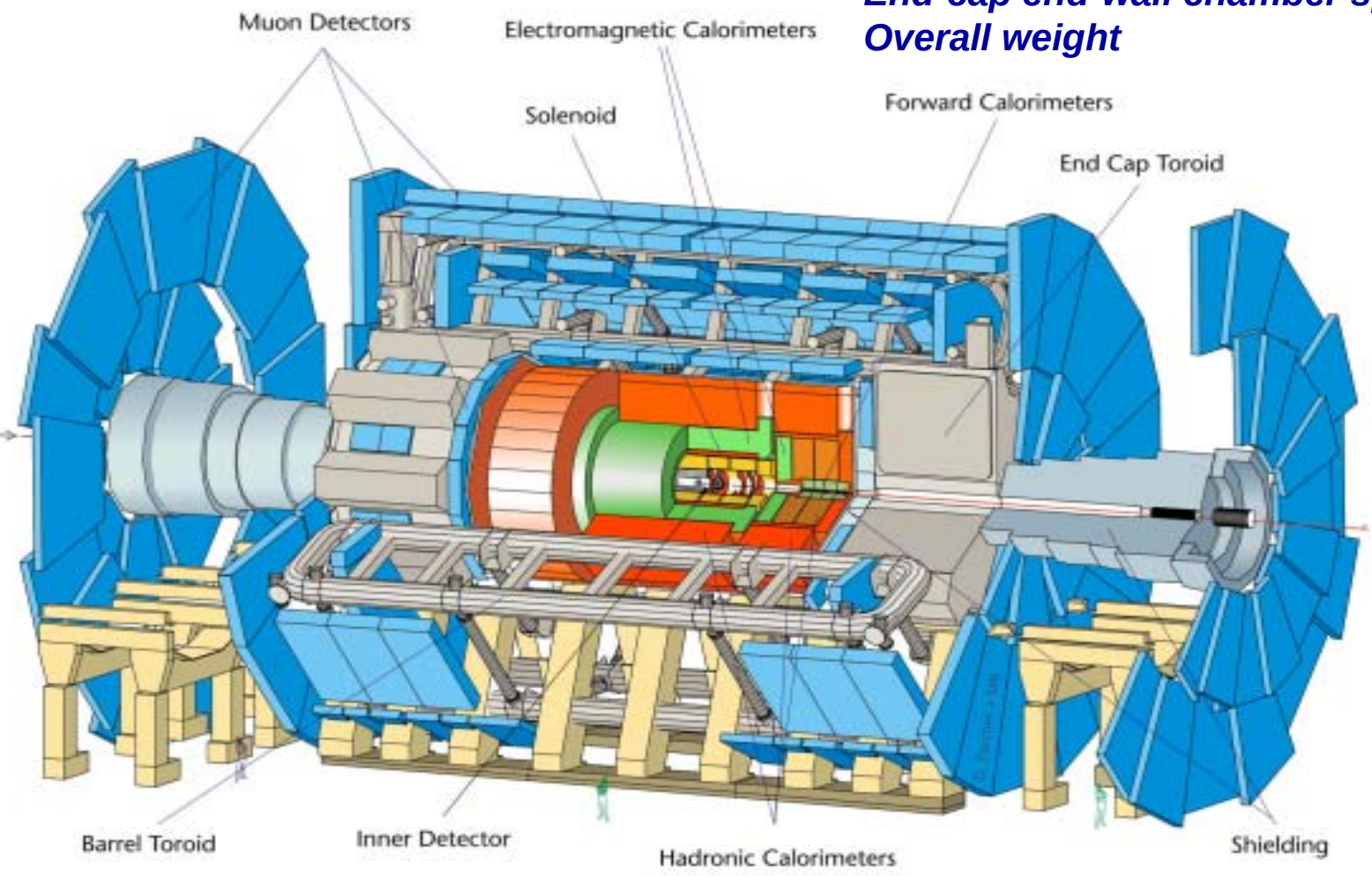


A Slice through CMS

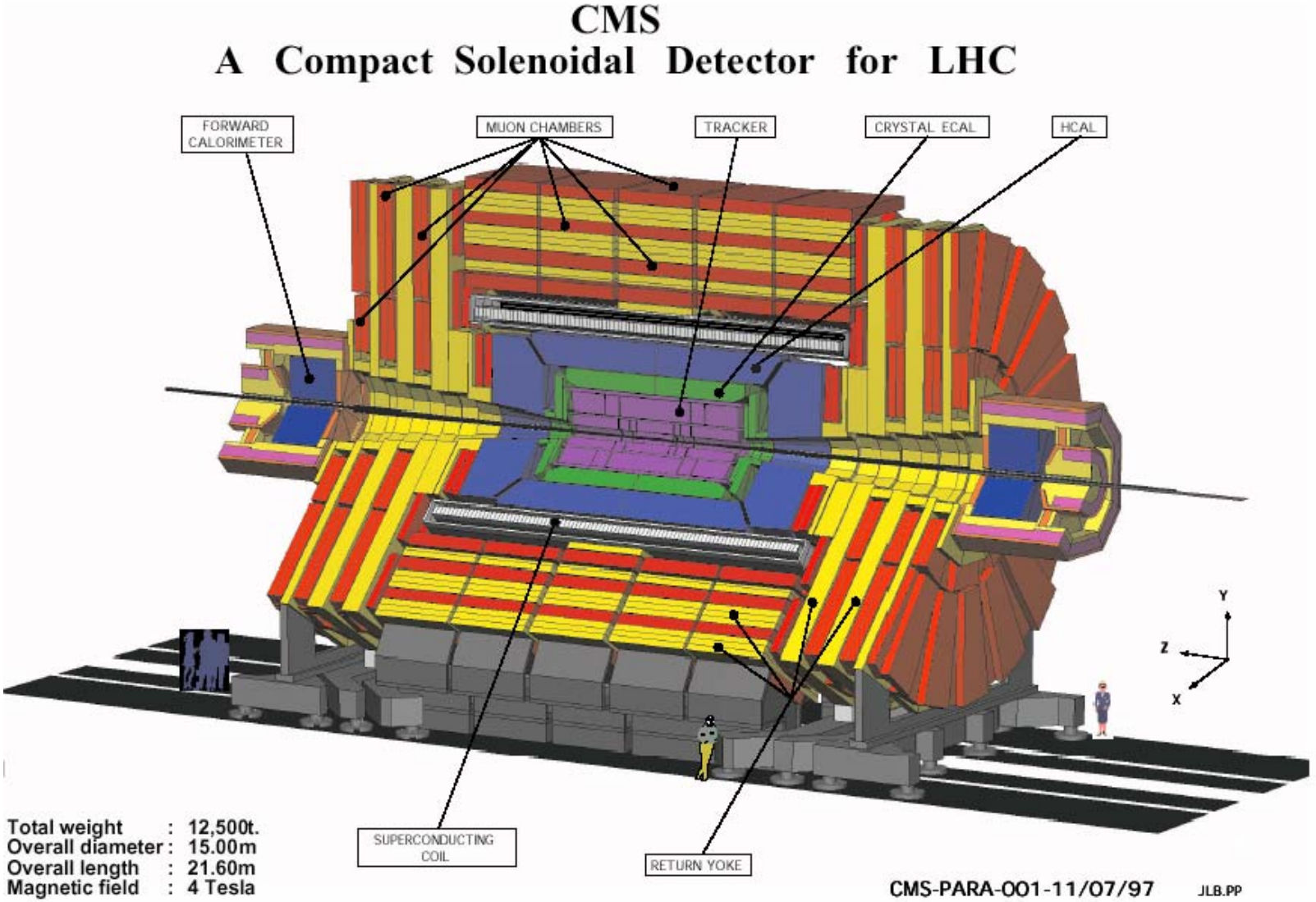


The ATLAS Detector

Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*



The CMS Detector



ATLAS SC TOROID

Design goal: measure 1 TeV muons with 10% resolution

ATLAS: <B>~0.6T over 4.5 m $\rightarrow$ s=0.5mm $\rightarrow$ need σ_s=50μm

- Ampere's theorem:

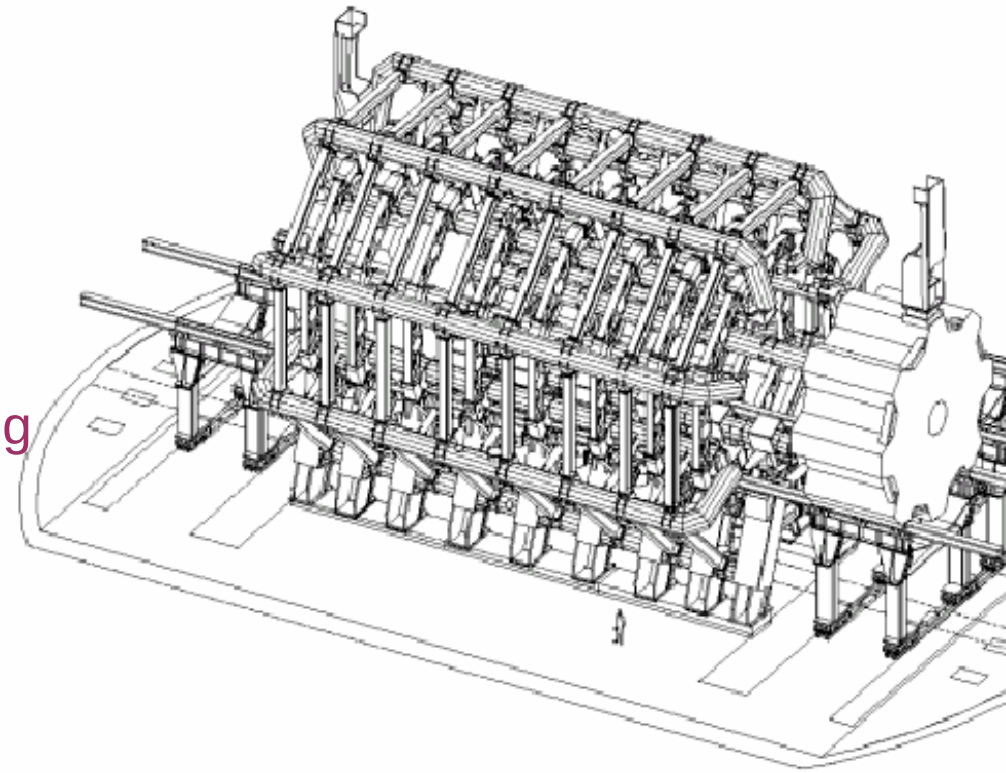
$2\pi RB=\mu_0 nI \rightarrow nI=2x10^7$ At

- With 8 coils, 2x2x30 turns: I=20kA (superconducting)
- Challenges:

Design of structure capable of holding the magnetic forces

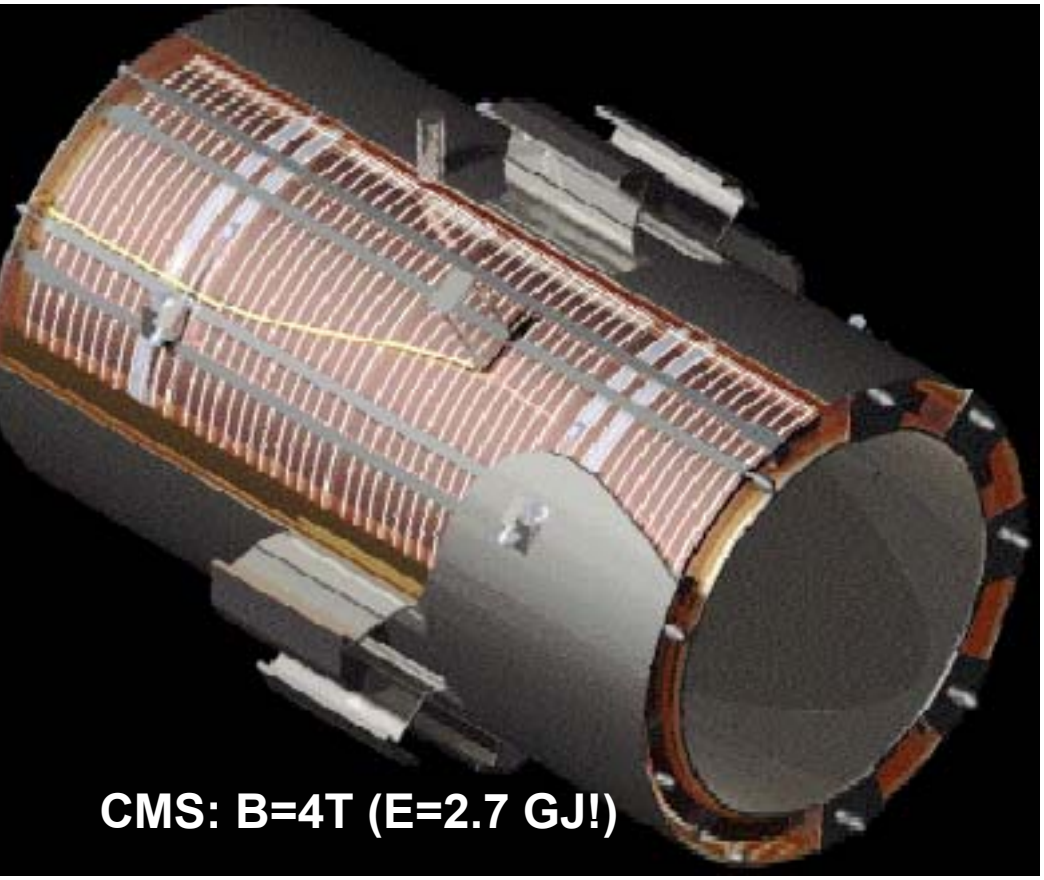
High stored energy 1.5GJ,

Spatial & alignment precision over large surface area



ATLAS: Assembly of Toroid Coils

CMS Solenoid



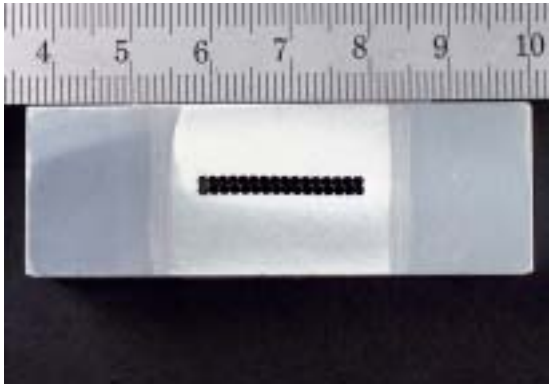
- $B=\mu_0 nI$;

2168 turns/m$\rightarrow$ I=20kA (Superconducting)

- Challenges:

4-layer winding to carry enough current,

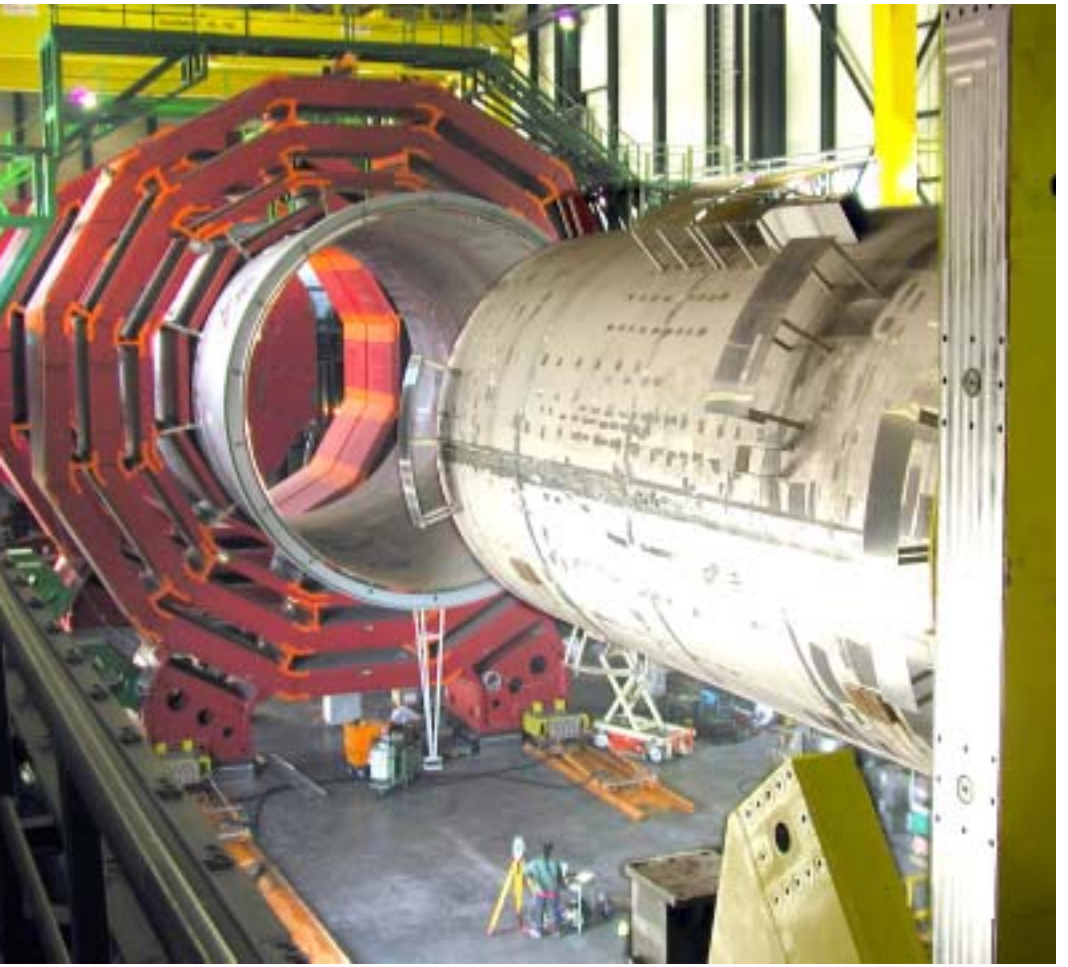
Design of reinforced superconducting cable



CMS Solenoid Assembly

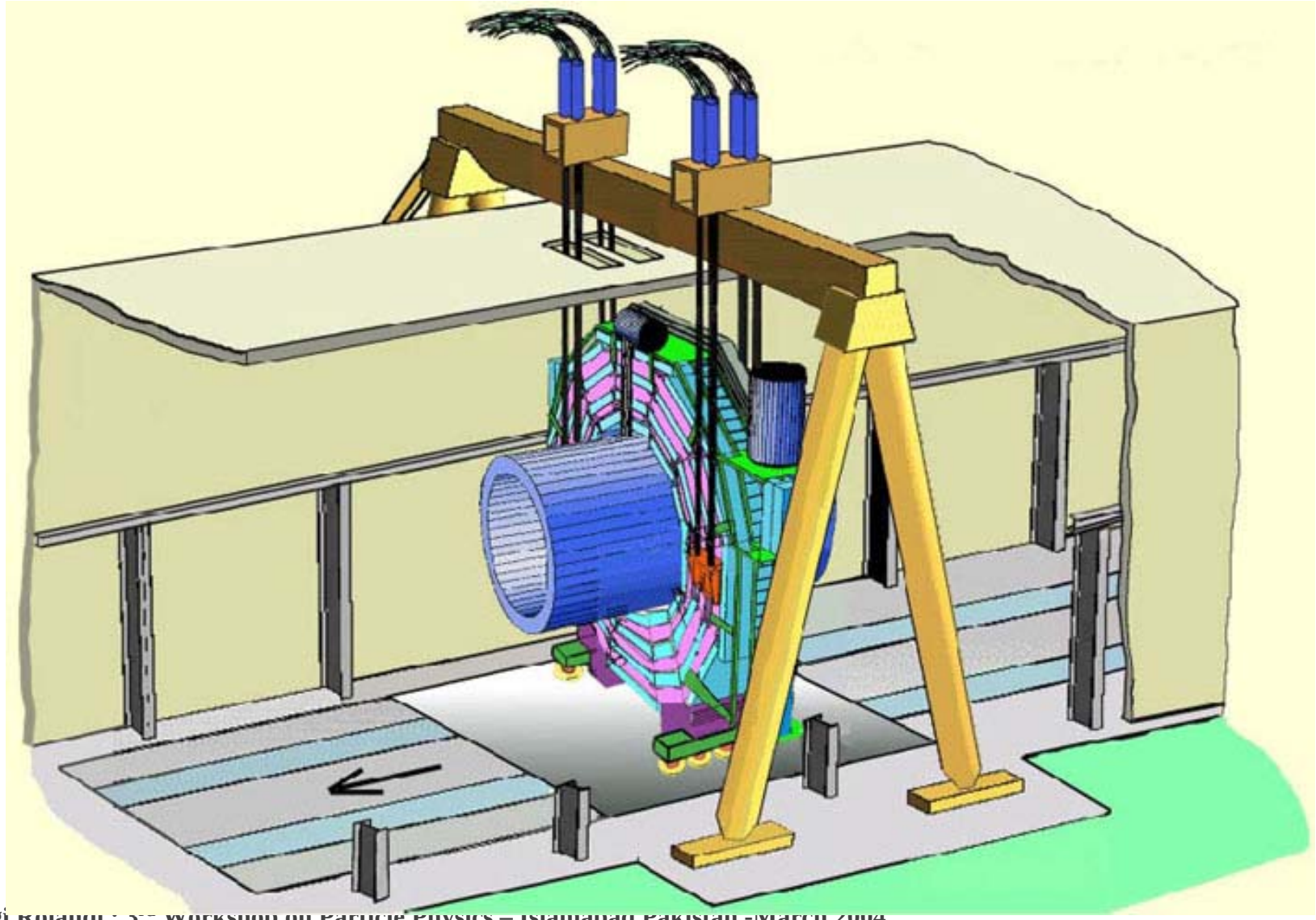
CMS Solenoid Coil

CMS Installation in Surface Building



CMS Installation in Surface Building

Transfer of Magnet Sections by Heavy Lifting



Tracking at LHC

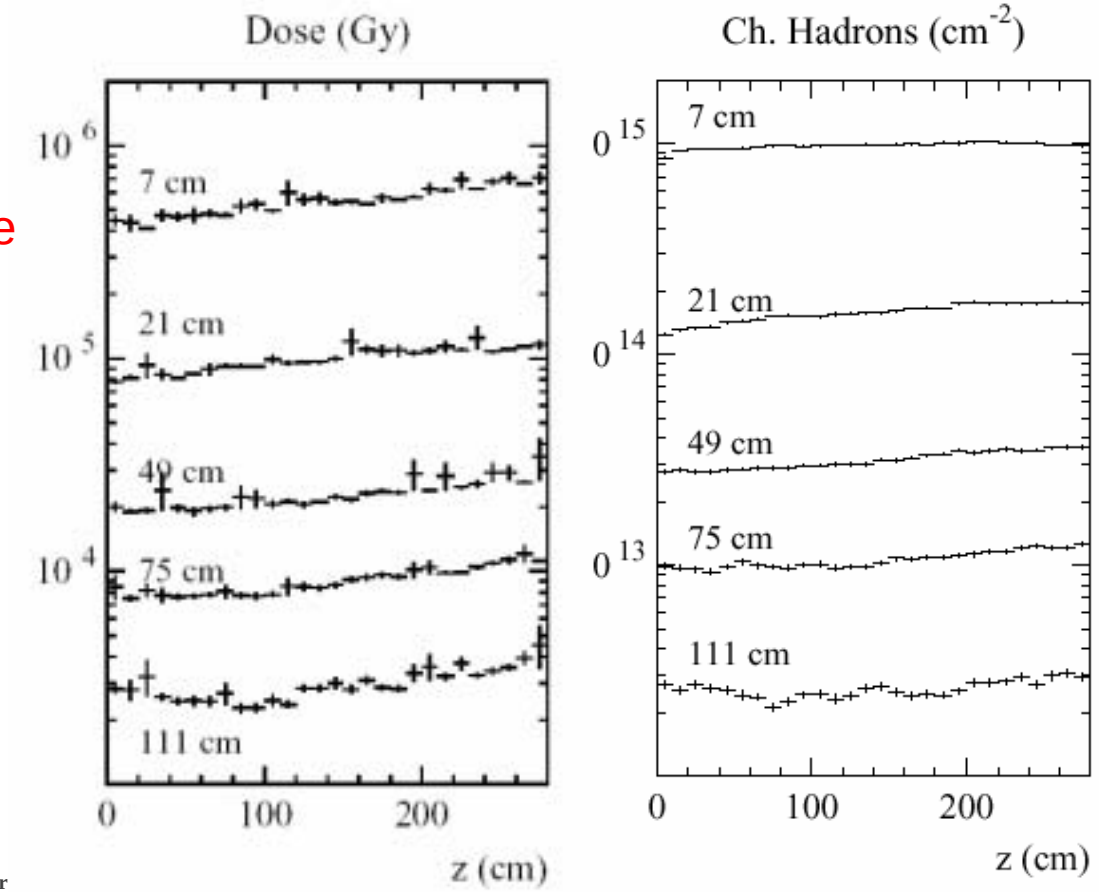
Factors that determine performance

Track finding efficiency – occupancy/crossing

Momentum resolution

Secondary vertex reconstruction

Dose & Fluence over 10 years

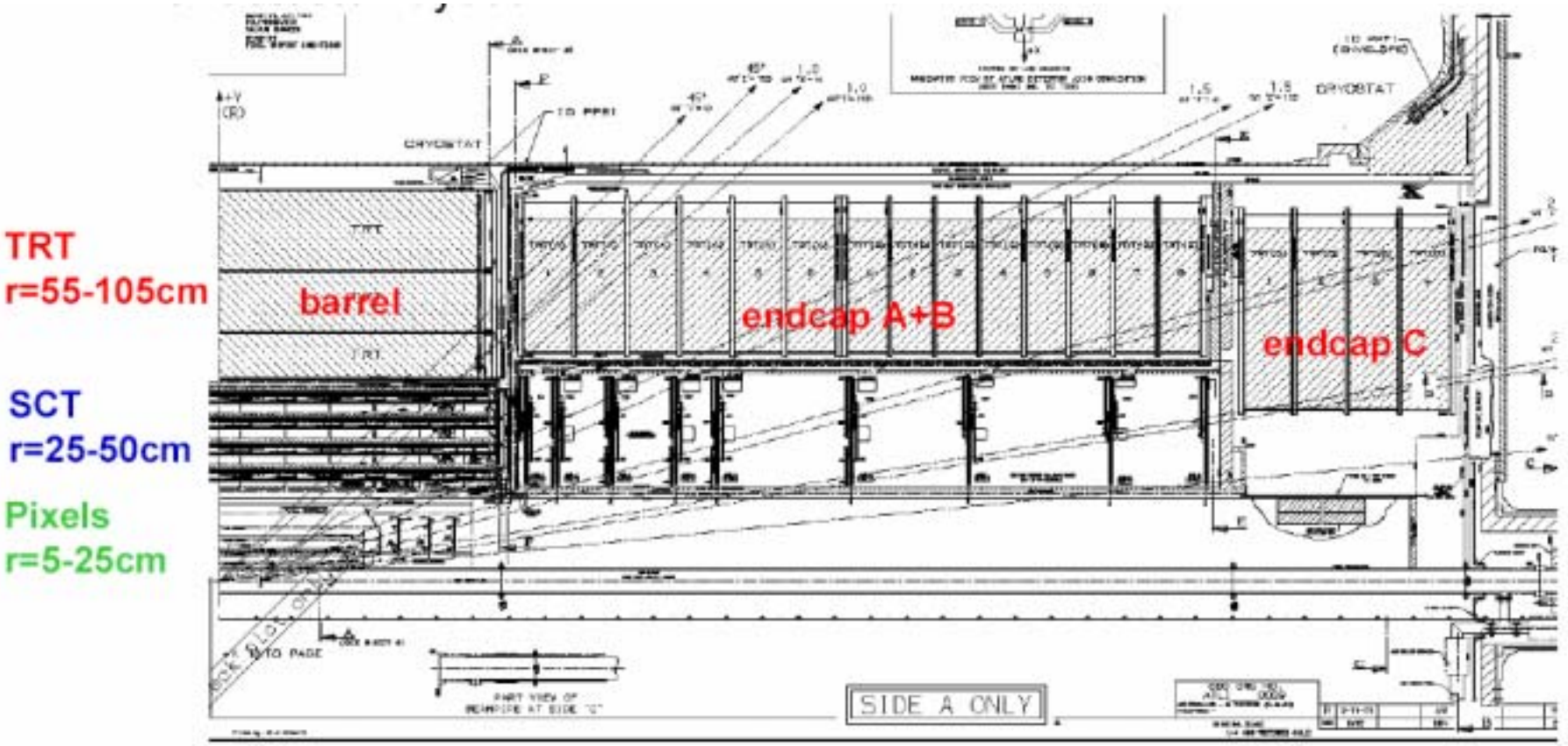


≤ 4.10^7 h±/cm²/s
pixels (≈10^4 μm²)
occupancy ≈ 10^{-4}

≤ 4.10^6 h±/cm²/s
Si μ-strip det.
(≈10 mm²)
occupancy ≈ 1%

≤ 4.10^5 h±/cm²/s
Si or Gas detectors.
(≈1 cm²)
occupancy ≈ 1%

ATLAS Tracker Layout

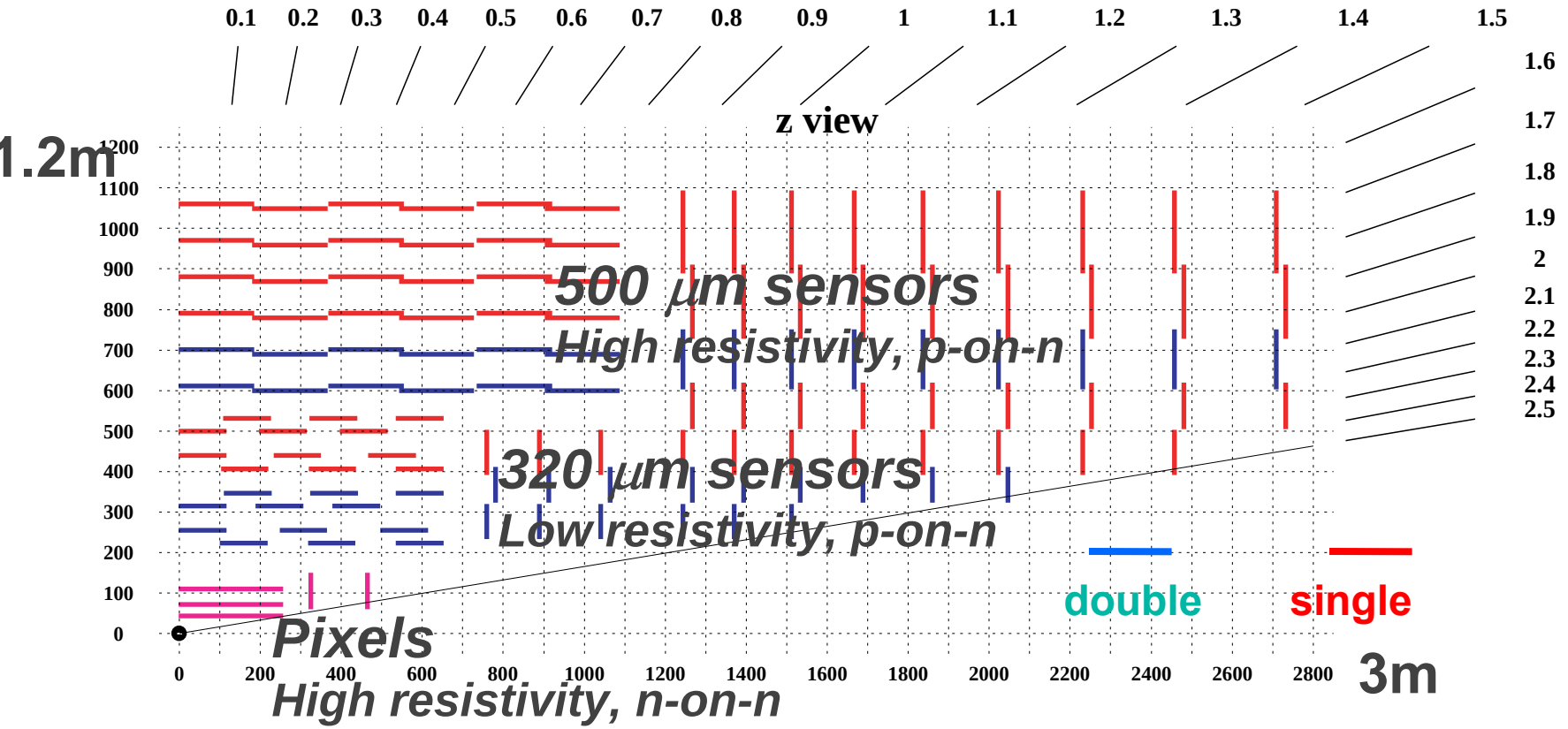


Hybrid Pixels: ~ 2.3 m^2 of silicon sensors, 140 M pixels, 50x300 μm^2, r = 5, 10, 13 cm

Si μ-strips : 60 m^2 of silicon sensors, 6 M strips, 4 pts, r = 30 - 50 cm

Straws TRT: 36 straws/track, Xe-CO_2-CF_4 ϕ=4mm, r = 56 - 107 cm

CMS Tracker Layout

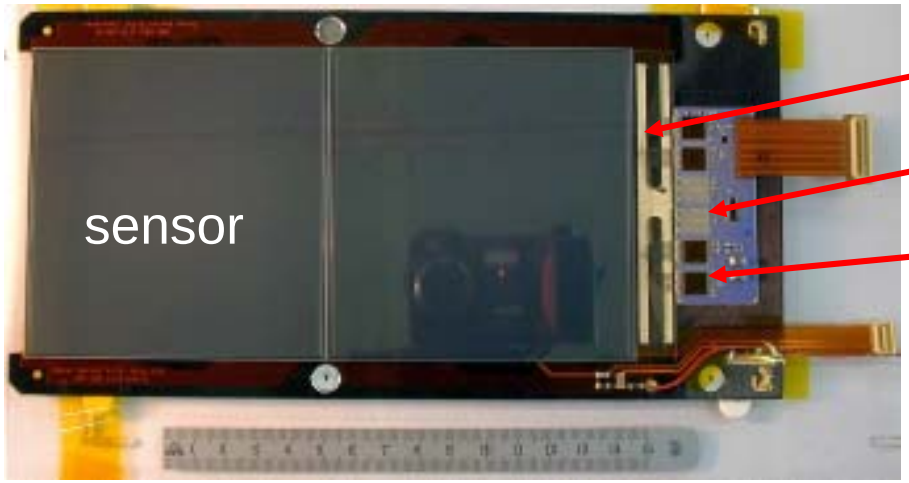


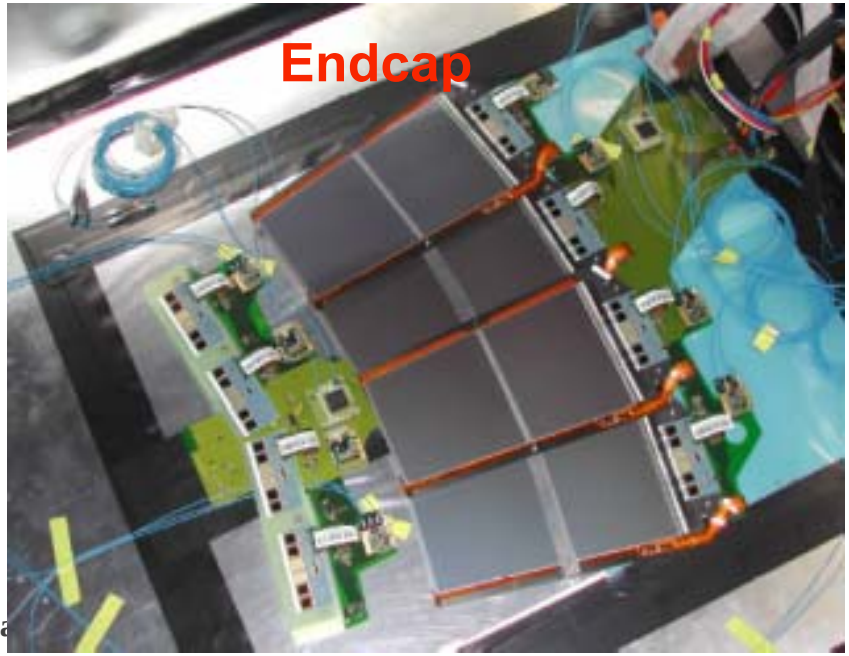
Hybrid Pixels: ~ 1 m^2 of silicon sensors, 67 M pixels, 100x150 μm^2 , 3 pts, r = 4, 7, 11 cm

Si μ-strips : 223 m^2 of silicon sensors (15 k modules) , 10 M strips, 10 pts, r = 20 – 120 cm

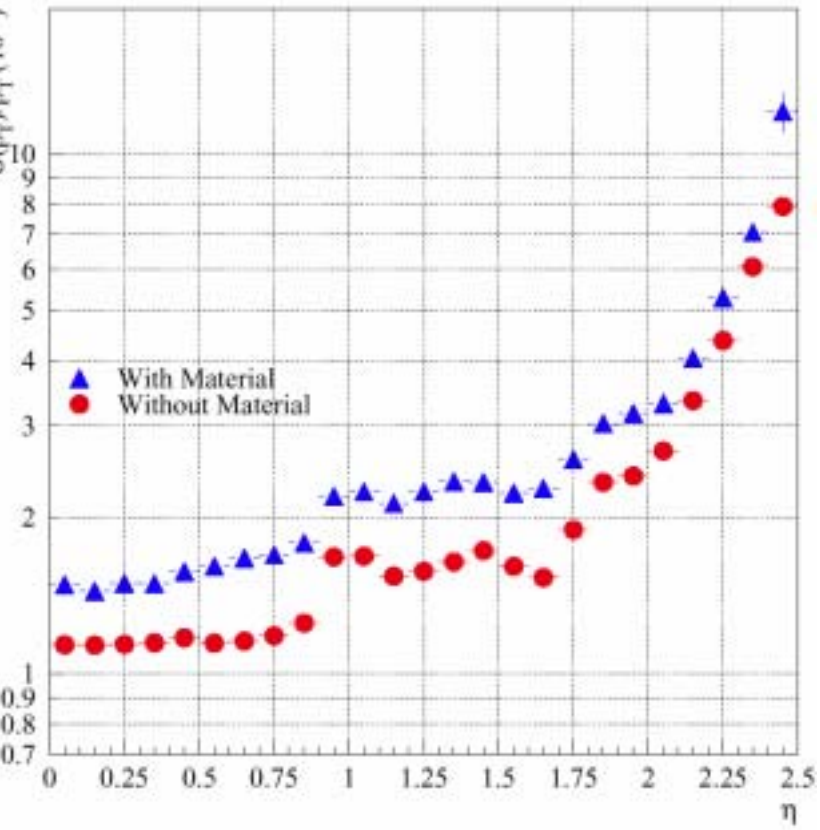
CMS Tracker: Some Components

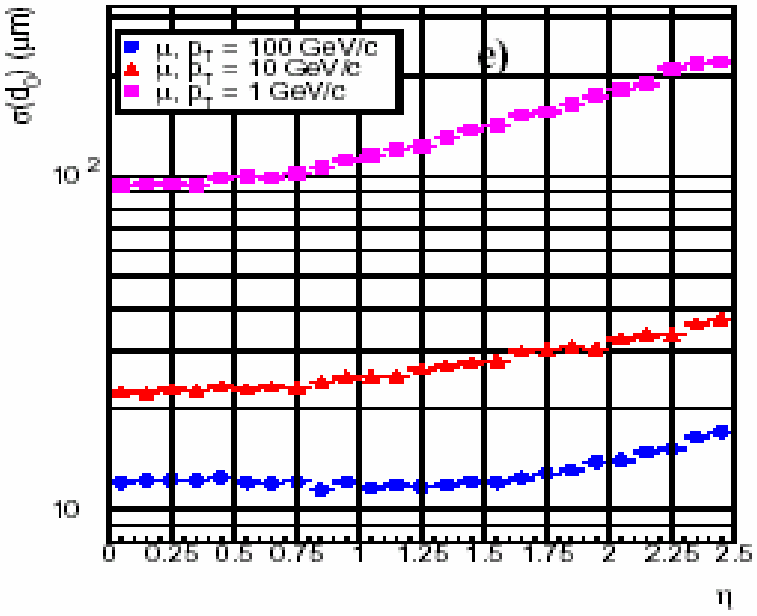
Si Strip Module

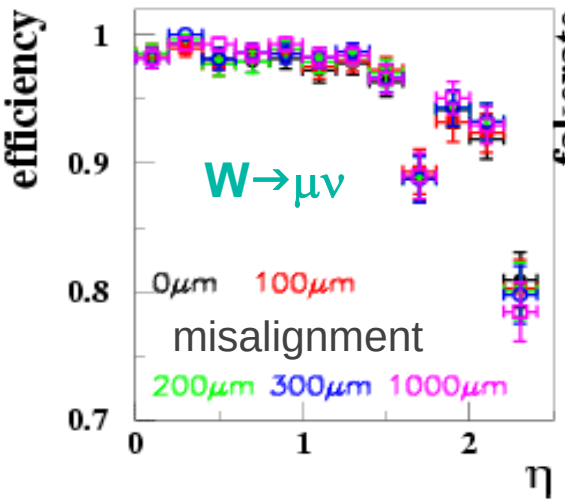


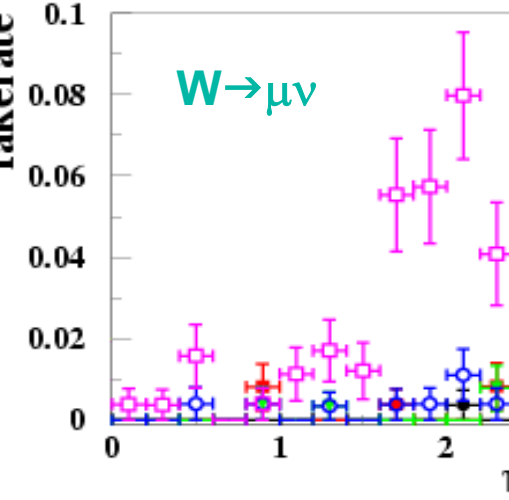


CMS Tracker Performance

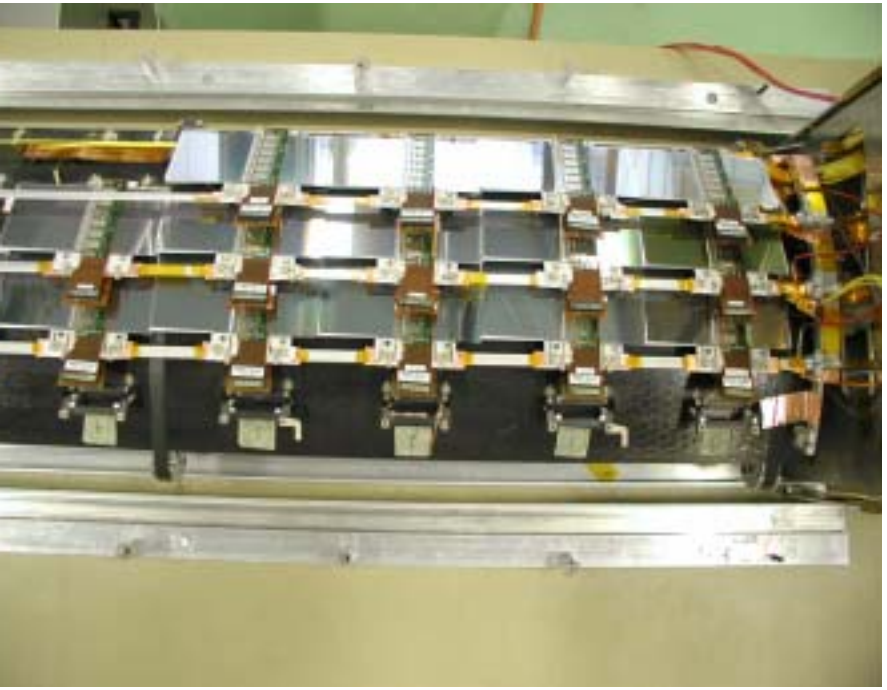








ATLAS Tracker: Some Components

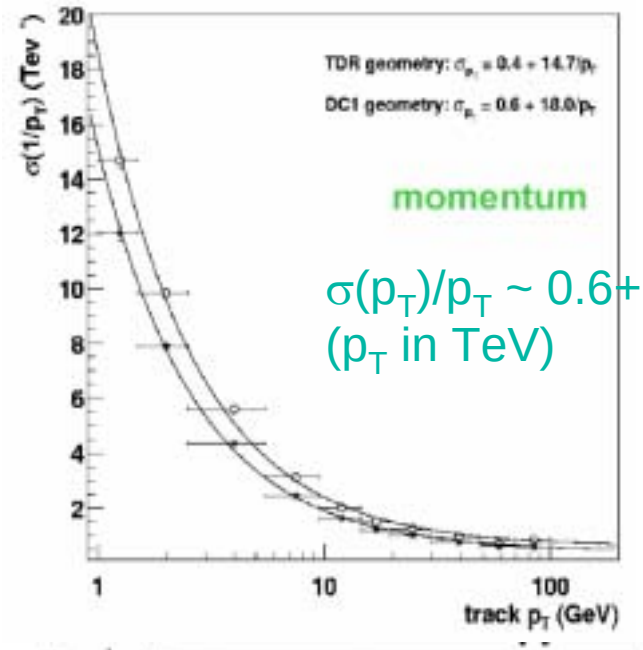


SCT barrel system test

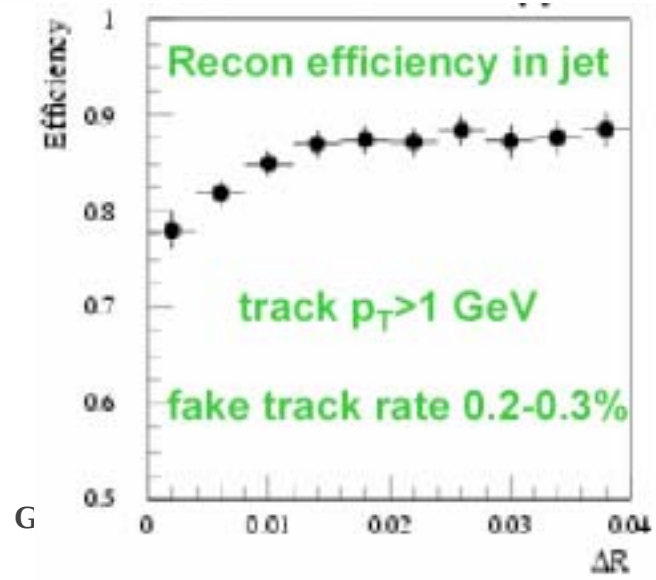
Two of the SCT barrel support structures

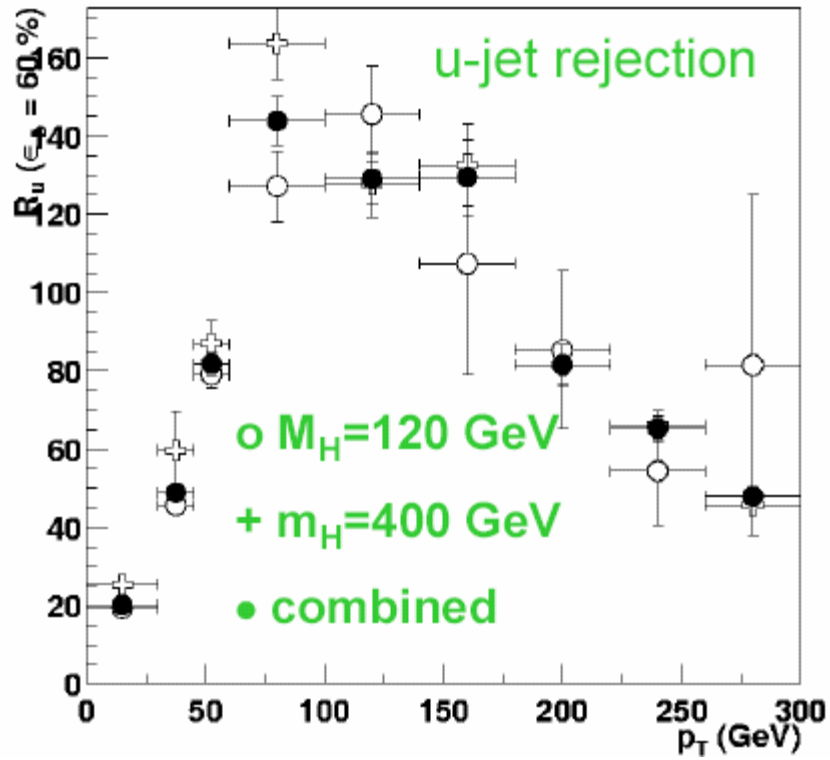
ilicon detector sensor production:
lmost complete, more than 90%
elivered and accepted

ATLAS Tracker Performance



$\sigma(p_T)/p_T \sim 0.6+18p_T$
(p_T in TeV)





Significant dependence on jet p_T:

- Balance between multiple scattering (lo
  p_T) and pattern recognition effects (high
  - Very dense jets at high energy
  - Best rejection around 100 GeV
  - Little intrinsic dependence on boson ma

CMS: Crystal Calorimeter

Advantages:
- Fast
- Dense
- Radiation hard
- Emission in visible

Disadvantages:
- Temperature dependence
- Low light yield

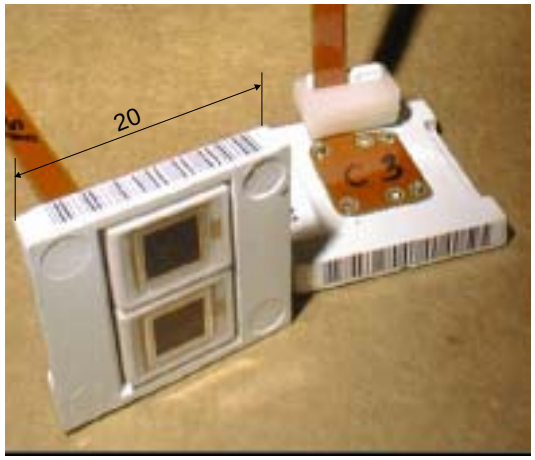
⇨ Photodetector with gain (in a strong magnetic field)

Density [g/cm^3]	8.28
Rad length, X_0 [mm]	8.9
Int length [mm]	224
Molière rad [mm]	21.9
Decay time [ns]	5(39%) 15(60%) 100 (1%)
Refractive index	2.30
Max emiss [nm]	420
Light yield [ph/MeV]	~50
Temp coeff [%/ºC]	-2

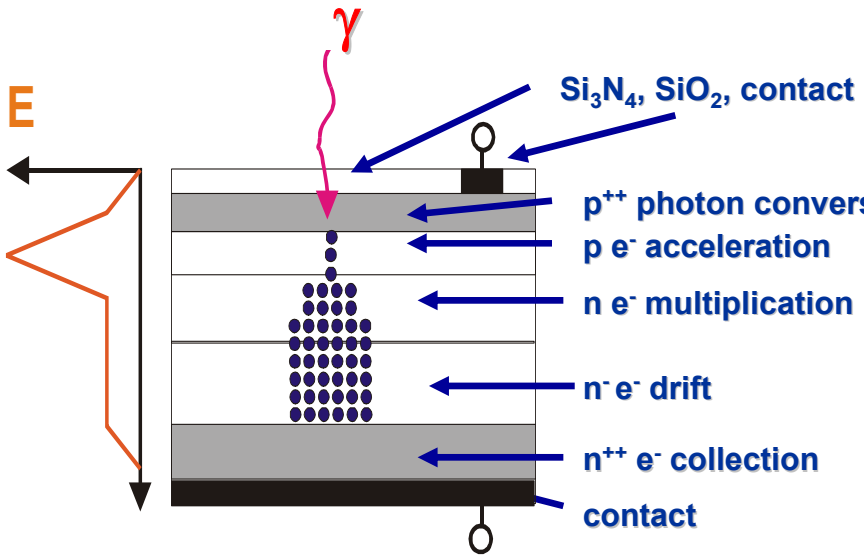
CMS Parameters

Parameter	Barrel	End caps
Xtal size (mm^3)	21.8 × 21.8 × 230	30.0 × 30.0 × 22
Depth in X_0	25.8	24.7
No. crystals	61200	14664
Volume (m^3)	8.14	2.77
Xtal mass (t)	67.4	22.9

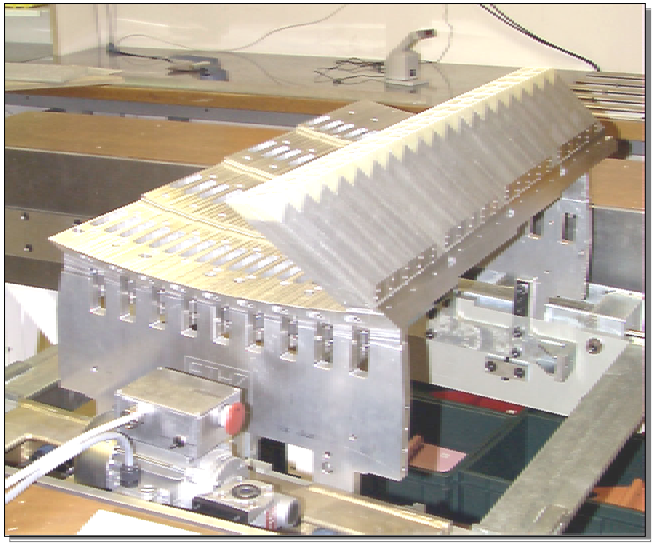
CMS: Crystals & APDs

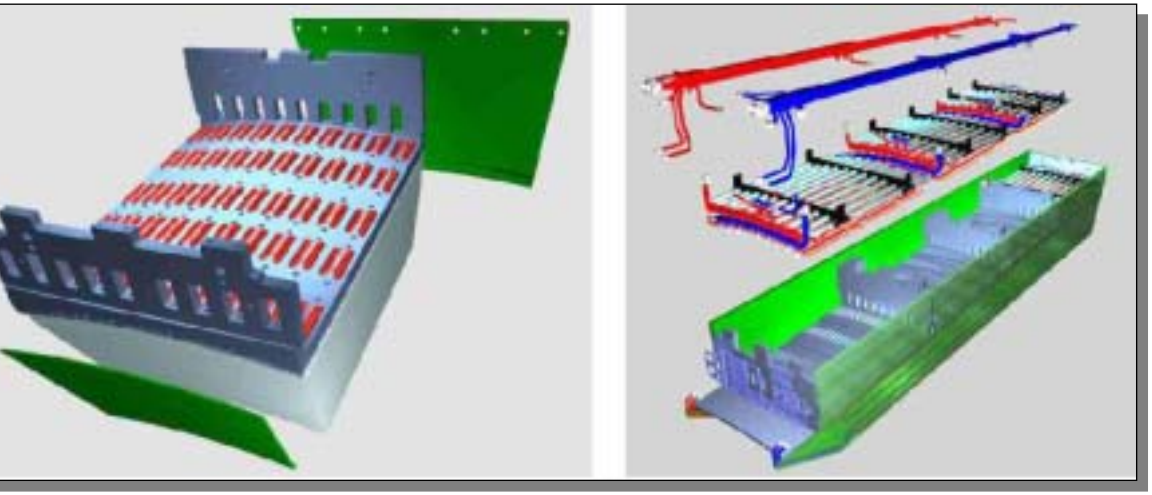


Si Avalanche Photodiodes

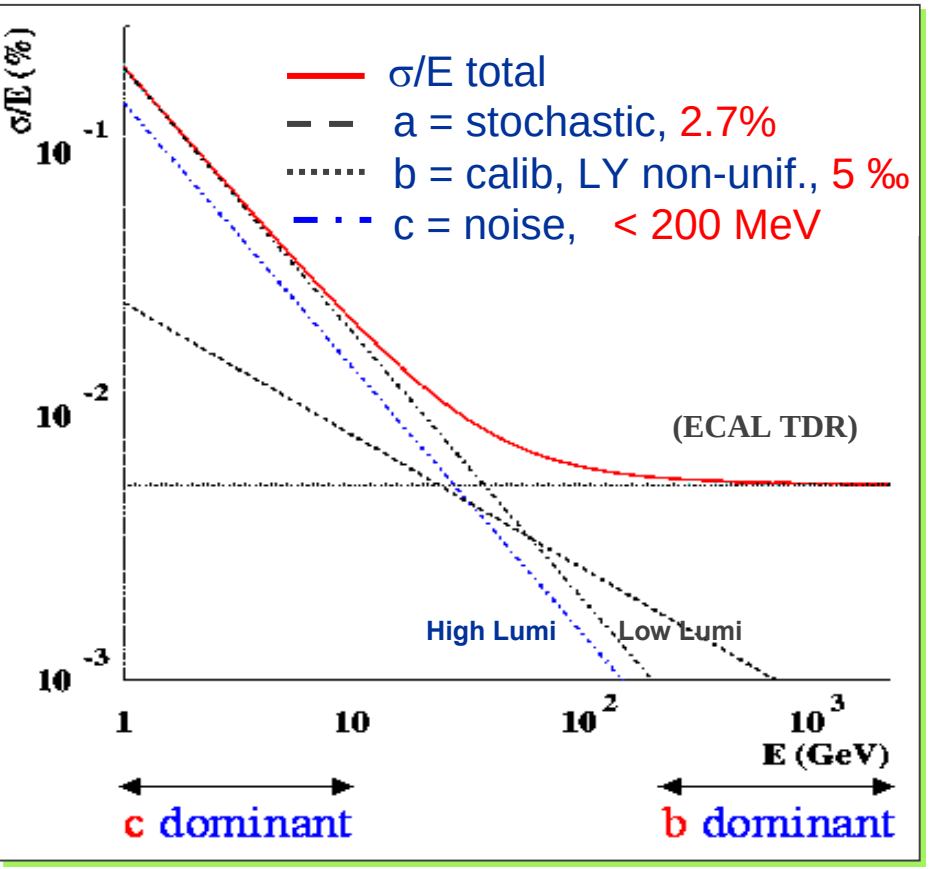


CMS: ECAL Components



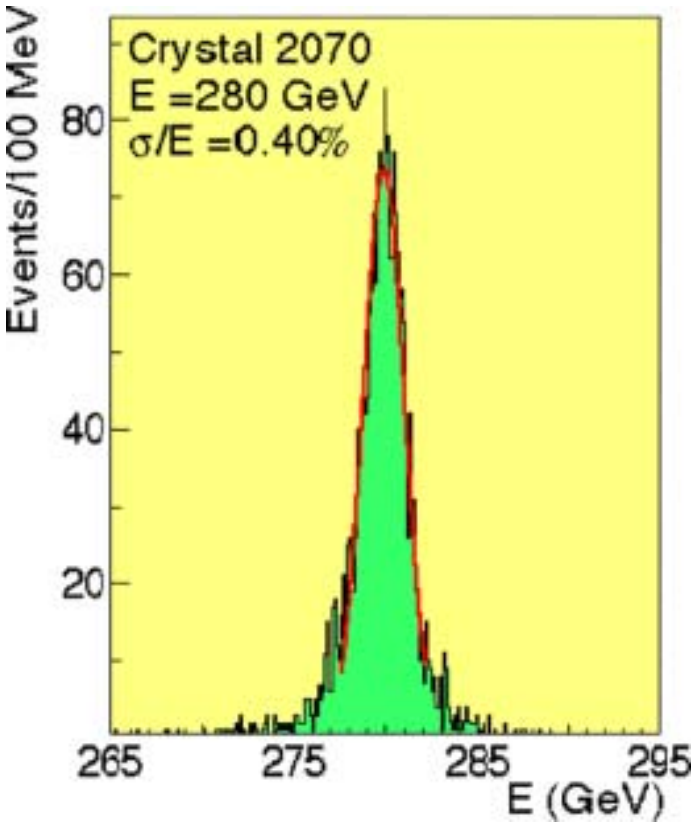


CMS ECAL: Performance



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

3 x 3 Crystals

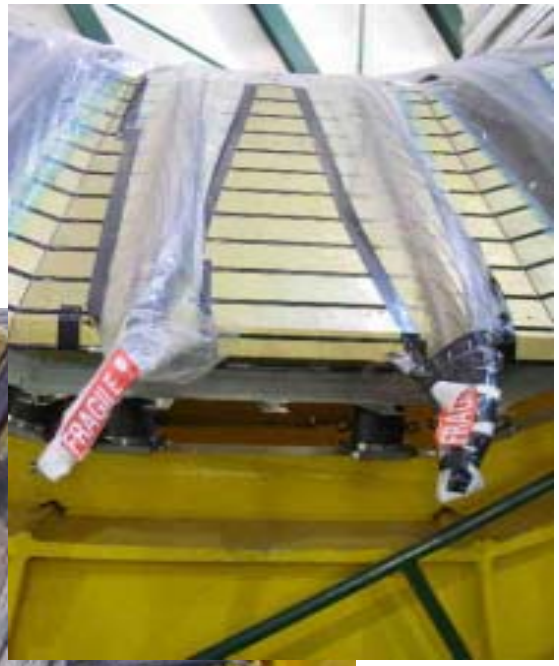


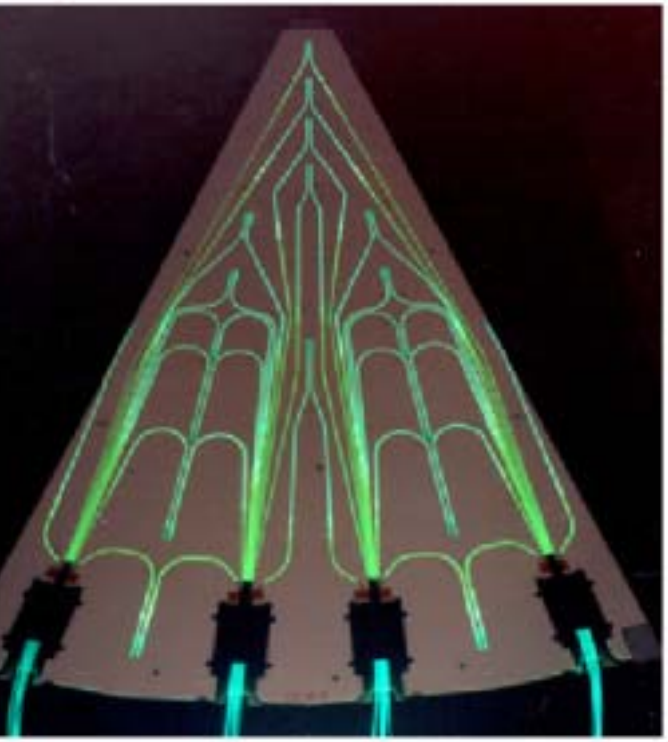
Goal $$\frac{\sigma}{E} = \frac{2.7\%}{E} \oplus 0.5\% \oplus \frac{200\,MeV}{E}$$

CMS HCAL

Routing of clear fibres to optical disconnects

WLS fibres Embedded in plastic scint. plates





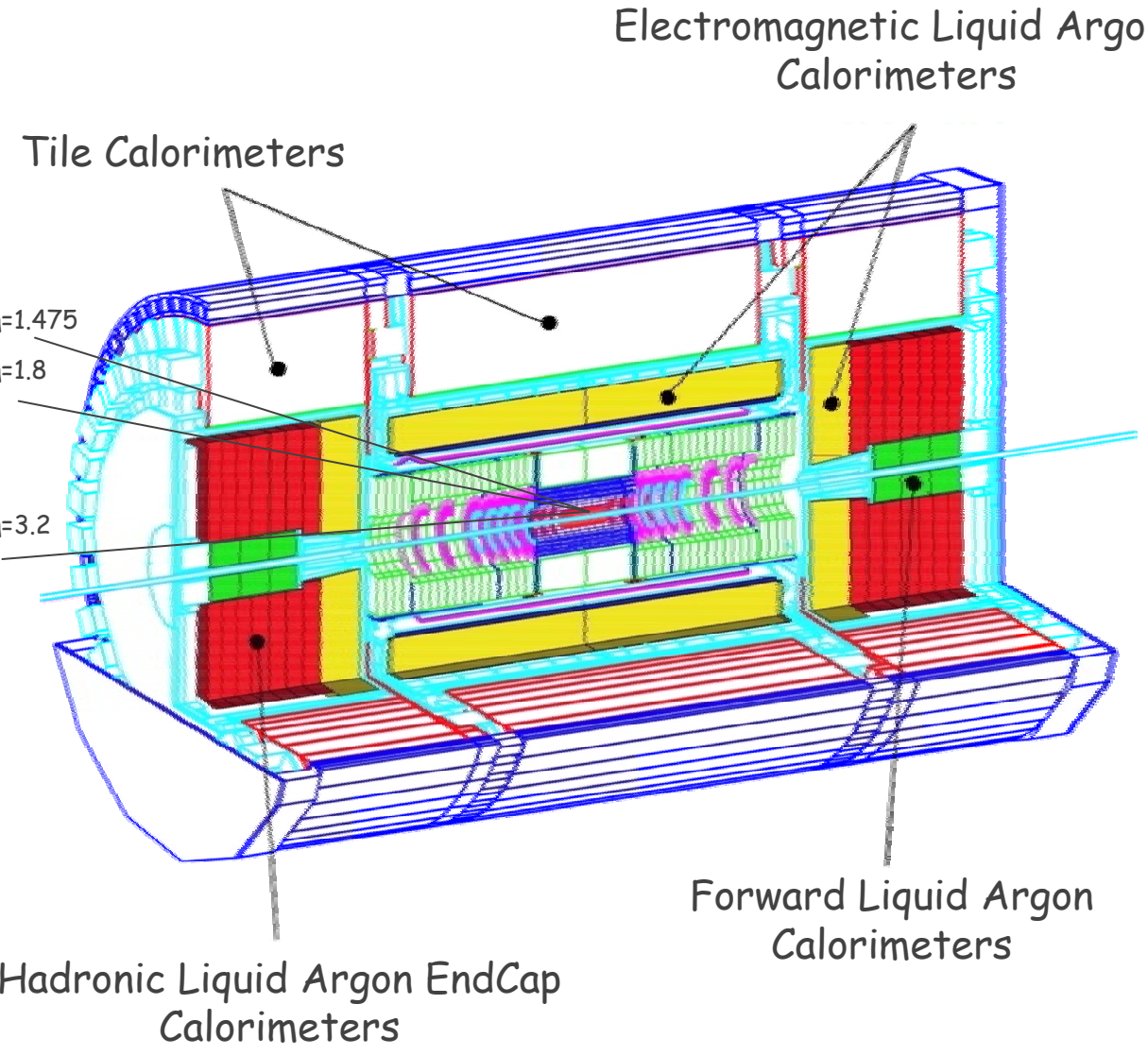
Central Region ($|\eta|<3$) : Brass/Scintillator with WLS fibre readout, projective geometry, granularity $\Delta\eta \times \Delta\phi = 0.0875 \times 0.0875$

CMS: Very Forward Calorimeter

Fibres insertion in HF wedges

Forward Region (3<|η|<5): Fe/Quartz Fibre, Cerenkov light

ATLAS Calorimeters



ECAL

Accordion Pb/LAr

$|\eta|<3.2$, 3 samplings

S1: $\Delta\eta x\Delta\phi = 0.025x0.1$

S2: $\Delta\eta x\Delta\phi = 0.025x0.025$

S3: $\Delta\eta x\Delta\phi = 0.05x0.025$

HCAL

Barrel: Fe/Scintillator with WLS fibre readout

3 samplings - $\Delta\eta x\Delta\phi = 0.1x0$

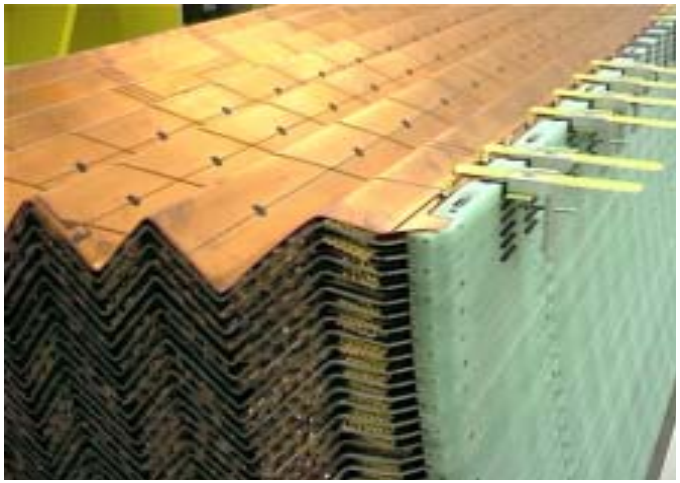
Endcap: Fe/LAr

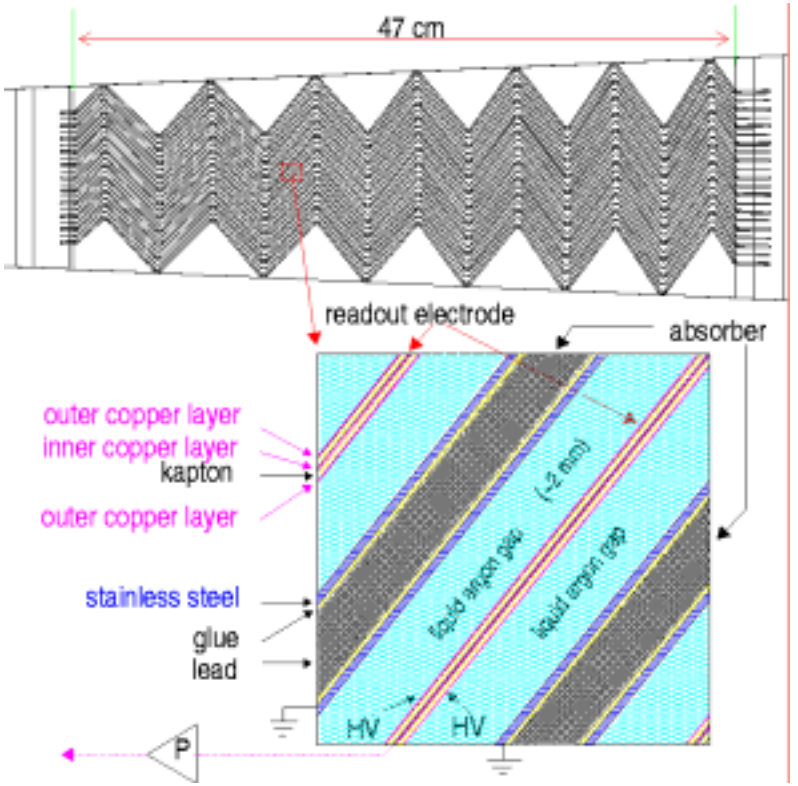
Forward: W/LAr

$3.1<|\eta|<4.9$

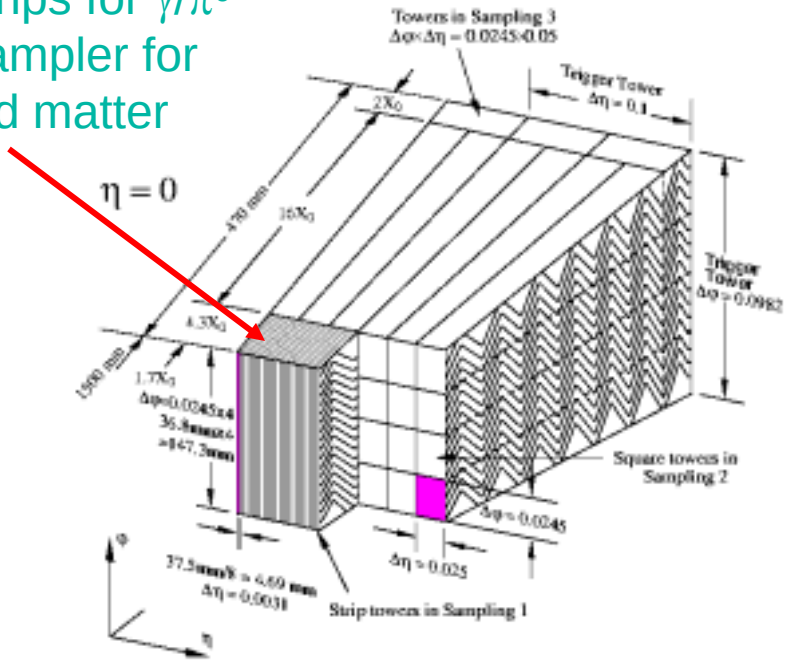
$\Delta\eta x\Delta\phi = 0.2x0.2$

ATLAS: LAr Calorimeter





Fine strips for γ/π^0
Presampler for dead matter



Accordion geometry benefits :

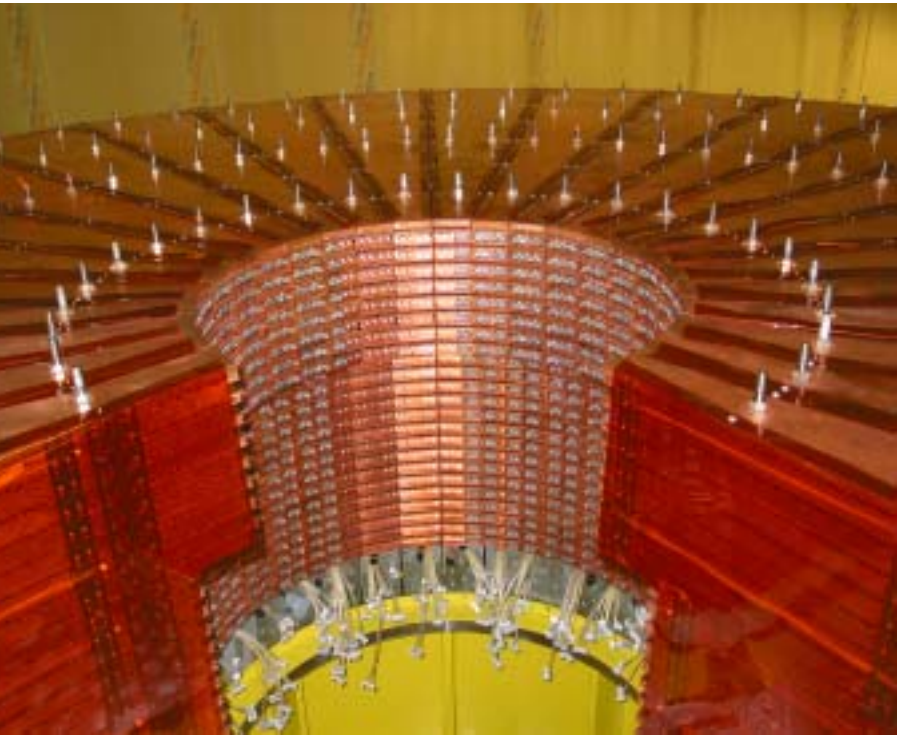
No cracks in φ

Small φ modulation (few per mille)

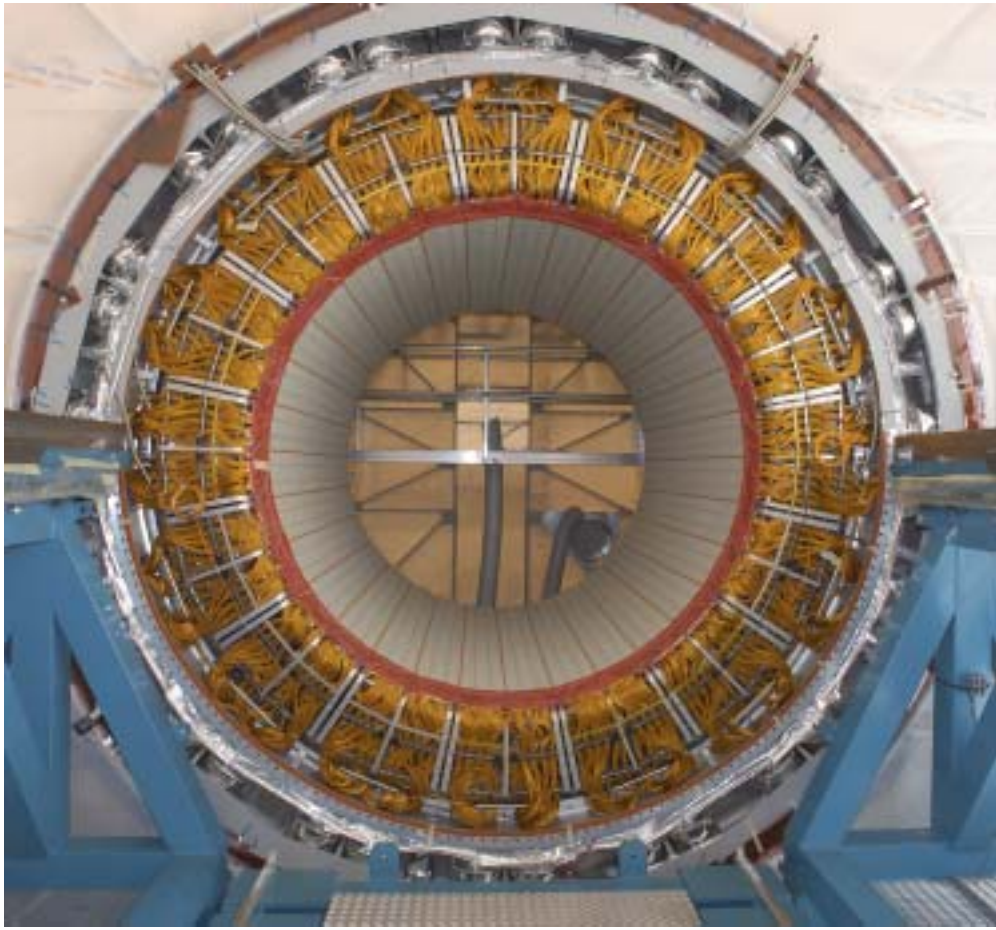
Cabling on front and back only

Low inductance

ATLAS: LAr Calorimeter

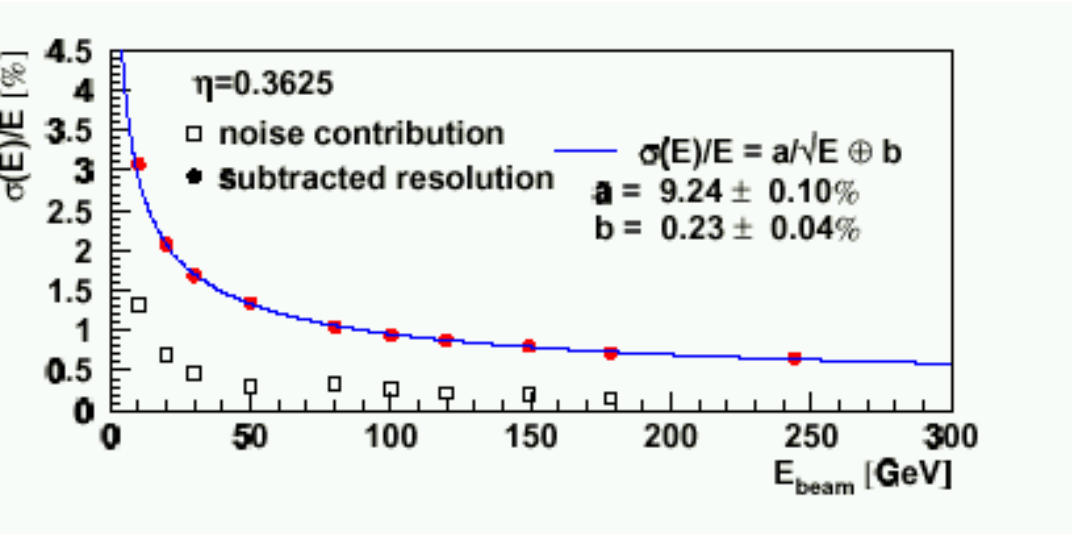


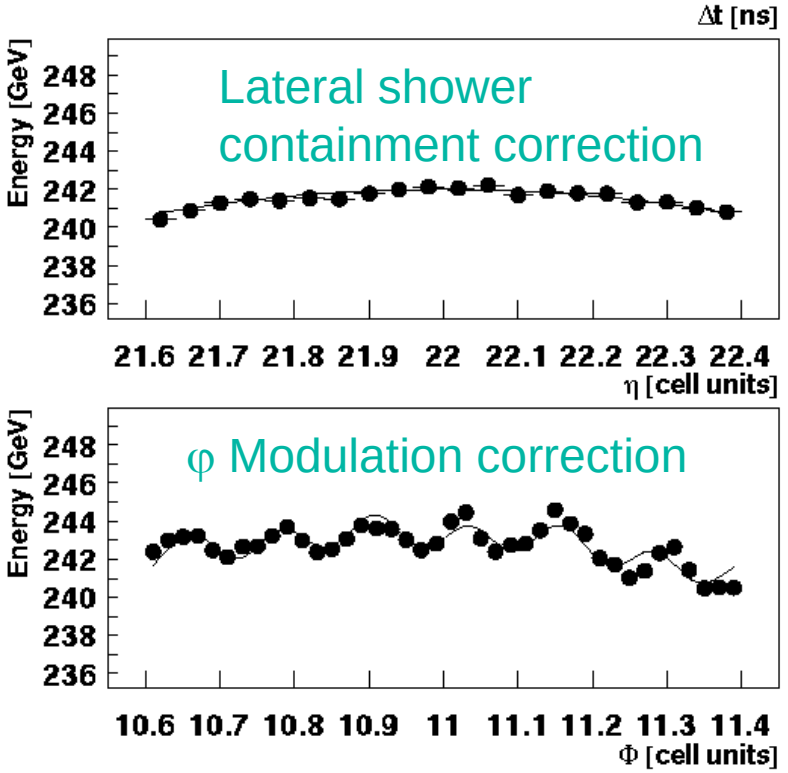
Assembly of the first HEC wheel (horizontal)



LAr EM half barrel after insertion into the cryostat

ATLAS: LAr Calorimeter

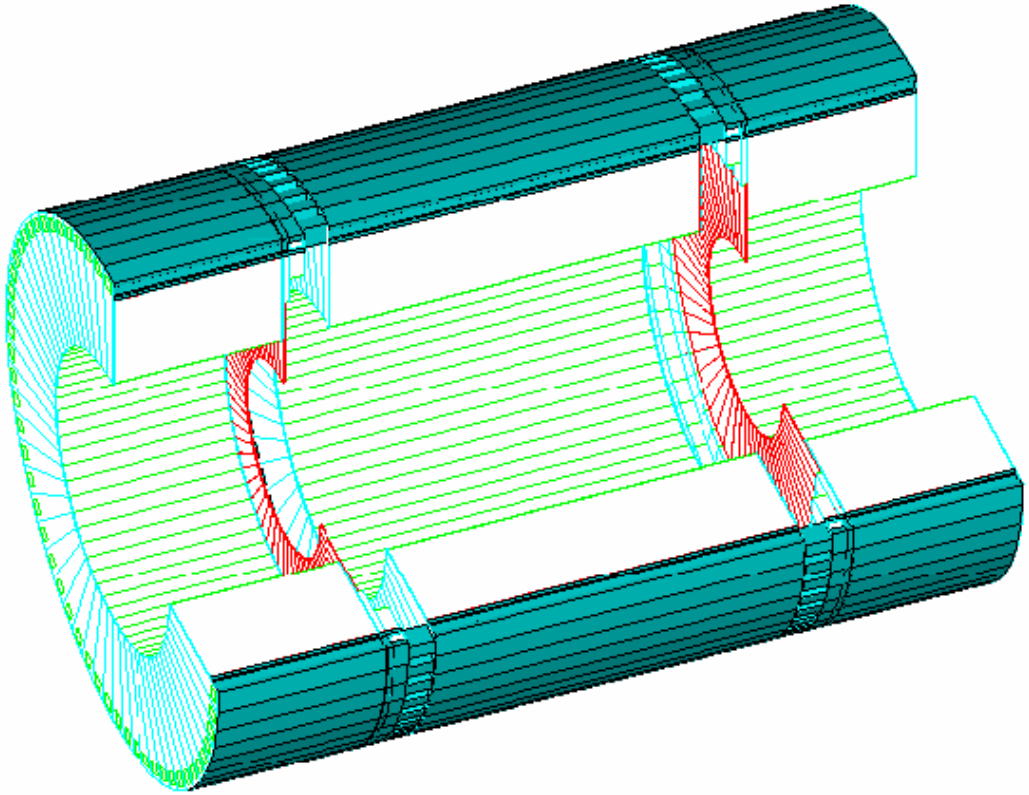


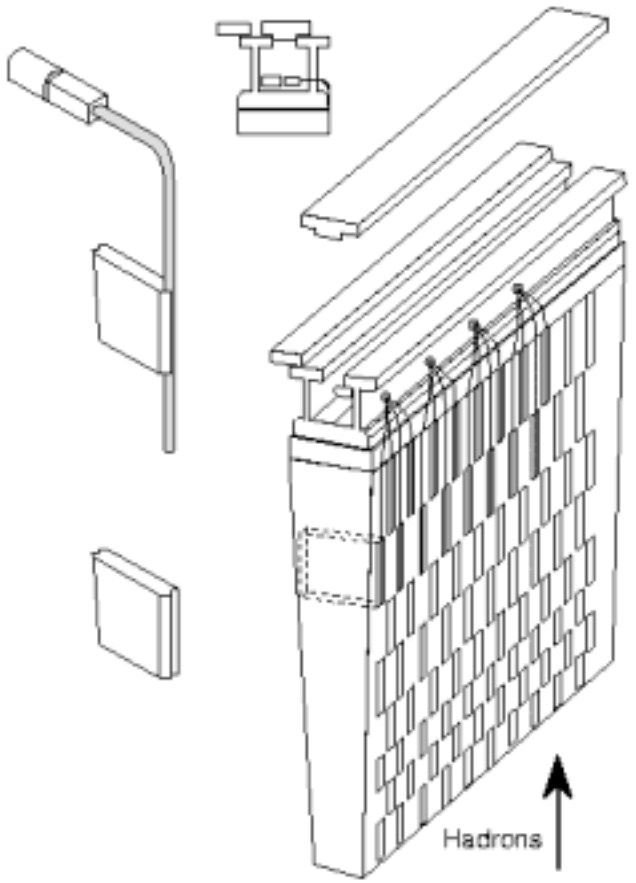


ATLAS: Tilecal

Fe absorber with scintillator tile readout with

$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$, 3 longitudinal samplings, $|\eta| < 1.7$





ATLAS: Tilecal Assembly

ATLAS: Calorimeter Performance

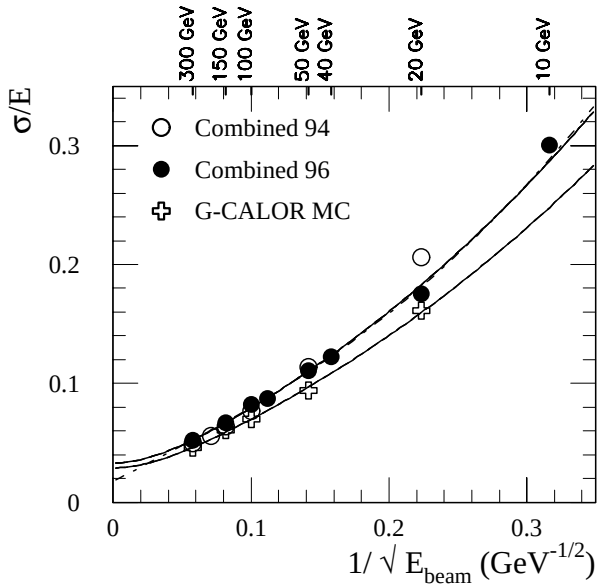
Combined Test:

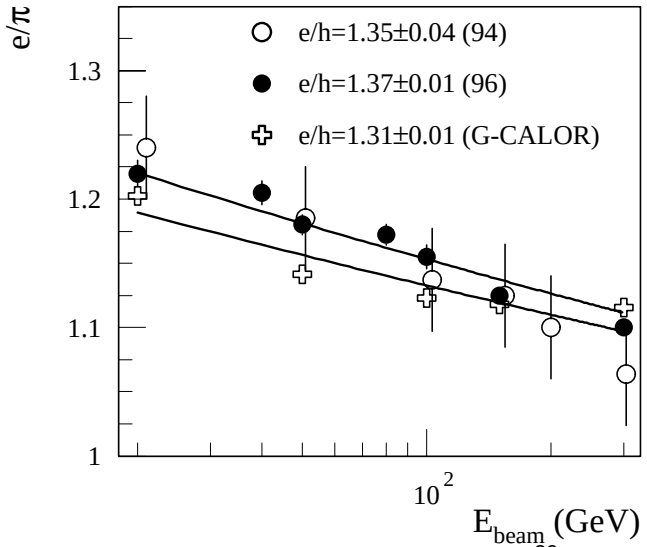
EM LAr and Hadronic Tile Calorimeter

π Energy Resolution

$$\sigma / E = a / \sqrt{E} \oplus b \oplus c / E$$

	a (%GeV$^{1/2}$)	b (%)	c (GeV)
Data	69.8 ± 0.2	3.3 ± 0.2	1.8± 0.1
G-CALOR	61.7 ± 0.1	2.9 ± 0.3	1.5 fixed

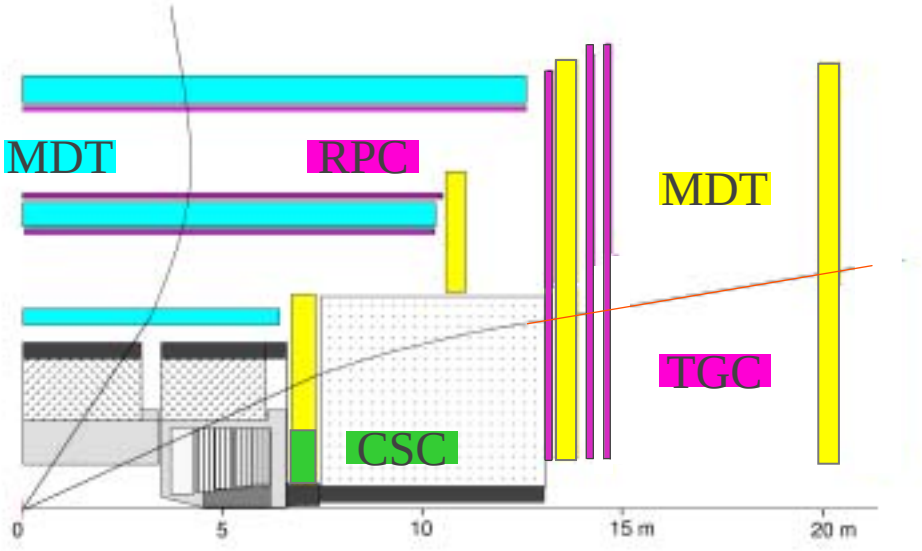




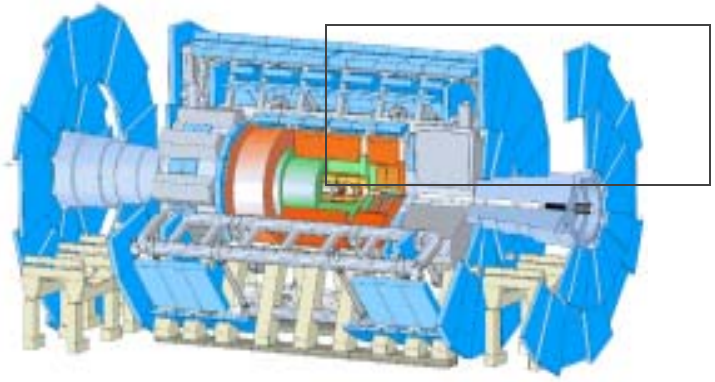
e/π ratio Degree of non-compensation *e/h*

$$e/\pi = \frac{e/h}{1+(e/h-1)\cdot F(\pi^0)}, F(\pi^0) = 0.11 \cdot \ln E$$

ATLAS Muon Detectors



Each detector has 3 stations.
Each station consists of 2-4 layers.



Precision chambers

Monitored **D**rift **T**ubes ($|\eta| < 2$)
with a single wire resolution of 80 μ m
1194 chambers, 5500m^2

Cathode **S**trip **C**hambers ($2 < |\eta| < 2.7$)
at higher particle fluxes
32 chambers, 27 m^2

Trigger chambers

Resistive **P**late **C**hambers ($|\eta| < 1.05$)
with a good time resolution of 1 ns
1136 chambers, 3650 m^2

Thin **G**ap **C**hambers ($1.05 < |\eta| < 2.4$)
at higher particle fluxes
1584 chambers, 2900 m^2

ATLAS Muon System: Monitored Drift Tubes

End-cap MDT chamber

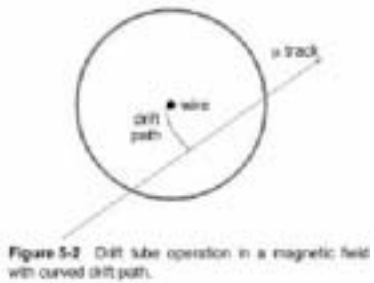
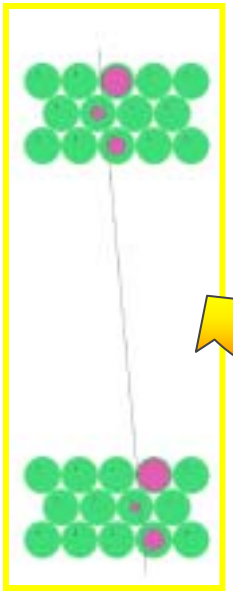


Figure 5-2 Drift tube operation in a magnetic field with curved drift path.

ϕ_{wire} = 50μm (W-Re)
3 bar, 3270V,
t_d = 500ns
Gas gain = 2.10^4



Measured Spatial Resolution

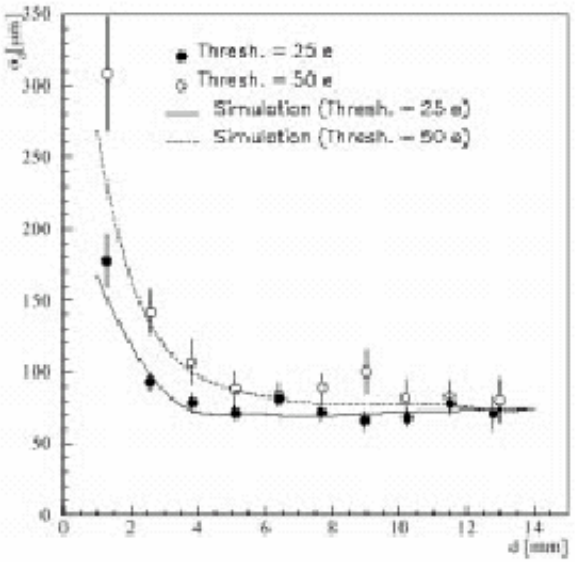
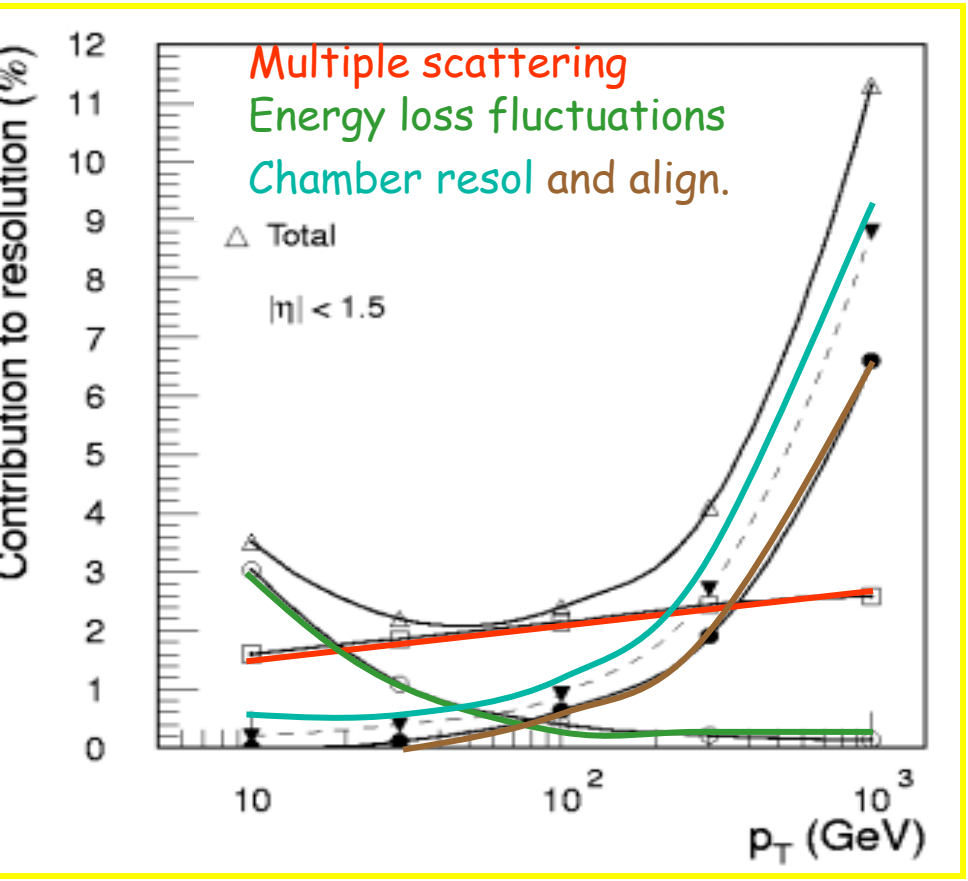
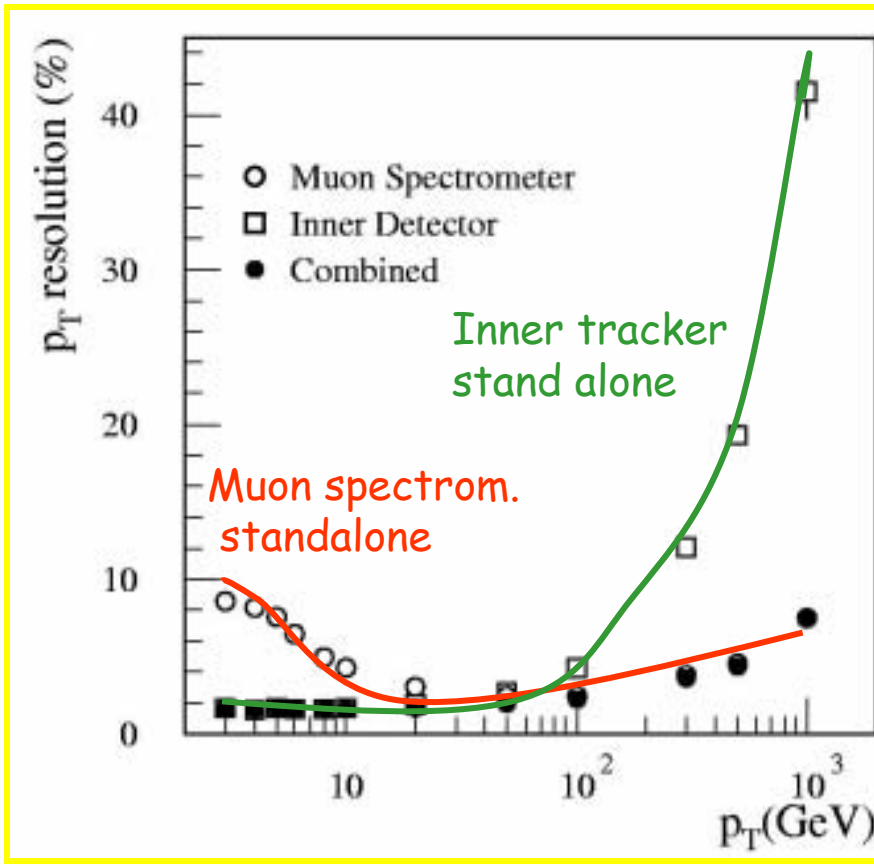


Figure 5-4 MDT resolution as a function of the drift distance, for an Ar/N2/CH4 (91/4/5 mixture). The curves correspond to two discriminator threshold settings.

ATLAS Muon System: Performance

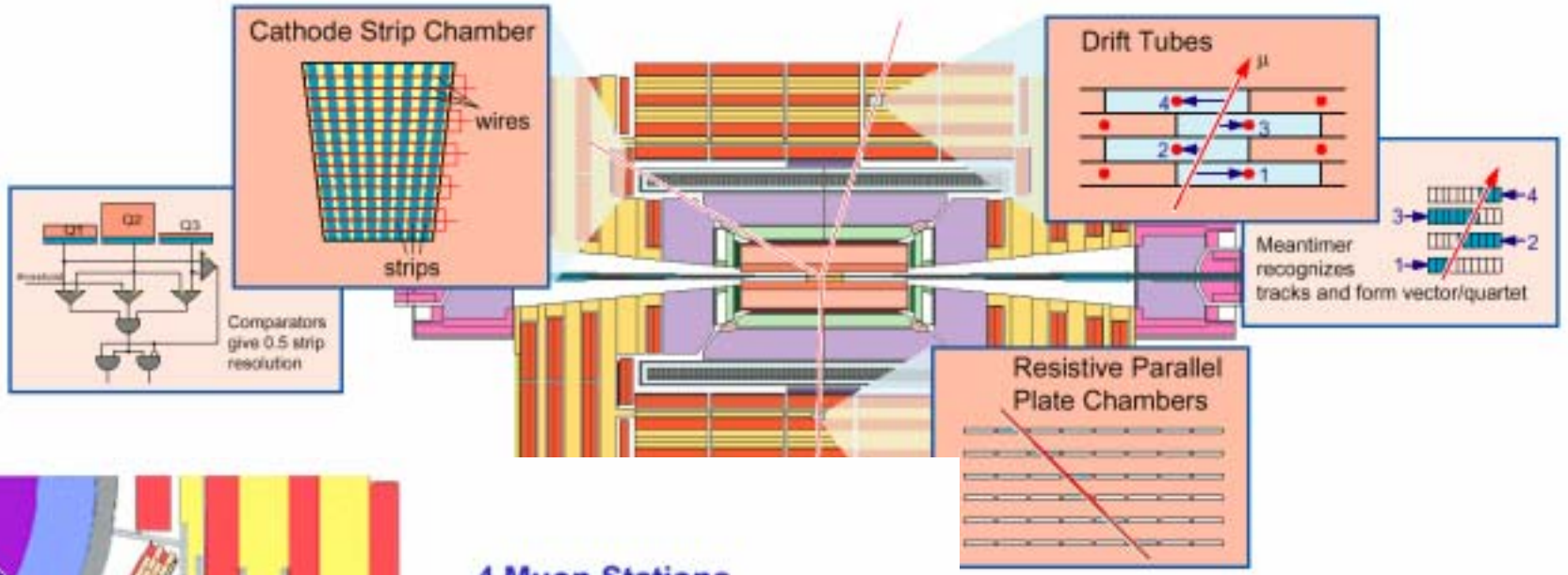


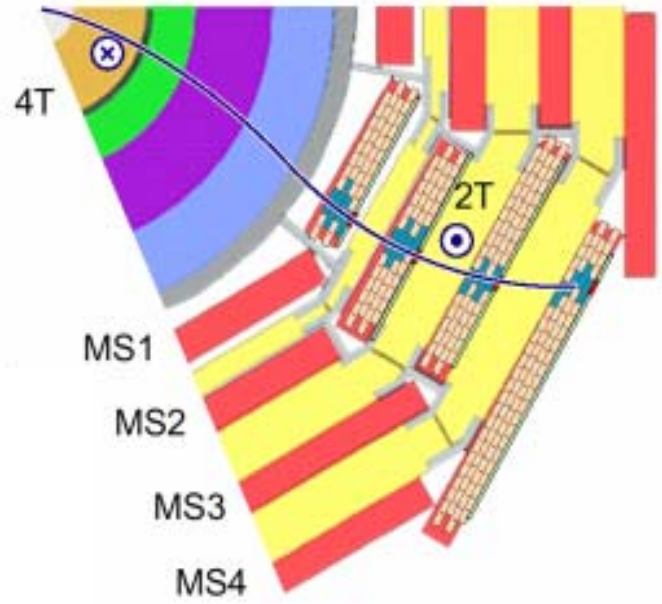
The muon spectrometer resolution dominates for $p_T > 100$ GeV/c



Resolution limited by :
m.m. and Energy Loss Fluct. @ 3%
for $10 < p_T < 250$ GeV/c
Chamber Resolution and Alignment
for $p_T > 250$ GeV/c

CMS Muon Detectors



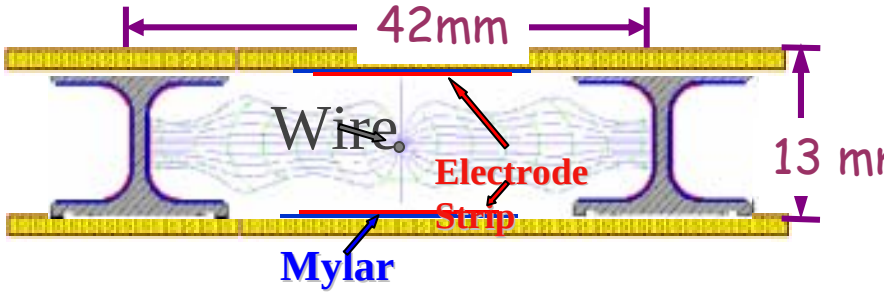


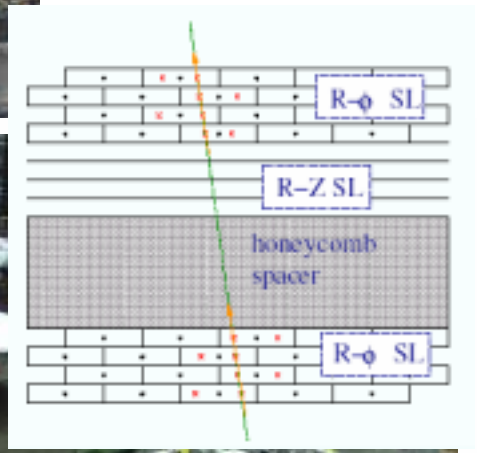
4 Muon Stations
redundancy
acceptance

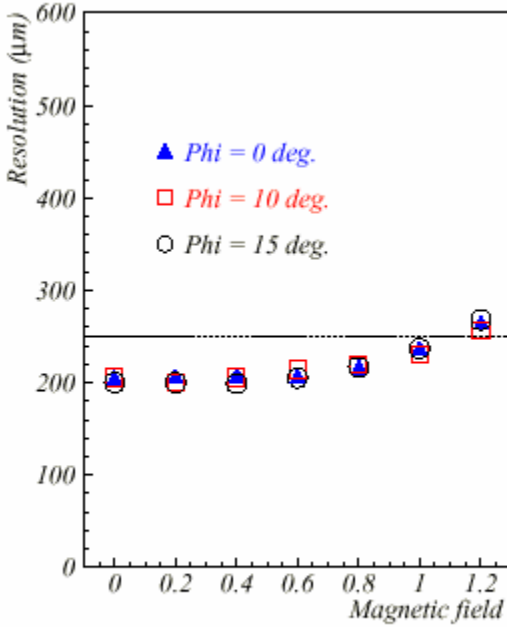
Per Station
barrel – 12 measuring planes
endcap – 6 measuring planes

Measurement Accuracy
position 70 – 100 μm /station
direction ~ 1 mrad

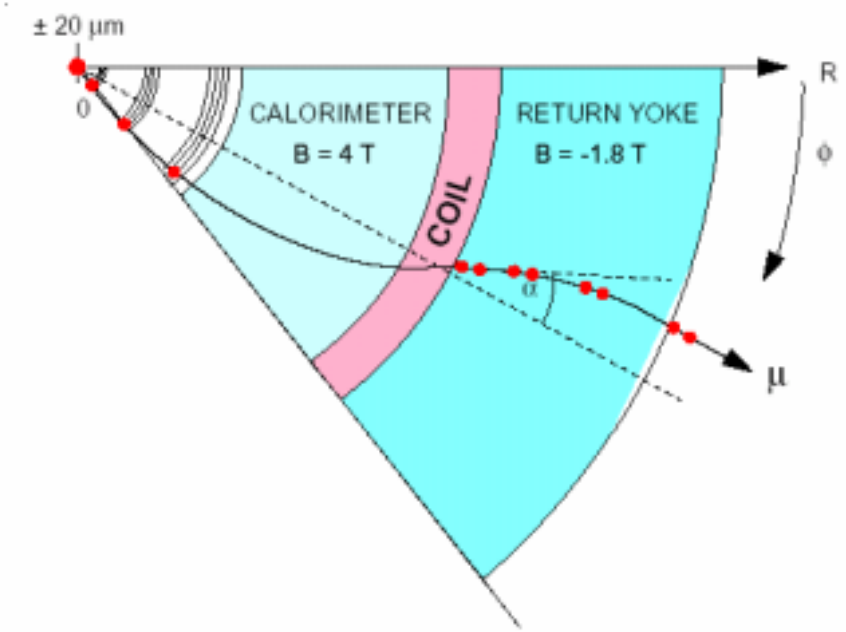
CMS Muon System: Drift Tubes







CMS Muon System: Performance

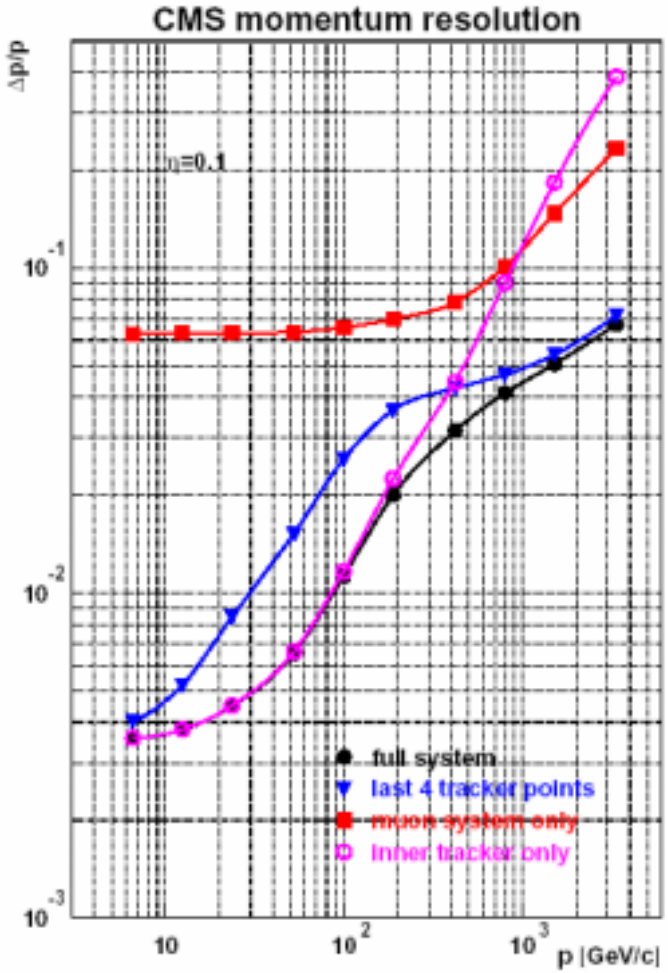


Tracking in Magnetized Iron (CMS)
(in multiple scattering dominated regime)

$$\frac{\Delta p}{p} \approx \frac{40\%}{B\sqrt{L}}$$

B~1.8T, and L ≈ 1.5 m
BUT measurement is much better !

p resolution worsens at |η| > 1.5



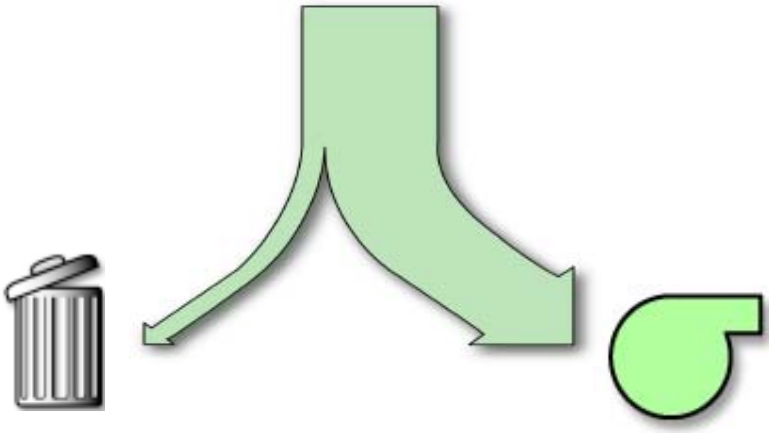
From LEP to LHC

Trigger&DAQ at LEP
- Event Size ~ 10^5 Bytes
- Event Rate ~ Hz
- **Event Selection ~ 10^{-1}**

10
10^4
10^{-3}

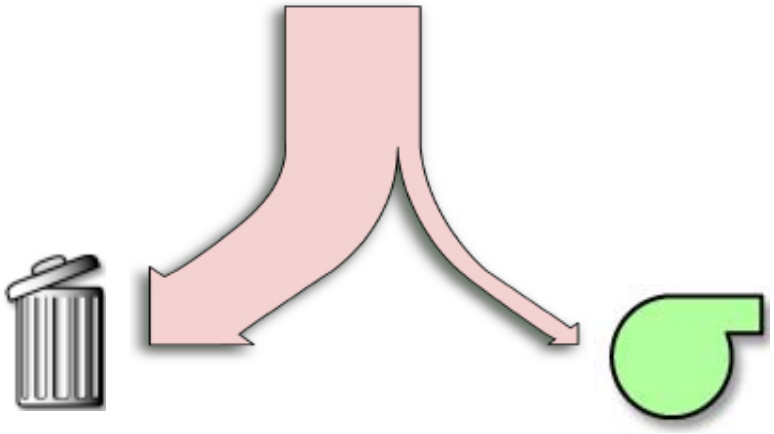
Trigger&DAQ at LHC
- Event Size ~ 10^6 Bytes
- Event Rate ~ 10^5 Hz
- **Event Selection ~ 10^{-4}**

100 % Level-1



0.1% Rejected **99.9 % Accepted**

100 % Level-1

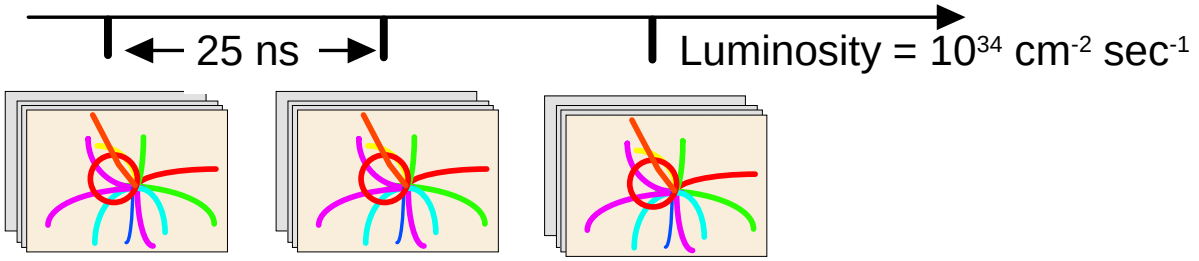


99.9% Rejected **0.1 % Accepted**

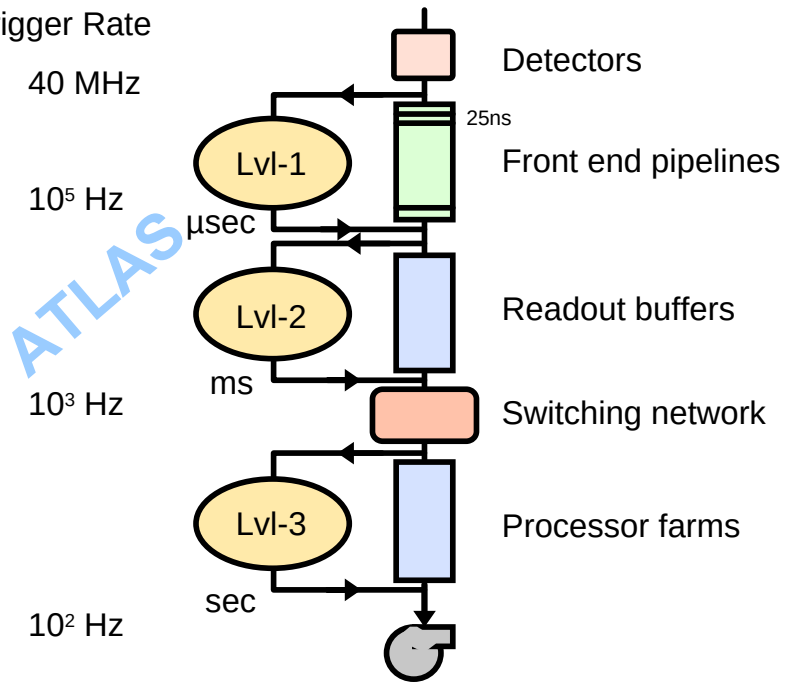
Trigger Architectures

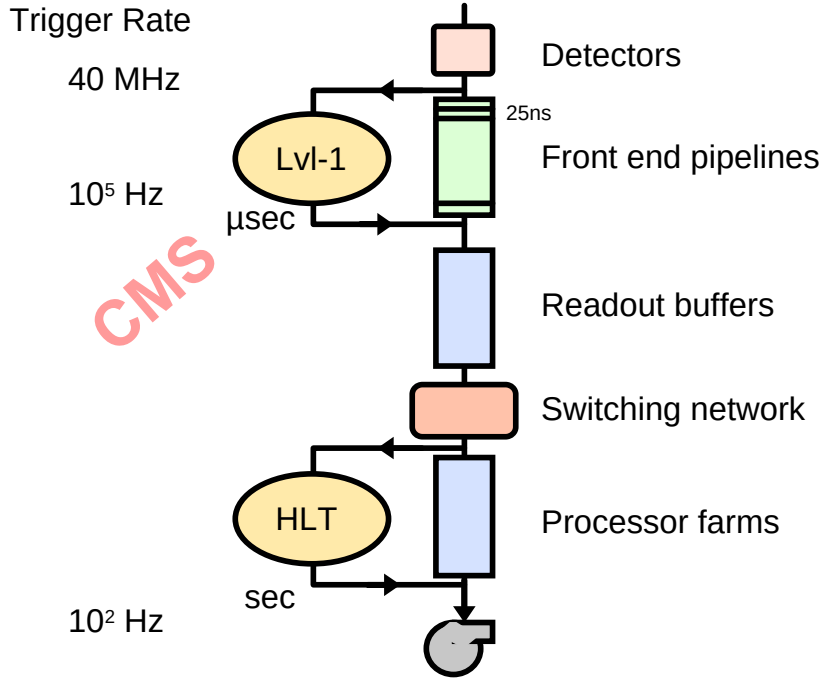
- 30 Collisions/25ns
10 9 event/sec)

10⁷ channels
10 16 bit/sec)



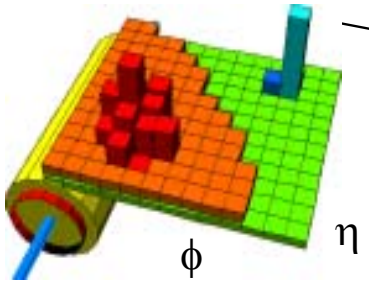
Multilevel trigger and readout systems



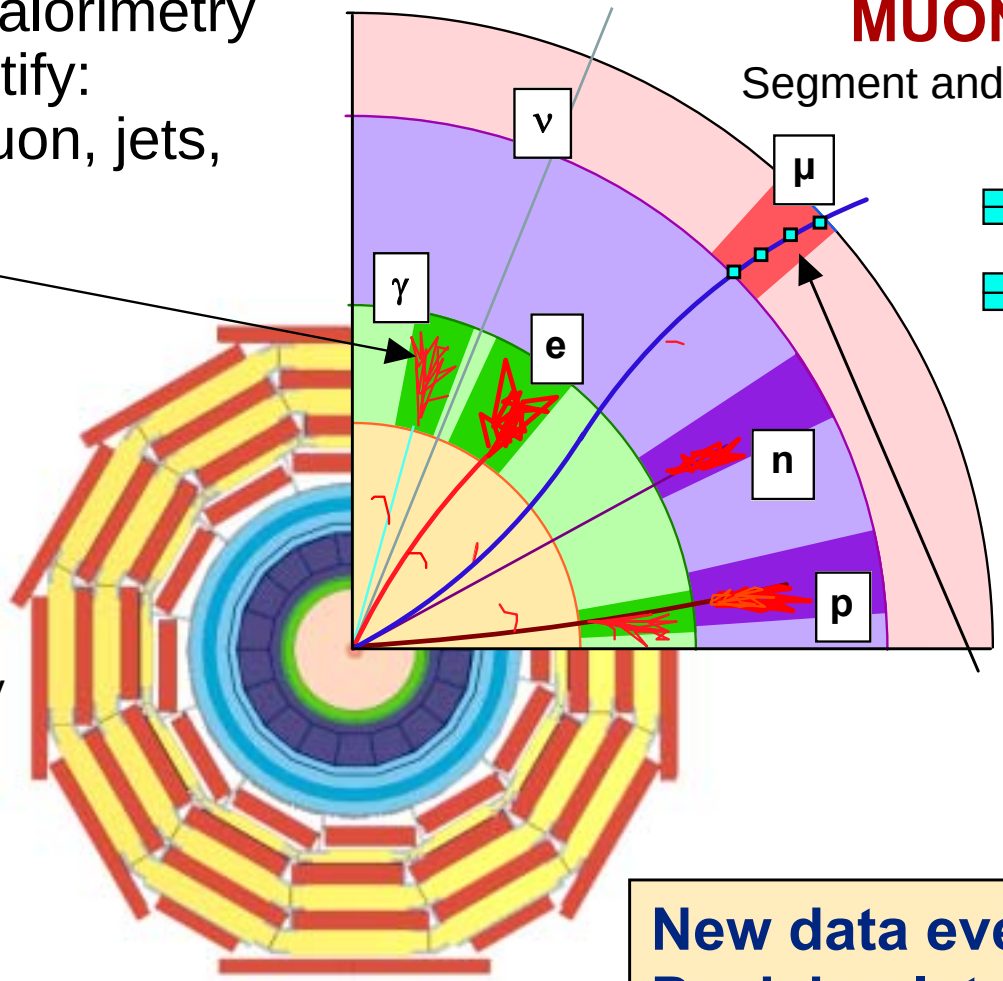


Level-1 Trigger

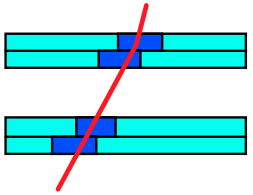
Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



CALORIMETERs
Cluster finding and energy deposition evaluation



MUON System
Segment and track finding



New data every 25 ns
Decision latency ~ μs

Level-1 Trigger Rates

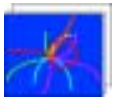
	e	ee	τ	ττ	j	jj	jjj	jjjj
Low $\mathcal{L}$	24	18	95	75	150	115	95	75
High $\mathcal{L}$	35	20	180	110	285	225	125	105
	τe	je	MET	e+MET	j+MET	e(NI)	ee(NI)	ΣET
Low $\mathcal{L}$	80,14	125,14	275	12,175	65,175	NA*	NA*	1000
High $\mathcal{L}$	125,20	165,20	350	18,250	95,250	58	28	1500
	μ	μμ	μe	μτ	μj	μ+ET	μ+MET	Rate:
Low $\mathcal{L}$	10	3	4,12	4,80	4,80	4,600	4,140	25 kHz
High $\mathcal{L}$	25	8,5	5,32	5,140	5,155	5,800	5,200	25 kHz

75 kHz x 33% safety factor = 25 kHz target for simulated rates
Threshold is defined as either 95% (e/γ, τ, j) & 90% (MET, μ) efficiency

Physics efficiencies

Channel	10^{33}	10^{34}
H(200)→ττ→*hadrons*	0.93	0.60
H(500)→ττ→*hadrons*	0.99	0.86
H(170)→*eeee*	1.00	0.99
H(110)→γγ	0.99	0.98
H(135)→ττ→*e, hadron*	0.96	0.72
H(200)→ττ→*e, hadron*	0.96	0.74
H(120)→*Invisible (tag j)*	0.96	0.58
tt →e, X	0.97	0.82

Data Acquisition

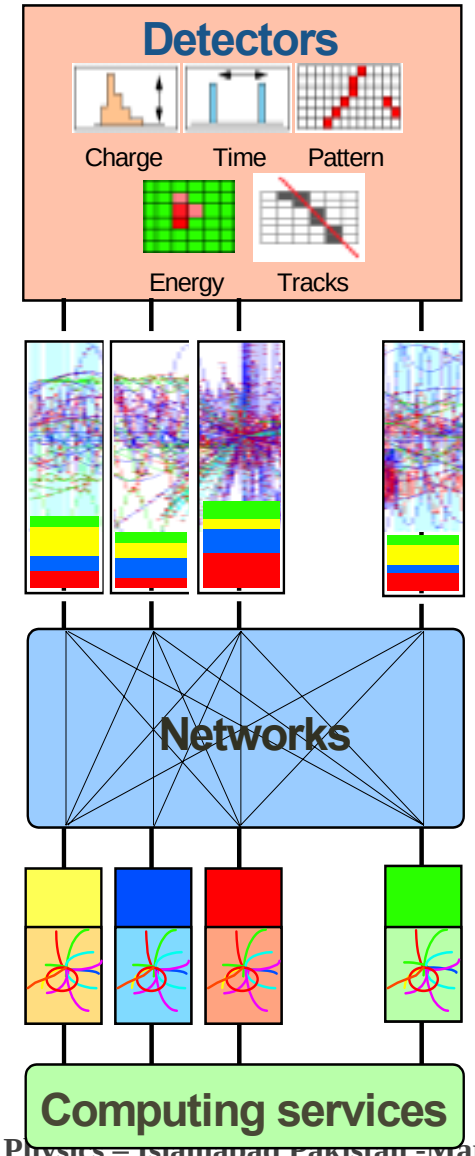


40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s



Gigabit/s SERVICE LAN

16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

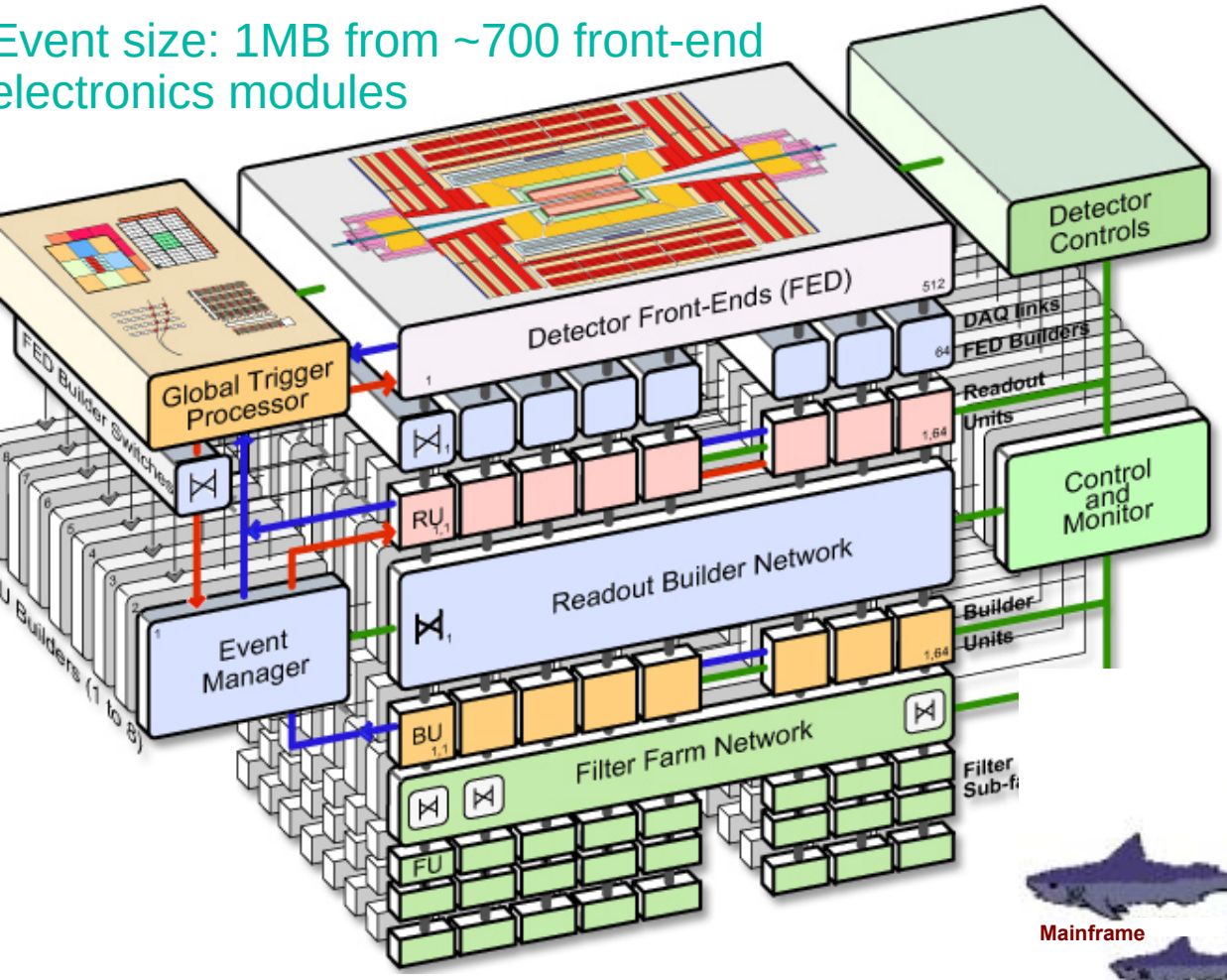
5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

CMS Event Builder

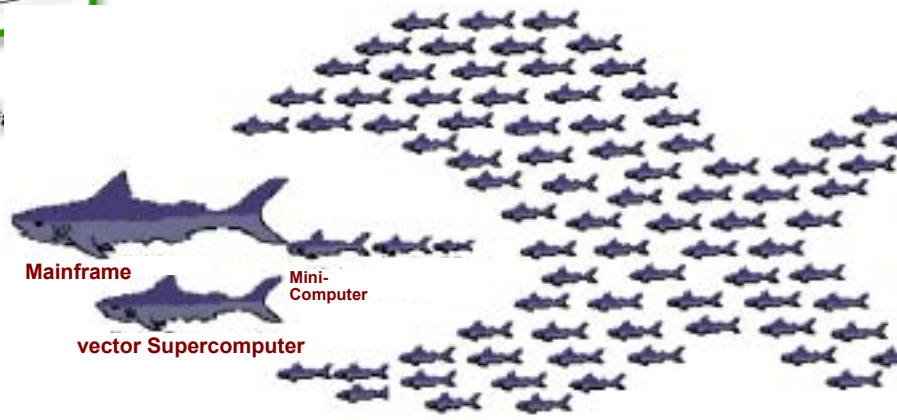
Event size: 1MB from ~700 front-end electronics modules



DAQ designed to accept Level-1 rate of 100kHz
Modular DAQ: 8 x 12.5kHz u

HLT designed to output $O(10^2)$Hz
– rejection of 1000

~1000 processor units



CMS HLT Summary

Physics object	CPU time (ms/Level-1)	Level-1 rate (kHz)	Total CPU time (s)
Electrons/photons	*160*	*4.3*	*688*
Muons	*710*	*3.6*	*2556*
Taus	*130*	*3.0*	*390*
Jets and E_T^{miss}	*50*	*3.4*	*170*
Electron + jet	*165*	*0.8*	*132*
b-jets	*300*	*0.5*	*150*

- ***Today: need ~300 ms on a 1GHz Pentium-III CPU***
  - **For 50 kHz, need 15,000 CPUs**
  - **Moore's Law: 2x2x2 times less time (fewer CPUs) in 2007**
    - Central estimate: 40 ms in 2007, i.e. 2,000 CPUs
    - Thus, basic estimate of 1,000 dual-CPU boxes