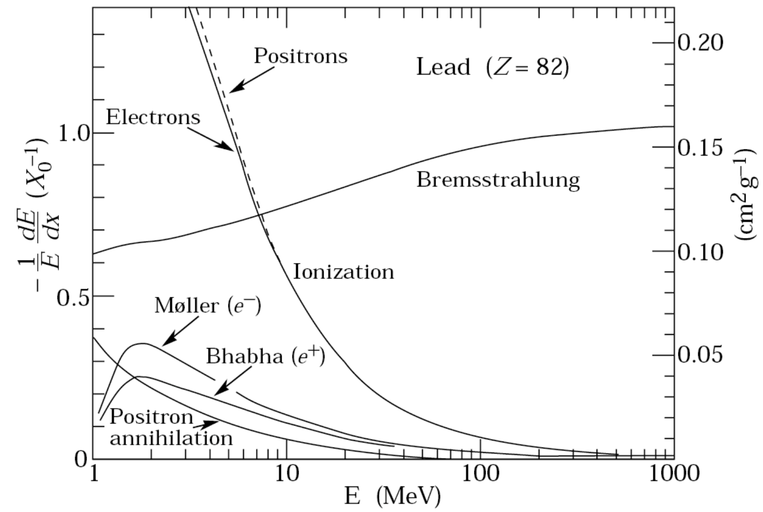
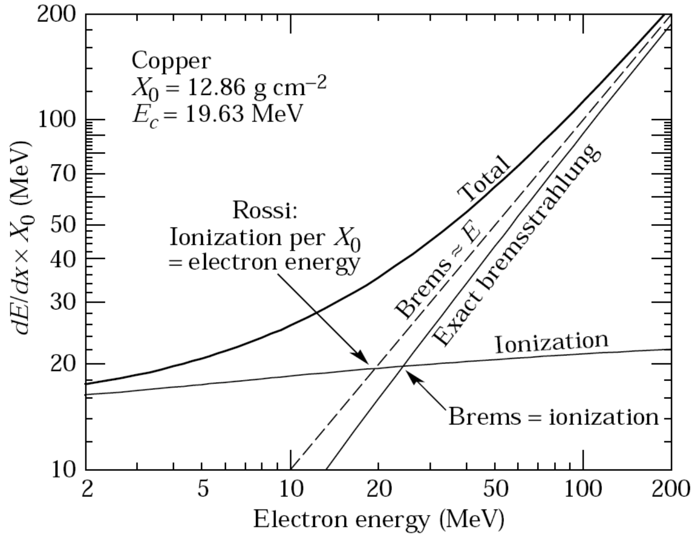
Instrumentation for the LHC

Outline

- What are the requirements for Detectors at the LHC?
  - The physics requirements
  - Coping with the LHC environment
- Particles passing through matter
- Tracking Detectors
- Calorimetry
- Muon Detection
- Detectors for triggering/timing/particle ID
- Preparing for the future - higher luminosity implications

Electron energy loss



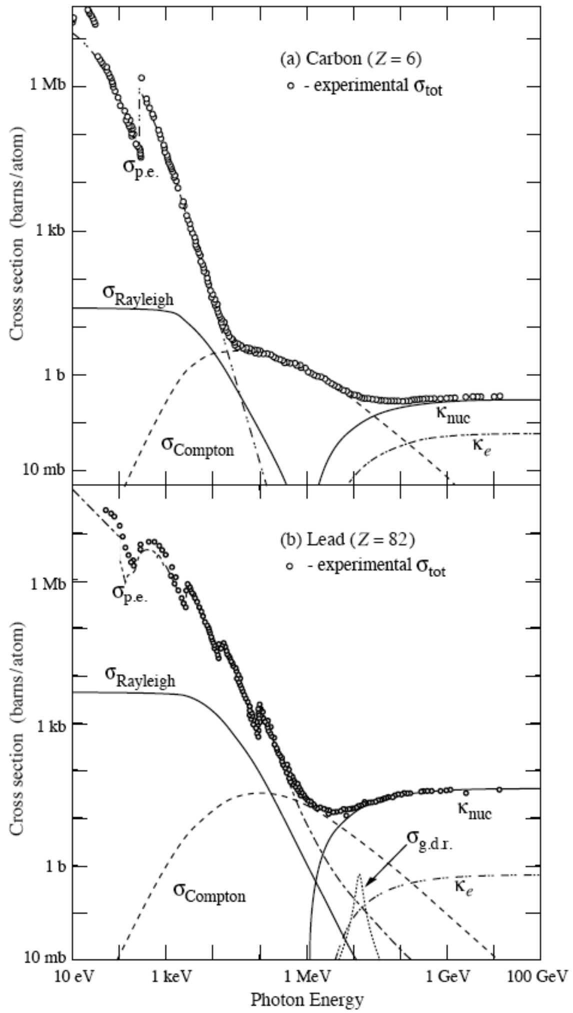


- Bremsstrahlung is the main mechanism for electron energy loss at energies above about 10 MeV
  - (Compare 400 GeV for Muons)
- Critical Energy
  - Where the ionization loss equals the loss from Bremsstrahlung

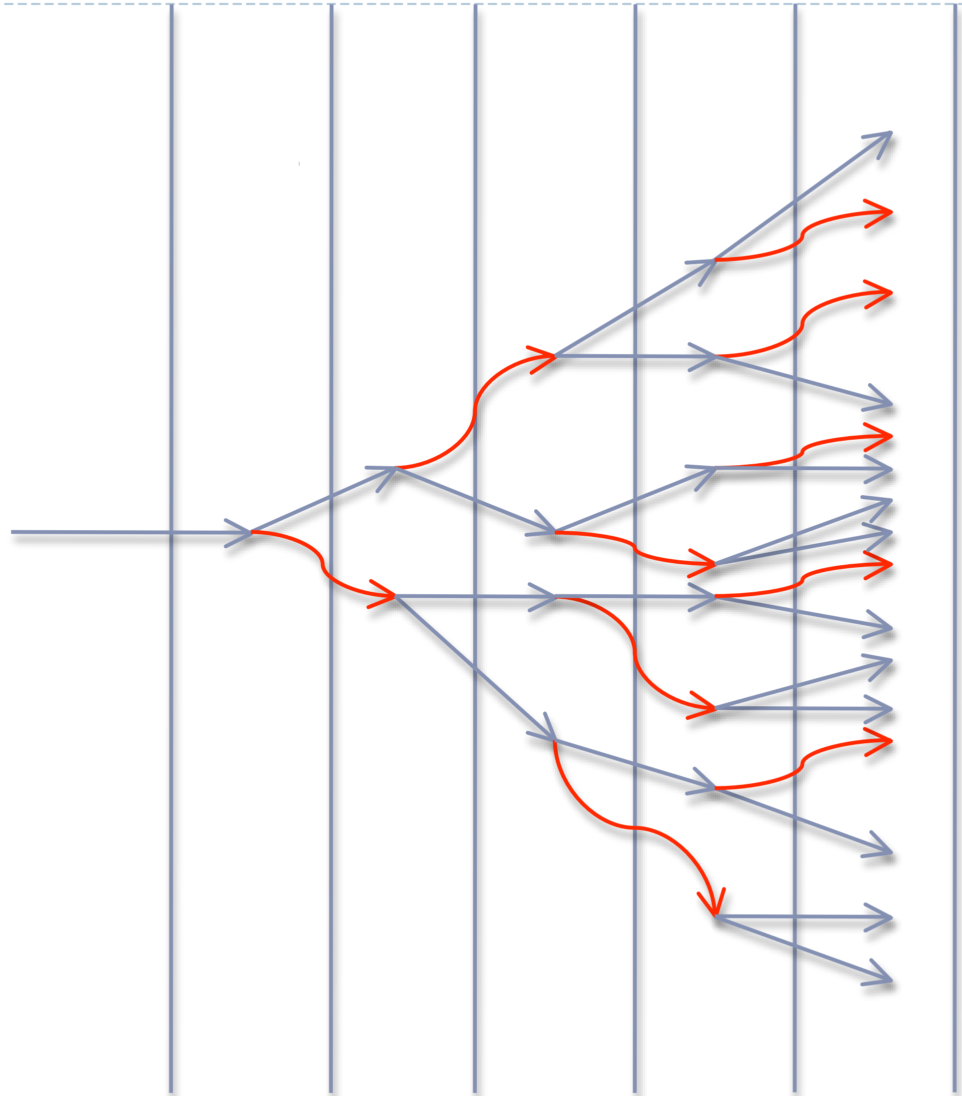
Photon Energy Loss

- For Photons, pair creation in the field of the nucleus is the dominant mechanism for energy loss at energies above an MeV.
- Compton scattering, then Rayleigh (and finally the photo-electric effect) dominate at lower energies

$$\sigma_{pair-creation} = \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$



Electromagnetic Showers



Each step t is about 1 X_0

The Number of particles grows ~ as 2^t

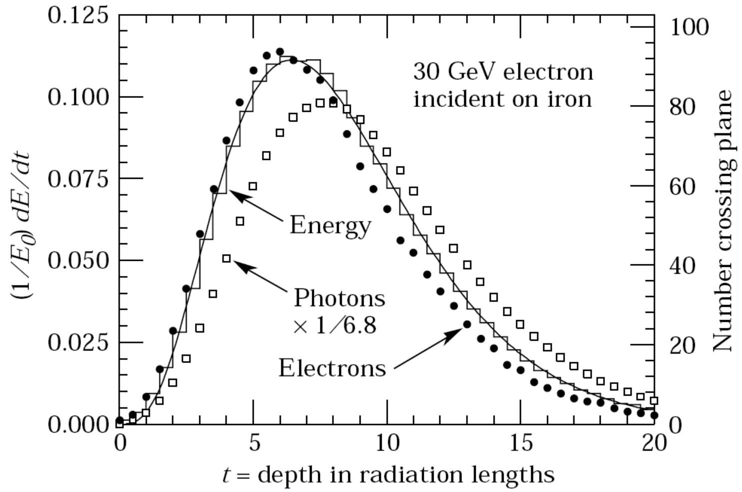
Particle $E(t) \sim E_0/2^t$

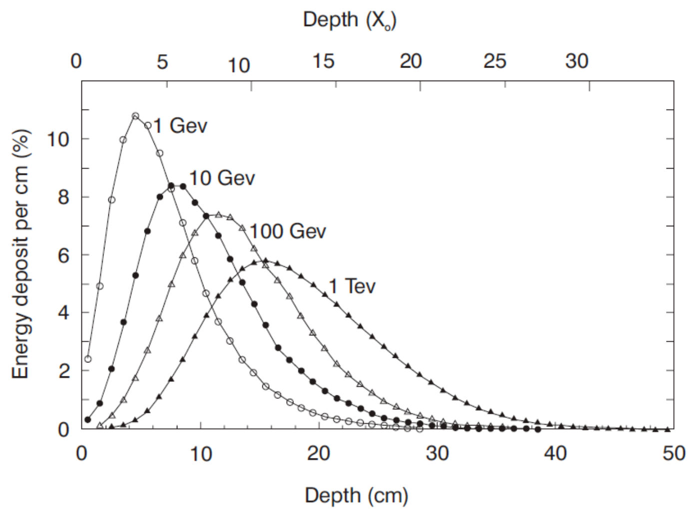
When $E(t)<E_c$ the number of particles starts to decrease

The Shower Maximum occurs when $t \sim \ln(E_0/E_c)$

Electromagnetic Shower development

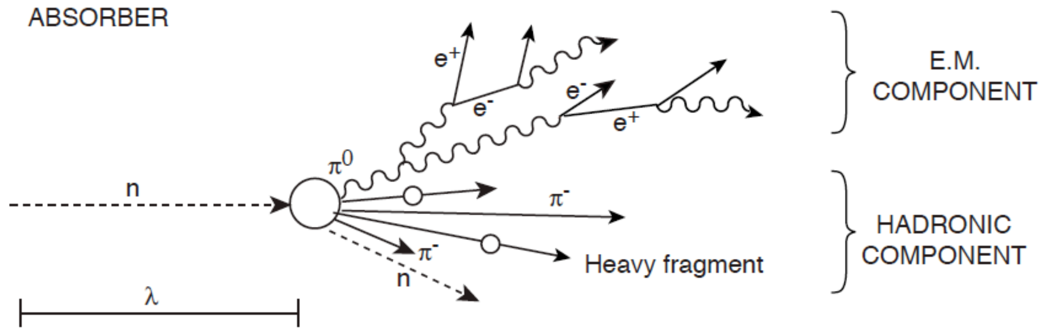
- Electromagnetic showers will deposit nearly all their energy within ~25 radiation lengths (at LHC energies)
  - Lower energy photons/electrons require much less depth
- Energy deposition tends to be relatively uniform for a given energy particle
  - Longitudinal and lateral shower profiles are clear signals of EM showers
- Lateral shower development characterized by the moliere radius
  - $R_m \sim 21 \text{ MeV } X_0/E_c$
  - Tends to be a few cm EM showers are narrow

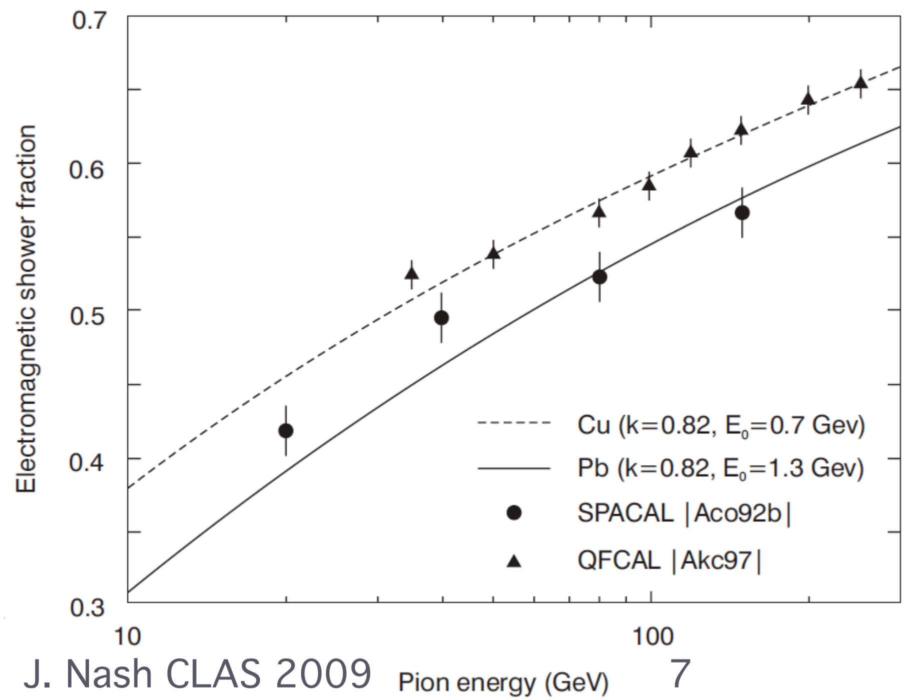




Hadronic Showers

- Most of the particles which come from the IP are pions
- π^0's will decay to two photons which are then seen as EM showers
- Charged pions have a relatively small energy loss by ionization
- Hadrons however can undergo nuclear interactions
  - About 1/3 of these will produce π^0's which then are quickly absorbed
    - Secondary charged pions can undergo further interactions which causes the EM fraction to rise for higher energy hadrons
  - Can also knock out protons which are more heavily ionizing
  - Energy can be lost in breaking up bound Nuclei
- Hadronic calorimeters have intrinsically non-linear responses to hardron energy

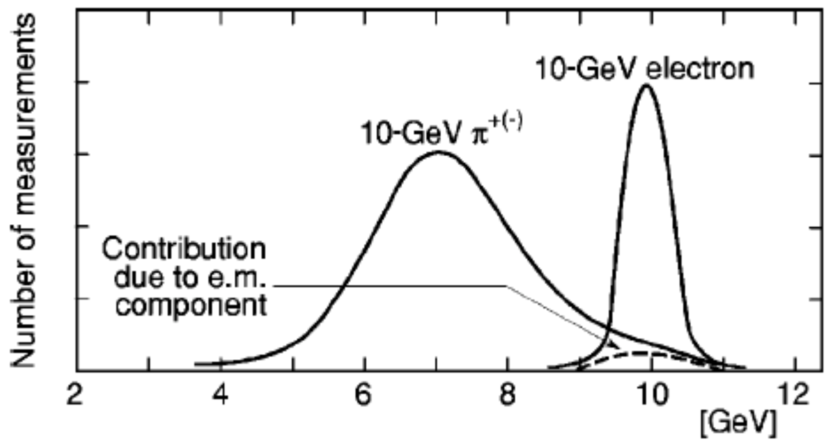




Interaction Length

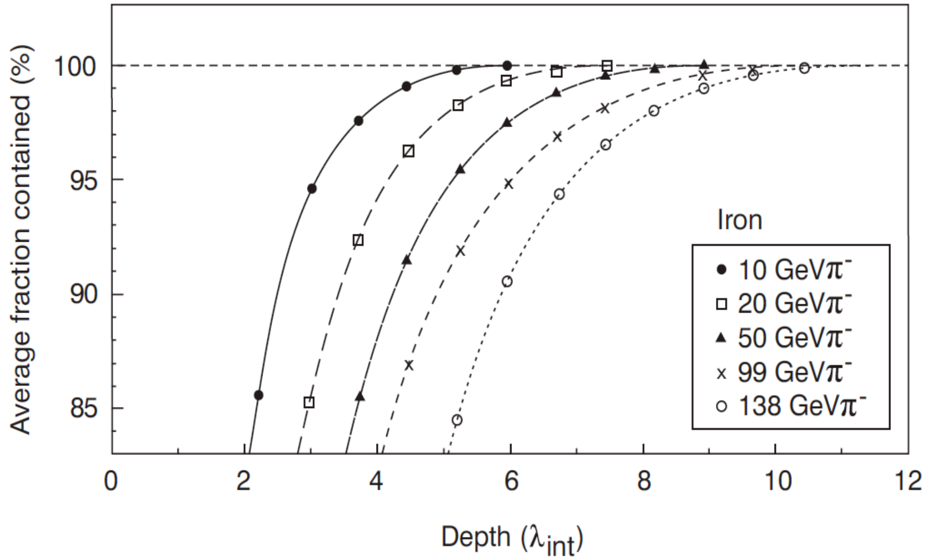
	Z	ρ g.cm^{-3}	I/Z eV	$(1/\rho)dT/dx$ MeV/g.cm^{-3}	ε MeV	X_0 cm	λ_{int} cm
C	6	2.2	12.3	1.85	103	$\approx$ 19	38.1
Al	13	2.7	12.3	1.63	47	8.9	39.4
Fe	26	7.87	10.7	1.49	24	1.76	16.8
Cu	29	8.96		1.40	$\approx$ 20	1.43	15.1
W	74	19.3		1.14	$\approx$ 8.1	0.35	9.6
Pb	82	11.35	10.0	1.14	6.9	0.56	17.1
U	92	18.7	9.56	1.10	6.2	0.32	10.5

- Characteristic lengthy over which a hadronic interaction will occur is λ similar to the radiation length for EM showers
- Interaction lengths tend to be much longer than radiation length for the same material
- Hadronic showers are much less uniform in their development than electromagnetic showers

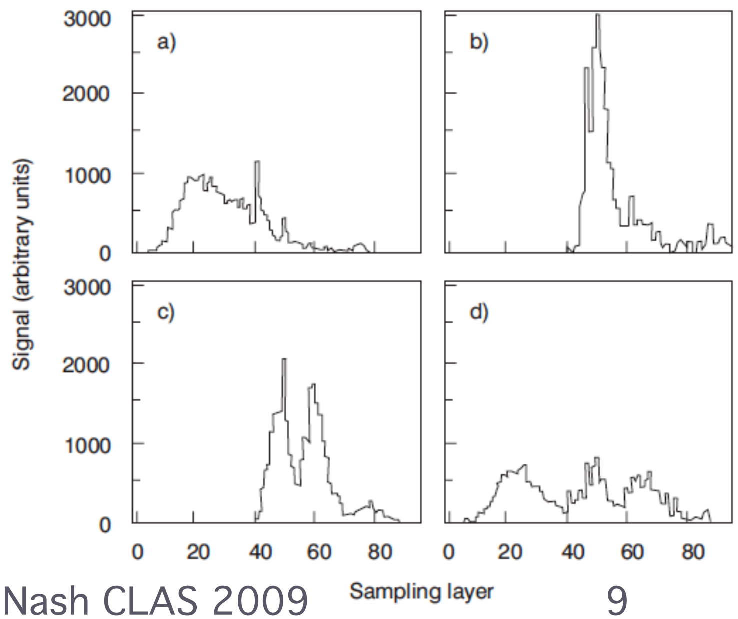


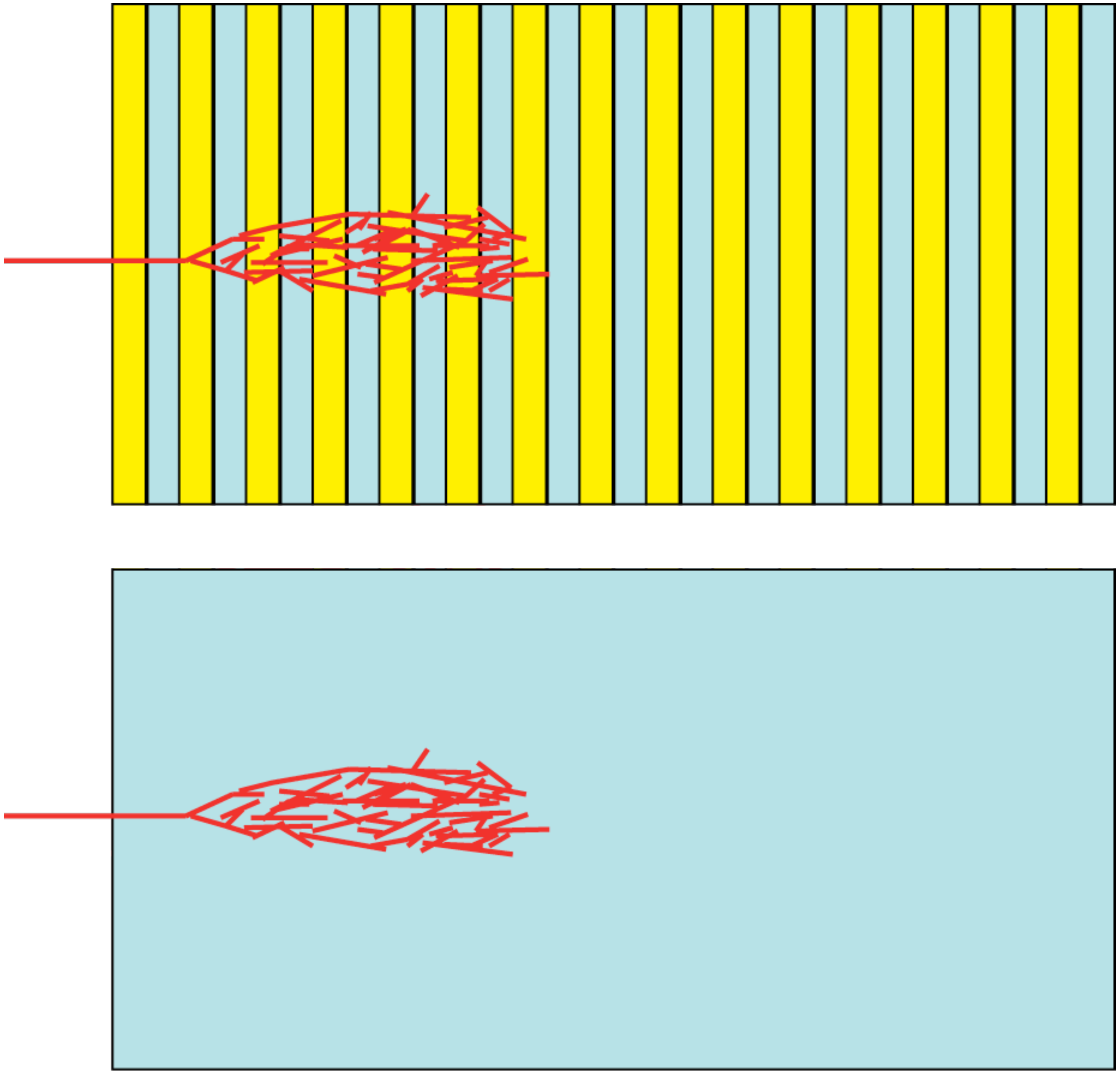
Signal (in energy units) obtained for a 10 GeV energy deposit

Hadronic shower development



- Hadron energy mostly contained in 8-10 interaction lengths
  - Note λ in Iron is ~ 17 cm
- Shower profiles are very non-uniform





Calorimetric measurements

Sampling Calorimeters

Mix layers which can detect energy deposited and passive layers which act as absorbers. Not all energy is detected

Homogenous Calorimeters

Absorber material is also the detecting material

All energy deposited in the calorimeter is detected

Comparing Sampling and Homogenous calorimeter performance

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

Stochastic Term – Depends on Signal fluctuations

Noise Term – determined by the electronics noise in the system and background

Constant Term – determined by the construction of the system – leakage of energy calibration errors, non-linearity

	Z	ρ g.cm^{-3}	I/Z eV	(1/ρ)dT/dx MeV/g.cm^{-3}	ε MeV	X_0 cm	λ_{int} cm
C	6	2.2	12.3	1.85	103	≈ 19	38.1
Al	13	2.7	12.3	1.63	47	8.9	39.4
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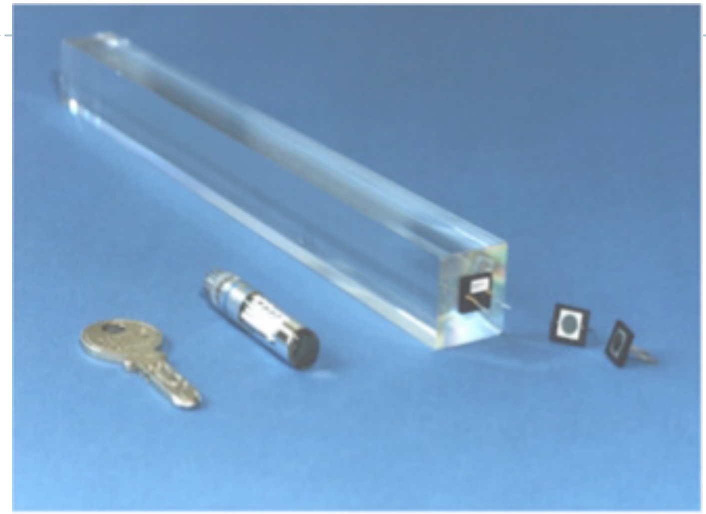
$$\frac{\sigma_s}{E} = \frac{5\%}{\sqrt{E}}\left(1 - f_{samp}\right)\ \Delta E_{cell}^{0.5\left(1-f_{samp}\right)}$$

$$f_{samp} = 0.6 f_{mip} = 0.6\,\frac{d\left(\frac{dE}{dx}\right)_{act}}{\left[d\left(\frac{dE}{dx}\right)_{act} + t_{abs}\left(\frac{dE}{dx}\right)_{abs}\right]}$$

Sampling calorimeters will have a larger stochastic term, and they measure only a fraction of the energy deposited in the calorimeter

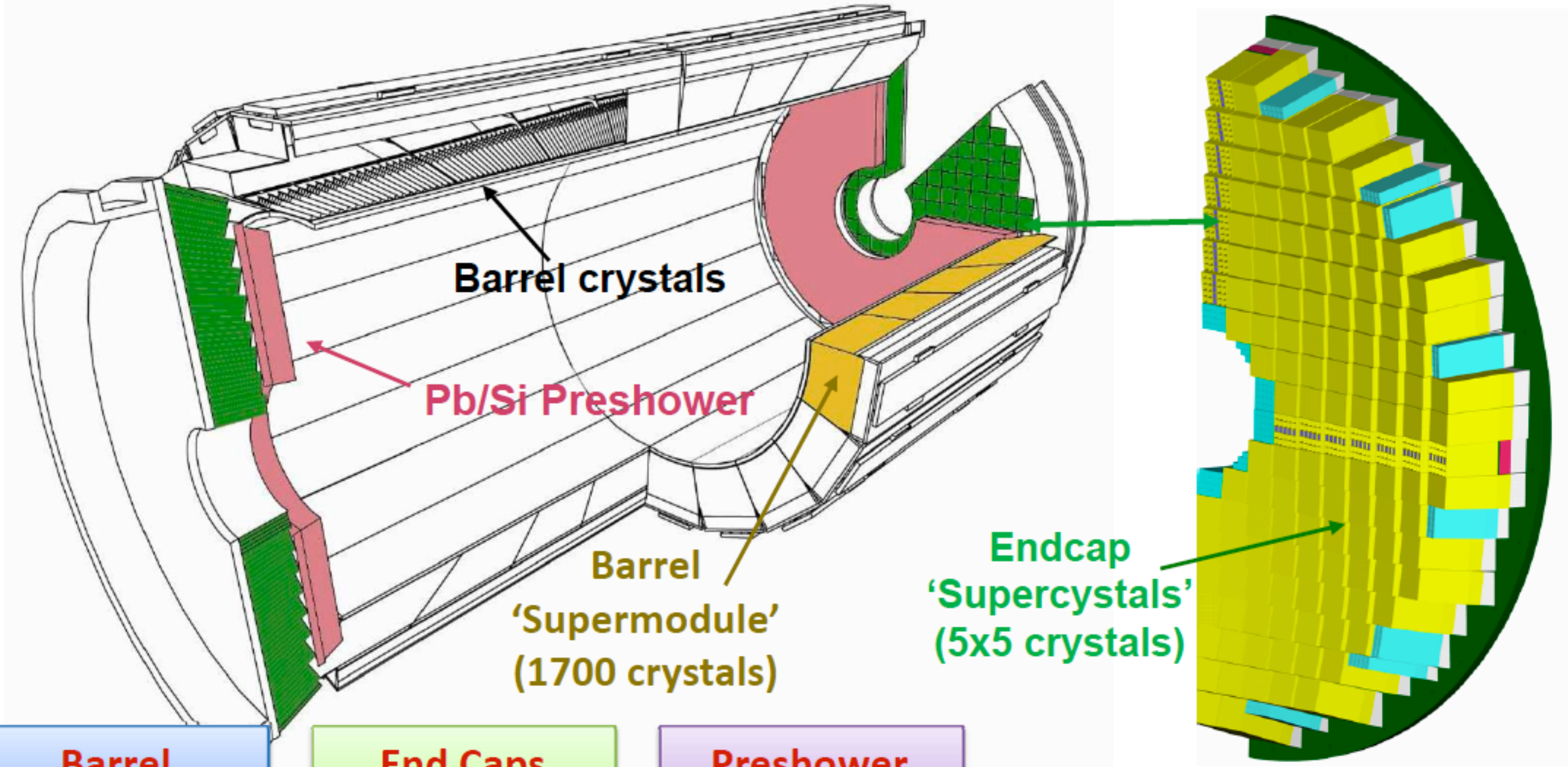
CMS Crystal EM calorimeter

- Crystal calorimeters absorb all EM shower energy and re-emit as scintillation photons
- Photons are collected at the ends of the crystal
- For LHC require crystal with fast response, high density, tolerance to high radiation levels
  - Lead Tungstate was chosen
- Crystals are cut to be about 1 R_m in size
  - EM energy is contained in only a few crystals
    - >95% in 9 crystals
    - Can cluster up to 25 crystals to try to catch all the shower energy
  - Search for small dense clusters of energy in the crystals
    - Can separate EM from Hadronic showers



property	NaI(Tl)	BGO	CsI(Tl)	$PbW0_4$
Density ($g\ cm^{-3}$)	3.67	7.13	4.53	8.28
X_0 (cm)	2.59	1.12	1.85	0.89
R_m (cm)	4.5	2.4	3.8	2.2
Decay Time (ns)	250	300	1000	10
Rel. Light Output	1.00	0.15	0.40	0.01

Calorimeter Construction



Barrel	End Caps	Preshower
• 61200 crystals • 36 super modules • $\lvert\eta\rvert < 1.48$ • ~ 26 X_0	• 14648 crystals • 4 Dees • $1.48 < \lvert\eta\rvert < 3$ • ~ 25 X_0	• Pb/Si • $1.65 < \lvert\eta\rvert < 2.6$ • 3 X_0

Life time:	• ~10 years
Maintenance:	• zero

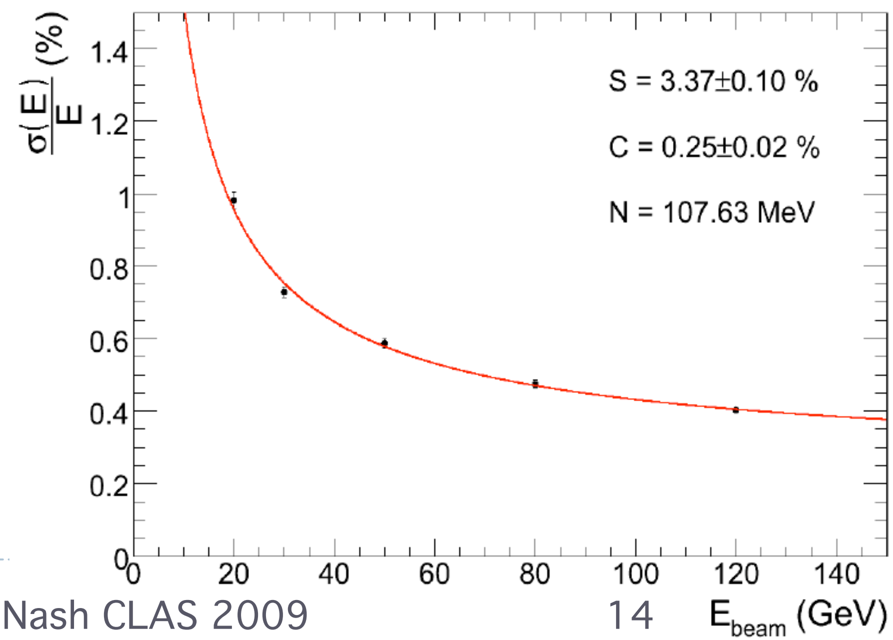
Performance of Crystal Calorimeter

- Crystal Calorimeters deliver extremely good energy resolution
- Need to control many things to achieve the best resolution
  - dead material between crystals
  - Electronics noise
  - Temperature stability
  - ...
- Difficult to get longitudinal shower information

Fluctuations in the shower development and in the measurement of the shower properties dominate the resolution

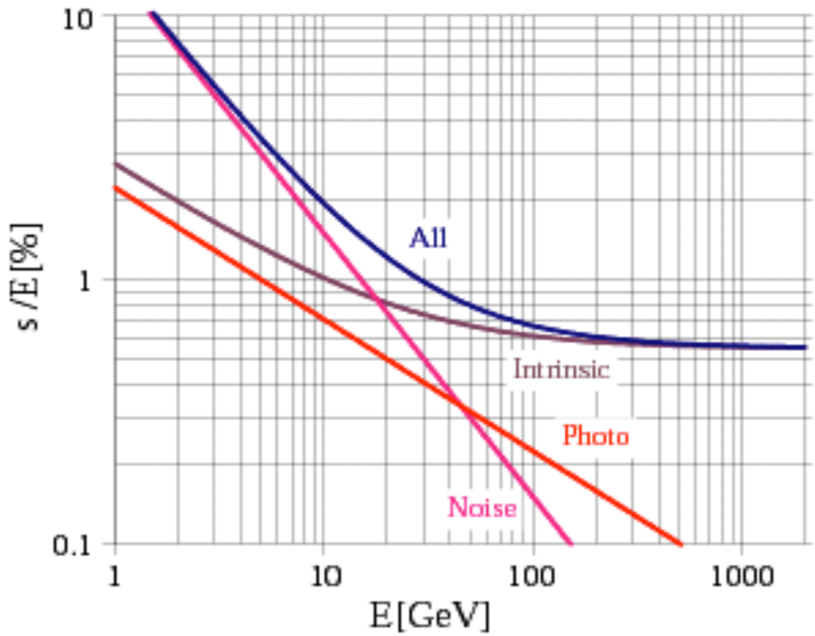
$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

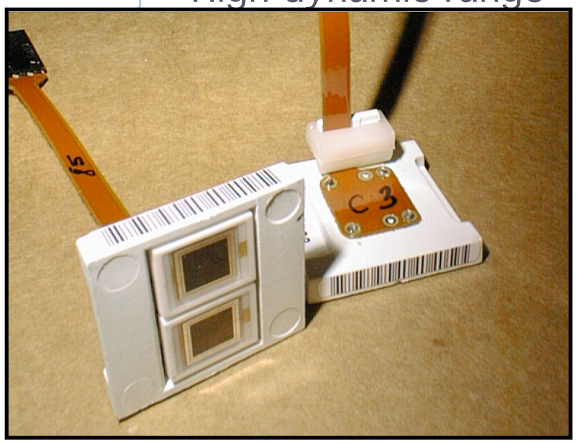
- A (Stochastic) comes from sampling fluctuations
- B (Noise) comes from Electronics and Beam Noise
- C (Constant) comes from Non-uniformity, Calibration errors, shower leakage

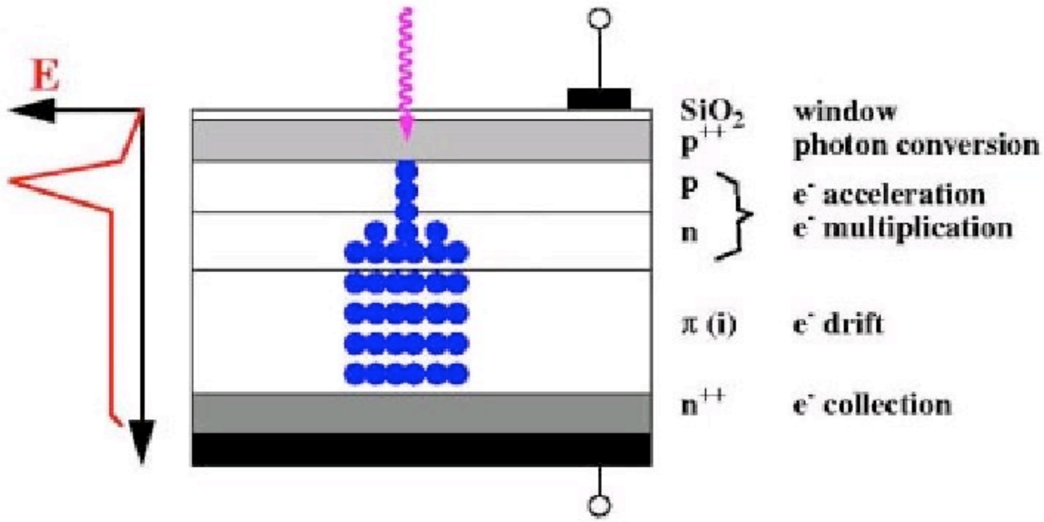


CMS ECAL photo detector

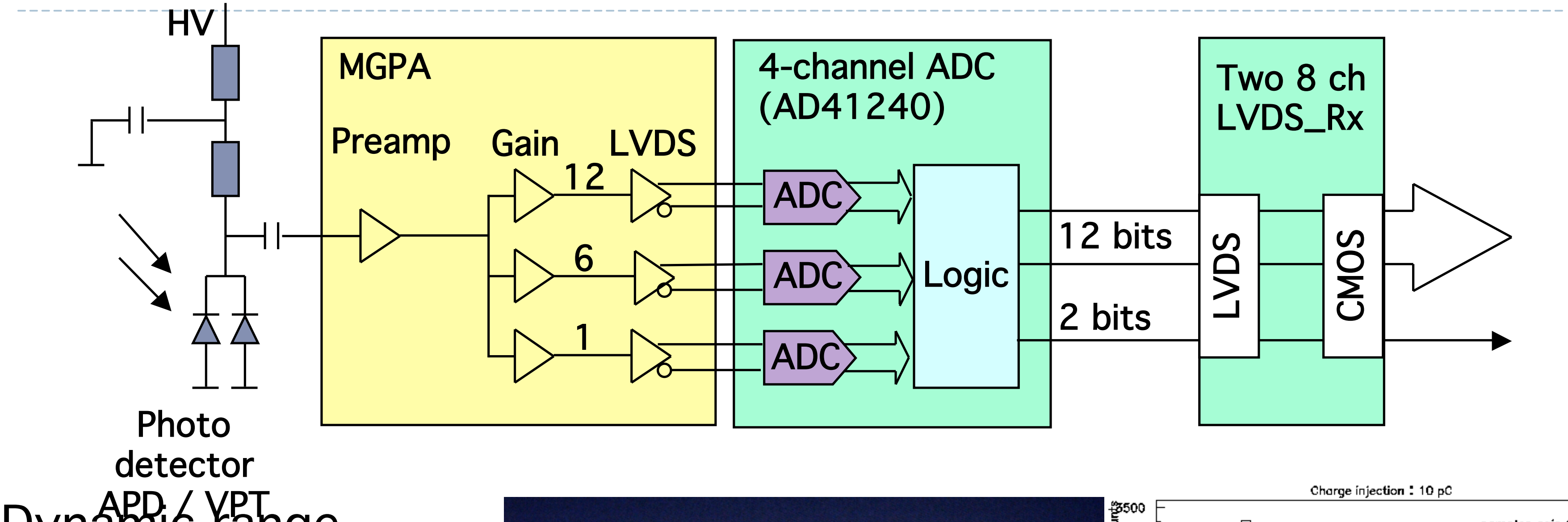
- 80,000 channels of lead tungstate crystal
  - Low light yield - Around 5 pe/MeV
- Avalanche PhotoDiode used in Ecal Barrel
  - Gain 50
- Vacuum Photo Triode used in Ecal Endcap
  - Lower gain
  - Can withstand high magnetic fields in EE
- To achieve the energy resolution electronics needs to have
  - Low noise
    - 50 MeV (8000 e-)
  - High dynamic range



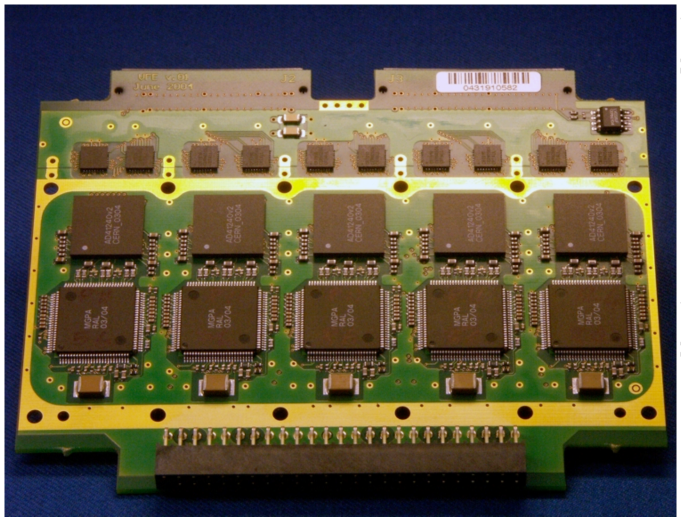


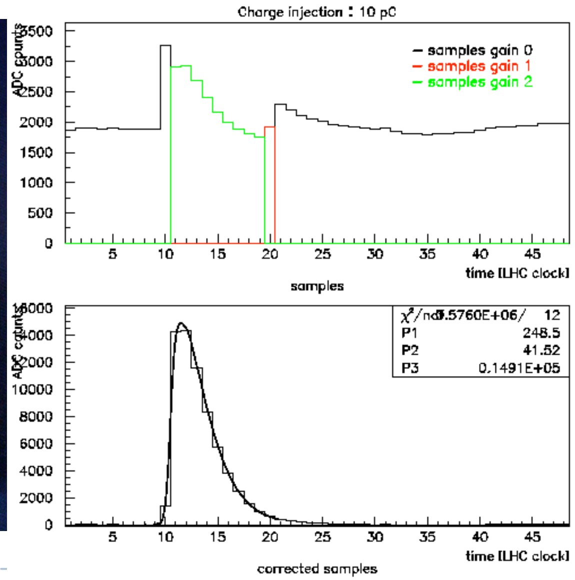


Ecal Very Front End

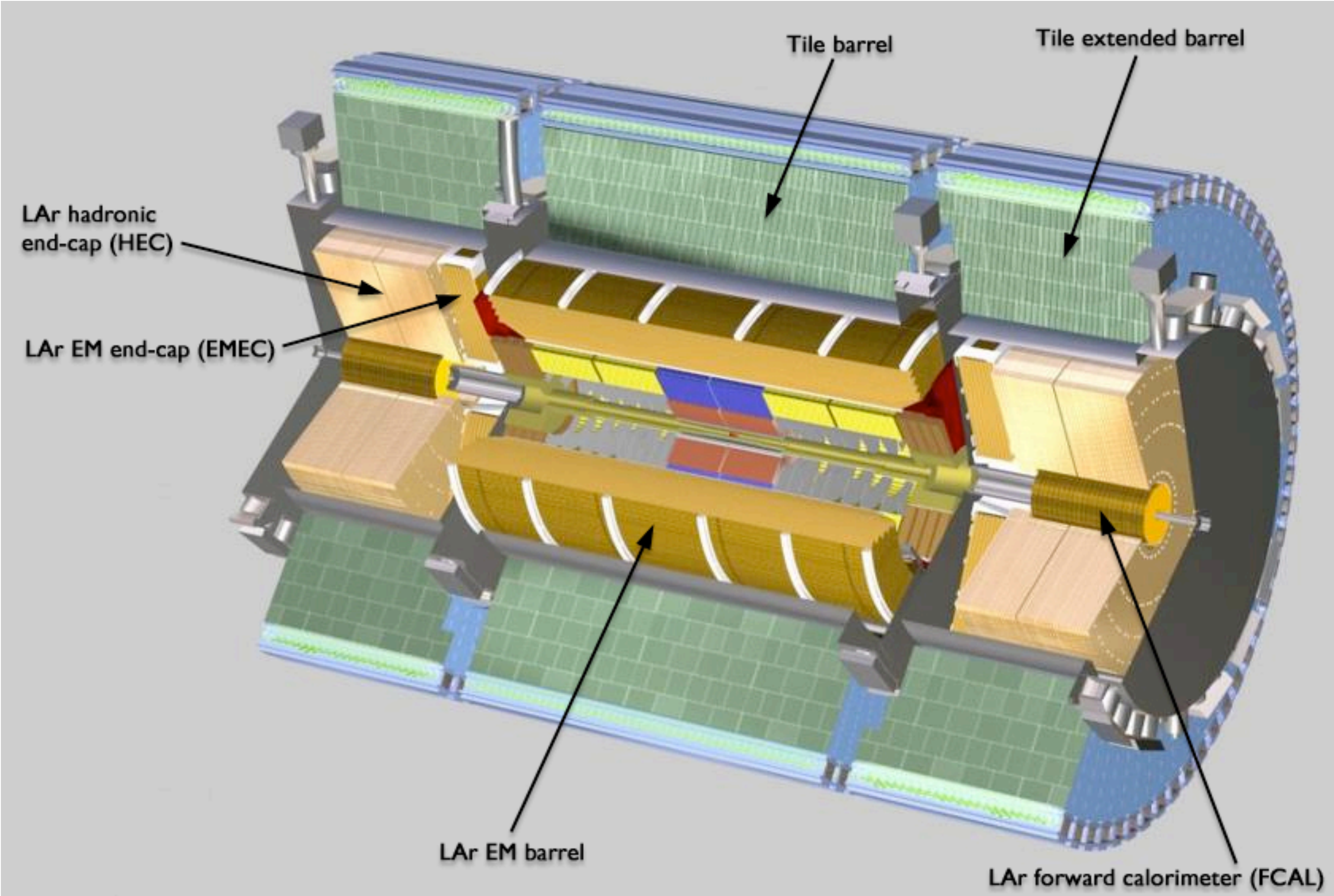


- Dynamic range achieved using multi-gain system
- Three parallel digitization stages
- Digital selection of highest gain non-saturated stage
- Two new custom ASICs in 0.25 μm CMOS



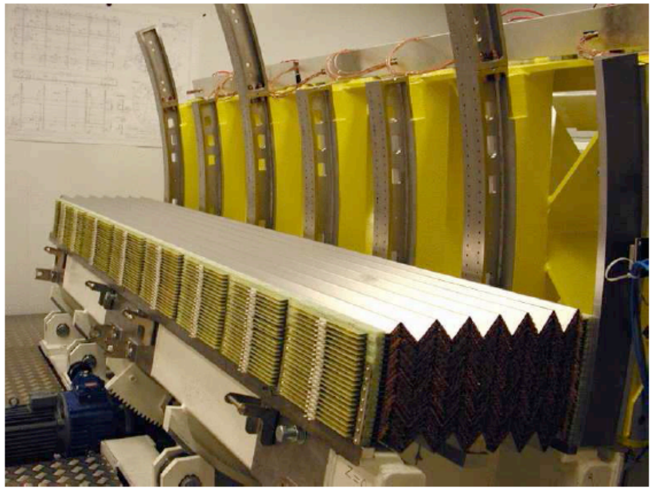


ATLAS Calorimetry



ATLAS Liquid Argon Sampling Calorimeter

- Stacks of Lead (1-2mm) with Liquid Argon gaps of about 4mm in between the lead plates
  - Lead X_0 about 5.5 mm
  - Liquid Ar X_0 14 cm
  - 24 X_0 of lead/LAr
- EM Showers in lead, electrons ionize the LAr and leave a signal which is proportional to the energy deposited
  - Deposited charge is large so no charge multiplication is needed
- Accordion design to avoid dead areas, and cables running through the detection volume
- Resolution is slightly worse than crystals due to sampling fluctuations
  - 10% vs 3% Stochastic Term



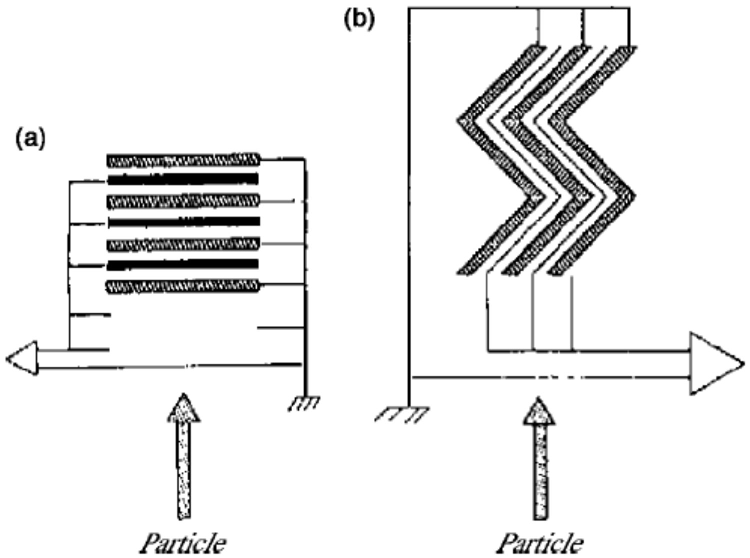
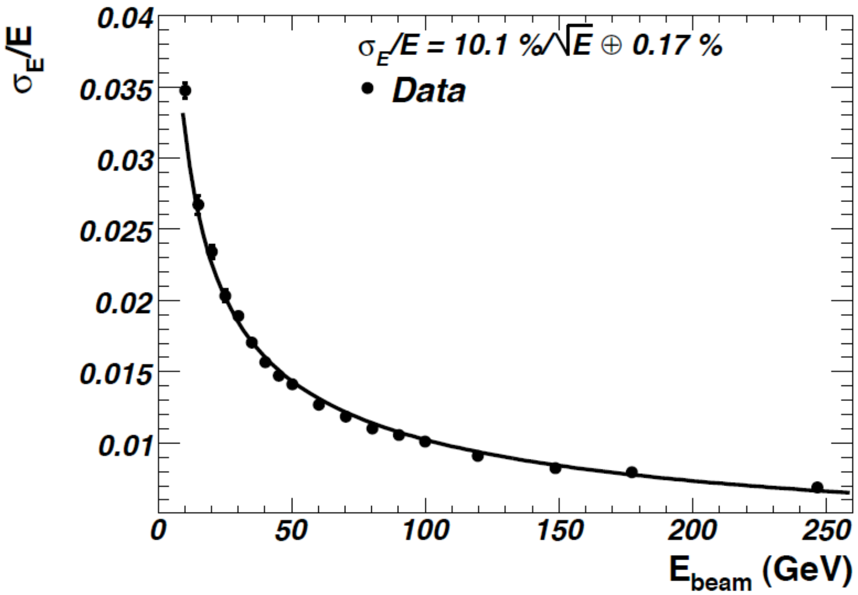
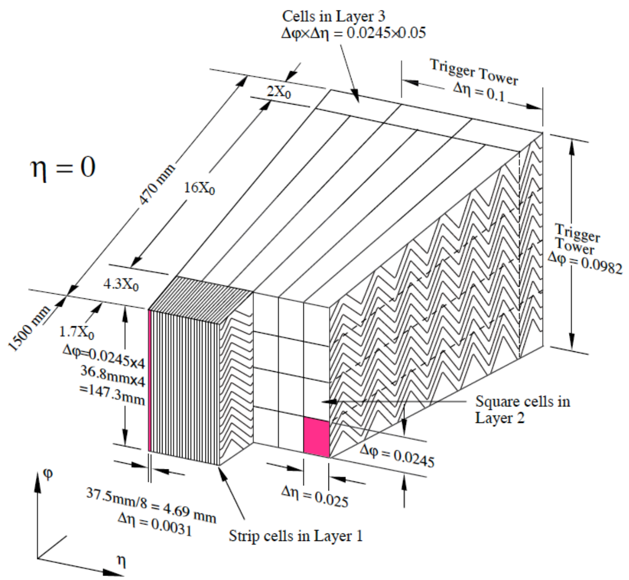
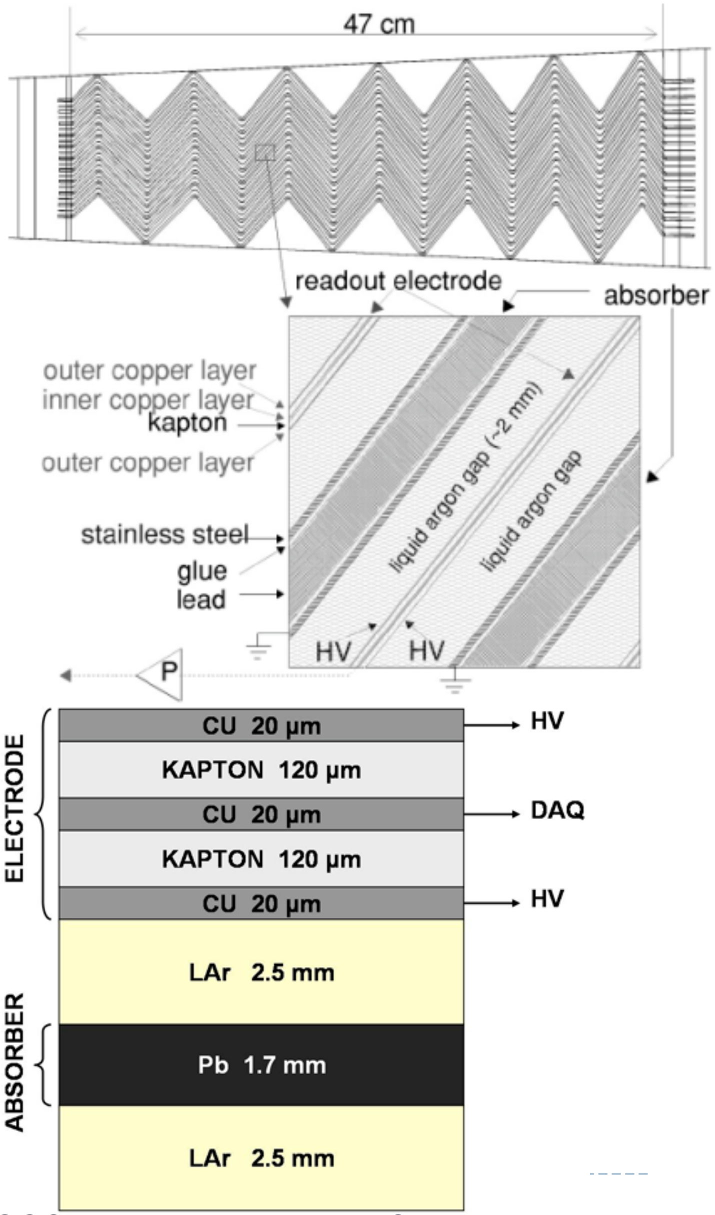


FIG. 15. Schematic view of a traditional sampling calorimeter geometry (a) and of the accordion calorimeter geometry (b).

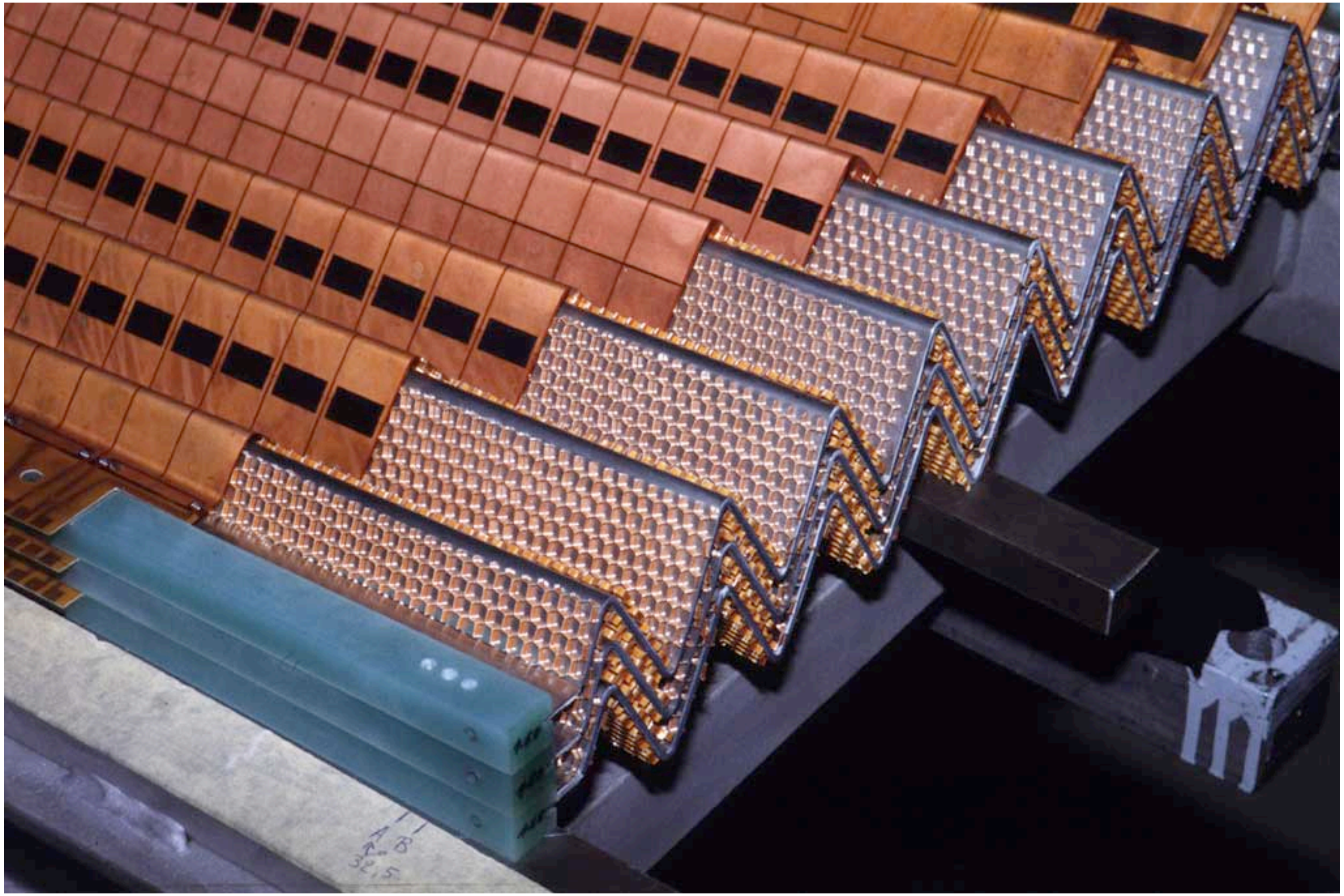
ATLAS EM Module “Accordion”



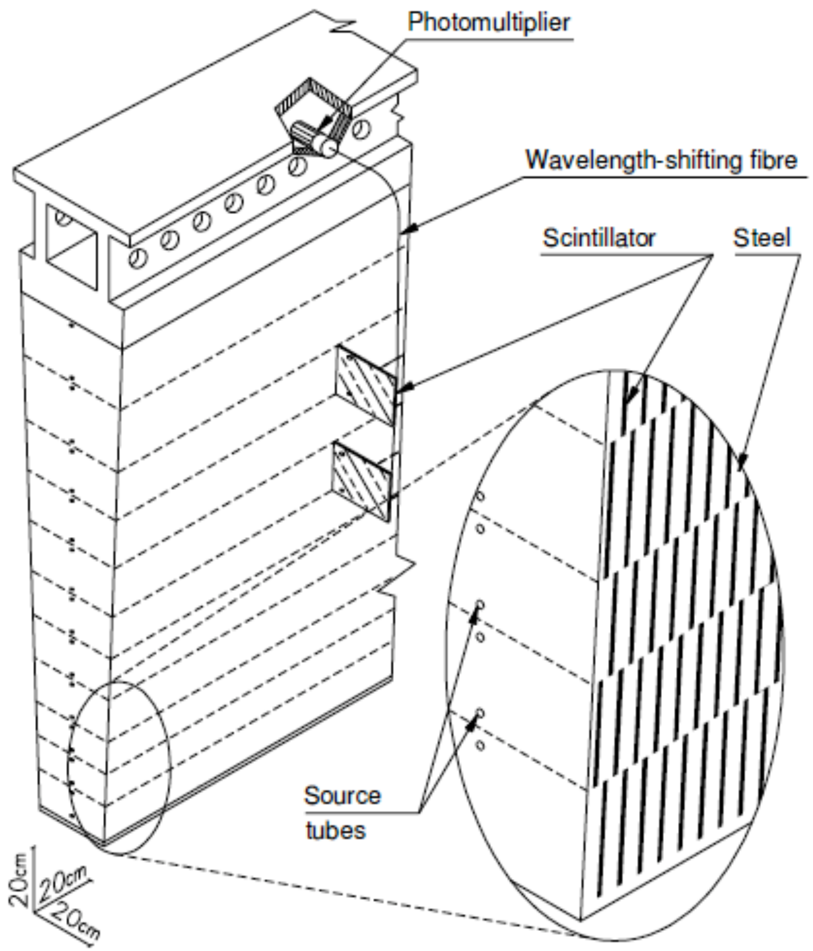




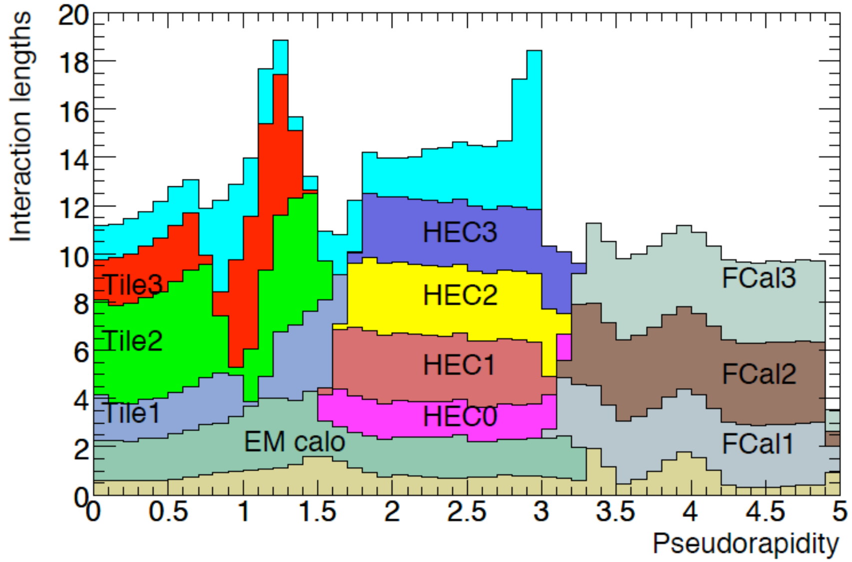
Accordion



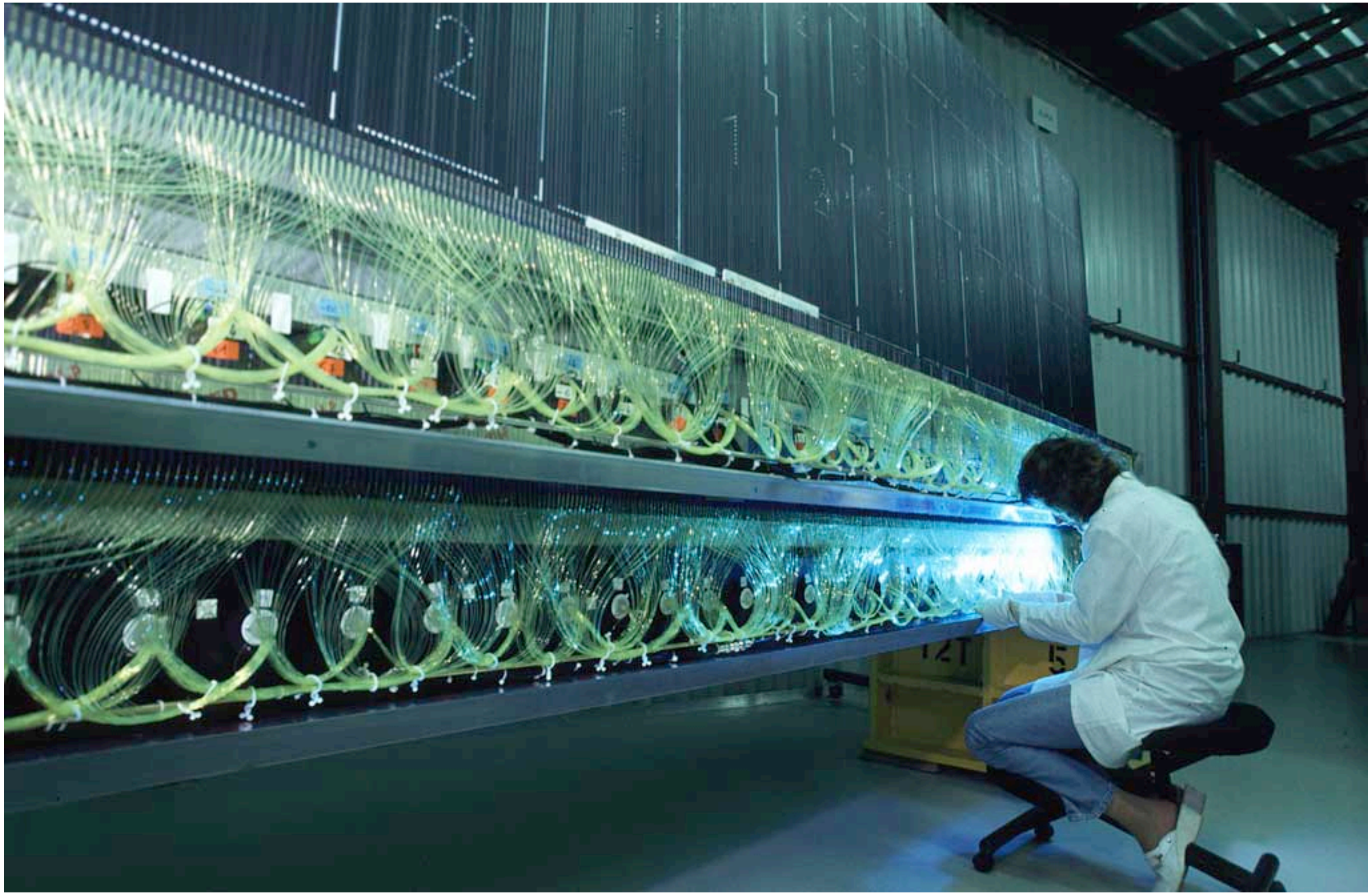
ATLAS Tile Hadronic calorimeter



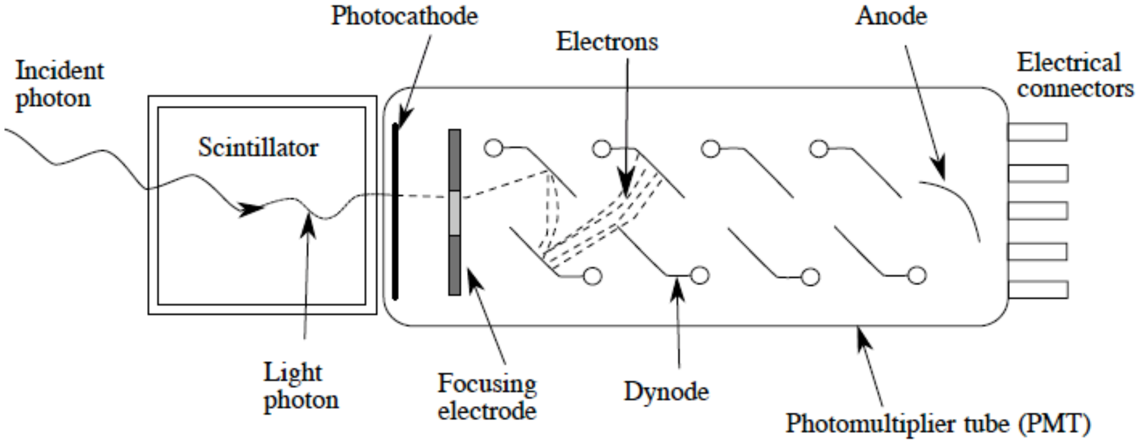
- Iron/Scintillator sampling calorimeter
- Scintillator phton signals routed out on fibres
- Fibres bundled together in three regions of depth
  - Gives ability to look at the longitudinal profile of the hadronic shower
- 8 Interaction lengths of material



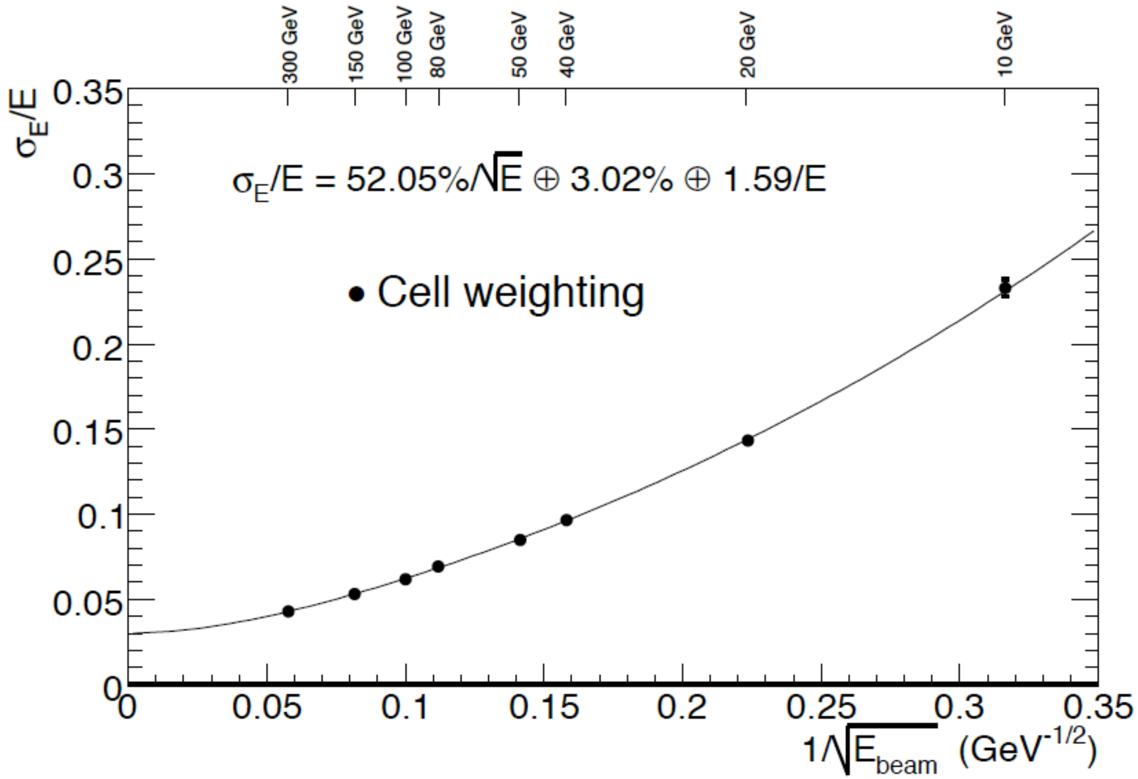
Fibre routing for the ATLAS Tile Cal



Tile Cal Readout Photo Multiplier Tube



- Scintillator signals are typically a small number of photons emitted for a minimum ionizing particle
- Traditional detector for small number of photons is the Photo Multiplier
  - Initial photon strikes a photocathode and emits electrons
  - These are then amplified in a cascade of dynodes
    - There is a potential between each dynode pair with accelerates the electrons
  - Much larger amount of charge appears at the Anode can even detect single photons
- Trade-offs



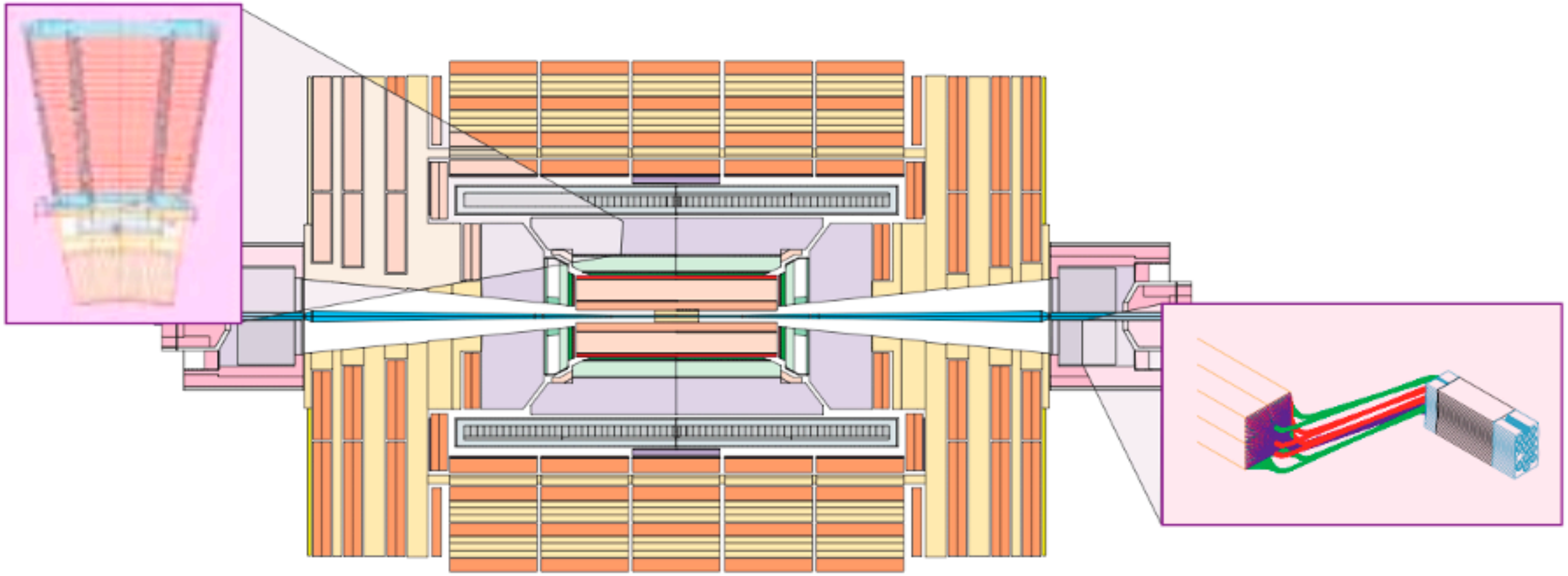
TileCal Performance

Resolutions for Hadron calorimeters is clearly not as precise as for EM calorimeters

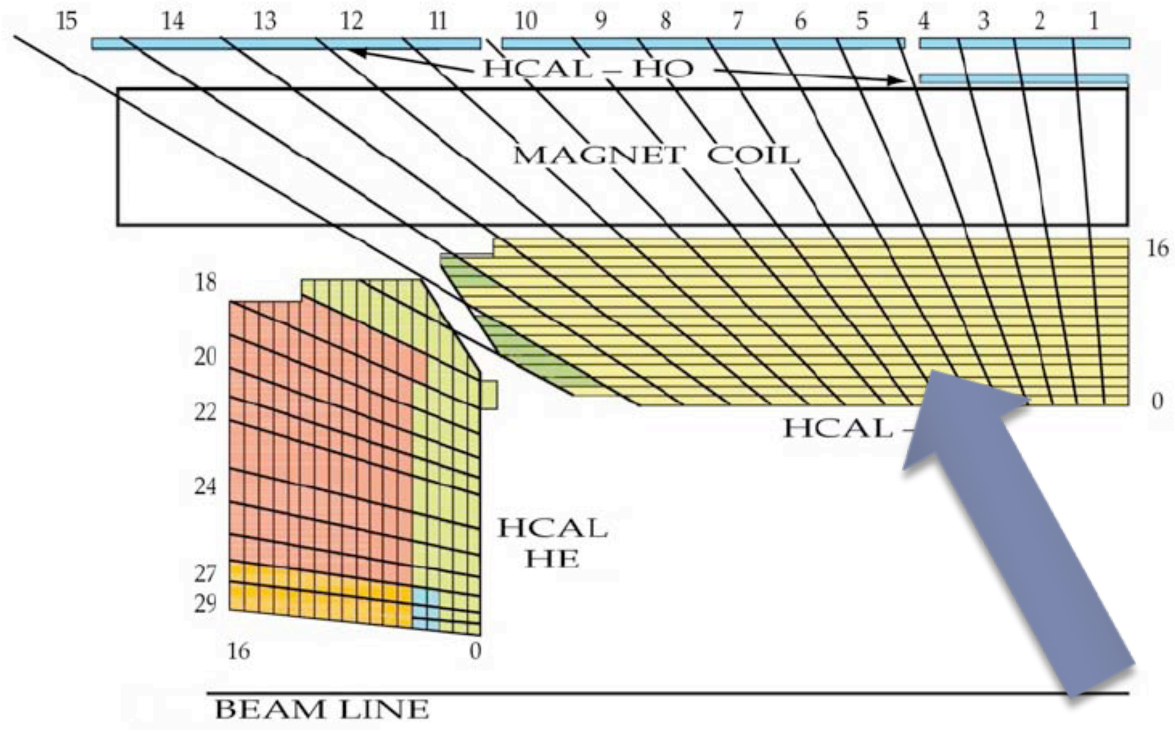
The stochastic term dominates, the sampling fraction, and the “lost” energy mean resolutions in the region of 50-100%/sqrt(E)

They are much more difficult devices to make precision energy measurement with

CMS Calorimeters overview



- We want calorimeters to be
- Hermetic
  - Important when we are searching for missing energy signatures – These are determined by summing up all the energy we see in the calorimeters and seeing where Energy doesn't balance
  - Instrumental effects can cause us to mistakenly think we have missing energy
- Have the best possible position and energy resolution
  - The better we measure the energy, the better job we do at understanding the physics process which produced the jets/leptons we are measuring
- However they need to be very large, and have to be built at finite cost (time/money)



Projective Geometry of calorimeters

Calorimeters are designed to be projective in eta.

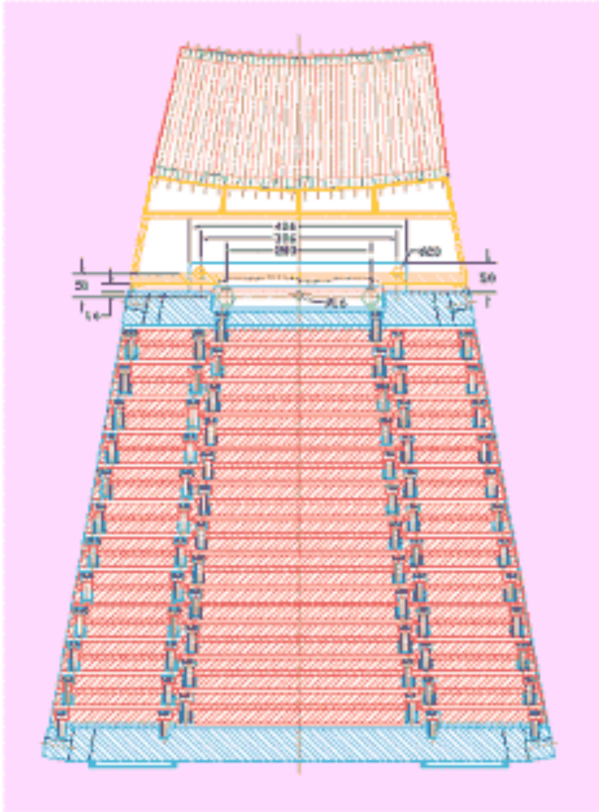
Energy which is emitted along a direction coming from the interaction point is captured in a "tower"

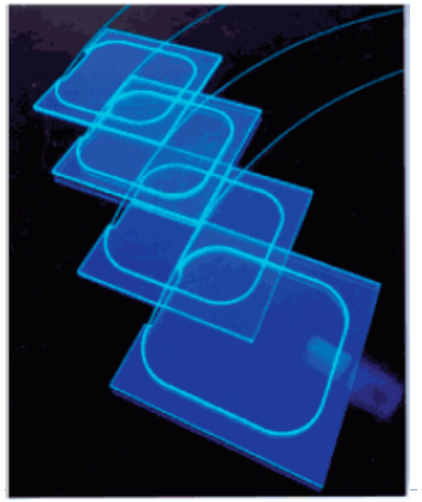
Data is summed over a tower – This reduces the number of readout channels, and also allows the energy in a jet to be determined (for trigger purposes for example)

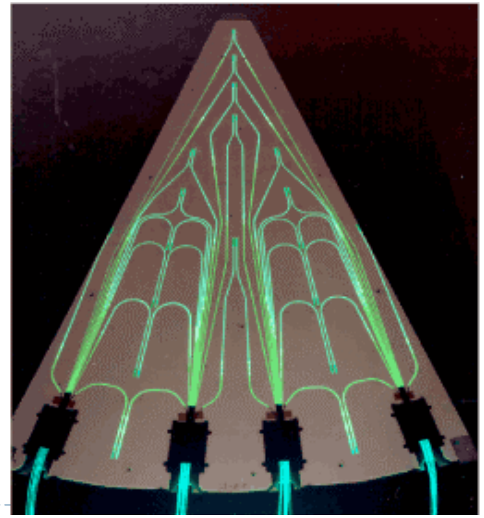
CMS HCAL

- Brass-Scintillator sandwich
  - Brass from old Russian army shells
- About 10,000 Channels in the system
- Signal is light in scintillator
  - Summing over depth of calorimeter done optically by bundling fibres
- Large dynamic range needed

chemical composition	70% Cu, 30% Zn
density	8.53 g/cm^3
radiation length	1.49 cm
interaction length	16.42 cm

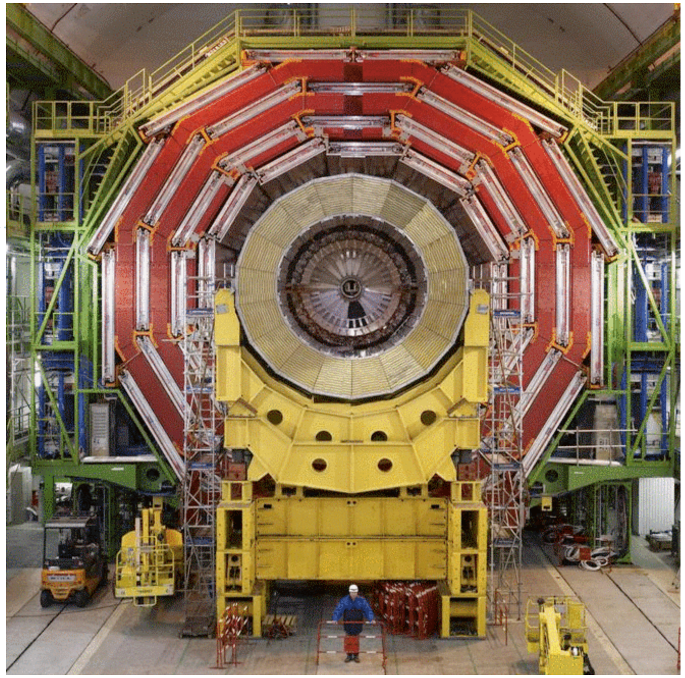


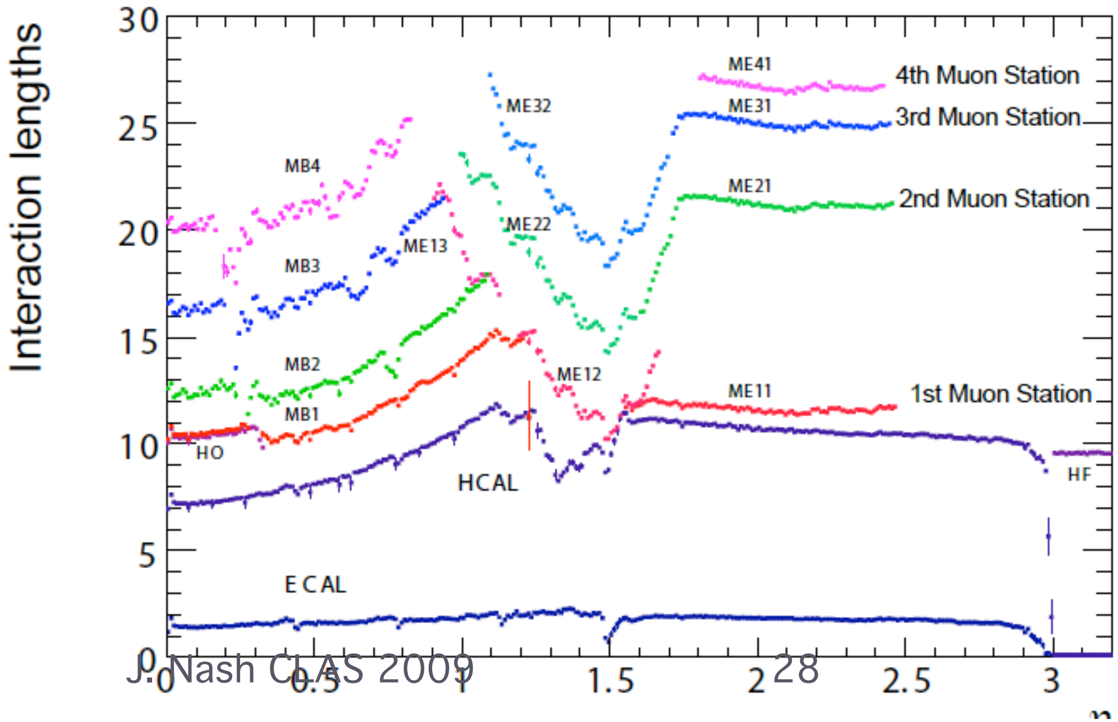




CMS HCAL

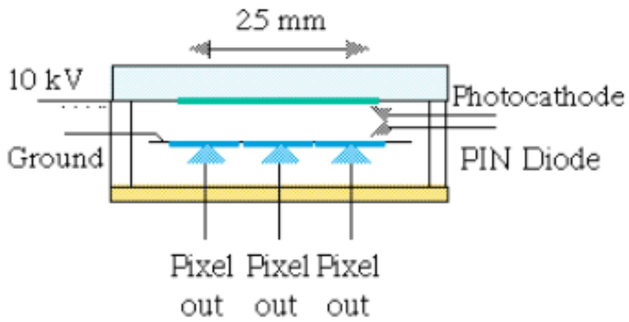
- About 7-8 interaction lengths of material in the calorimeter
- The HCAL is inside the CMS solenoid
- Tail catcher outside the CMS coil (an extra 4 interaction

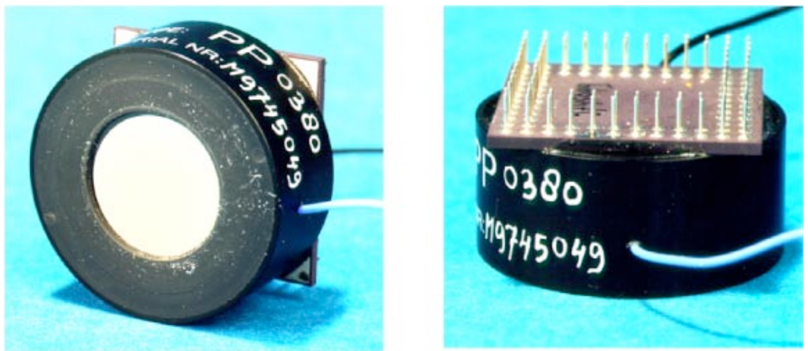


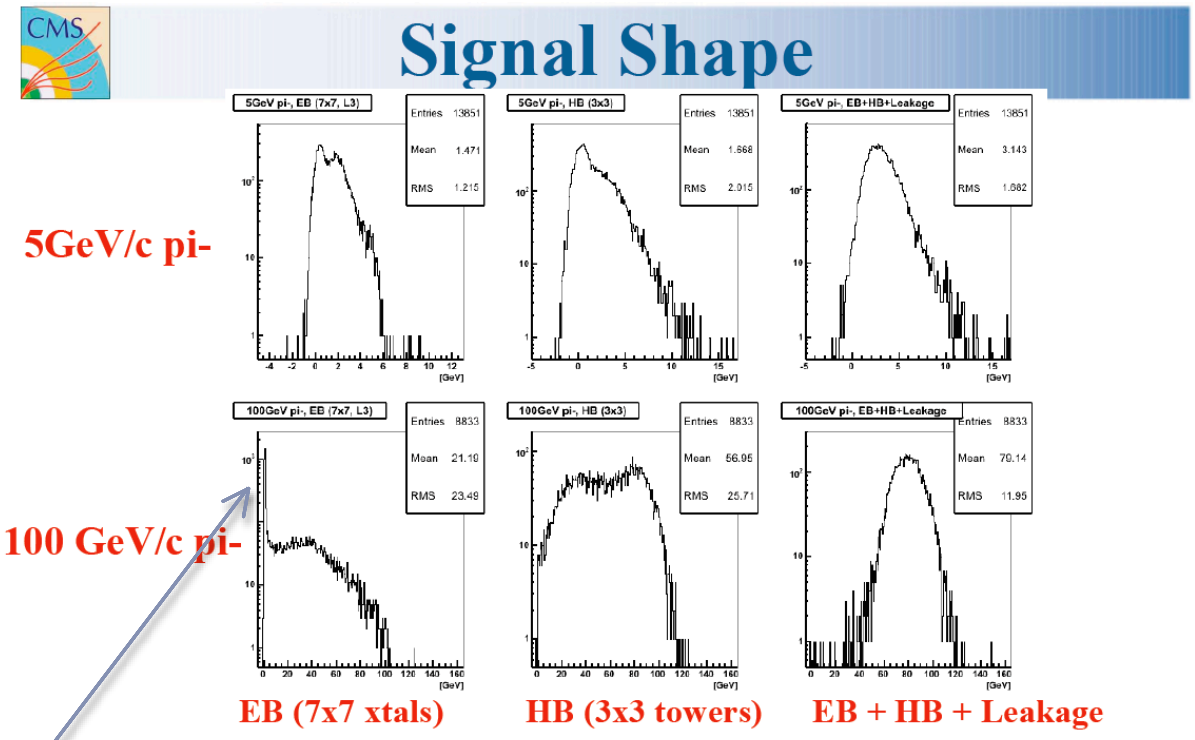


HCAL Readout

- Readout is provided by HPDs which consist of a fibre-optic entrance window onto which a multialkali photocathode is deposited, followed by a gap of several millimeters over which a large applied electric field accelerates photoelectrons onto a silicon diode target. The target is subdivided into individual readout elements called pixels. For CMS, 19-channel HPDs are used.
- The gain of HPDs is typically 2000-3000 for applied voltages of 10-15 kV. HPDs are capable of operating in high axial magnetic fields and provide a linear response over a large dynamic range.
- HPD has much smaller gain than a PMT implies electronics needs
  - High sensitivity/low noise
  - Large Bandwidth for BCID







Note Peak at minimum Ionizing deposit in ECAL

Response Functions of Calorimeters

Turning the measured signals from Hadronic and Electromagnetic calorimeters into energy measurements for Jets requires a lot of detailed calibration

Testbeam measurements as well as detailed simulations are essential in understand had to turn the raw signals in the calorimeters into quantities which can be used for physics like Jet Energies and Missing Transverse Energy

Outline

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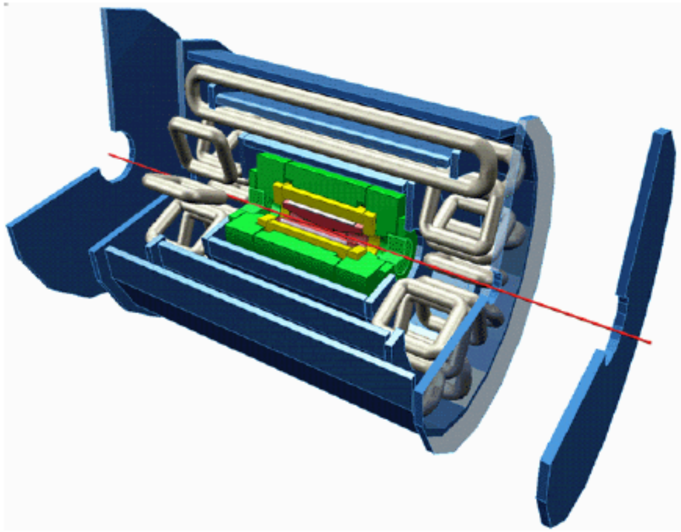
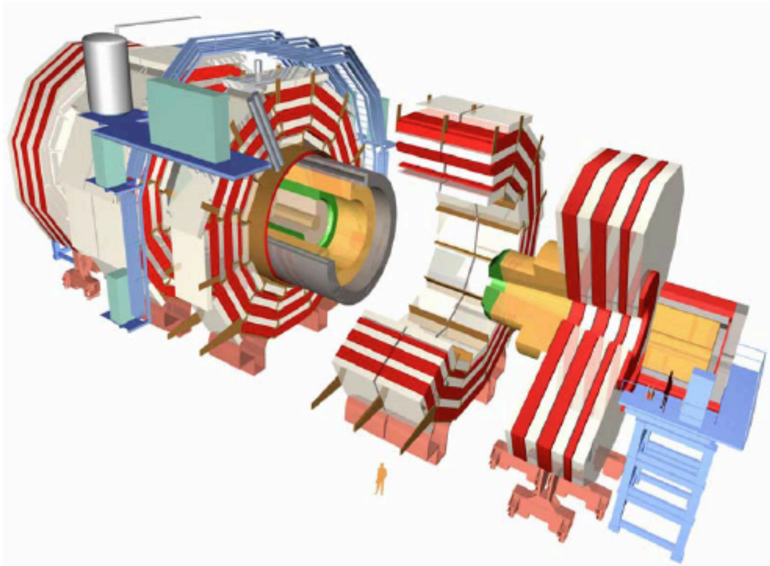
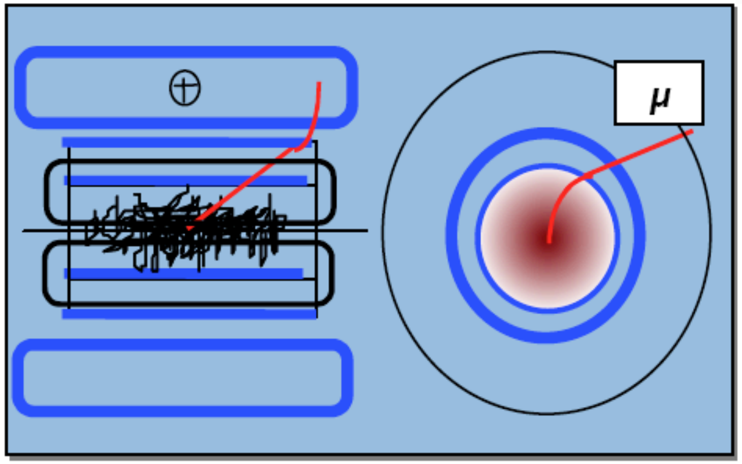
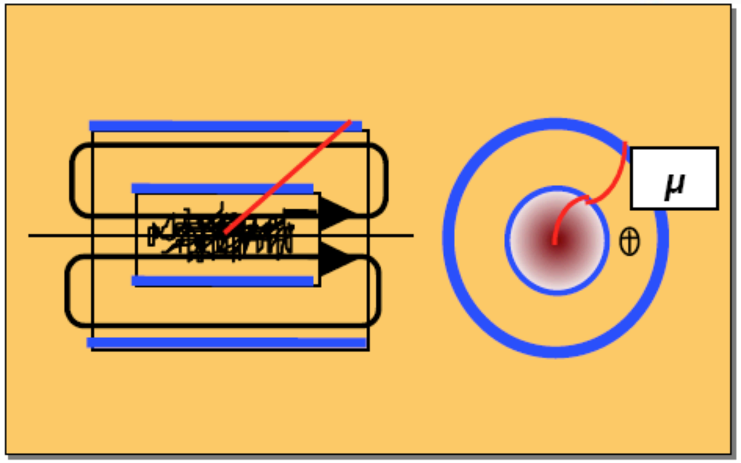
  - The physics requirements
  - Coping with the LHC environment
- Particles passing through matter
- Tracking Detectors
- Calorimetry
- Muon Detection
- Detectors for triggering/timing/particle ID
- Preparing for the future - higher luminosity implications

Muon Tracking



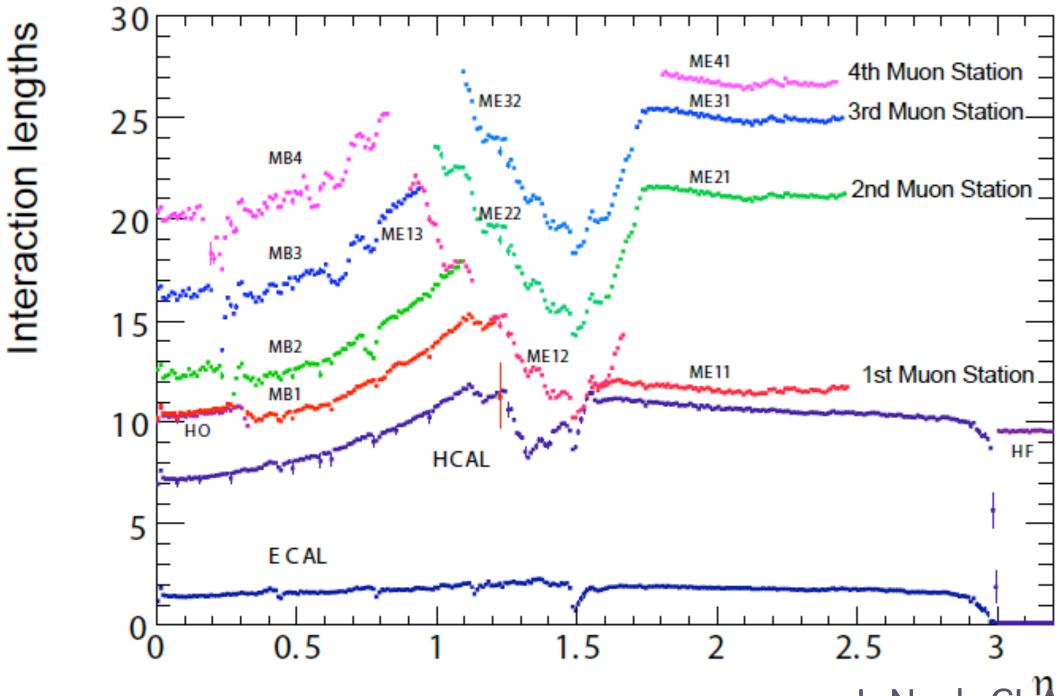


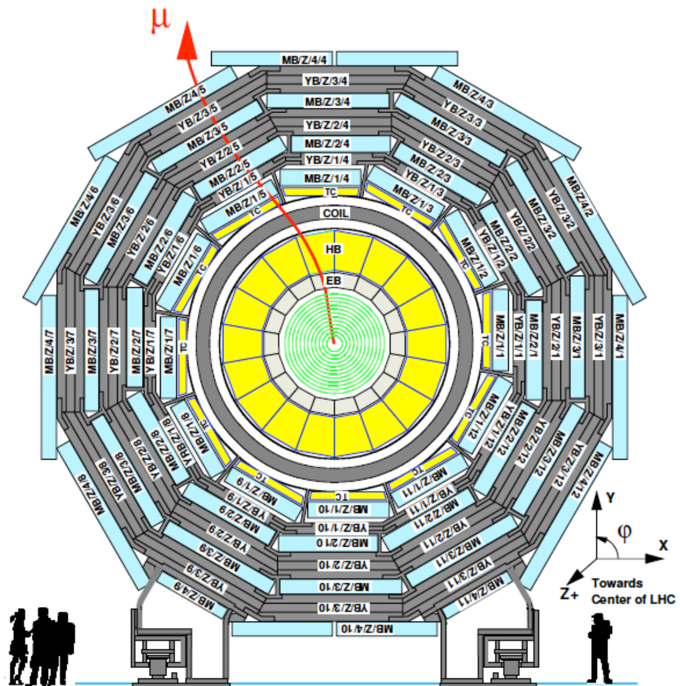




Finding Muons

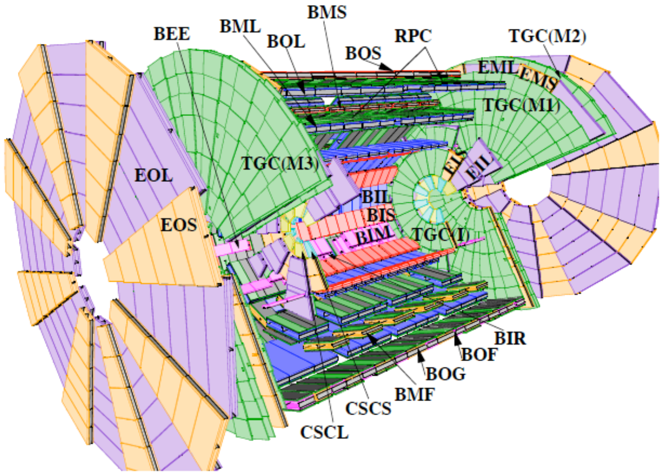
- The flux return of the CMS coil returns through the steel of the yoke.
  - Notice the opposite sign of bending in the muon system
  - This allows CMS to be compact
- This is instrumented with muon chambers to track (and trigger) the muons which easily pass through the iron

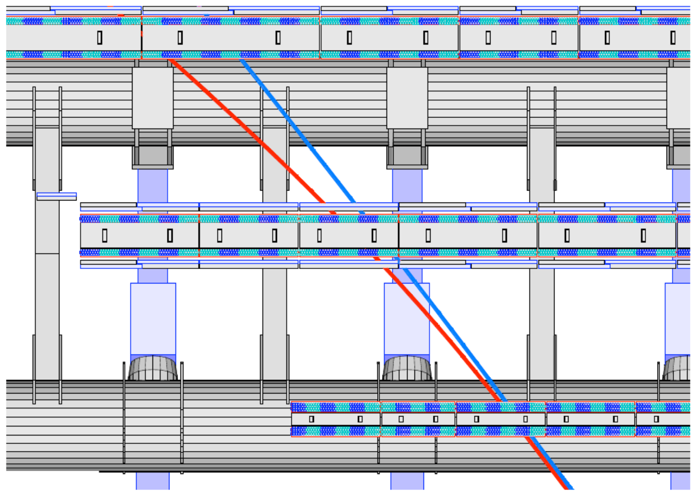




Atlas Muon detection

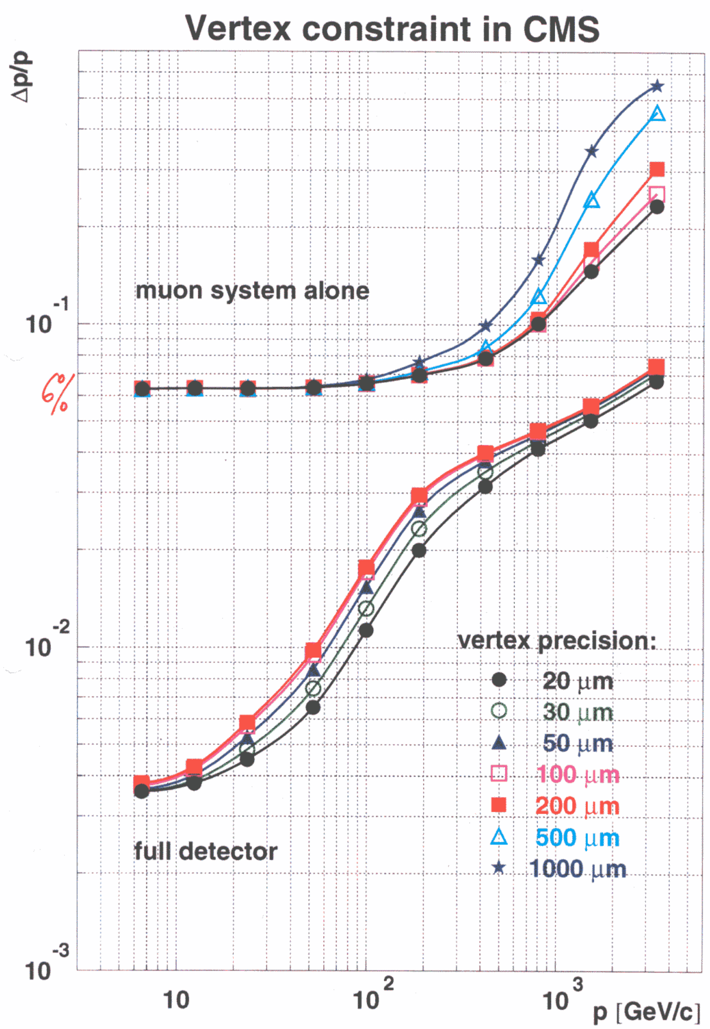
- The low material allowed by the ATLAS torroid magnet allows for precision tracking of muons
  - Lower multiple scattering
- Precision tracking chambers covering a very large surface area
  - Need something which is easy to mass produce

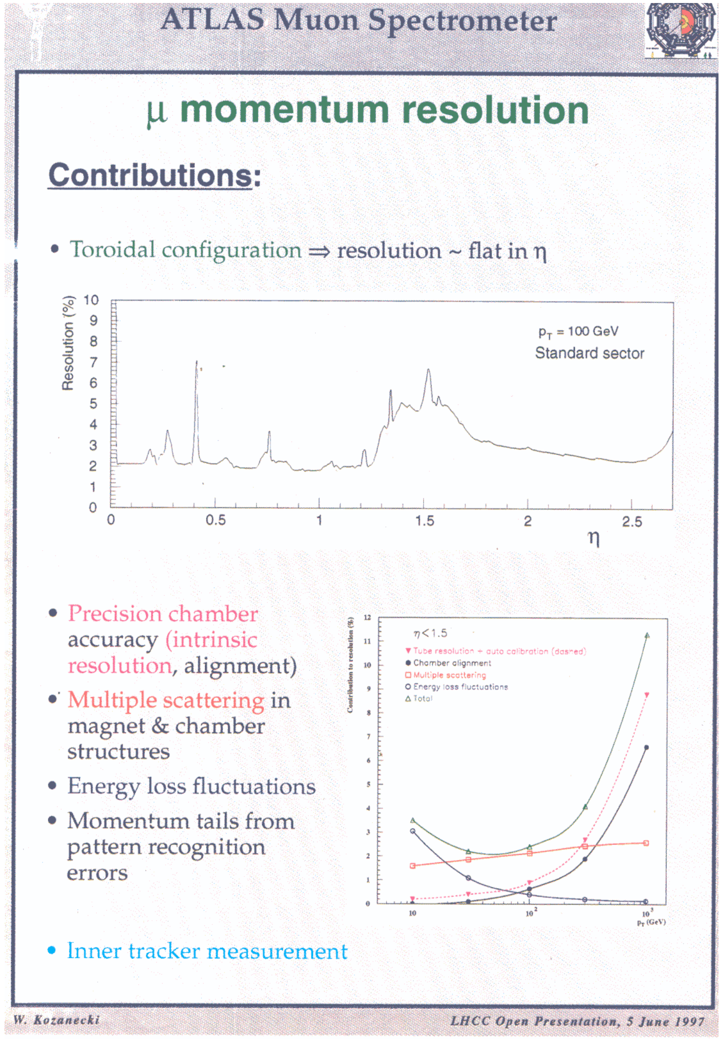




20 GeV and 4 GeV muons

ATLAS/CMS Muon System Resolutions



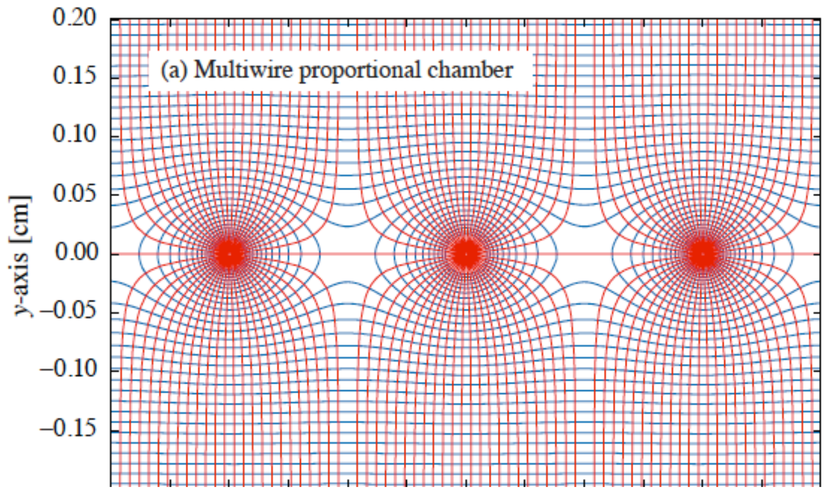


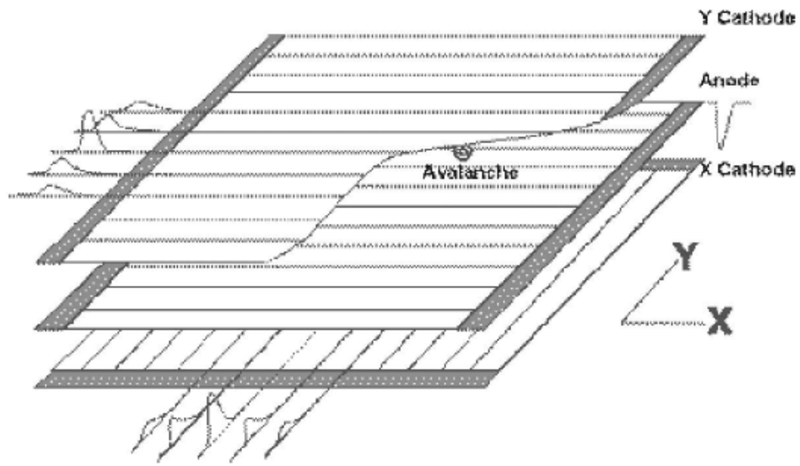
General considerations for Muon tracking detectors

- Muon tracking detectors need to cover a very large surface area
- Need a technology which is relatively inexpensive to produce on a large scale
- The occupancy should be much lower in the outer parts of the detectors, so can relax some of the requirements on granularity
  - Detectors with lower rate capability and less position resolution can be considered
  - We still want reasonable position resolution to allow us to determine the muon momentum precisely
- These chambers are often also used to form an input to the trigger system
  - High momentum muons are a very important signal of some interesting physics which we would like to trigger on

Multi Wire Proportional Counters

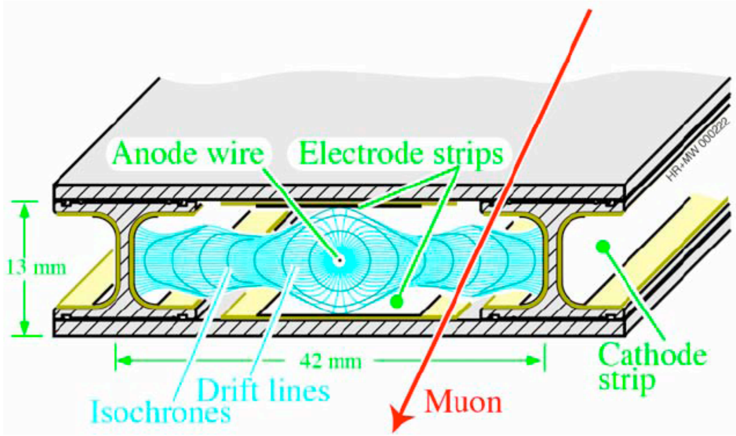
- String together several wires in parallel
  - 2mm separation
- Place between two cathode planes
- Charged tracks ionization causes avalanche
  - Determine which wire the track passed closest to
- More information
  - stack perpendicular plane on top to get second coordinate
  - read charge on both ends of the wire
  - segment the cathode into strips and measure the induced chage on the cathode strips
- This configuration of wires cant be unstable

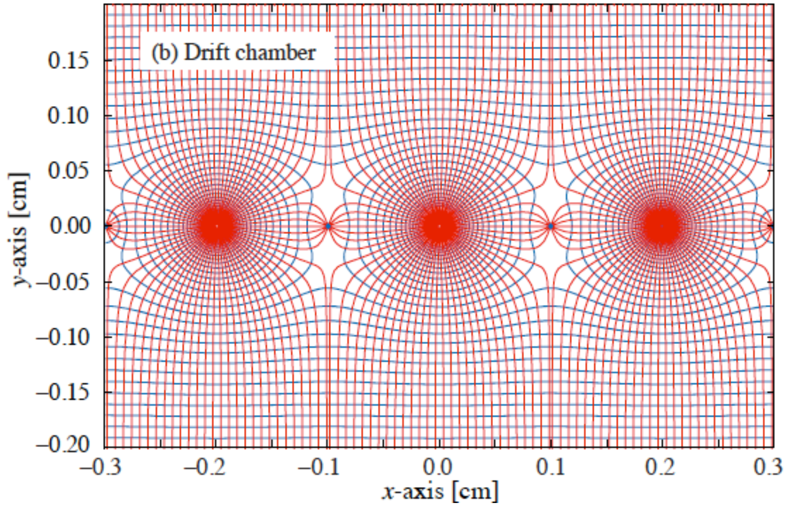




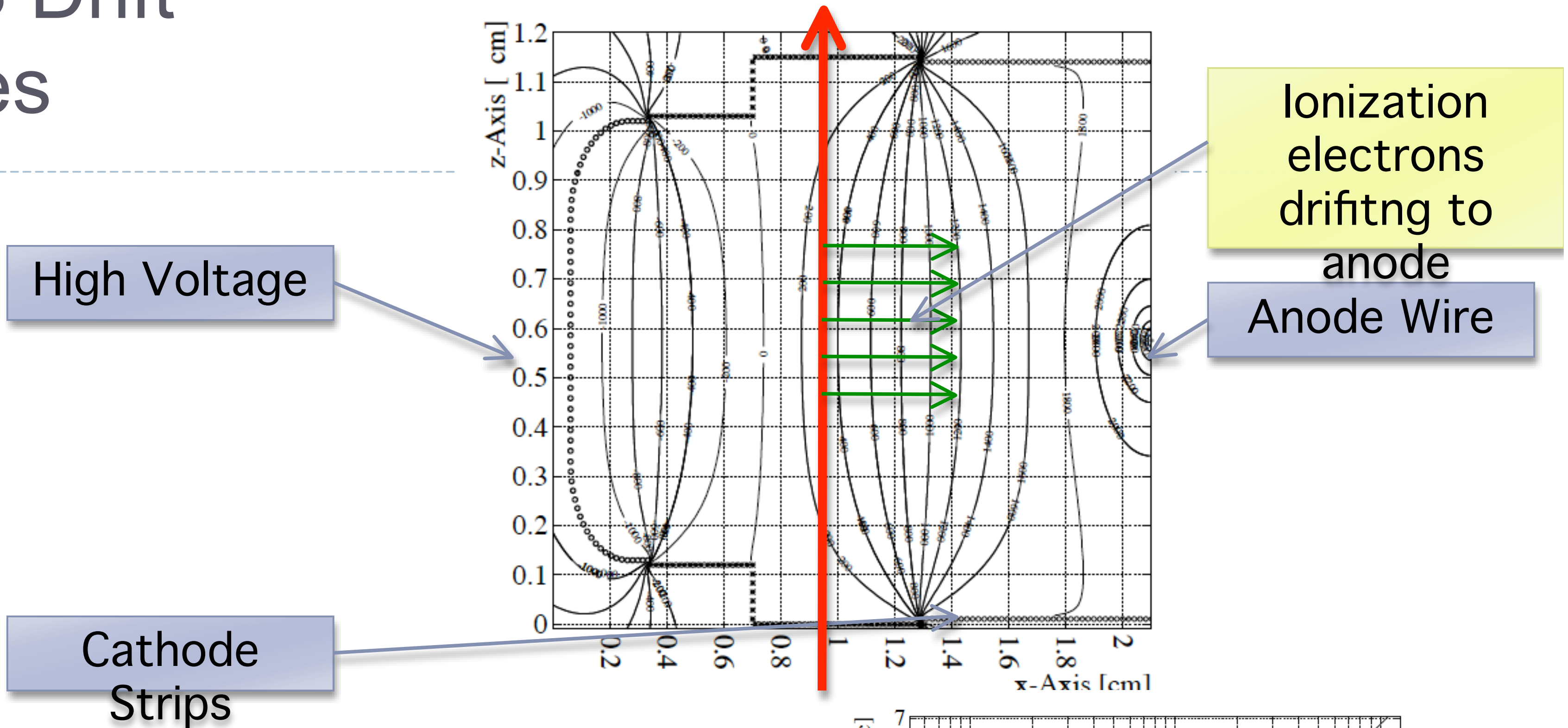
Drift Chambers/Drift Cells

- Insert extra wires at intermediate fields to help shape the field lines
- Wires can be further apart
- Drift of electrons can be made very uniform
  - Time to distance relationship allows for precise location of passage of charged track

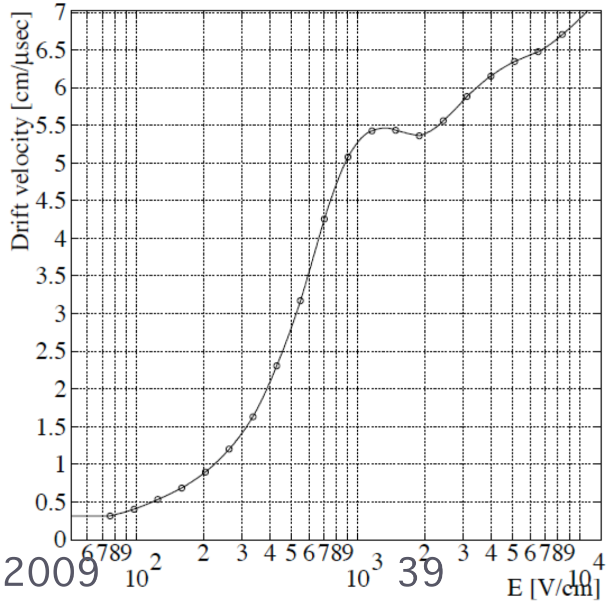




CMS Drift Tubes

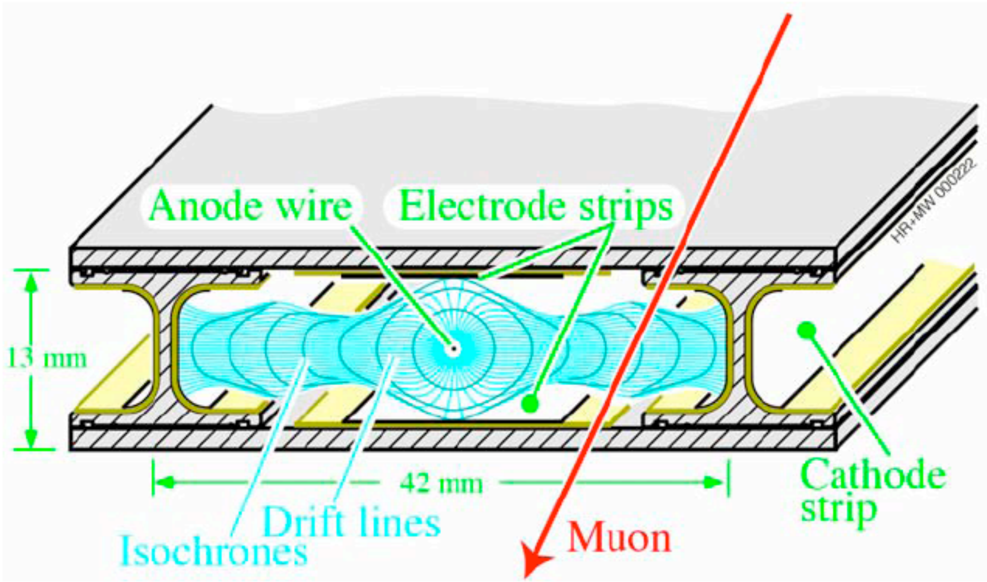


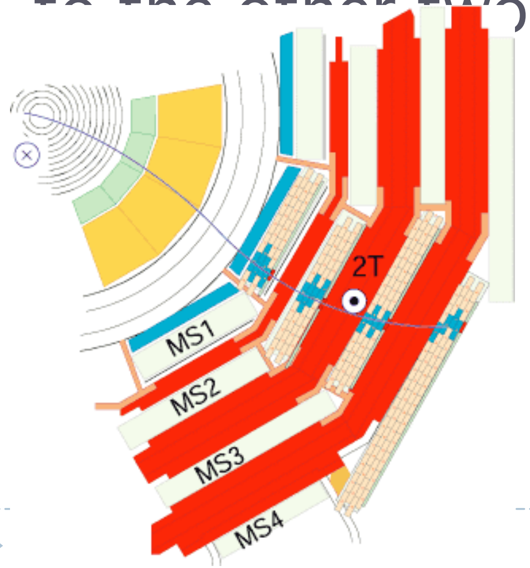
- Drift Cells 4cm x 1cm
- Cathode strips on the cell walls to shape the field
- Uniform and fairly rapid drift to the wire
  - Drift velocity around 50μ m/ns
- Can measure position in cell from the drift time

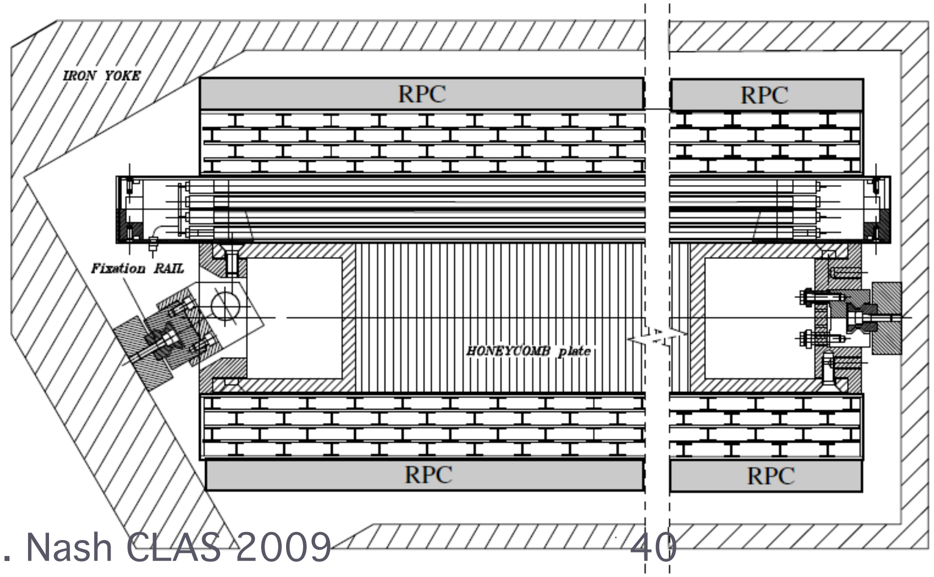


CMS Muon Drift Tubes

- Cells are mass produced and stacked in 3 stacks of 4 chambers
  - About 2mx2m
  - one stack of chambers orthogonal to the other two

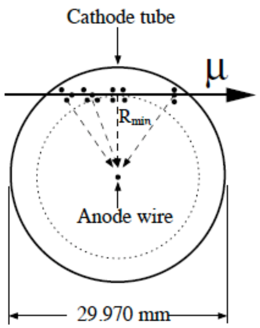


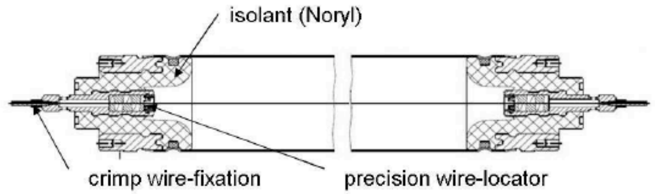


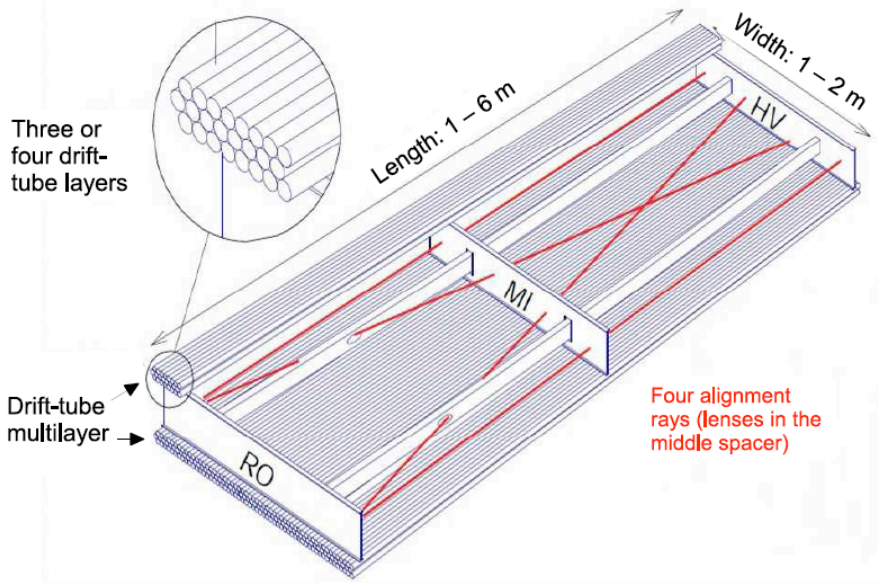


ATLAS Monitored Drift Tube

- Drift Tubes 3cm in Diameter
- Gas gain 10^4
- Long drift time (up to 25 Beam crossings)
  - Limits rate to about
    - 150 Hz/cm^2
- Position resolution about 80 μm

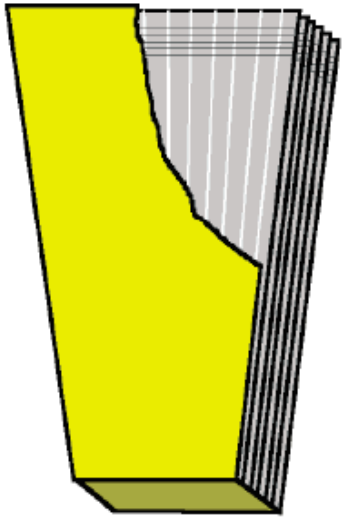


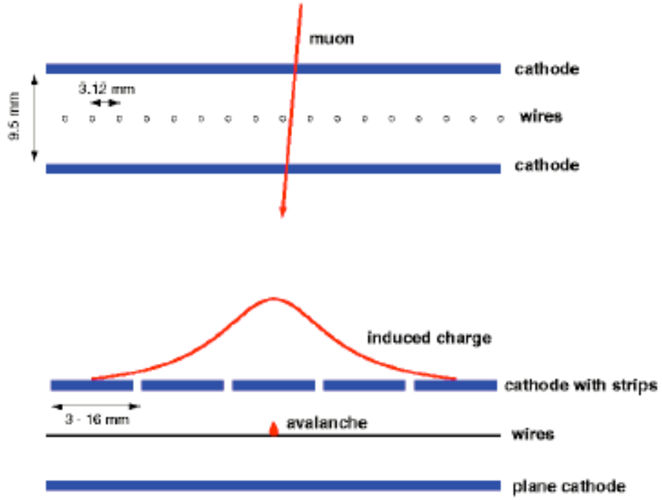


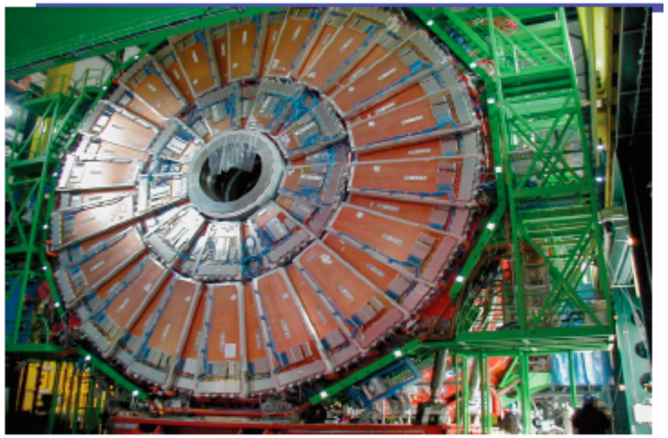


Parameter	Design value
Tube material	Al
Outer tube diameter	29.970 mm
Tube wall thickness	0.4 mm
Wire material	gold-plated W/Re (97/3)
Wire diameter	50 μm
Gas mixture	$Ar/CO_2/H_2O$ (93/7/$\leq$ 1000 ppm)
Gas pressure	3 bar (absolute)
Gas gain	2 x 10^4
Wire potential	3080 V
Maximum drift time	$\sim$ 700 ns
Average resolution per tube	$\sim$ 80 μm

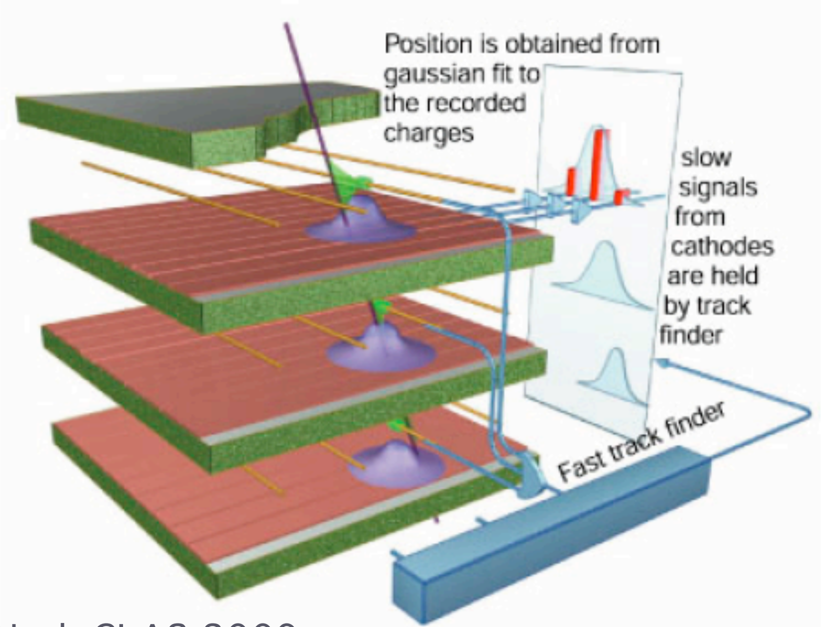
Muon Cathode Strip Chambers (CSC)







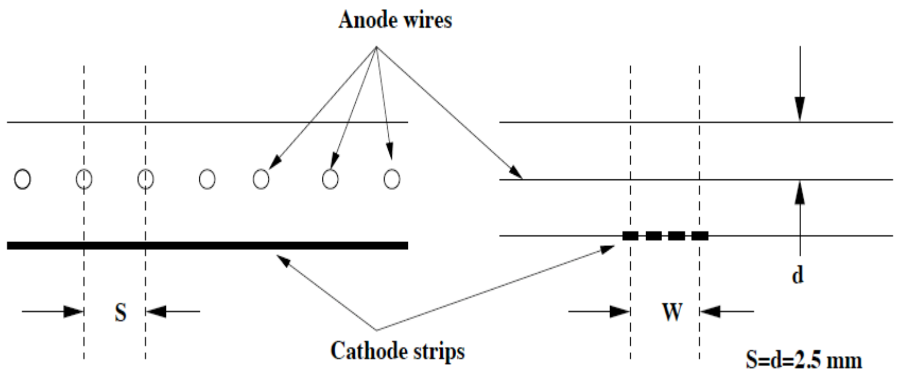
- Anode Wires in Azimuth
  - Bending is in Azimuthal direction
  - Give Precise timing
- Cathode Strips radial
  - Give Precise positioning from knowledge of charge in strips
- 6 Layers used for fast track finding
  - 160,000 channels

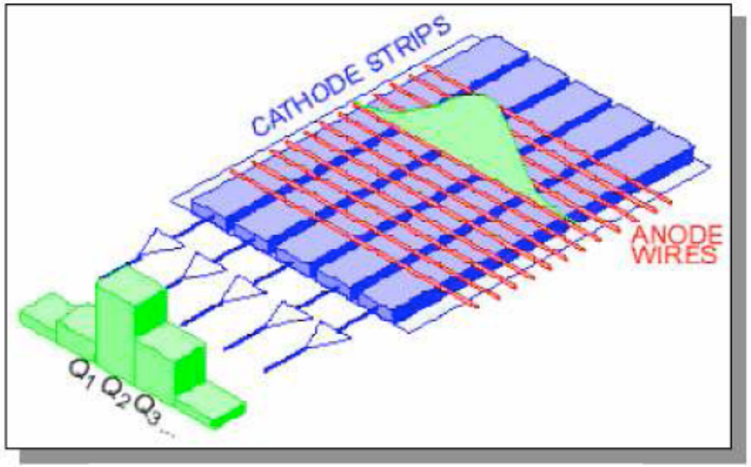


CMS Cathode Strip Chambers

- Cathode strip chambers (CSC) are used in the endcap disks
  - magnetic field is uneven
  - particle rates are high
- Positive ions move away from the wire and towards the copper cathode, also inducing a charge pulse in the strips, at right angles to the wire direction.
  - the strips and the wires are perpendicular giving two position coordinates for each passing particle.
  - the closely spaced wires make the CSCs fast detectors suitable for triggering.
- Each CSC module contains six layers making it able to accurately identify muons and match their tracks to those in the tracker

ATLAS CSC





- Endcap region of ATLAS
- Need high rate capability
  - Up to 1000 Hz/cm2
- Segmented cathode strips have a charge induced on them by the avalanche on the anode wires
- Strips about 1.5 mm wide separated by .25 mm

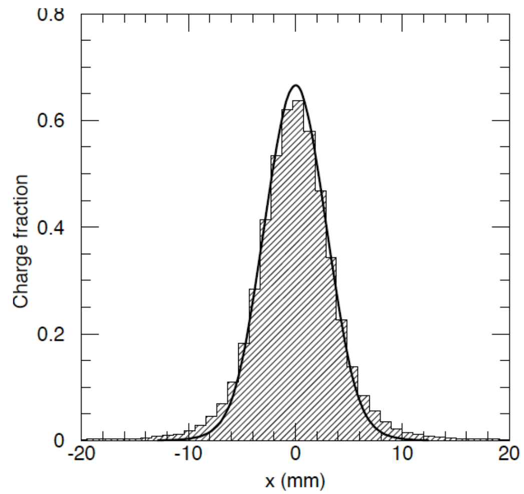


Figure 6.15: Charge distribution on the CSC cathode induced by the avalanche on the wire.

ATLAS Muon system summary

		Chamber resolution (RMS) in			Measurements/track		Number of	
Type	**Function**	z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	tracking	35 μm (z)	—	—	20	20	1088 (1150)	339k (354k)
CSC	tracking	40 μm (R)	5 mm	7 ns	—	4	32	30.7k
RPC	trigger	10 mm (z)	10 mm	1.5 ns	6	—	544 (606)	359k (373k)
TGC	trigger	2–6 mm (R)	3–7 mm	4 ns	—	9	3588	318k

- ATLAS uses four types of technologies to track and trigger on Muons
- This system covers a huge surface area
- More than a million channels of readout required

Outline

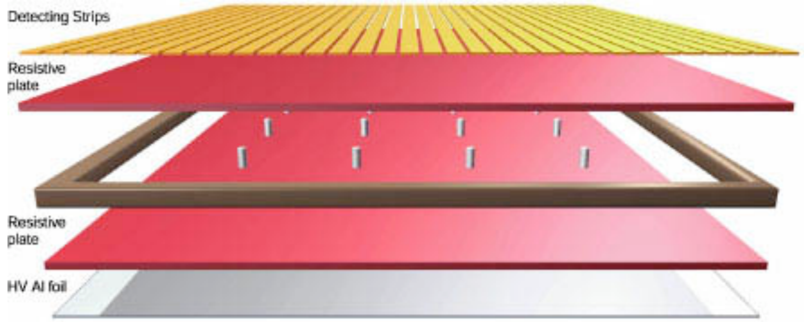
- What are the requirements for Detectors at the LHC?
  - The physics requirements
  - Coping with the LHC environment
- Particles passing through matter
- Tracking Detectors
- Calorimetry
- Muon Detection
- Detectors for triggering/timing/particle ID
- Preparing for the future - higher luminosity implications

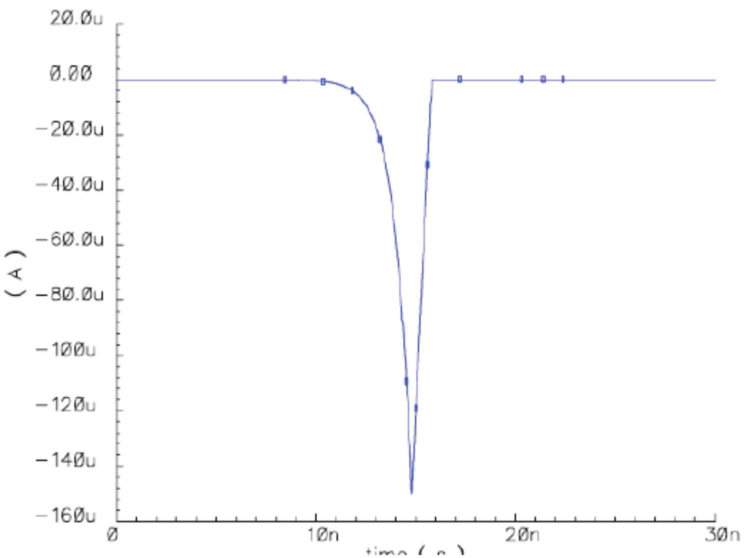
Building *Trigger Primitives*

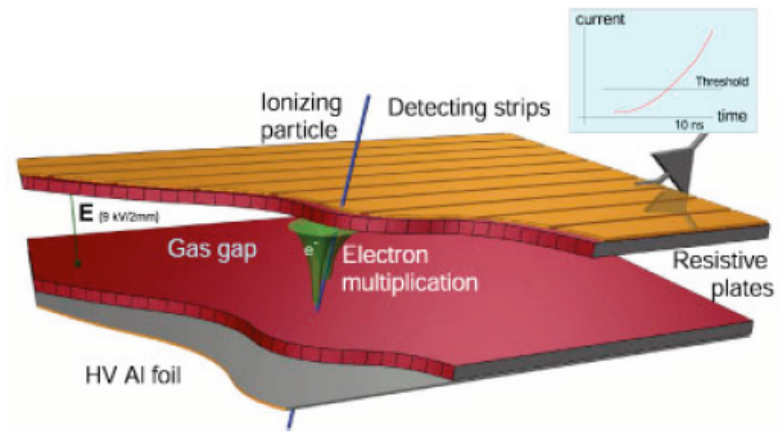
- Nick has told you how we need to put together signals from the detectors to build a trigger for the experiment.
- The trigger systems work with inputs from the detector which give a very fast signal that there is something worth looking at in the detector
- The instrumentation for this must very quickly
  - Gather the signal from the detector (can't have very long drift times for instance)
  - Put together the signals from several detector elements to look for interesting patterns
    - For example high momentum muon tracks
    - Large deposits of energy in the calorimeters in a small region
  - Send this information to the trigger system for further processing

RPCs

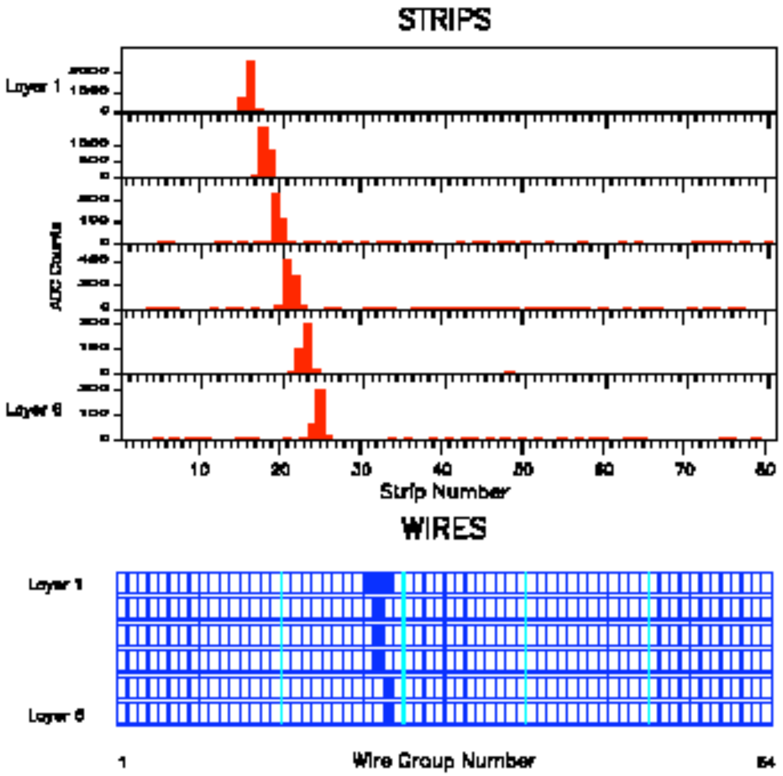
- Resistive plate chambers (RPC) fast gaseous detectors
  - Relatively inexpensive to cover a large area
- RPCs consist of two parallel plates
  - a positively-charged anode and a
  - negatively-charged cathode,
- Plates are made of a very high resistivity plastic material and separated by a gas volume.
- Ionizing muons cause an avalanche of electrons.
- The electrodes are transparent to the signal (the electrons), which are instead picked up by external metallic strips after a small but precise time delay.
- RPCs combine a good spatial resolution with a time resolution of just one nanosecond.

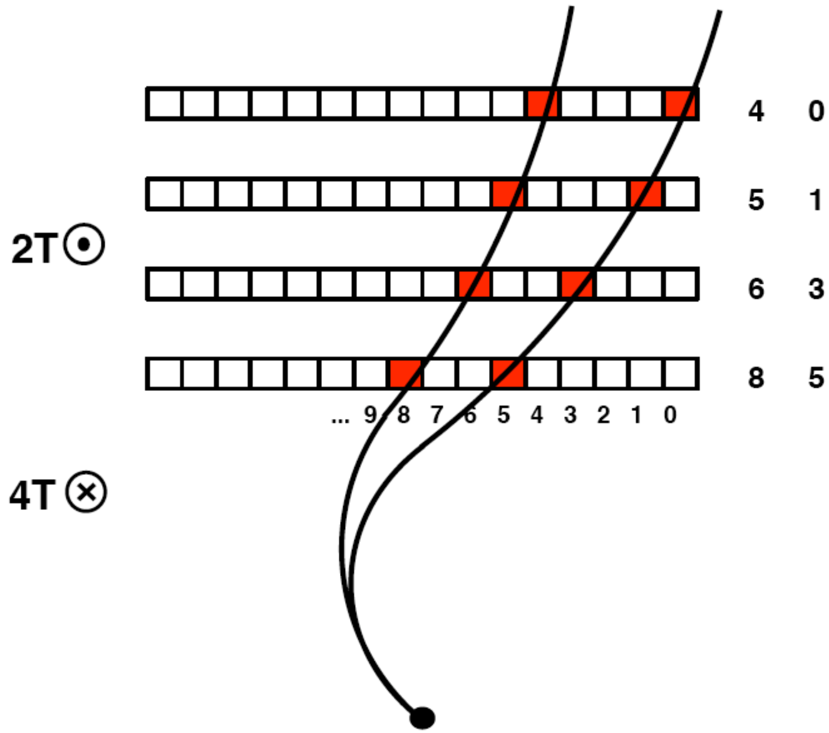






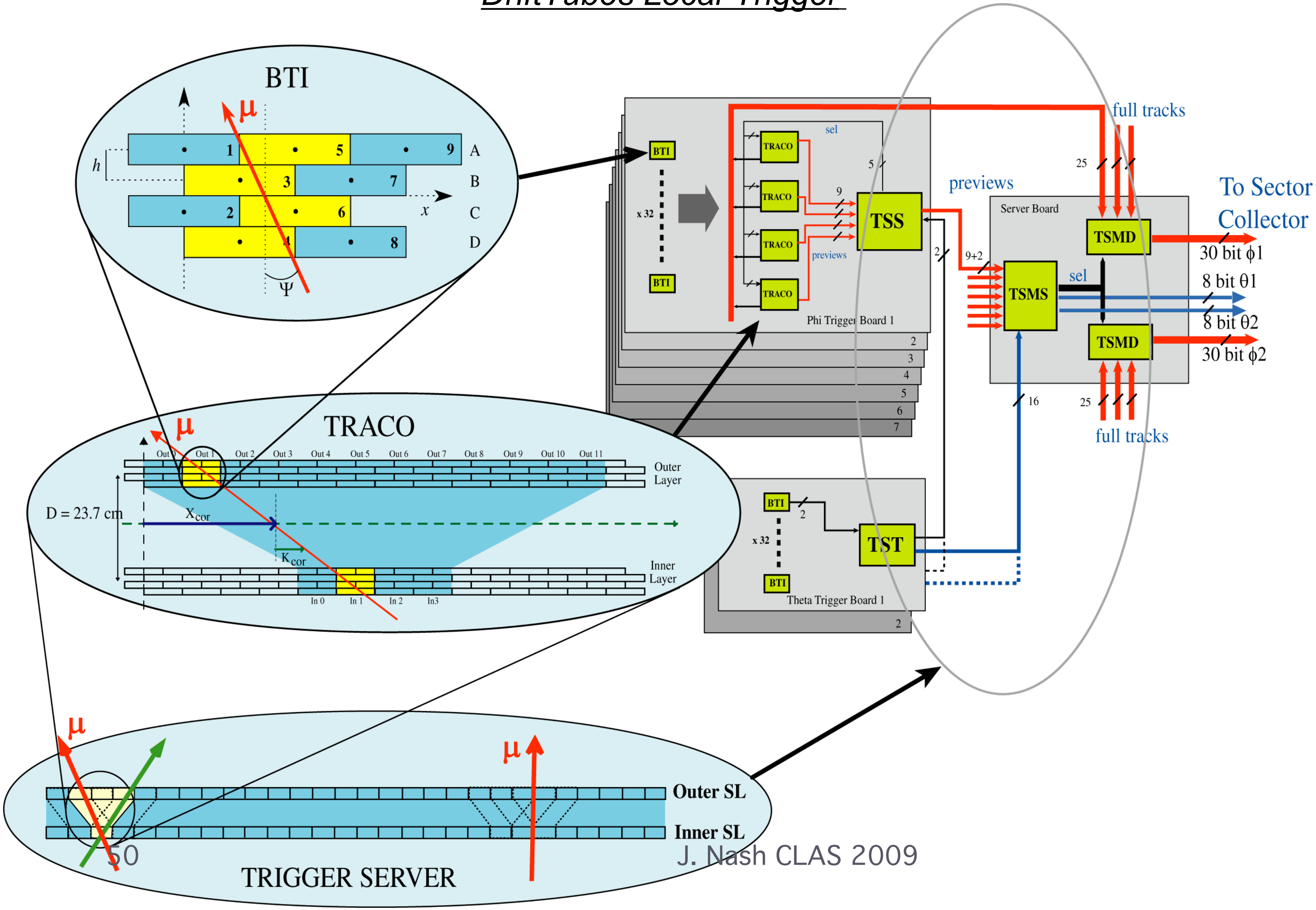
Muon Triggers Primitives





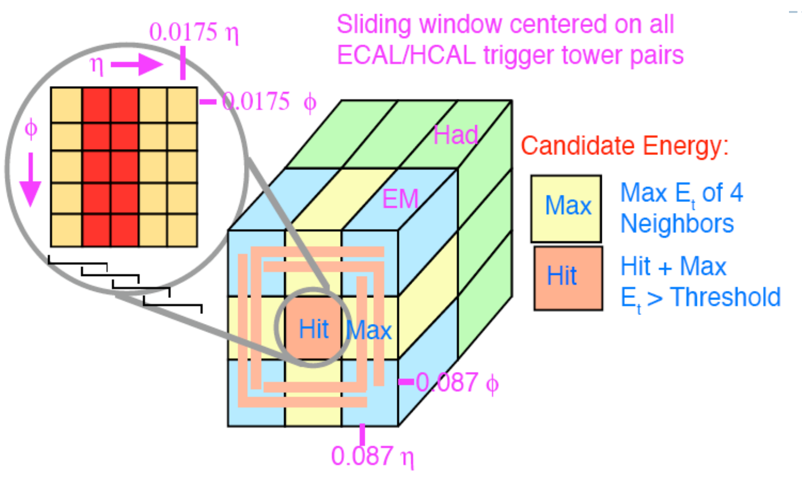
Pattern of hit strips is compared to predefined patterns corresponding to various p_T

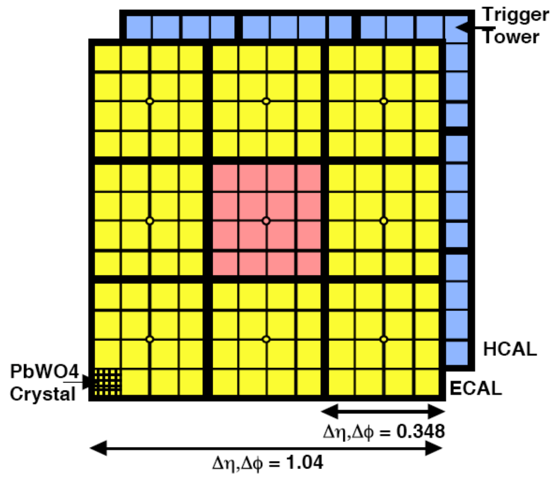
DriftTubes Local-Trigger



Calorimeter trigger objects

- Electrons
  - Look at Sum Et and H/E
    - Isolated
    - Non-Isolated
- Jets
  - Looking for energy deposited in a cluster in the calorimeters
  - Requires handling information from larges areas of the calorimeter
  - Large amount of data to collect/correlate at 40 Mhz





Particle ID

TRD

RICH

TOF

Outline

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- Preparing for the future - higher luminosity implications

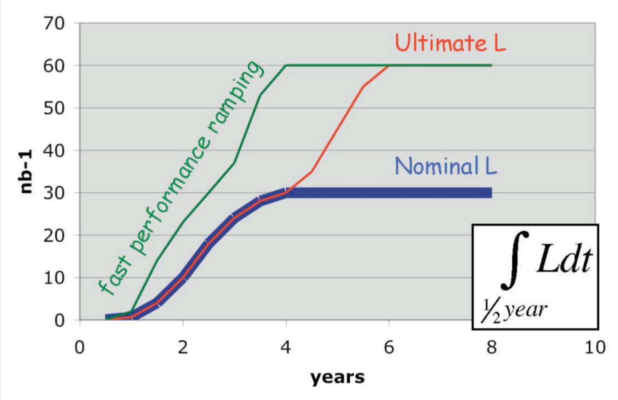
Increasing the luminosity of the LHC

- If the integrated luminosity delivered by the LHC reaches a plateau, then after a few years, it takes a very long time to reduce the statistical error on a measurement by a factor of 2.
- If we want to look at channels where we are statistically limited in the information we can extract, or to look for very rare decay channels, then we have to find ways to increase the peak and integrated luminosity of the LHC machine
- This can have very serious implications on the performance and requirements of the detectors

Walter Scandale: Status of LHC Upgrade

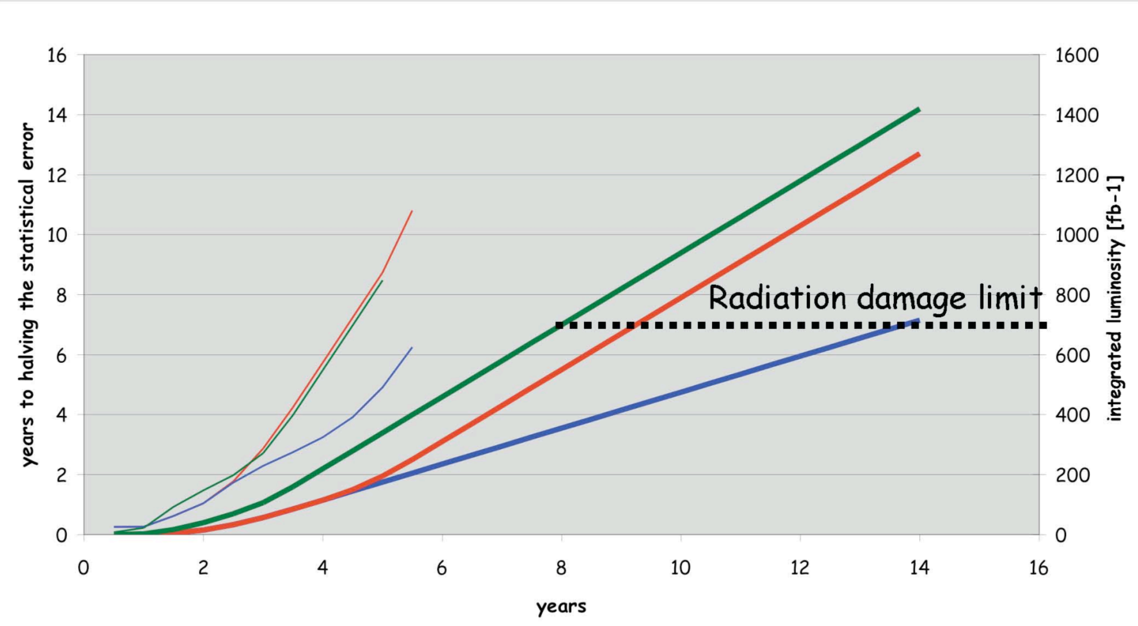
LHC luminosity upgrade: why and when?

CARE-HHH



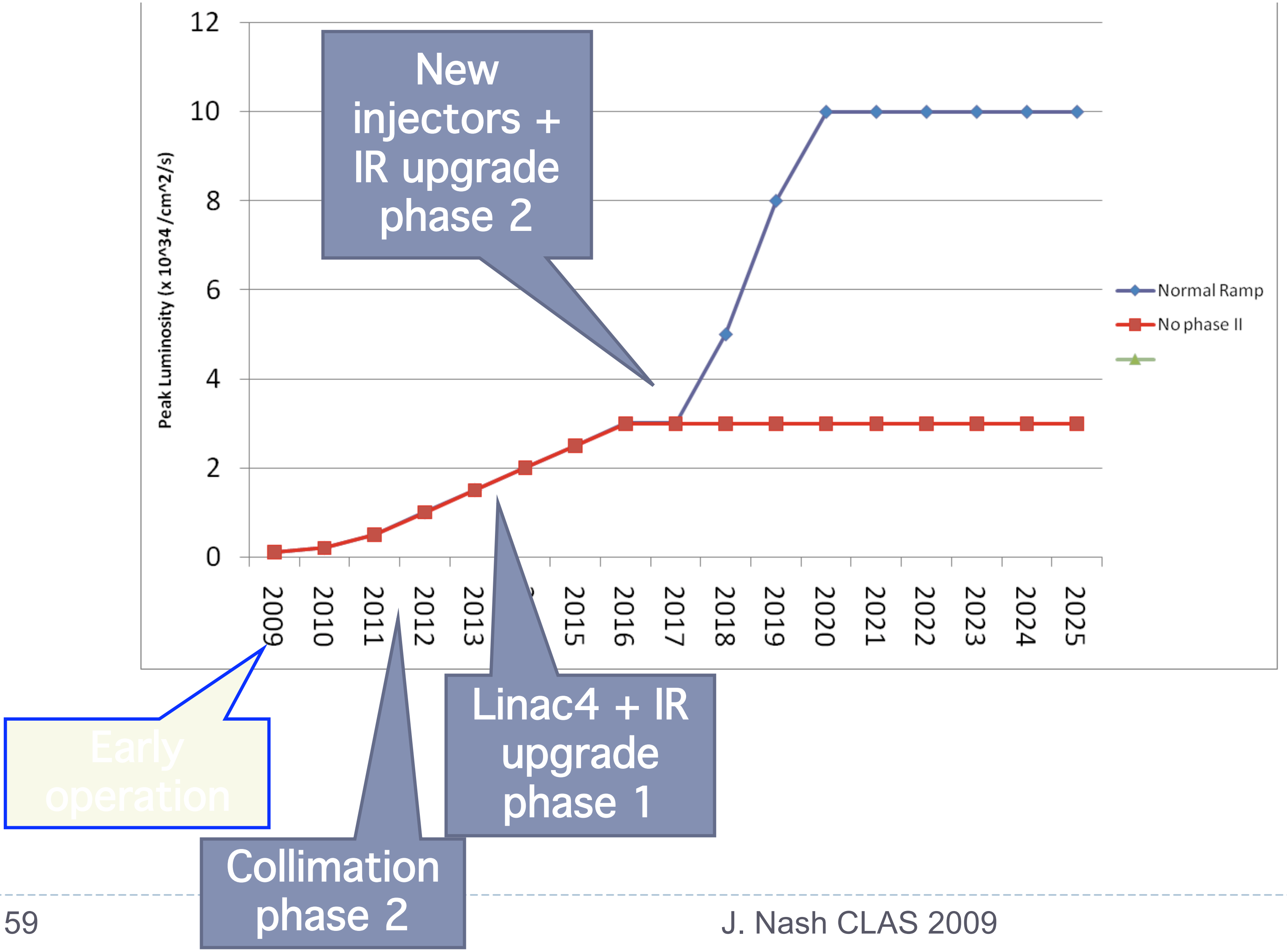
How fast performance is expected to increase:

- 4 y up to nominal *L*
- 4 y up to nominal *L* & 2 y up to ultimate *L*
- 4 y up to ultimate



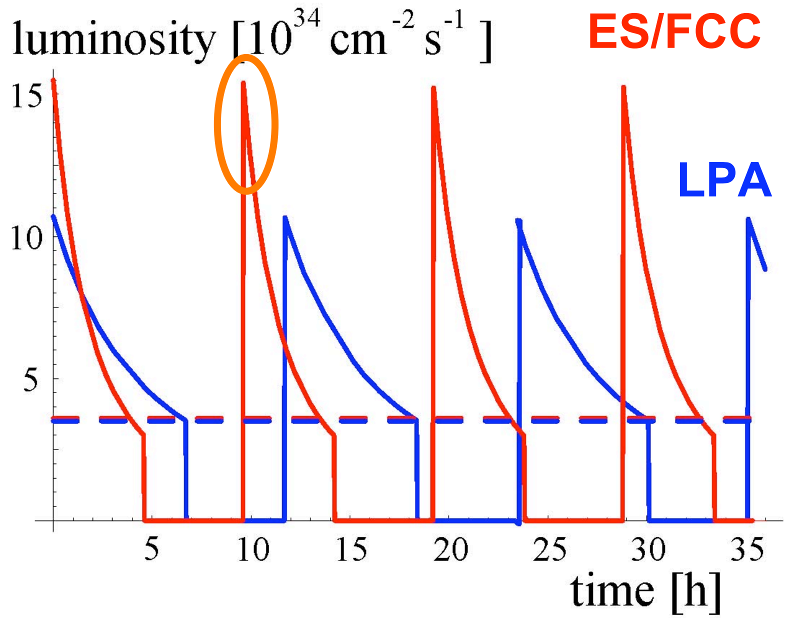
- IR quadrupole lifetime ≥ 8 years owing to high radiation doses
- halving time of the statistical error ≥ 5 y already after 4-5 y of operation
- luminosity upgrade to be planned by the middle of next decade

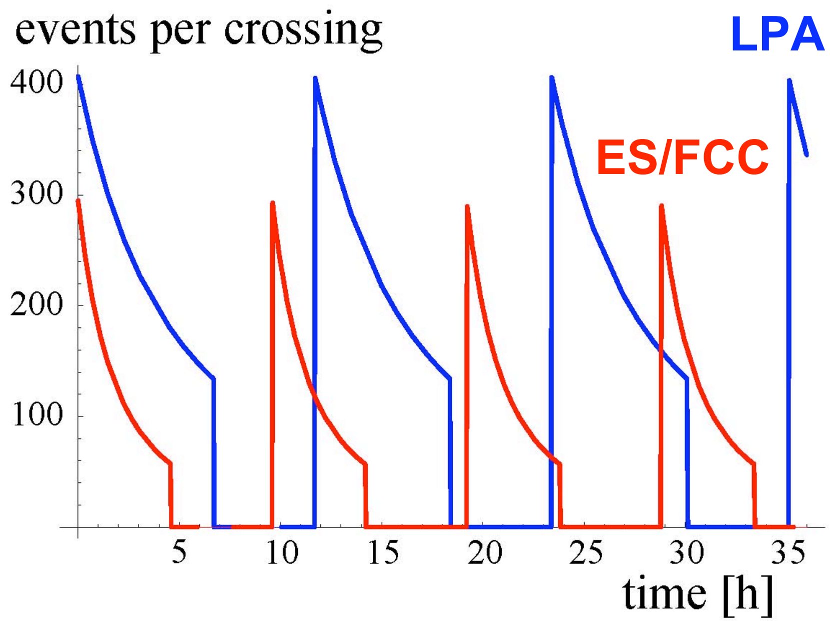
Some current plans for increasing the luminosity



Luminosity evolution for potential schemes

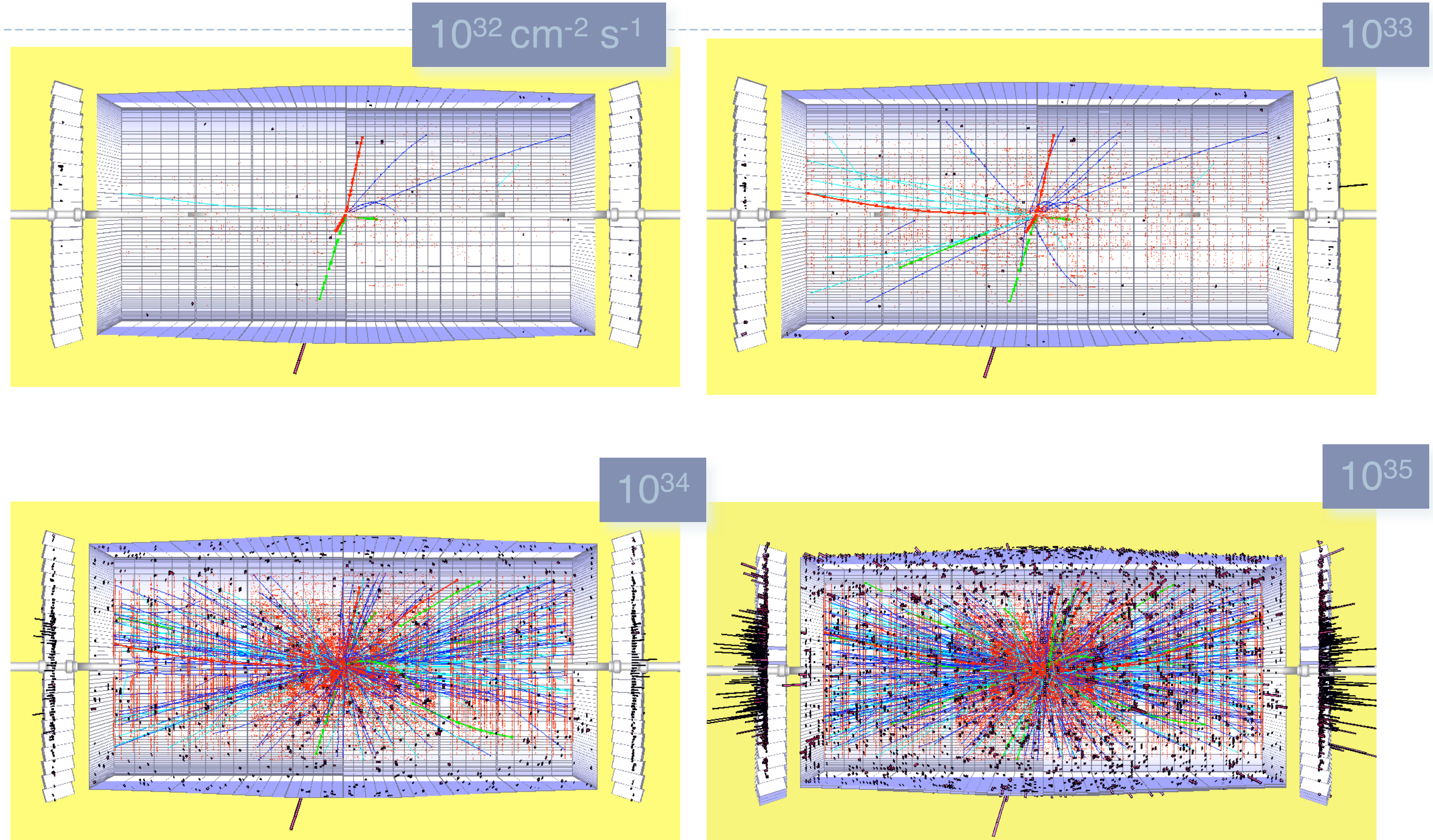
- It may be possible to reach between 10 and 15 times the peak luminosity of the LHC design





- **However the number of underlying events in every corossing can become extremely large**

CMS from LHC to SLHC

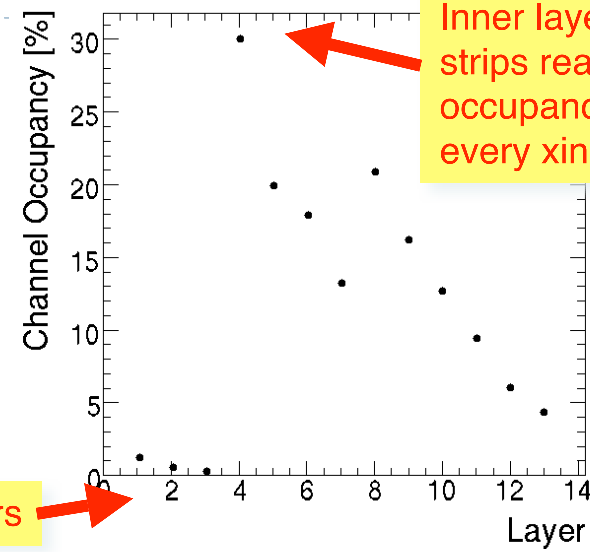


The tracker is the key detector which will require upgrading for SLHC Phase 2

I. Osborne

Tracking with 500 min Bias events

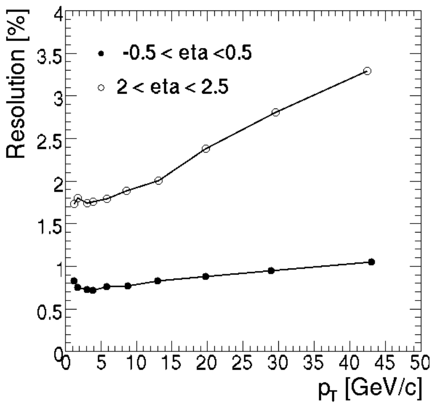
- Study of current CMS tracker for Heavy Ion events
- Track density very similar to 50ns running
  - $dn^{ch}/d\eta$/crossing ≈ 3000
  - Tracker occupancy very high
  - Need more pixel layers/shorter strips
- Tracking possible
  - When tracks are found they are well measured
  - Efficiency and fake rate suffer
  - CPU Intensive



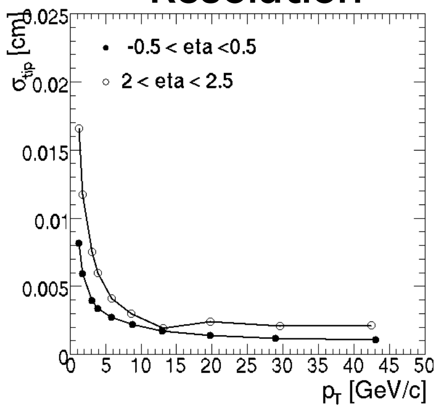
Inner layers of strips reach 30% occupancy on every xing!

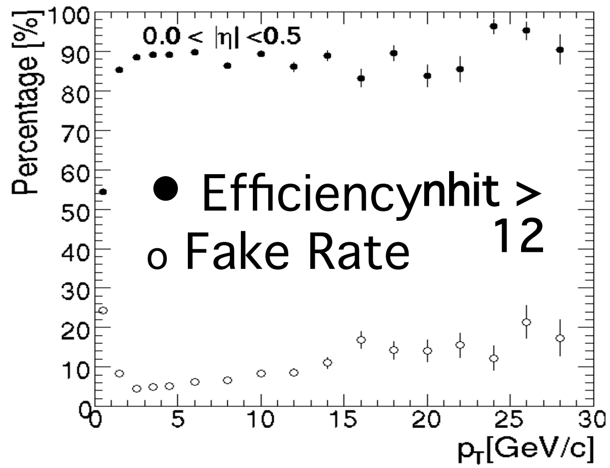
Pixel layers

Momentum Resolution



Transverse Impact Parameter Resolution

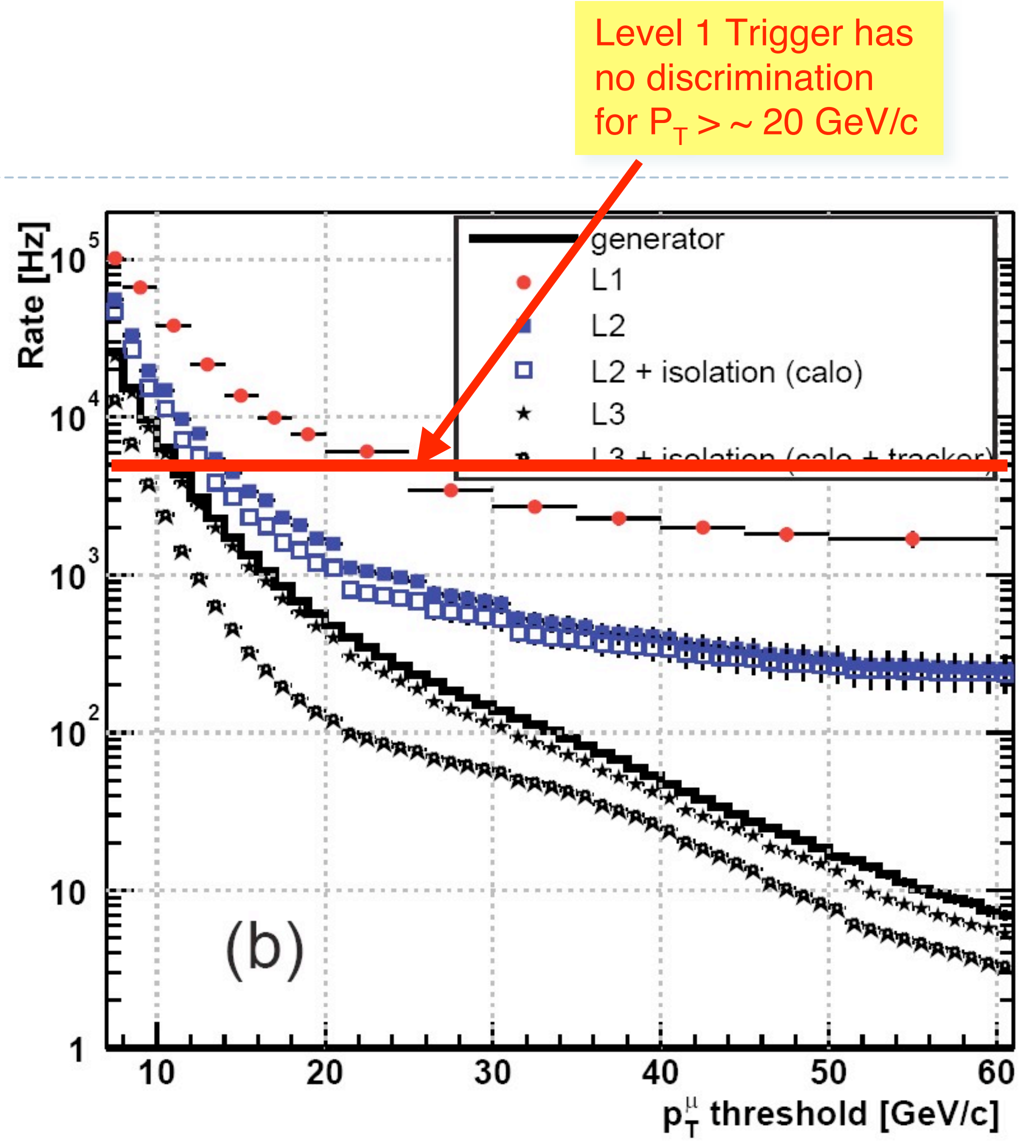




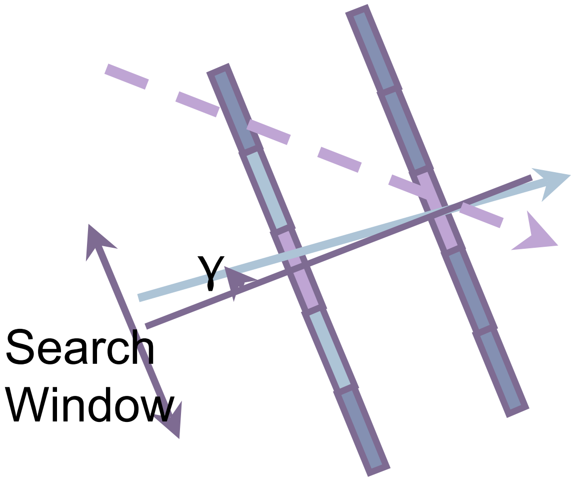
C. Roland

Level 1 Trigger

- One of the key issues for CMS is the requirement to include some element of tracking in the Level 1 Trigger
  - There may not be enough rejection power using the muon and calorimeter triggers to handle the higher luminosity conditions at SLHC
- Adding tracking information at Level 1 gives the ability to adjust P_T thresholds

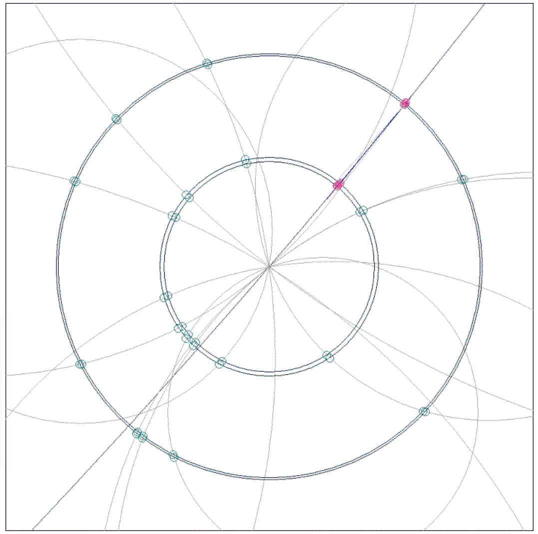


Concepts:Tracking Trigger



High momentum tracks are straighter so pixels line up

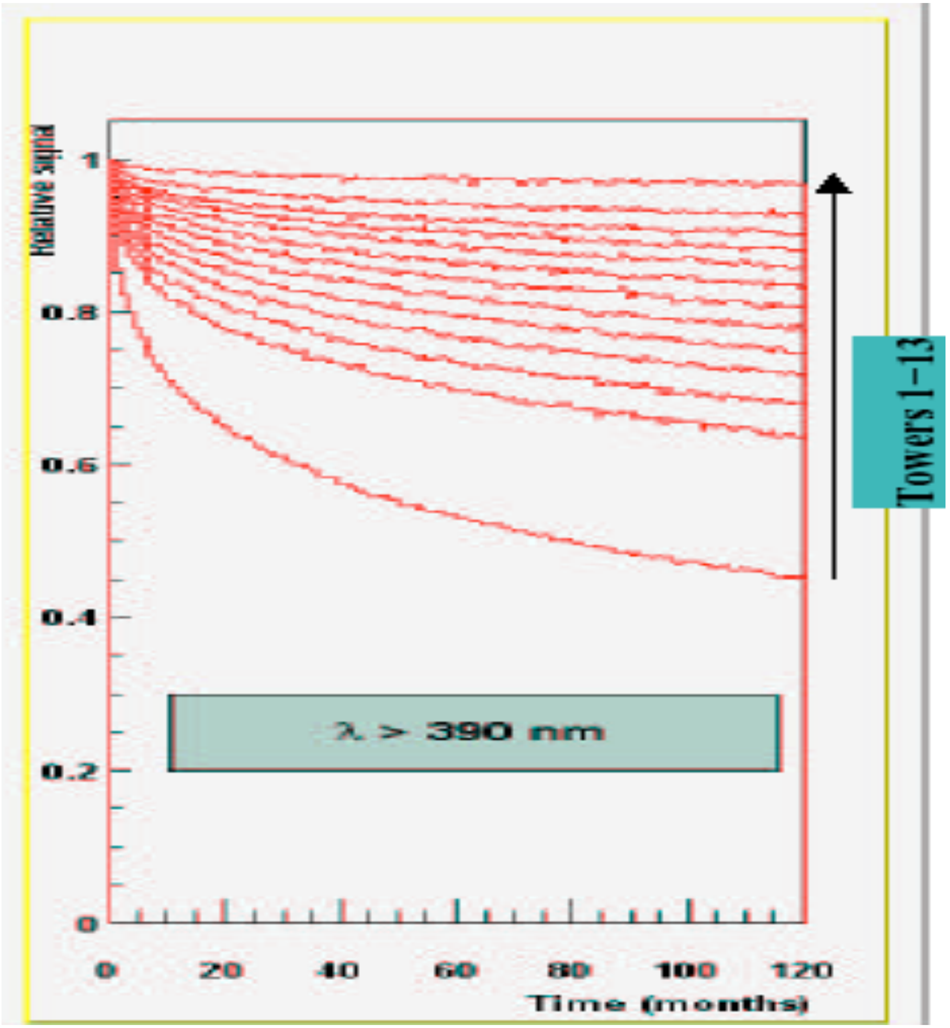
Pairs of stacked layers can give a P_T measurement



Geometrical p_T-cut - J. Jones, A. Rose, C. Foudas LECC 2005

- Why not use the inner tracking devices in the trigger?
  - Number of hits in tracking devices on each trigger is enormous
  - Impossible to get all the data out in order to form a trigger inside
  - How to correlate information internally in order to form segments?
- Topic requiring substantial R&D
  - "Stacked" layers which can measure p_T of track segments locally
    - Two layers about 1mm apart that could communicate

Radiation Damage to calorimeters



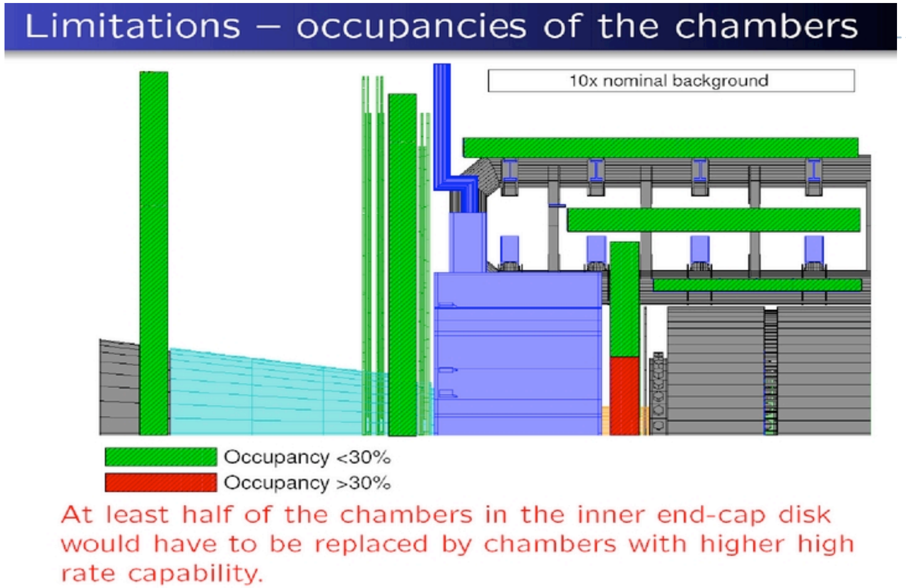
♣Tower 1 loses 60% of light during LHC, down to 4% of original after SLHC.

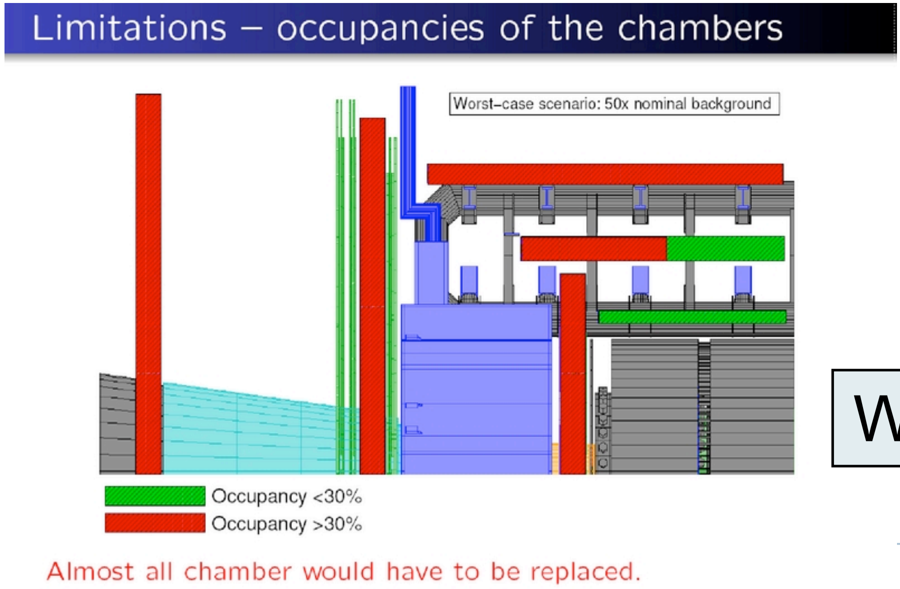
♣ Tower 2 down to 23% after SLHC.

♣SLHC “kills” a few high eta towers.

Andre Gribushin

High Backgrounds rates in the ATLAS Muon detectors



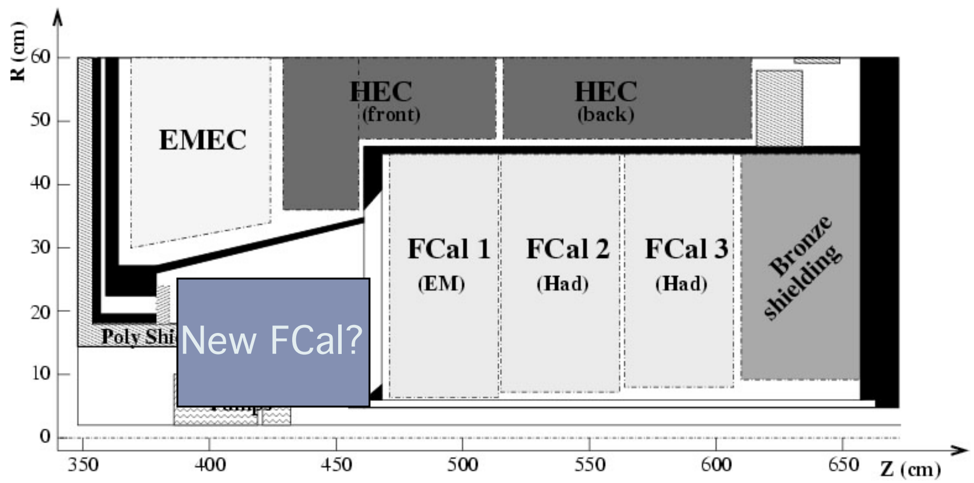


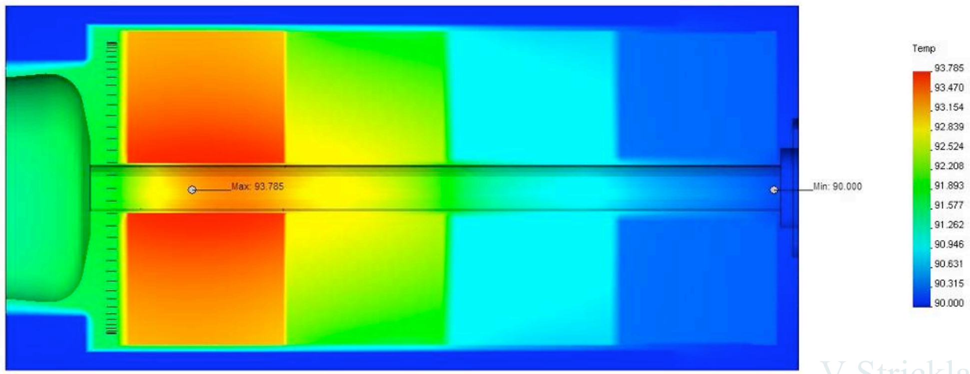
- Background rates very uncertain (~5x)
  - Need LHC experience
- Start before LHC:
  - Aging studies
  - Rad hard electronics
  - Selective readout
  - High-rate chamber prototypes
- Use existing chambers as far as possible

Worst case

ATLAS Forward calorimetry

- However, FCAL (|η|>3.1) particularly subject to beam radiation
- Simulation of LAr FCAL beam heating (pessimistic case)
- Maximum temperature 93.8K – enough to boil LAr
- Uncertainties in heat load, convection could make things better or worse; other endcap calorimeters also implicated
  - Improve FCAL cooling (open endcap cryostat)
    - Big challenge
  - New "warm" FCAL plug?





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