Review on EM calorimetry

Collider calorimetry today: status and possible developments

Speculations on the future needs

Apologies: in order to be focused on issues related to performance at extreme colliders I will consider only ATLAS and CMS as representative of current baseline. This does not imply any quality judgment on the variety of extraordinary calorimeters available on the HEP market today

Framework

- Present colliders: Lumi $10^{34}cm^{-2}s^{-1}$, E=14 TeV, bunch spacing 25 ns
- Future colliders:
  - – Minimal (SLHC): Lumi $10^{35}cm^{-2}s^{-1}$, E=14 (28) TeV
  - – Maximal(Eloisatron,VLHC): Lumi 10^{35}-$10^{36}cm^{-2}s^{-1}$,E=100 TeV

  Possibly with bunch spacing < 5ns
- Keep in mind that physics is the driver (and today we do not really know what is in store past LHC)

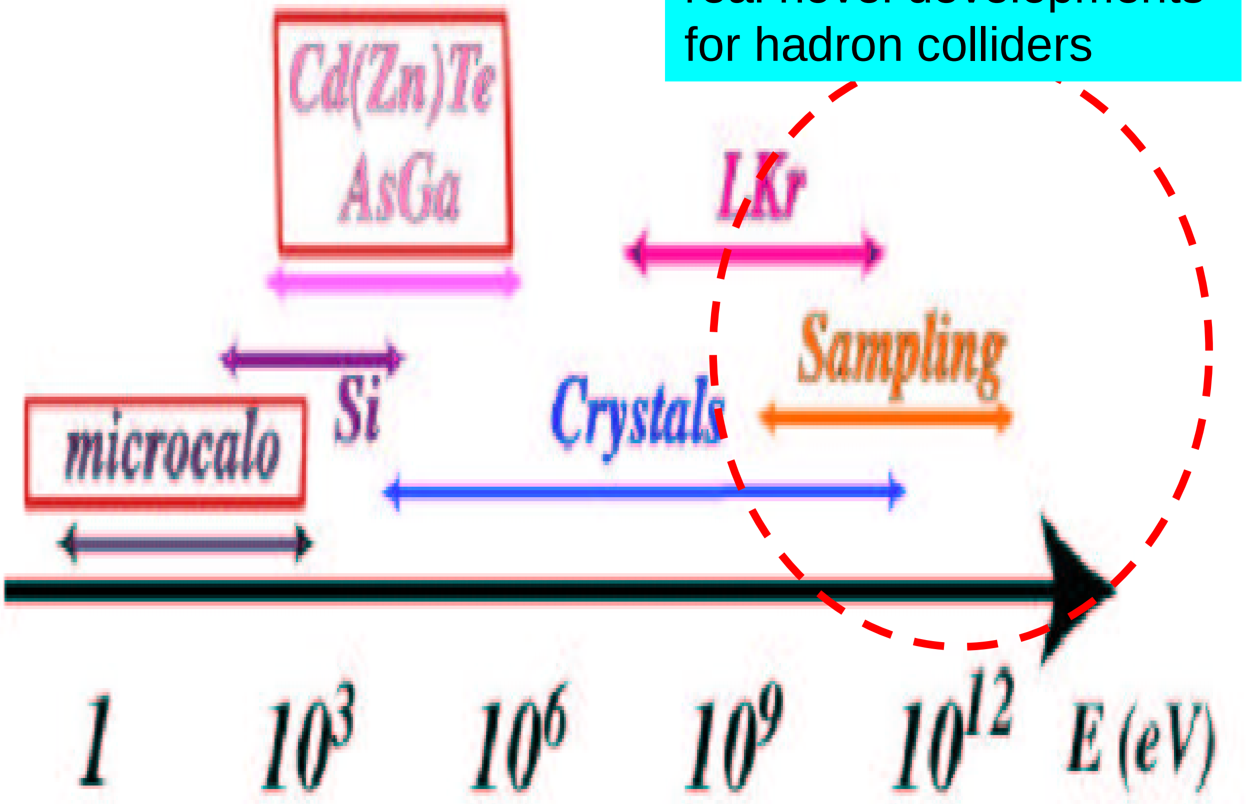
Major constraints

- Radiation: up to and beyond 100 MRad: major constraint for any calorimeter technique and for electronic readout
- Time response: present day electronics barely copes with bunch structure
- Pileup of interactions (>20 interactions/crossing @LHC)

Photon detection with calorimeters

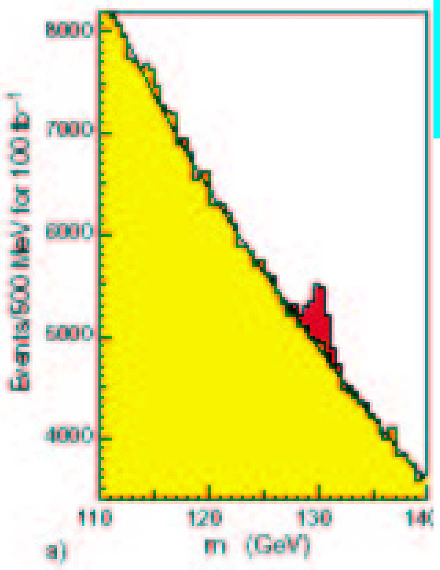
Substitute for Heat:

Ionization charge
Scintillation light
Cerenkov light
Phonons
Sound waves
Activated halides
Radiation Damage
Nuclear Transmutation
Neutron Flux
Shock Wave
Seismic Waves
….



HEP area of interest: well established… no real novel developments for hadron colliders

LHC calorimeters



- Main physics manifesto: low mass higgs decaying into $\gamma\gamma$ (reject π^0,good energy and angular resolution for mass reconstruction and primary vertex identification). In reality a bit of an excuse: with material budget in excess of 1 X_0 (in a multi Tesla field) the bare calorimeter performance is less important. Nevertheless the implied fine grain and projectivity are a must to cope with the particle flow

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

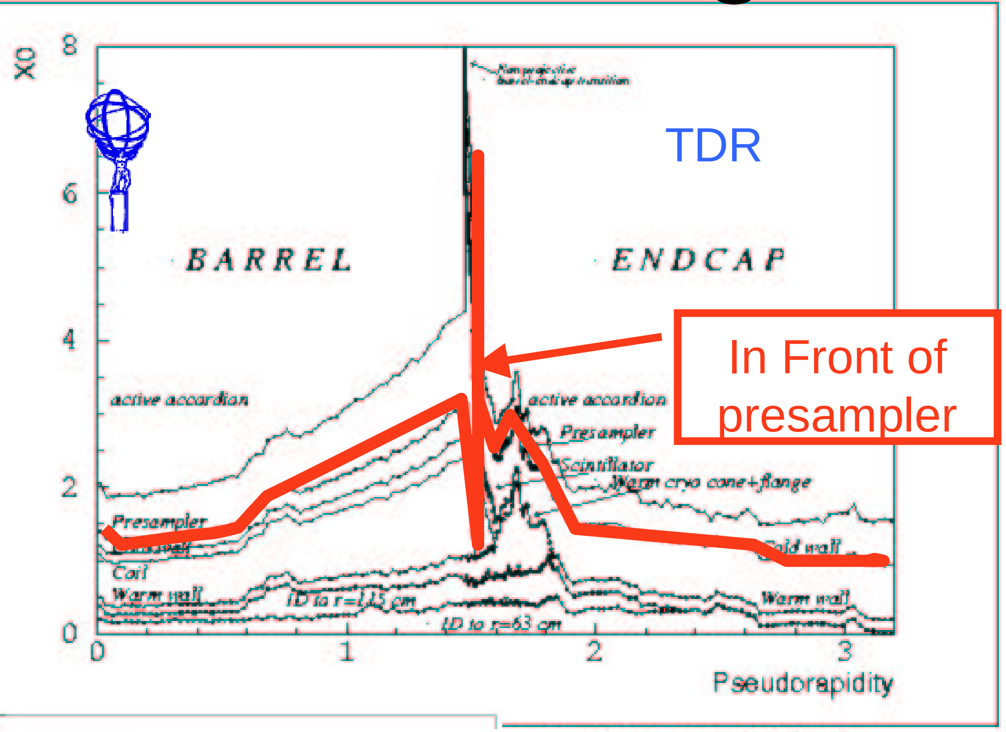
Sampling,leakage, ~~Landau~~,intrinsic

Inhomogeneities, intercalibration, effect of material in front

Noise,pileup, radioactivity

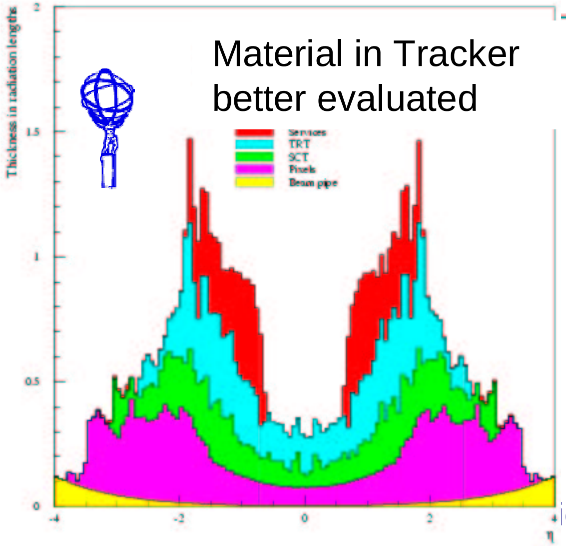
Goal: c<10%, b<1%

Material budget

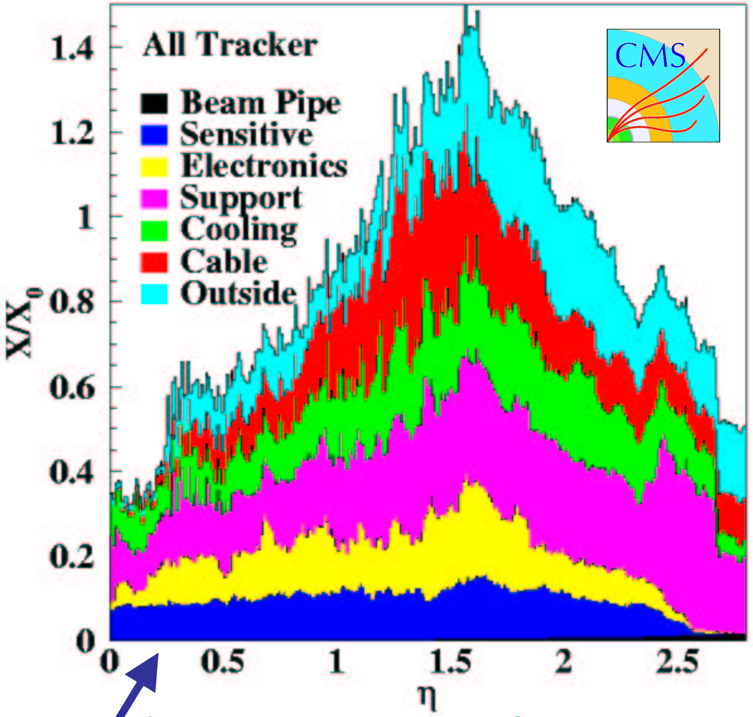


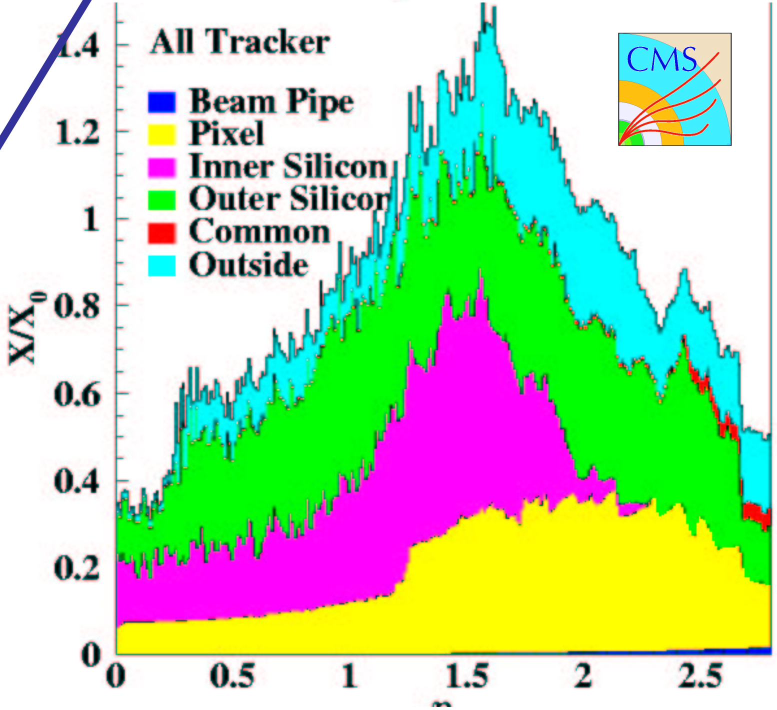
In Front of presampler

calorimeter, as a function of η.



Material in Tracker better evaluated

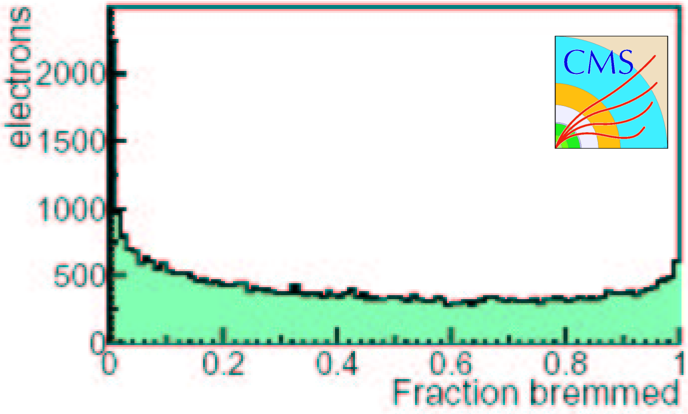


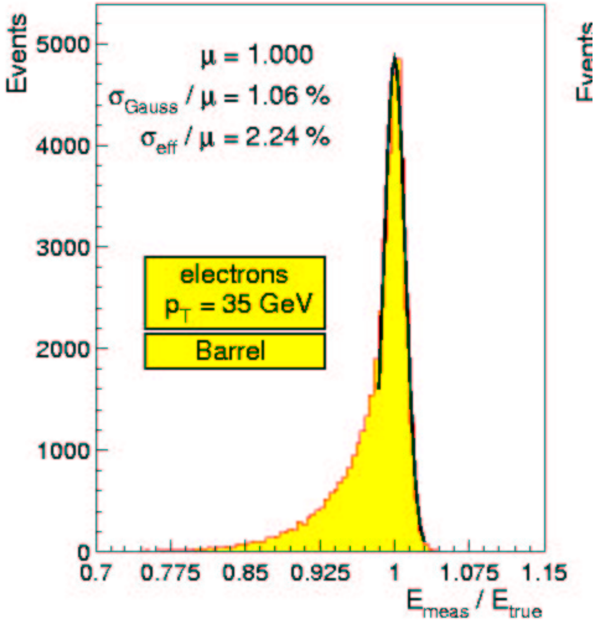


Tracker R&D should look after infrastructure more than sensor material budget !

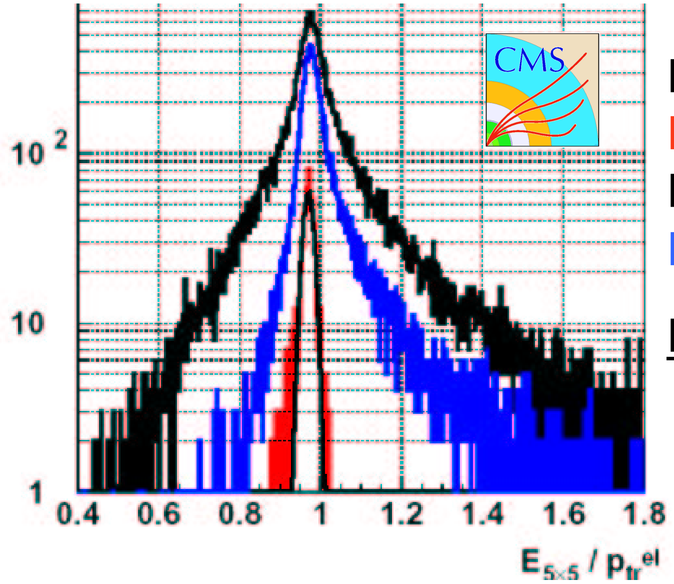
Effect of material in front of calorimeter

CMS MC: 35 GeV p_t electrons, η<1.5 (courtesy C. Seez)





Worst effect is not so much energy lost, but the confusion induced by the brem spray.



E/p for simulated W to eν evts in CMS

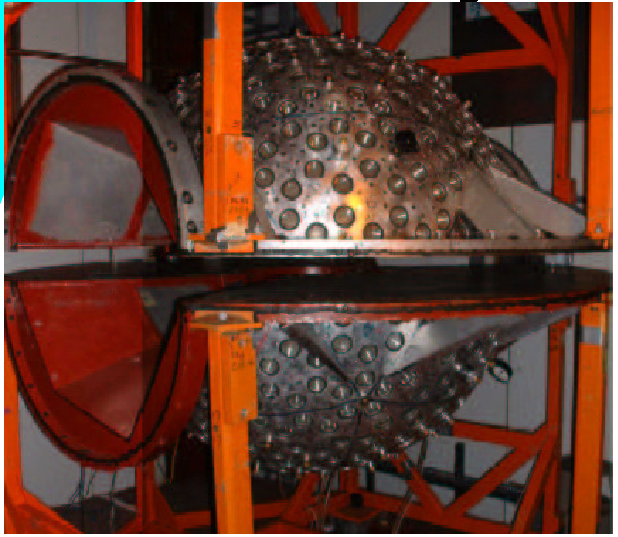
Red no brems

Black no selection

Blue pattern reco cuts to reject hard brem

<u>Energy tails are smaller than momentum tails</u>

Homogeneous Calorimeters: crystals (CMS, ALICE)

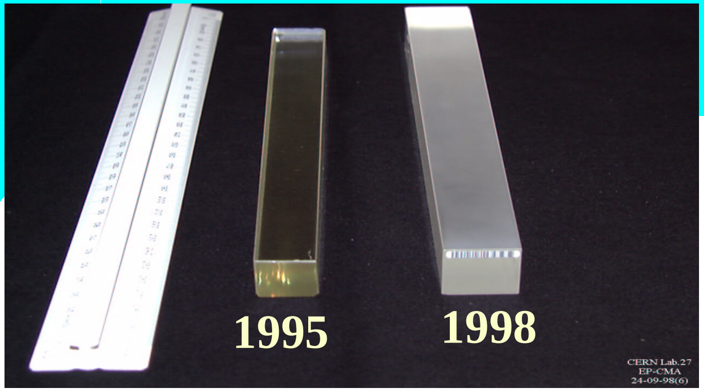


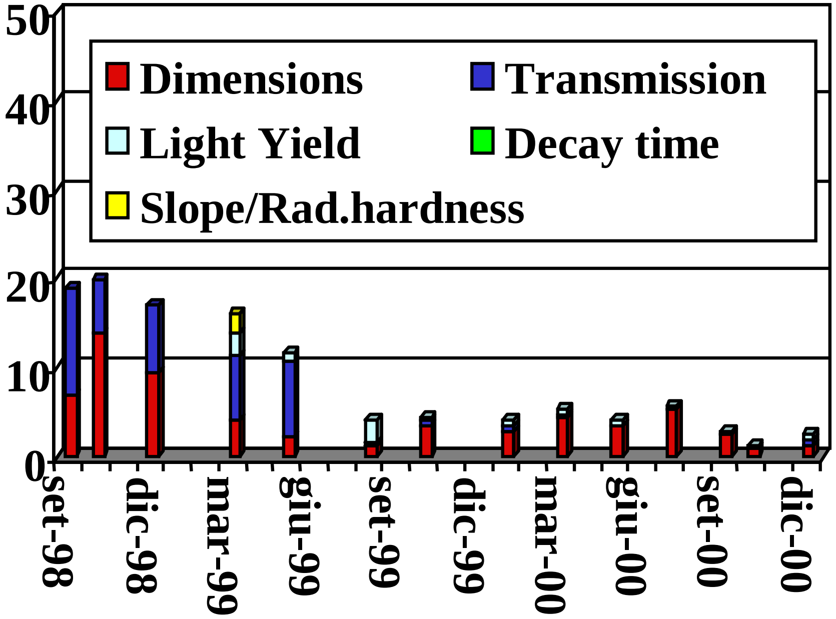
Crystal Ball, Spear, 1978

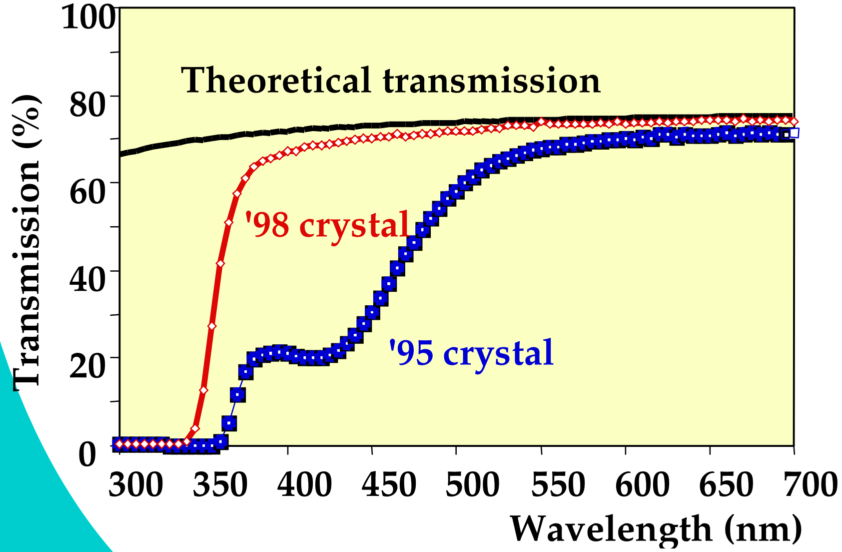
Crystal		NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	CeF_3	$PbWO_4$	
Density	$g.cm^{-2}$	3.67	4.51	4.51	4.89	7.13	6.16	8.28	
Rad. length	cm	2.59	1.85	1.85	2.06	1.12	1.68	0.89	☺
Moliére radius	cm	4.5	3.8	3.8	3.4	2.4	2.6	2.2	
Int. length	cm	41.4	36.5	36.5	29.9	22.0	25.9	22.4	
Decay Time	ns	250	1000	35	630	300	10-30	<20>	☺
				6	0.9				
Peak emission	nm	410	565	420	300	480	310-340	425	☺
				310	220				
Rel. Light Yield	%	100	45	5.6	21	9	10	0.7	☹
				2.3	2.7				
d(LY)/dT	$\%/^{0}C$	˜ 0	0.3	- 0.6	- 2	- 1.6	0.15	-1.9	☹
					˜ 0				
Refractive Index		1.85	1.80	1.80	1.56	2.20	1.68	2.16	

Major advances in last decade:
eg. L3 11000 crystals, 1.1 μs, homogeneity 1%
vs CMS 100000 crystals, 50 ns, 0.4% homogeneity!)

PBWO crystals have come a long way





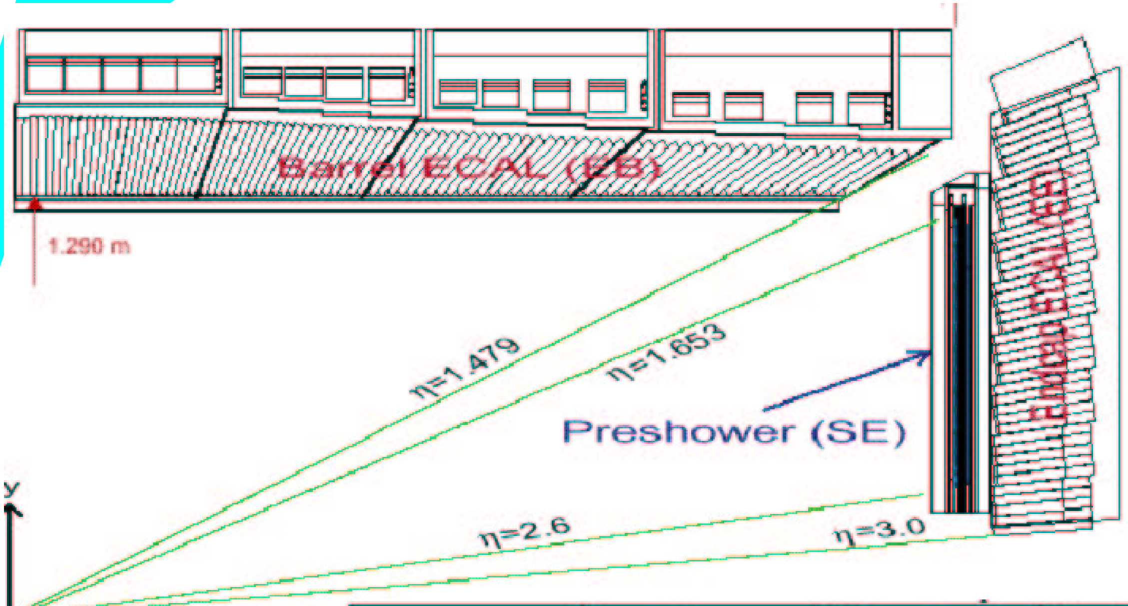


◆1994-1998 R&D phase

◆1998-2000 : Pre-Production of 6000 crystals

◆2001 : Start of the Production

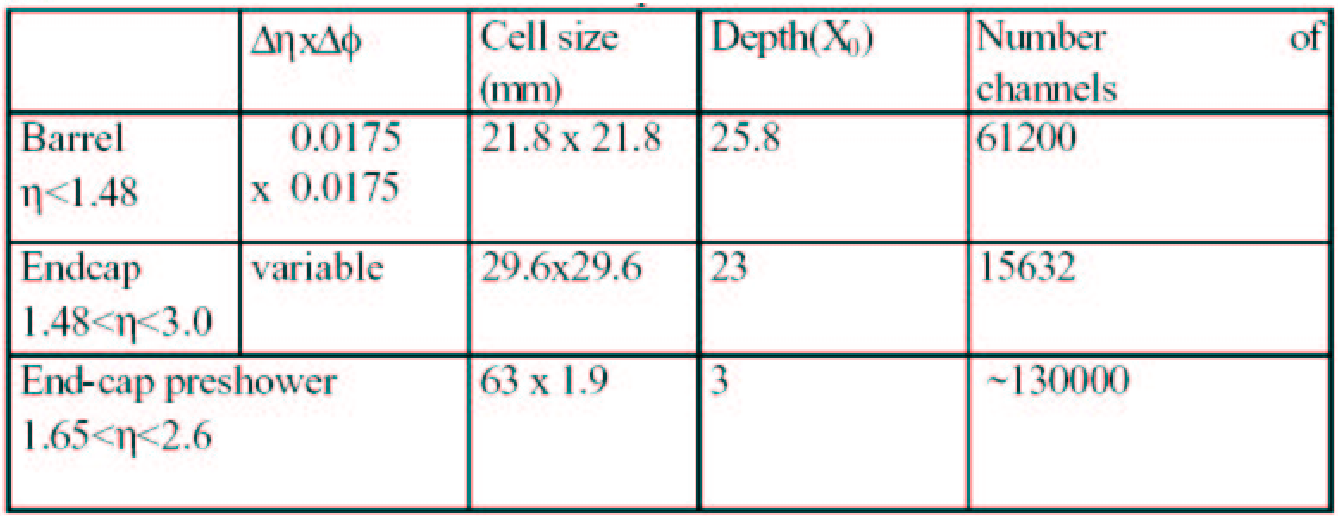
CMS calo structure



- PWO Light Yield is rather low: ~10 pe/MeV

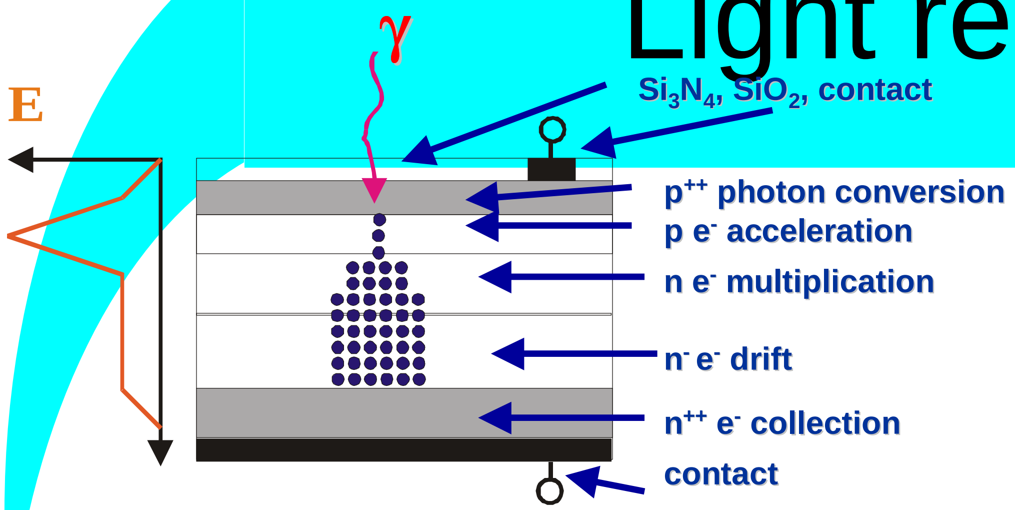
so photon sensors with some amplification are needed (Avalanche PhotoDiodes in the barrel, VacuumPhotoTriodes in the Endcap)

⇒Low S/N ratio and complex electron



	$\Delta\eta \times \Delta\phi$	Cell size (mm)	Depth(X_0)	Number of channels
Barrel $\eta<1.48$	0.0175 x 0.0175	21.8 x 21.8	25.8	61200
Endcap $1.48<\eta<3.0$	variable	29.6x29.6	23	15632
End-cap preshower $1.65<\eta<2.6$		63 x 1.9	3	~130000

Light readout



Si_3N_4, SiO_2, contact

p^{++} photon conversion

p e^- acceleration

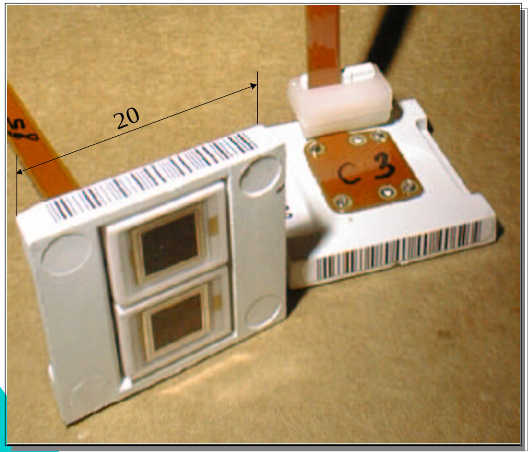
n e^- multiplication

n^- e^- drift

n^{++} e^- collection

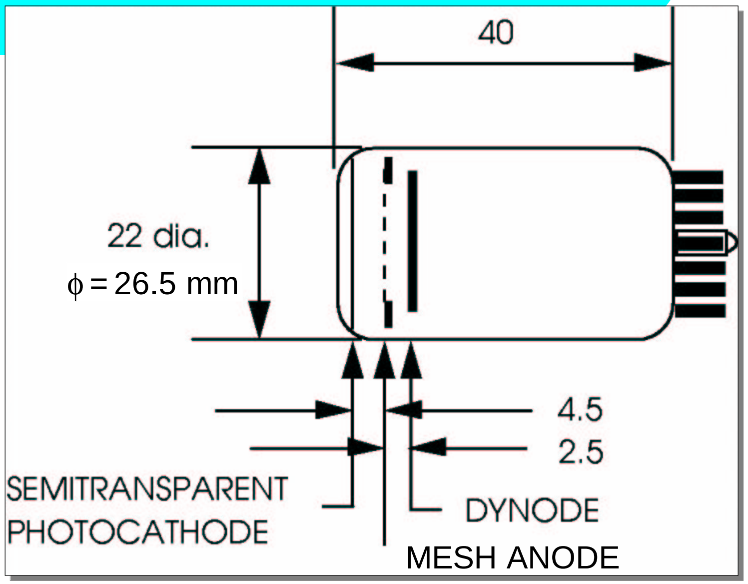
contact

Internal gain=50 for V=380 V



Two APDs per capsule

Barrell: 50% delivered



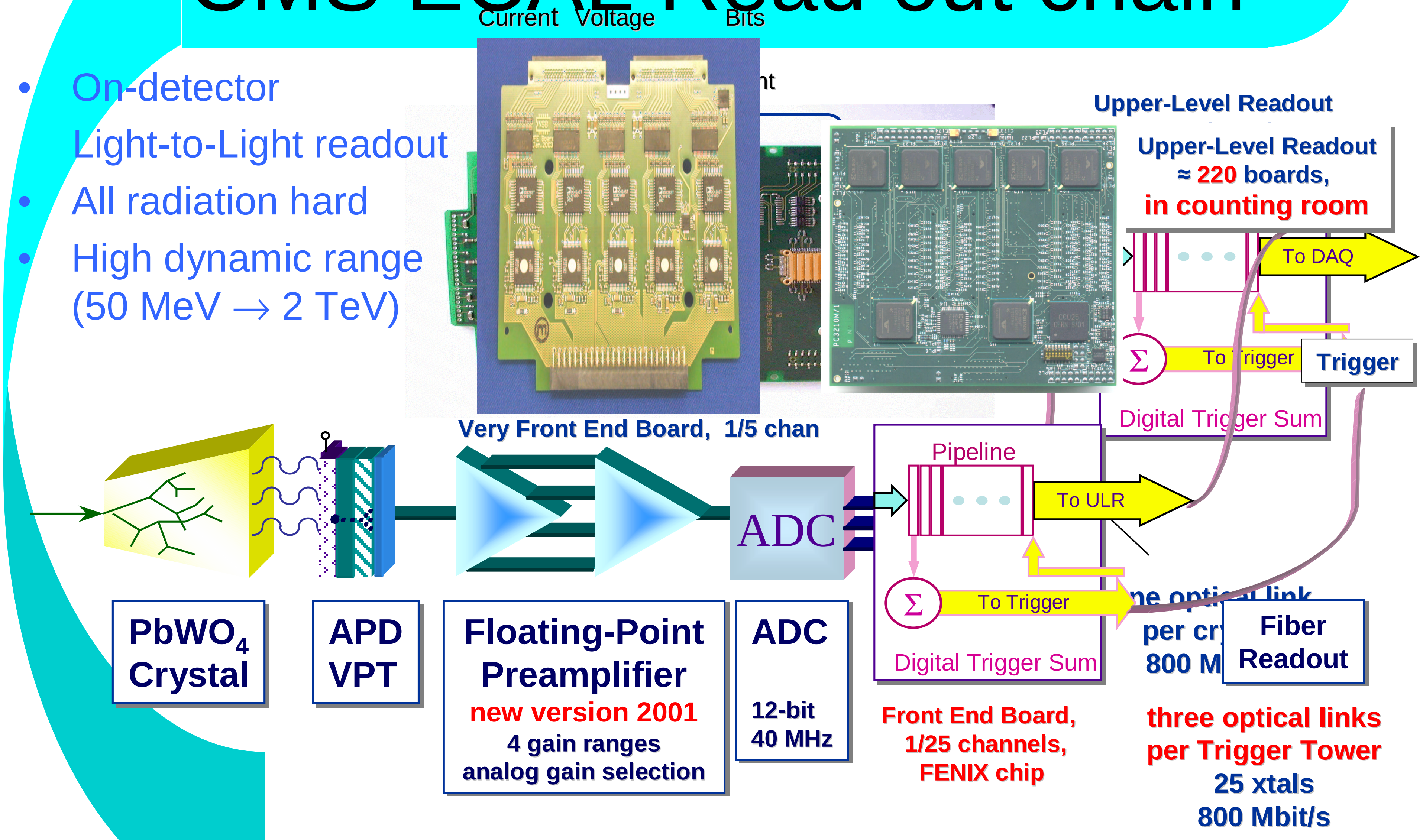
Single stage photomultiplier tube

ENDCAP:
25% delivered

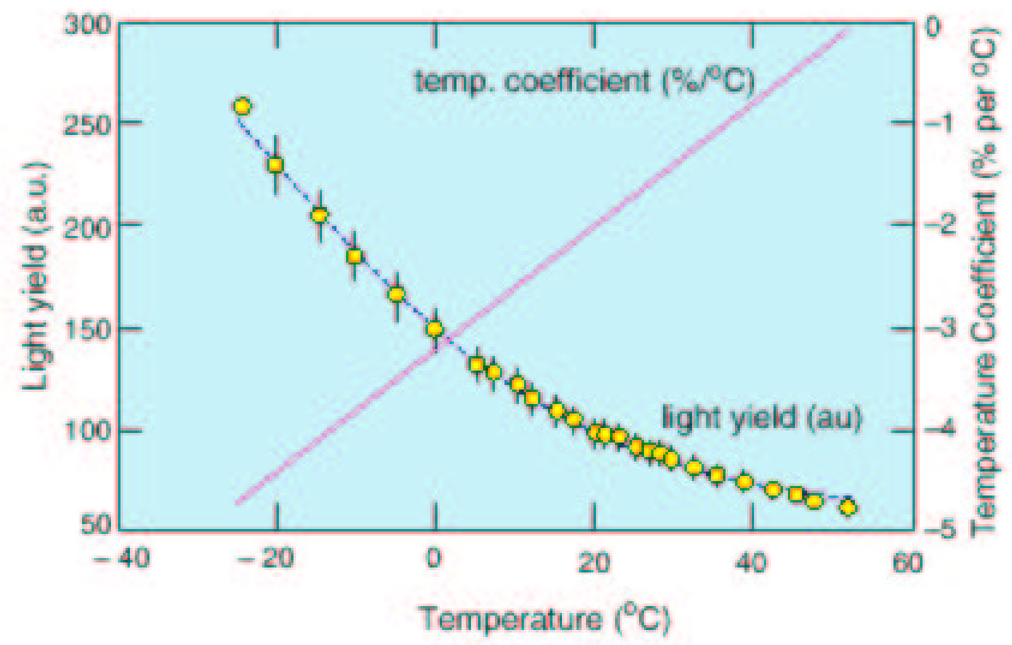
Gain 8-10 at B=4T, QE ≈ 20% at 420 nm

CMS ECAL Read out chain

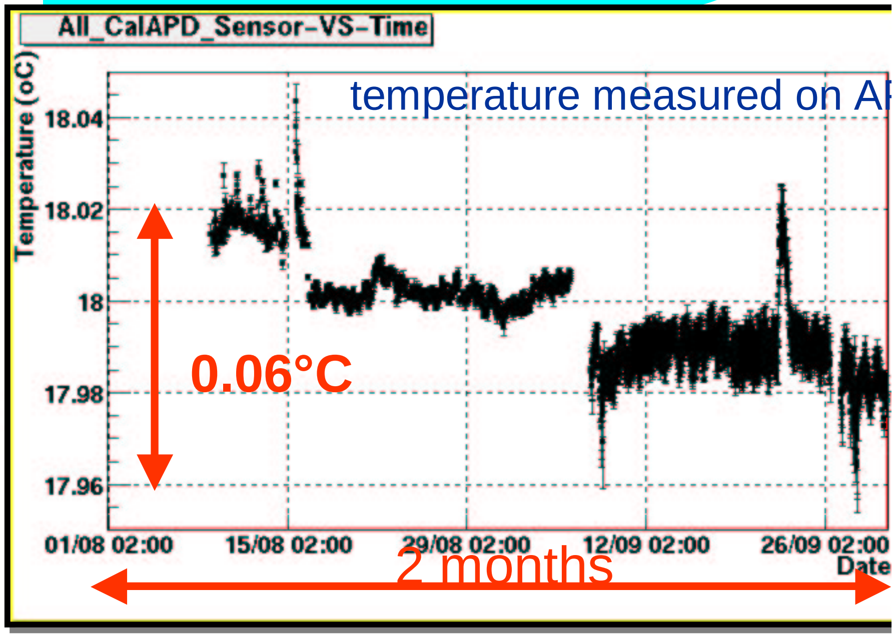
- On-detector
  Light-to-Light readout
- All radiation hard
- High dynamic range
  (50 MeV → 2 TeV)



CMS ECAL features



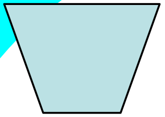
Light yield dependance from T -2%/C



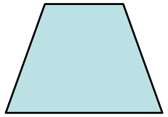
Challenge: 92300 kg of crystal dissipating 200 KW… and temp controlled to 0.1 degrees

Separate cooling for crystals and electronics

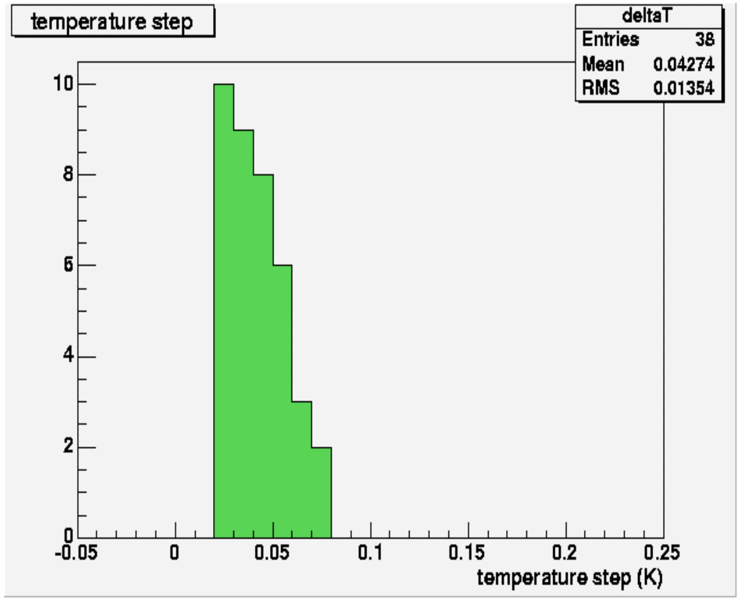
T control to < 0.1 C

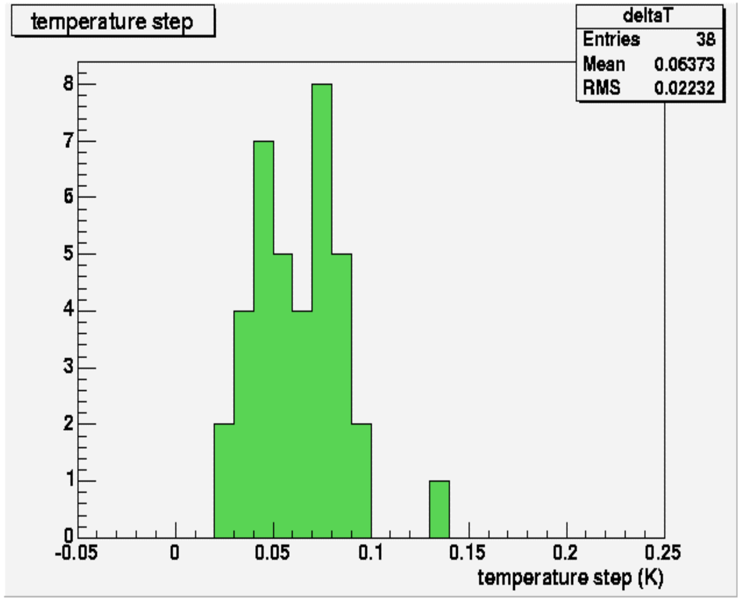


12 o’clock



6 o’clock



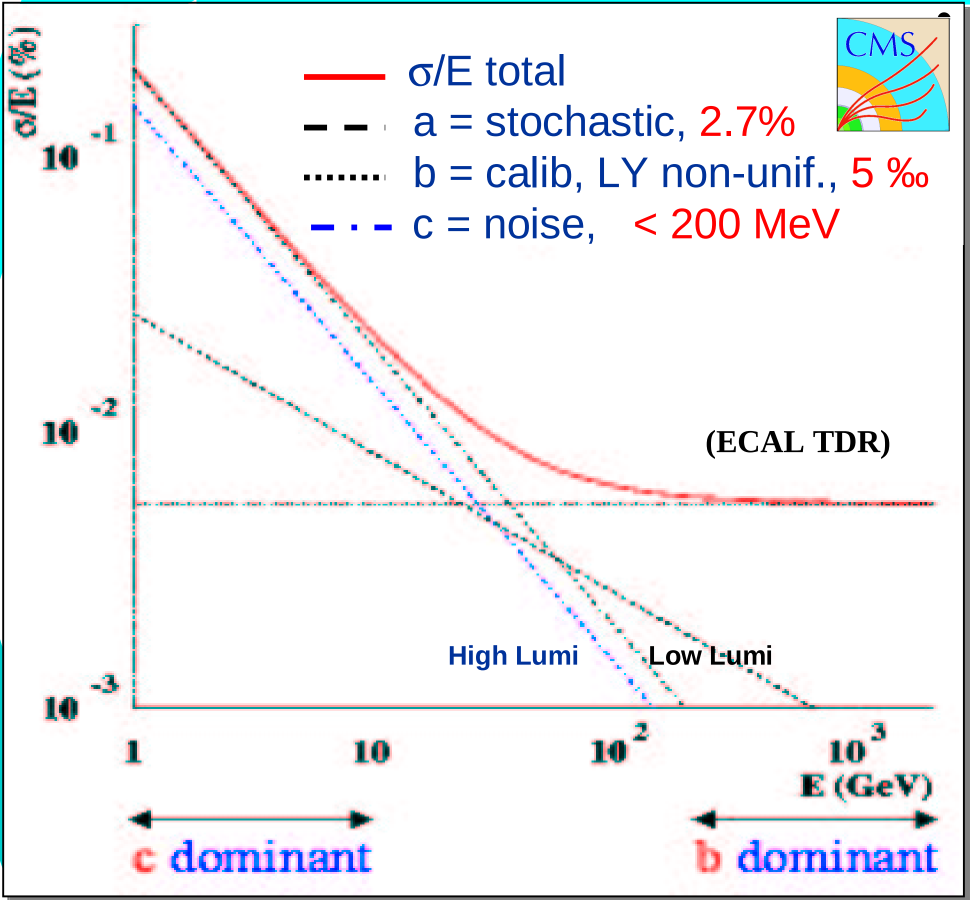


w/o cavalier

w/o cavalier

Small convection effect, <0.02ºC>

CMS Resolution



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

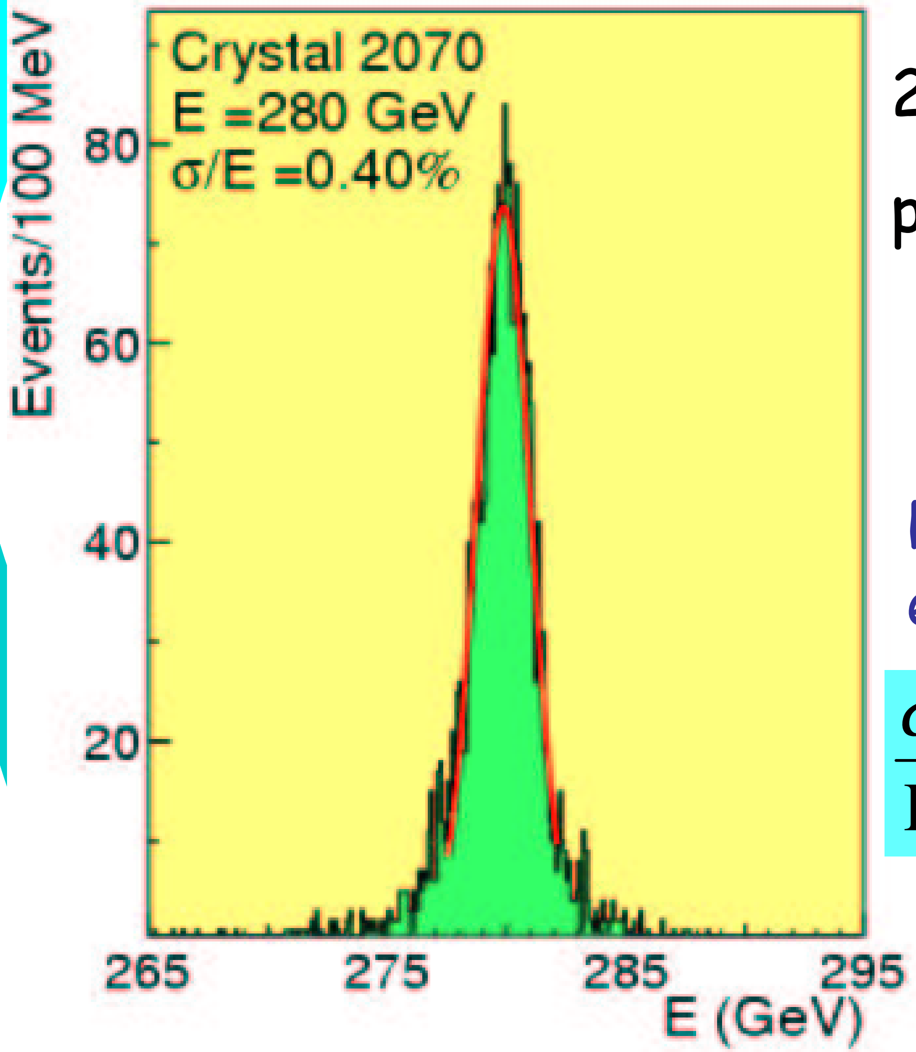
If you want precision…

- **Longit. and lateral shower containment**
- **Light production, collection uniformity**
- **Nuclear counter effect (APD)**
- **Stability of PD gain**
- **Channel to channel intercalibration**
- **Electronic noise**
- **Temperature stability and uniformity**
- **Radiation damage**
- **Pileup**
- **…**

Stochastic term
dominated by photon statistics

Test-beam performance

The single crystal can achieve the goal



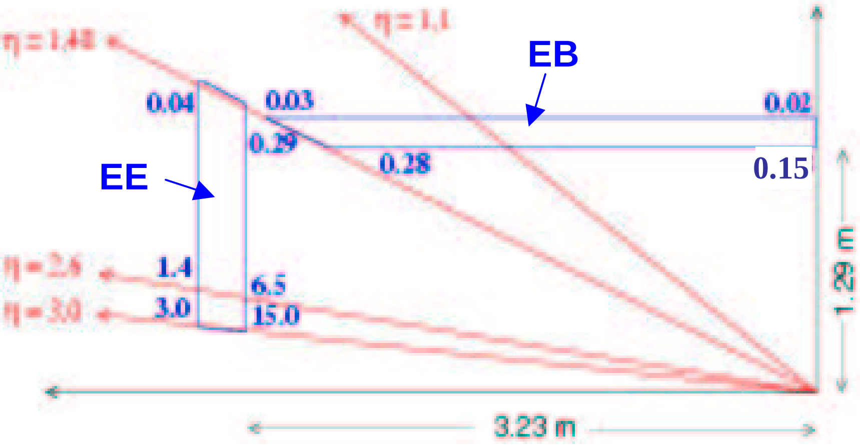
280 GeV electrons

preprod. crystals (1999)

Resolution as a function of energy

$$\frac{\sigma}{\mathrm{E}} = \frac{2.74\%}{\sqrt{E}} \oplus 0.40\% \oplus \frac{142\,MeV}{E}$$

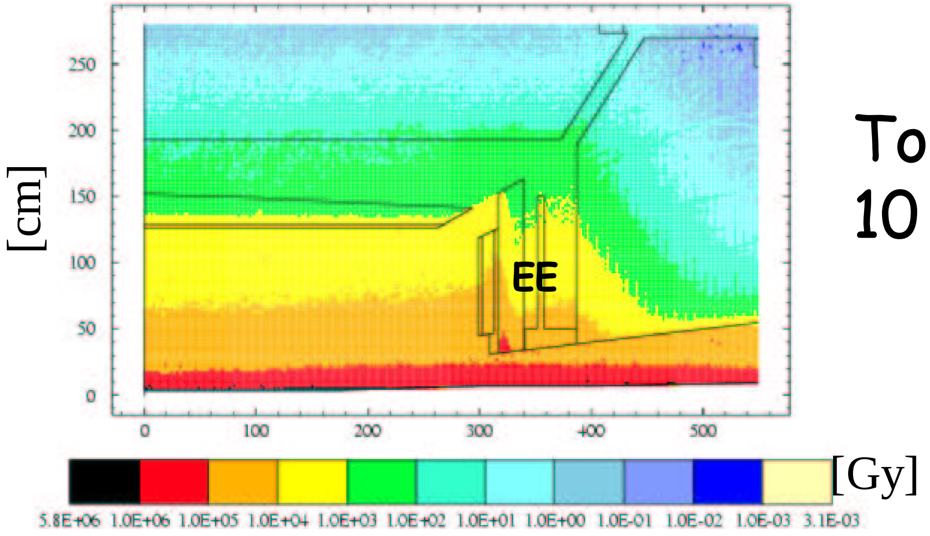
CMS Ecal rad dam



Dose rates [Gy/h] in ECAL at luminosity L=$10^{34}cm^{-2}s^{-1}$

Dose rate at high L in the Barrel is 0.15 - 0.3 Gy/h in the Endcaps 0.3-15 Gy/h

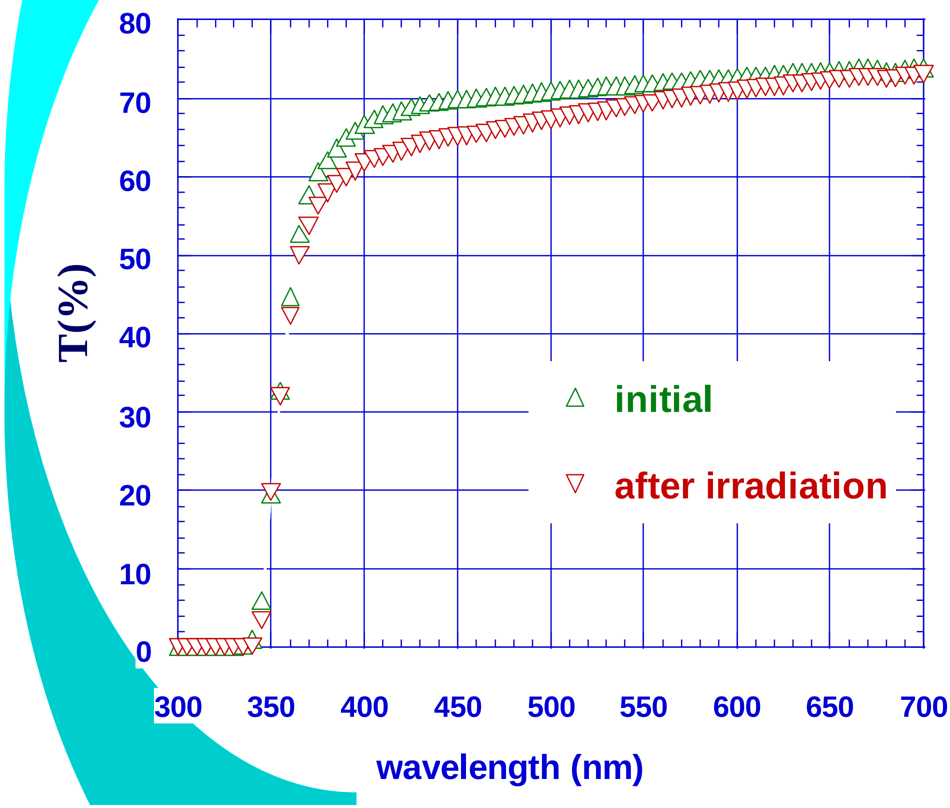
Total dose after 10 years of running ($5x10^5$ pb^{-1})



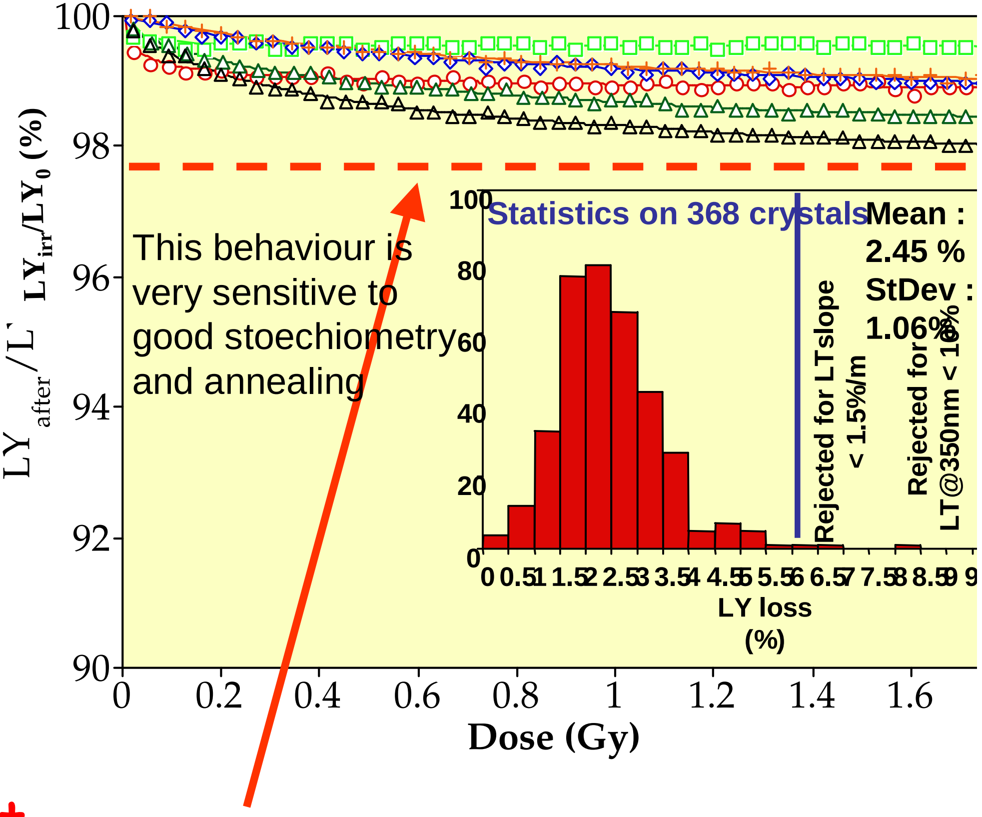
Total dose in the barrel after 10 years at the LHC is ~$2*10^3$Gy

CMS ECAL rad dam

Front irrad., 1.5Gy, 0.15Gy/h



$LYloss=(LY_0-LY_{irr})/LY_0$ (%)



This behaviour is very sensitive to good stoechiometry and annealing

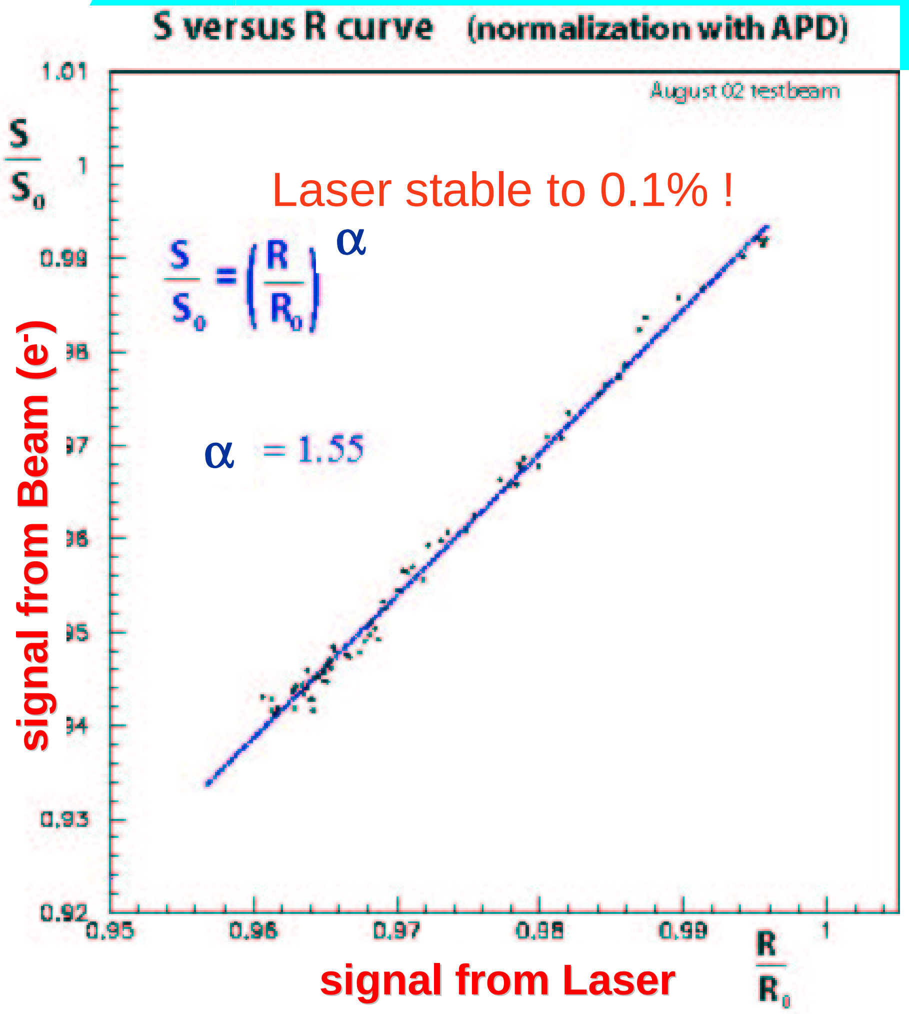
1) Scintillation mechanism not affected but Transparency loss

2) Saturation level (reached after a few hours of LHC!)

Radiation damage certification

- **Irradiation of ingot’s top and bottom parts**
  - All crystals
  - At Bogoroditsk
  - To control radiation hardness uniformity
- **High dose & dose rate side irradiatio (induced absorption at all λ)**
  - Sampling (20%)
  - At Bogoroditsk after March 99
  - To control absolute radiation hardness a uniformity (att > 75 cm)
- **Transverse transmission along the crystal**
  - All crystals
  - At Bogoroditsk and at CERN
  - To control doping uniformity
- **Longitudinal transmission band edg slope**
  - All crystals
  - At Bogoroditsk and at CERN
  - To predict radiation hardness
- **High dose & dose rate side irradiation (induced absorption at all λ)**
  - Sampling (20%)
  - At Geneva hospital (CERN)
  - To control absolute radiation hardness & uniformity
- **Low dose rate front irradiation (LY loss)**
  - Sampling (20%)
  - At CERN (TIS)
  - To control radiation hardness in LHC conditions
- **Low dose rate side irradiation (transmission loss at ≠ λ)**
  - Sampling (20%)
  - At CERN (X5)
  - To control radiation hardness uniformity

Laser monitoring

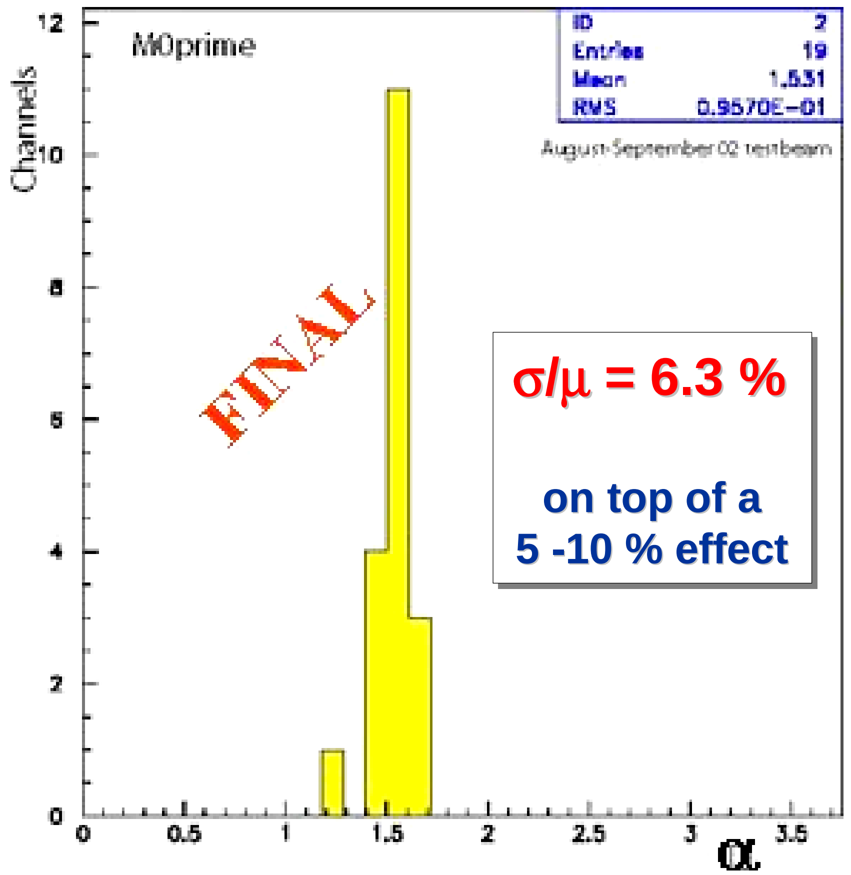


Laser stable to 0.1% !

$$\frac{S}{S_0} = \left(\frac{R}{R_0}\right)^{\alpha}$$

$\alpha = 1.55$

Dispersion of α for 19 crystals



σ/μ = 6.3 %

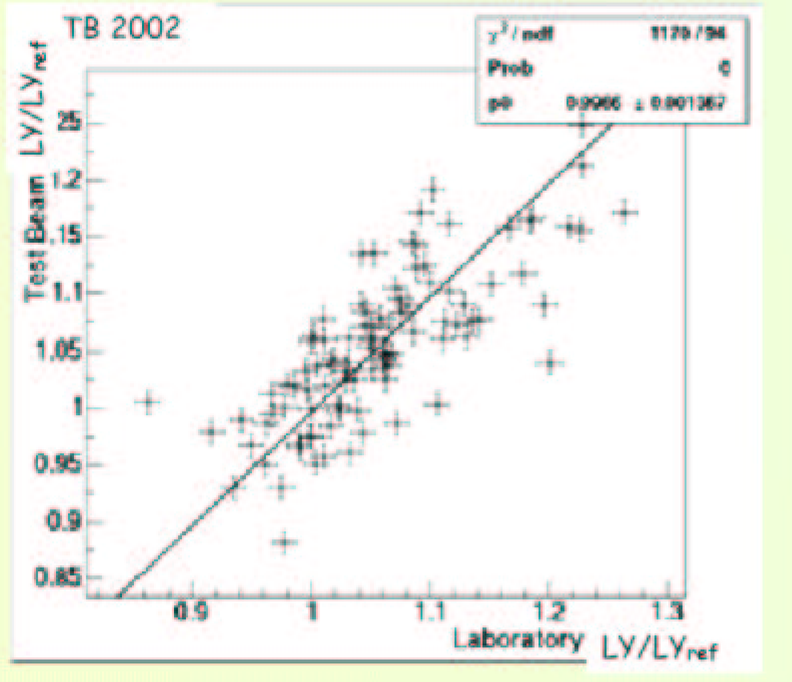
on top of a
5 -10 % effect

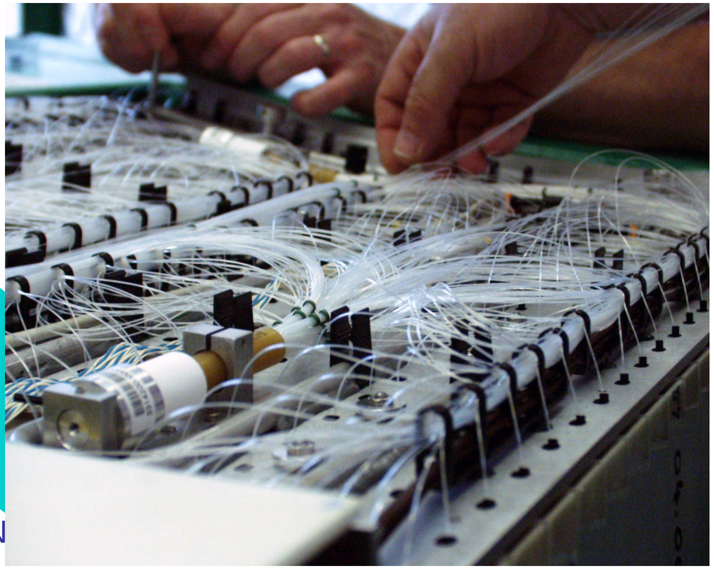
⇒ Use of same coefficient for
⇒all crystals possible !...and no need of pre-irradiaton

Measure relative light loss after/during irradiation for beam and laser: laser can be used to track changes (and parametrization is straighforward)

Calibration

- As most of shower is contained in a single crystal the precision of the absolute intercalibration of single crystals contributes directly to the constant term. Due to project delay and the stop of the beams at CERN in 2005 only few of the crystals will be calibrated on beam. For the startup will have to rely on pre-calibrations done in the lab (~2-4%).
- The in situ calib using physics events will have crucial importance!



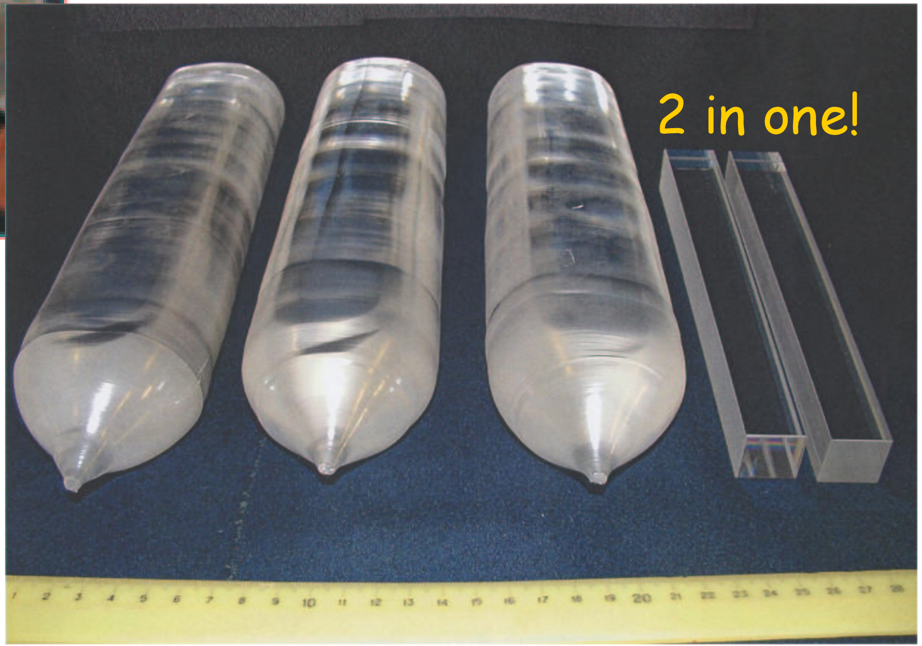


Monitoring fibers being mounted on the back of an ECAL SM

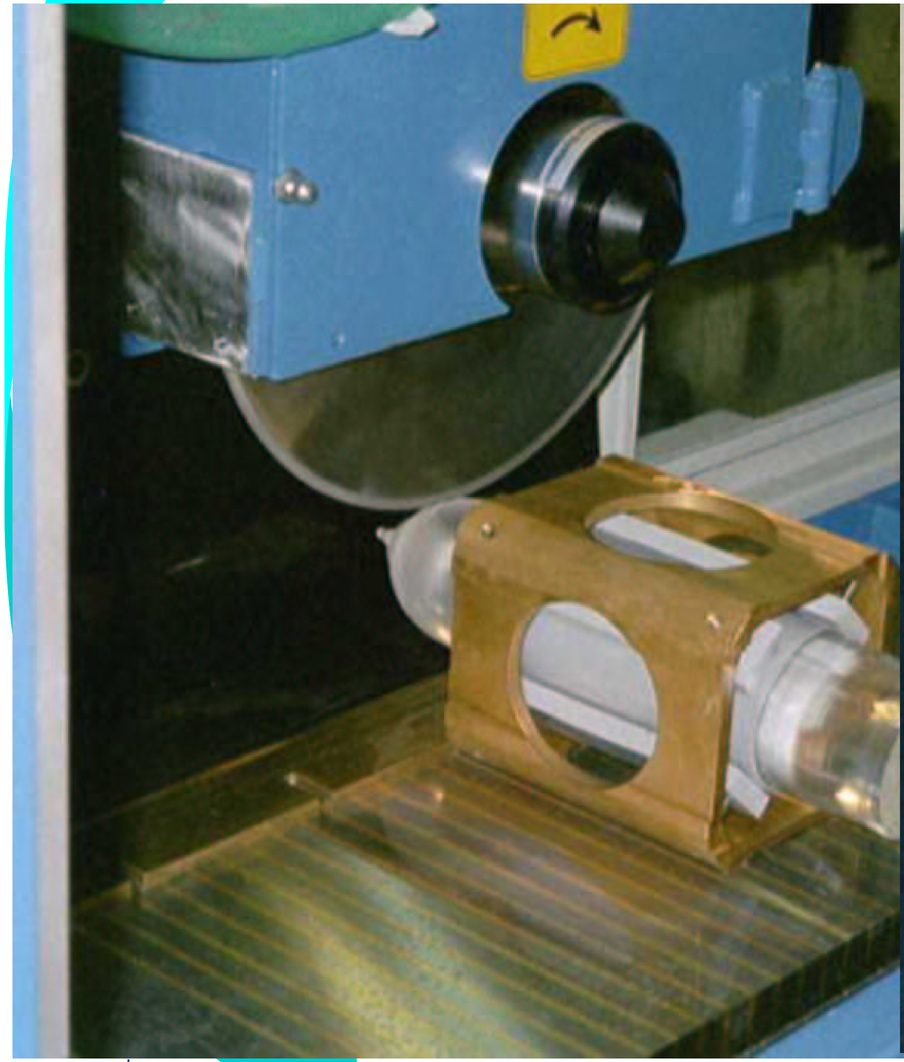
CMS ECAL

~20000 barrel crystals accepted

First supermodule assembled in spring 2002 (5 by end 2003)



Few photos

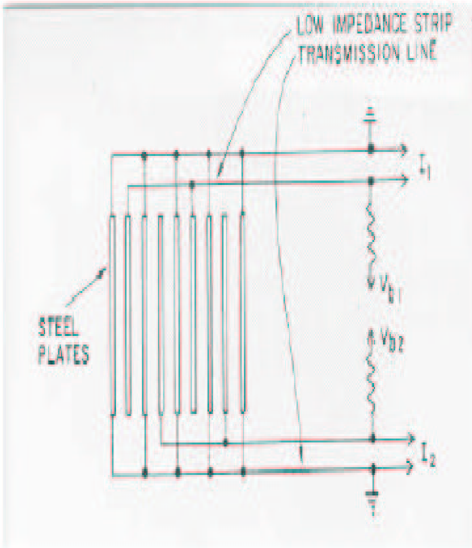


More photos

Before annealing

After cut and annealing

Ionisation calorimeters: Liquid Argon ATLAS



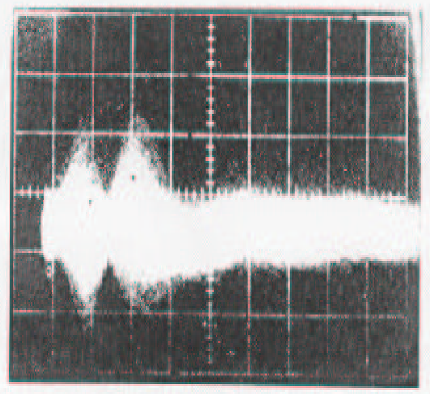
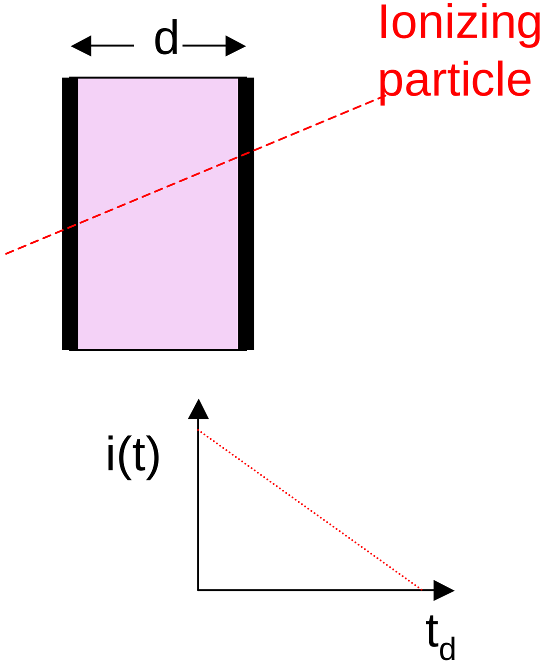


Fig. 15. Difference signals from two interleaved chambers for 7 GeV electrons (see text).

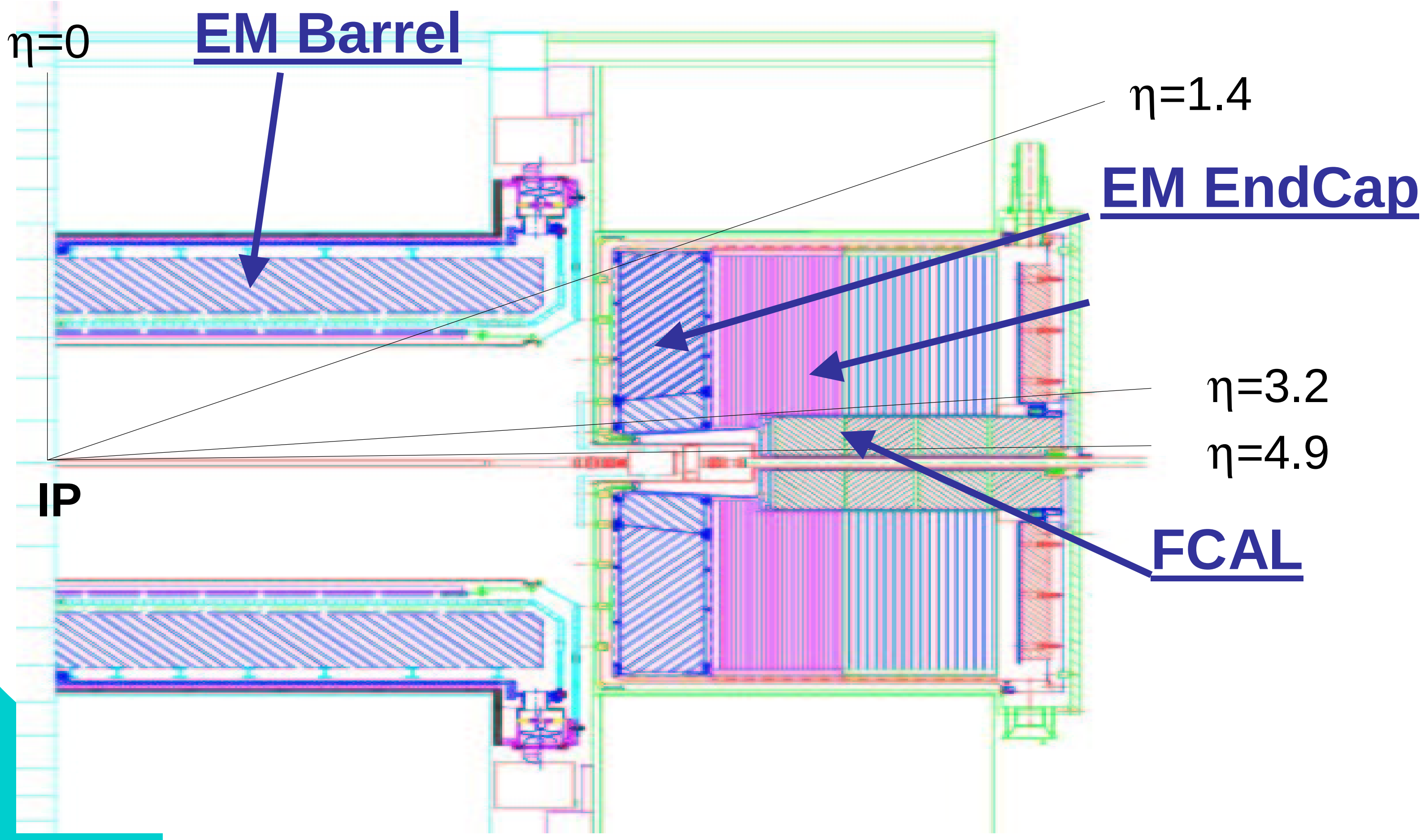
Willis & Radeka , 1974



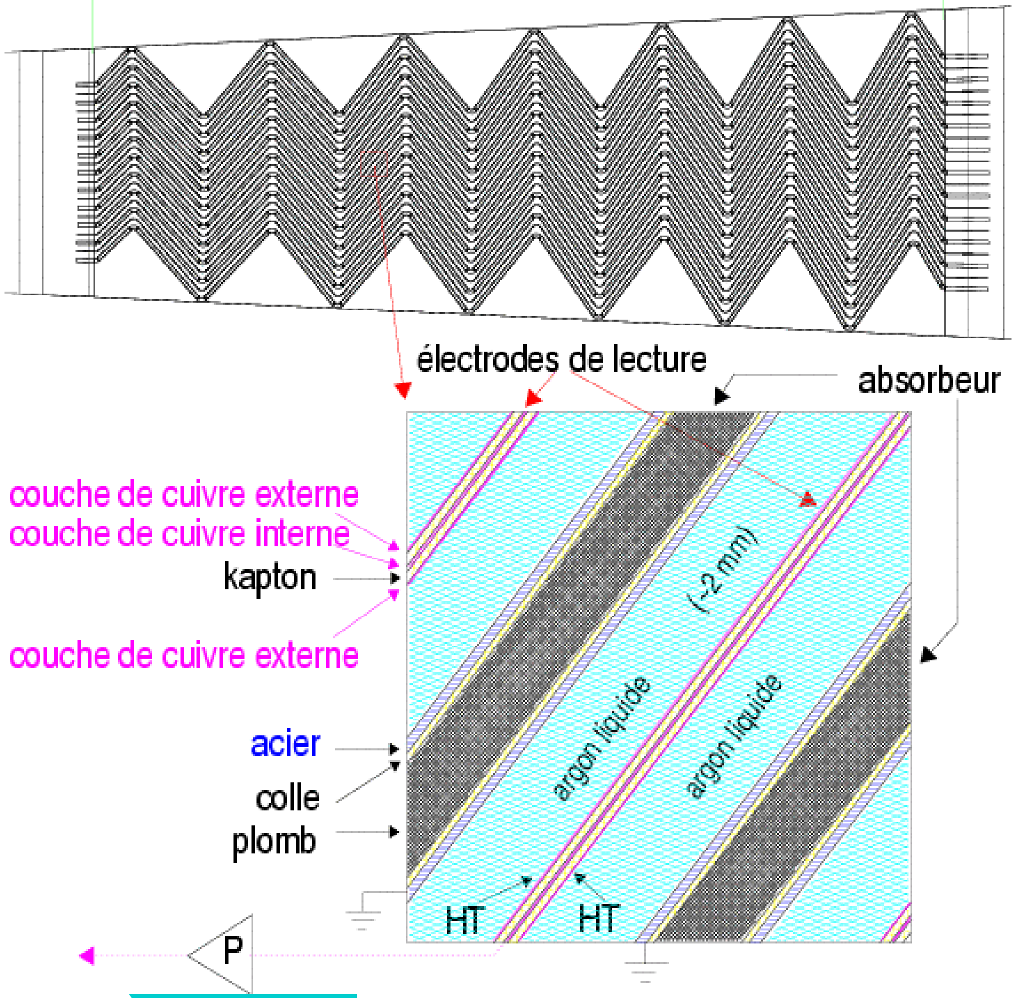
Major progress done in recent years (mostly thanks to RD3 and NA48 and ATLAS) on detector structure, speed of response (e.g. H1 45000 channels, 2.4 μs shaping)

Advantages: uniformity, flexibility of electrode geometry,speed
Disadvantages: difficult to build (cryogenics …)

The ATLAS LAr system

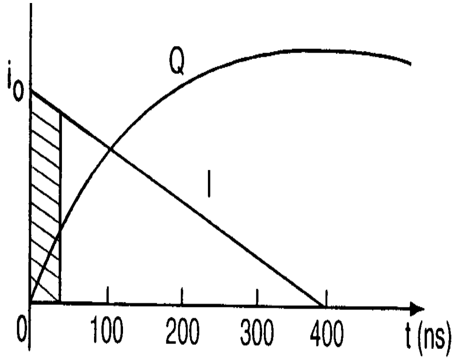


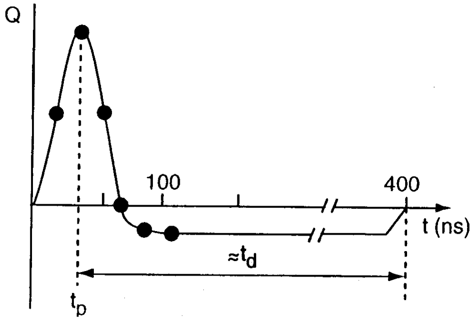
ATLAS LAr : the basic structure



Argon double gap 2x2 mm

Thickness of absorber plates: 1.1mm for pseudorapidities > 0.8 and 1.5 mm close to the center of the detetctor: total of ~26 X_0



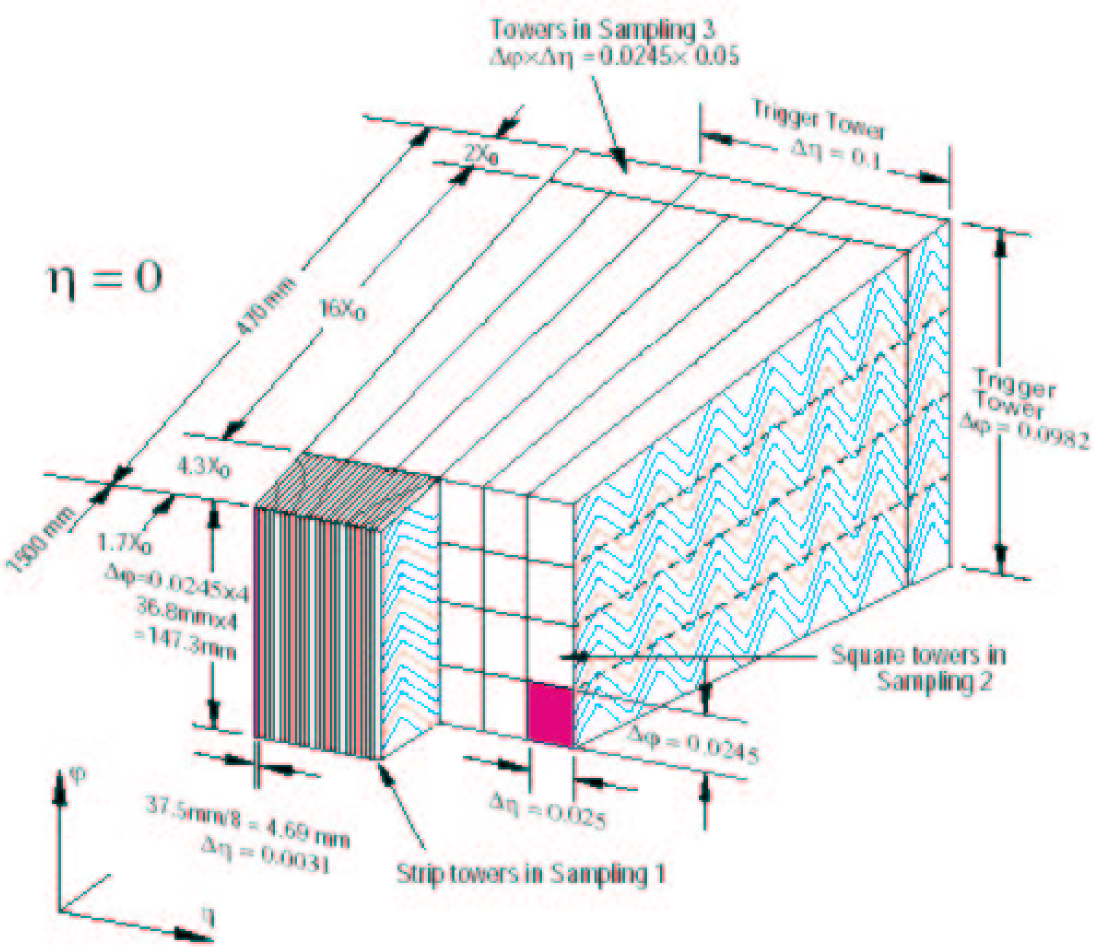


ATLAS LAr

Direction of γs: strip towers in 1st sampling….
First fine grained sampling acts as a pre-shower for γ/π^0 separation

Factor 3 π^0 rejection at E_t=50GeV

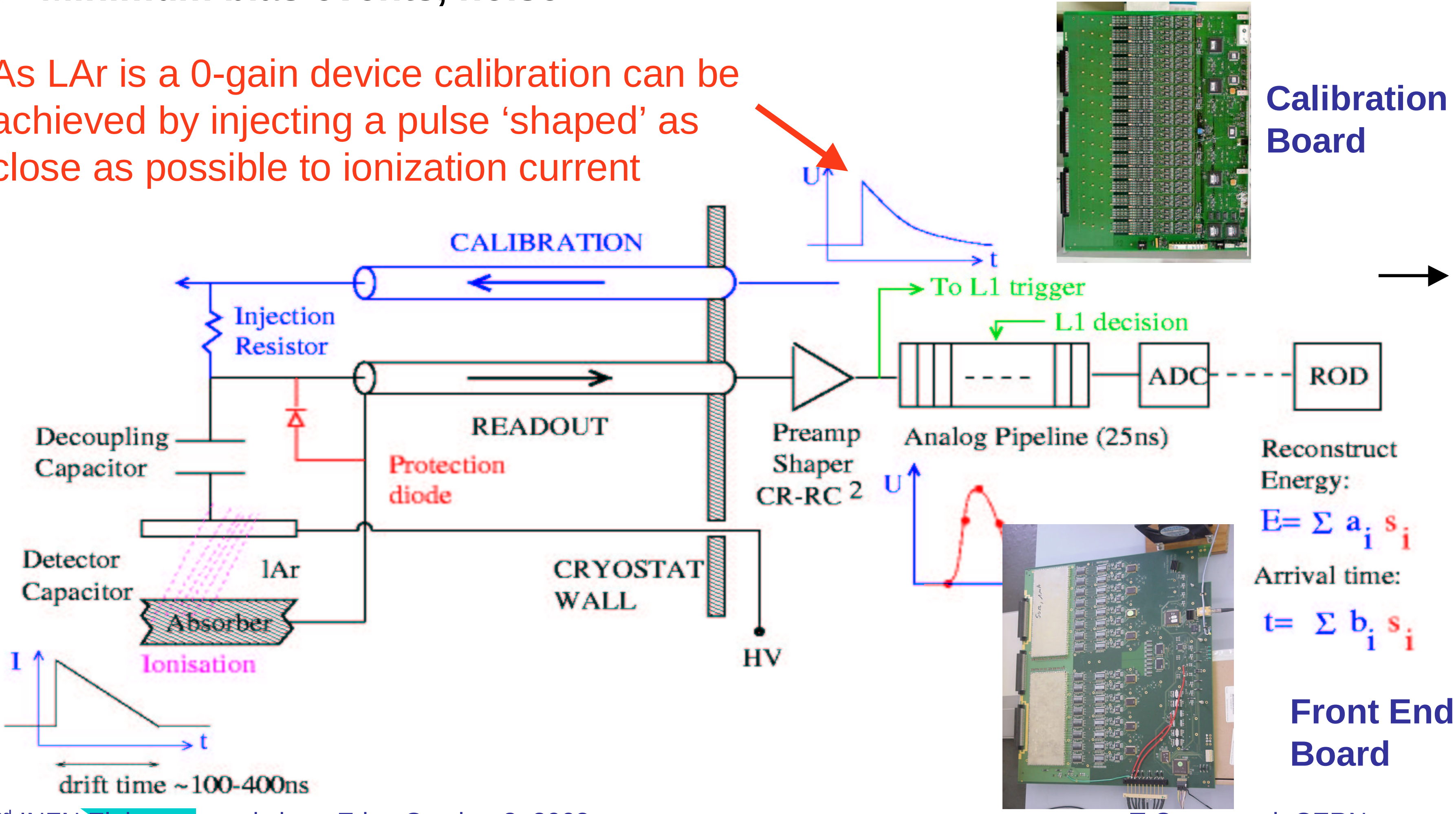
Factor 5000 jet rejection for E_{jet}>20 GeV



Signal processing

- **Beam Crossing 25 ns, drift time 400 ns**
- **Minimum bias events, noise**

As LAr is a 0-gain device calibration can be achieved by injecting a pulse ‘shaped’ as close as possible to ionization current



Calibration Board

Reconstruct Energy:

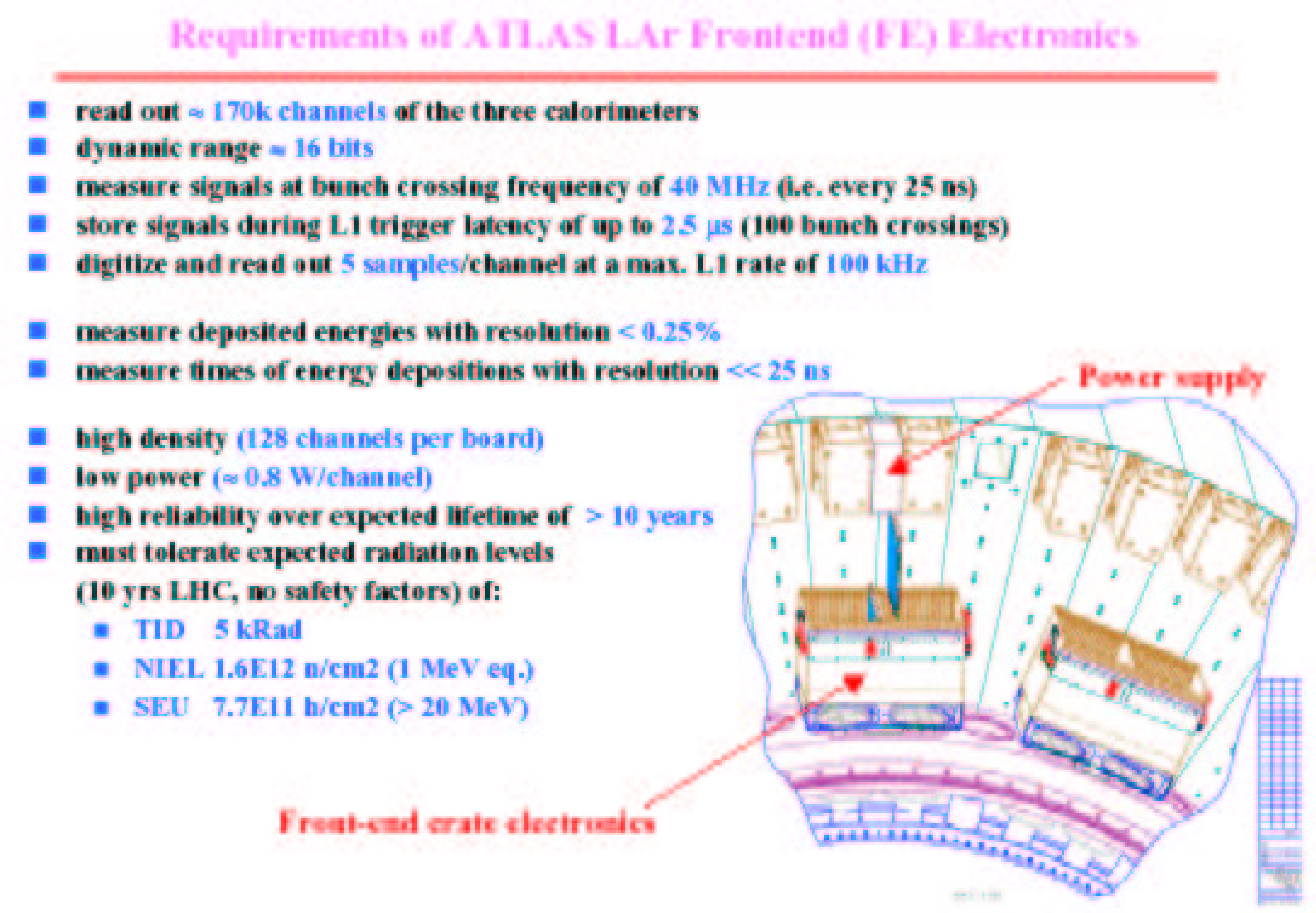
$E = \Sigma\, a_i\, s_i$

Arrival time:

$t = \Sigma\, b_i\, s_i$

Front End Board

ATLAS Electronics: requirements



Requirements of ATLAS LAr Frontend (FE) Electronics

- read out ≈ 170k channels of the three calorimeters
- dynamic range ≈ 16 bits
- measure signals at bunch crossing frequency of 40 MHz (i.e. every 25 ns)
- store signals during L1 trigger latency of up to 2.5 µs (100 bunch crossings)
- digitize and read out 5 samples/channel at a max. L1 rate of 100 kHz

- measure deposited energies with resolution < 0.25%
- measure times of energy depositions with resolution << 25 ns

- high density (128 channels per board)
- low power (≈ 0.8 W/channel)
- high reliability over expected lifetime of > 10 years
- must tolerate expected radiation levels (10 yrs LHC, no safety factors) of:
  - TID 5 kRad
  - NIEL 1.6E12 n/cm2 (1 MeV eq.)
  - SEU 7.7E11 h/cm2 (> 20 MeV)

Signal shaping

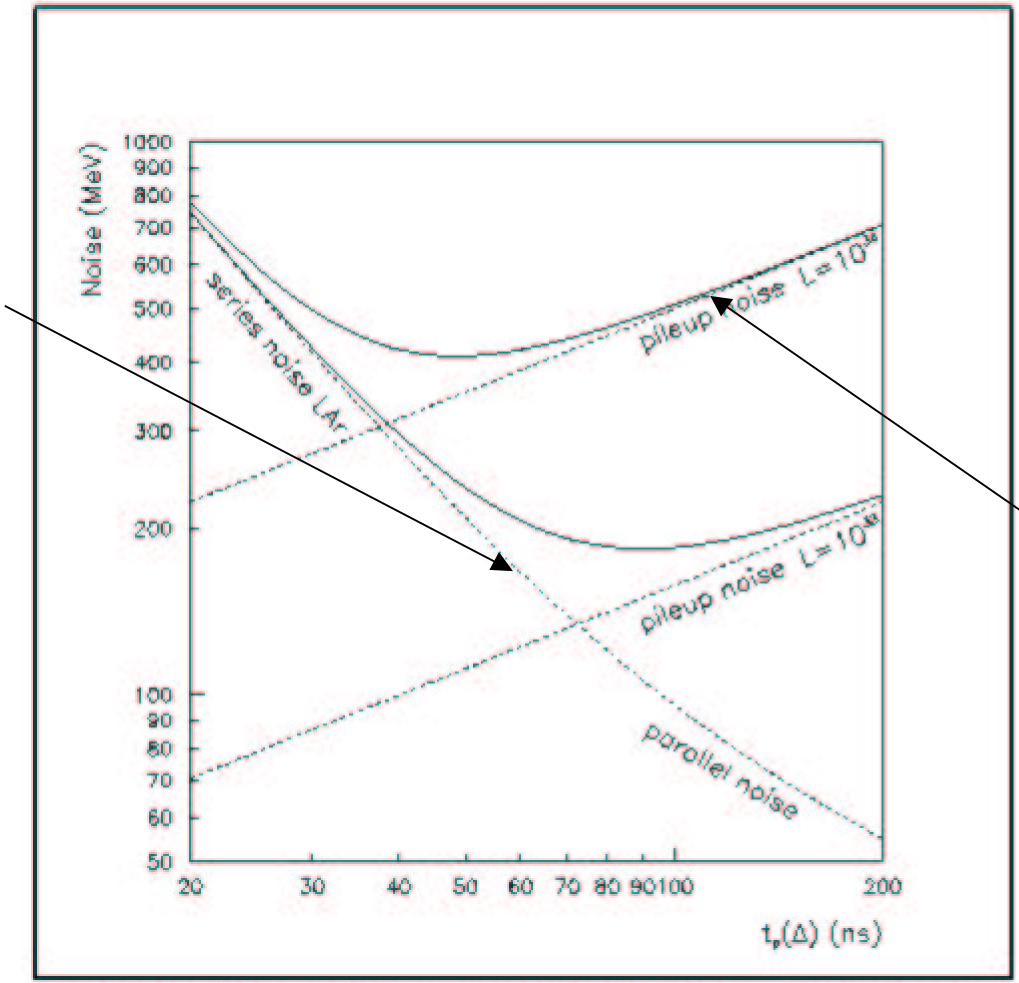
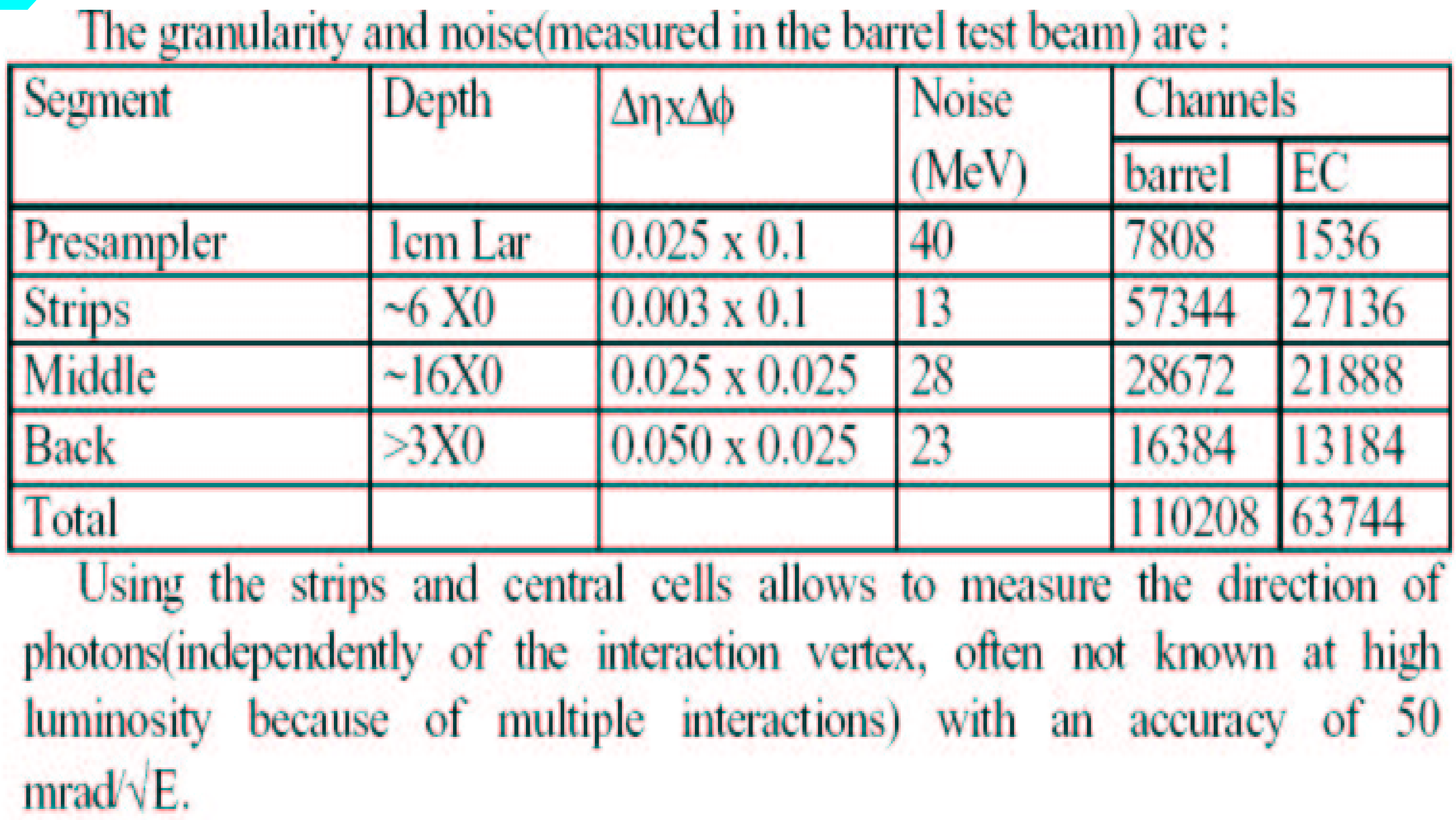


Figure 1-12 Optimization of the shaping time for high and low luminosity.

Electronic noise

Pileup noise

Noise and granularity

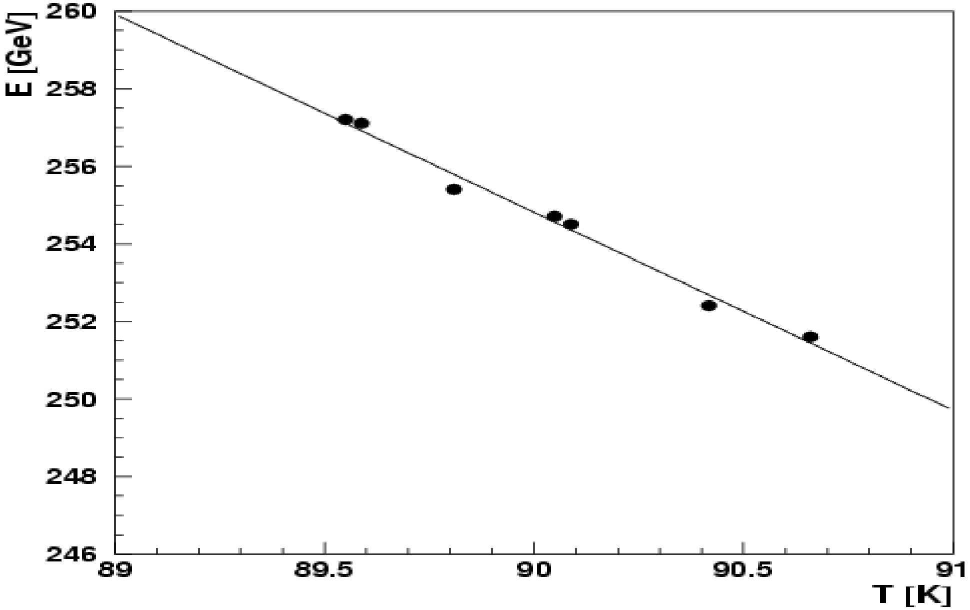


The granularity and noise(measured in the barrel test beam) are :

Segment	Depth	$\Delta\eta x \Delta\phi$	Noise (MeV)	Channels	
				barrel	EC
Presampler	1cm Lar	0.025 x 0.1	40	7808	1536
Strips	~6 X0	0.003 x 0.1	13	57344	27136
Middle	~16X0	0.025 x 0.025	28	28672	21888
Back	>3X0	0.050 x 0.025	23	16384	13184
Total				110208	63744

Using the strips and central cells allows to measure the direction of photons(independently of the interaction vertex, often not known at high luminosity because of multiple interactions) with an accuracy of 50 mrad/√E.

Atlas LAr: T dependence



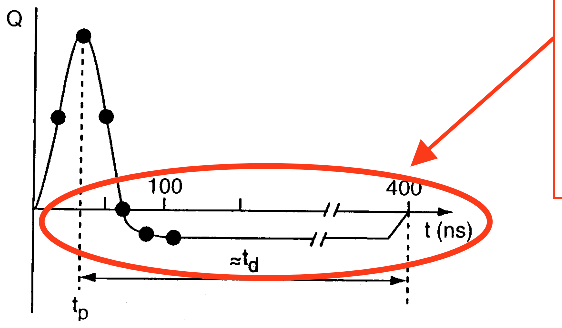
In agreement with expectation :

2% / K on the energy

Due to the fast shaping (sampling of the initial current) the dependance on the LAr temperature is not only through density (as for time-integrating LAr calorimeters) but also through the drift velocity

AIM to have < 0.3 °K temp difference between any point of the calo bath

T can be monitored from the data themselves by logging the full pulse (negative lobe) for sample events

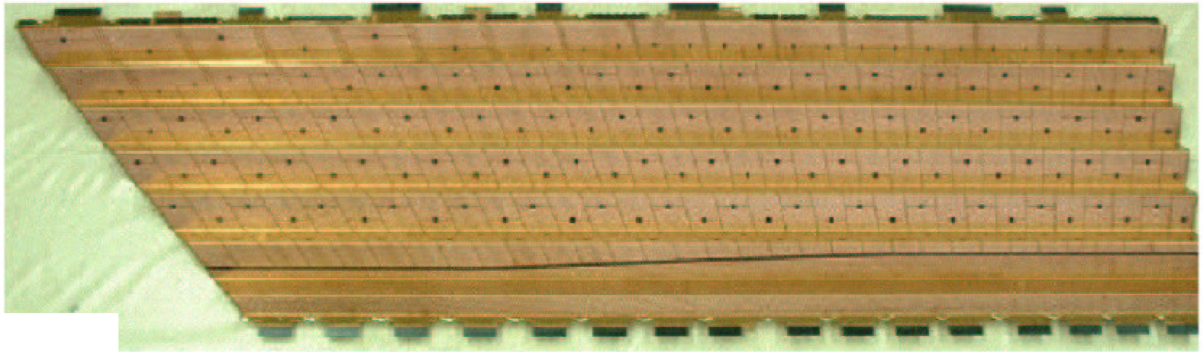


Bonus of fast readout: less sensitive to electronegative impurities (monitored by test cells)

Construction difficulties

- Fabrication of large electrodes

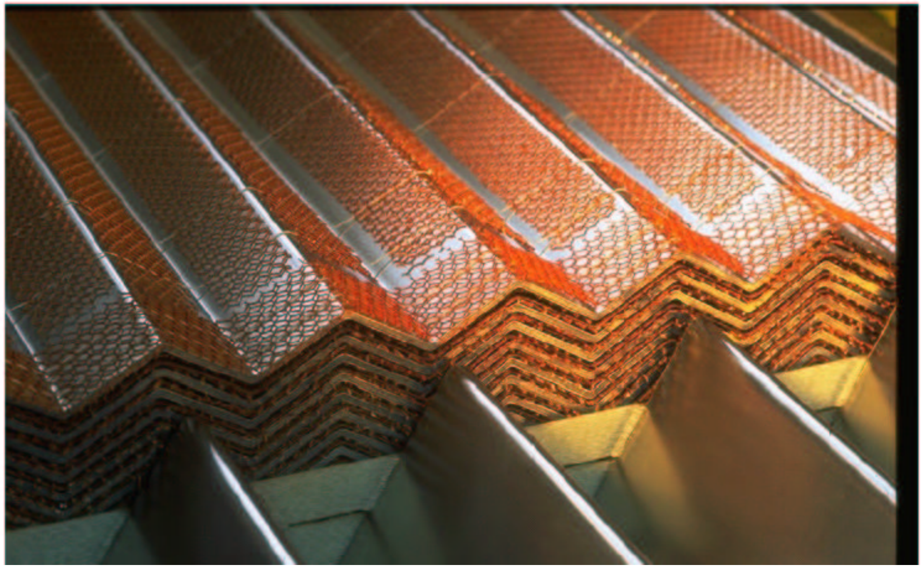
~2 meters



almost 1000 resistive pads per electrode.

- **HV trouble shooting**

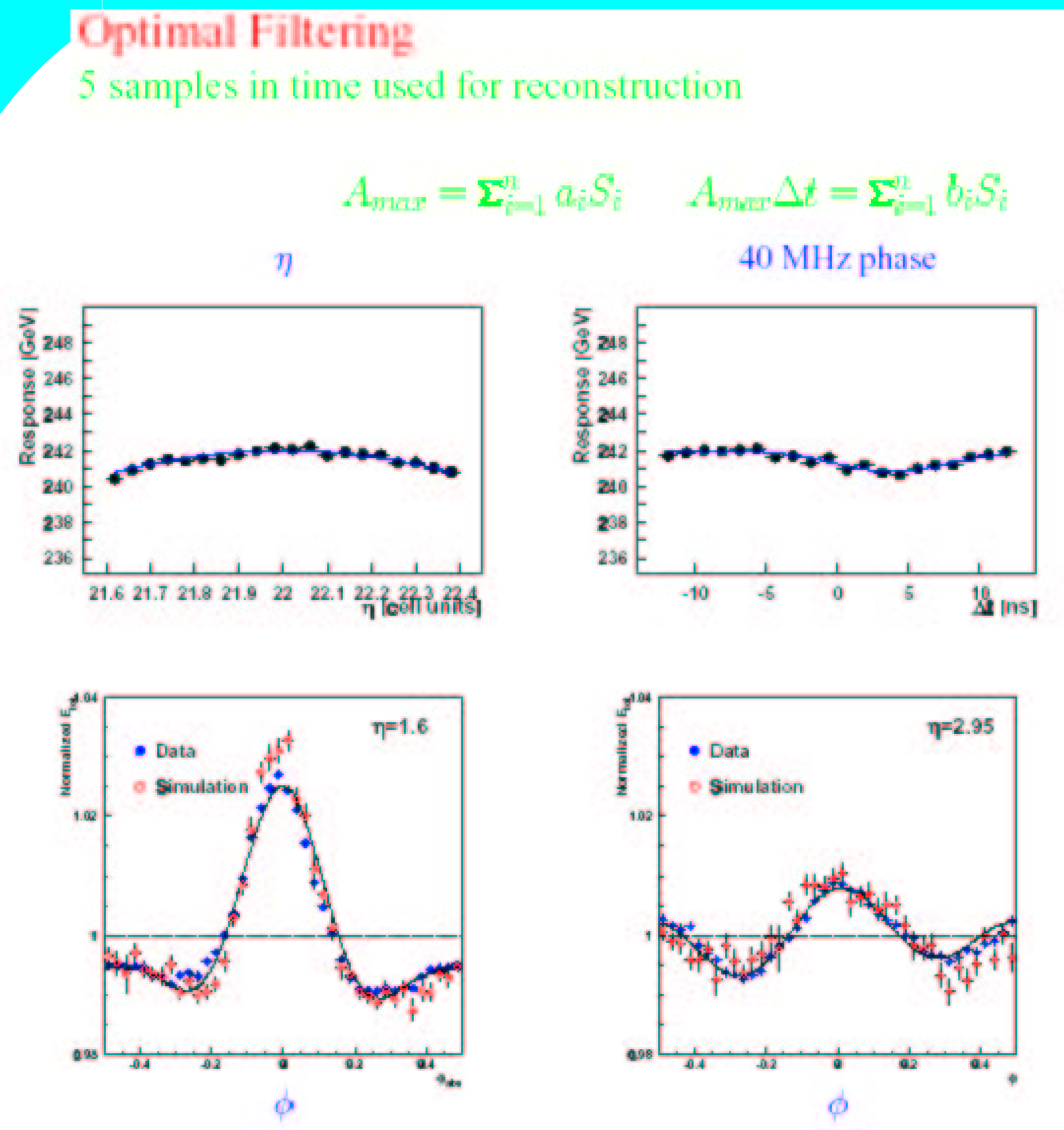
About $20000\,m^2$ of honeycomb spacer to maintain flexible electodes centred in the gap between absorbers.



From finished barrel wheels:
HV :22/28672 channels
show a problem (offline correction needed)
Readout: 4/53014 channels dead…

Impressive QC!

ATLAS performance



Optimal Filtering

5 samples in time used for reconstruction

$$A_{max} = \Sigma_{i=1}^{n} a_i S_i \qquad A_{max}\Delta t = \Sigma_{i=1}^{n} b_i S_i$$

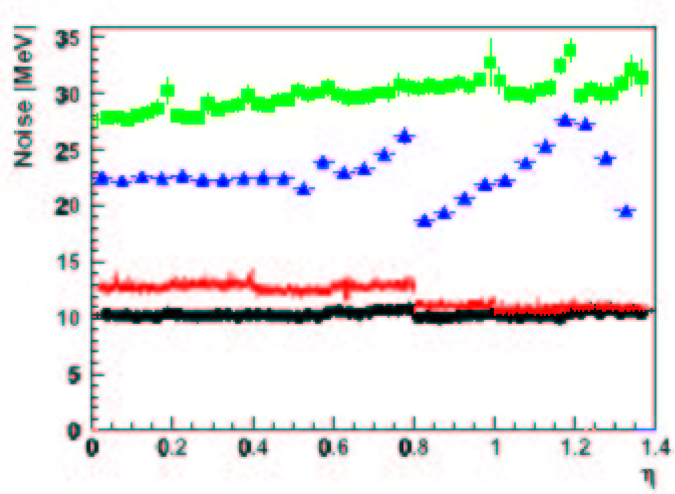
Reconstruction not trivial:

5 time samples used to smooth noise

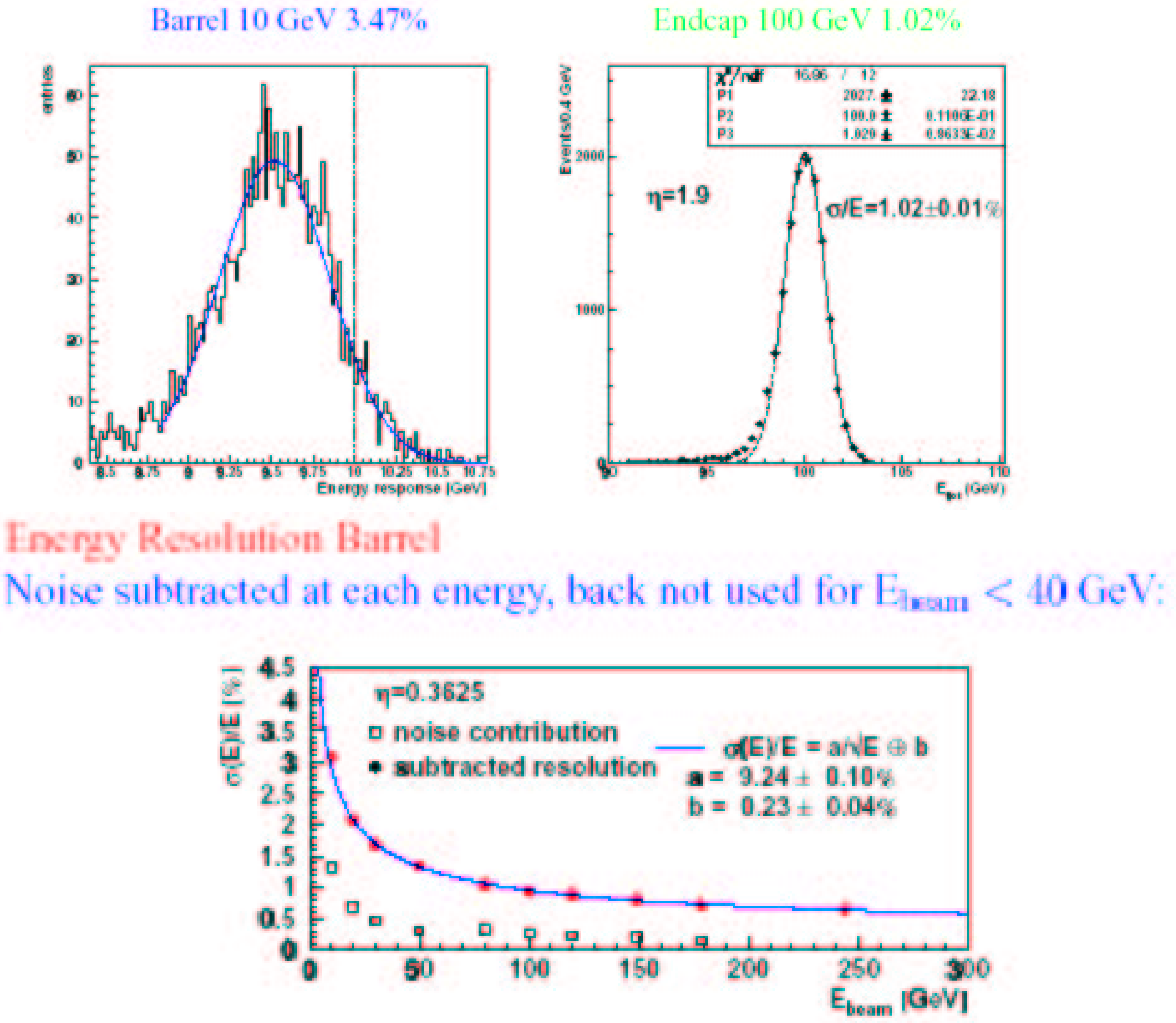
Correct for η containment

Correct for cathode modulation

Noise:presampler, strip, middle and back



ATLAS performance



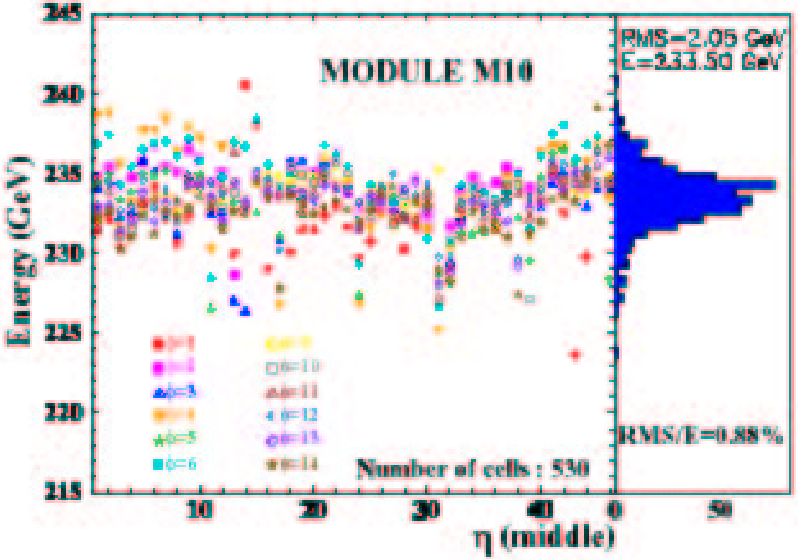
Barrel 10 GeV 3.47%

Endcap 100 GeV 1.02%

Energy Resolution Barrel

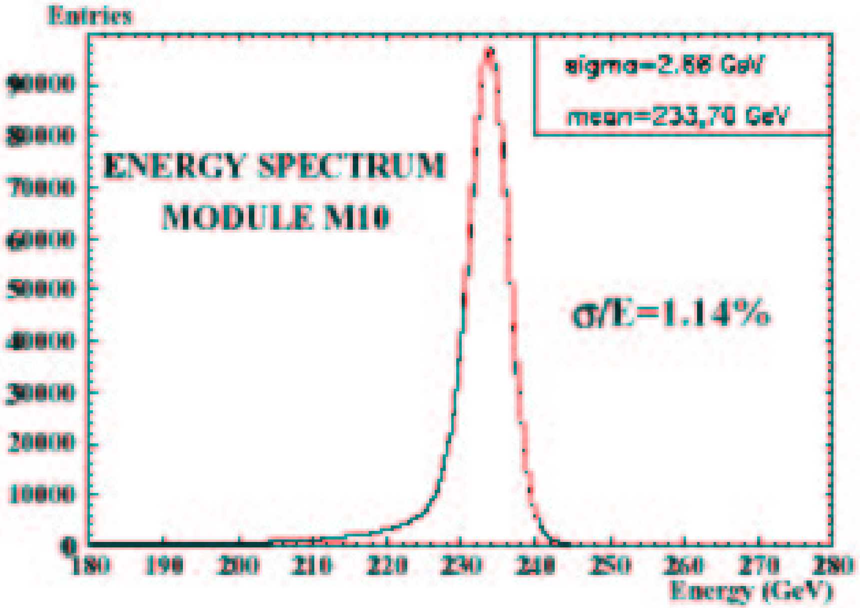
Noise subtracted at each energy, back not used for $E_{beam} < 40$ GeV:

ATLAS LAr uniformity



Constant term =0.93 %

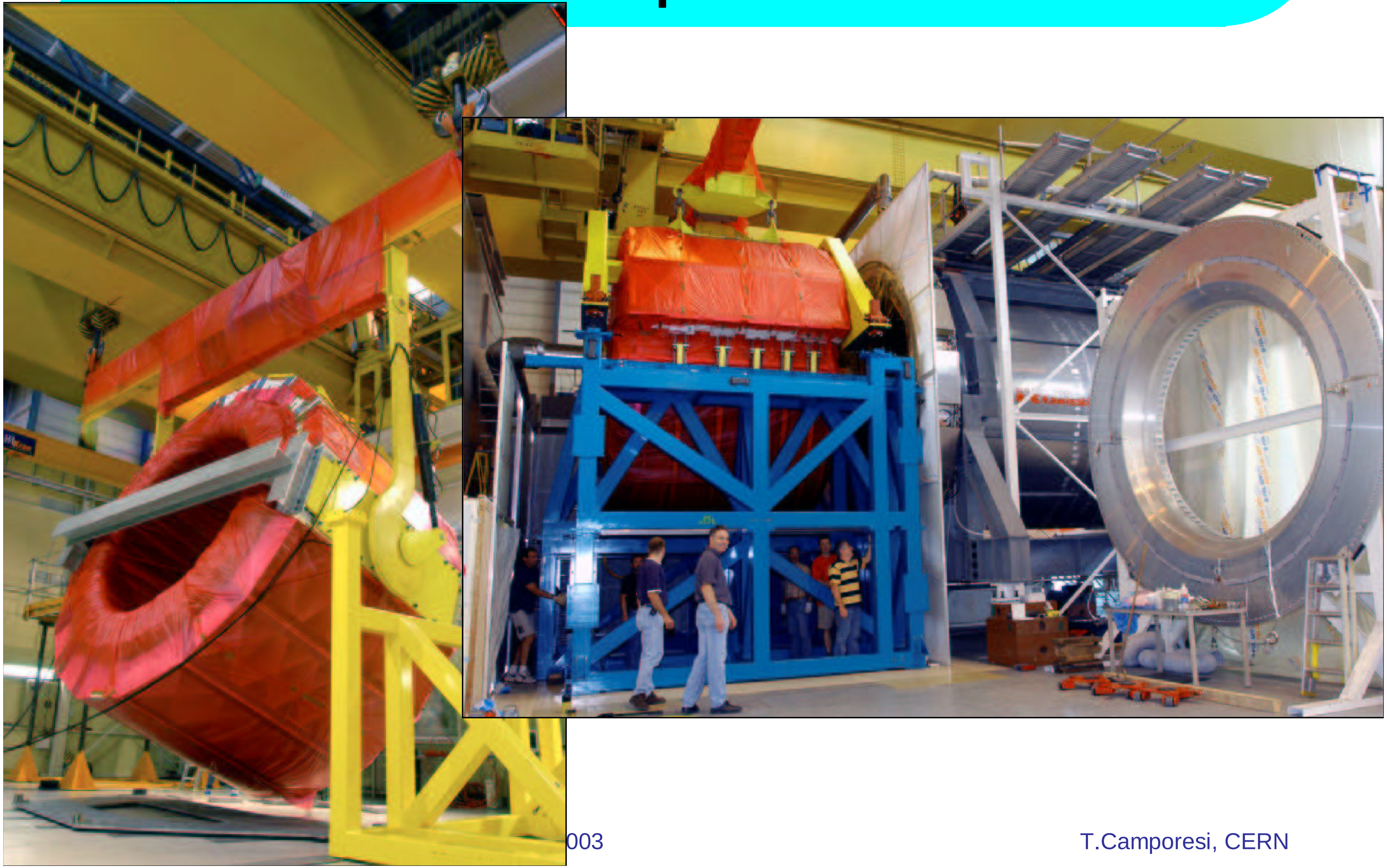
Constant term =0.94 %

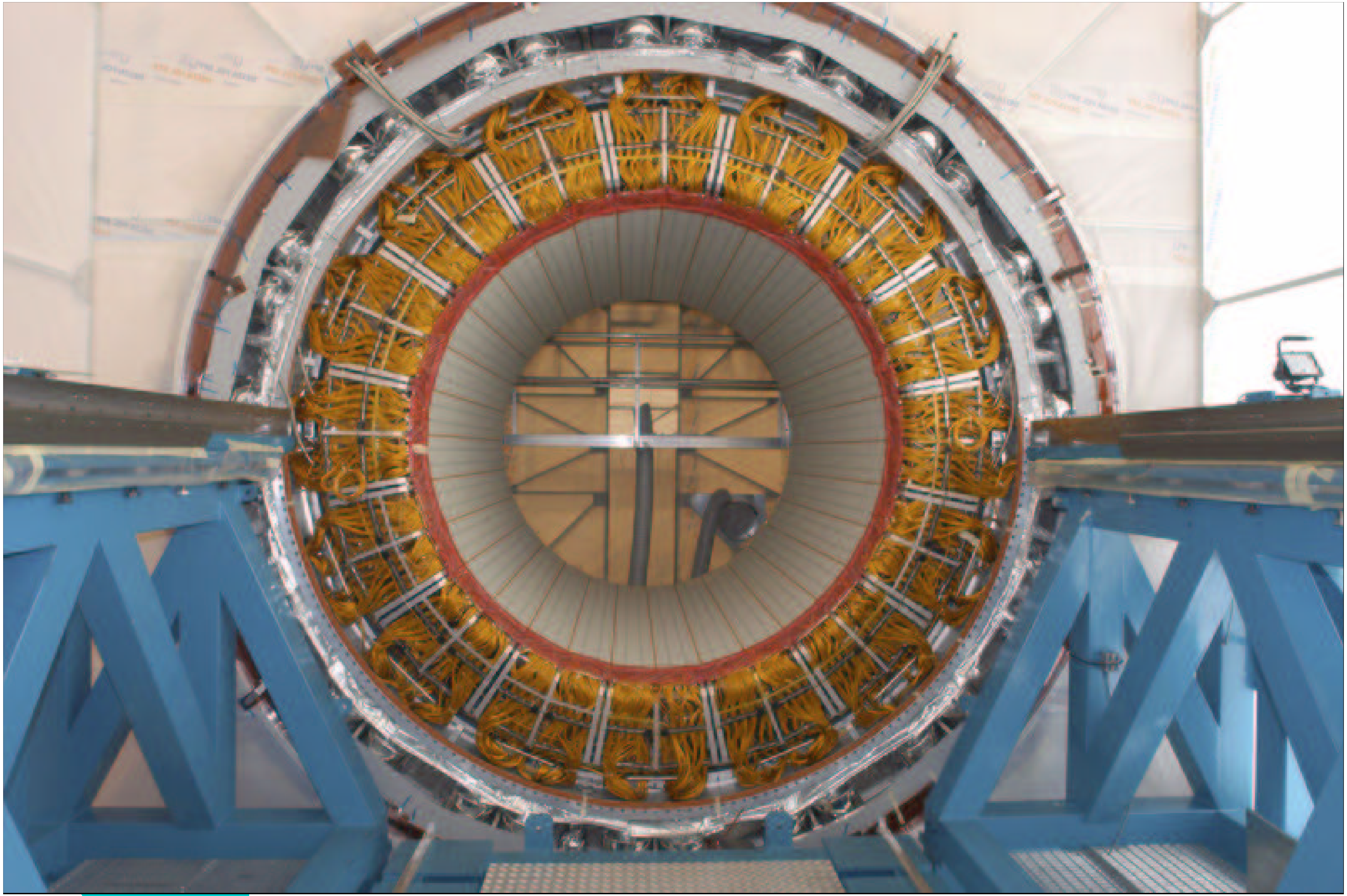


Few pictures

Closing of 1st wheel

More pictures



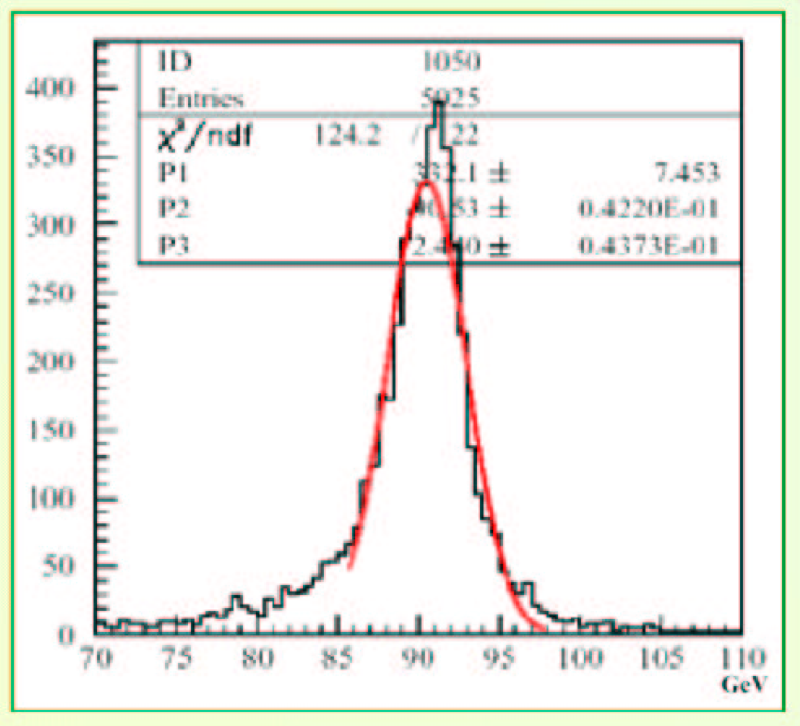


The first wheel inside the cryostat

Absolute Calibration in situ

- Imposing ϕ symmetry obtain intercalibration of towers to 1-2% relative in few hours
- The best calibration of ECALs will be using the Z^0 and W produced at LHC:

  $Z \longrightarrow e^+e^-$ has a rate ~1Hz. The constrained mass fit (no tracker info necessary) will give the calibration (production almost flat in η) estimate to achieve absolute 1-2% in a few days
- $W \longrightarrow e\nu$ is even more copious e.g. CMS estimates to obtain 0.5% error on crystals cross calibration using e/p (once tracker is understood!)



(Near?) Future collider: SLHC

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
L /cm^{2}sec	10^{34}	10^{35}
fb^{-1}/yr	100	1000
Bunch spacing dt	25 ns	12.5 ns
N(interactions/x-ing)	~ 12	~ 62
$dN_{ch}/d\eta$ per x-ing	~ 75	~ 375
Tracker occupancy	$\equiv 1$	5
Pile-up noise	$\equiv 1$	~2.2
Dose central region	$\equiv 1$	10

Main problem for trackers, barrel calorimeters should not suffer too much, Impact on forward is major.

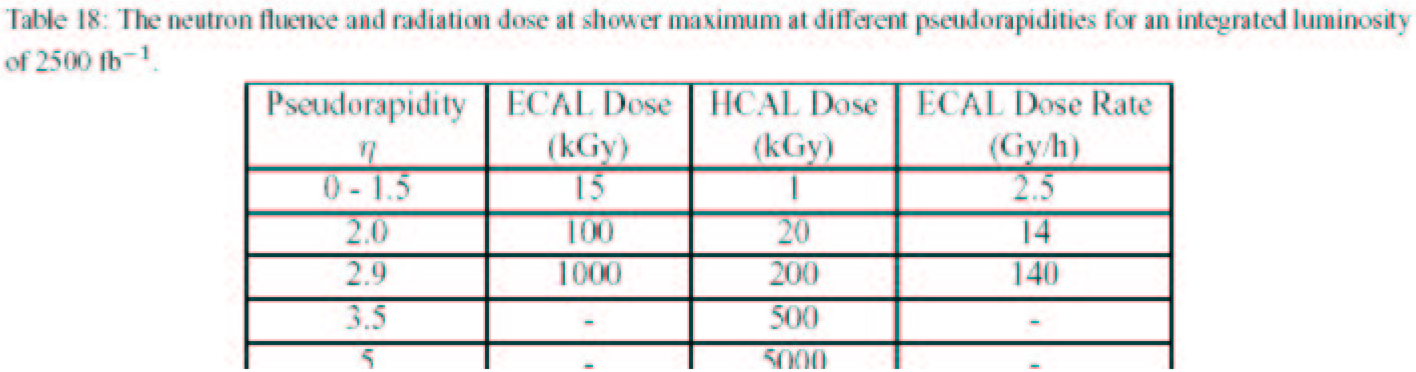


Table 18: The neutron fluence and radiation dose at shower maximum at different pseudorapidities for an integrated luminosity of 2500 fb^{-1}.

Pseudorapidity η	ECAL Dose (kGy)	HCAL Dose (kGy)	ECAL Dose Rate (Gy/h)
0 - 1.5	15	1	2.5
2.0	100	20	14
2.9	1000	200	140
3.5	-	500	-
5	-	5000	-

SLHC: EM cals

- ATLAS:
  - Space charge effects: if drifting ions start modifying the field near the anode signal is affected (onset of regime goes like $V^2/d^4\mu$, V volt, d gap and μ ion mobility). Measurements in test beam show 1% loss with energy flow $5\ 10^6$ GeVcm^{-2}s^{-1}

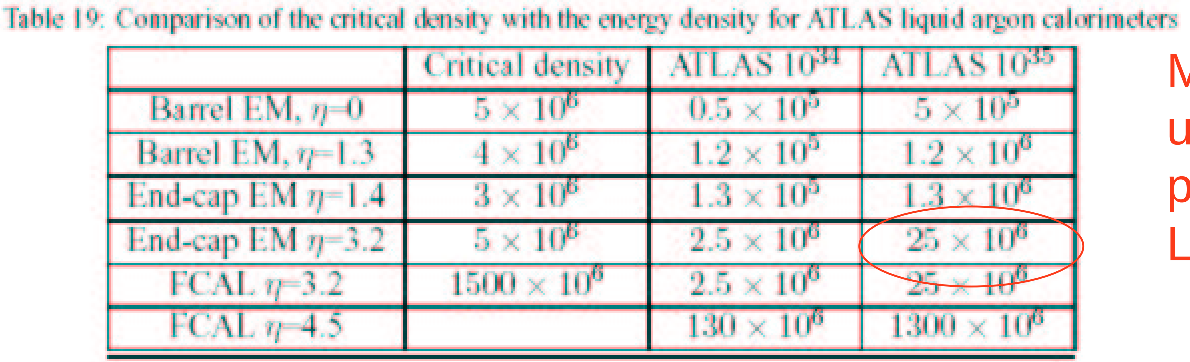


Table 19: Comparison of the critical density with the energy density for ATLAS liquid argon calorimeters

	Critical density	ATLAS 10^{34}	ATLAS 10^{35}
Barrel EM, η=0	5×10^6	0.5×10^5	5×10^5
Barrel EM, η=1.3	4×10^6	1.2×10^5	1.2×10^6
End-cap EM η=1.4	3×10^6	1.3×10^5	1.3×10^6
End-cap EM η=3.2	5×10^6	2.5×10^6	25×10^6
FCAL η=3.2	1500×10^6	2.5×10^6	25×10^6
FCAL η=4.5		130×10^6	1300×10^6

Might decide to use cold pressurized gas or LKr in this region!

SLHC, ATLAS cont.

- Voltage drop due to ionization currents: the HV supply chain has resistors meant to decouple the various electrodes. At low temperature the value of the resistor increases by a factor 10 (possibly with large fluctuation).

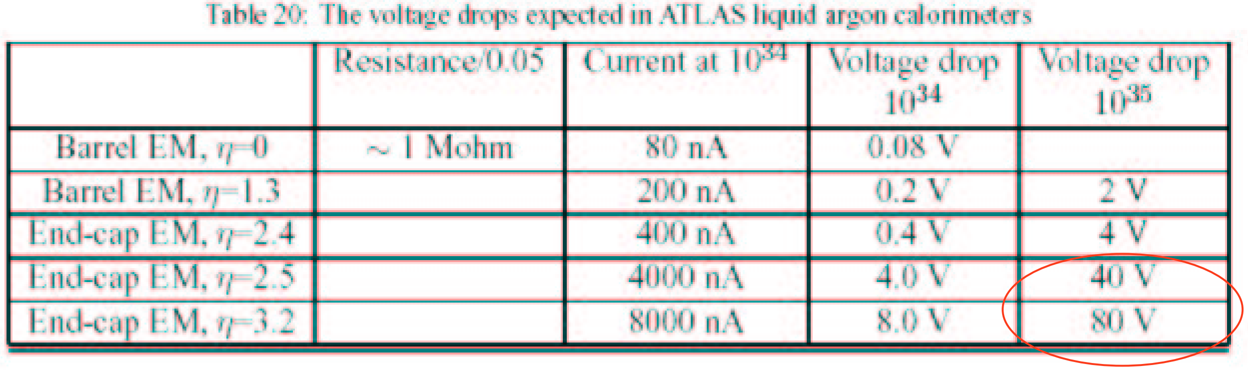


Table 20: The voltage drops expected in ATLAS liquid argon calorimeters

	Resistance/0.05	Current at 10^{34}	Voltage drop 10^{34}	Voltage drop 10^{35}
Barrel EM, η=0	~ 1 Mohm	80 nA	0.08 V	
Barrel EM, η=1.3		200 nA	0.2 V	2 V
End-cap EM, η=2.4		400 nA	0.4 V	4 V
End-cap EM, η=2.5		4000 nA	4.0 V	40 V
End-cap EM, η=3.2		8000 nA	8.0 V	80 V

Cold pressurized gas will do…

SLHC, CMS ECAL

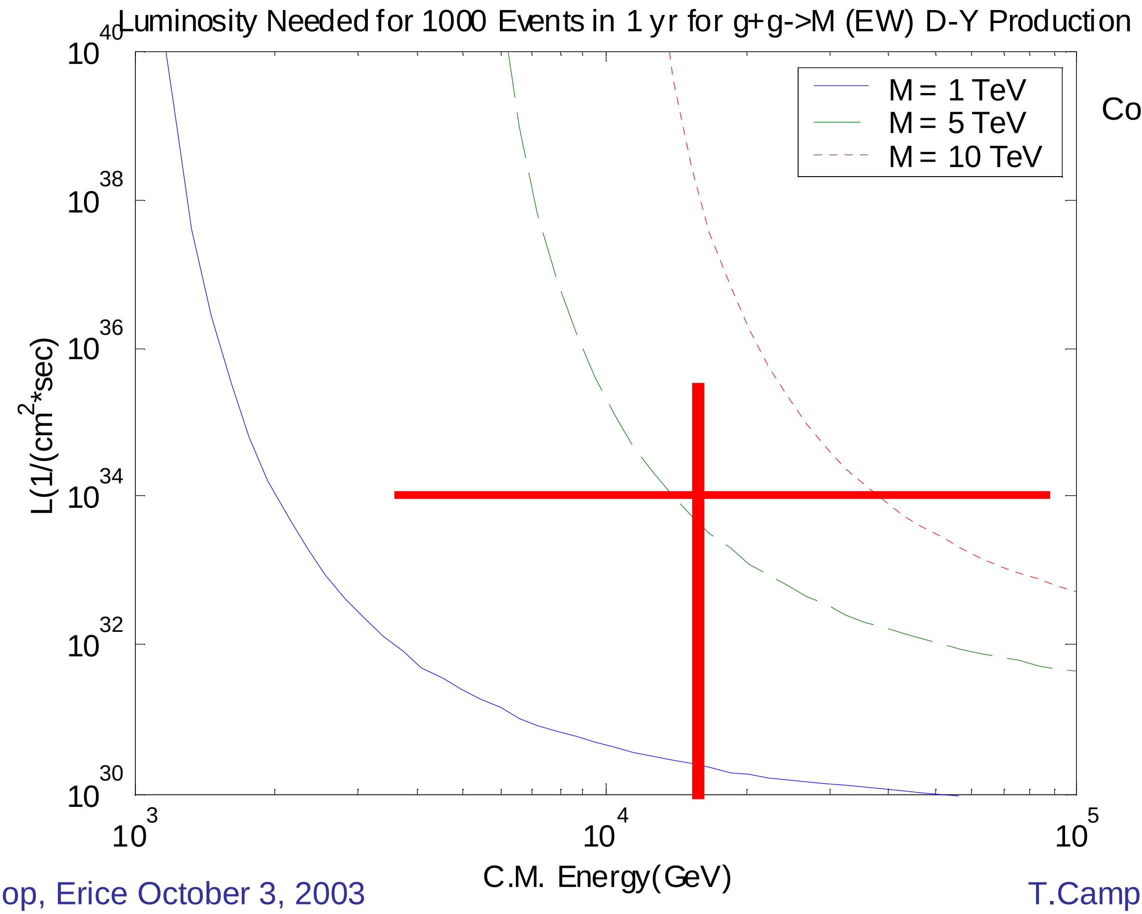
- Irradiation will reach 1.5 Gy/h at shower max in the barrell (which corresponds to the LHC situation at η =2.4) and 75 Gy/h at h=3. This is close to the ‘saturation’ irradiation condition used during the crystal acceptance when irradiating at the Hopital Cantonal. Should lead to a, manageable 25% light loss.
- As for other readout component one expects deterioration of noise/crystal up to 100 MeV.
- More extensive studies are needed to see long term effects and to test all other components (even if one does not anticipate show stoppers)

SLHC, calorimeter electronics

- Running the current electronics at 80 MHz is impossible for both ATLAS and CMS. Could be possible to use the 40 MHz sampling and several time samples to reconstruct the actual bunch crossing. Need further studies.
- Effects of pileup on physics have to fully assessed….

Future colliders: exploring new physics (LHC should show the way)

- Parton cross section ~1/s_{eff} hence Luminosity should increase like $s=E^2$ if we want to 'saturate' physics reach: aim to 10^{36} cm^2/s



Courtesy D. Green

Effect of min bias

Occupancy for a detector element at a distance r of area dA for a time dt with a luminosity l and a min bias pion density ρ_c

$$O = \ell \sigma_I \rho_c (dAdt)/[2\pi r^2]$$

To deal with increased min bias noise: get smaller or faster or further away (possibly combination of the three!)

For calorimeters today's structures might be ~adequate, but getting faster will most likely be a requirement anyway due to accelerator bunch spacing!

How much faster to cope with Minimum bias increase ?

$\sigma_{\text{min bias}}$ ~log(s) ~log(E)

$$\nu_{mibias} \propto Lumi \cdot \sigma_{mibias} \propto E^2 \log(E) \qquad evts/s$$

The fluctuations induced by pileup can be parametrized as

$$rms_{pileup} = E_{lowPt}\sqrt{\nu_{mibias}\tau} \propto E\sqrt{\log(E)\tau}$$

Where τ is the signal shaping time.

$$\frac{rms_{mibias}}{E} \propto const \ \text{if} \quad \tau \propto \frac{1}{\log(E)}$$

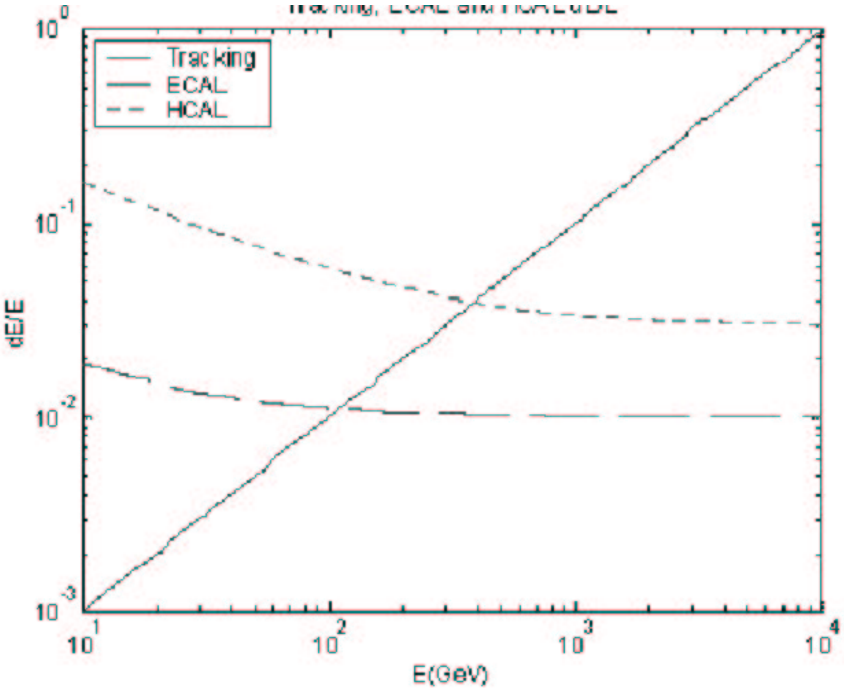
Not
Too
Bad !

Constraints from beam structure likely to be more severe!

(Far?) Future(?) collider: The detector for the Eloisatron/VLHC

- Tracker at r >30 cm (radiation)
- Physics: discovery of ‘predicted’ particles after LHC or measurement with high stats of ‘discovered’ particle. If this needs lepton id and/or accurate photon reconstruction then tracker structure should compromise: three ‘sets’ of (4 strip+1 pixel?) clustered at 3 radii (30-100-170?) so to allow easier recovery of converted photons, brems of electrons (instead of distributing uniformly the layers in radius)

With increasing E calorimeters wil become more and more important: $\Delta E/E$ goes constant at worse, while $\Delta p/p$ grows like p



Depending on the scale of particles sought for the ‘shower’ maximum might become a discriminant: the min bias background will ‘max out’ earlier in the calorimeter.

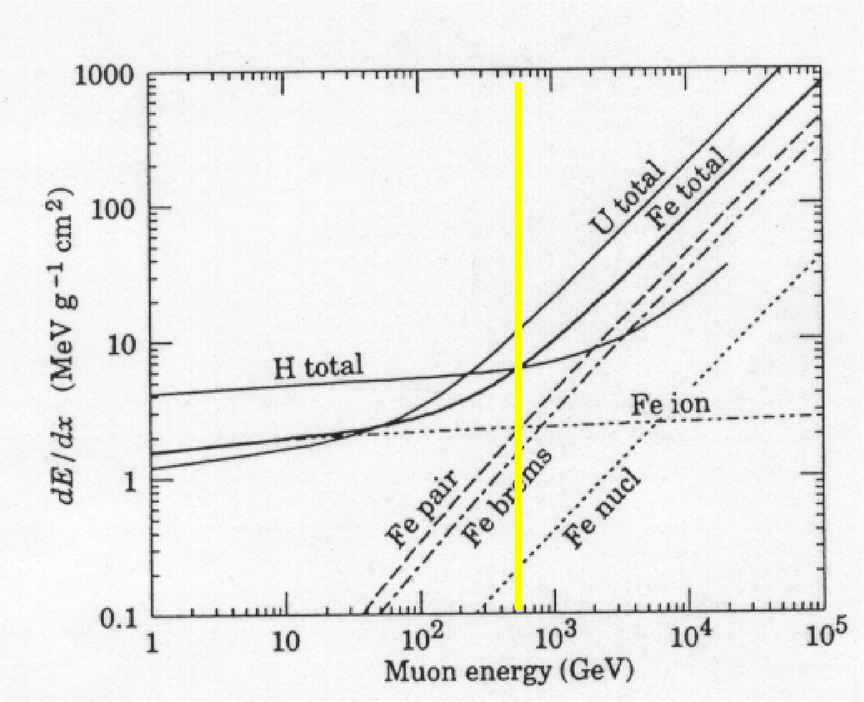
A few more points

Shape more important than central value

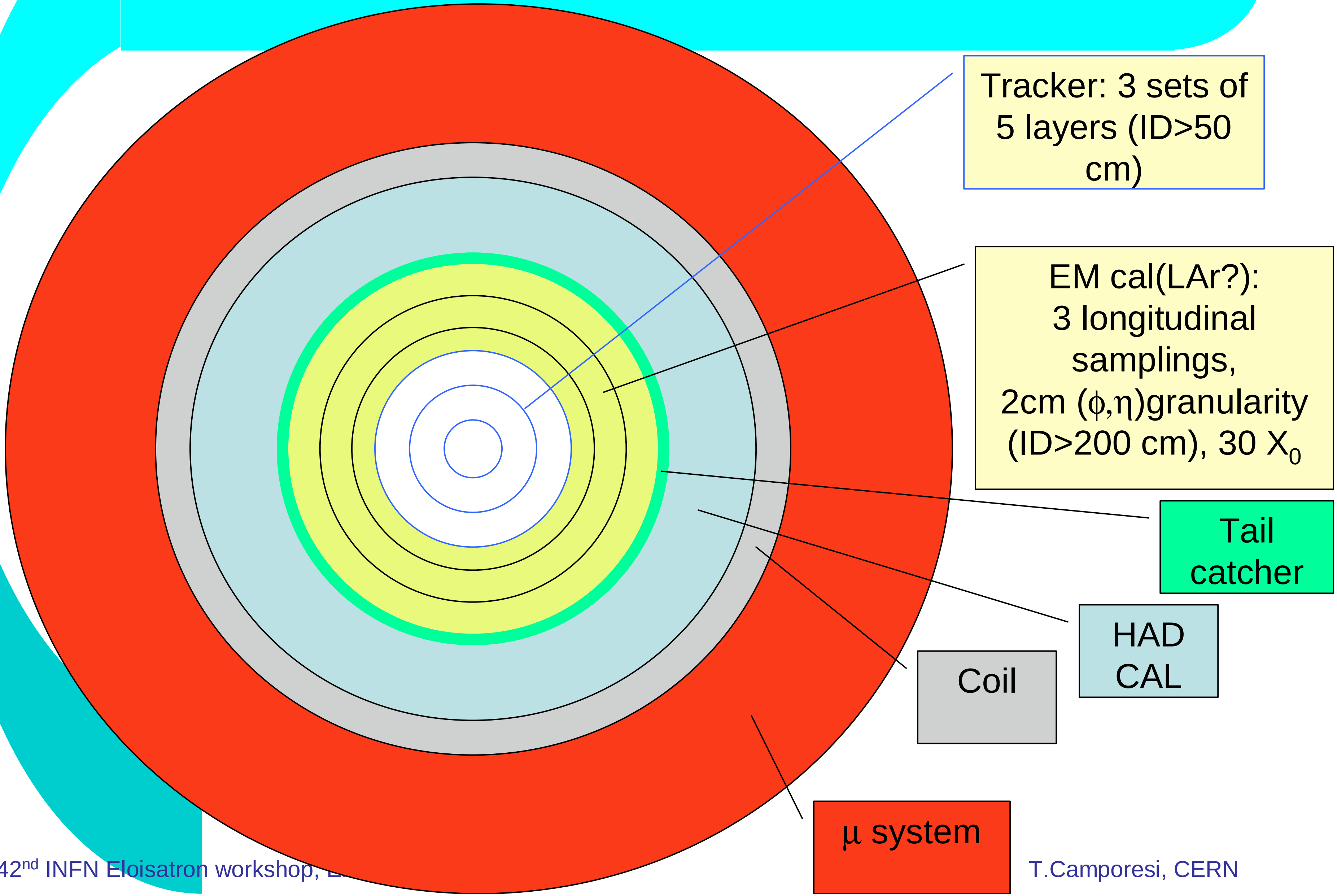
- No matter the physics goal having a good gaussian response (no tails) will be more important than having a good jet energy resolution (avoid creation of fake missing E_t): as it is difficult to imagine an EM calorimeter with a good e/π ratio, foresee tail catcher to use to weight in the HAD calorimeter response the fluctuations due to shower started in the ECAL… even more important if there is ‘empty’ space in high B field between ECAL and HCAL.

μ like e

At some point (E>300 GeV) Muon cannot be considered a particle that only ionizes !



Detector sketch



Tracker: 3 sets of 5 layers (ID>50 cm)

EM cal(LAr?): 3 longitudinal samplings, 2cm (ϕ,η)granularity (ID>200 cm), 30 X_0

Tail catcher

HAD CAL

Coil

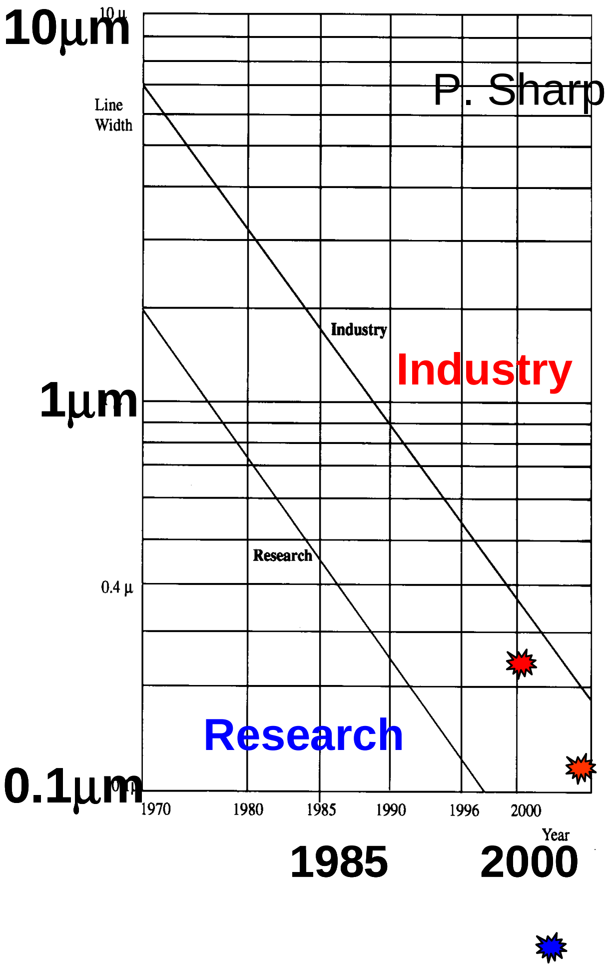
μ system

Forward region

- The forward region EM calorimeter structure will be determined mainly by the radiation field: liquid ionization counters will have space charge problems: My guess is that only gas ionization will withstand the environment and allow the necessary granularity.

Electronics

- Hard to guess, but if the trend continues it should not be a major problem: smaller integration scales tend to increase rad hardness beside speed.



Conclusions

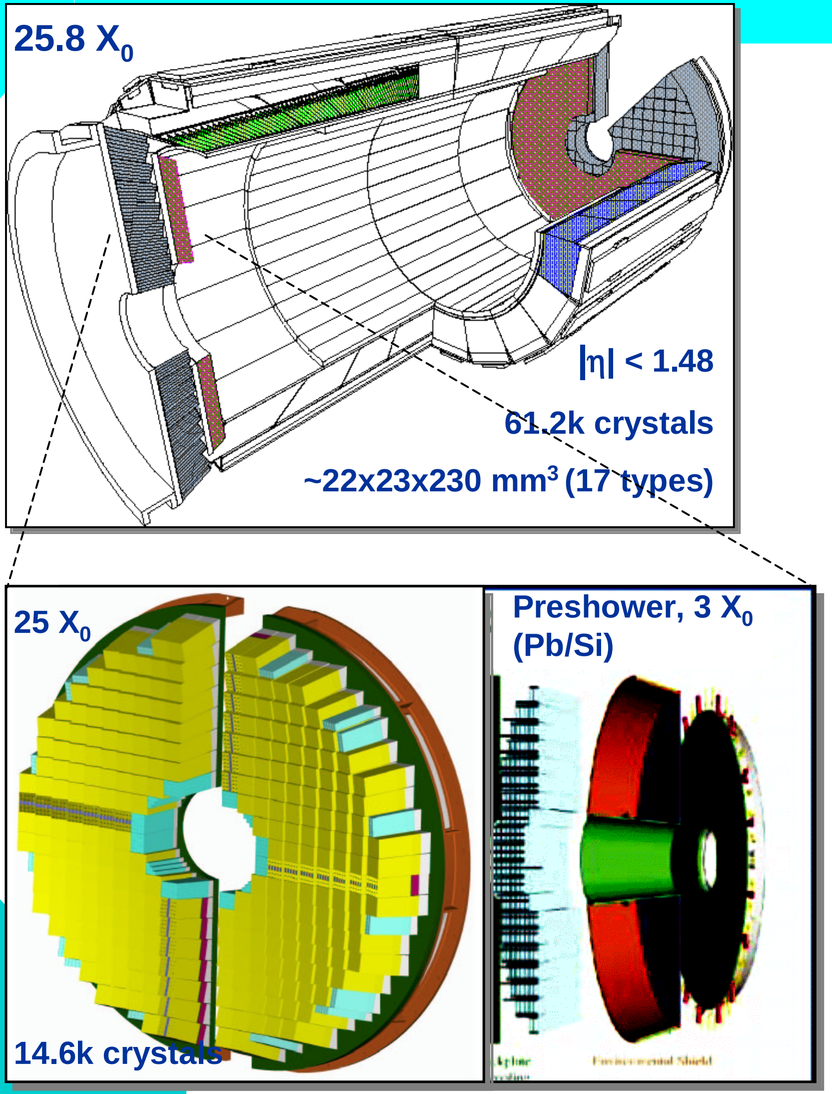
- EM calorimeters technology for hadron colliders is fully developed
- SLHC will require ‘minor’ adaptation (may be with some changes in the forward region)
- For a VLHC present day technology (e.g. LAr, LKr, crystals?) would probably do. Main r&d needed is on the readout side: do not expect major problems with rad hardness, but the challenge is to gain a factor ~5 in shaping time.

Aknowledgements

- I would like to thanks F. Gianotti, D.Fournier, P.Bloch, P.Lecoq, D. Green and all the colleagues in the calorimeter teams of ATLAS and CMS
- Best references are the TDR of the calorimeters and for recent developments/status report check the web sites of the calorimetry conferences

Calor2000 : http://wwwlapp.in2p3.fr/Calor2000/Welcome.html
Calor2002 : http://3w.hep.caltech.edu/calor02/

CMS Lead Tungstate



Why crystals?

Energy resolution
Compactness
Natural tower structure

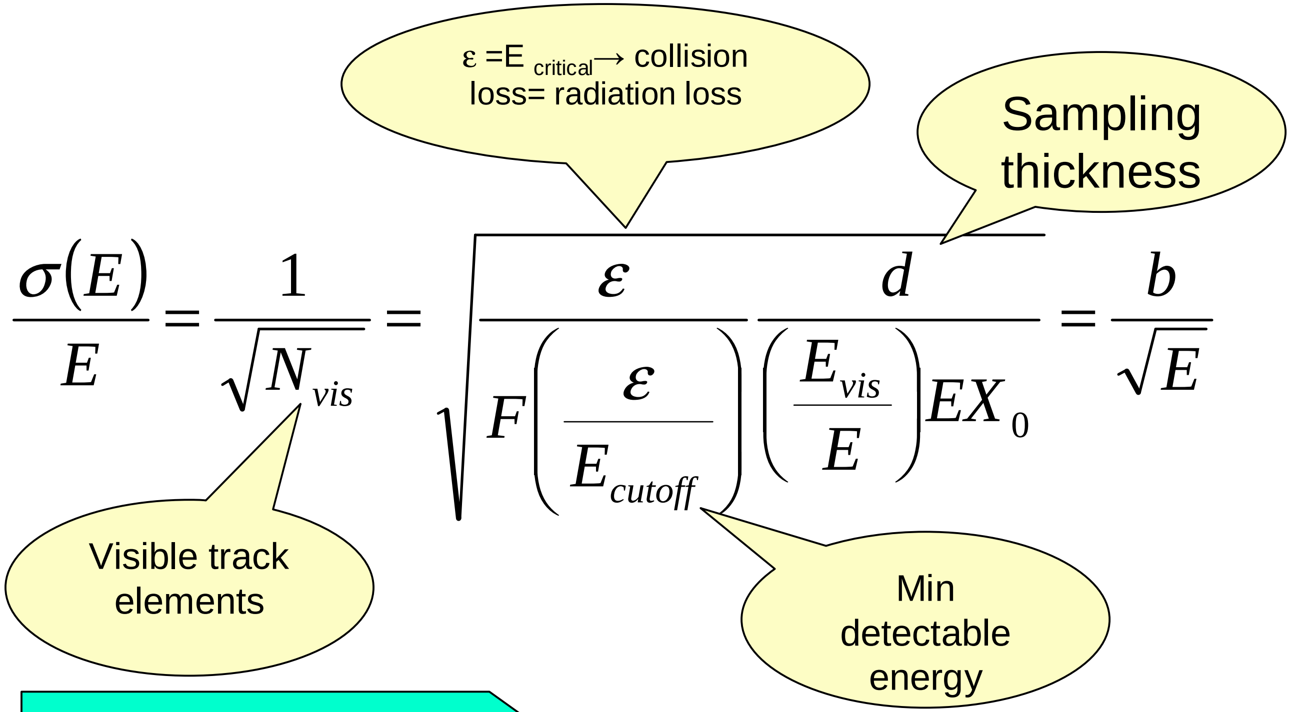
Why $PbWO_4$?

Speed (LHC bunch spacing 25 ns)
Radiation Hardness
Density (X_0)

Readout: APD, PhotoTriodes

B= 4T
Gain : low light yield
Radiation resistant

the stockastic term



$\varepsilon = E_{critical}$ → collision loss= radiation loss

Sampling thickness

$$\frac{\sigma(E)}{E}=\frac{1}{\sqrt{N_{vis}}}=\sqrt{\frac{\varepsilon}{F\left(\frac{\varepsilon}{E_{cutoff}}\right)}\,\frac{d}{\left(\frac{E_{vis}}{E}\right)EX_0}}=\frac{b}{\sqrt{E}}$$

Visible track elements

Min detectable energy

Small stockastic term → Low d/X_0 and large sampling fraction E_{vis}/E

Radiation

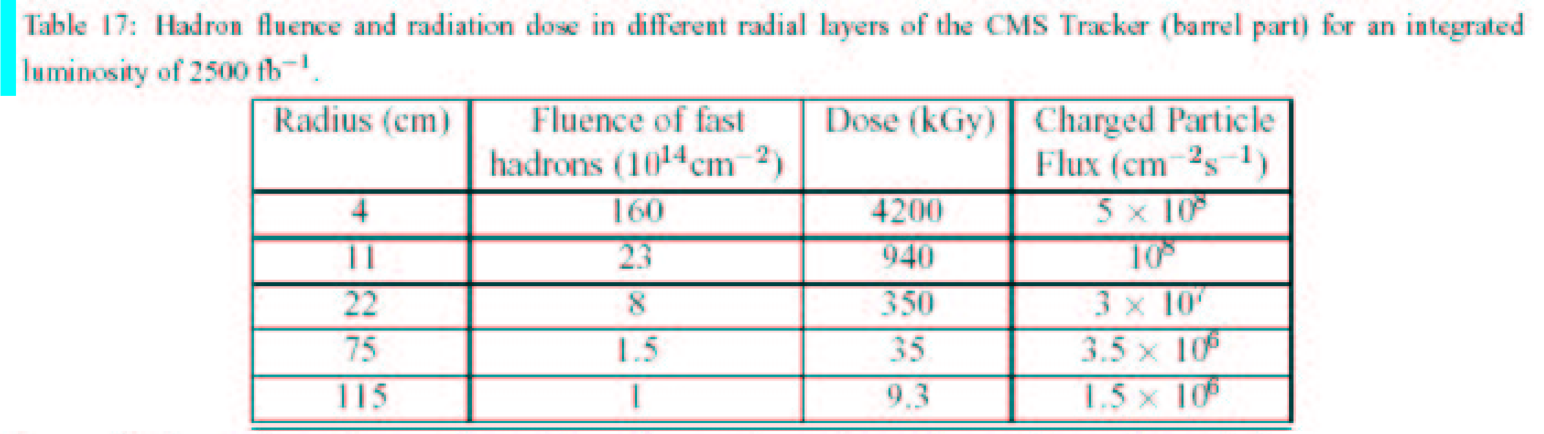
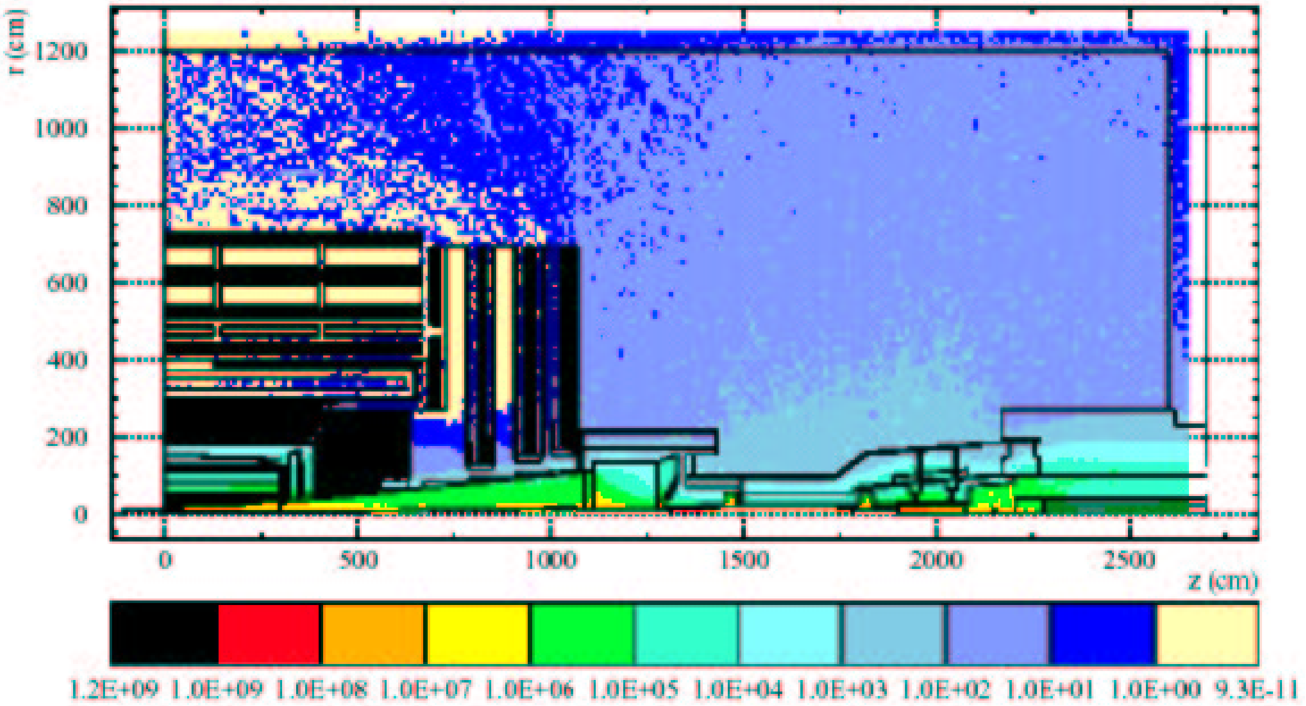


Table 17: Hadron fluence and radiation dose in different radial layers of the CMS Tracker (barrel part) for an integrated luminosity of 2500 fb^{-1}.

Radius (cm)	Fluence of fast hadrons (10^{14}cm^{-2})	Dose (kGy)	Charged Particle Flux (cm^{-2}s^{-1})
4	160	4200	5×10^8
11	23	940	10^8
22	8	350	3×10^7
75	1.5	35	3.5×10^6
115	1	9.3	1.5×10^6



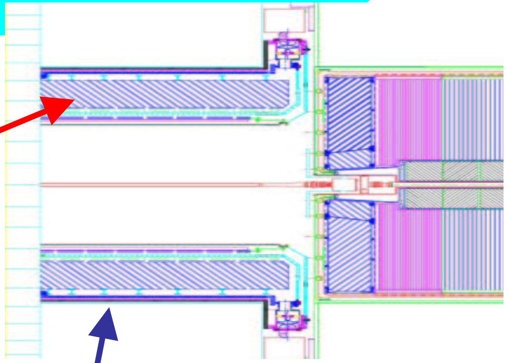
Dose in CMS after 2500 fb^{-1}

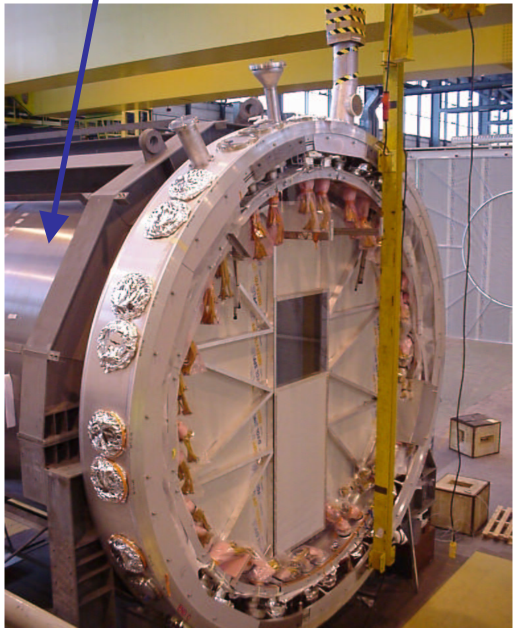
ATLAS

Module construction finished,
1st wheel completely assembled May 2003

Accordion

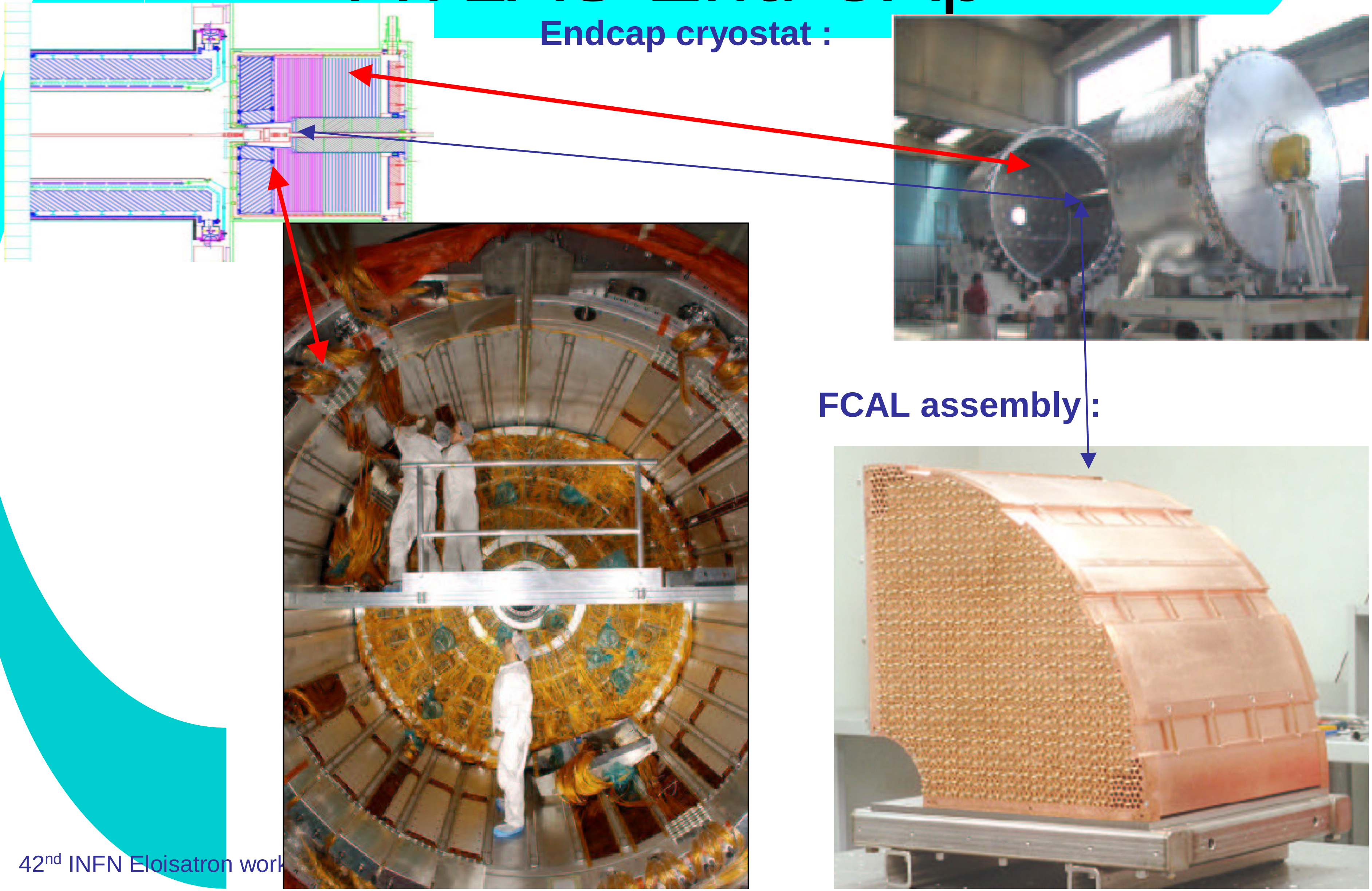
Structure





barrel cryostat

ATLAS End CAp

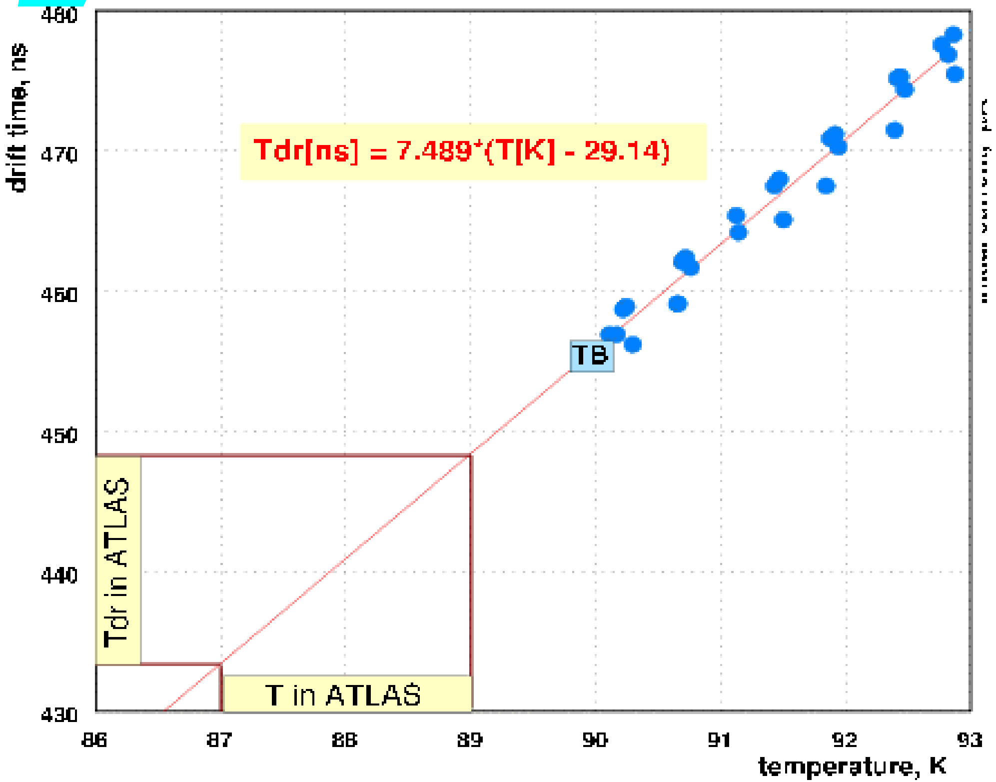


Endcap cryostat :

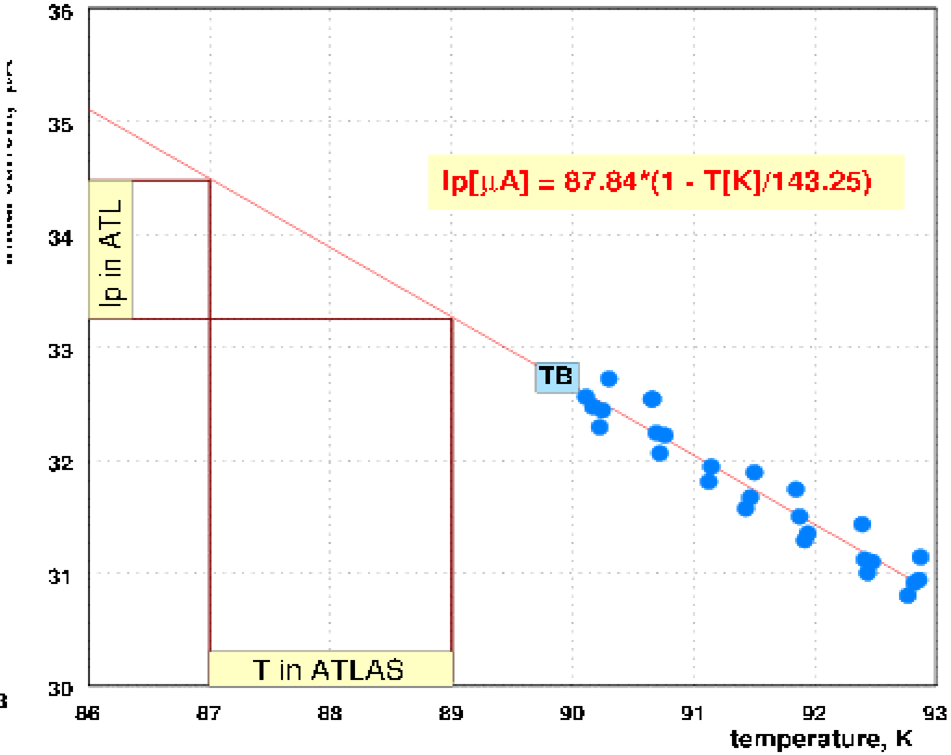
FCAL assembly :

ATLAS LAr: T dependance

Drift time measured from the physics shape in the HEC :



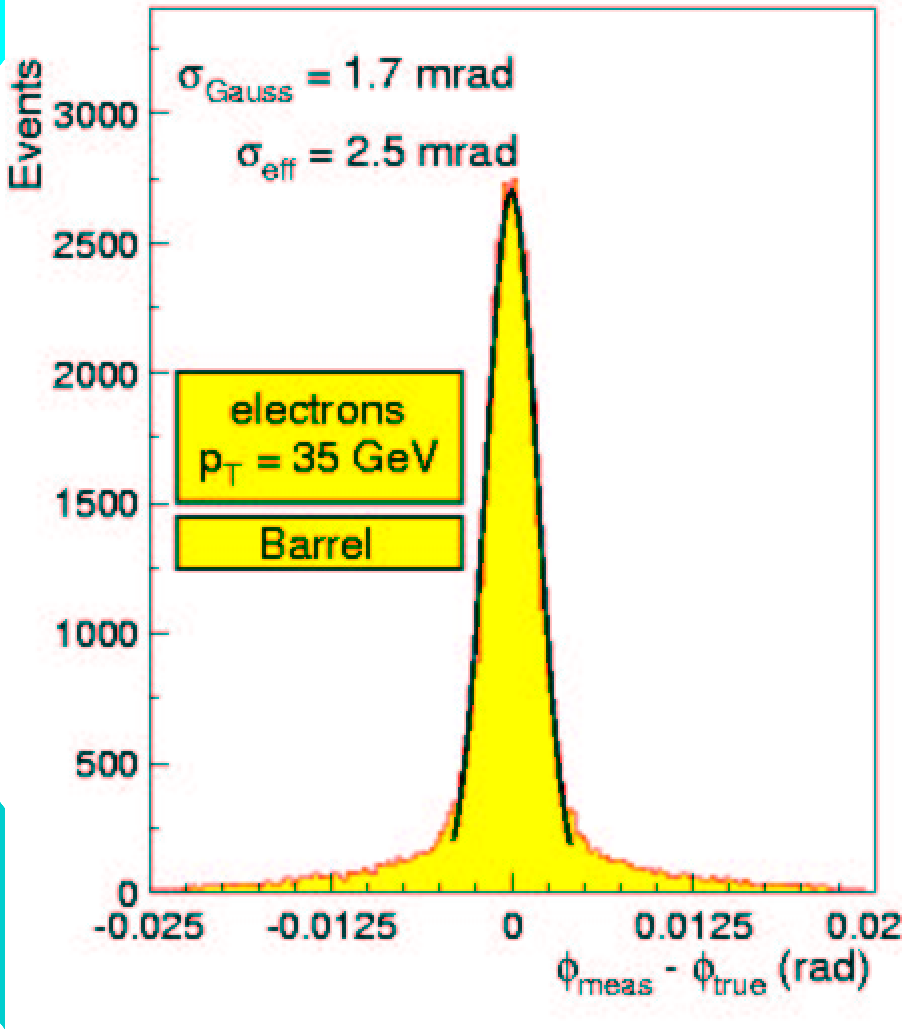
HEC : I= f(T)



In agreement with expectation :

2% / K on the energy

CMS ecal performance



Position resolution (fullMC)

ATLAS electronics