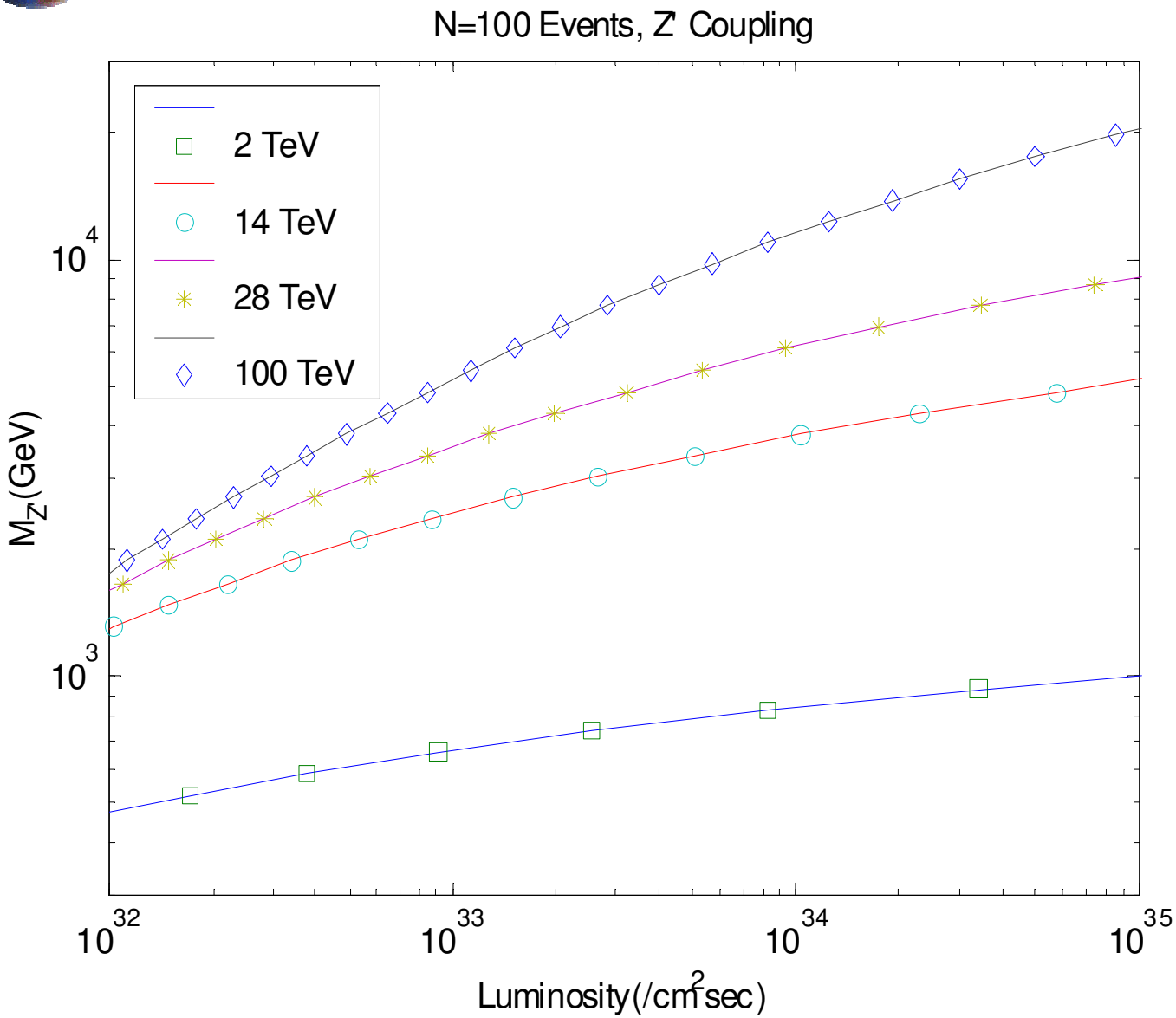
Hadron Calorimetry

For Future Hadron Colliders

Jim Freeman

Fermilab

Mass Reach vs energy and L



VLHC/ Eloisatron

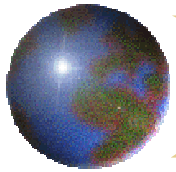
LHC

Tevatron

SLHC Detector Environment

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
L	10^{34} /($cm^2 \cdot$sec)	10^{35} /($cm^2 \cdot$sec)
$\int Ldt$	100 fb^{-1} / yr	1000 fb^{-1} / yr
Bunch spacing dt	25 ns	12.5 ns
N. interactions/x-ing	~ 20	~ 100
$dN_{ch}/d\eta$ per x-ing	~ 100	~ 500
Tracker occupancy	1	5
Pile-up noise	1	~2.2
Dose central region	1	10

Bunch spacing reduced 2x. Interactions/crossing increased 5 x. Pileup noise increased by 2.2x if crossings are time resolvable.

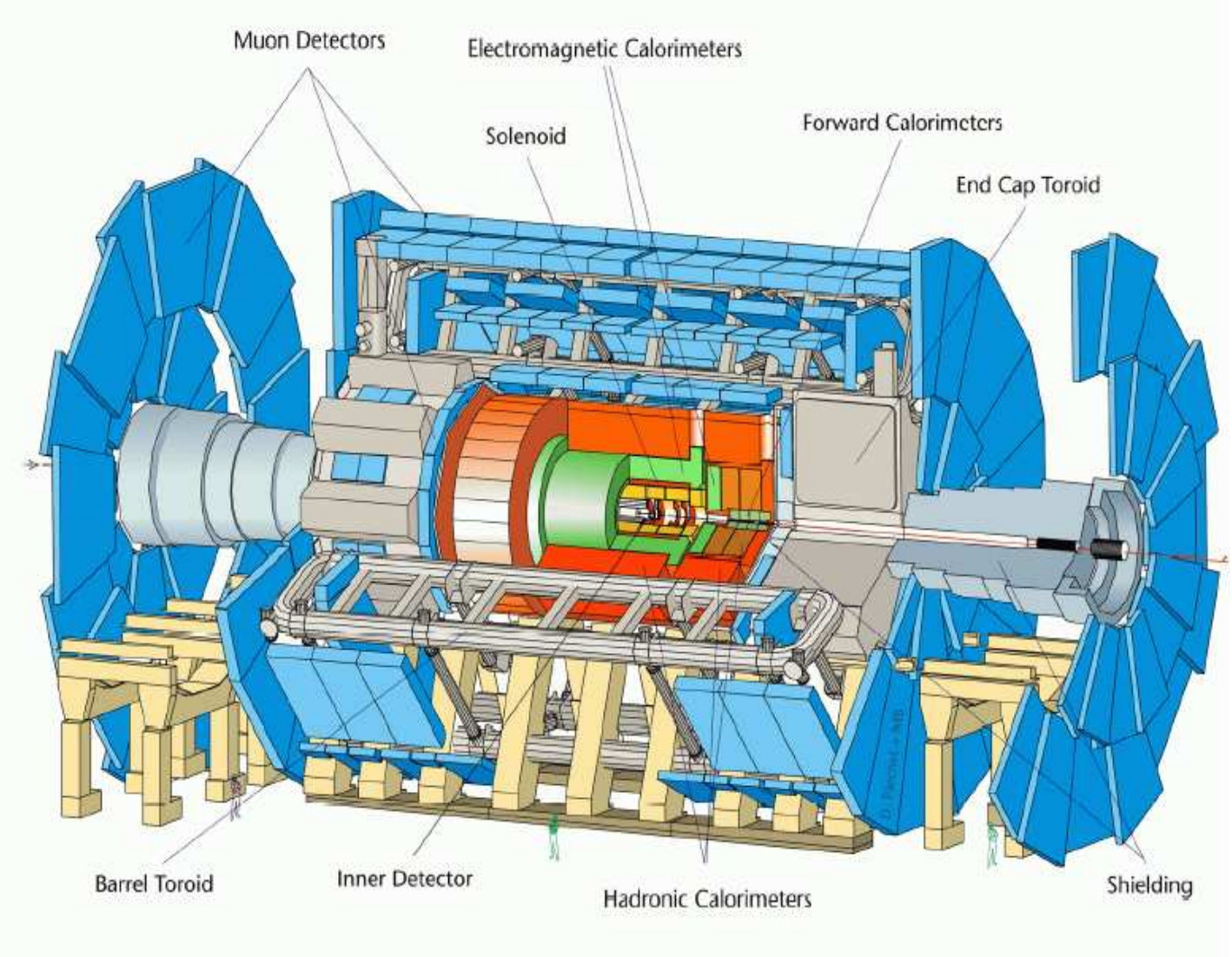


VLHC/ Eloisatron Detector Environment

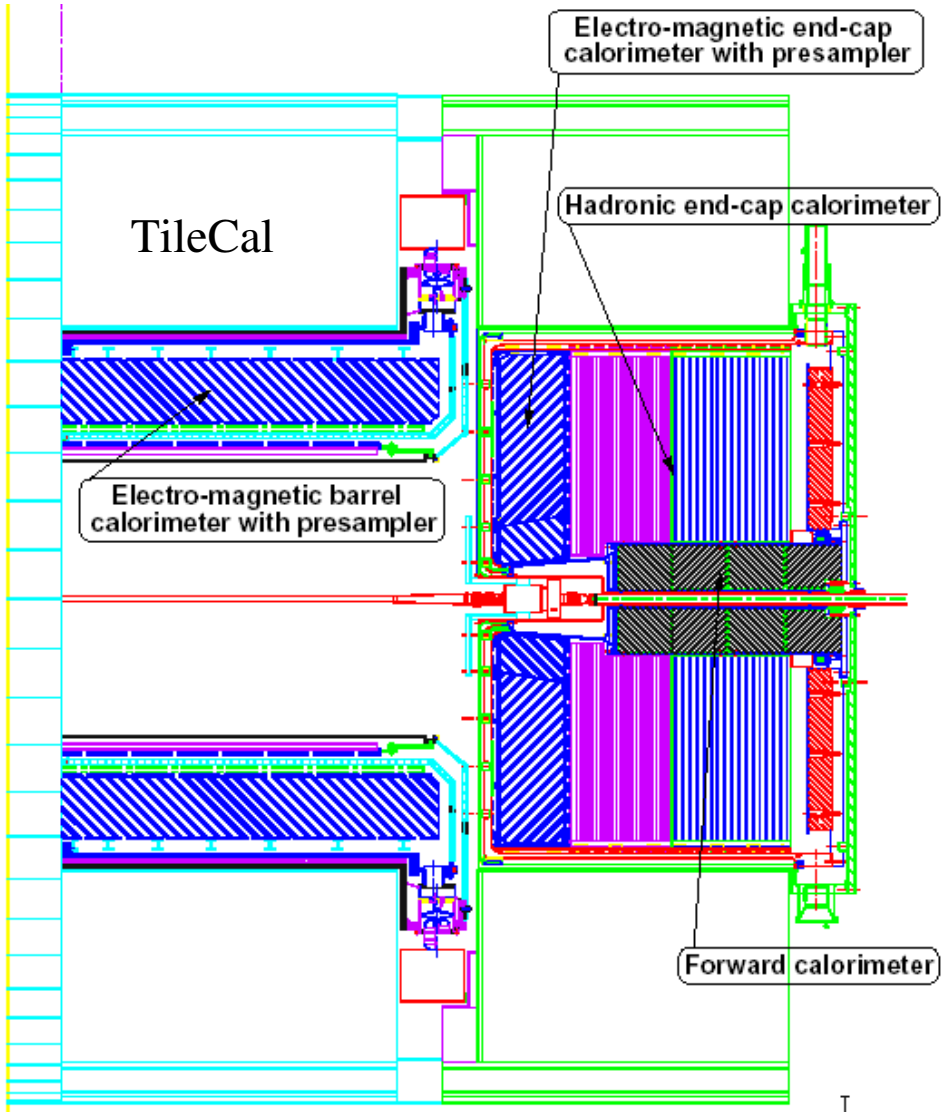
	LHC	VLHC
$\sqrt{s}$	14 TeV	100 TeV
L	$10^{34}\ /(cm^2 \cdot \mathrm{sec})$	$10^{34}\ /(cm^2 \cdot \mathrm{sec})$
$\int Ldt$	100 $fb^{-1}\ /\ yr$	100 $fb^{-1}\ /\ yr$
Bunch spacing dt	25 ns	19 ns
N. interactions/x-ing	~ 20	~ 25**
$dN_{ch}/d\eta$ per x-ing	~ 100	~ 250**
Tracker occupancy	1	2.5**
Pile-up noise	1	2.5**
Dose central region	1	5**

**** 130 mB inelastic cross section, $\langle N_{ch} \rangle$ ~ 10, $\langle Et \rangle$ = 1GeV**

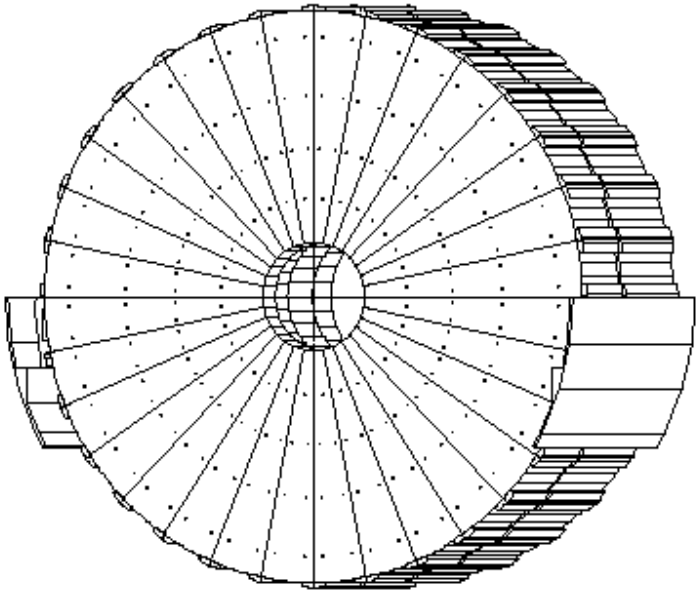
ATLAS Calorimeters



ATLAS Calorimeter



ATLAS LAR Hadron EndCap

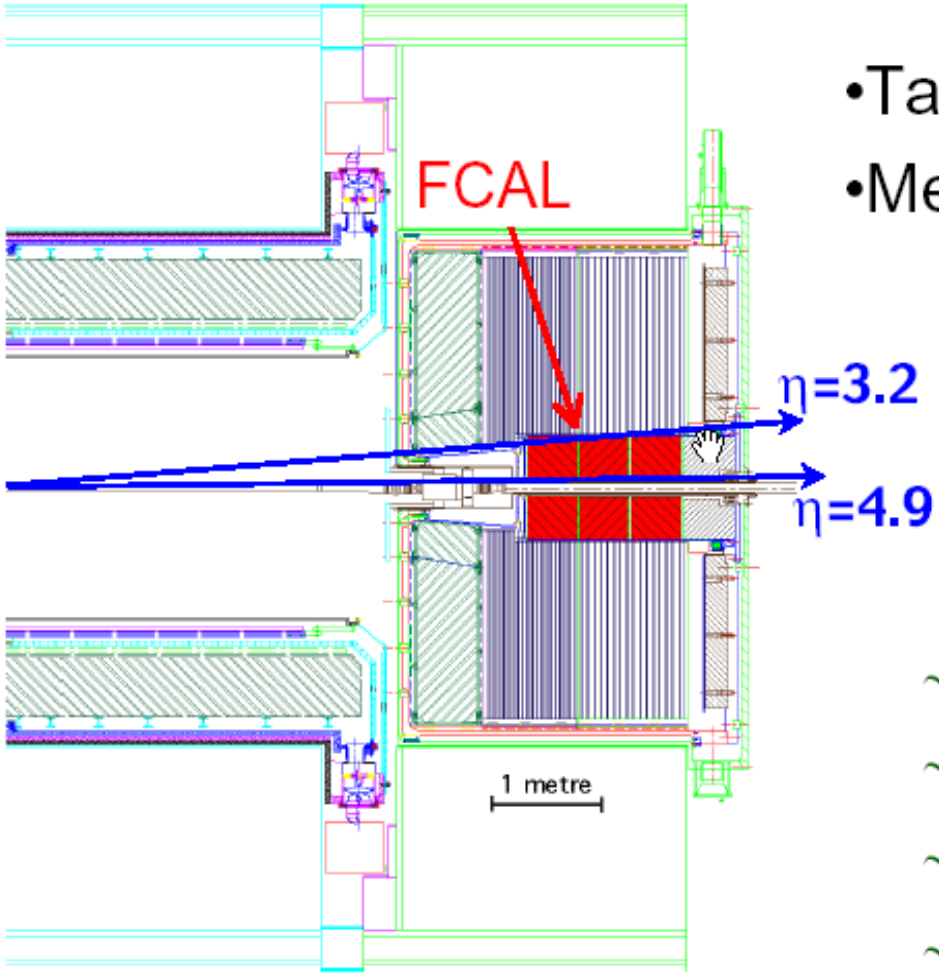


	HEC
Number of modules	128
Pseudorapidity-coverage	$1.5 < \|\eta\| < 3.2$
Total thickness	$\geq$10 λ
Longitudinal samplings	4 (4)†
Transverse granularity $\Delta\eta \times \Delta\varphi$	0.1×0.1 (0.2×0.2)†
Number of channels	~5 600

† — values in brackets for $|\eta| > 2.5$

ATLAS FCAL

ATLAS Forward Calorimeter



- Tag forward jets
- Measure missing E_T

$$\frac{\sigma(E_T)}{E_T} \leq 10\%$$

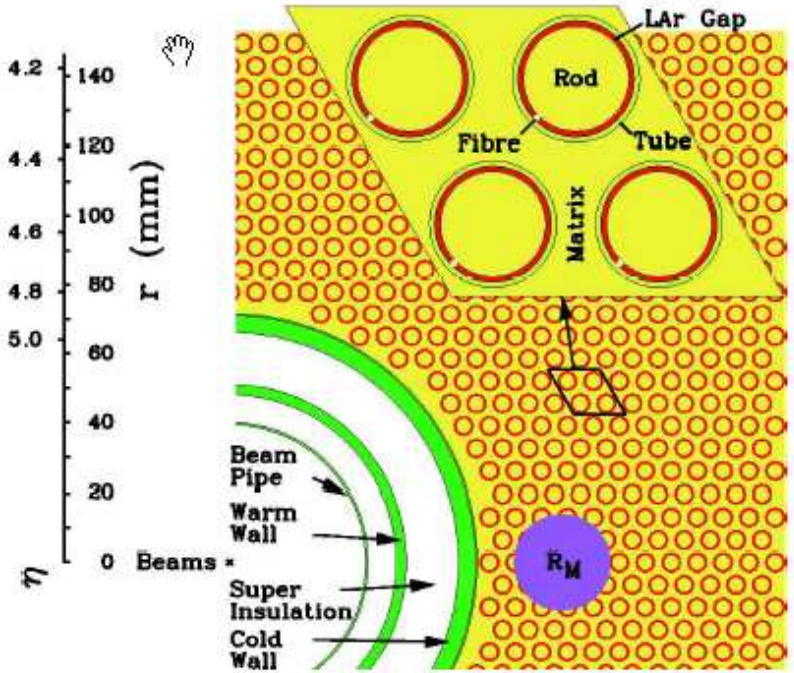
~ 40Mhz

~ 10^8 GeV/cm^2/s at η=4.5

~ 10^6 Gy/year

~ 100 Watts absorbed

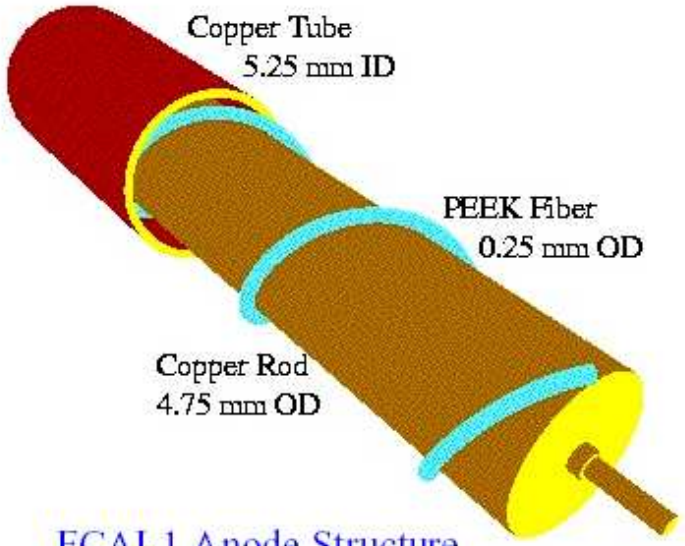
ATLAS FCAL



FCAL End View

Anode Spacing (FCAL1/2/3)

- 7.5 / 8.18 / 9.00 mm

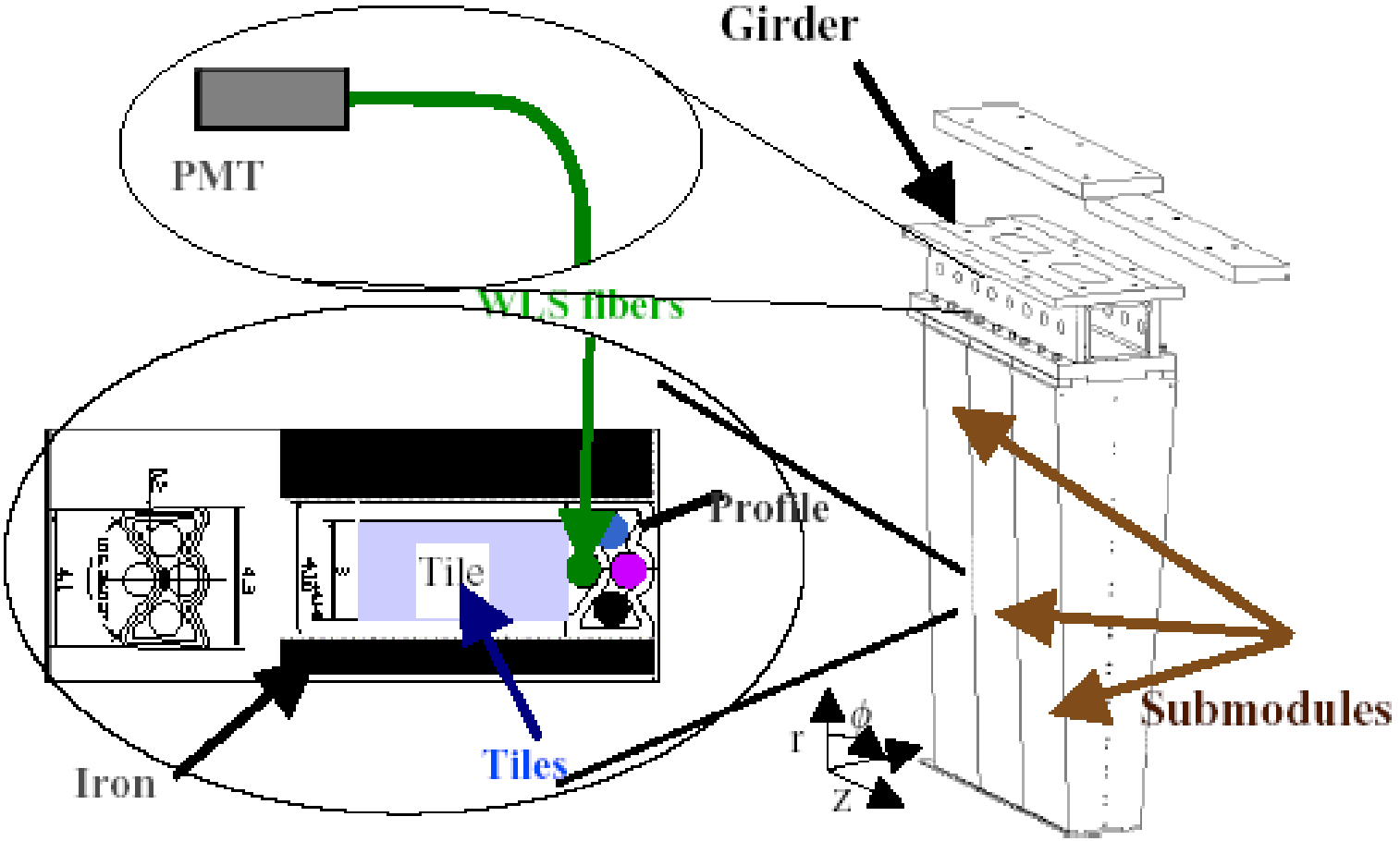


FCAL1 Anode Structure

Liquid Argon gap

- 250 / 375 / 500 μm

ATLAS Tilecal



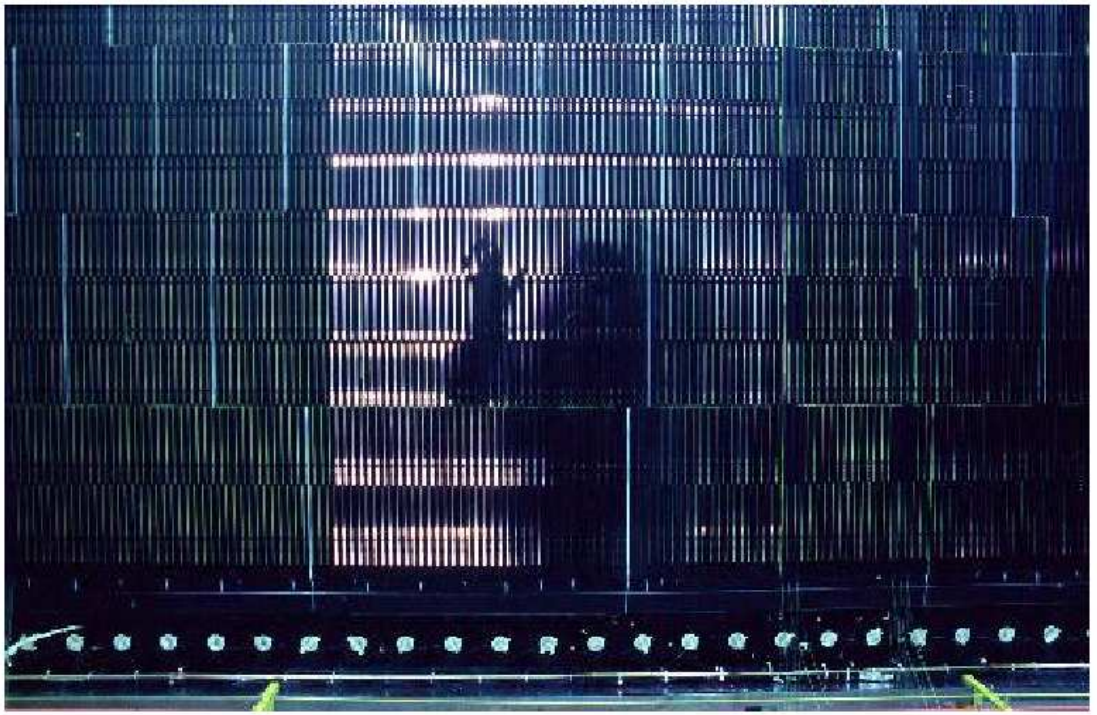
Longitudinal tile configuration ⇒ good hermeticity and "easy" construction

Fe/Scint/WLS fiber

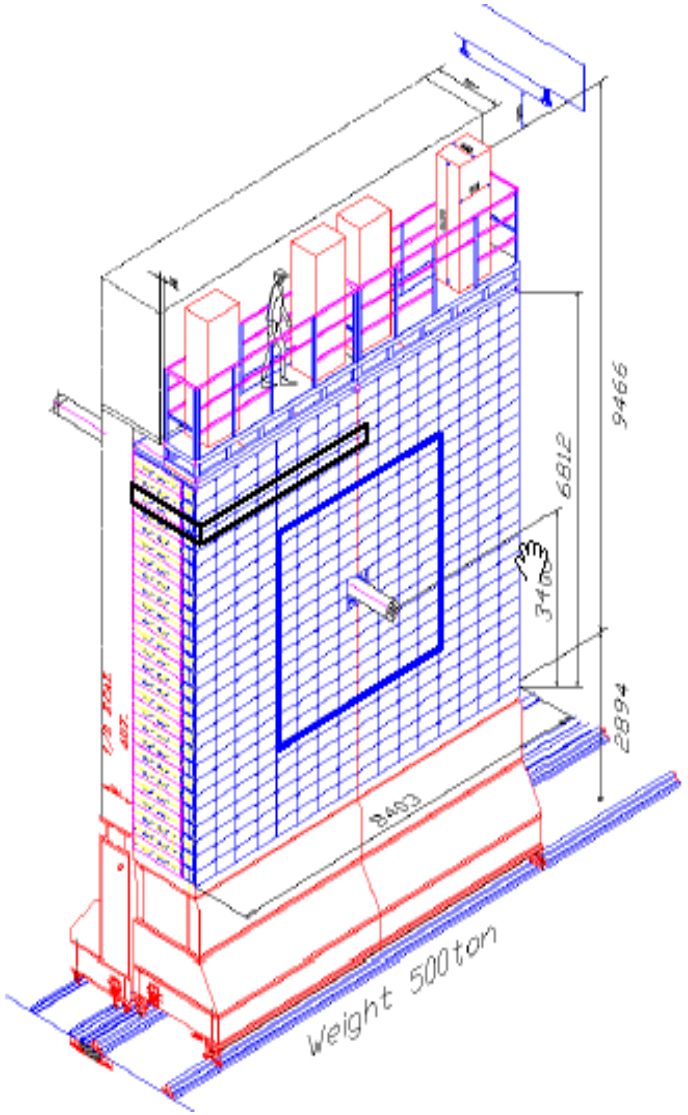
4:1 Fe:Scint

ATLAS TILECAL

36 modules of +/- endcaps, central wheel



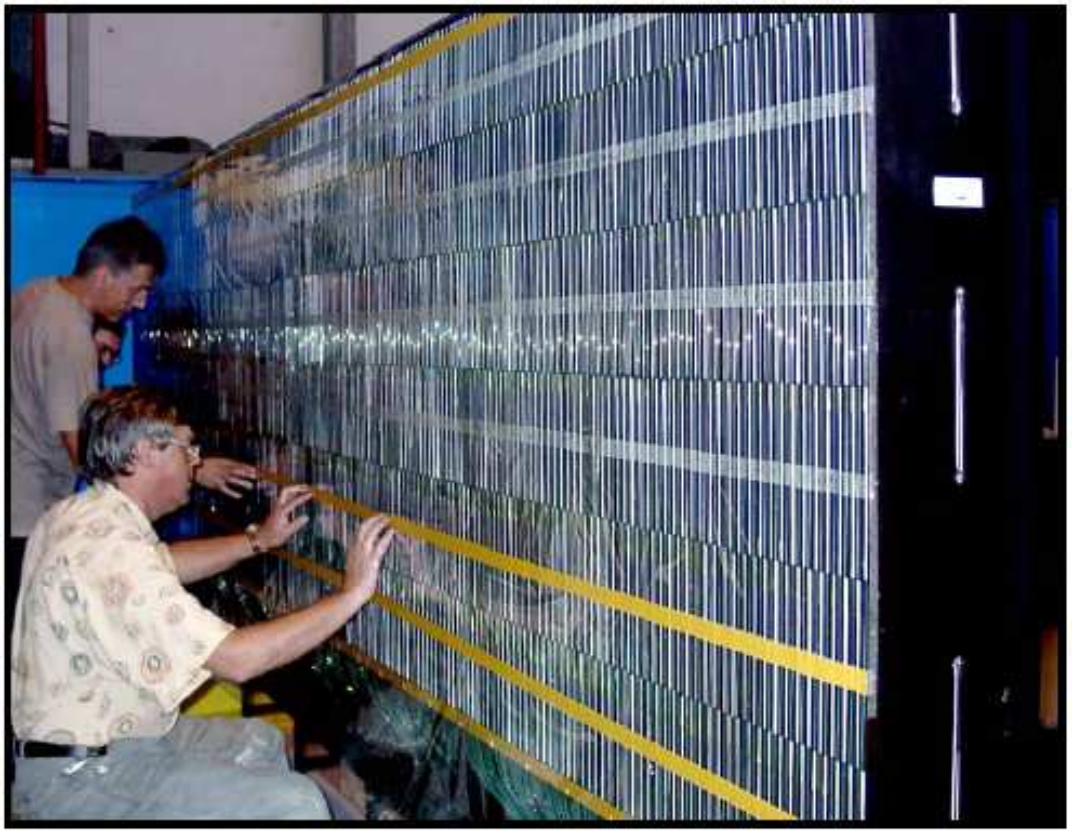
LHCB HCAL

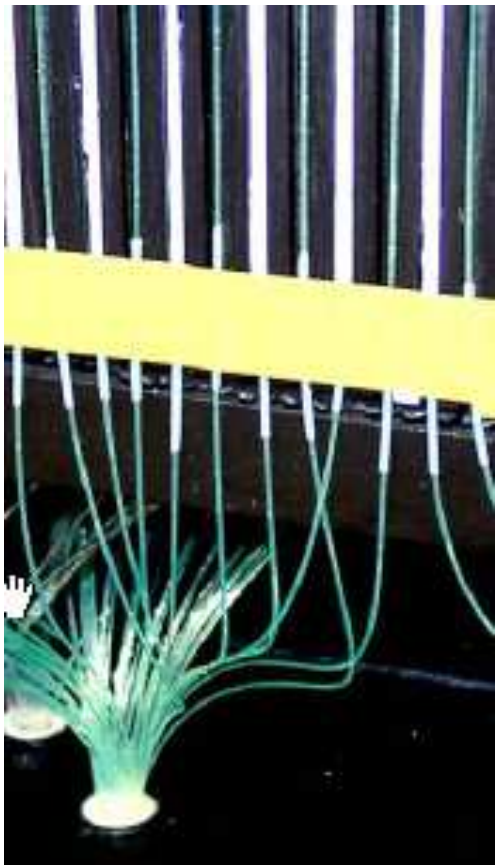


two separate movable halves:

- *stack of 26 modules in each half*
- *5.6 λ instrumented depth*
- *4.2(w) x 0.26(h) x 1.66(l) m*
- *module weight 9.5 ton*
- *read-out electronics on detector*

LHCB Hadron Calorimeter



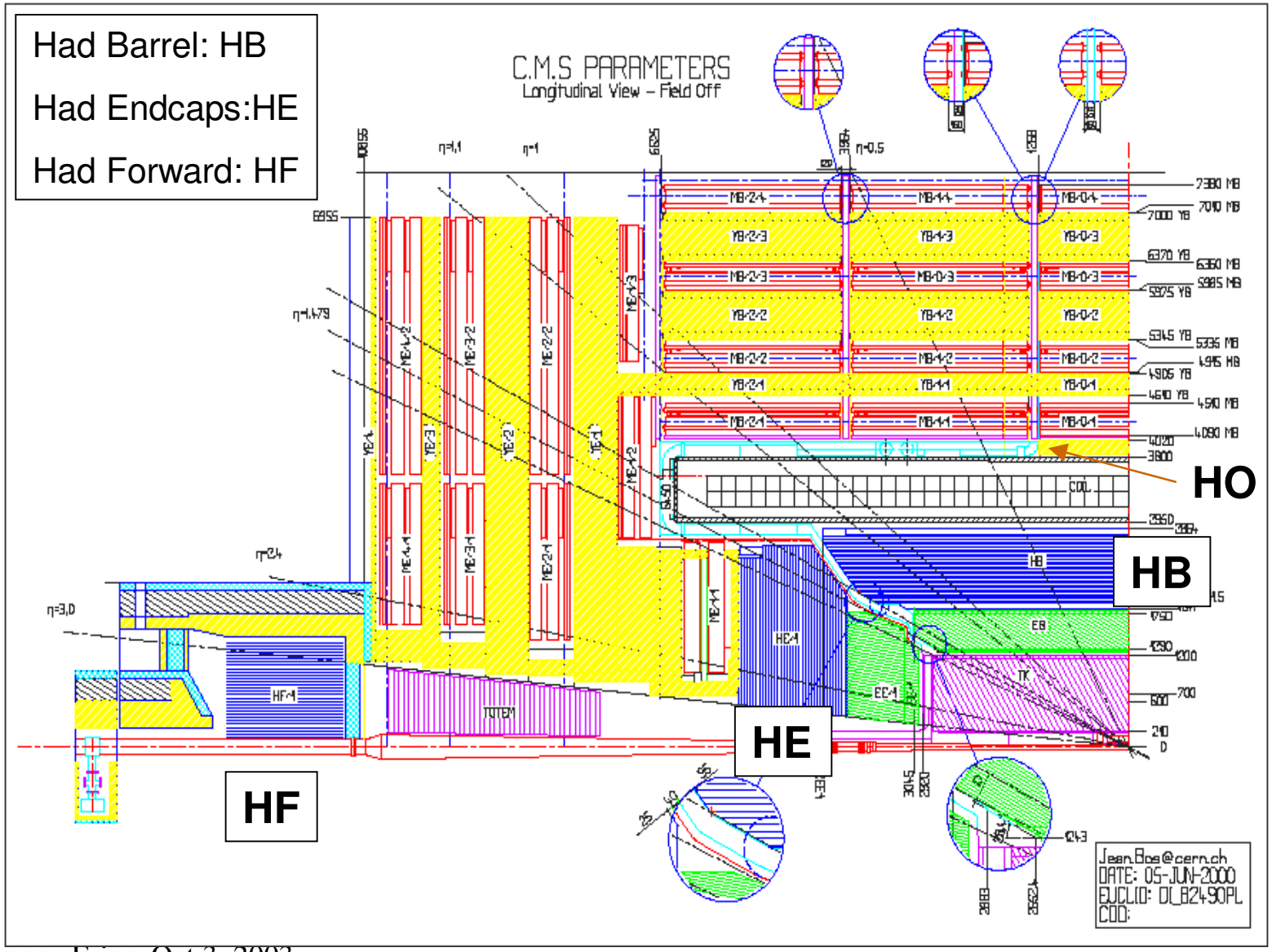


CMS HCALs

Had Barrel: HB

Had Endcaps:HE

Had Forward: HF



HCAL : HE and HB

CMS HB Calorimeter

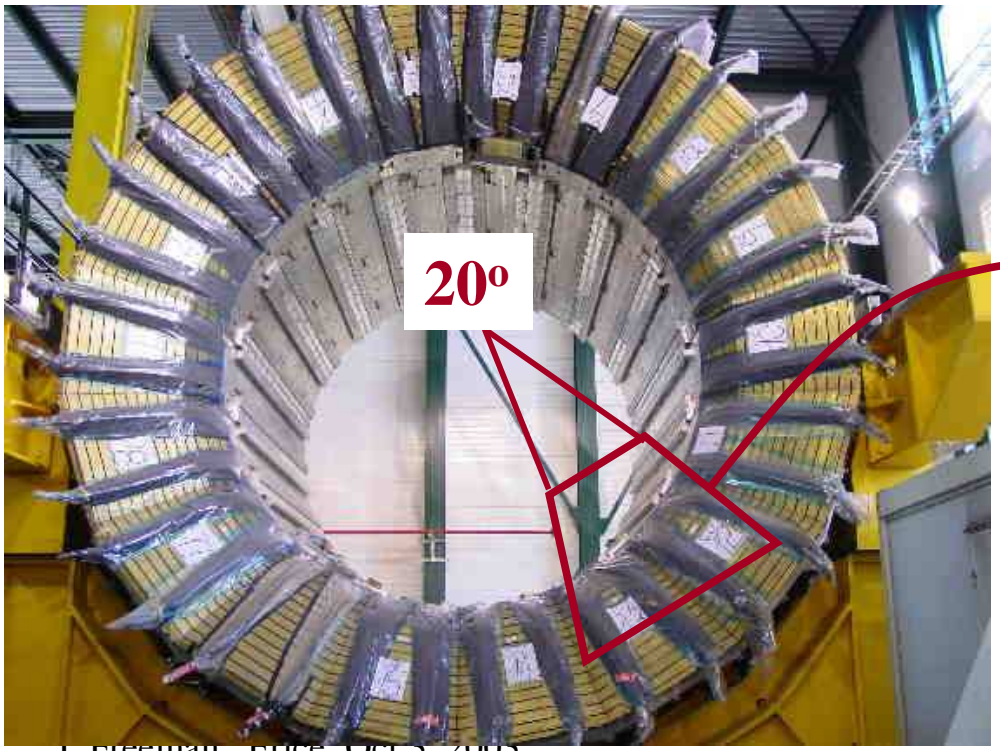
Sampling calorimeter: brass (passive) & scintillator (active)

Coverage: $|\eta|<1.3$

Depth: 5.8 λ_{int} (at η=0)

π resolution: ~ 120 %/ $\sqrt{E}$

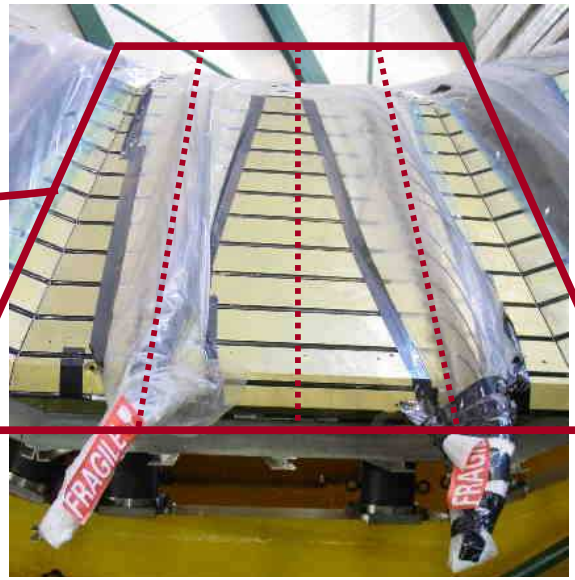
Completed & assembled



segmentation: $\phi \times \eta$ = 0.087x0.087

17 layers longitudinally,

ϕ x η = 4 x 16 towers



CMS HE Calorimeter

Sampling calorimeter: brass (passive) & scintillator (active)

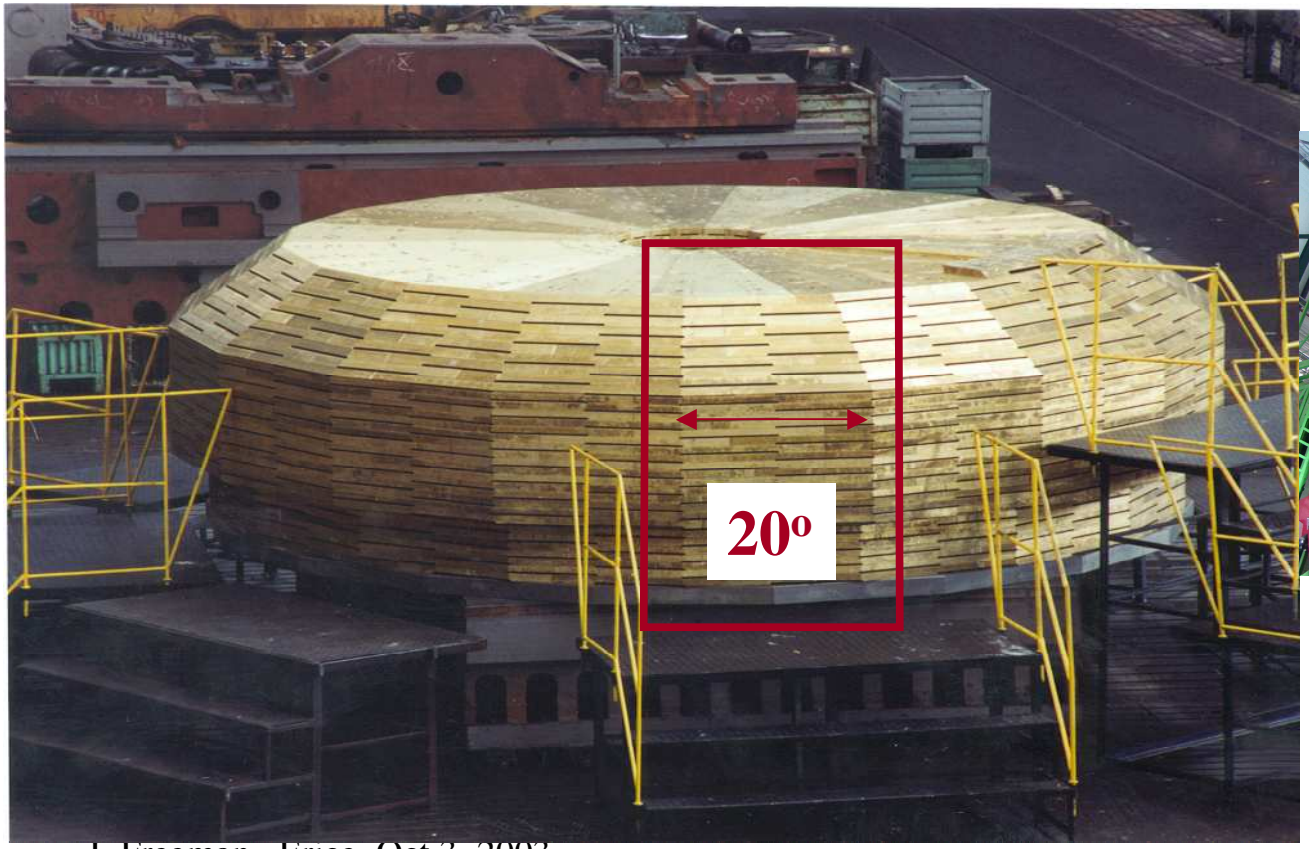
Coverage: $1.3<|\eta|<3$

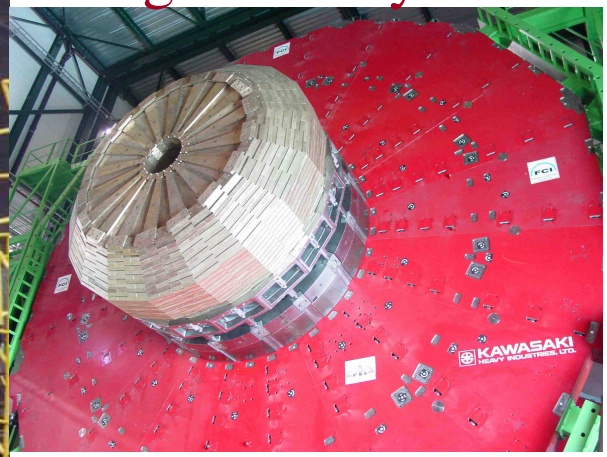
Depth: $10\ \lambda_{int}$

π resolution: $\sim 120\%/\sqrt{E}$

segmentation: $\phi \times \eta =$ 0.087×0.087

19 layers longitudinally

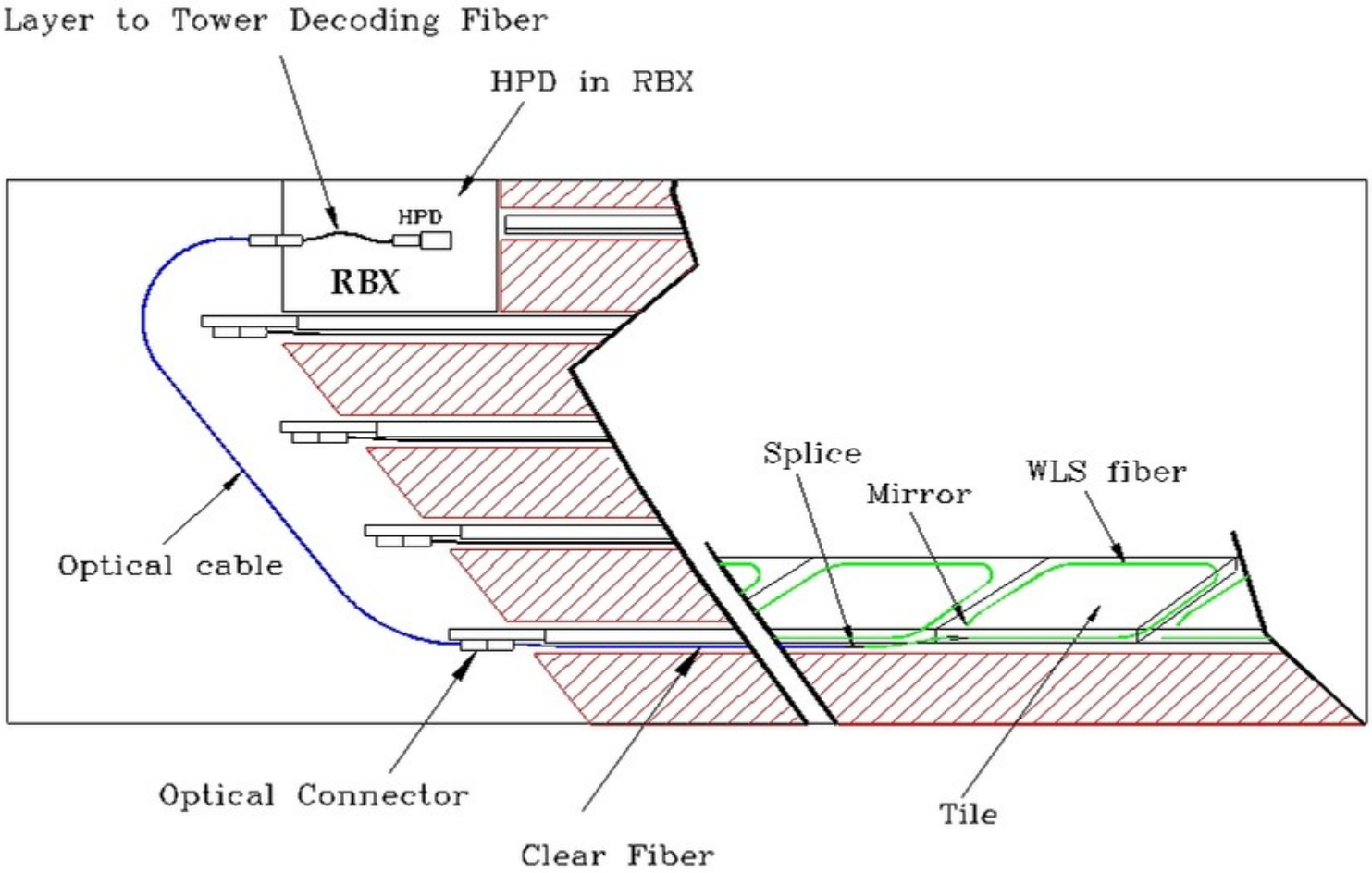




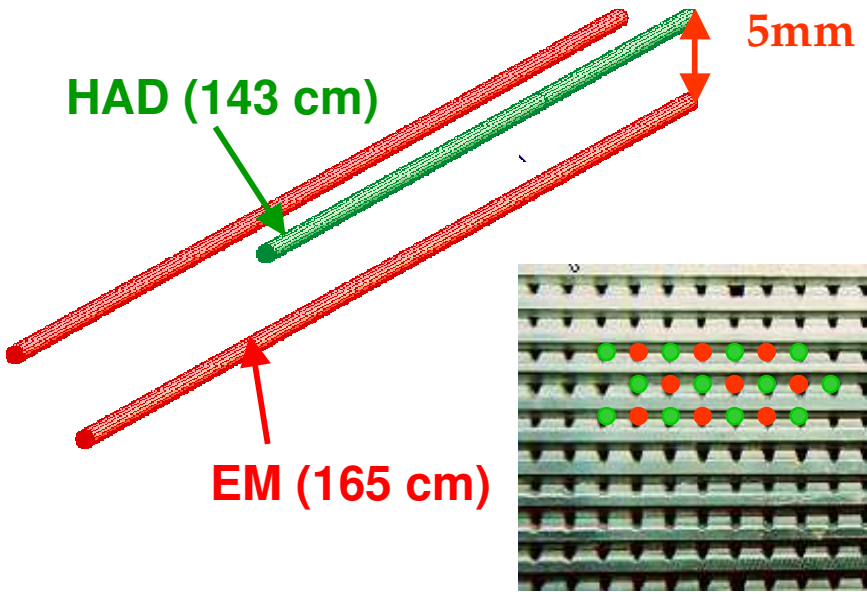
Completed, assembled, HE-1 installed

Optical Design for CMS HCALs

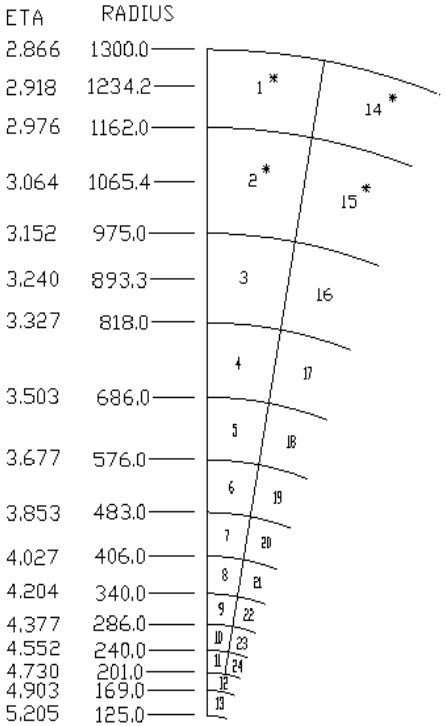
Common Technology for HB, HE, HO



HF detector

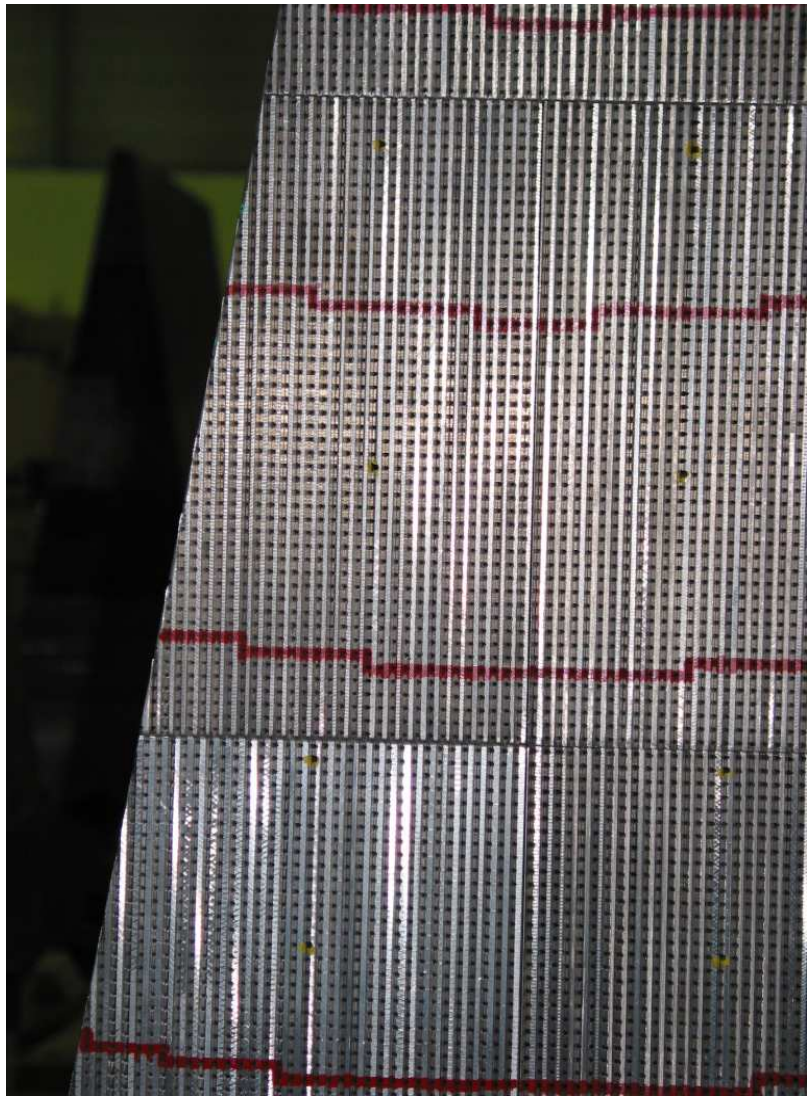


To cope with high radiation levels (>1 Grad accumulated in 10 years) the active part is Quartz fibers: the energy measured through the Cerenkov light generated by shower particles.

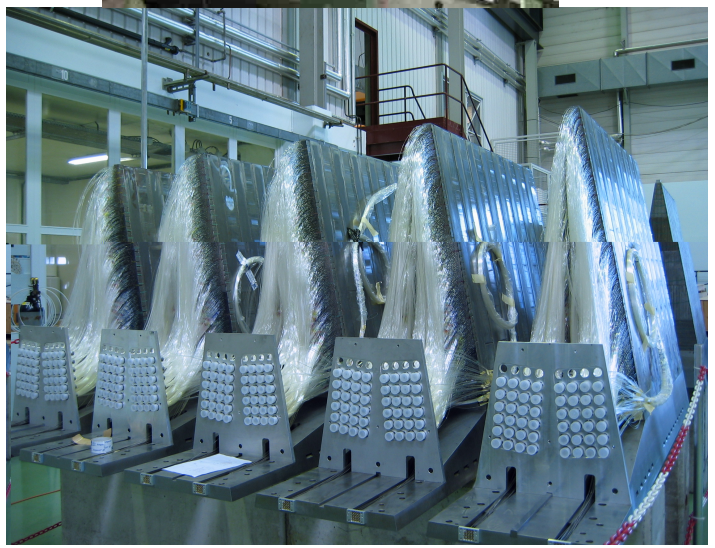


Iron calorimeter
Covers $5 > \eta > 3$
Total of 1728 towers, i.e.
2 x 432 towers for EM and HAD
η x ϕ segmentation (0.175 x 0.175)

Fibers in the HF absorber



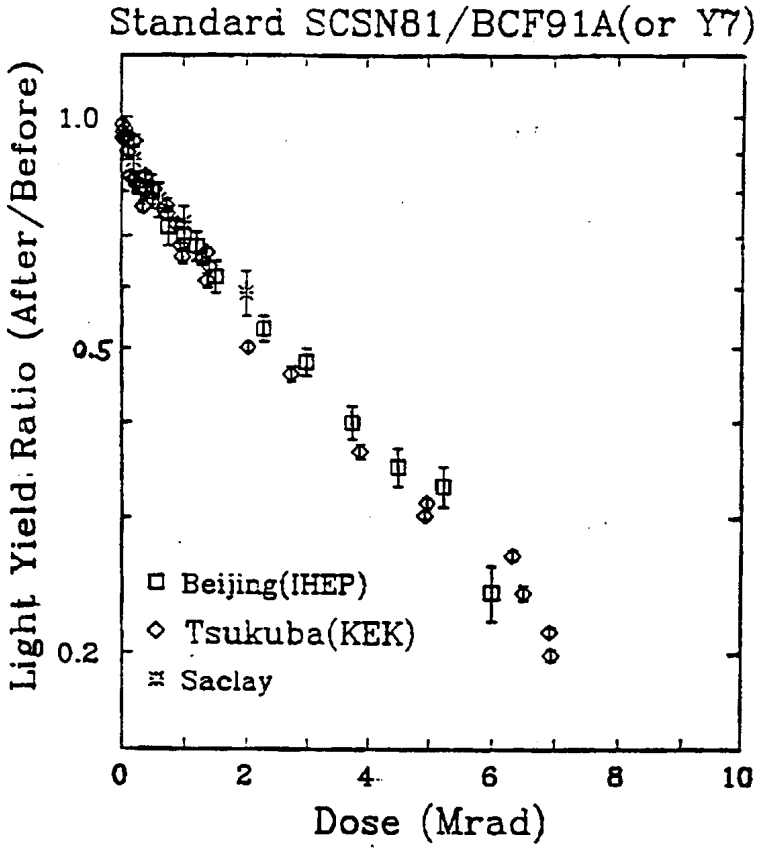
HF Fiber stuffing at CERN



Issues for SLHC

- Radiation Damage
- Rate Effects
- Bunch ID determination

Scintillator - Dose/Damage

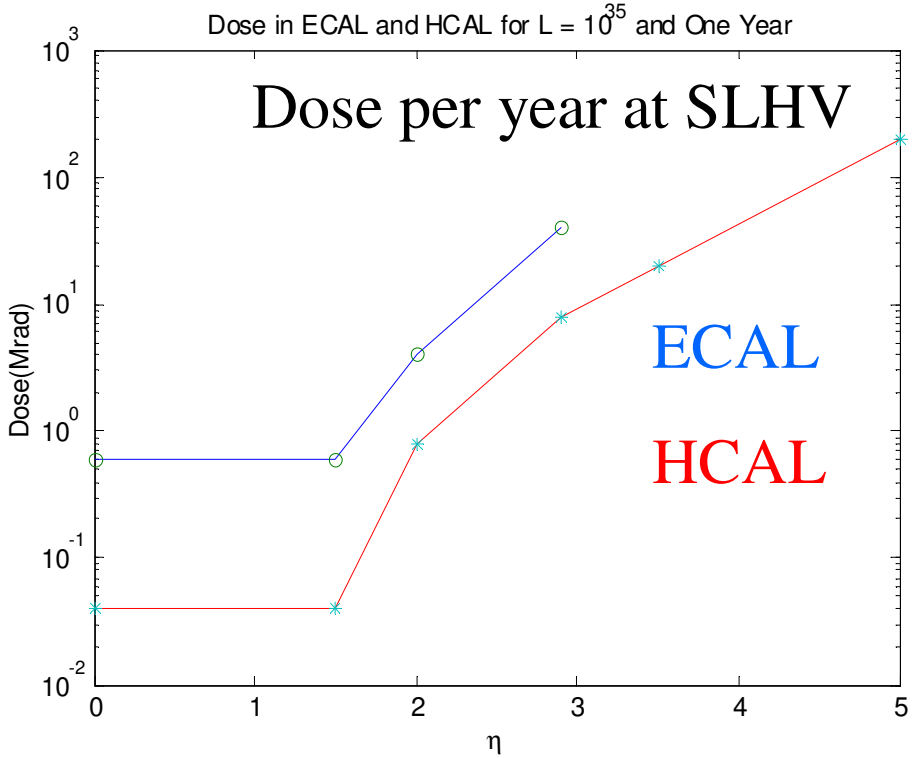


Scintillator under irradiation forms
Color centers which reduce the
Collected light output (transmission loss).

LY ~ exp[-D/Do], Do ~ 4 Mrad

Current operational limit ~ 5 Mrad

Radiation damage to scintillators



Barrel doses are not a problem. For the endcaps a technology change may be needed for 2 < |y| < 3 for the CMS HCAL.

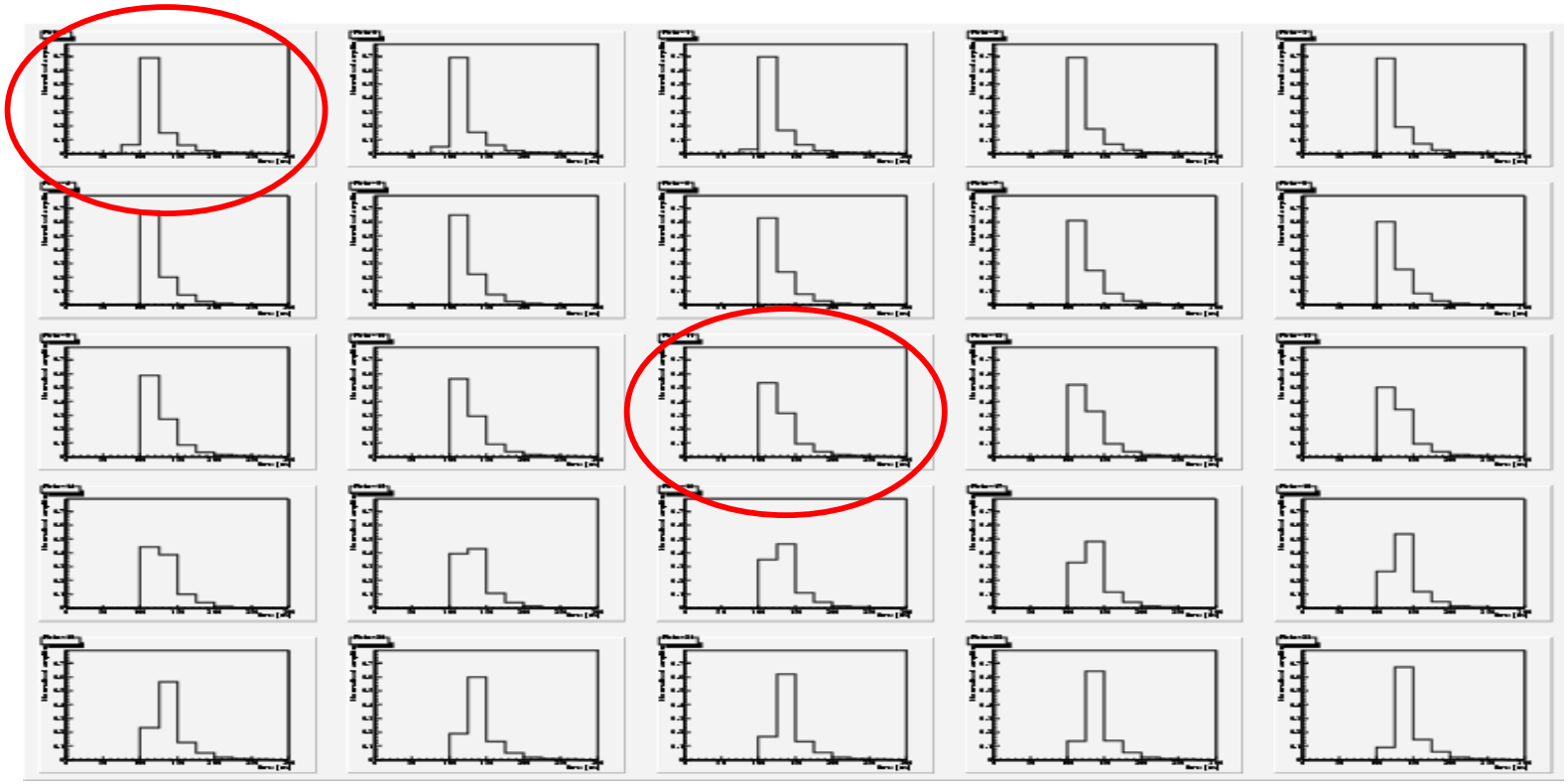
Liquid Ar Ionization

	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

At SLHC, ATLAS LAR will stop working at η~ 1.5
Switch to liquid Xe, ?

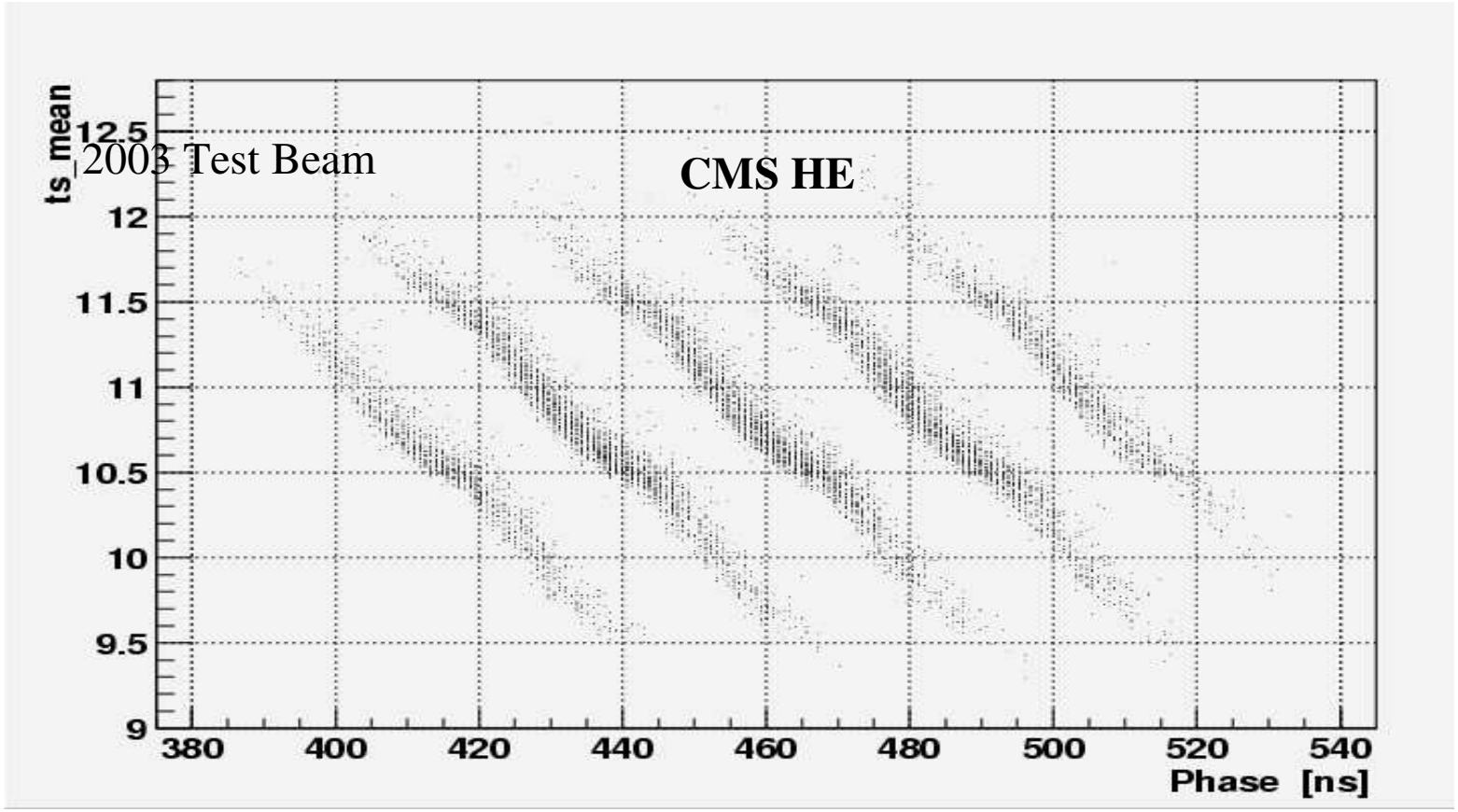
CMS HB Pulse Shape

100 GeV electrons. 25ns bins. Each histo is average pulse shape, phased +1ns to LHC clock



12 ns difference between circled histo's → no problem with bunch ID

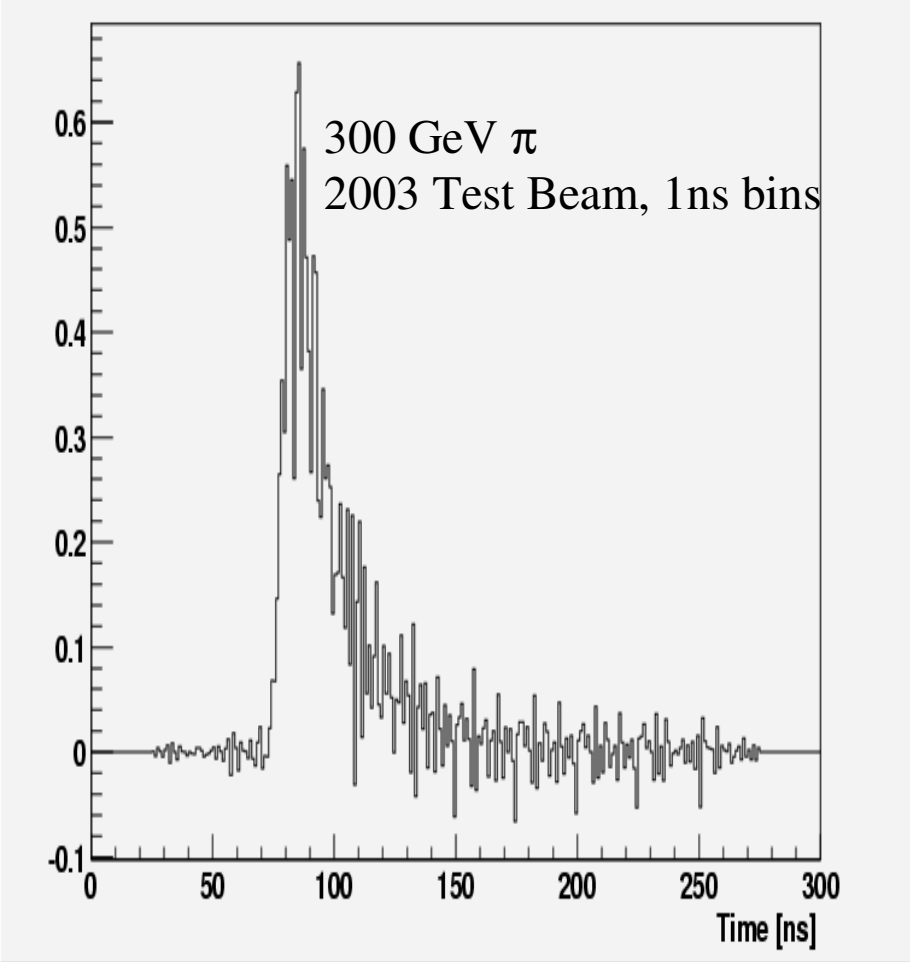
Timing using calorimeter pulse shape



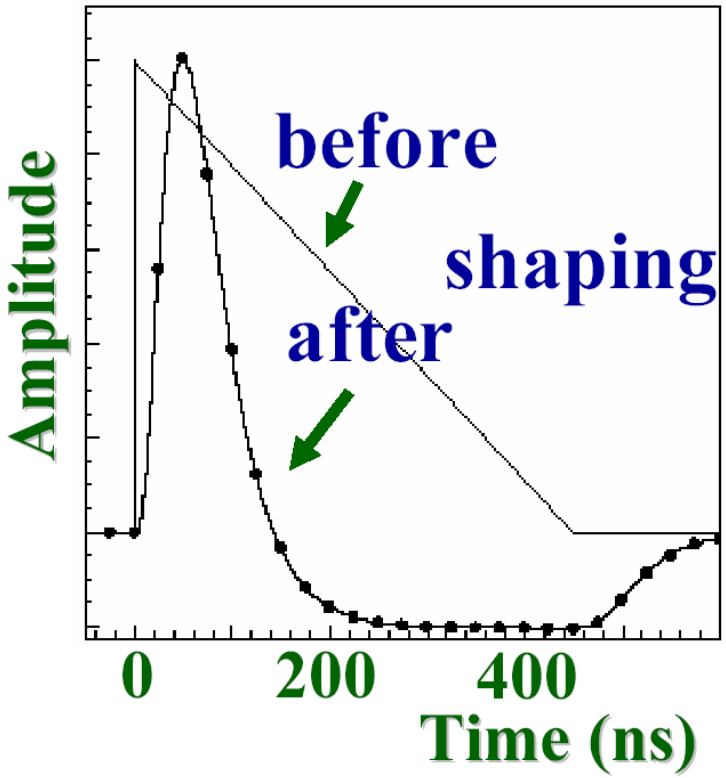
Calculated event time (vertical scale) vs actual event time. CMS HE, 100GeV pions. Also works for lAr. DO timing resolution 4ns/E (in GeV). Watch pile-up though. The faster the calorimeter, the less important pile-up will be.

What about ATLAS?

CMS HE Calorimeter

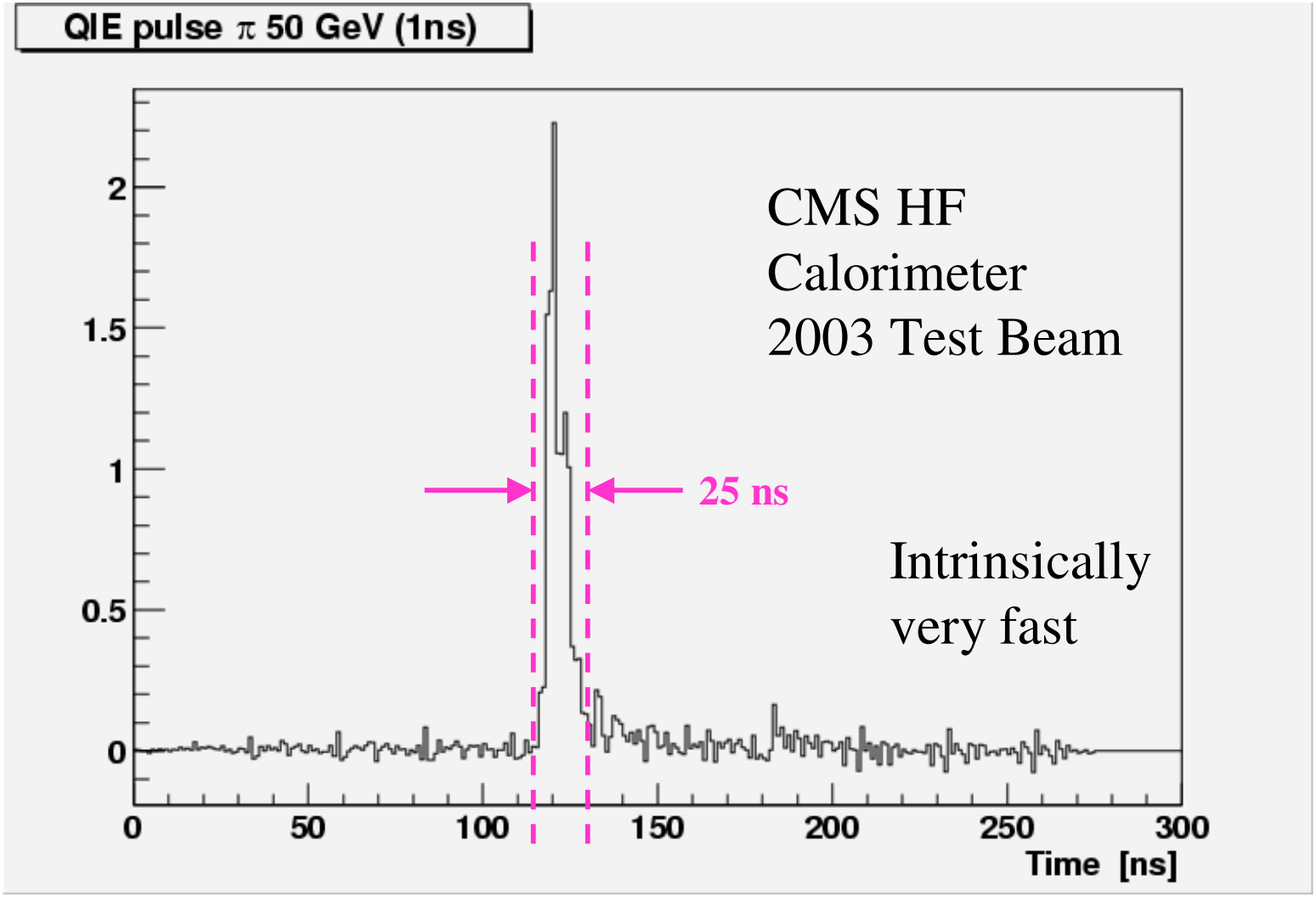


Atlas lAr EM Calorimeter



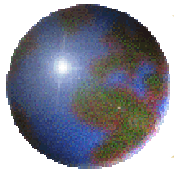
Not so different, after shaping. Bunch ID should be no problem

HF Cerenkov Calorimeter Pulse Shape



ATLAS/CMS at SLHC

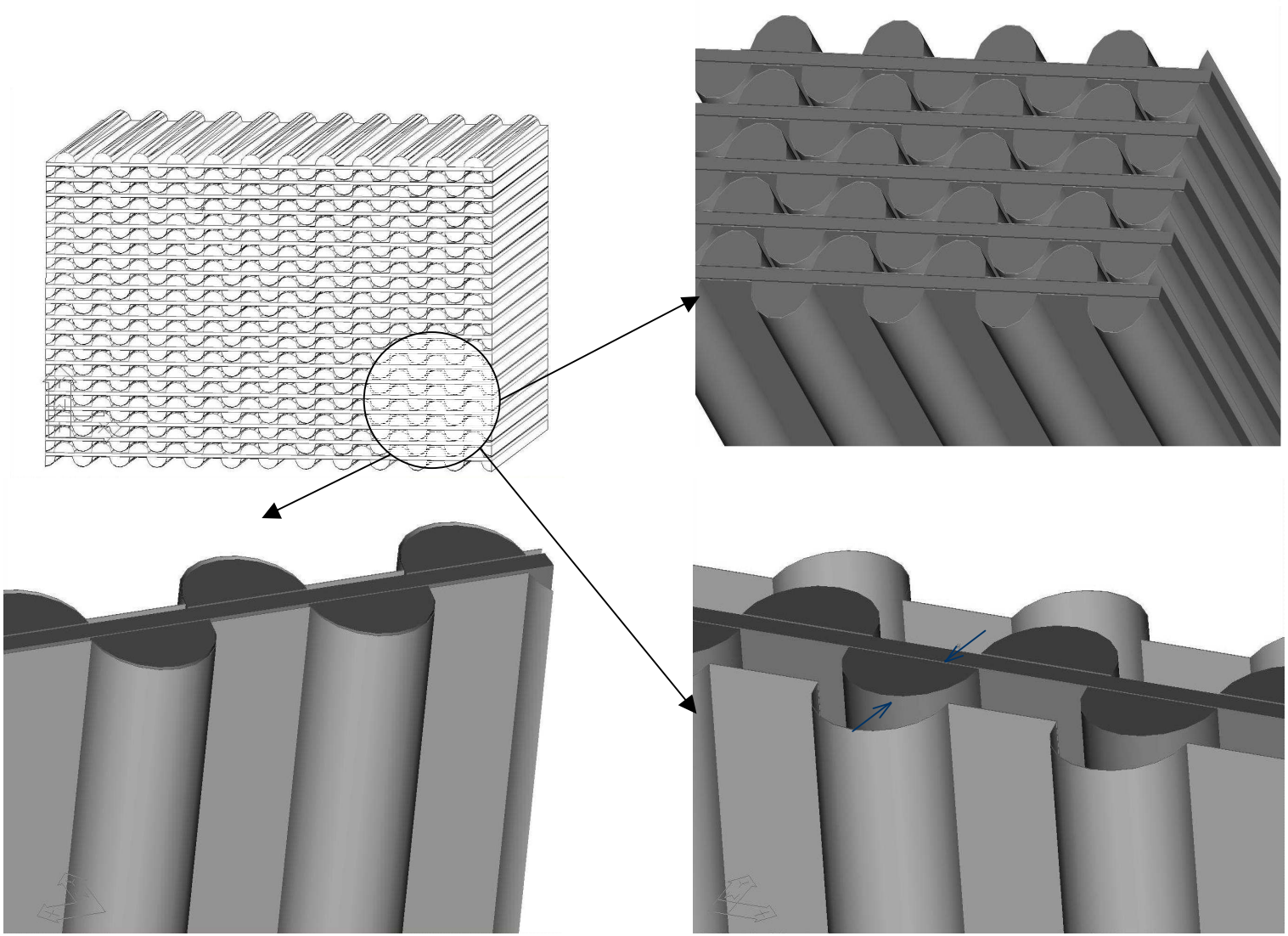
- Both detectors will have problems in the endcap region.
- ATLAS → rate problems. Replace lAr for $\eta > 1.5$?
- CMS → radiation damage problems in endcap. New scintillators? Or new technology?
- → New R&D



Profitable R&D Directions?

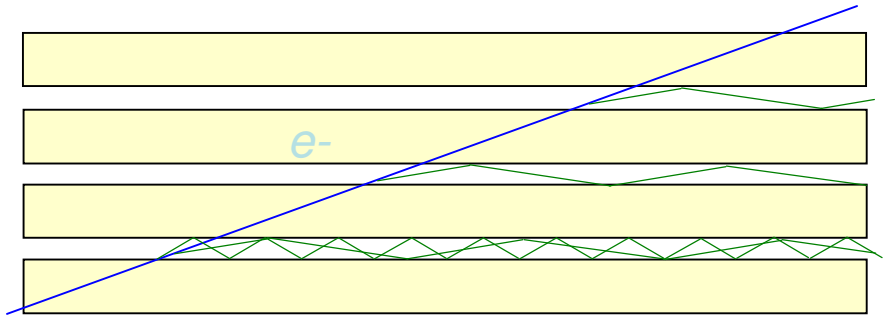
- Cerenkov calorimeters are rad-hard and fast → good candidates for future colliders
  - Quartz fiber or plate
  - Gas cerenkov
- New photon detectors → low cost, small, rad-hard
  - Red-sensitive HPDs
  - Geiger-mode photodiodes
- New scintillator materials → rad-hard
- New directions:
  - "Spacal" with liquid scintillator capillaries coupled to quartz fiber light guides?

Gas Cerenkov Lasagna



Gas Cerenkov operation

- The Cherenkov light is generated by shower particles that cross gas gaps between absorber elements.

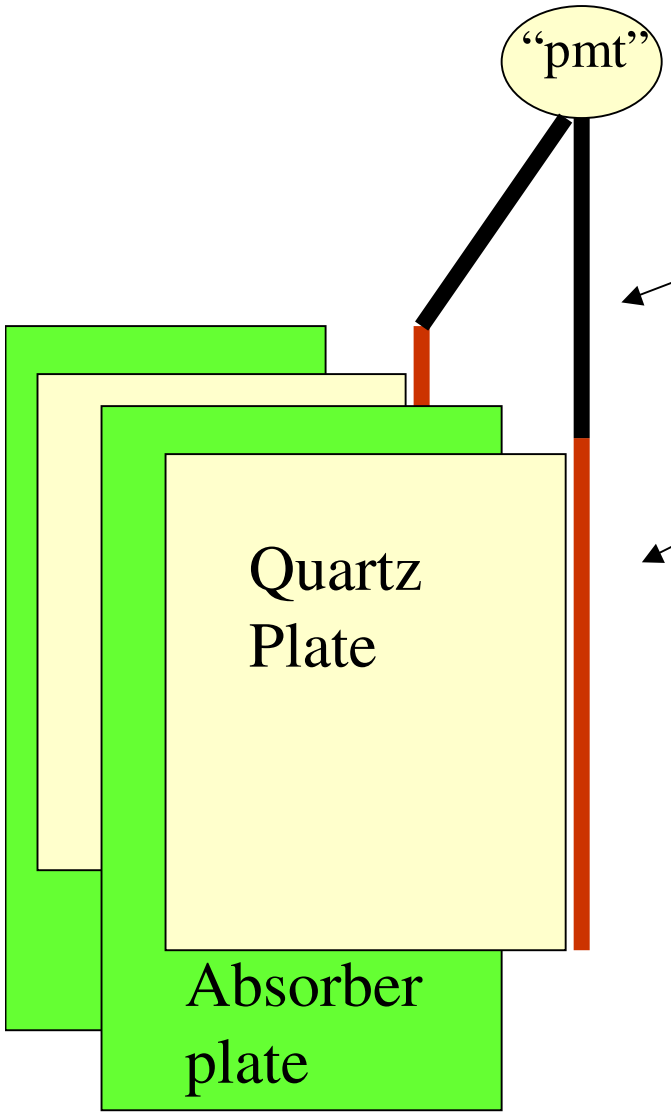


- Shower particles co-move with the Cherenkov light as two overlapped pancakes. The width of these pancakes is about 50 ps.

- Inside surfaces must be highly reflective at grazing incidence.

3w.hep.caltech.edu/calor02/abstract/ Presentation/cerenkov/atramenov.ppt

Cerenkov Tile/Fiber



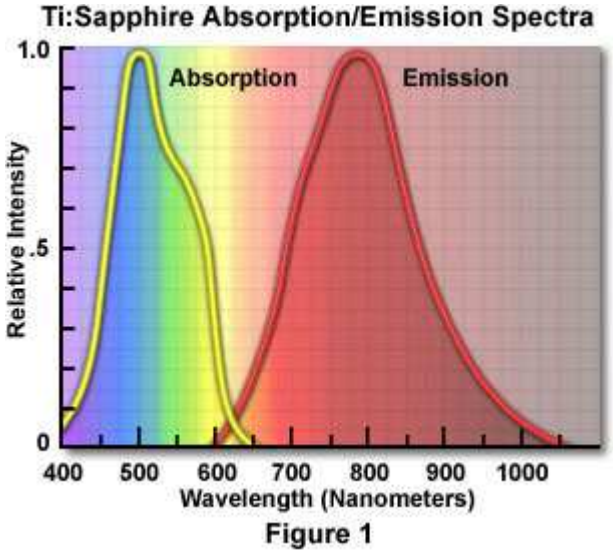
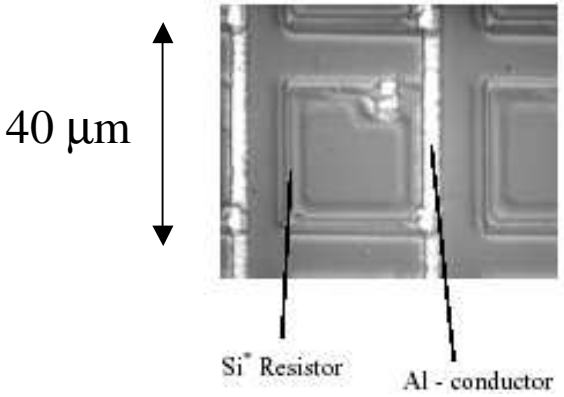


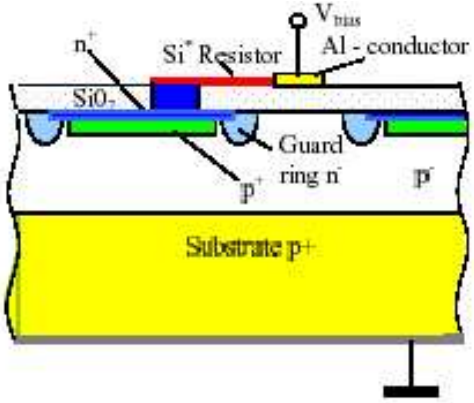
Figure 1

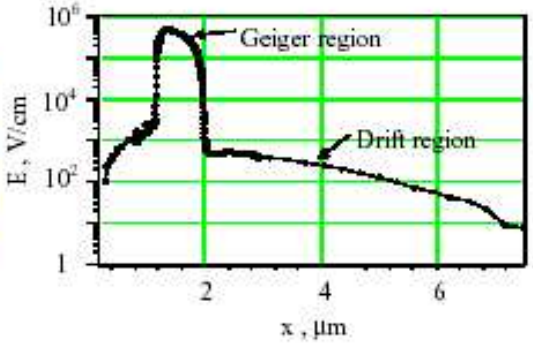
Ti:Sapphire is a wavelength shifter and rad-hard. Index of refraction = 1.7

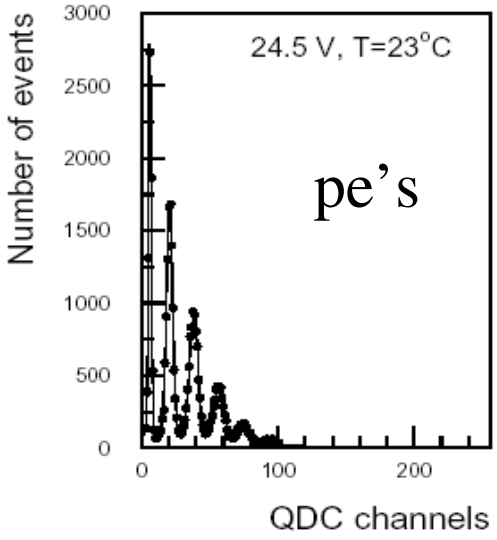
Issues: light yield, purity of plate, speed of shifter.

Geiger-mode silicon pmt (SPMT)





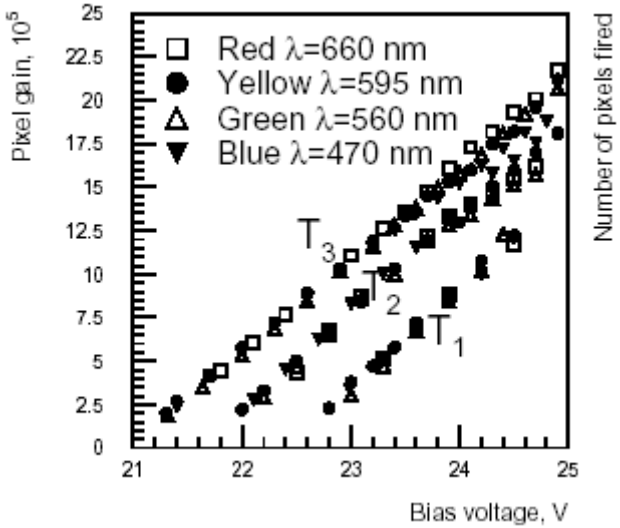


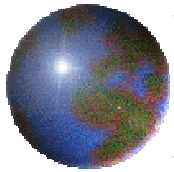


100 – 10000 SPMTs tied in parallel to same substrate.

High gain, 10^6, low noise

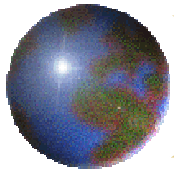
Issues are rad-hardness and rate ability





New Scintillators and Shifters

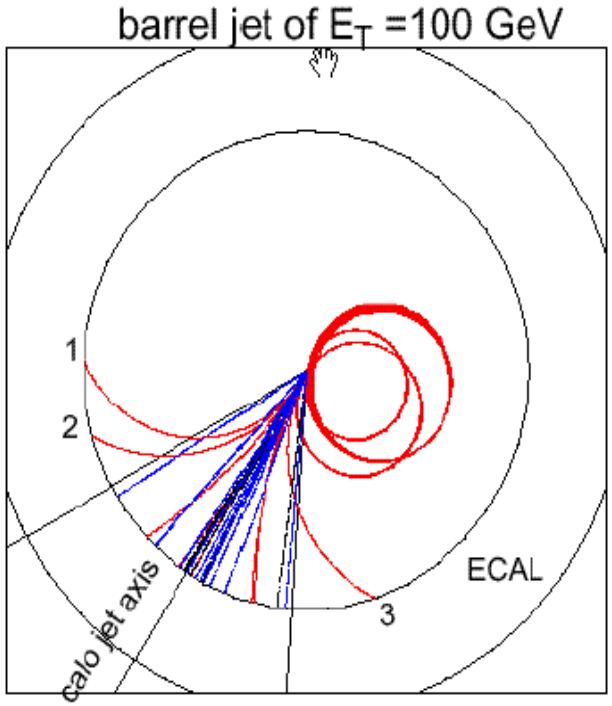
- A 10 year long search for new organic scintillators that are rad-hard. (bulk damage to scintillator base → longer wavelengths.
- Waveshifter chemicals that are rad-hard, fast.
- Inorganic wavelength shifters for cerenkov tile calorimeters.



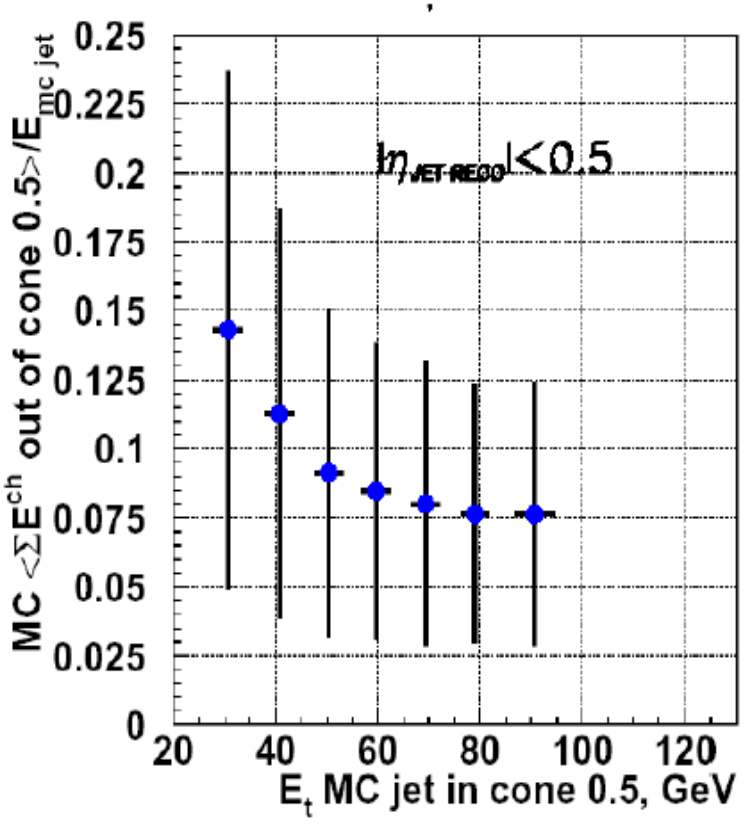
Tracking and Energy Flow

- Use tracking to improve jet response

Jet Res improvement using tracking. CMS 4T B field



Fraction of energy escape from a jet cone (R=0.5) in 4T field.



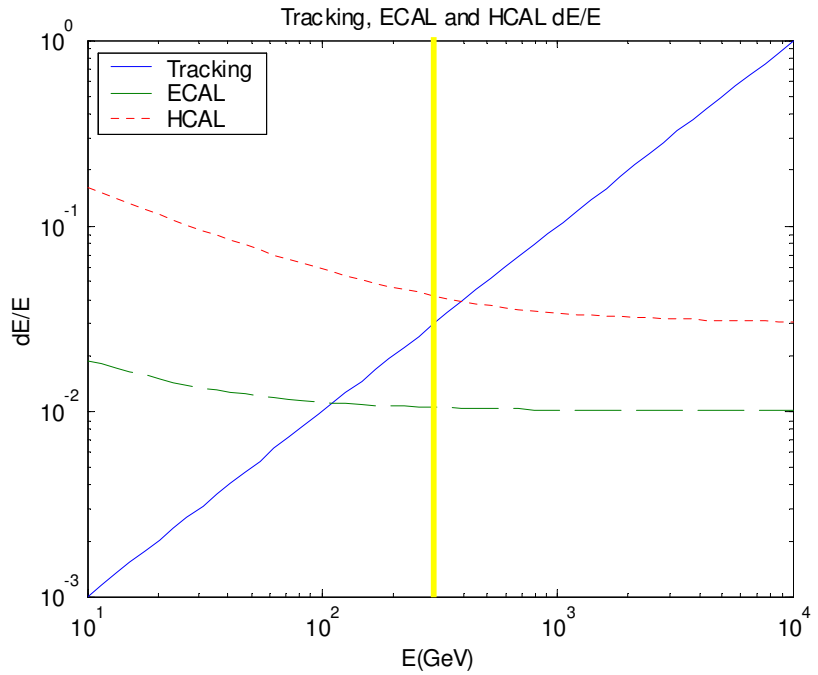
Radius of ECAL front ~ 1.3 meters

Charged particles P_T < 0.8GeV
→ Looper in barrel.

Jet improvement by using tracking info

"Energy Flow"

- **Tracking from CMS, ECAL 5% stochastic, 1% constant, and HCAL 50% stochastic and 3% constant.**
- **Note that a jet has $\langle z_{max} \rangle \sim 0.22$. For charged particles < 100 GeV (jets < 0.5 TeV) use tracks to measure E.**



For present energy scales at the LHC use tracker energy measurement if possible. At a VLHC this will not help. (Without substantial improvements in tracking)

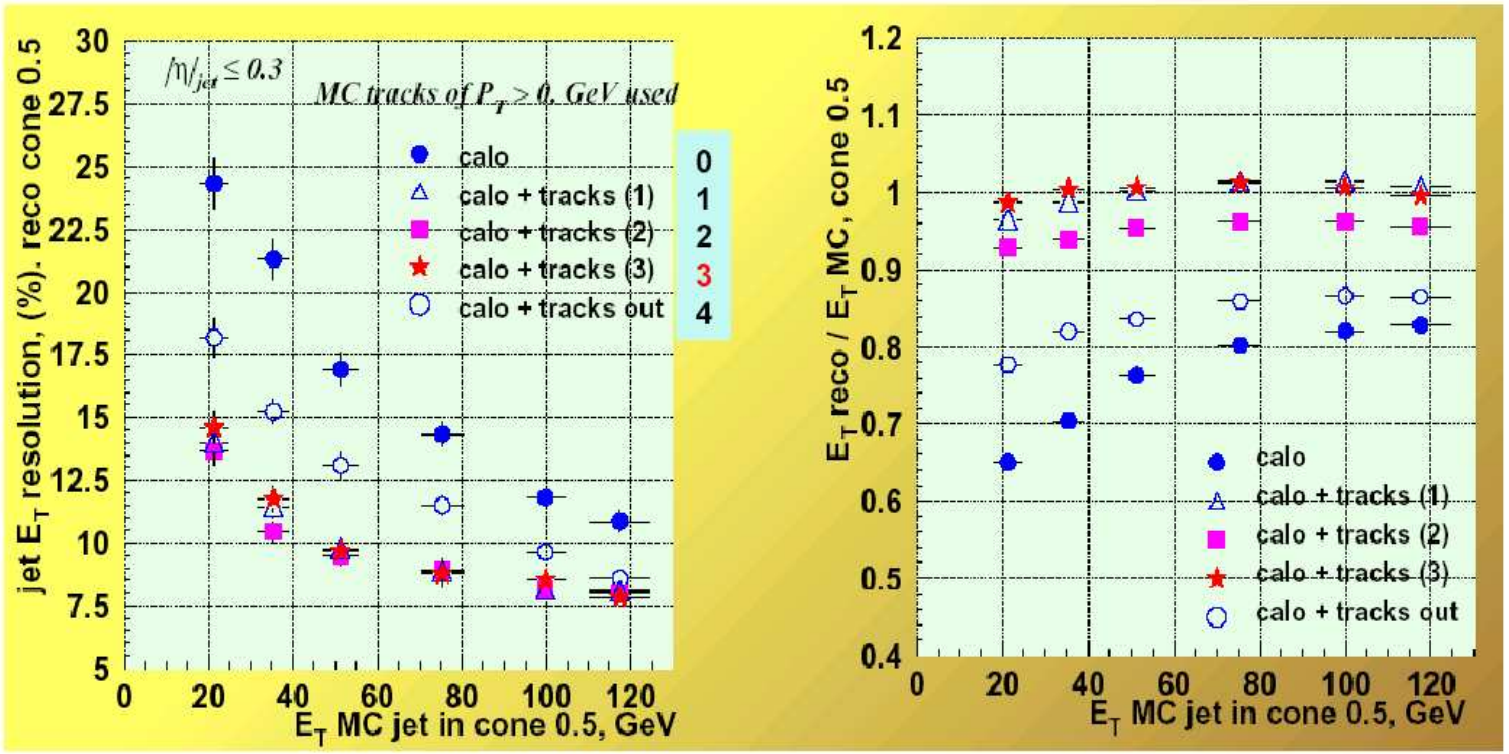
Energy Flow Jet Improvement

Resolution

20GeV 24% → 14%
100GeV 12% → 8%

E_T Scale

< 2% in 20-20GeV



0: no correction (calorimeter only) 1: calo response - simple average 2: calo response – library
3: full correction (library of response, track-cluster match, out-of-cone tracks)
4 out-of-cone tracks correction only

CDF Study – Photon+Jet

- **CDF studied energy flow in photon + J events using shower max (particle id) and tracking information. A similar ~ 24% improvement was seen.**

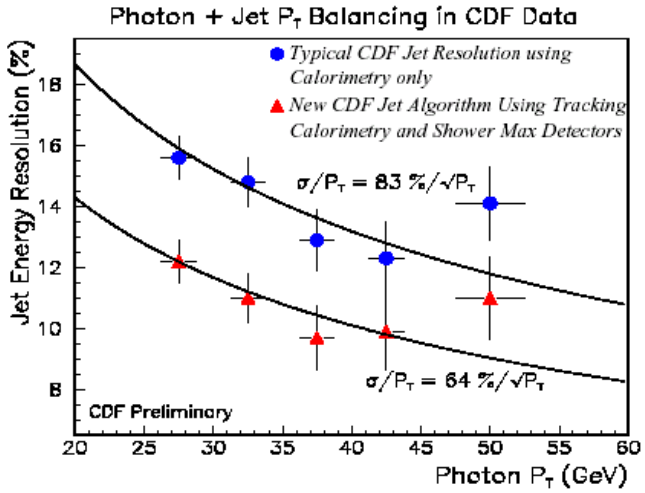
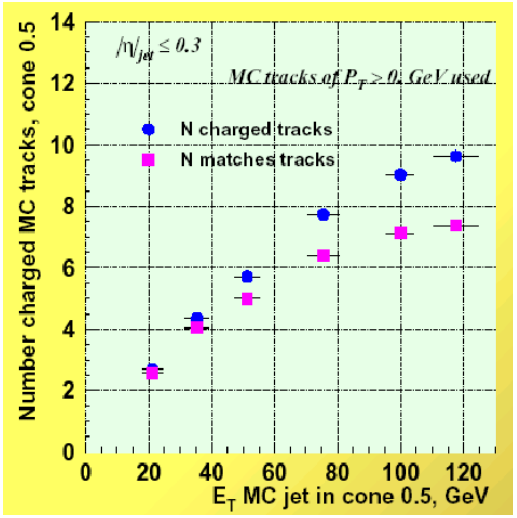


Figure 4: *The central detector resolution σ_D is plotted as a function of P_T^γ for the two methods.*

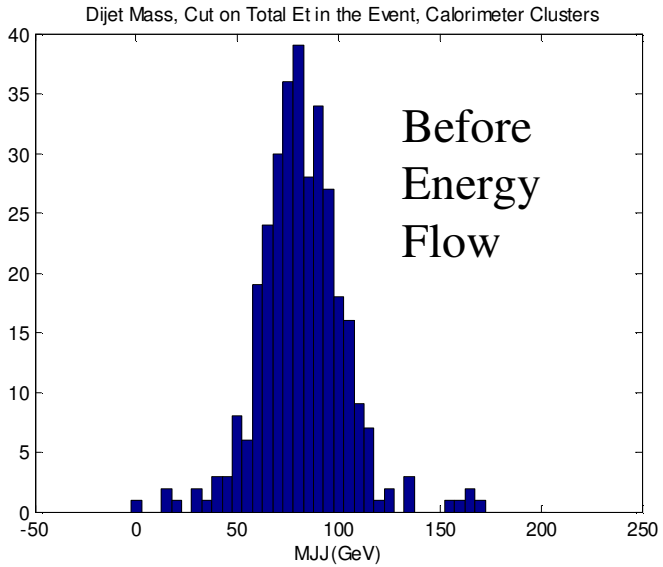
Improved Dijet Mass

- **There is a ~ 22 % improvement in the dijet mass resolution. Implies that calorimeter resolution is not the whole story.**

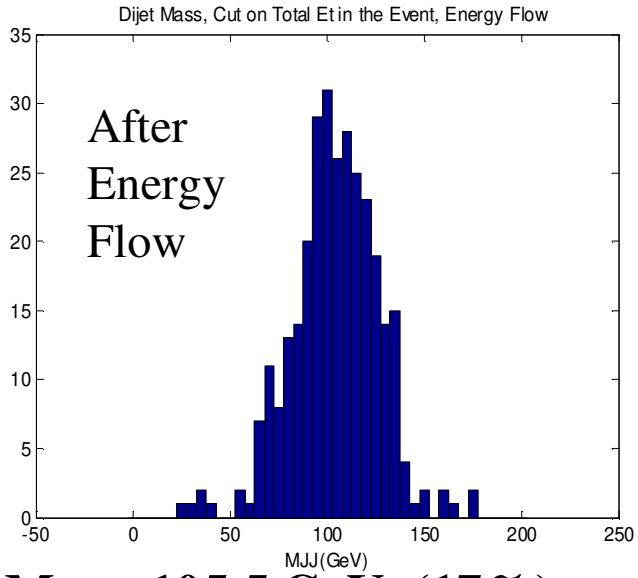


Energy Flow

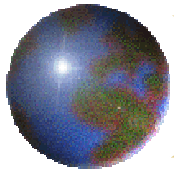
Nr charged tracks generated/matched vs jet E_T. At E_T ~ 50, almost all tracks matched



Mean 81.7 GeV, (21%)



Mean 105.5 GeV, (17%)

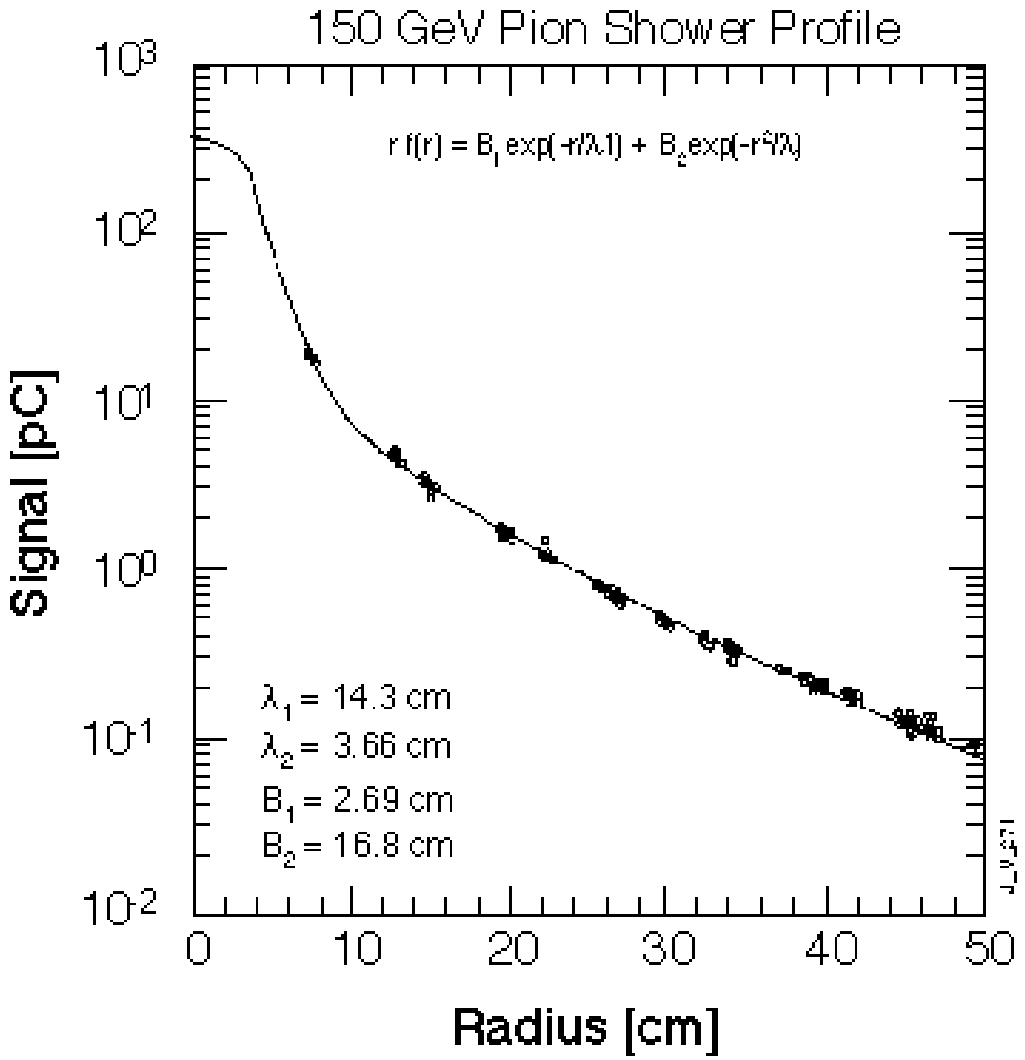


New Calorimeter

- Issues for designing new calorimeter for VLHC/Eloisatron

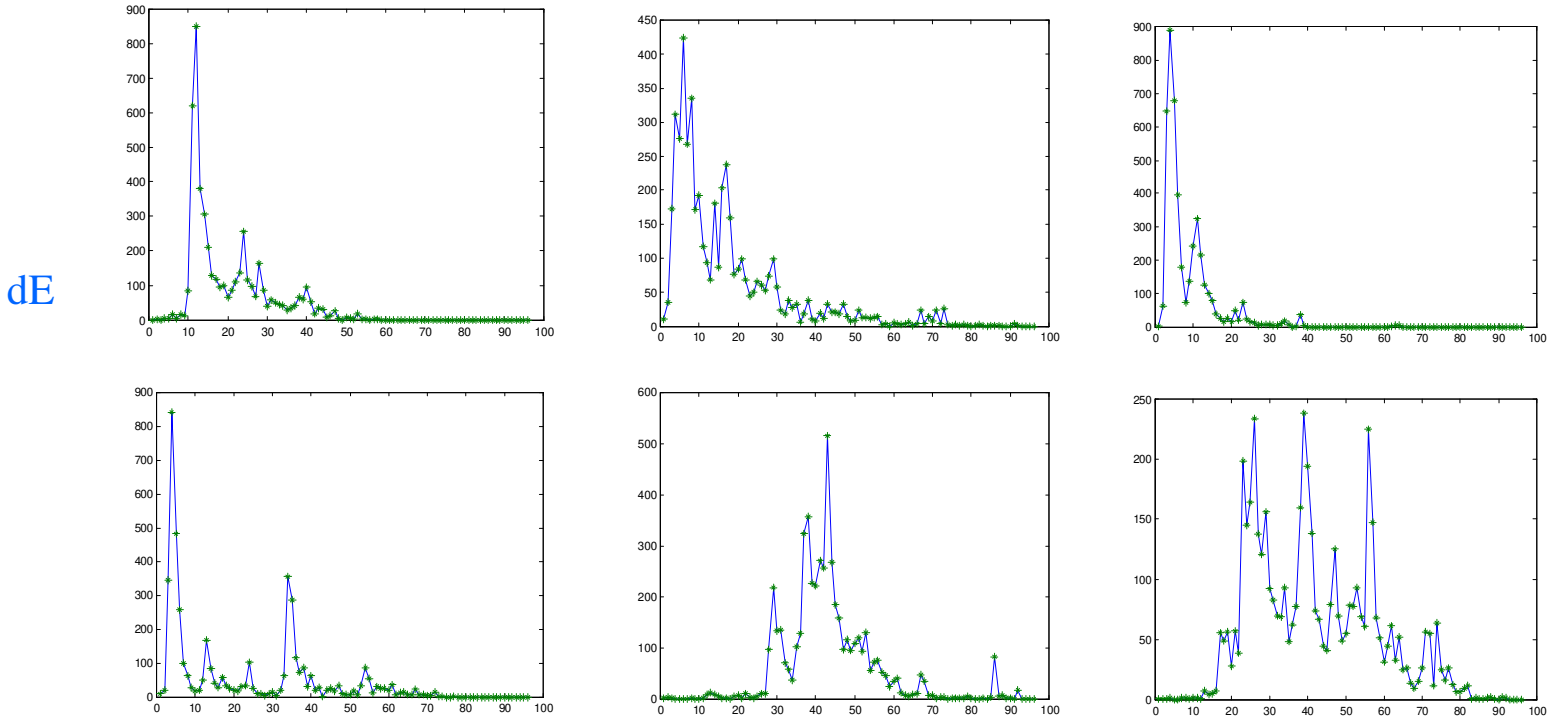
Transverse Size - HCAL

- **Shower size limits the number of resolvable "particles" in a jet, especially the dense "core" of a jet. Limits set to "energy flow"**



Hadron Cascades and Energy Flow

Large Fluctuations in longitudinal development of hadron showers set limits on utility of depth segmentation. → fine longitudinal depth segmentation only samples intrinsic fluctuations in shower development

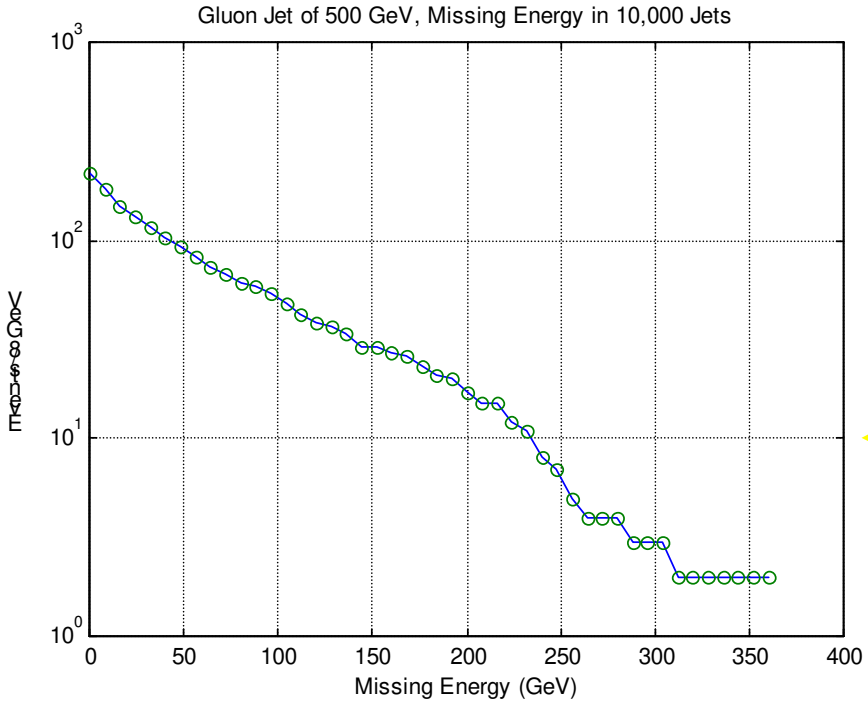


SDC Hanging File Calorimeter Data. 96 layers of scintillator, each read out with separate pmt.

Intrinsic Limitations to Containment

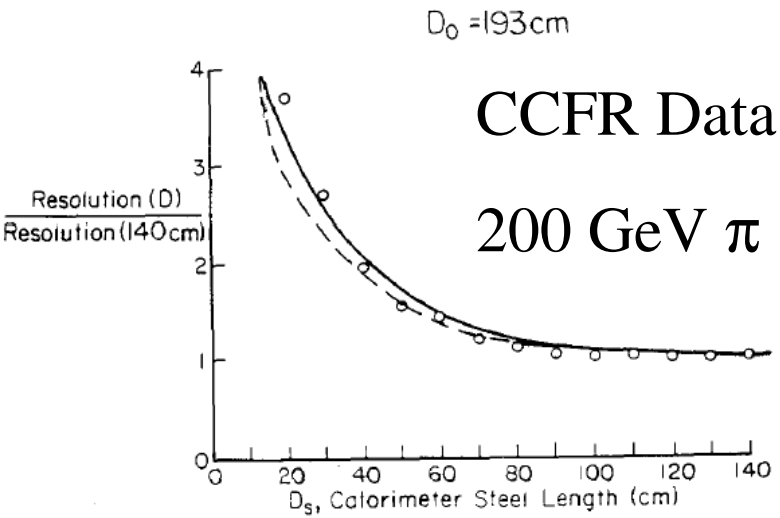
- **Jet "splitting", g -> QQ and Q -> qlv, puts intrinsic limit on required depth. Jets themselves "leak".**

Jets with energy > Missing ET



Jets "leak" too – 0.1 % will lose > ½ of the energy due to splitting.

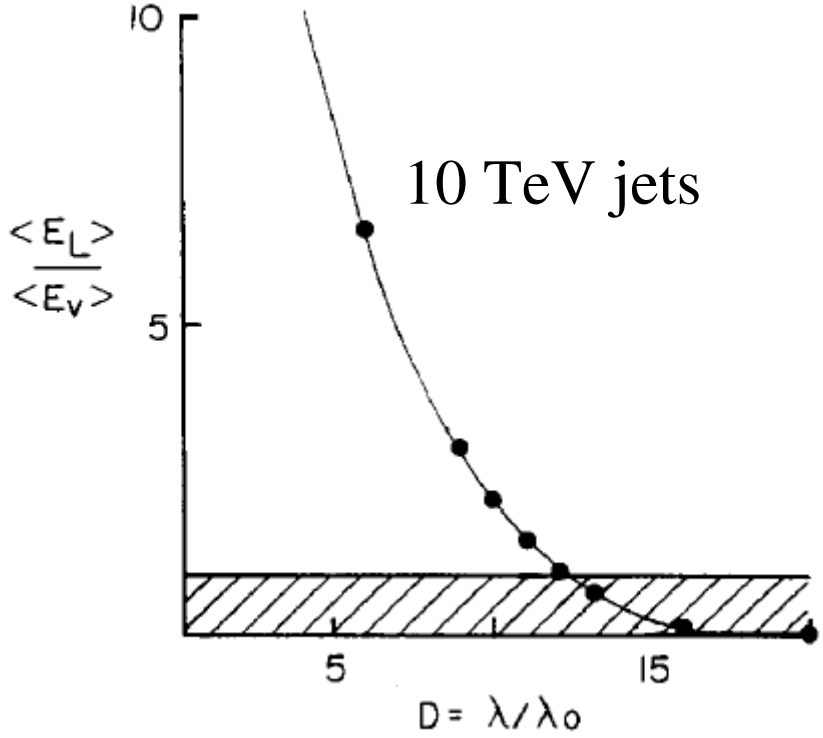
Calorimeter Depth Requirements



CCFR Data

200 GeV π

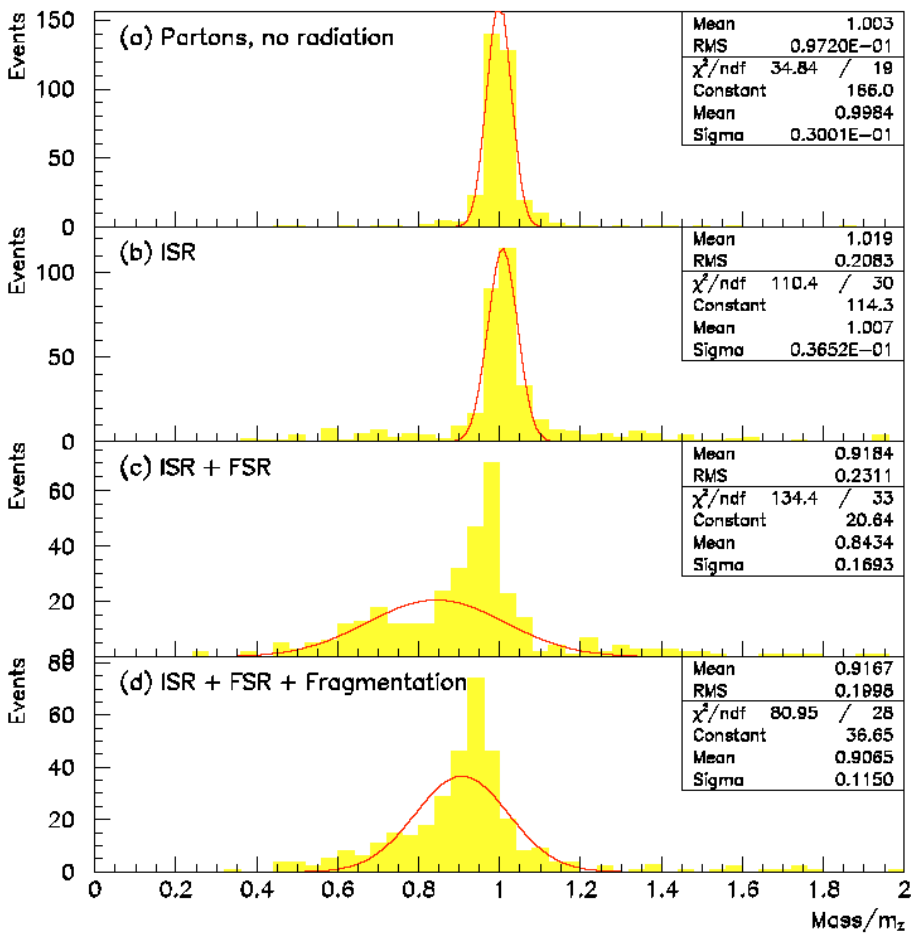
Relative Resolution vs depth



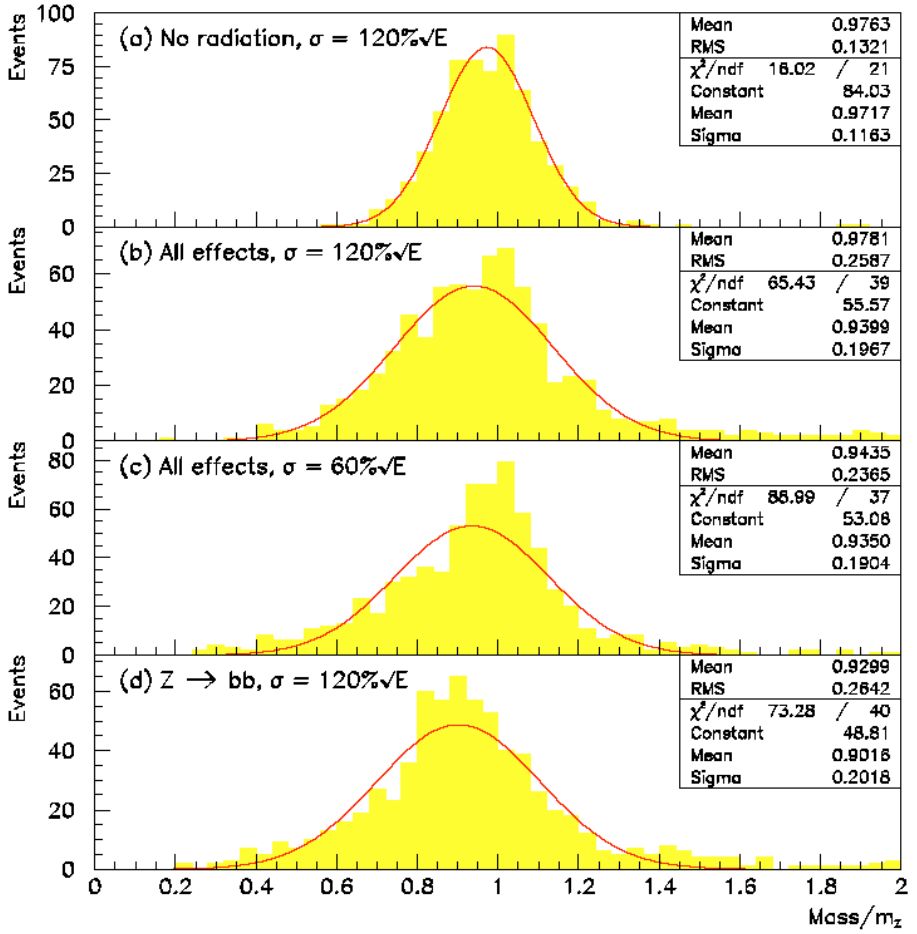
Conclusion → no gain for calorimeters thicker than ~ 10-12 λ

E_{leak}/E_ν as a function of depth. Hatched area is where neutrinos dominate

Effects of Final State Radiation



No detector simulation



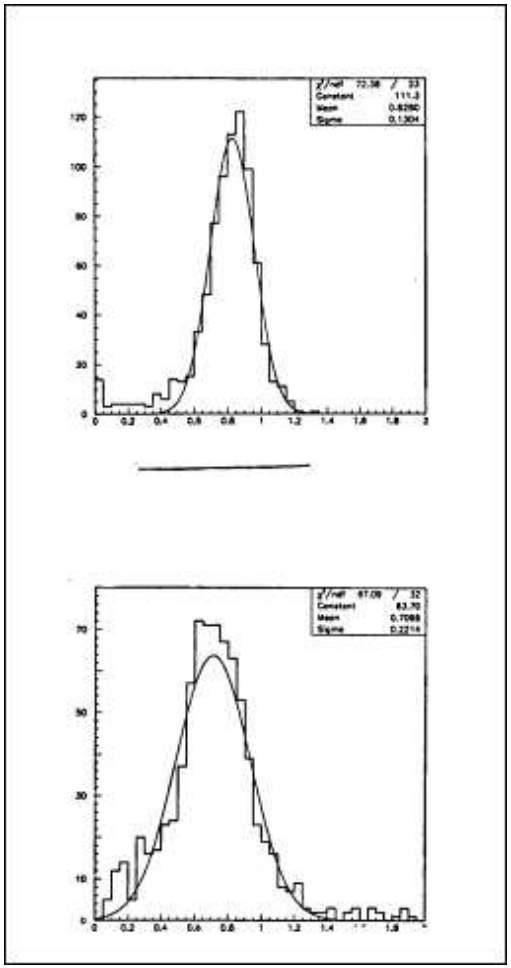
Full detector simulation

Z's at the LHC in "CMS" detector

LHC – CMS Study of FSR

- **M_{JJ}/Mo plots for dijets in CMS with and without FSR. The dominant effect of FSR is clear.**
- **The d(M/Mo)/(M/Mo) rms rises from ~ 11% to ~ 19%, the distribution shifts to smaller M/Mo, and a radiative low mass tail becomes evident.**

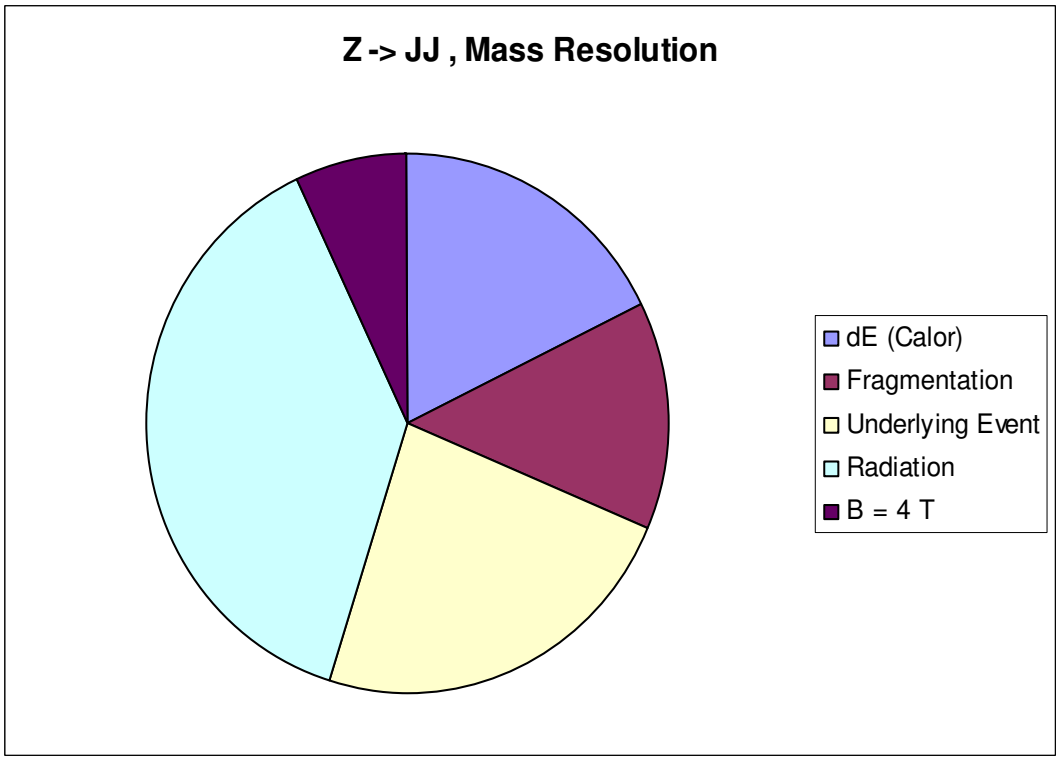
dM/M



M/Mo

Hadron Collider- Dijet dM/M

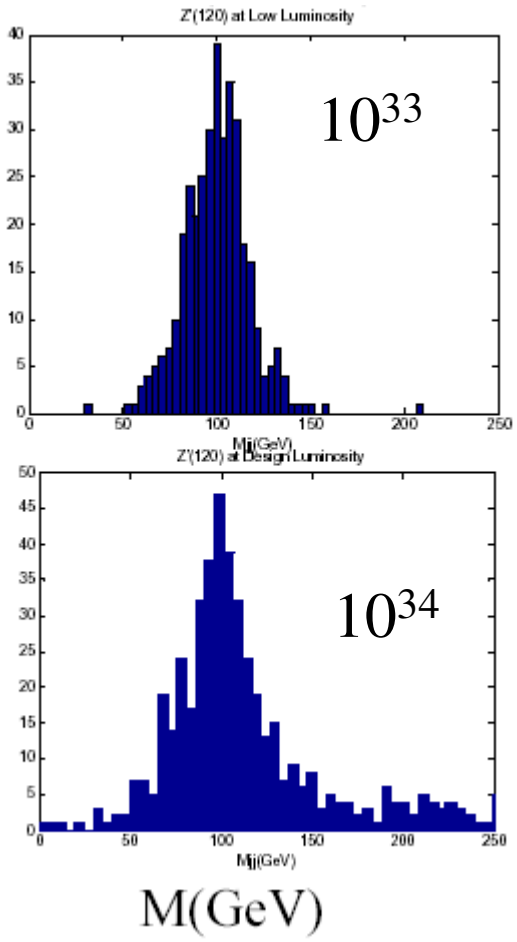
- **A series of Monte Carlo studies were done in order to identify the elements contributing to the mass error. Events are low P_T, Z -> JJ. dM/M ~ 13% without FSR.**



FSR is the biggest effect. The underlying event is the second largest error (if cone R ~ 0.7). Calorimeter resolution is a minor effect.

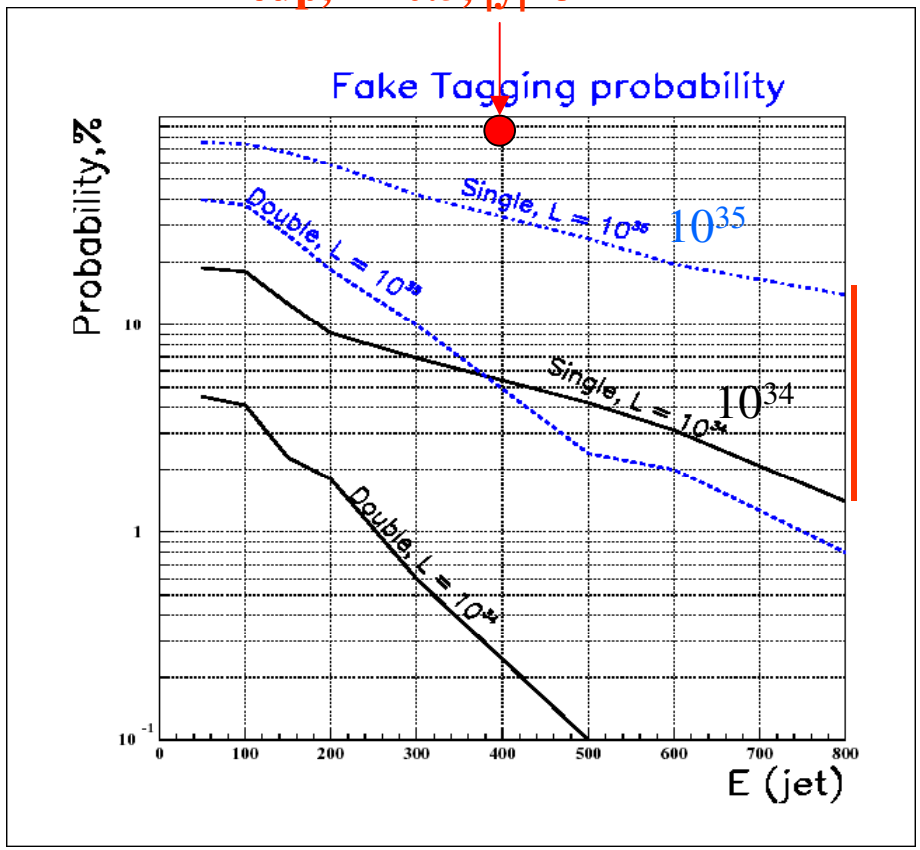
Effects of Pileup Events

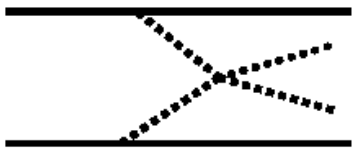
120 GeV Z'



M(GeV)

Pileup, R=0.5, |y|=3

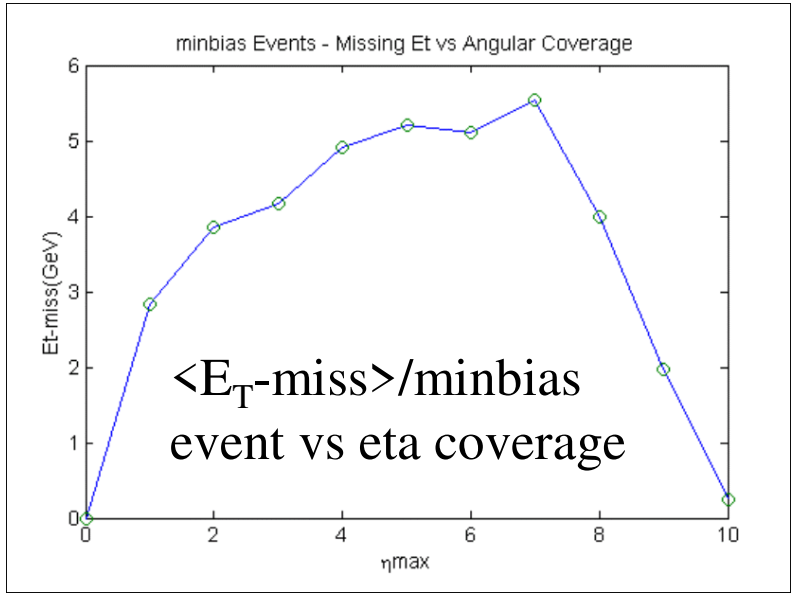


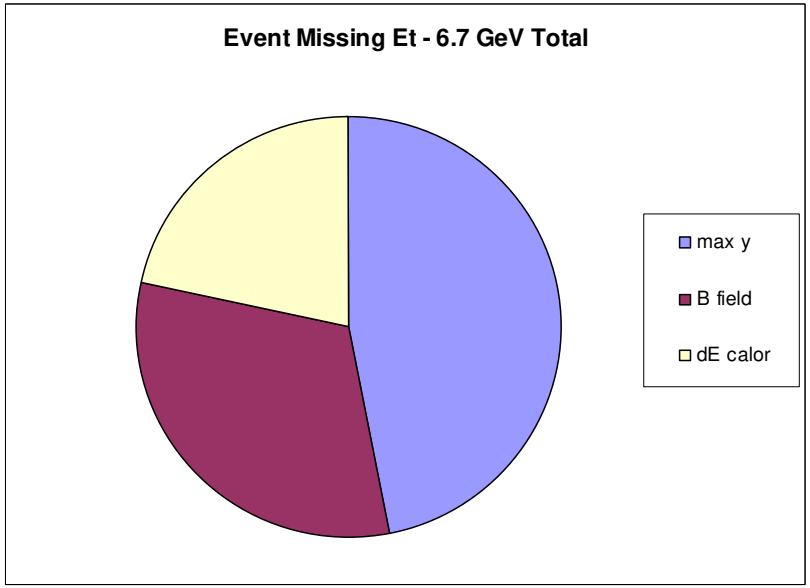


WW fusion → Forward tag jets, E_T~ 40 GeV

Pile-up Missing Et

- **Study done for CMS. Three major sources of detector induced missing E_T – incomplete angular coverage, B field "sweeping" to small angles and calorimetric energy resolution.**
- **Clearly need radiation hard calorimetry to go to smaller angles – as C.M. energy increases particularly. Presently dose < 1 Grad at $|\eta| = 5$.**
- **At SLHC, pileup events create a background of ~ 5GeV * sqrt(62) = 40 GeV E_T-miss / crossing. Fatal for W's, no problem for SUSY.**

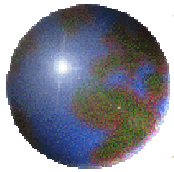




Contributions to E_T-miss for minbias events

Intrinsic Limitations

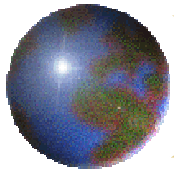
- Transverse size set by shower extent, either Xo or λ -> limit to tower size.
- Longitudinal depth set by containment to ~ 10 λ. Limit on depth set by jet leakage.
- Speed needs to be fast enough to identify bunch crossing (25 ns/LHC ; 12.5 ns/SLHC; 18 ns VLHC)
- Jet resolution limited by FSR at LHC, not calorimeter energy resolution.



New Calorimeter Design

If you are building a new calorimeter for SLHC/VLHC

- Speed is very important (12.5ns bunch spacing)
- Radiation resistance critical
- Any new calorimeter will be designed with Energy Flow in mind. To take good advantage of Energy Flow, ~5X5 cm HCAL tower size
- Limited longitudinal segmentation
- 10-12 λ thick
- Energy resolution not too important.
- Can see two variants:
  - ATLAS-like liquid ionization
  - CMS-like optical



Summary

- ATLAS and CMS Hadron calorimeters will need upgrade for SLHC
- New algorithms (Energy Flow) improve jet resolution. Ultimate limits of method include finite shower sizes. Unfortunately utility decreases for increasing jet energies.
- Final State radiation remains major limitation to di-jet mass resolution. Address this with improved analysis methods?
- Studies of higher mass states will require higher luminosity which will put in premium on radiation resistance.
- Colliders with increased luminosity and energy will require detector development:
  - Cerenkov calorimeters
  - Replacement fluids for LAr in forward regions
  - Advanced photodetectors
  - Improved materials (scintillators or quartz fiber)
  - Possible new directions (gas-cerenkov calorimeter)