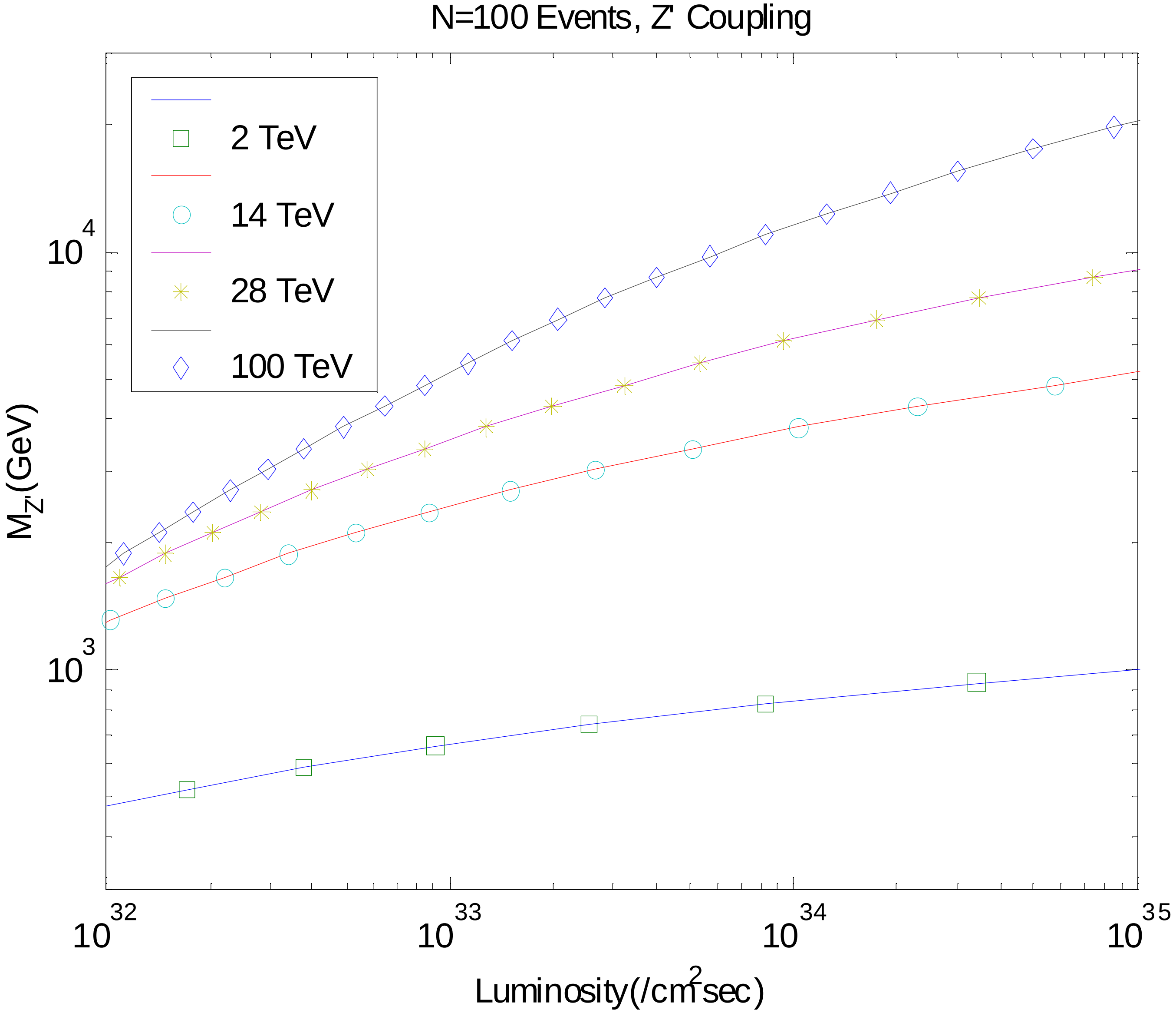
Hadron Calorimetry

For Future Hadron Colliders

Jim Freeman

Fermilab

Mass Reach vs energy and L



VLHC/ Eloisatron

LHC

Tevatron

J. Freeman Erice Oct 3, 2003

SLHC Detector Environment

	LHC	**SLHC**
$\sqrt{s}$	14 TeV	14 TeV
L	$10^{34}\,/(cm^2 \cdot \mathrm{sec})$	$10^{35}\,/(cm^2 \cdot \mathrm{sec})$
$\int L dt$	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

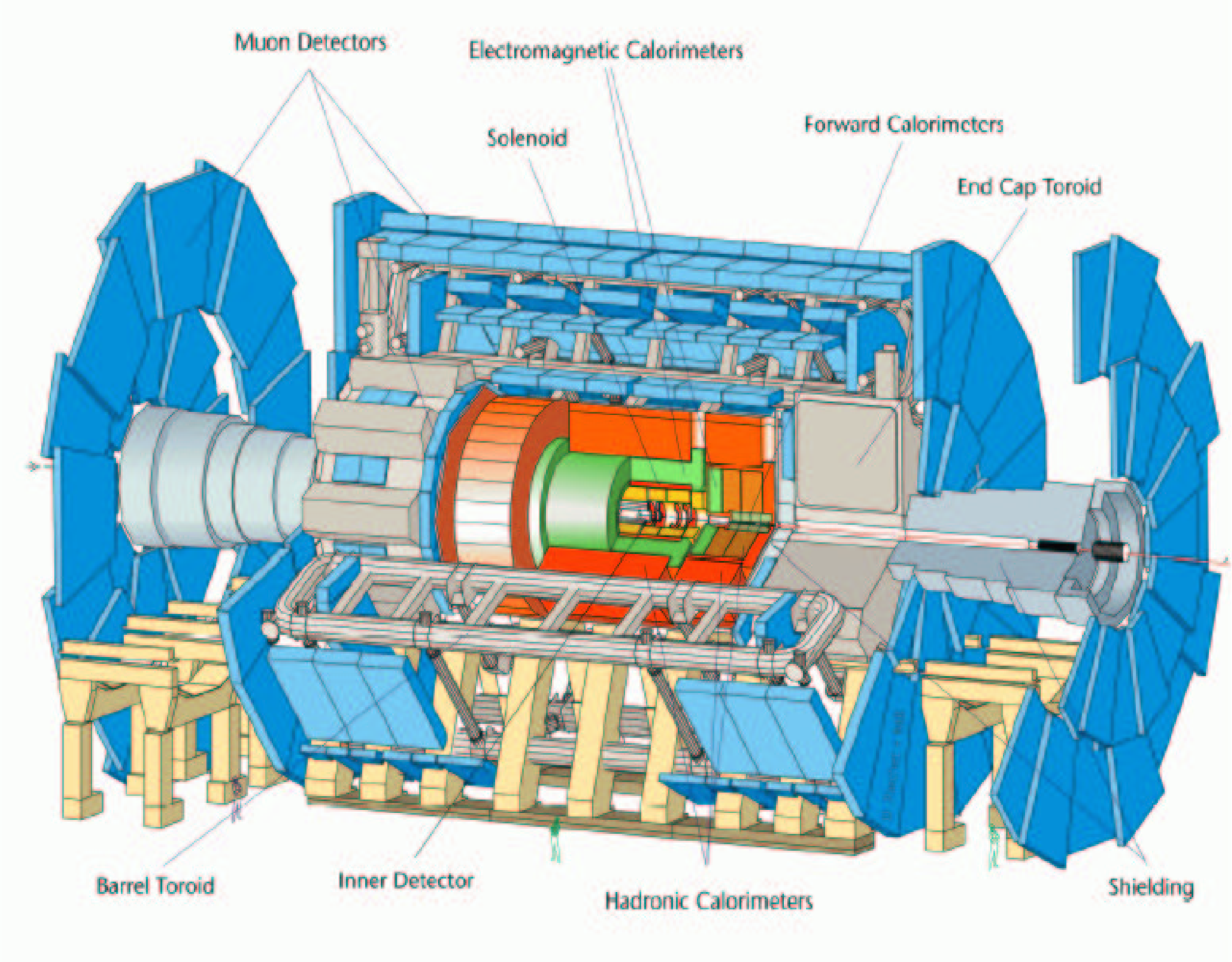
Bunch spacing reduced 2x. Interactions/crossing increased 5 x. Pileup noise increased by 2.2x if crossings are time resolvable.

VLHC/ Eloisatron Detector Environment

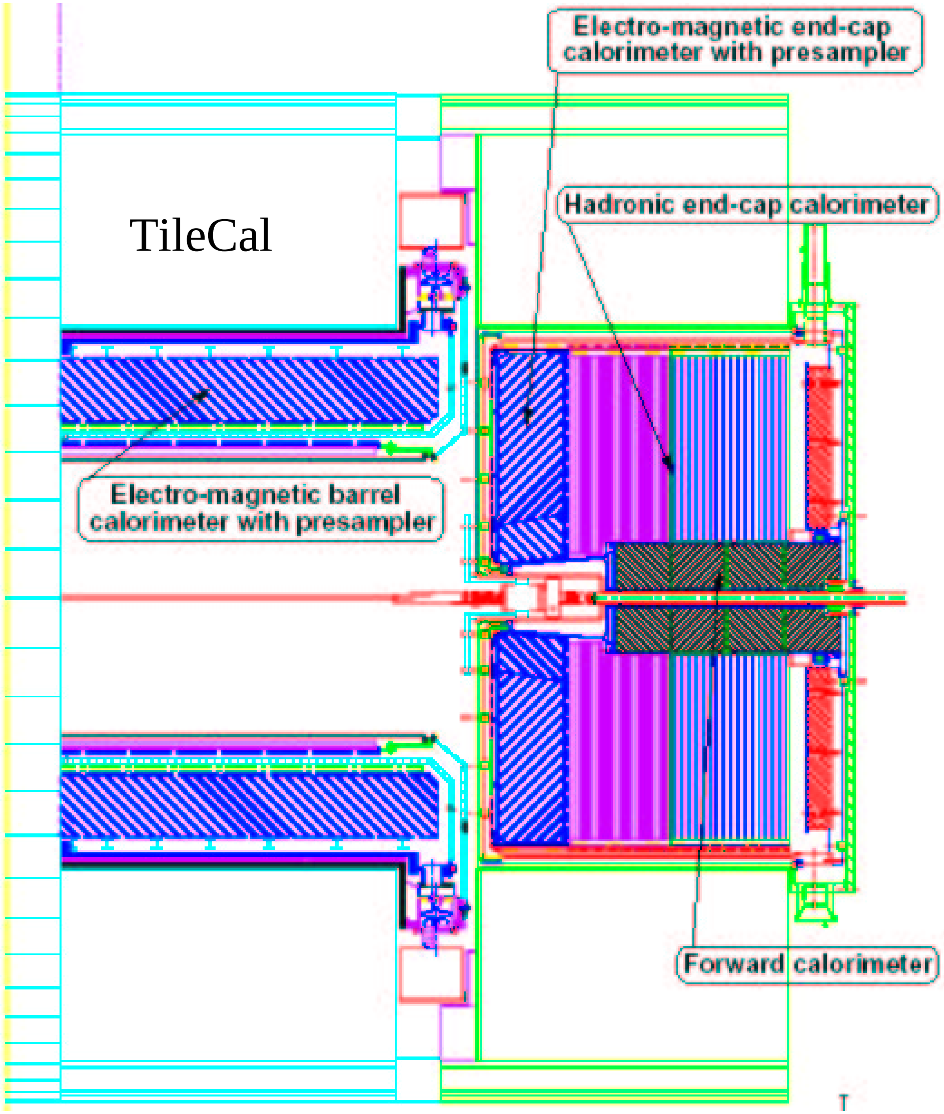
	LHC	**VLHC**
$\sqrt{s}$	14 TeV	100 TeV
L	$10^{34}/(cm^2 \cdot \sec)$	$10^{34}/(cm^2 \cdot \sec)$
$\int L dt$	100 fb^{-1}/yr	100 fb^{-1}/yr
Bunch spacing dt	25 ns	19 ns
N. interactions/x-ing	~ 20	~ 25**
$dN_{ch}/d\eta$ per x-ing	~ 100	~ 250**
Tracker occupancy	1	2.5**
Pile-up noise	1	2.5**
Dose central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

**** 130 mB inelastic cross section, $<N_{ch}>$ ~ 10, <Et> = 1GeV**

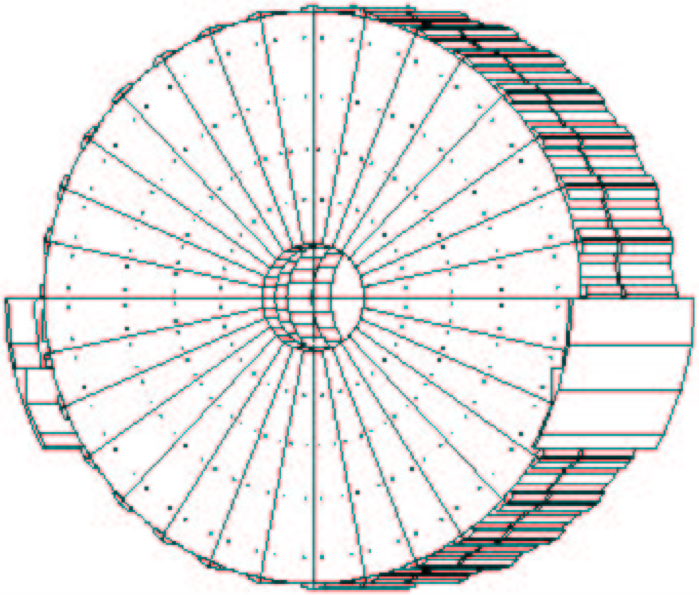
ATLAS Calorimeters

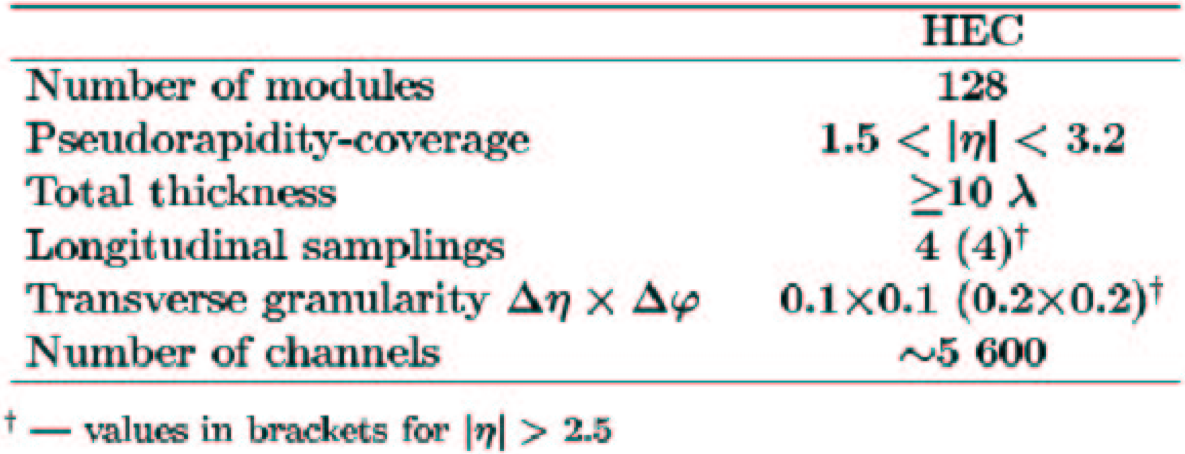


ATLAS Calorimeter



ATLAS LAR Hadron EndCap



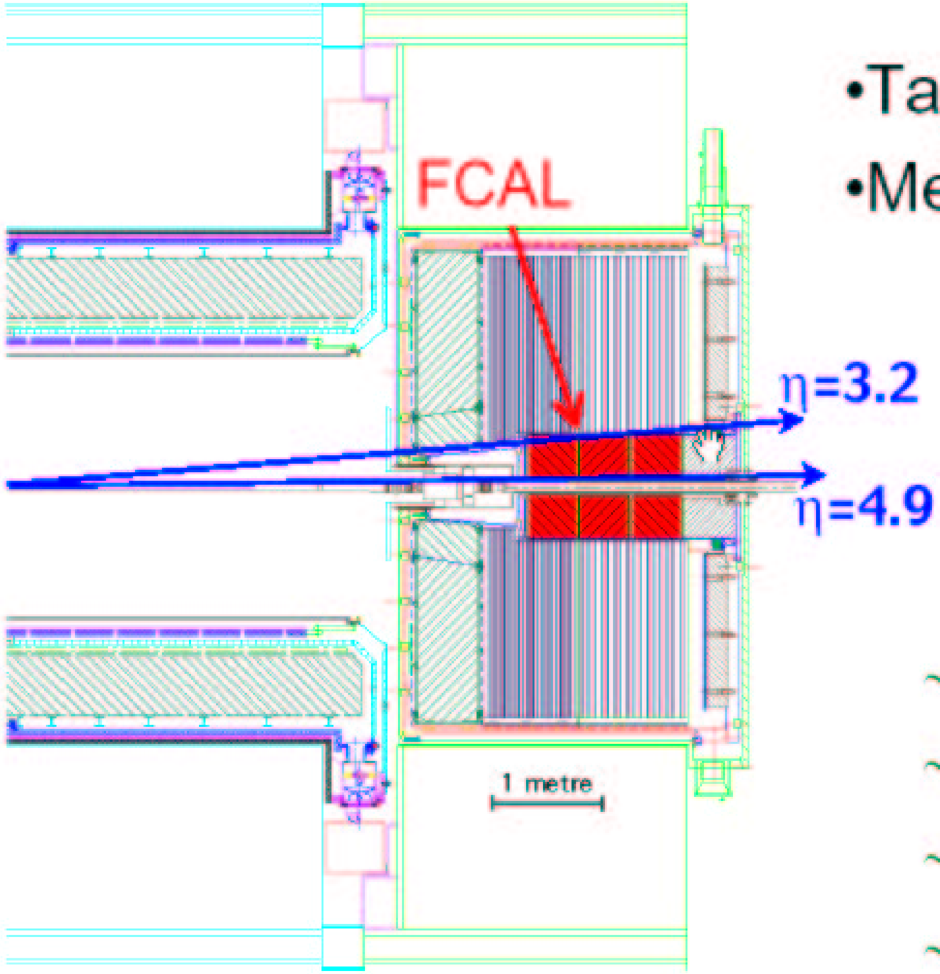


	HEC
Number of modules	128
Pseudorapidity-coverage	$1.5 < \|\eta\| < 3.2$
Total thickness	$\geq 10\ \lambda$
Longitudinal samplings	$4\ (4)^{\dagger}$
Transverse granularity $\Delta\eta \times \Delta\varphi$	$0.1\times 0.1\ (0.2\times 0.2)^{\dagger}$
Number of channels	~5 600

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

ATLAS FCAL

ATLAS Forward Calorimeter



- Tag forward jets
- Measure missing E_T

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

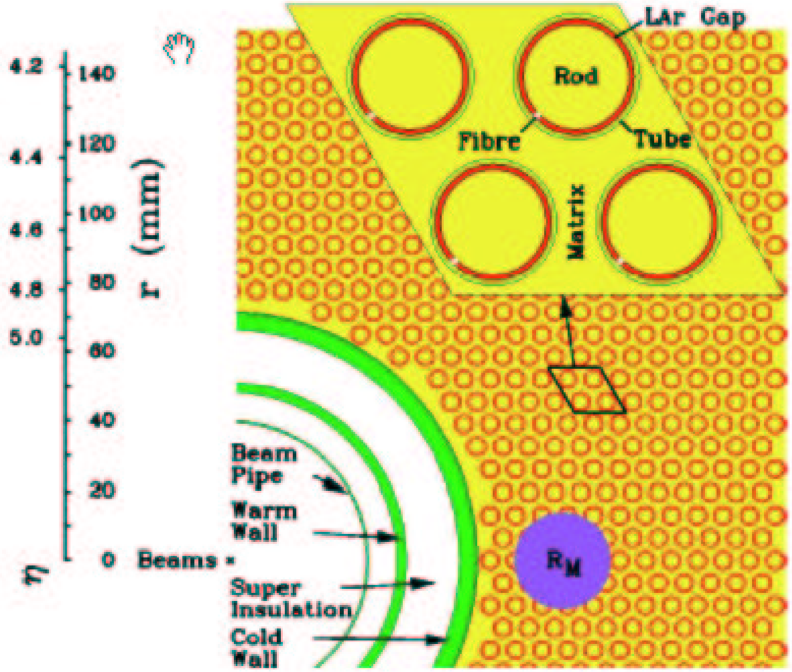
~ 40Mhz

~ 10^8 GeV/cm^2/s at $\eta=4.5$

~ 10^6 Gy/year

~ 100 Watts absorbed

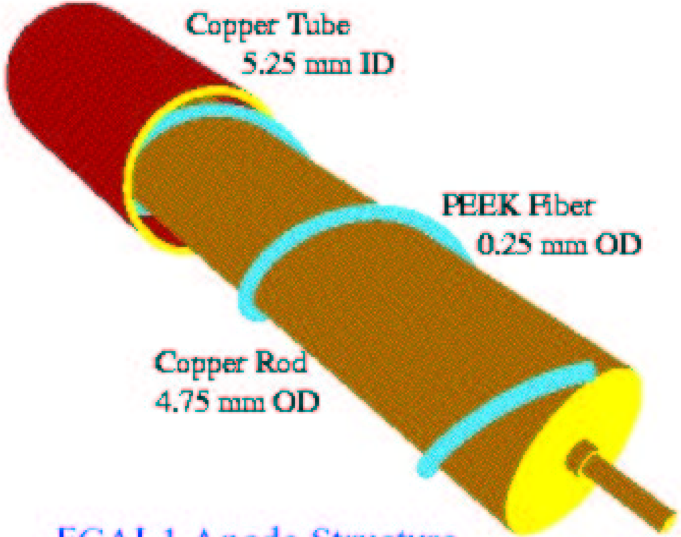
ATLAS FCAL



FCAL End View

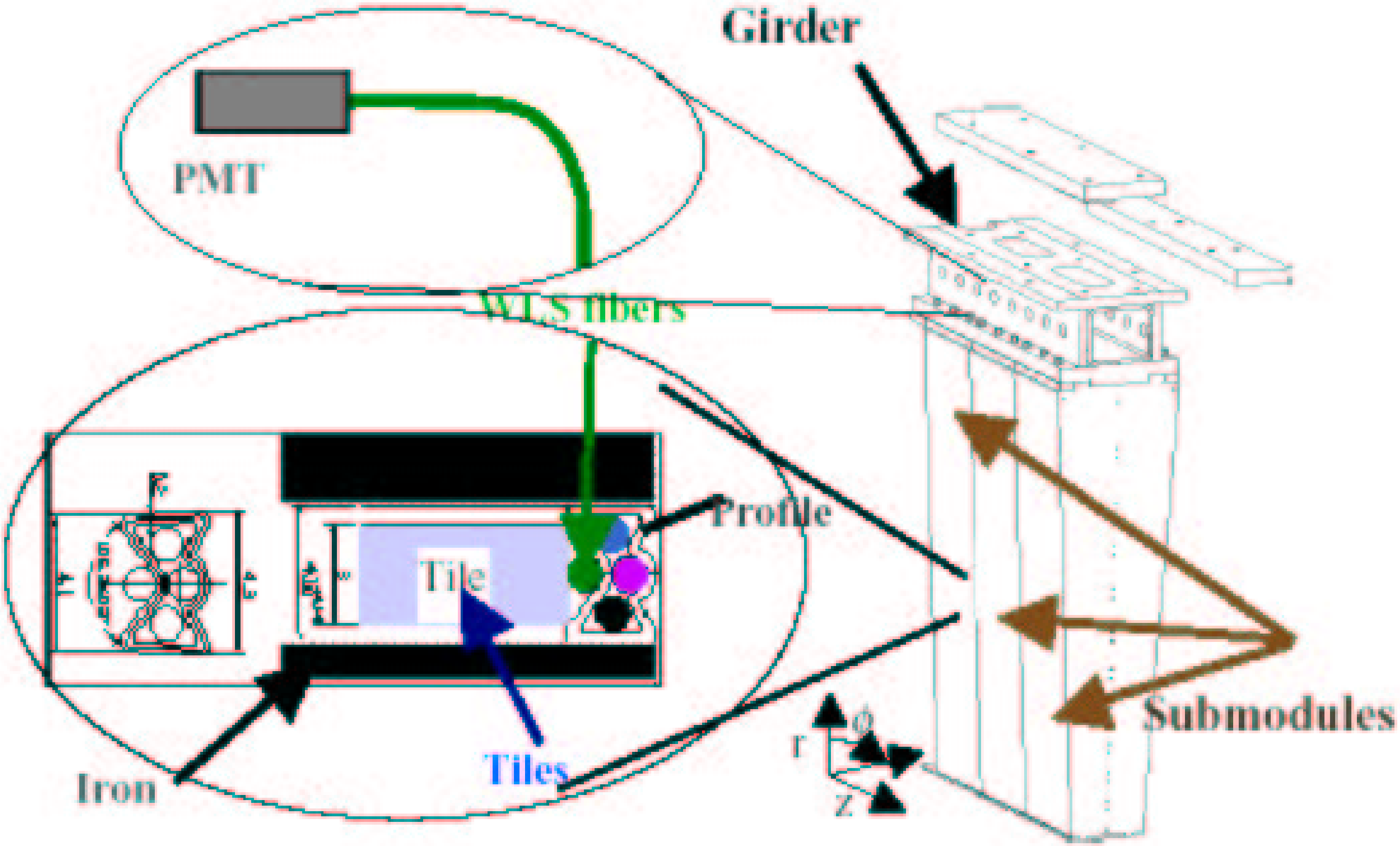
Liquid Argon gap
- 250 / 375 / 500 μm

Anode Spacing (FCAL1/2/3)
- 7.5 / 8.18 / 9.00 mm



FCAL1 Anode Structure

ATLAS Tilecal



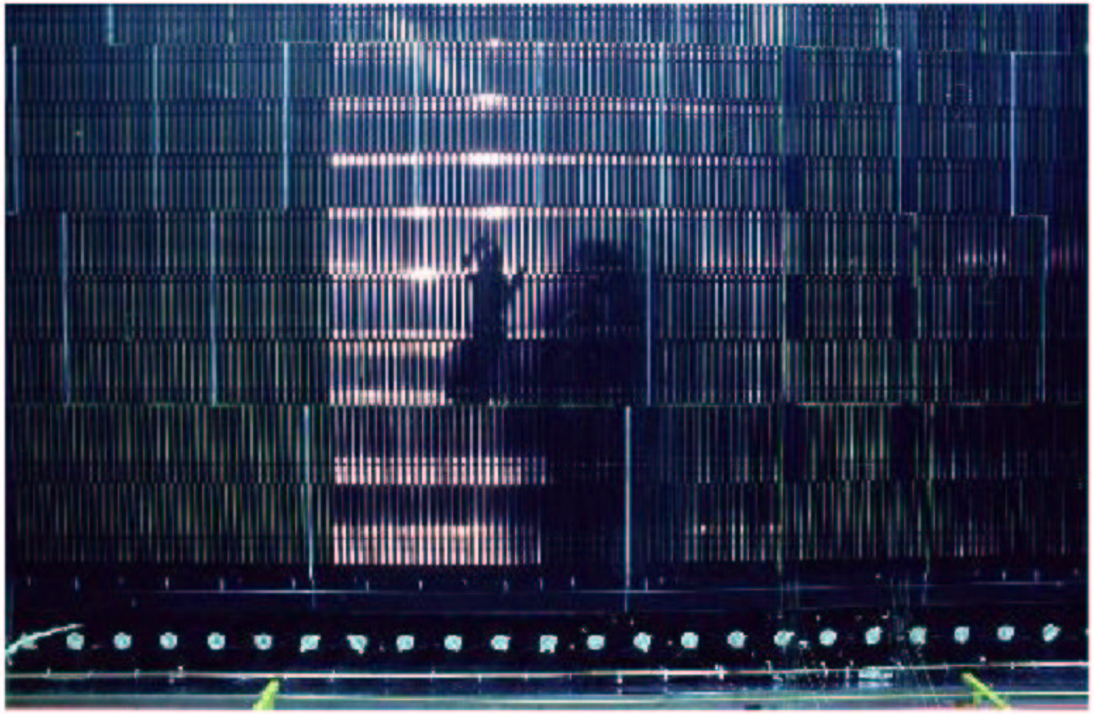
Longitudinal tile configuration ⇒ good hermeticity and "easy" construction

Fe/Scint/WLS fiber

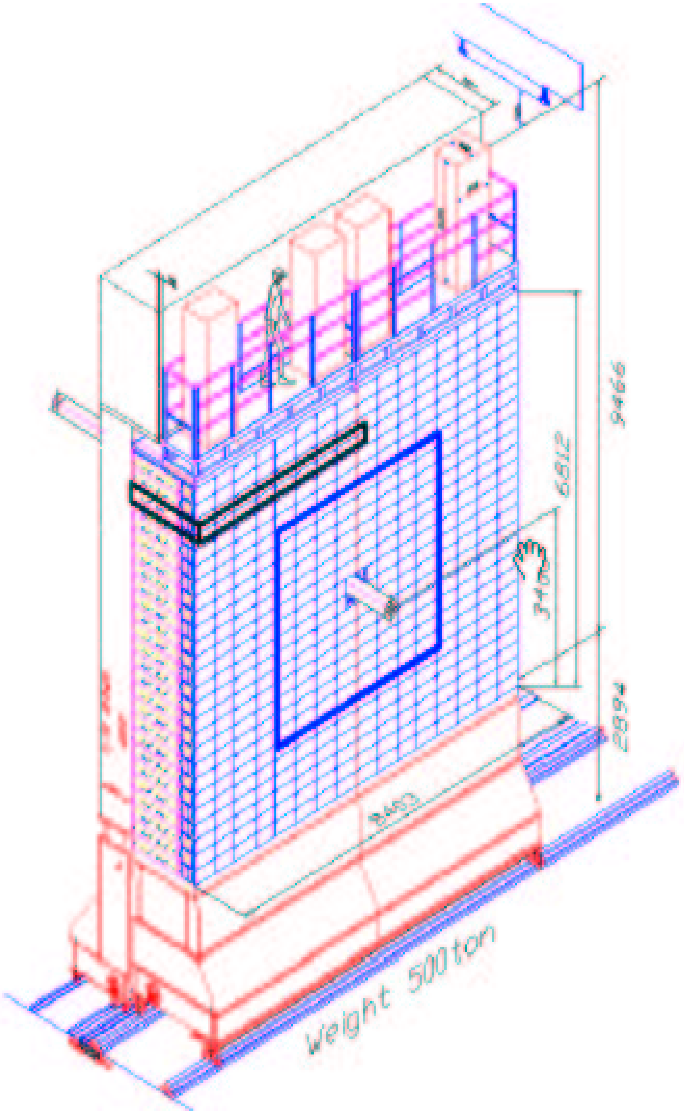
4:1 Fe:Scint

ATLAS TILECAL

36 modules of +/- endcaps, central wheel



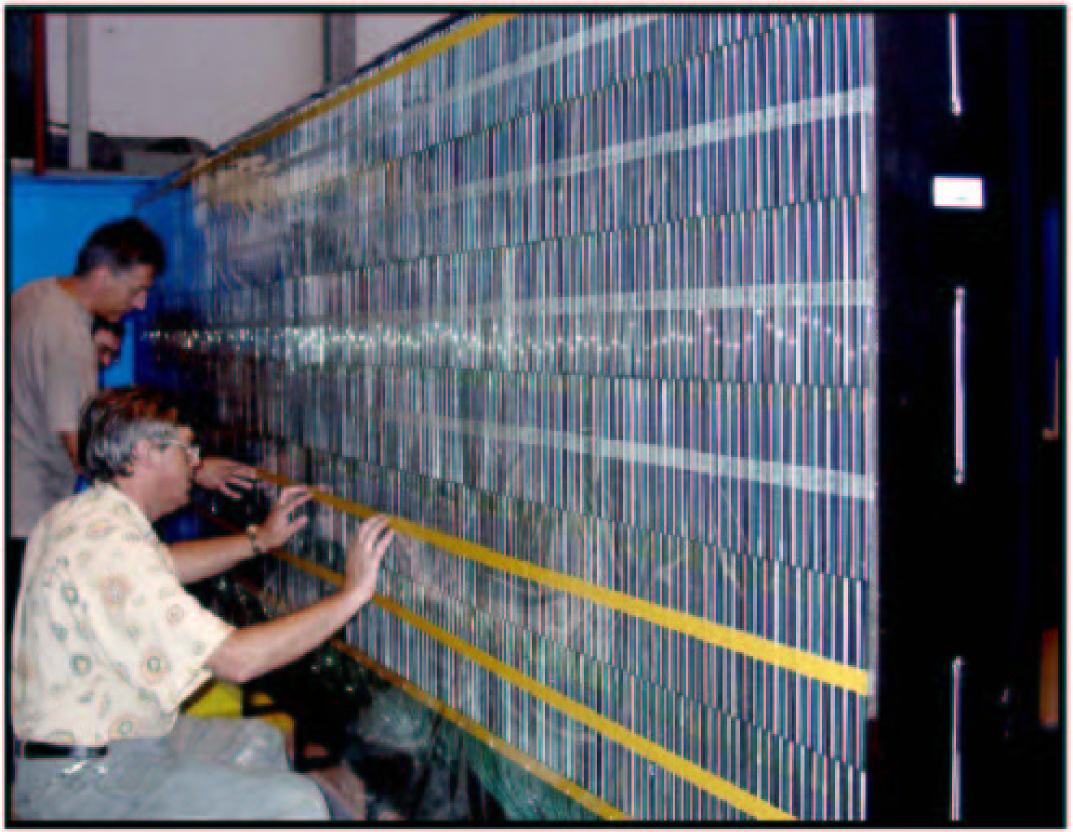
LHCB HCAL

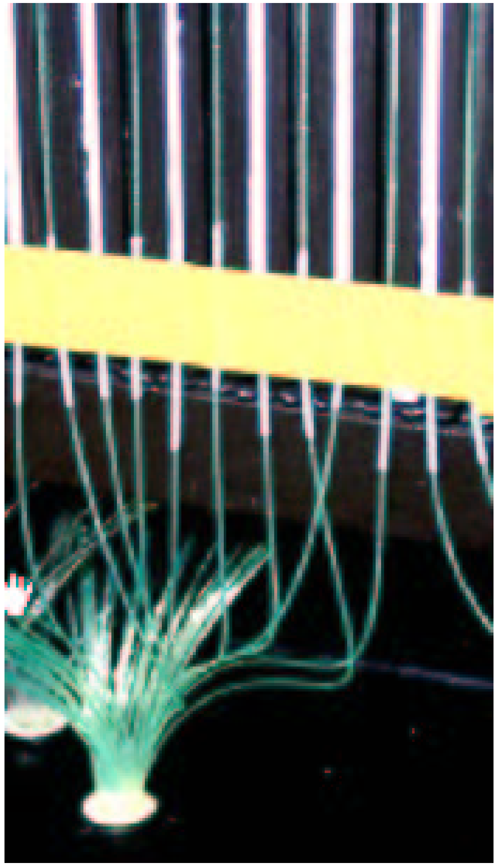


two separate movable halves:

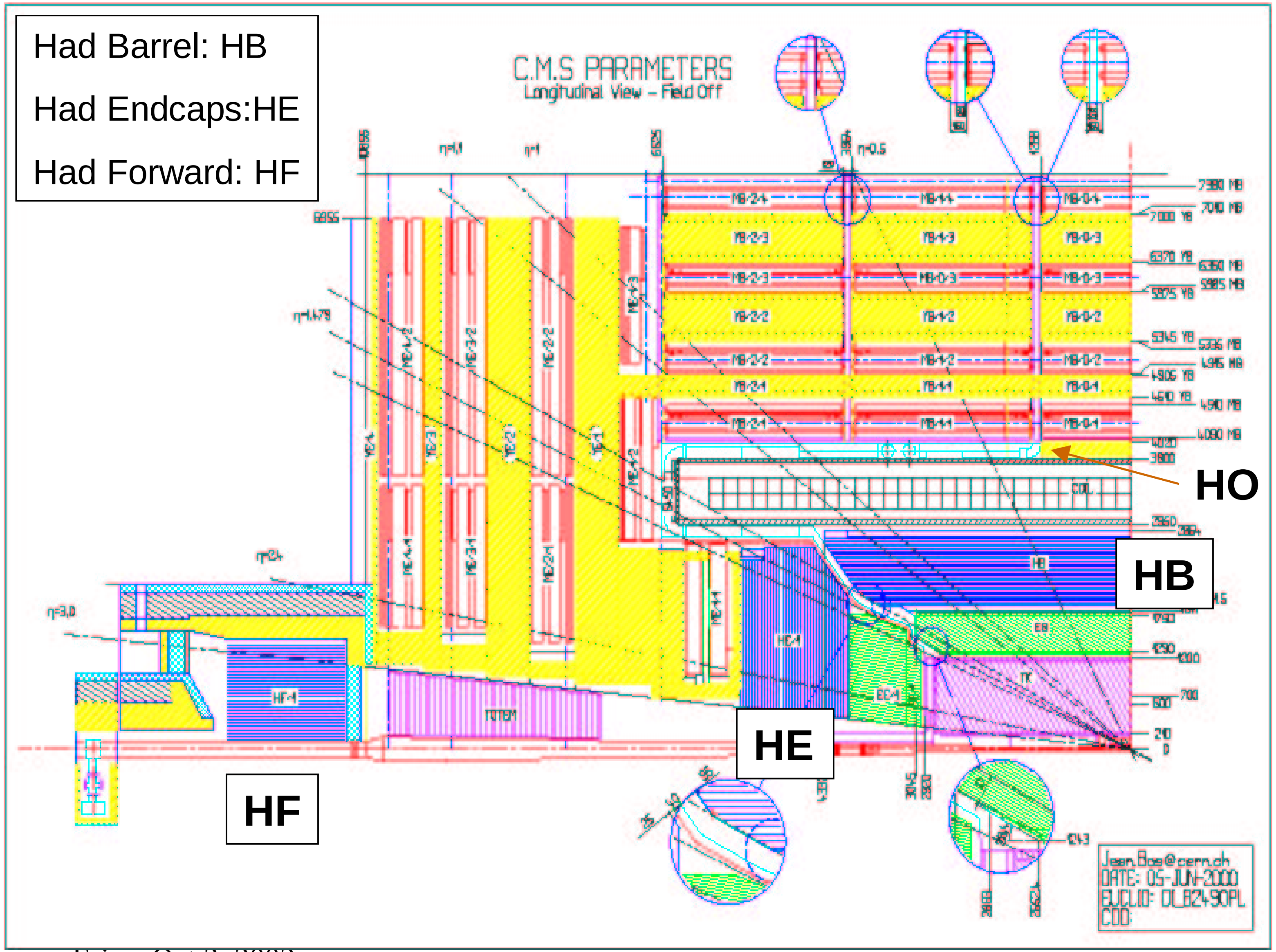
- *stack of 26 modules in each half*
- *5.6 λ instrumented depth*
- *4.2(w) x 0.26(h) x 1.66(l) m*
- *module weight 9.5 ton*
- *read-out electronics on detector*

LHCB Hadron Calorimeter





CMS HCALs



Had Barrel: HB

Had Endcaps:HE

Had Forward: HF

HO

HB

HE

HF

HCAL : HE and HB

CMS HB Calorimeter

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

Coverage: $|\eta|<1.3$

Depth: $5.8\ \lambda_{int}$ (at $\eta=0$)

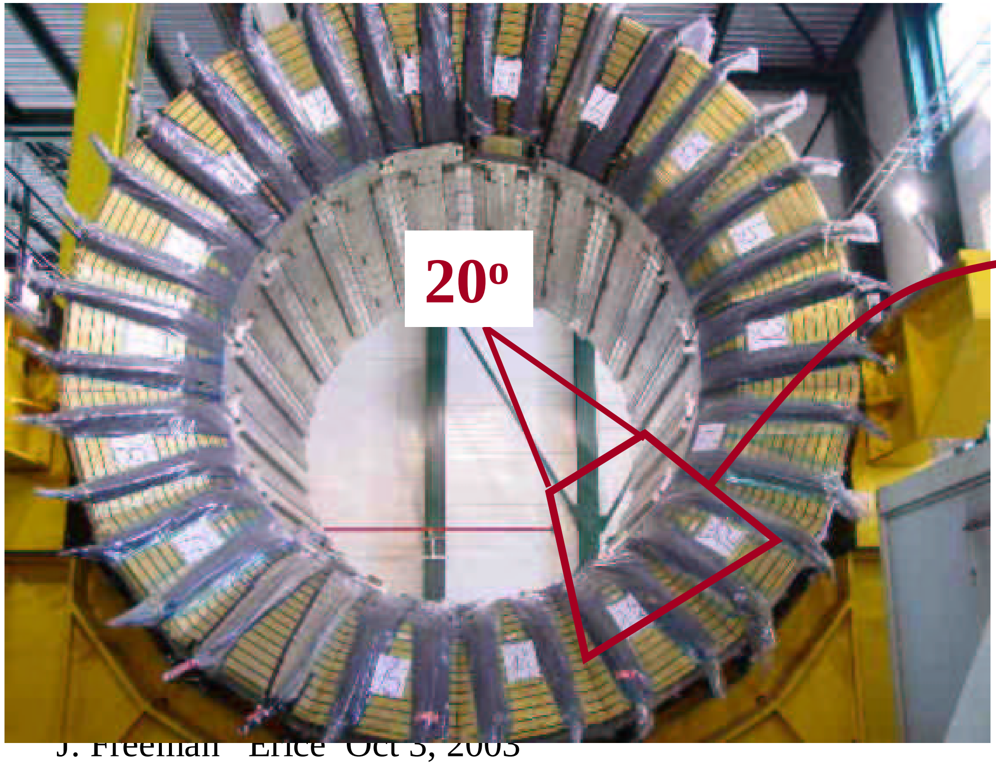
π resolution: $\sim 120\%/\sqrt{E}$

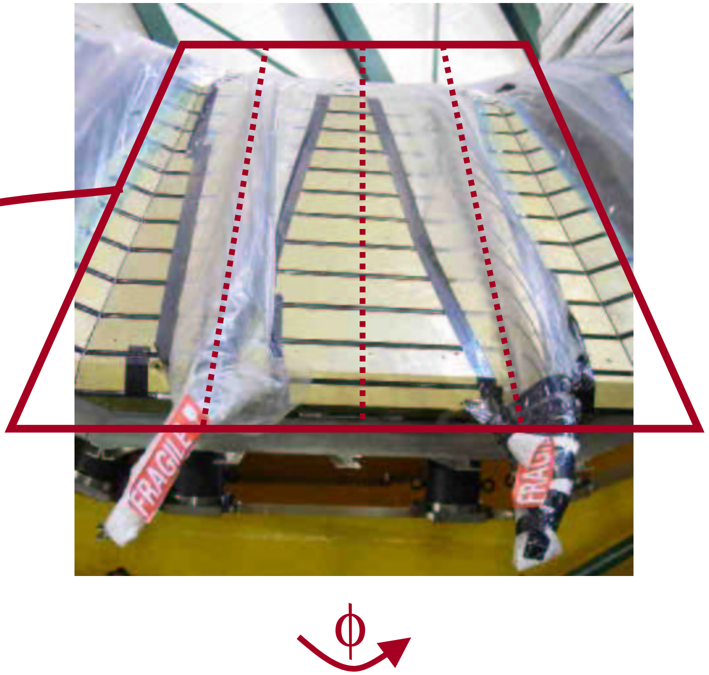
Completed & assembled

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

17 layers longitudinally,

$\phi \times \eta = 4 \times 16$ towers





CMS HE Calorimeter

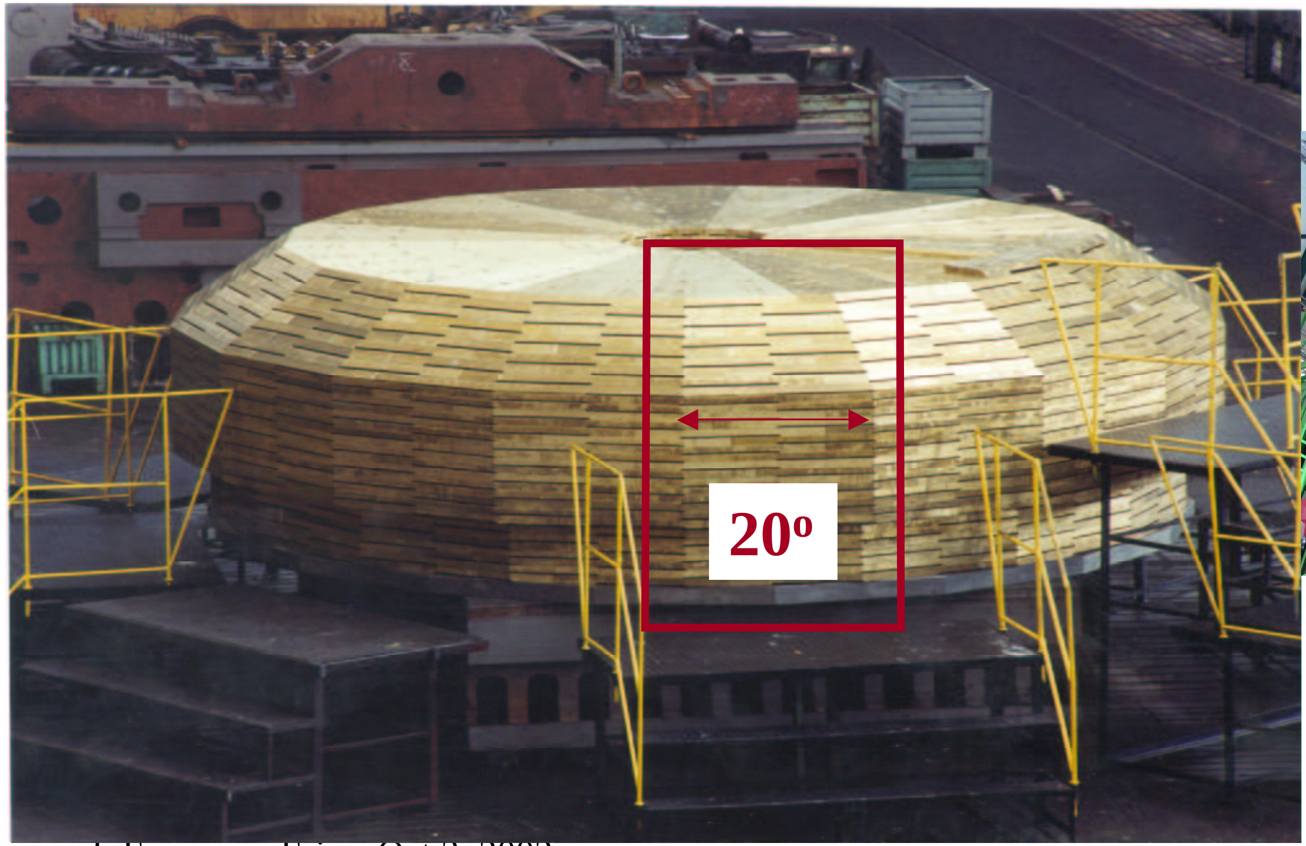
Sampling calorimeter: brass (passive) & scintillator (active)

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

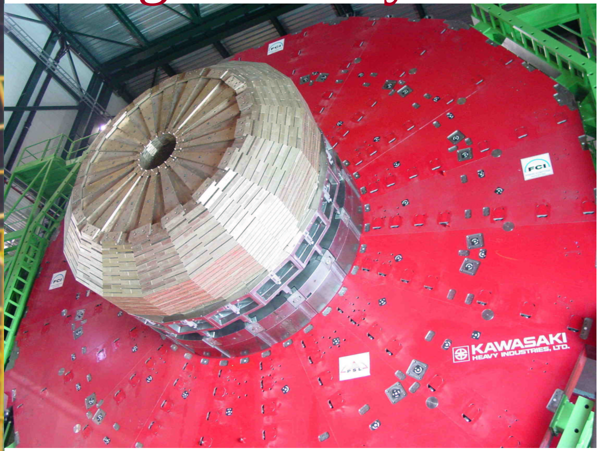
Depth: $10\ \lambda_{int}$

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

π resolution: $\sim 120\%/\sqrt{E}$



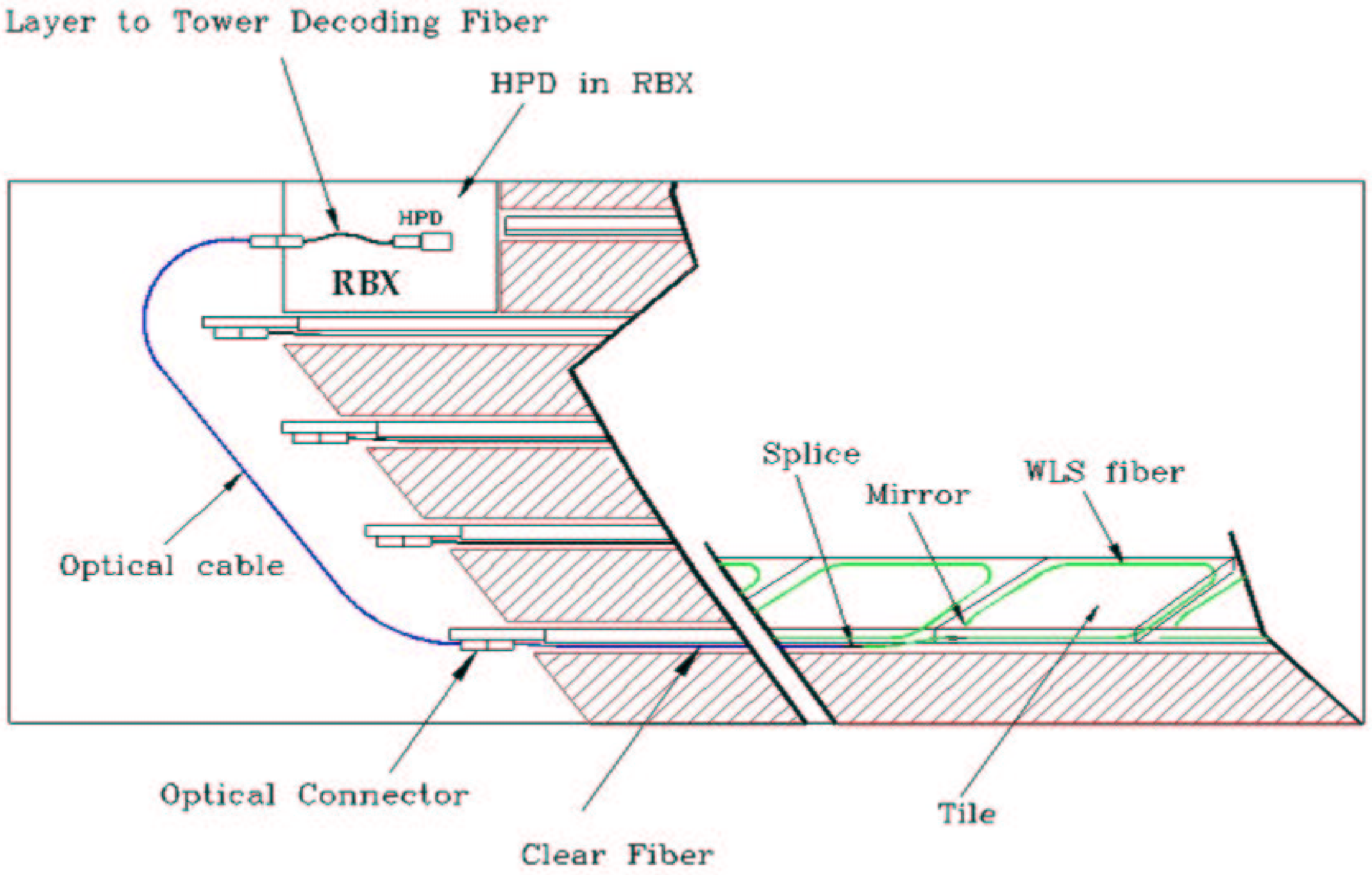
19 layers longitudinally



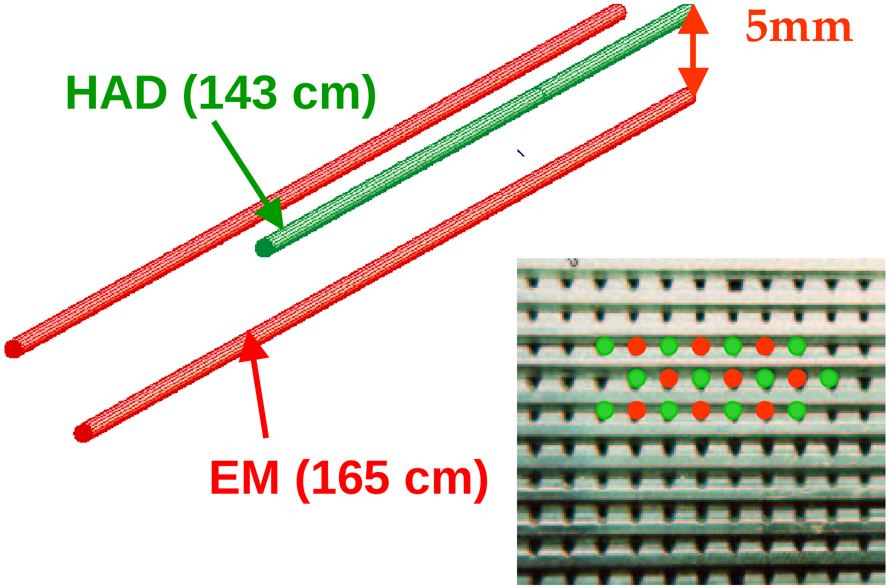
Completed, assembled, HE-1 installed

Optical Design for CMS HCALs

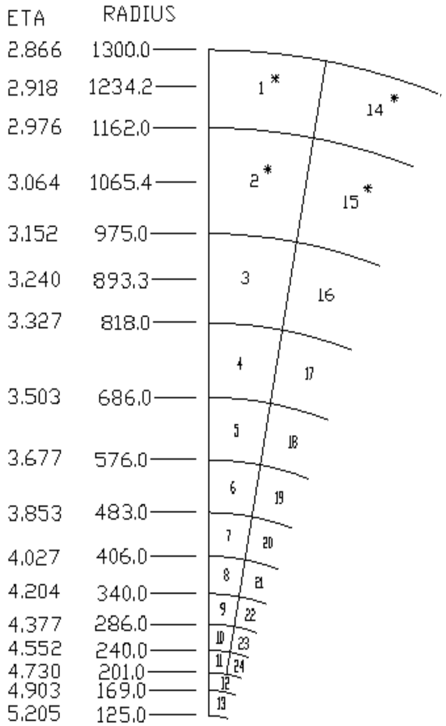
Common Technology for HB, HE, HO



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

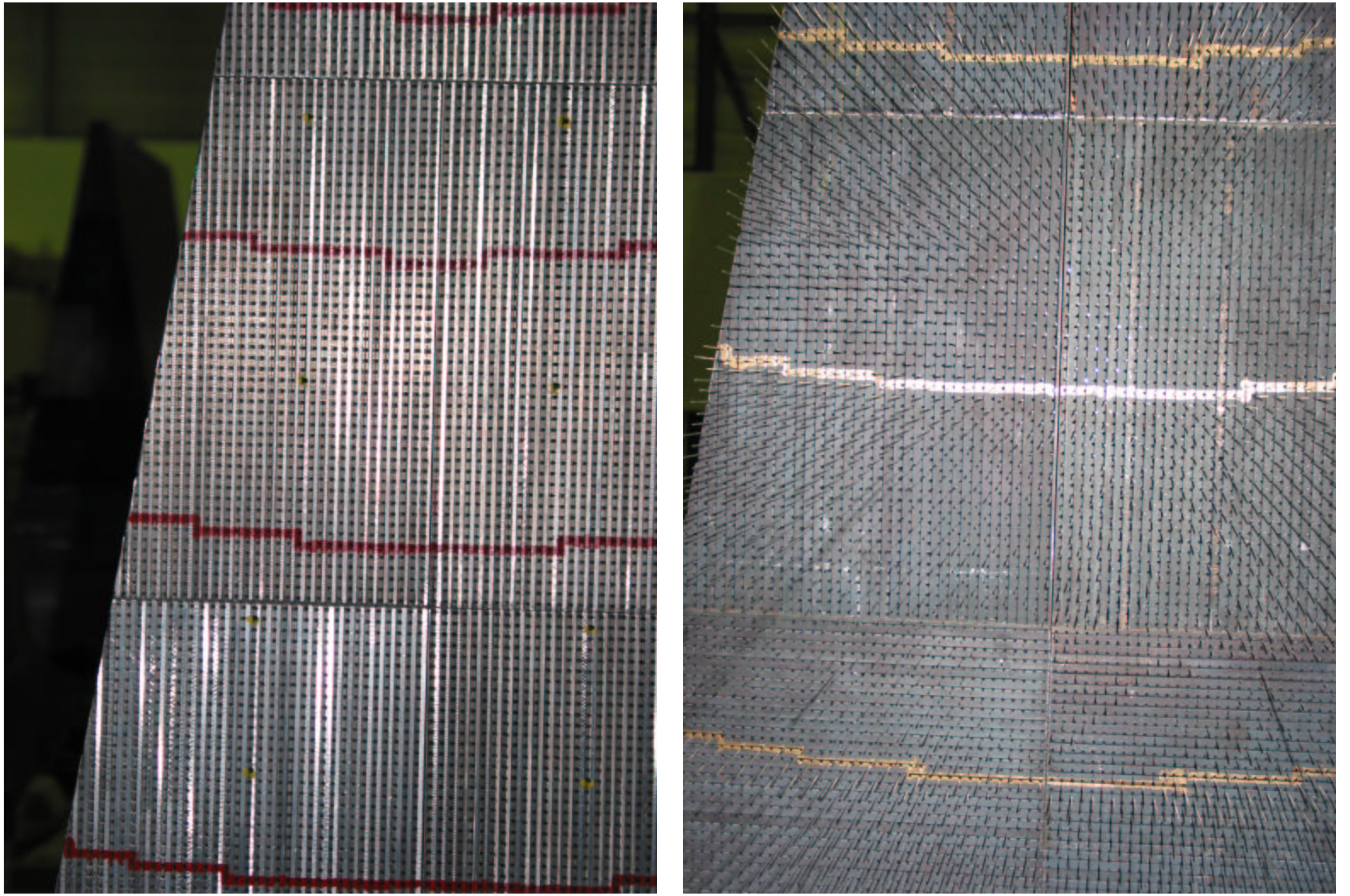
Covers $5 > \eta > 3$

Total of 1728 towers, i.e.

2 x 432 towers for EM and HAD

$\eta \times \phi$ segmentation (0.175 x 0.175)

Fibers in the HF absorber



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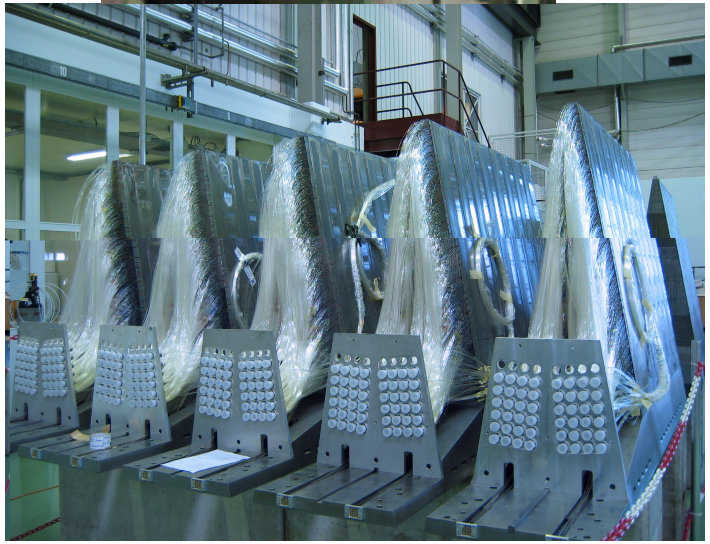
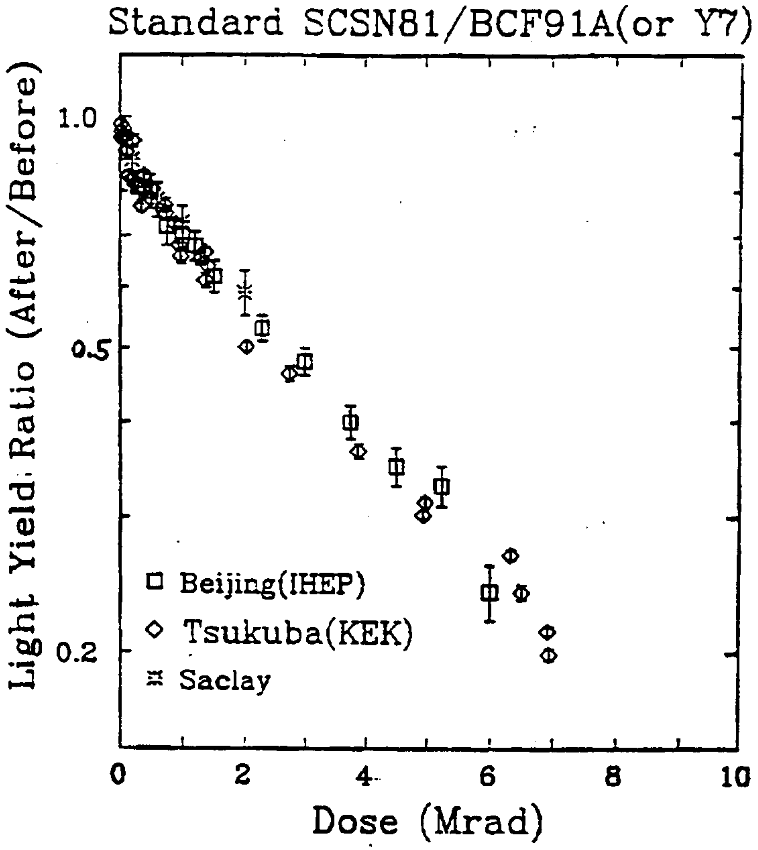
HF Fiber stuffing at CERN



Issues for SLHC

- Radiation Damage
- Rate Effects
- Bunch ID determination

Scintillator - Dose/Damage

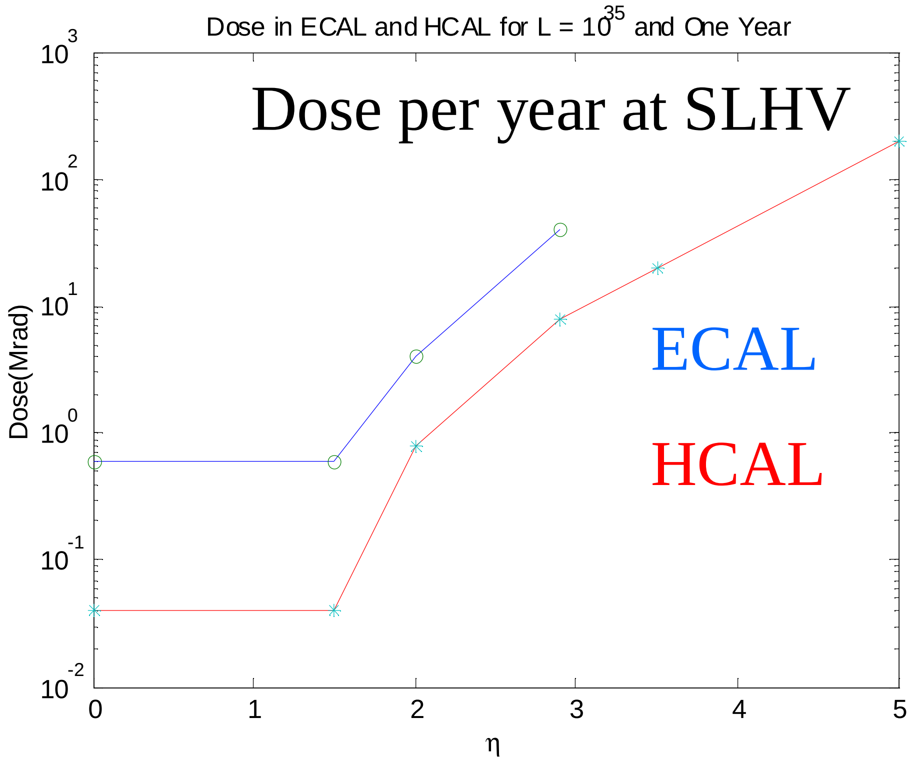


Scintillator under irradiation forms
Color centers which reduce the
Collected light output (transmission loss).

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

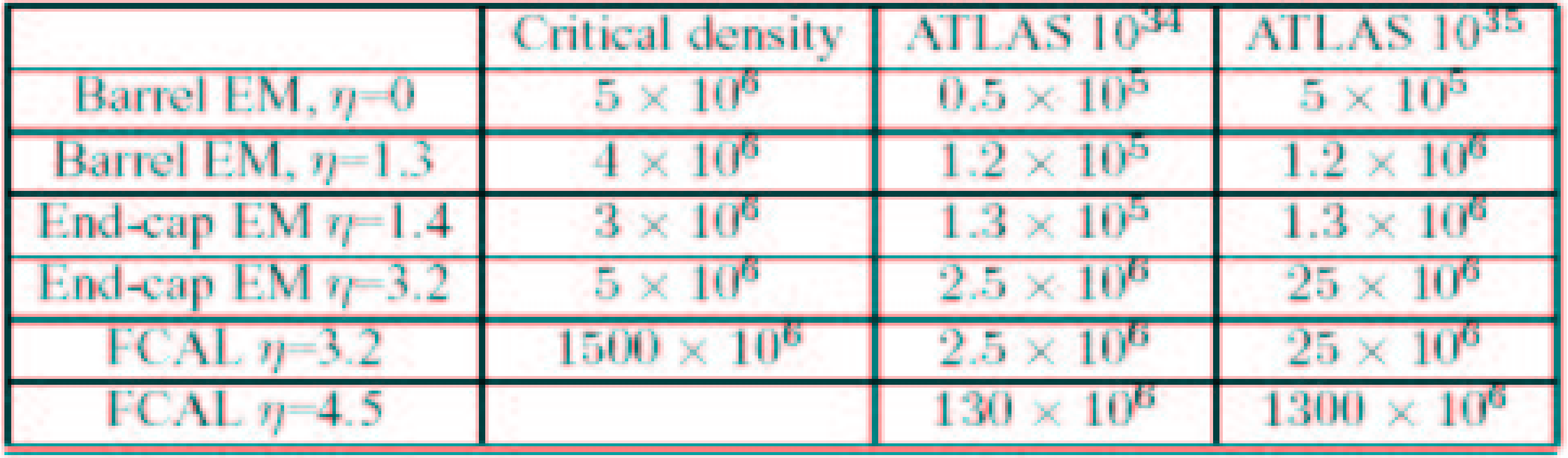
Current operational limit ~ 5 Mrad

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



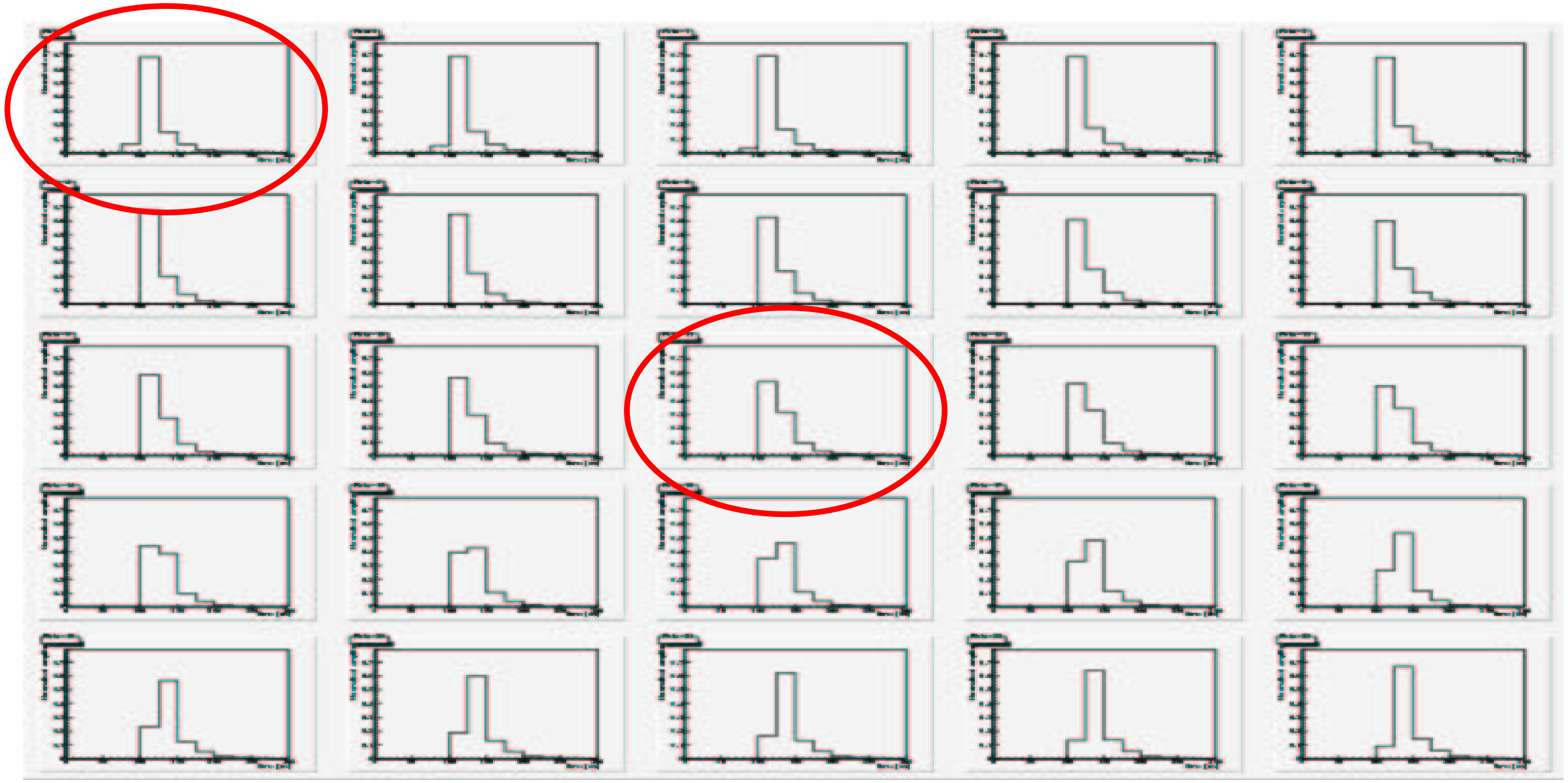
	Critical density	ATLAS 10^{34}	ATLAS 10^{35}
Barrel EM, η=0	5×10^6	0.5×10^5	5×10^5
Barrel EM, η=1.3	4×10^6	1.2×10^5	1.2×10^6
End-cap EM η=1.4	3×10^6	1.3×10^5	1.3×10^6
End-cap EM η=3.2	5×10^6	2.5×10^6	25×10^6
FCAL η=3.2	1500×10^6	2.5×10^6	25×10^6
FCAL η=4.5		130×10^6	1300×10^6

At SLHC, ATLAS LAR will stop working at $\eta \sim 1.5$

Switch to liquid Xe, ?

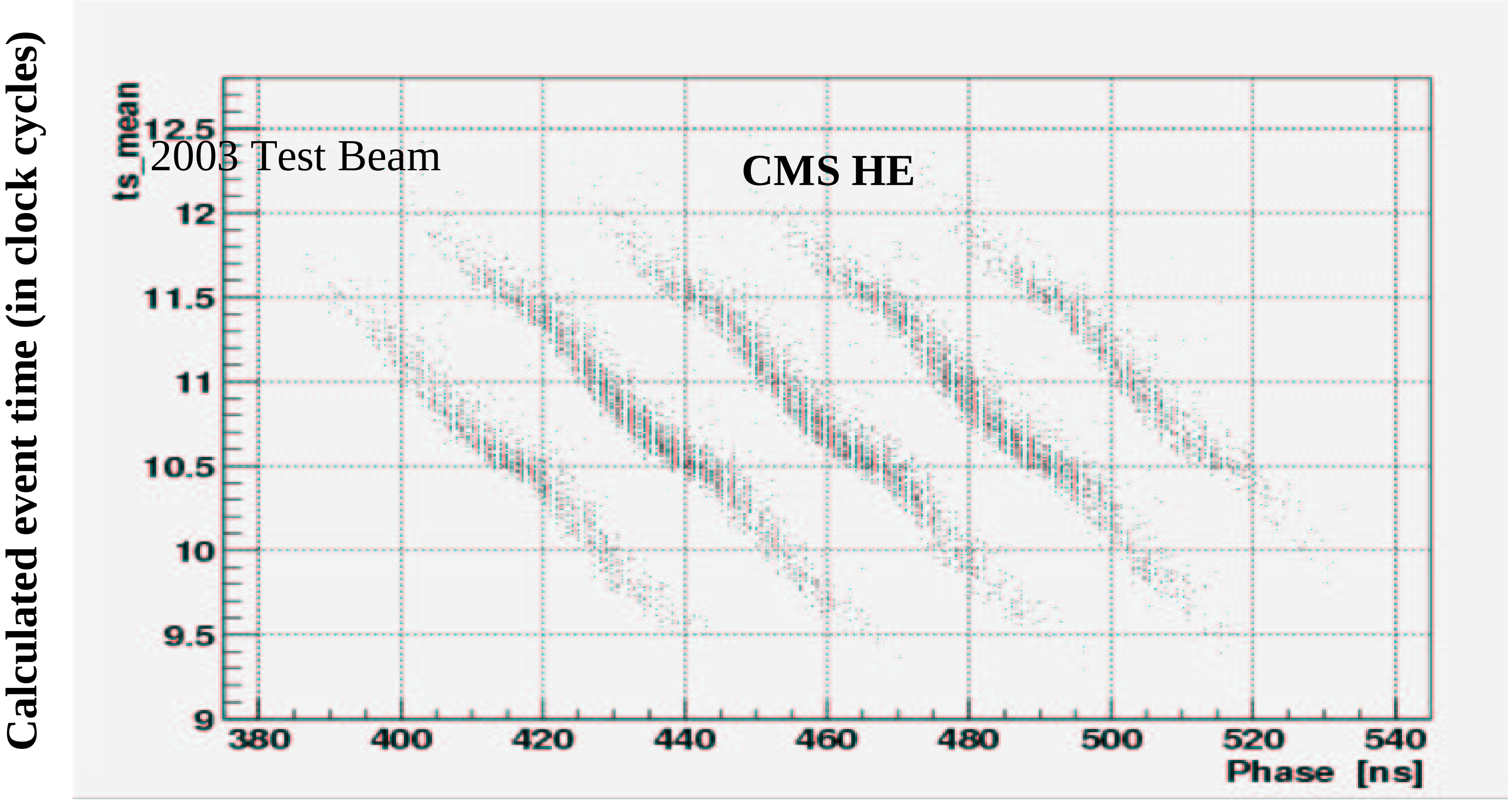
CMS HB Pulse Shape

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

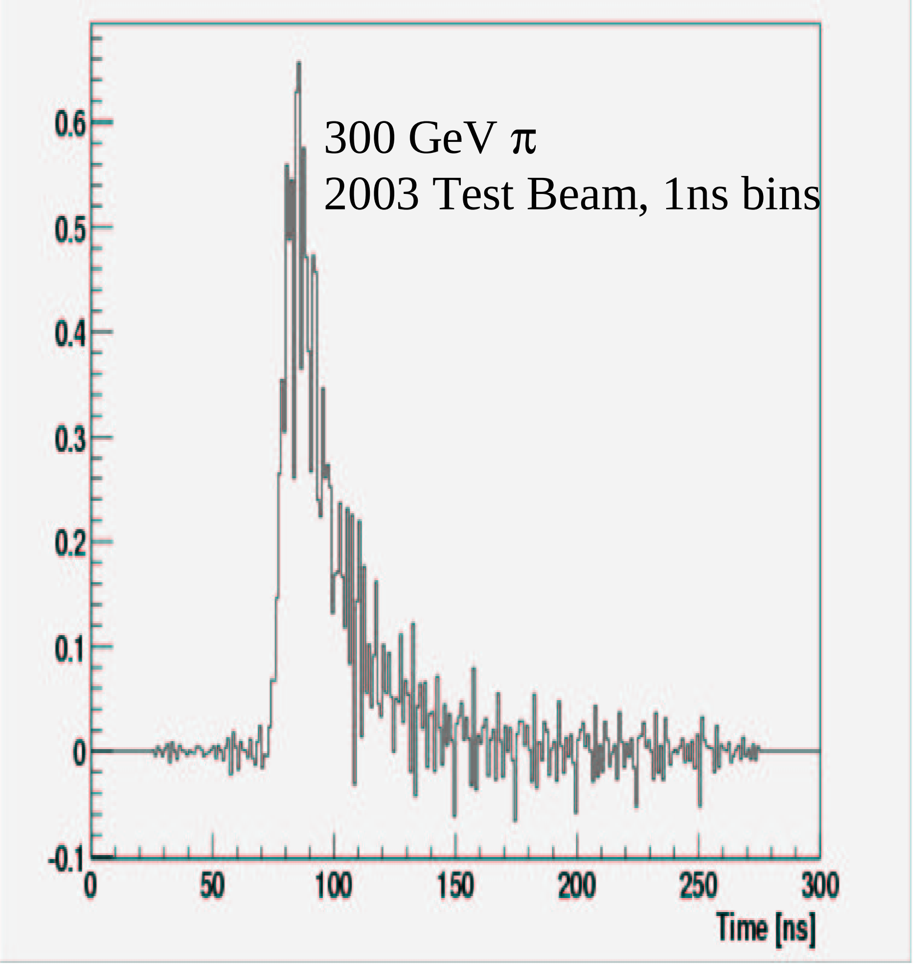
Timing using calorimeter pulse shape



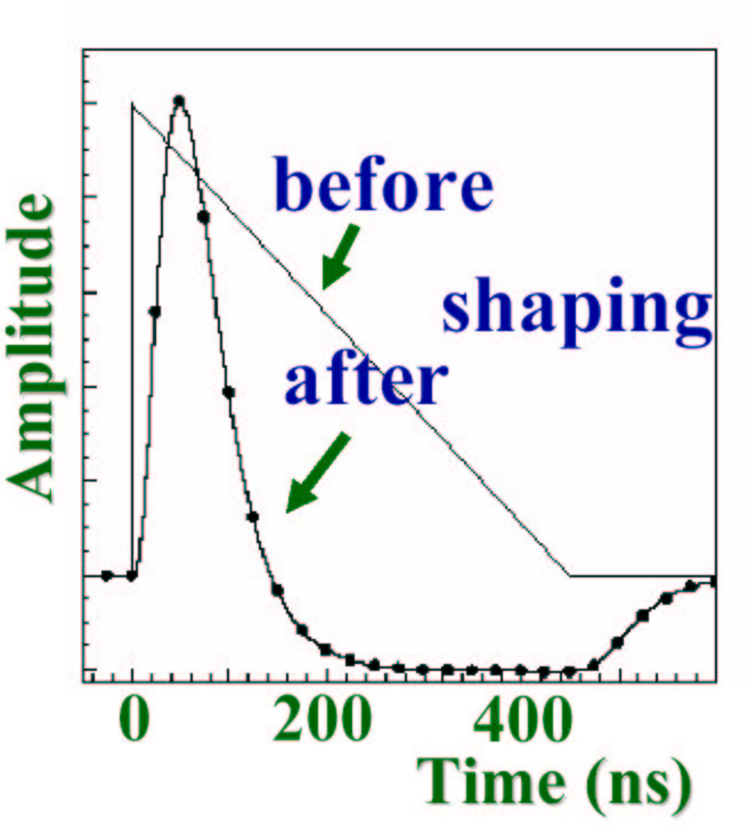
Calculated event time (vertical scale) vs actual event time. CMS HE, 100GeV pions. Also works for lAr. DO timing resolution 4ns/E (in GeV). Watch pile-up though. The faster the calorimeter, the less important pile-up will be.

What about ATLAS?

CMS HE Calorimeter

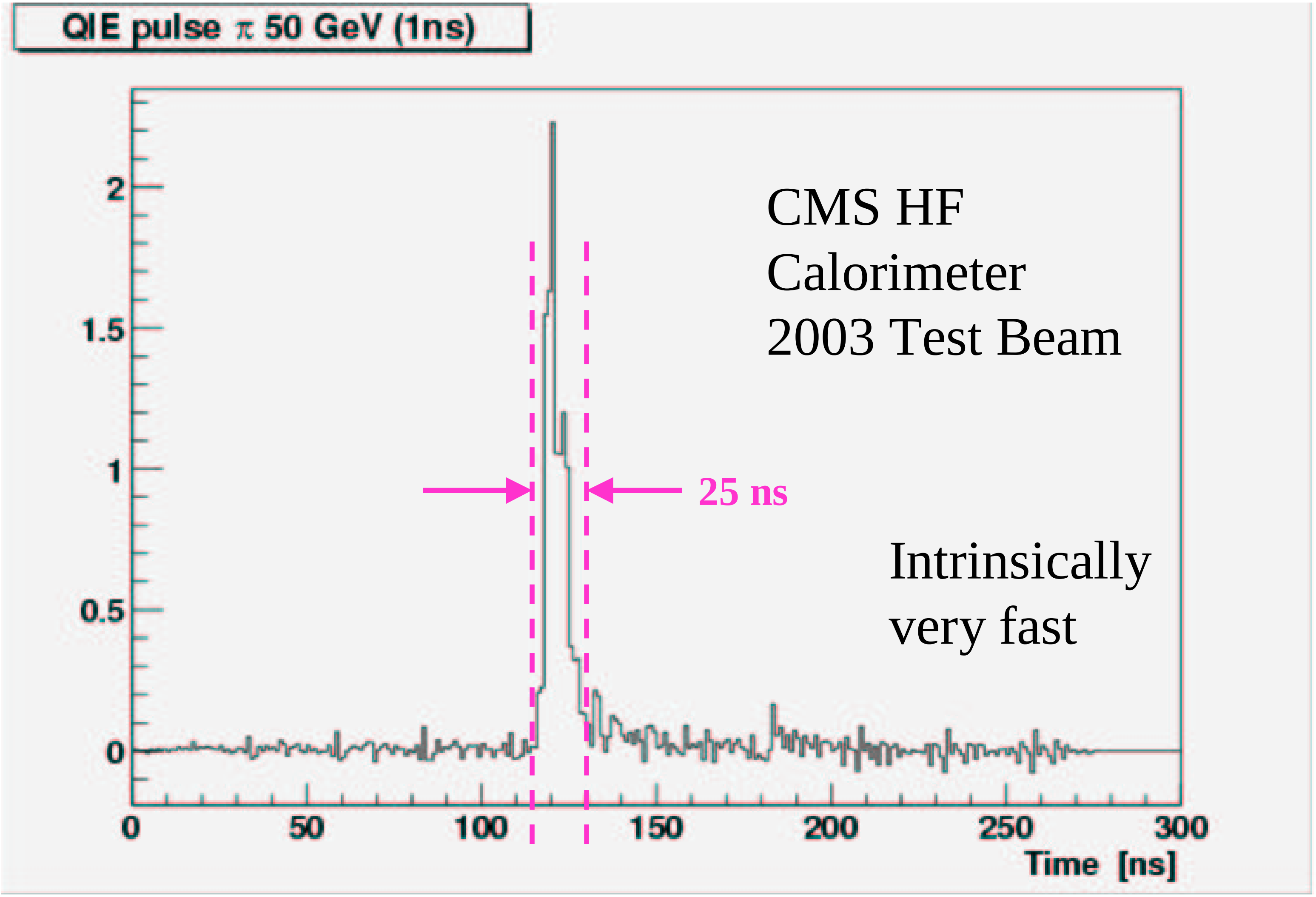

300 GeV π
2003 Test Beam, 1ns bins

Atlas lAr EM Calorimeter



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

HF Cerenkov Calorimeter Pulse Shape



CMS HF
Calorimeter
2003 Test Beam

Intrinsically
very fast

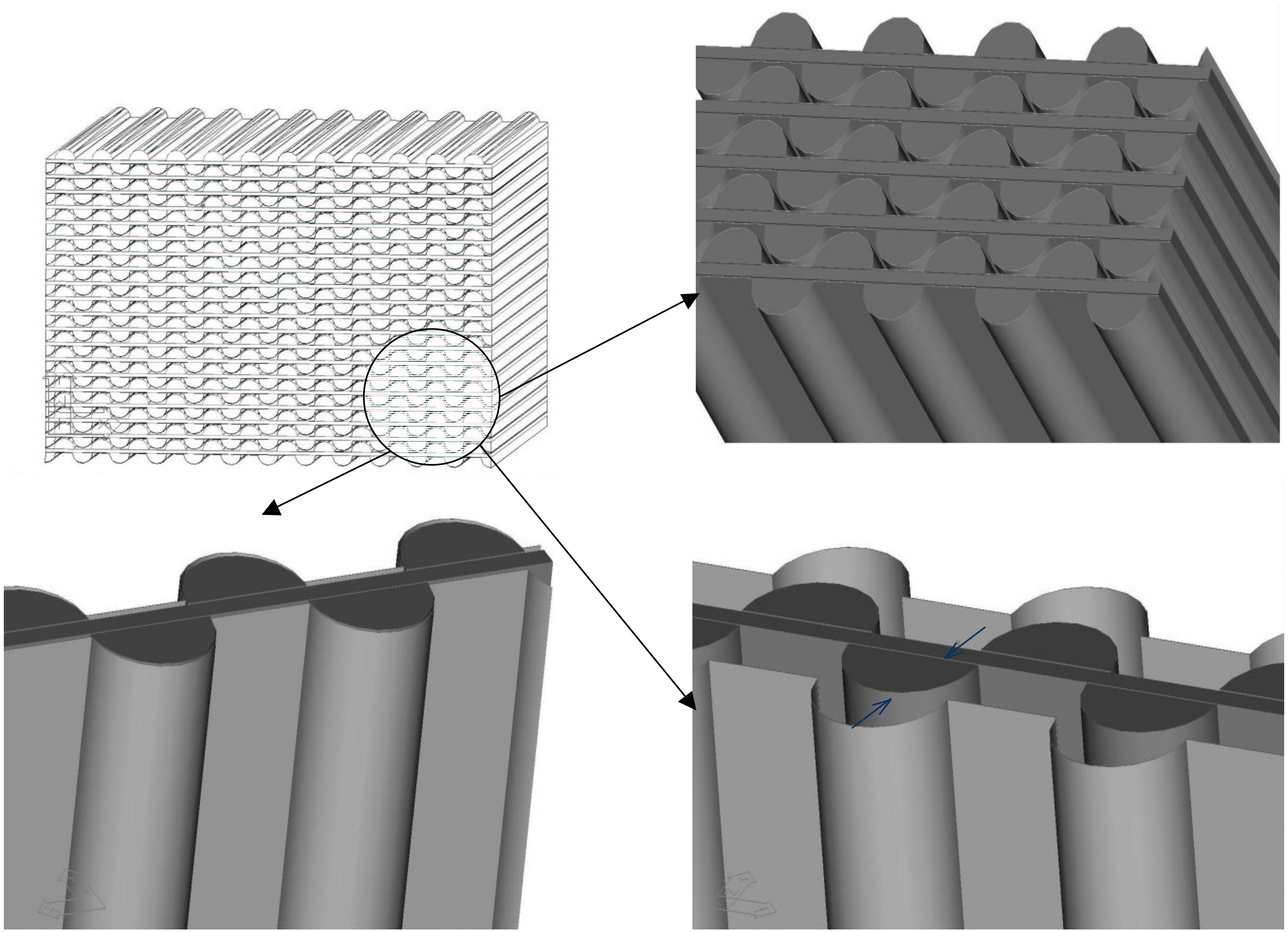
ATLAS/CMS at SLHC

- 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?

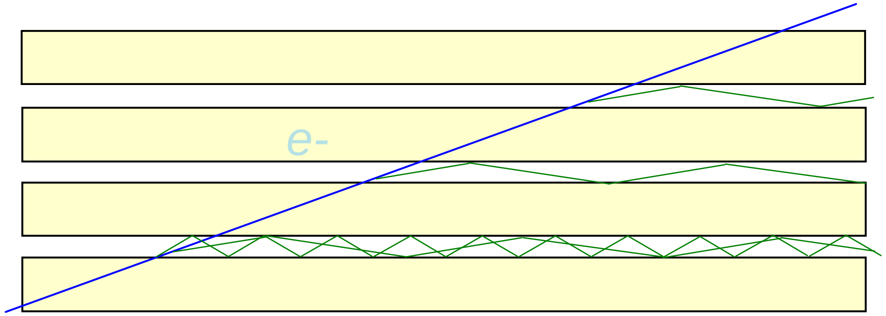
- Cerenkov calorimeters are rad-hard and fast → good candidates for future colliders
  - Quartz fiber or plate
  - Gas cerenkov
- New photon detectors → low cost, small, rad-hard
  - Red-sensitive HPDs
  - Geiger-mode photodiodes
- New scintillator materials → rad-hard
- New directions:
  - “Spacal” 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.

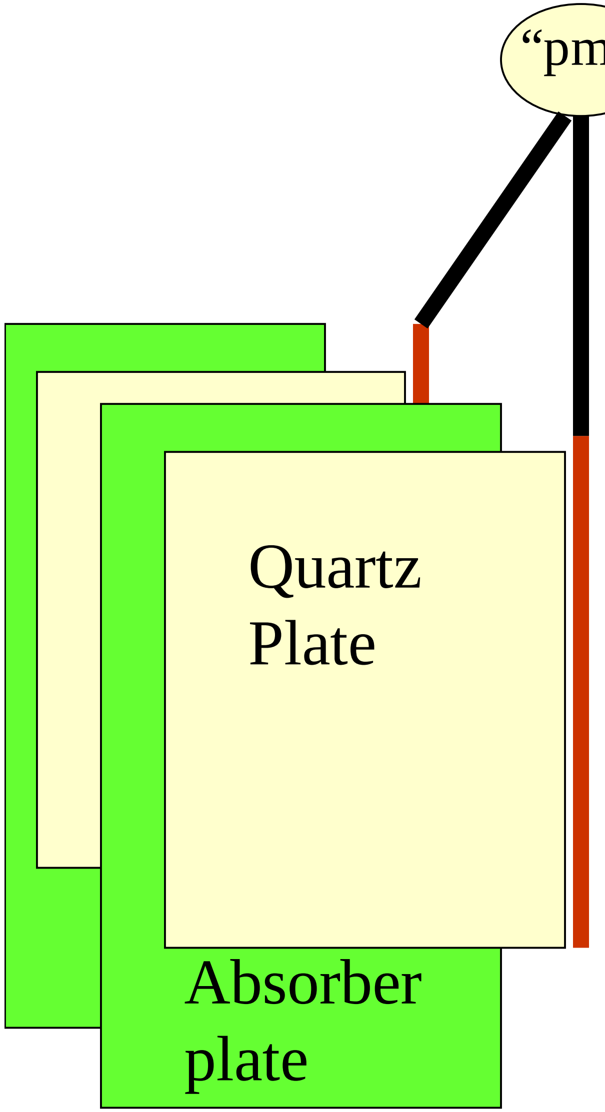


- Shower particles co-move with the Cherenkov light as two overlapped pancakes. The width of these pancakes is about 50 ps.

- Inside surfaces must be highly reflective at grazing incidence.

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

Cerenkov Tile/Fiber



“pmt”

Quartz fiber

Ti:Sapphire fiber with cladding

Quartz Plate

Absorber plate

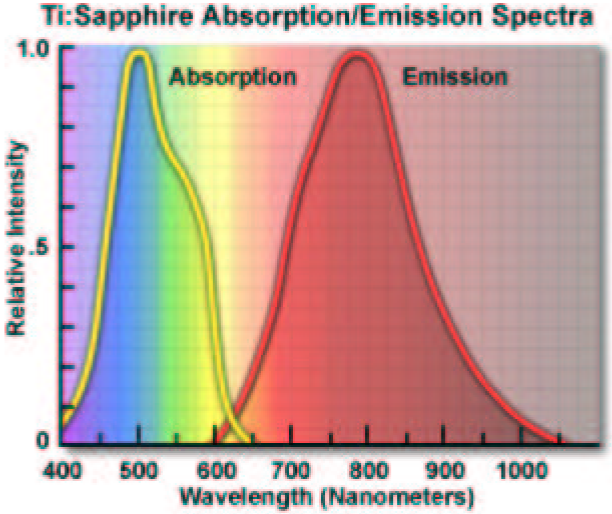
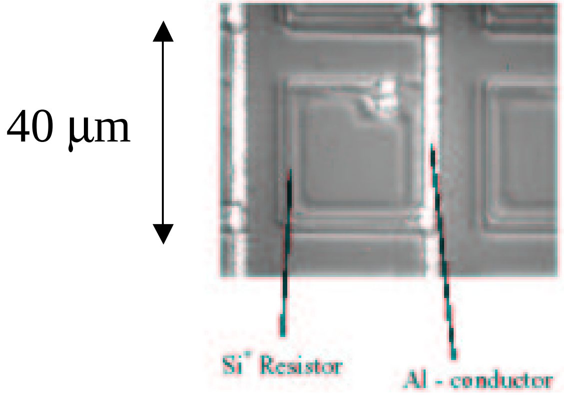


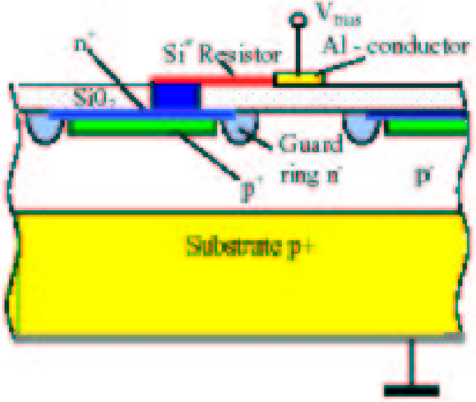
Figure 1

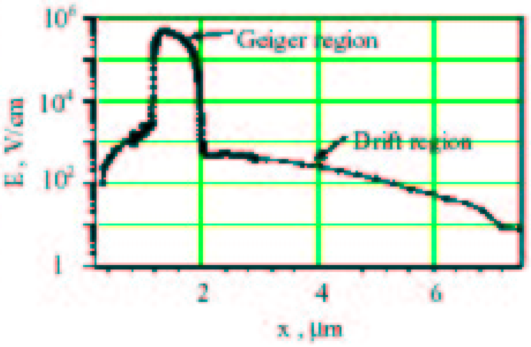
Ti:Sapphire is a wavelength shifter and rad-hard. Index of refraction = 1.7

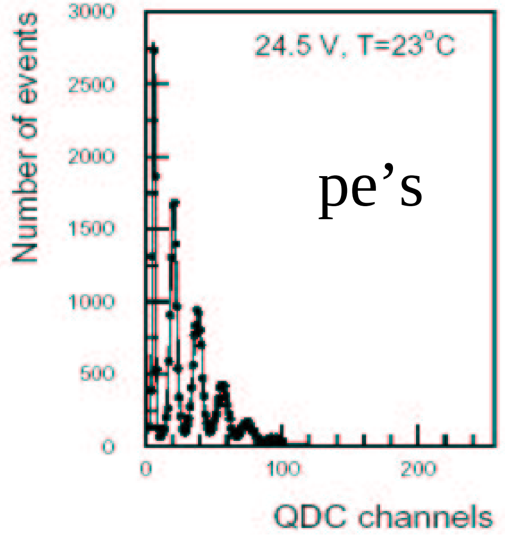
Issues: light yield, purity of plate, speed of shifter.

Geiger-mode silicon pmt (SPMT)





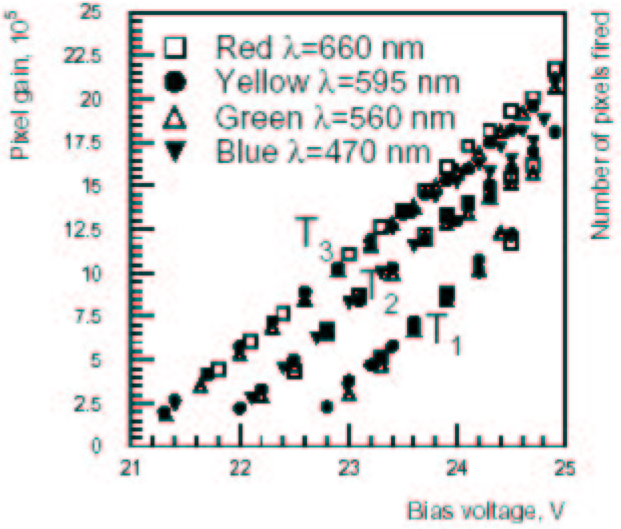




100 – 10000 SPMTs tied in parallel to same substrate.

High gain, 10^6, low noise

Issues are rad-hardness and rate ability



http://www.slac.stanford.edu/pubs/icfa/fall01/paper3/paper3.pdf

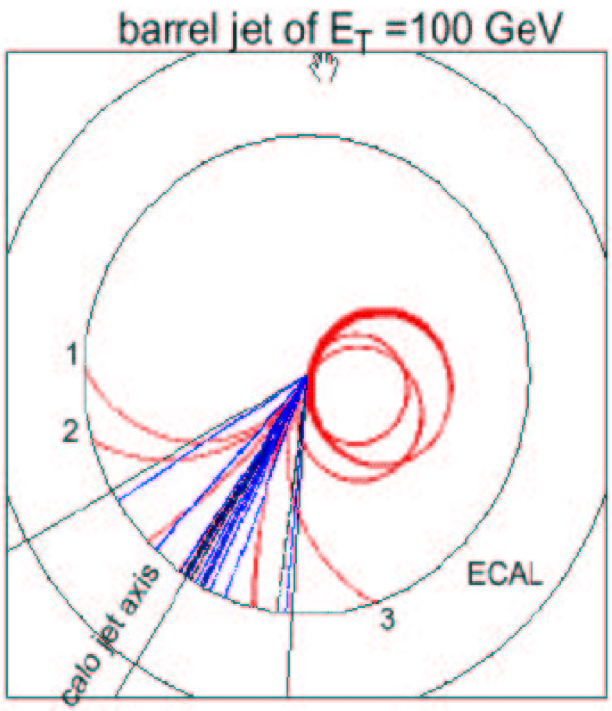
New Scintillators and Shifters

- 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

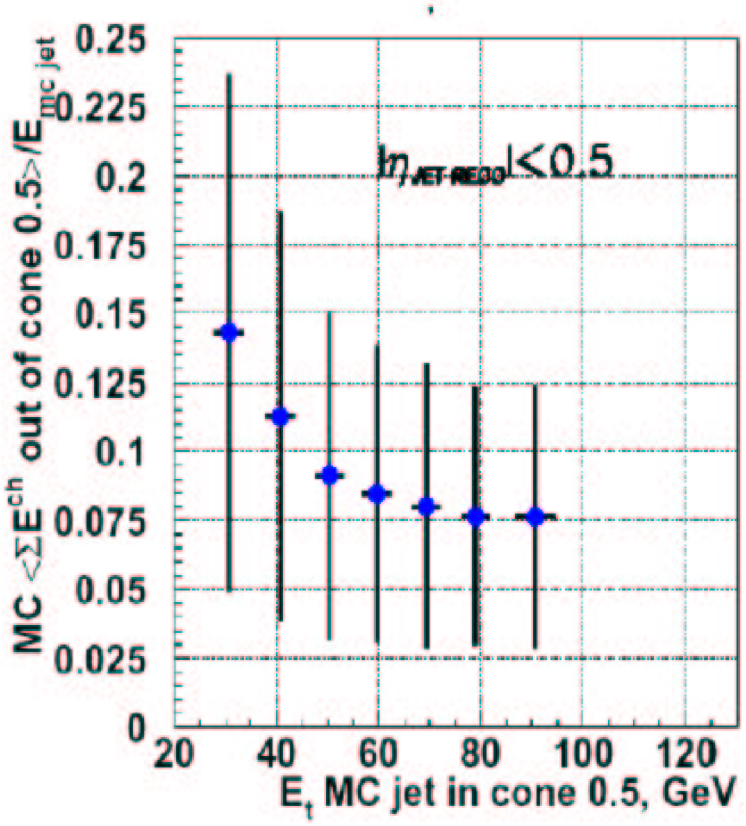
Jet Res improvement using tracking. CMS 4T B field



Radius of ECAL front ~ 1.3 meters

Charged particles $P_T < 0.8$GeV
→ Looper in barrel.

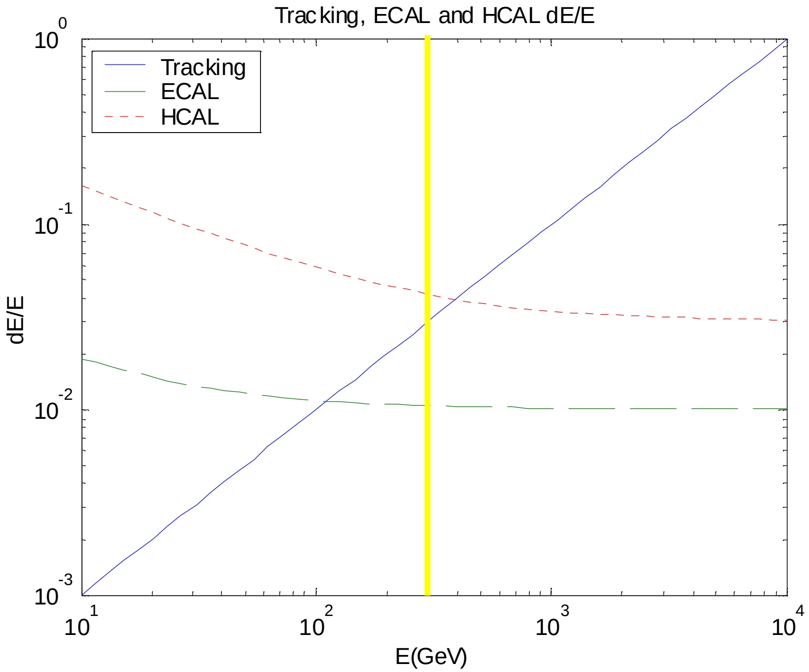
Fraction of energy escape
from a jet cone (R=0.5)
in 4T field.



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 $<z_{max}> \sim 0.22$. 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)

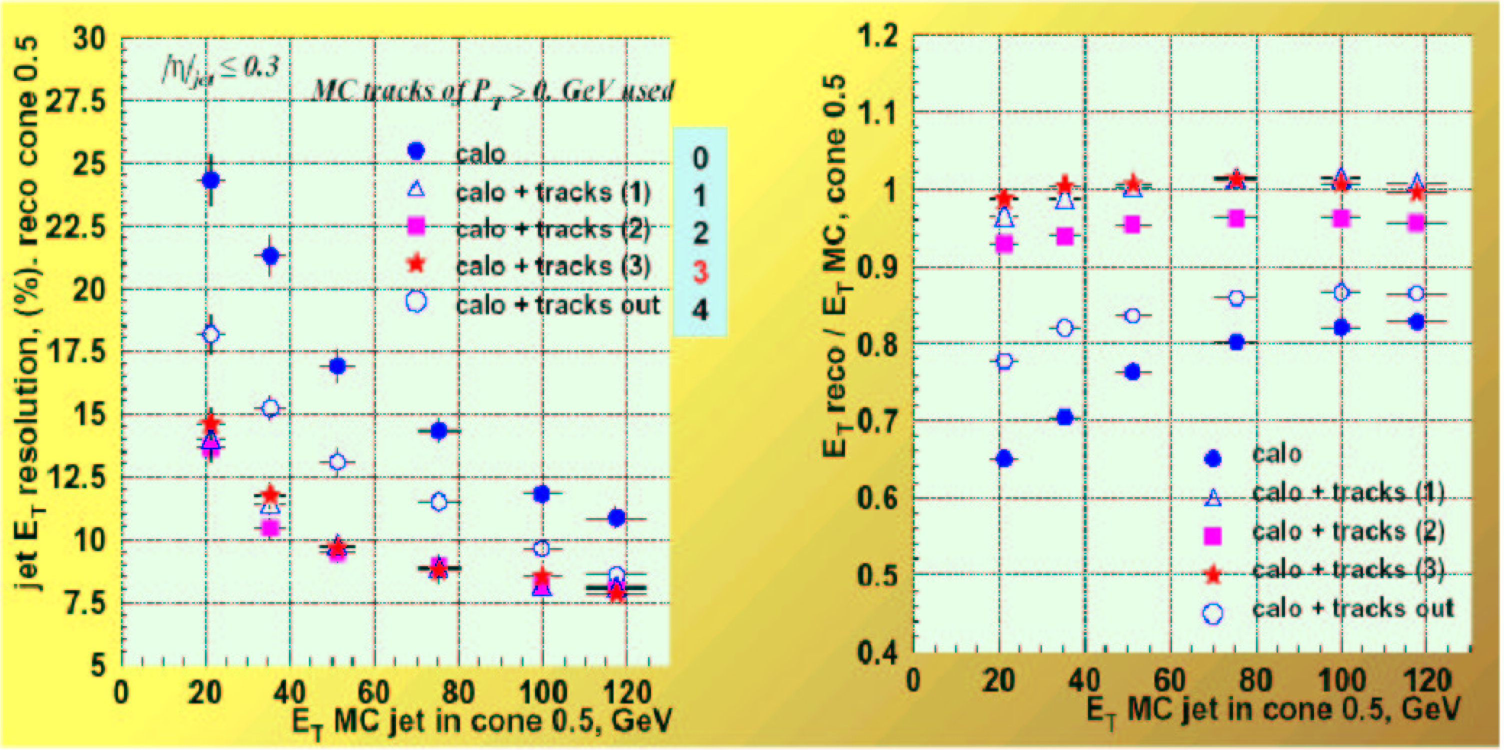
Energy Flow Jet Improvement

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.**

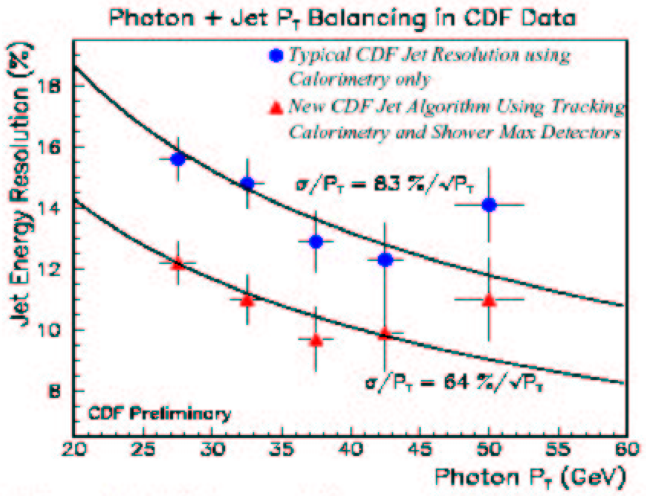
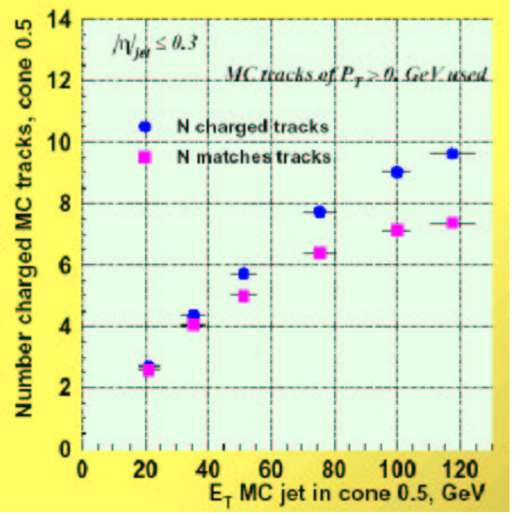


Figure 4: The central detector resolution σ_D is plotted as a function of P_T^γ for the two methods.

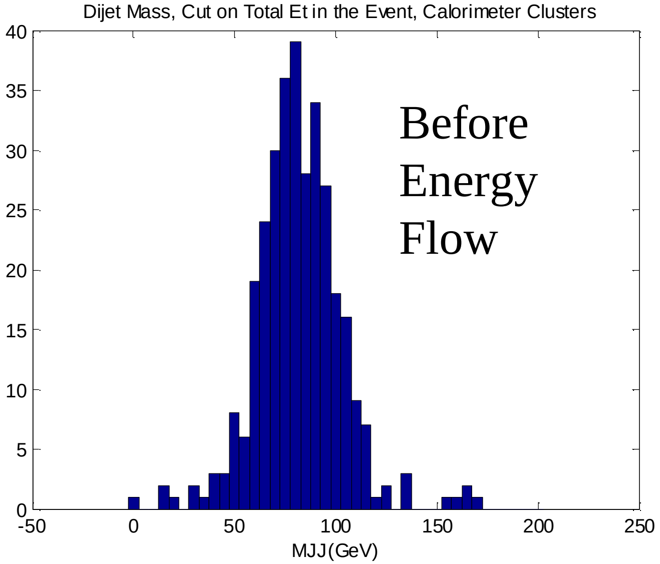
Improved Dijet Mass

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



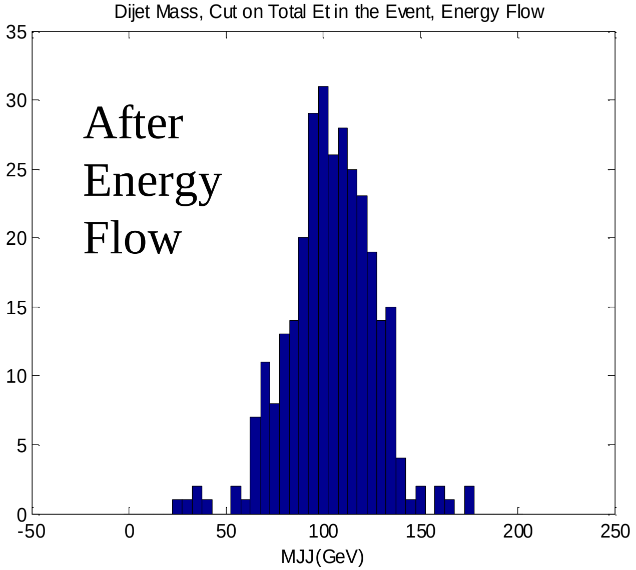
Energy Flow

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



Before Energy Flow

Mean 81.7 GeV, (21%)



After Energy Flow

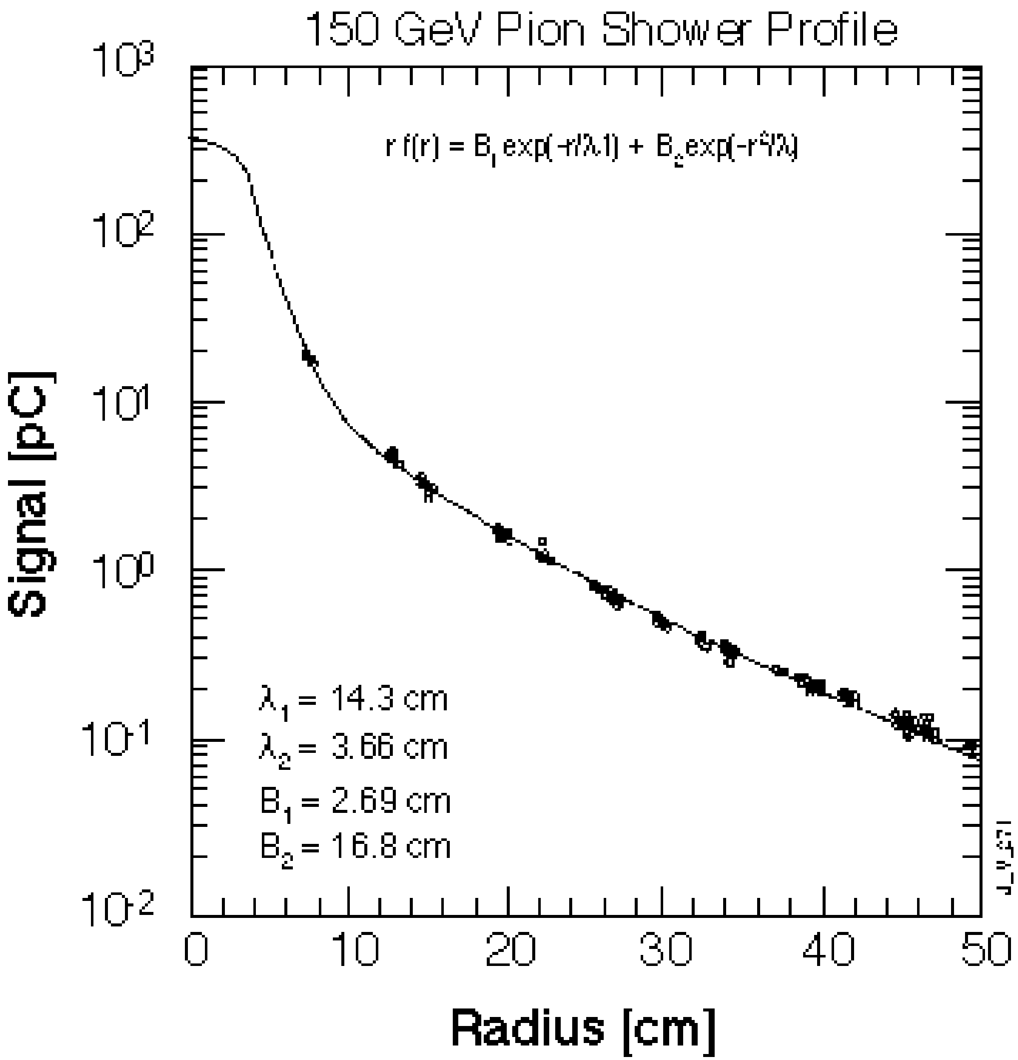
Mean 105.5 GeV, (17%)

New Calorimeter

- Issues for designing new calorimeter for VLHC/Eloisatron

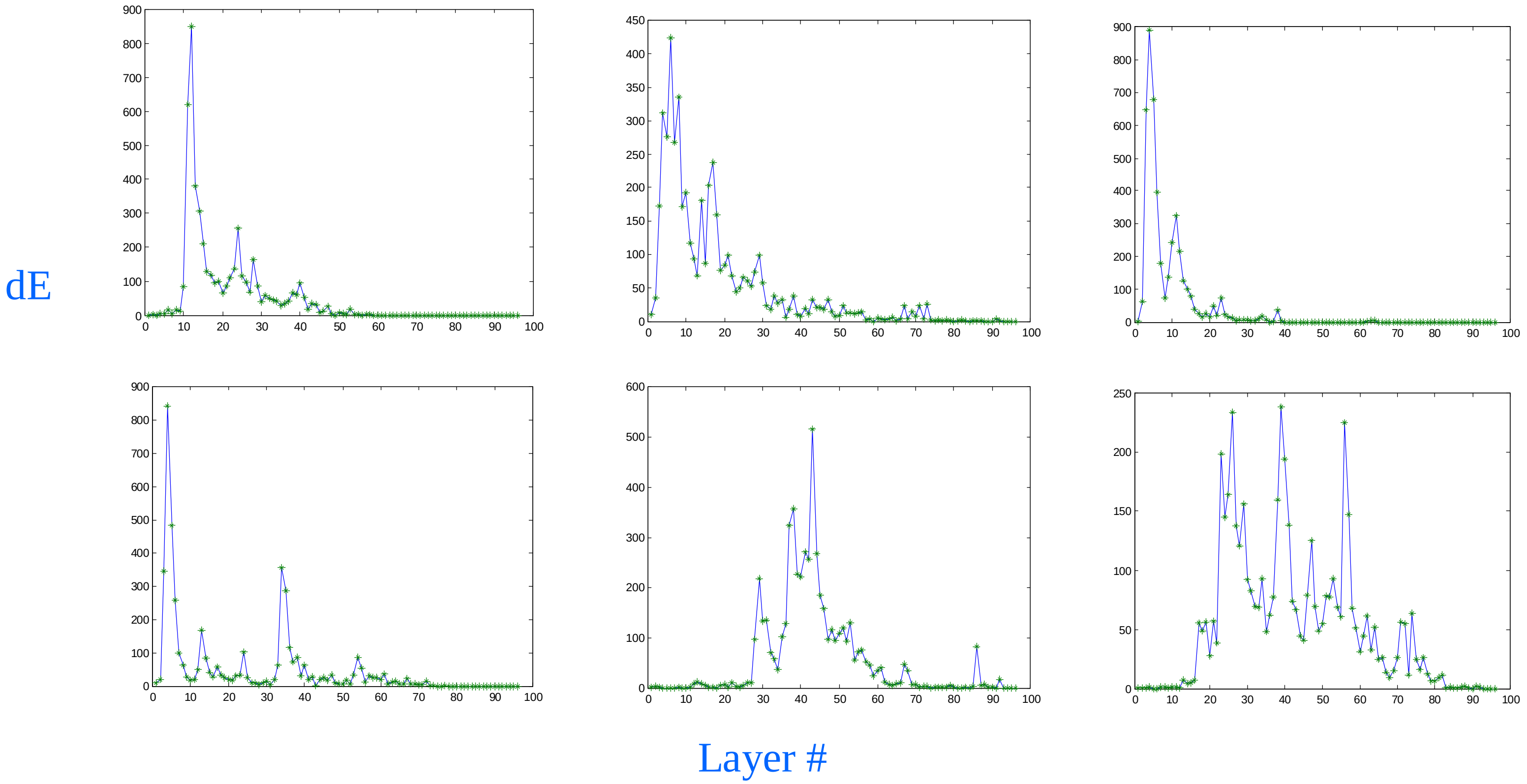
Transverse Size - HCAL

- **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

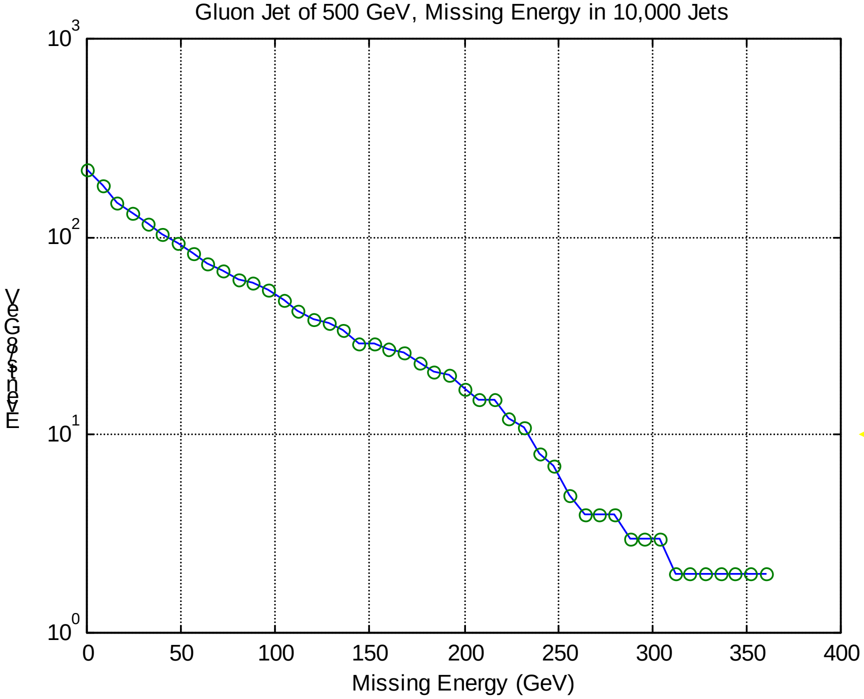


SDC Hanging File Calorimeter Data. 96 layers of scintillator, each read out with separate pmt.

Intrinsic Limitations to Containment

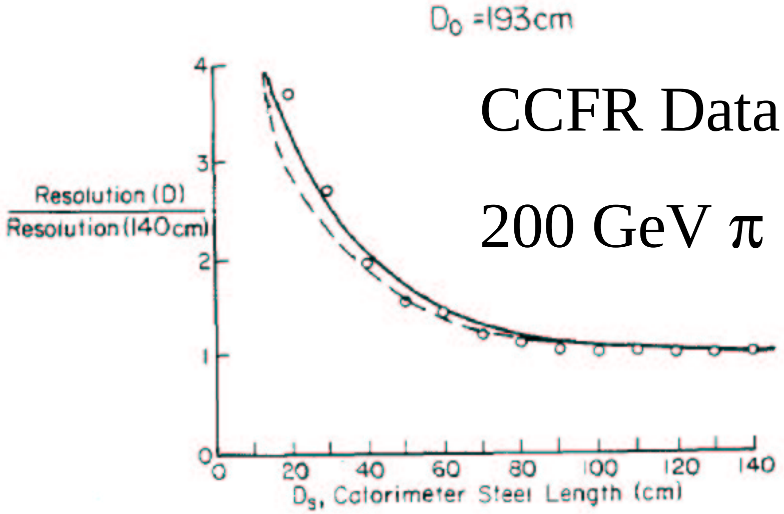
- **Jet "splitting", g -> QQ and Q -> qlv, puts intrinsic limit on required depth. Jets themselves "leak".**

Jets
with
energy >
Missing
ET



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

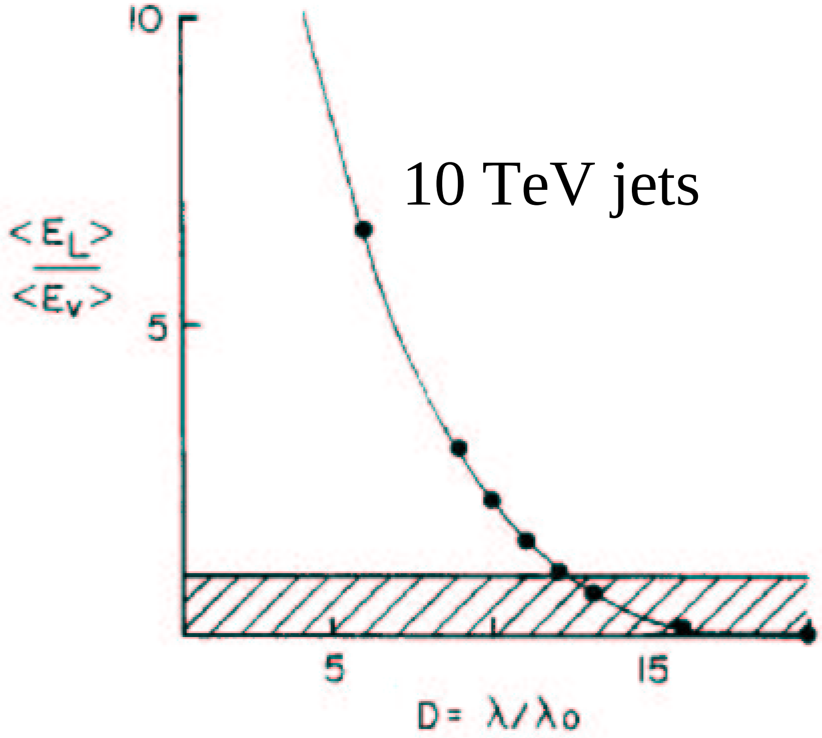
Calorimeter Depth Requirements



CCFR Data

200 GeV π

Relative Resolution vs depth

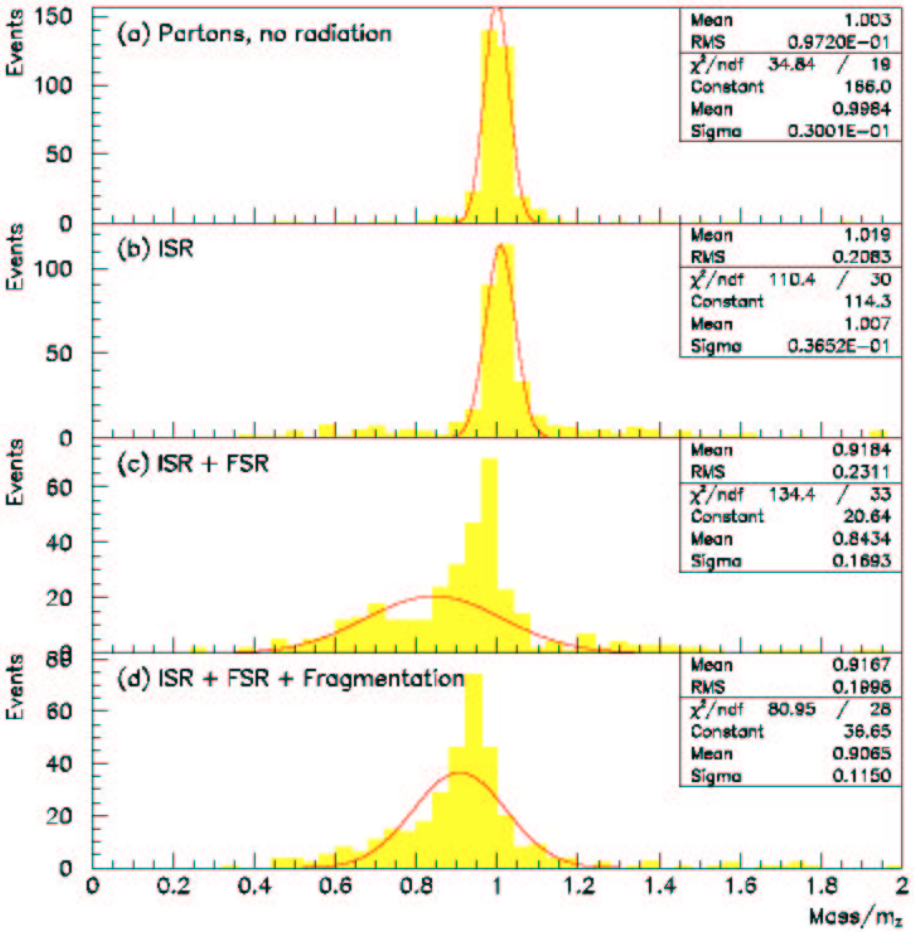


10 TeV jets

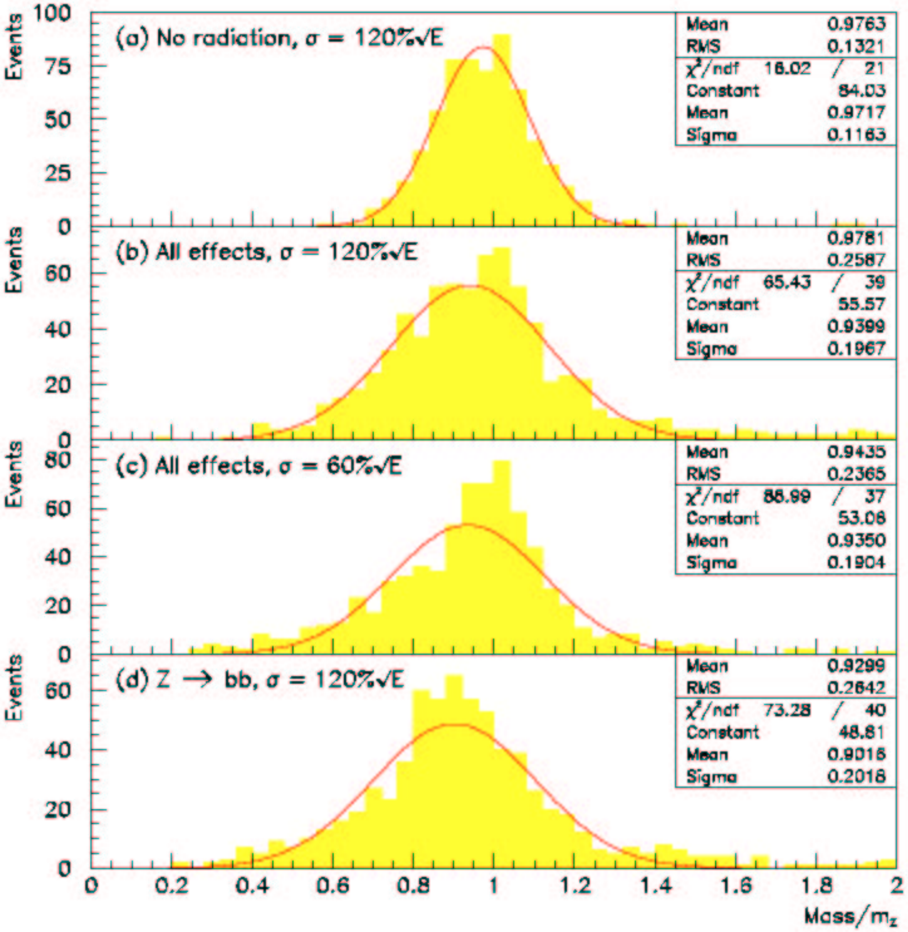
Conclusion → no gain for calorimeters thicker than ~ 10-12 λ

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

Effects of Final State Radiation



No detector simulation

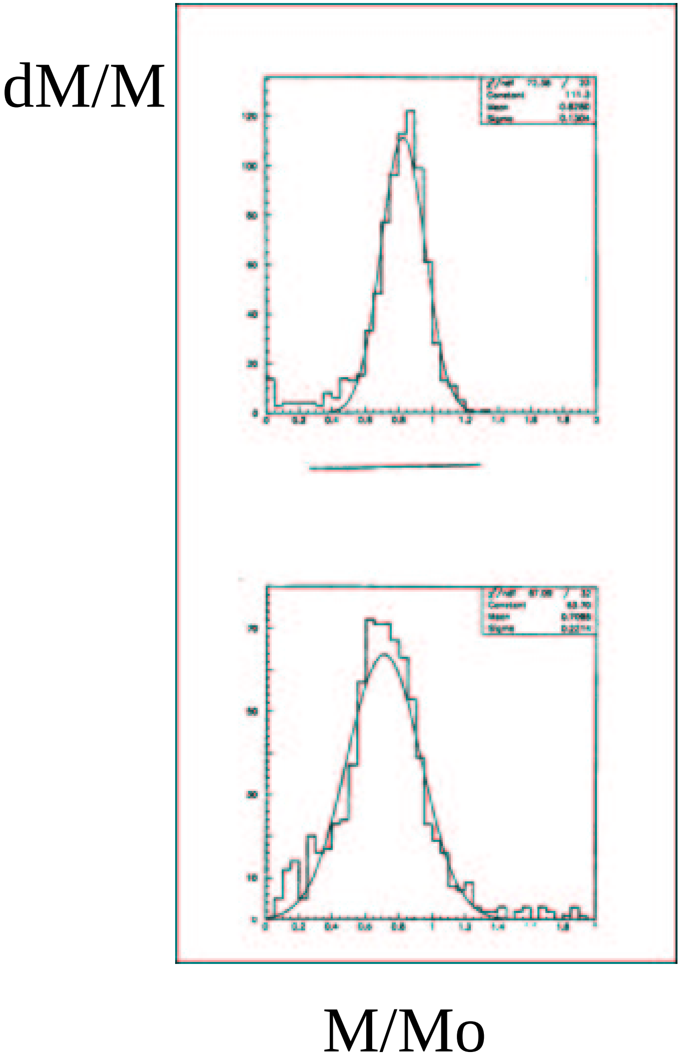


Full detector simulation

Z’s at the LHC in “CMS” detector

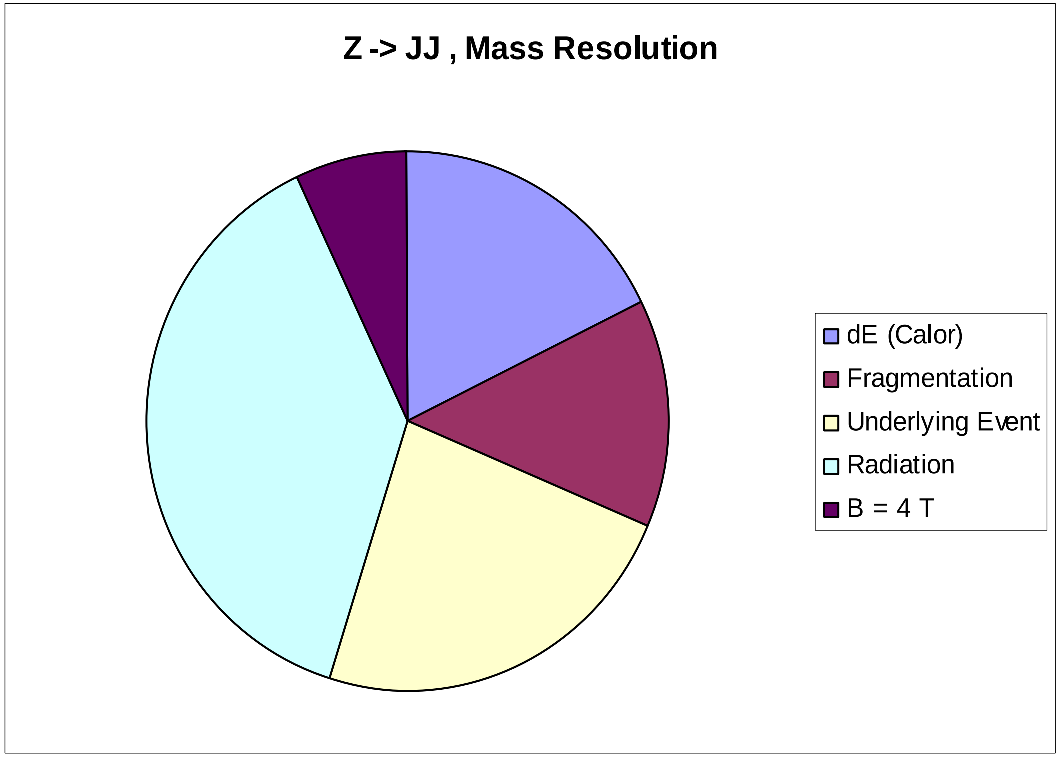
LHC – CMS Study of FSR

- 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.



Hadron Collider- Dijet dM/M

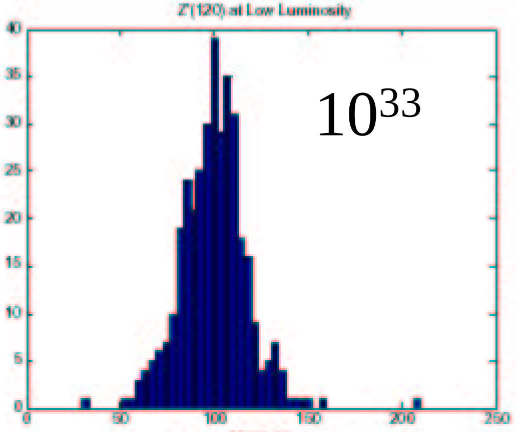
- A series of Monte Carlo studies were done in order to identify the elements contributing to the mass error. Events are low P_T, Z -> JJ. dM/M ~ 13% without FSR.

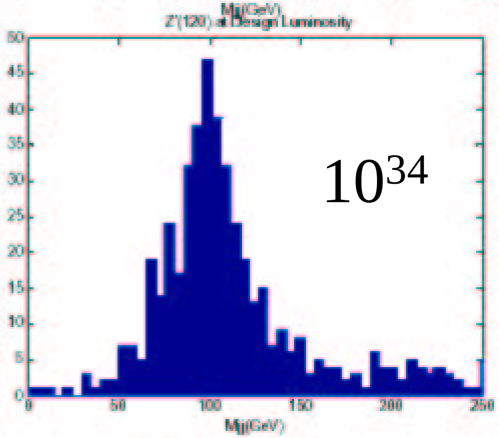


FSR is the biggest effect. The underlying event is the second largest error (if cone R ~ 0.7). Calorimeter resolution is a minor effect.

Effects of Pileup Events

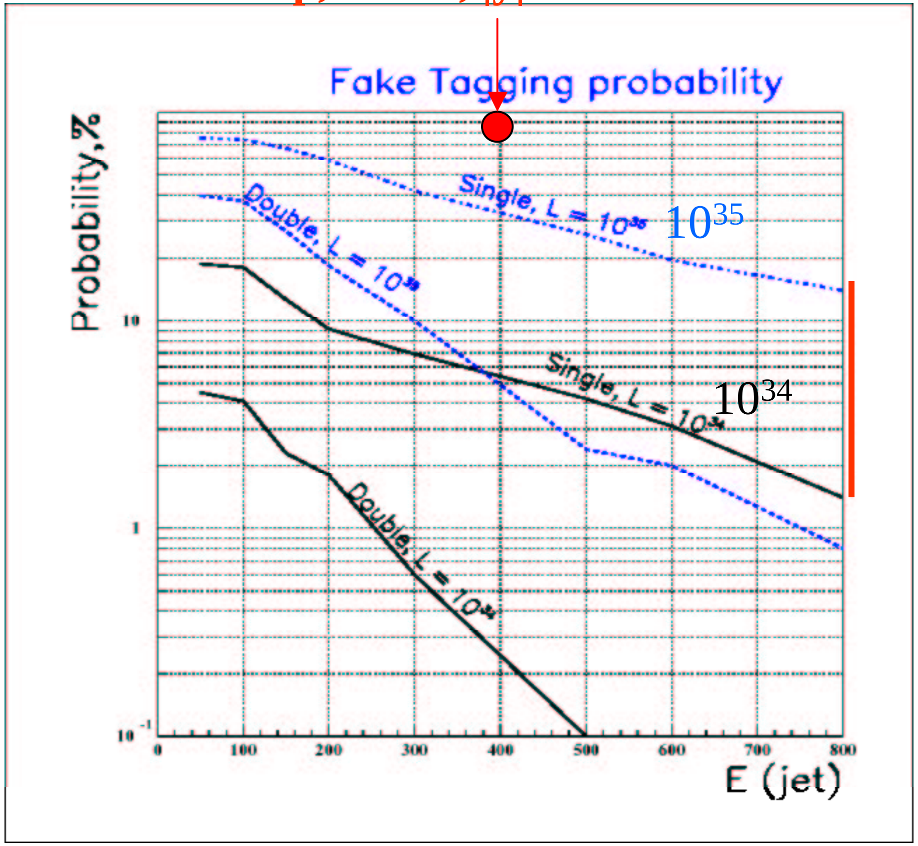
120 GeV Z’

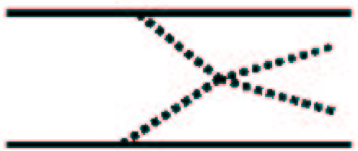




M(GeV)

Pileup, R=0.5, |y|=3



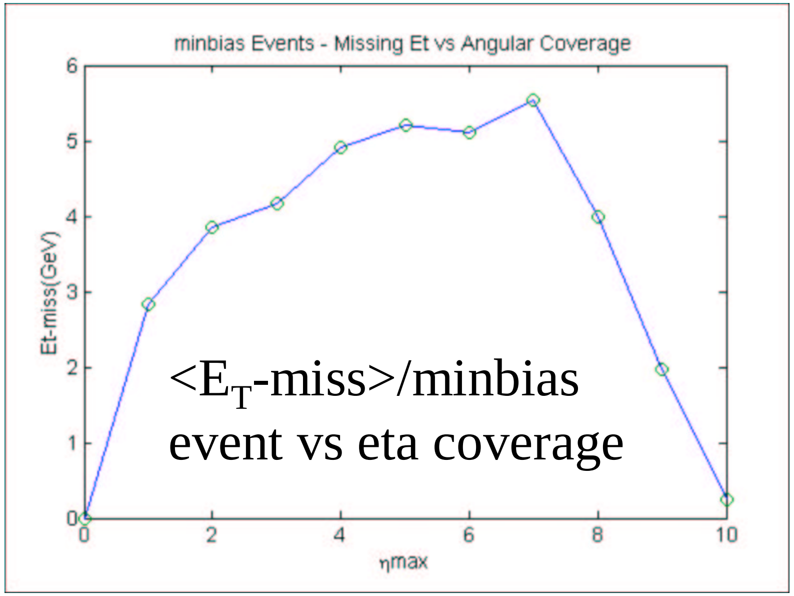


WW fusion → Forward tag jets, E_T~ 40 GeV

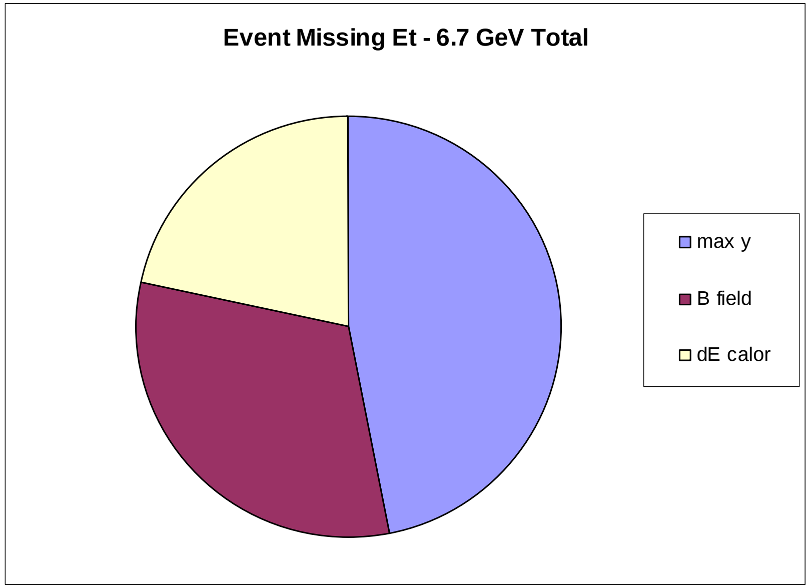
J. Freeman Erice Oct 3, 2003

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.



<E_T-miss>/minbias event vs eta coverage



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)