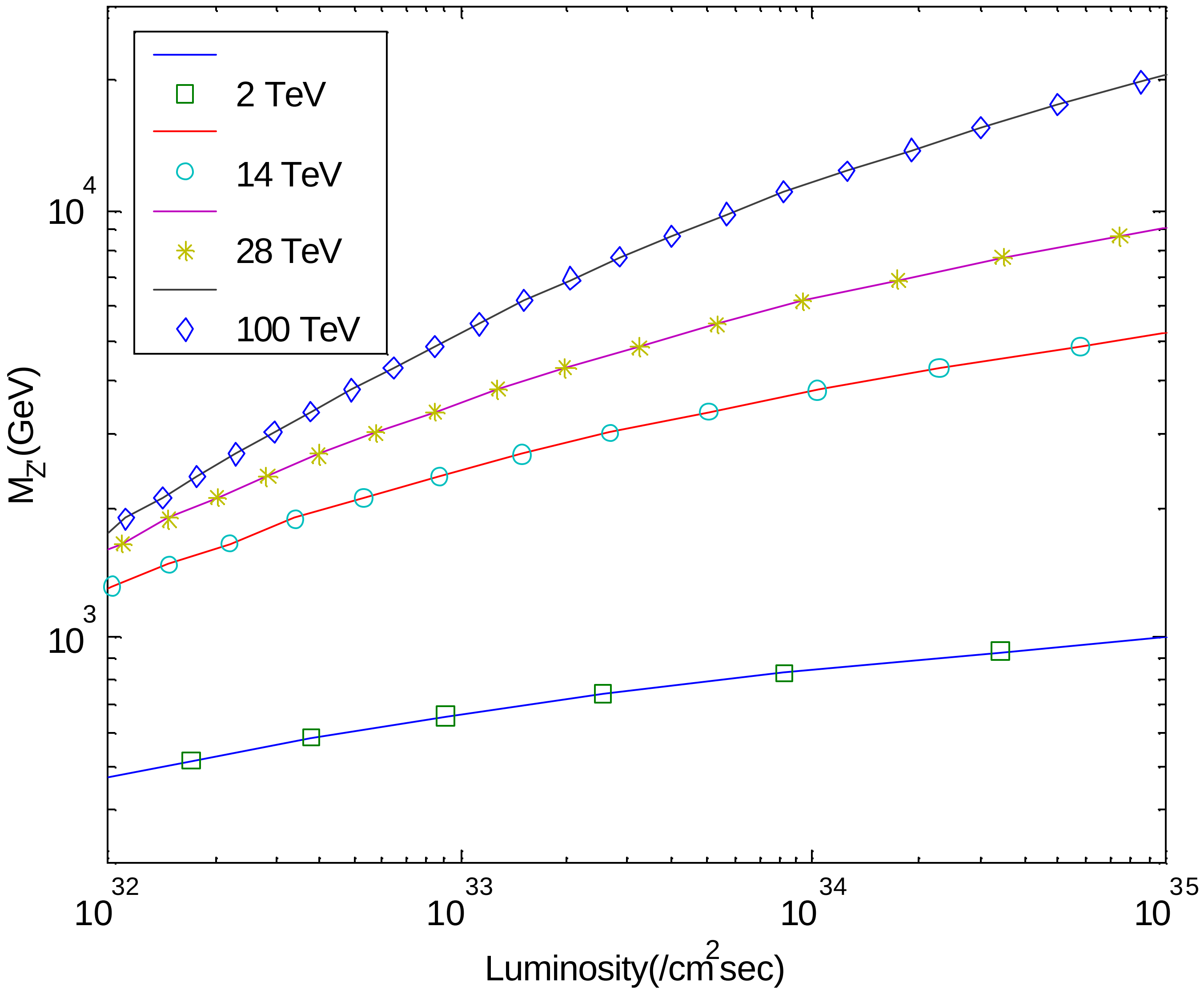
Calorimeters for the SLHC and VLHC

Jim Freeman

Fermilab

Mass Reach vs energy and L

N=100 Events, Z' Coupling



VLHC

LHC

Tevatron

J. Freeman FNAL Oct 17, 2003

SLHC Detector Environment

	LHC	**SLHC**
$\sqrt{s}$	14 TeV	14 TeV
L	$10^{34}\ /(cm^2 \cdot \mathrm{sec})$	$10^{35}\ /(cm^2 \cdot \mathrm{sec})$
$\int Ldt$	$100\ \ fb^{-1}/yr$	$1000\ \ fb^{-1}/yr$
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

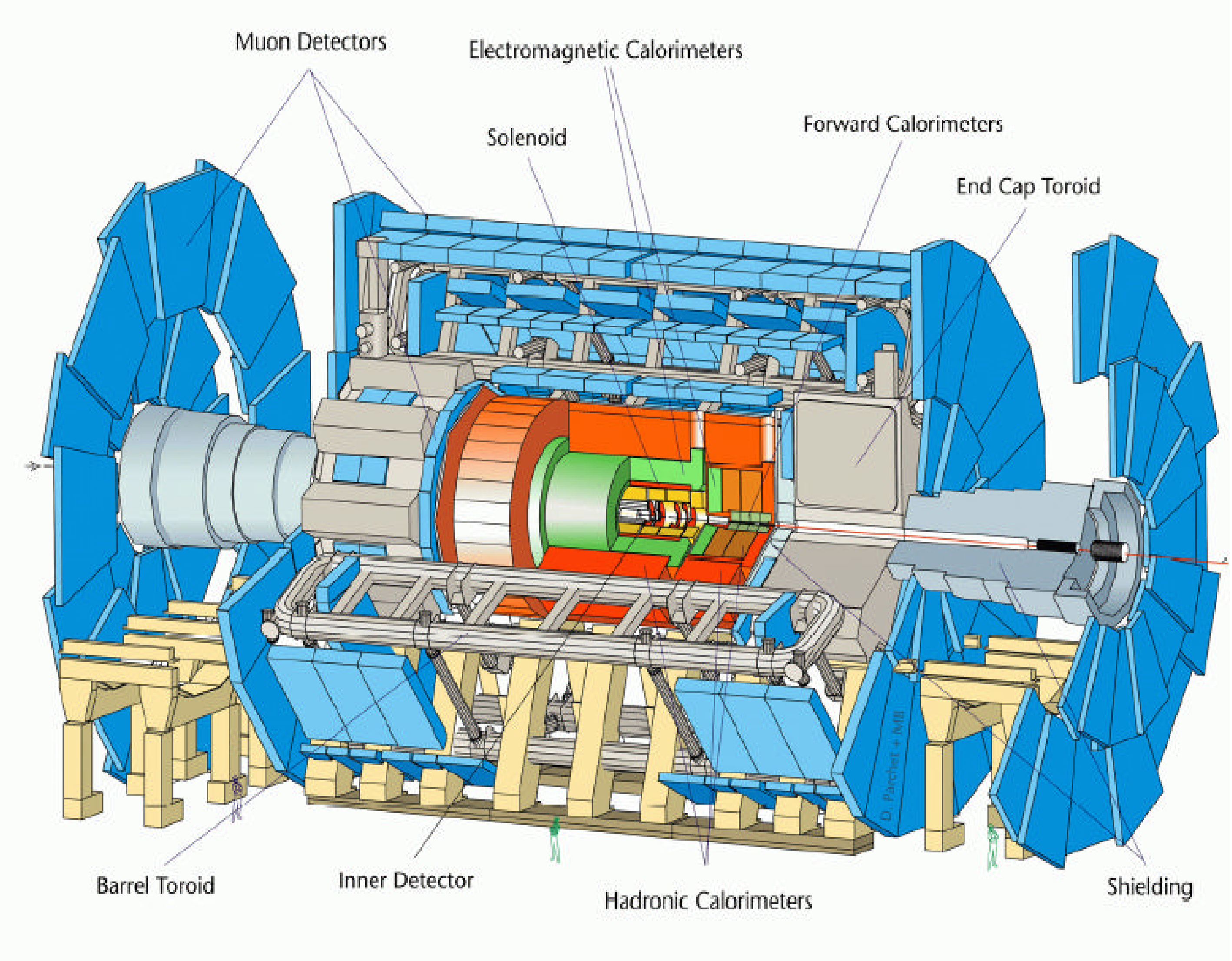
Bunch spacing reduced 2x. Interactions/crossing increased 5 x. Pileup noise increased by 2.2x if crossings are time resolvable.

VLHC Detector Environment

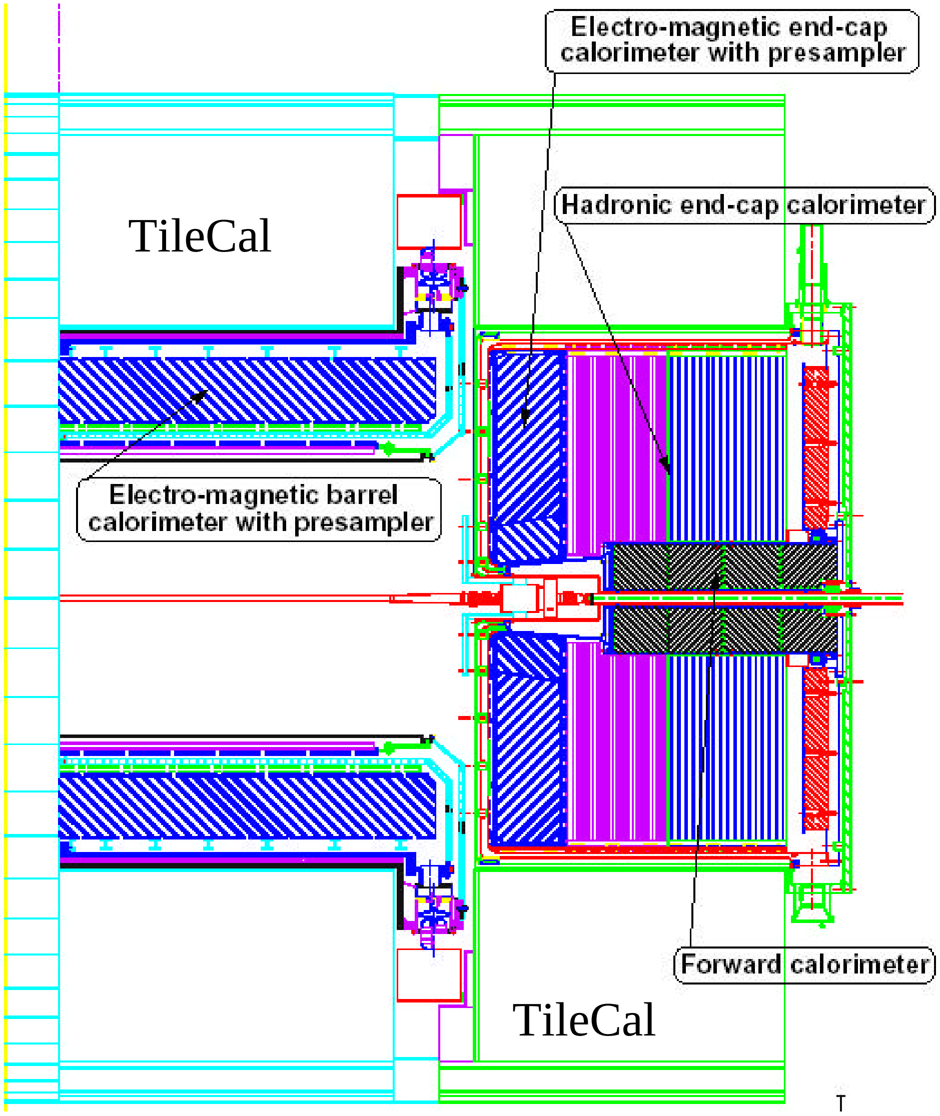
	LHC	**VLHC**
$\sqrt{s}$	14 TeV	100 TeV
L	$10^{34}\ /(cm^2 \cdot \mathrm{sec})$	$10^{34}\ /(cm^2 \cdot \mathrm{sec})$
$\int Ldt$	100 fb^{-1}/yr	100 fb^{-1}/yr
Bunch spacing dt	25 ns	19 ns
N. interactions/x-ing	~ 20	~ 25**
$dN_{ch}/d\eta$ per x-ing	~ 100	~ 250**
Tracker occupancy	1	2.5**
Pile-up noise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

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

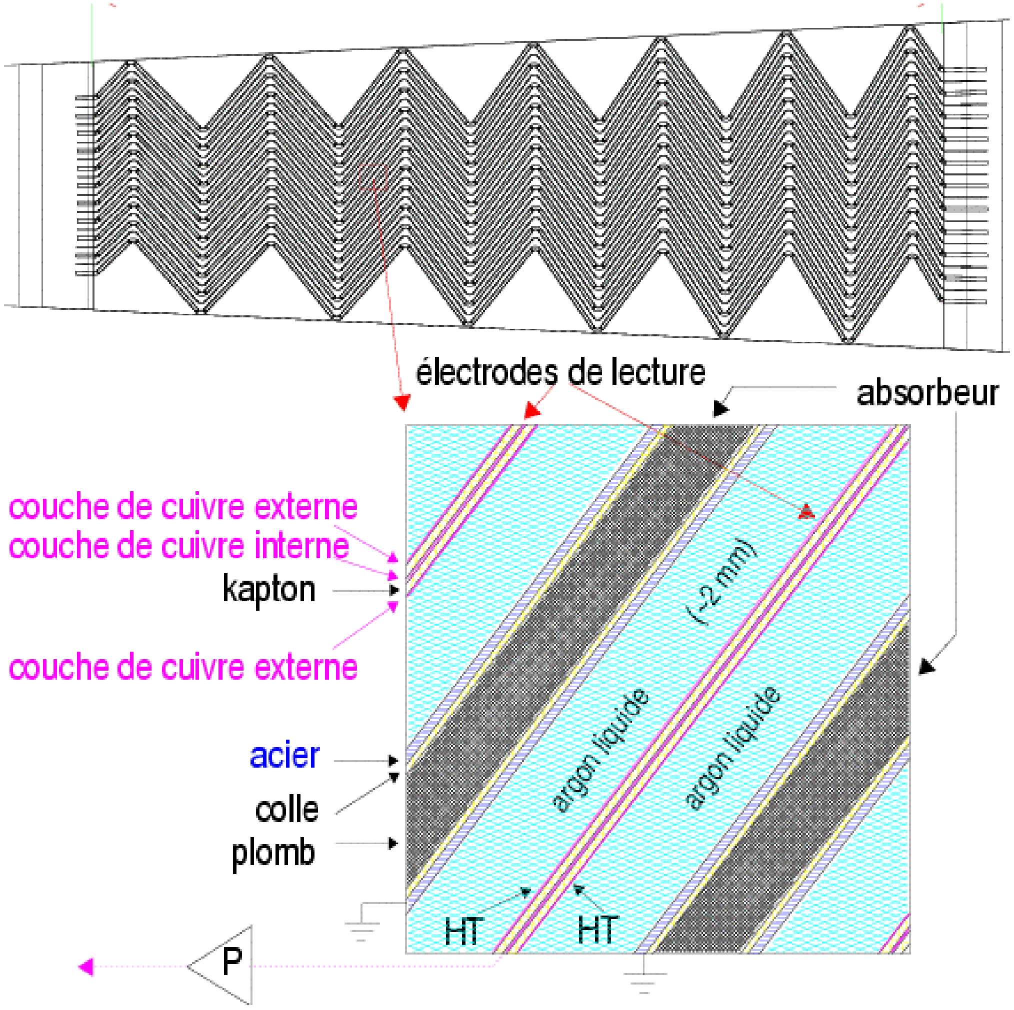
ATLAS Calorimeters



ATLAS Calorimeter

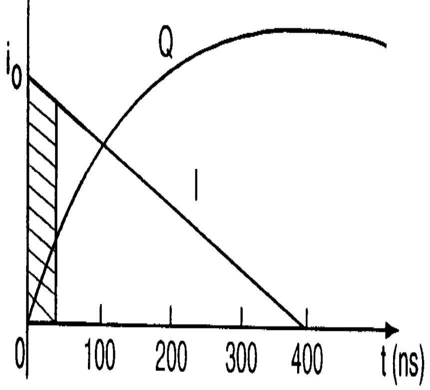


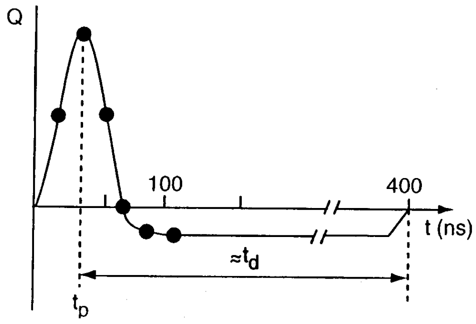
ATLAS LAr : the basic structure



Argon double gap 2x2 mm

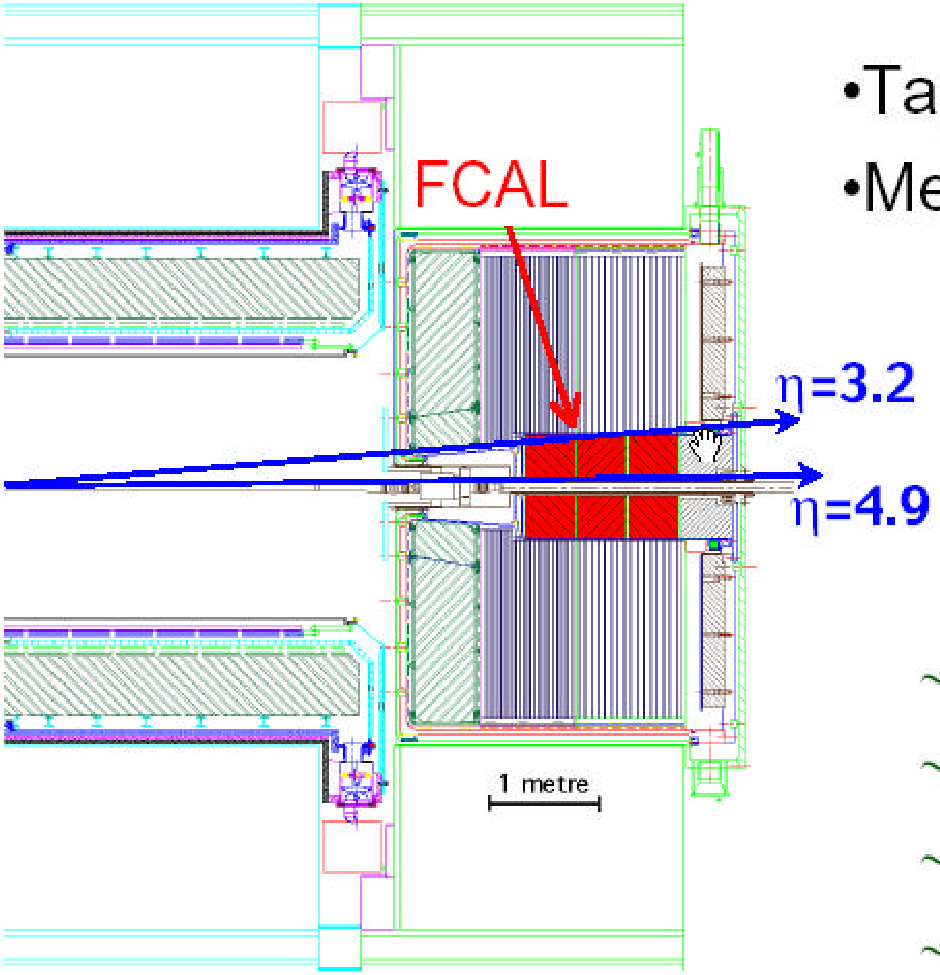
Thickness of absorber plates: 1.1mm for pseudorapidities > 0.8 and 1.5 mm close to the center of the detetctor: total of ~26 X_0





ATLAS FCAL

ATLAS Forward Calorimeter



- Tag forward jets
- Measure missing E_T

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

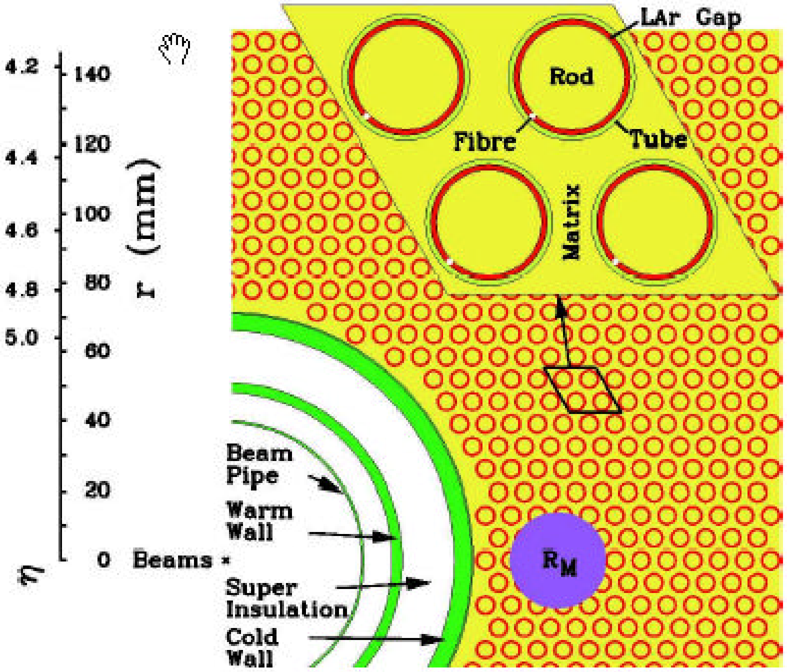
~ 40Mhz

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

~ 10^6 Gy/year

~ 100 Watts absorbed

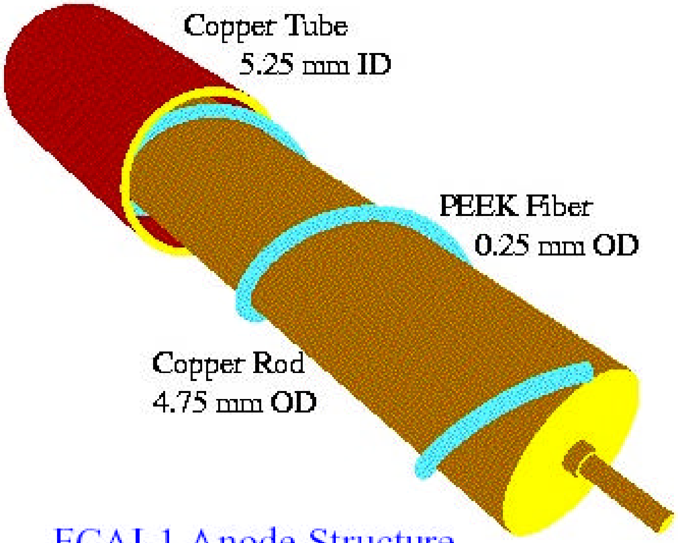
ATLAS FCAL



FCAL End View

Anode Spacing (FCAL1/2/3)

- 7.5 / 8.18 / 9.00 mm

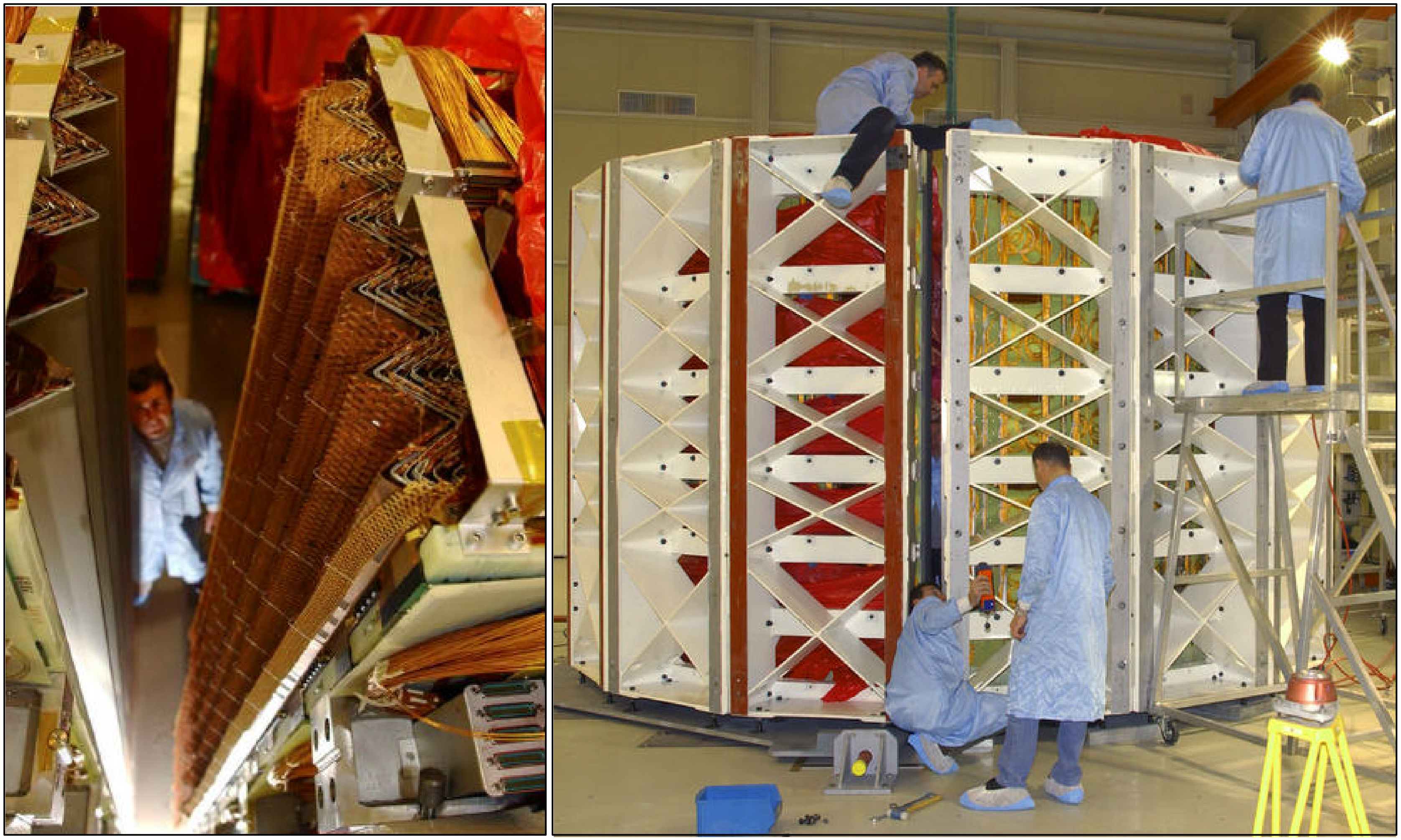


FCAL1 Anode Structure

Liquid Argon gap

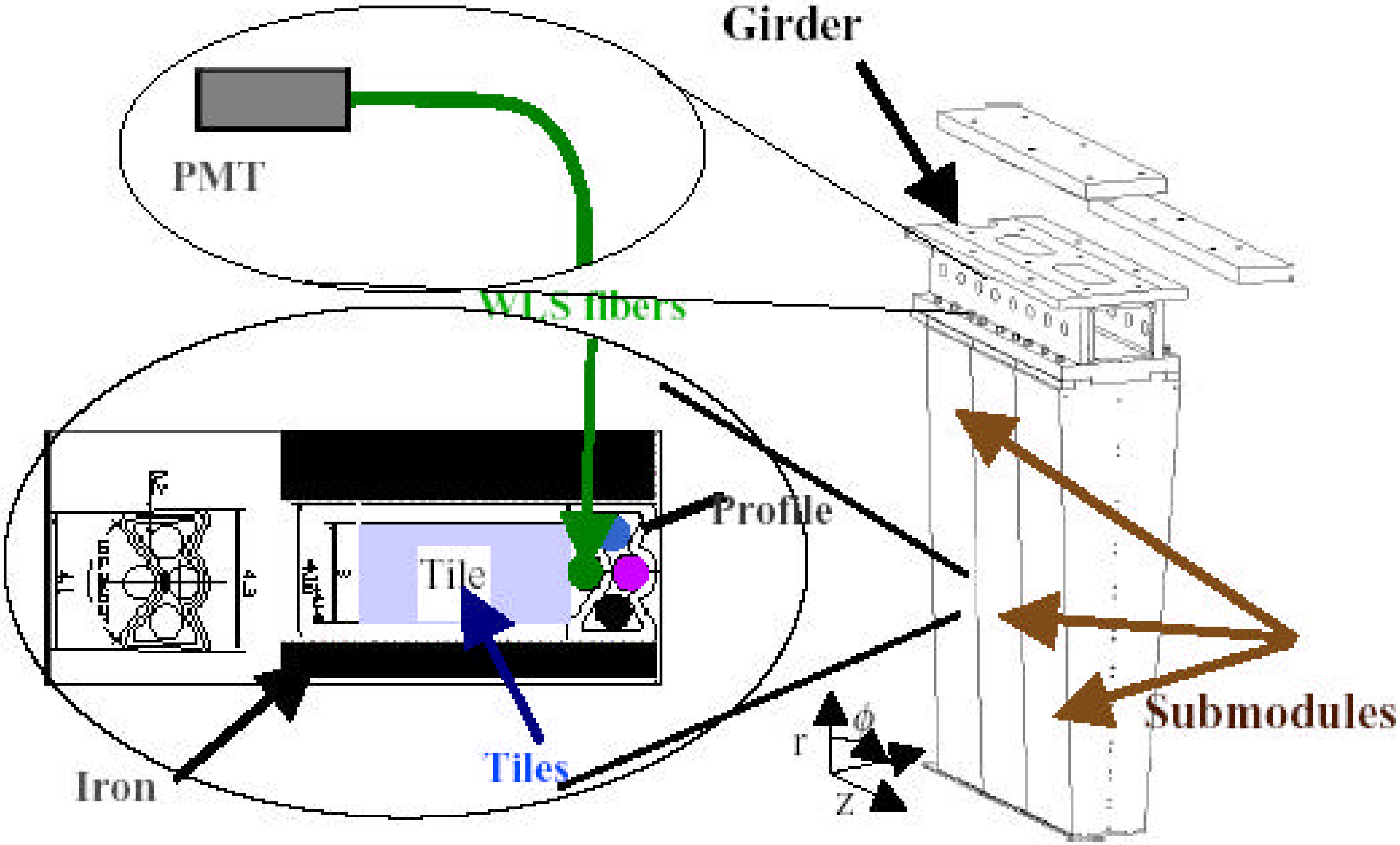
- 250 / 375 / 500 μm

Atlas LAr Calorimeter



Closing of 1st wheel

ATLAS Tilecal



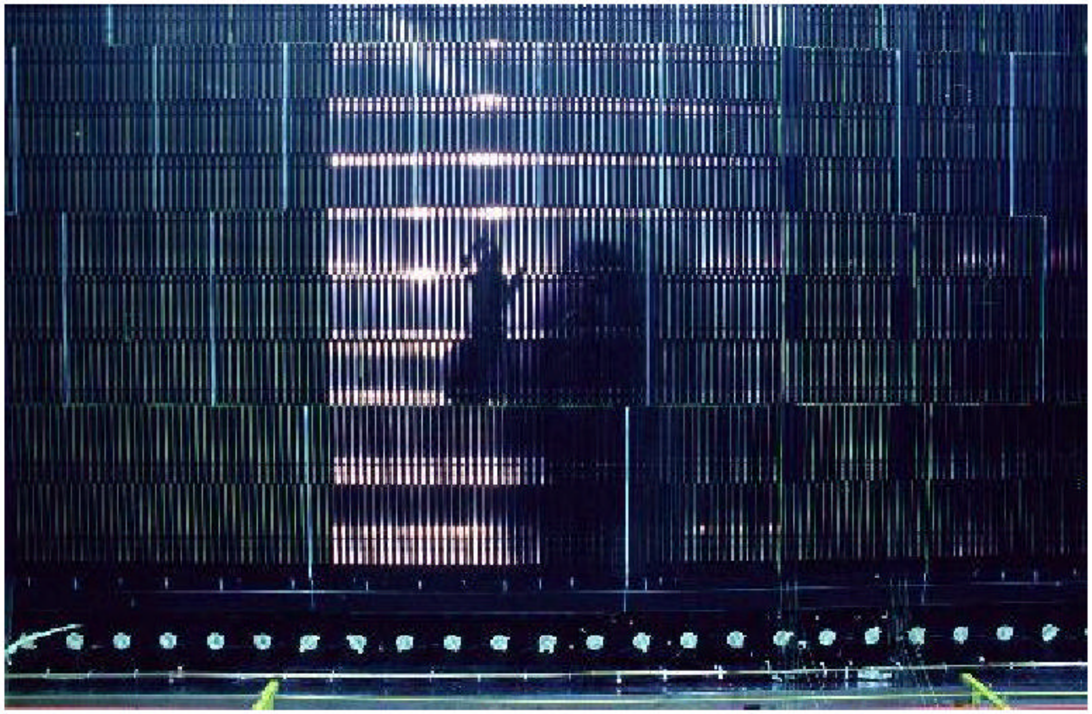
Longitudinal tile configuration ⇒ good hermeticity and "easy" construction

Fe/Scint/WLS fiber

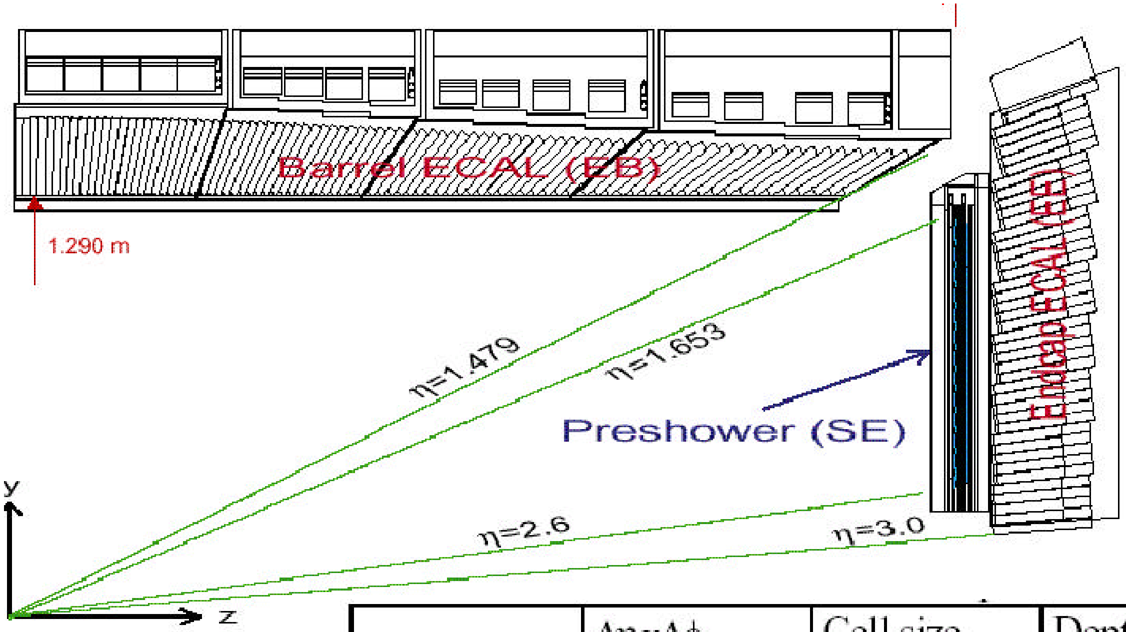
4:1 Fe:Scint

ATLAS TILECAL

36 modules of +/- endcaps, central wheel



CMS calo structure

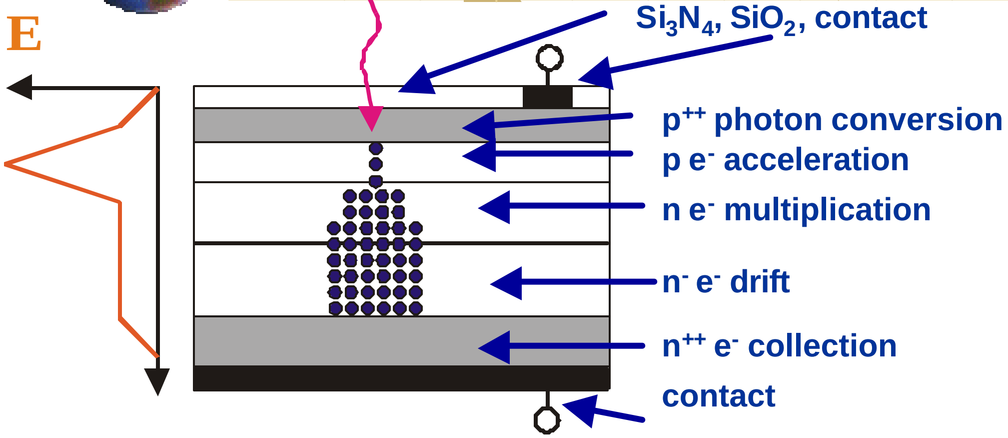


- PWO Light Yield is rather low: ~10 pe/MeV so photon sensors with some amplification are needed (Avalanche PhotoDiodes in the barrel, VacuumPhotoTriodes in the Endcap)

⇒Low S/N ratio and complex electronic

	$\Delta\eta \times \Delta\phi$	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

CMS ECAL Light readout



Si_3N_4, SiO_2, contact

p^{++} photon conversion

p e^- acceleration

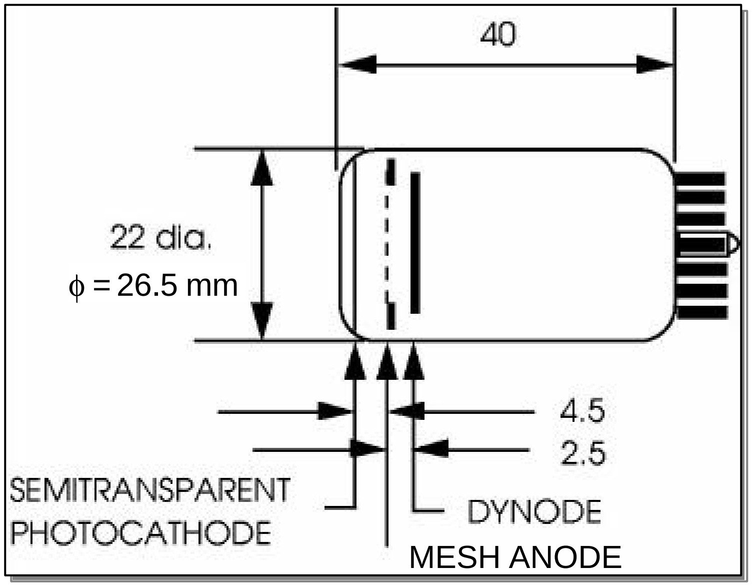
n e^- multiplication

n^- e^- drift

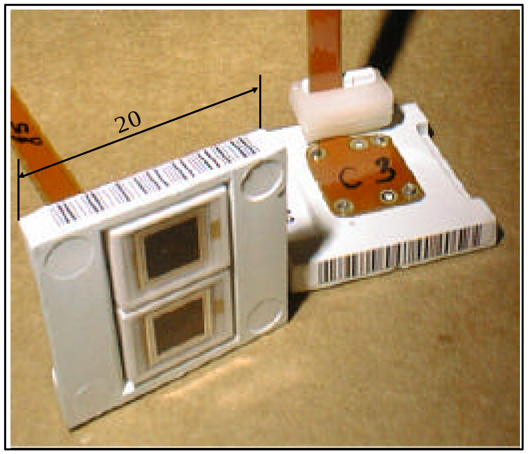
n^{++} e^- collection

contact

Internal gain=50 for V=380 V



Single stage photomultiplier tube



Two APDs per capsule

ENDCAP:
25% delivered

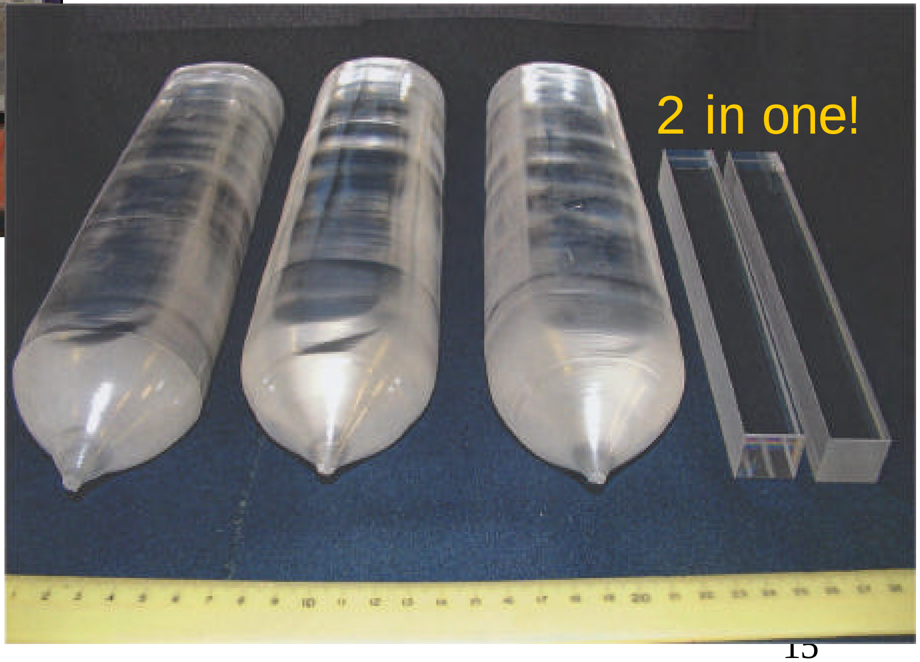
Barrell: 50% delivered

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

CMS ECAL

~20000 barrel crystals accepted

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

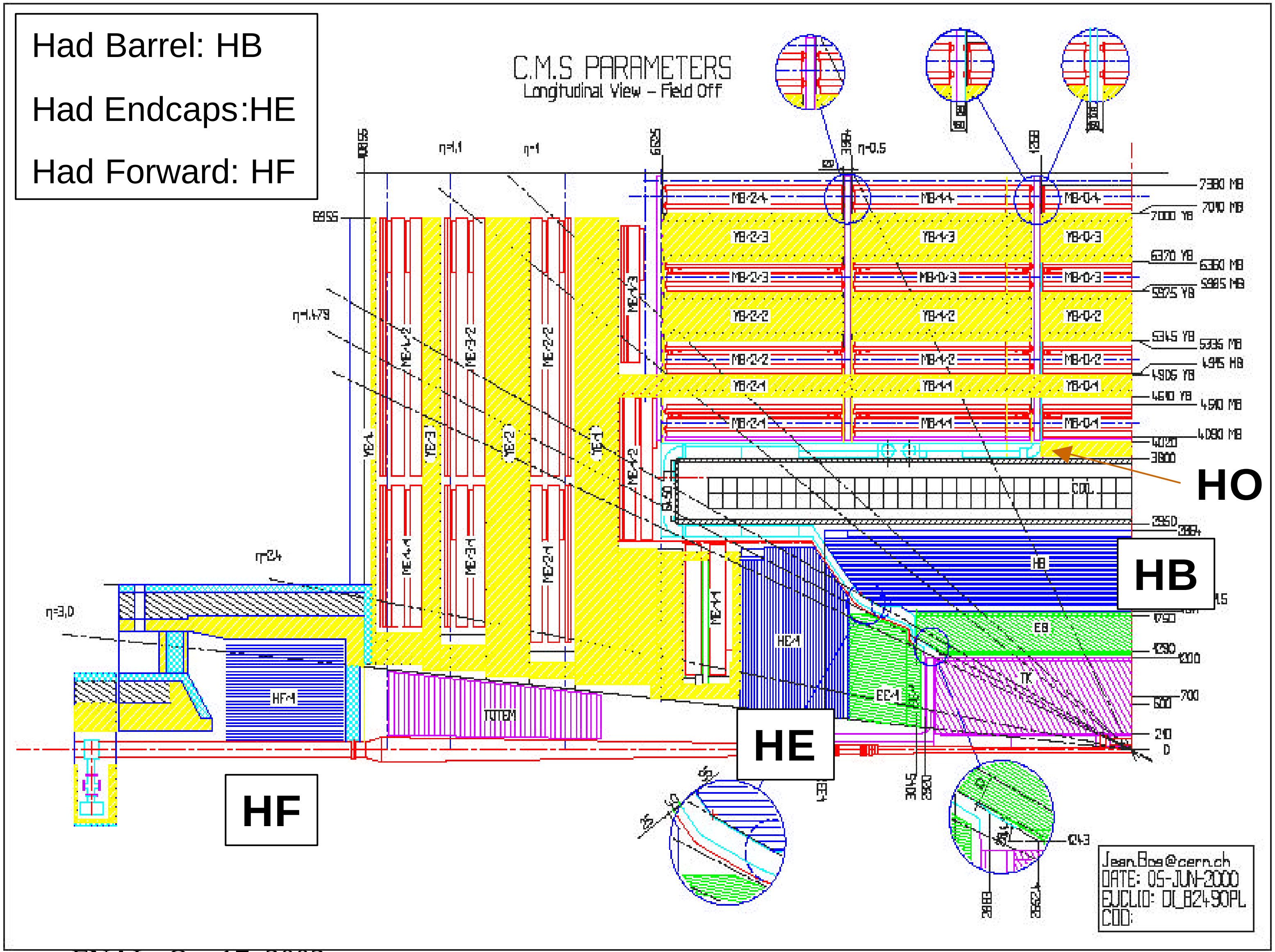


CMS HCALs

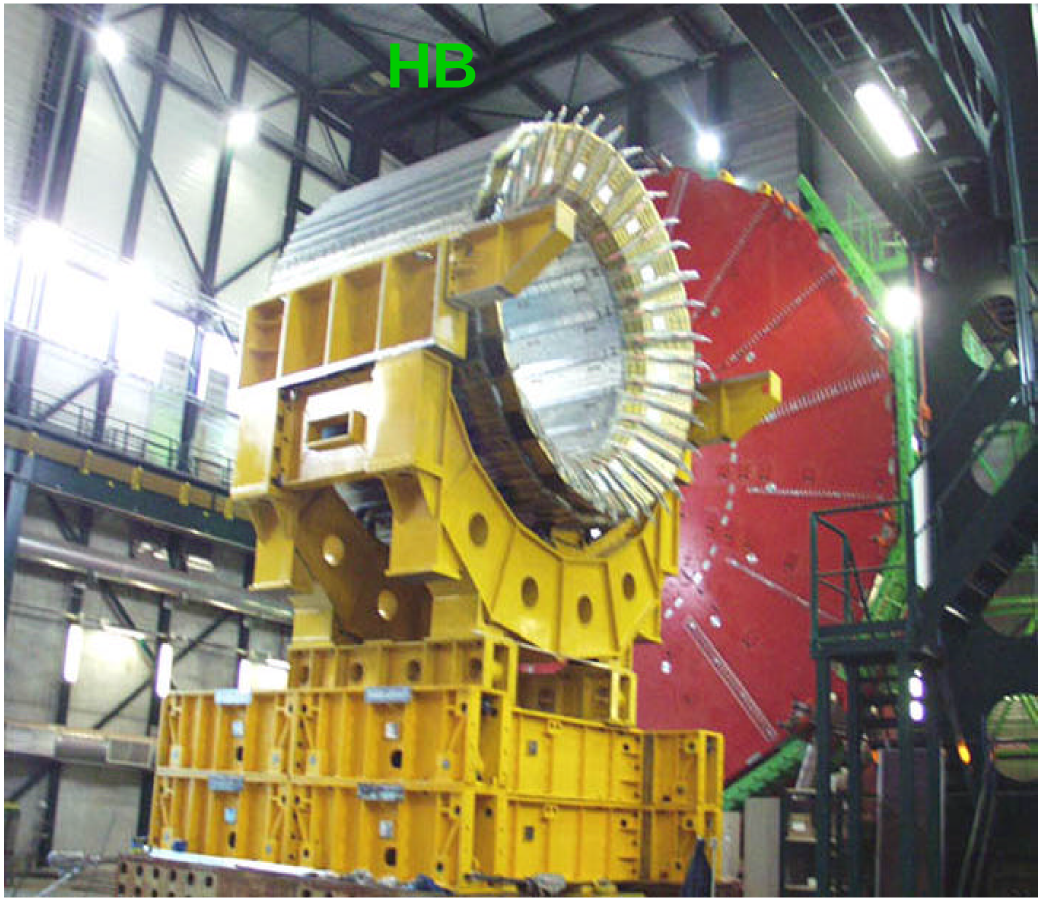
Had Barrel: HB

Had Endcaps:HE

Had Forward: HF

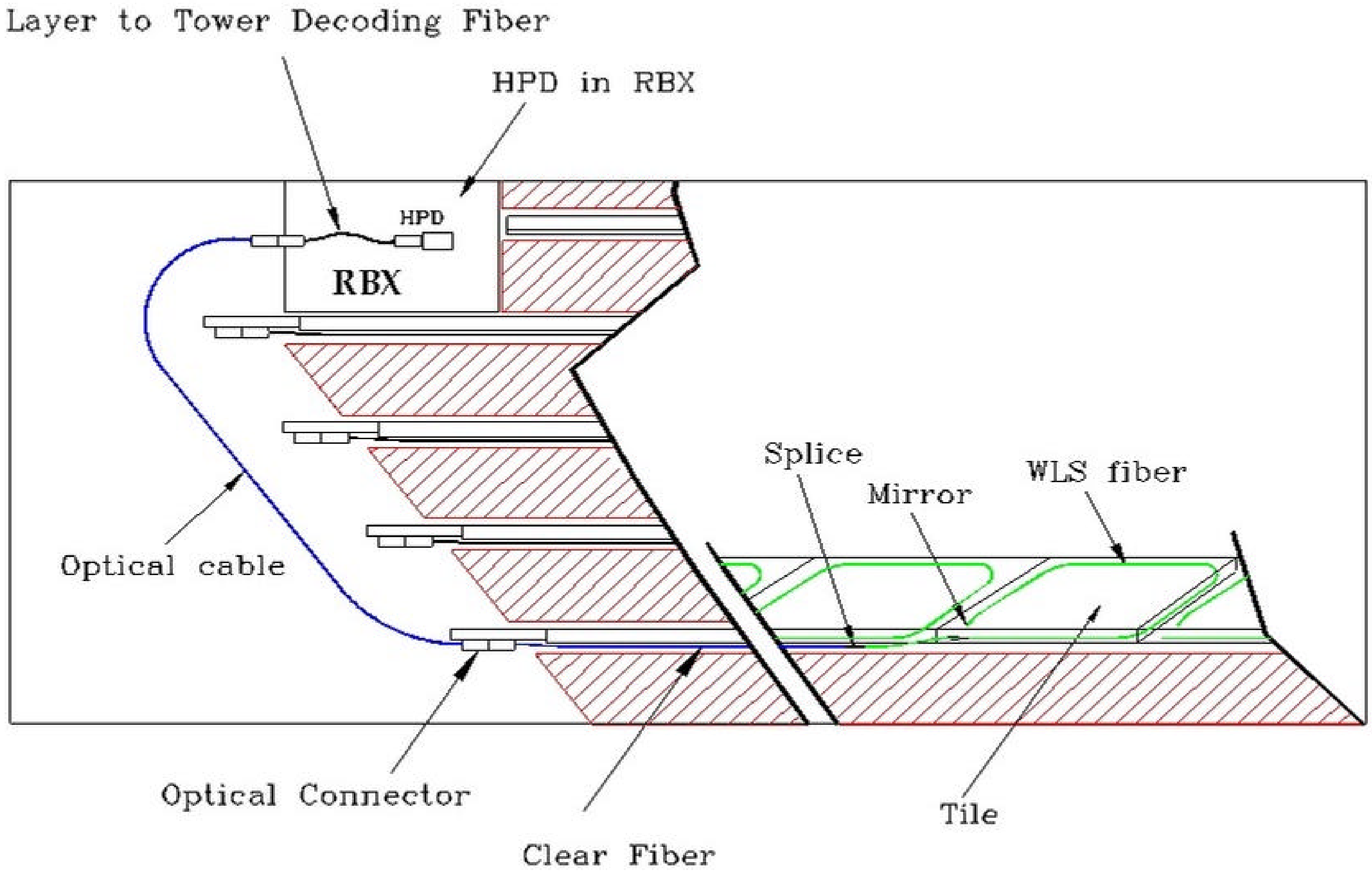


HCAL : HE and HB



Optical Design for CMS HCALs

Common Technology for HB, HE, HO



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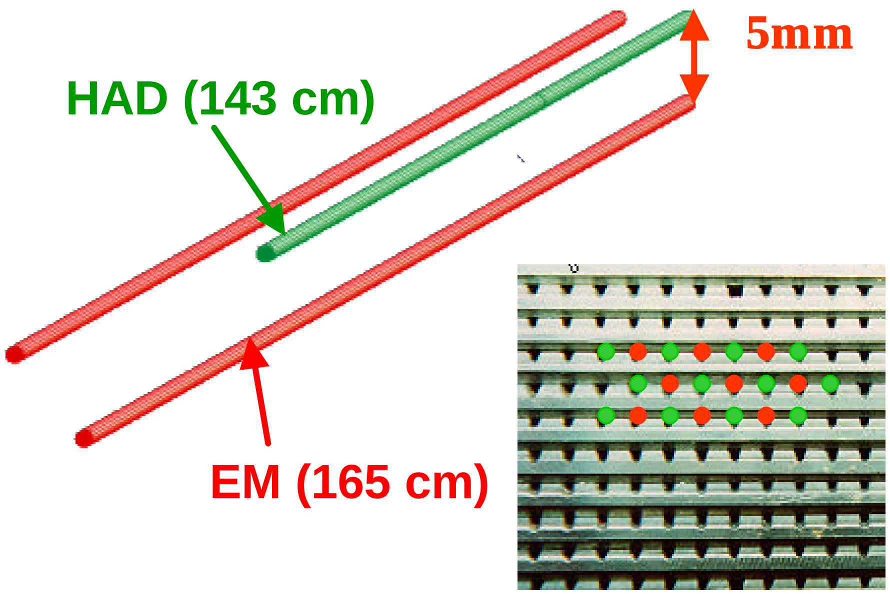
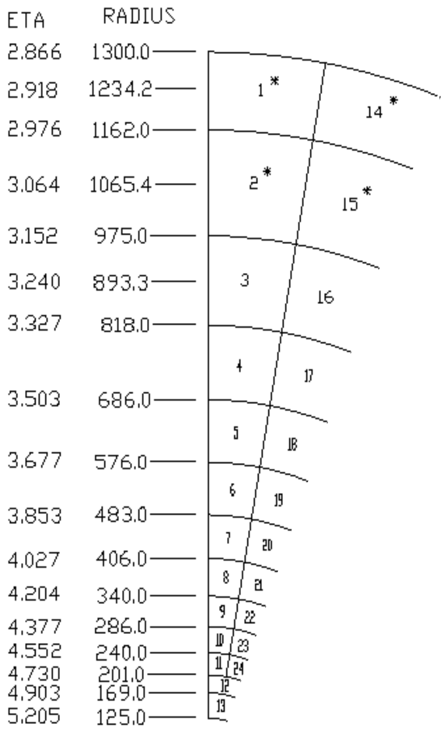
HF detector



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.



ETA	RADIUS
2.866	1300.0
2.918	1234.2
2.976	1162.0
3.064	1065.4
3.152	975.0
3.240	893.3
3.327	818.0
3.503	686.0
3.677	576.0
3.853	483.0
4.027	406.0
4.204	340.0
4.377	286.0
4.552	240.0
4.730	201.0
4.903	169.0
5.205	125.0

Iron calorimeter

Covers $5 > \eta > 3$

Total of 1728 towers, i.e.

2 x 432 towers for EM and HAD

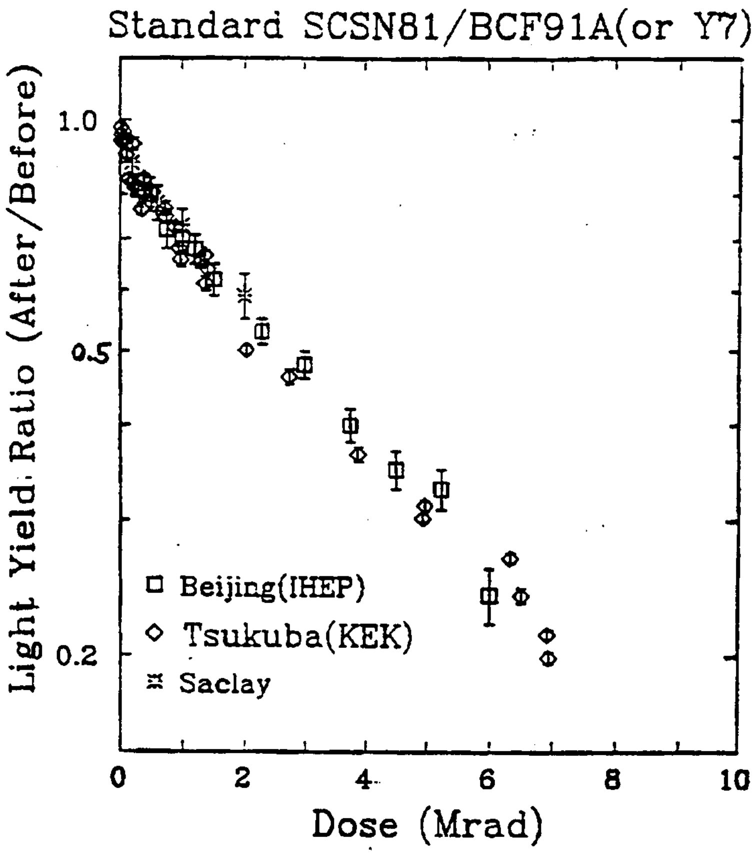
η x ϕ segmentation (0.175 x 0.175)

HF Fiber stuffing at CERN

Issues for SLHC

- Radiation Damage
- Rate Effects
- Bunch ID determination
- Activation/access

Scintillator - Dose/Damage

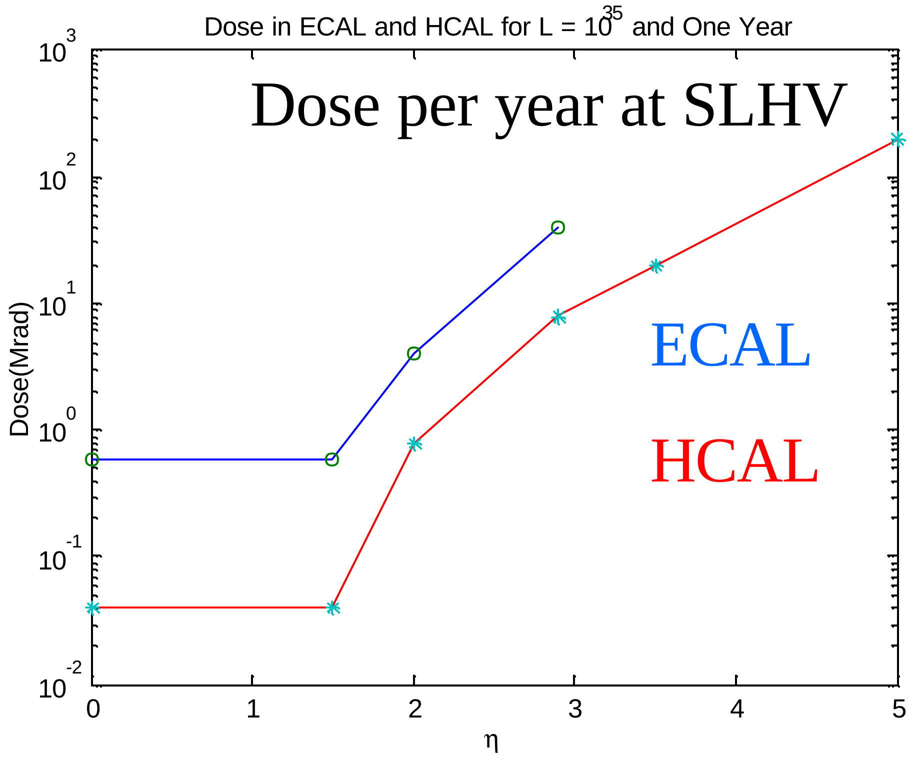


Scintillator under irradiation forms
Color centers which reduce the
Collected light output (transmission loss).

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

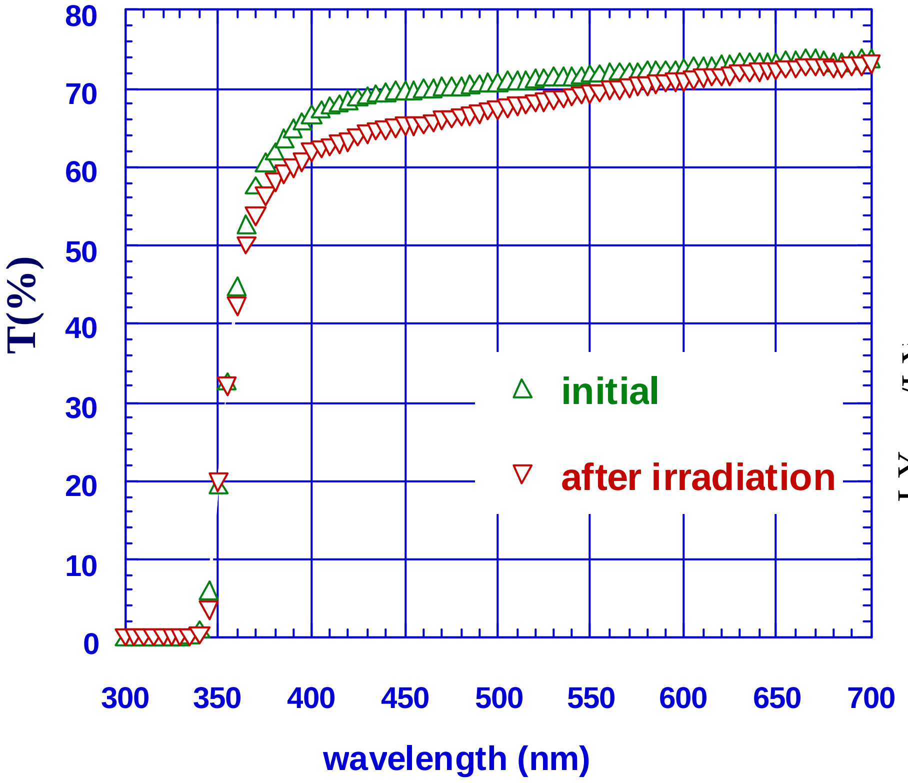
Current operational limit ~ 5 Mrad

Radiation damage to scintillators



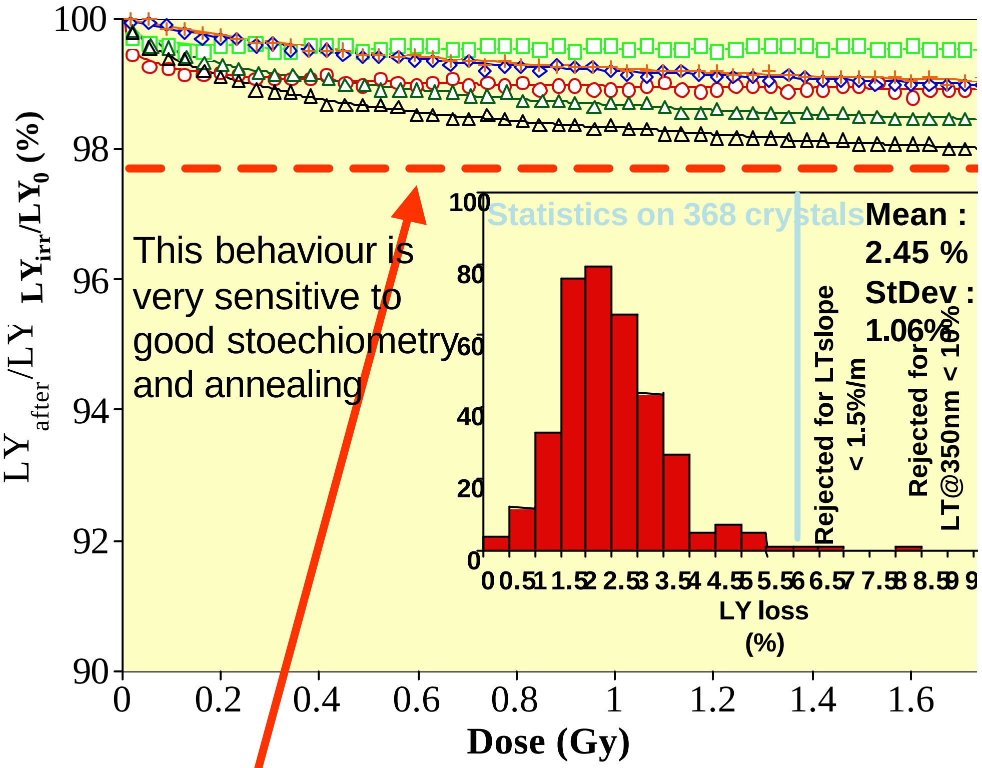
Barrel doses are not a problem. For the endcaps a technology change may be needed for 2 < |y| < 3 for the CMS HCAL.

CMS ECAL rad dam



Front irrad., 1.5Gy, 0.15Gy/h

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



Mean :
2.45 %
StDev :
1.06%

This behaviour is very sensitive to good stoechiometry and annealing

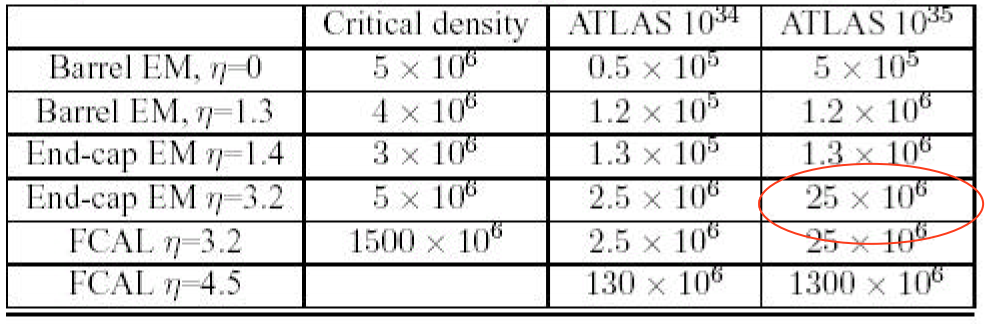
1) Scintillation mechanism not affected but Transparency loss

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

SLHC: ATLAS

- 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 $5\ 10^6$ GeV$\text{cm}^{-2}\text{s}^{-1}$

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).

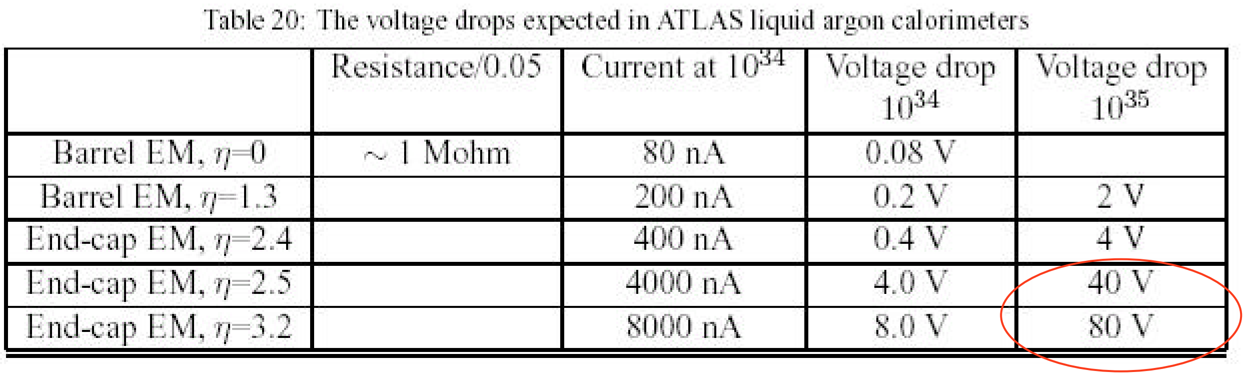


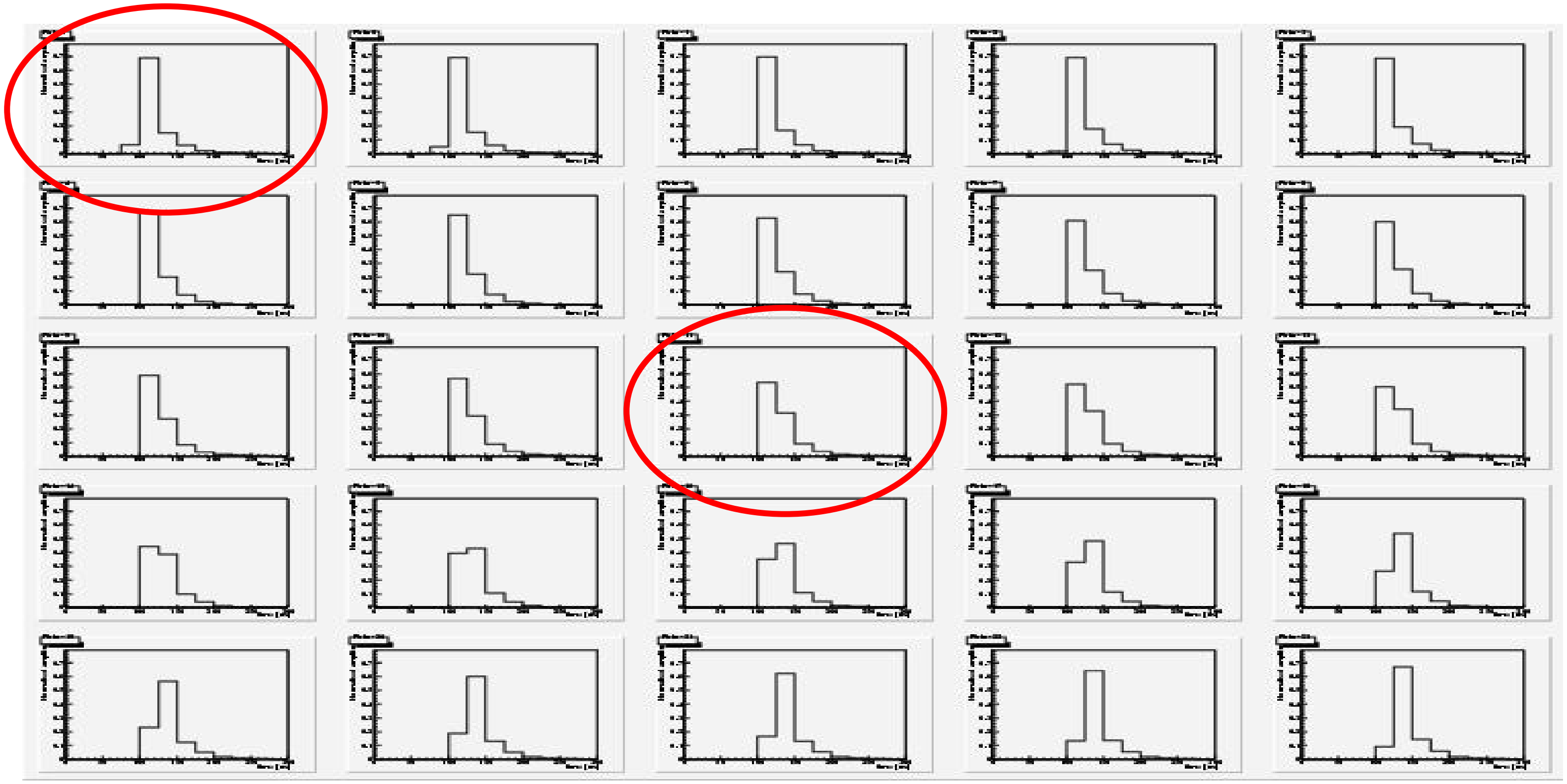
Table 20: The voltage drops expected in ATLAS liquid argon calorimeters

	Resistance/0.05	Current at 10^{34}	Voltage drop 10^{34}	Voltage drop 10^{35}
Barrel EM, η=0	$\sim$ 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…

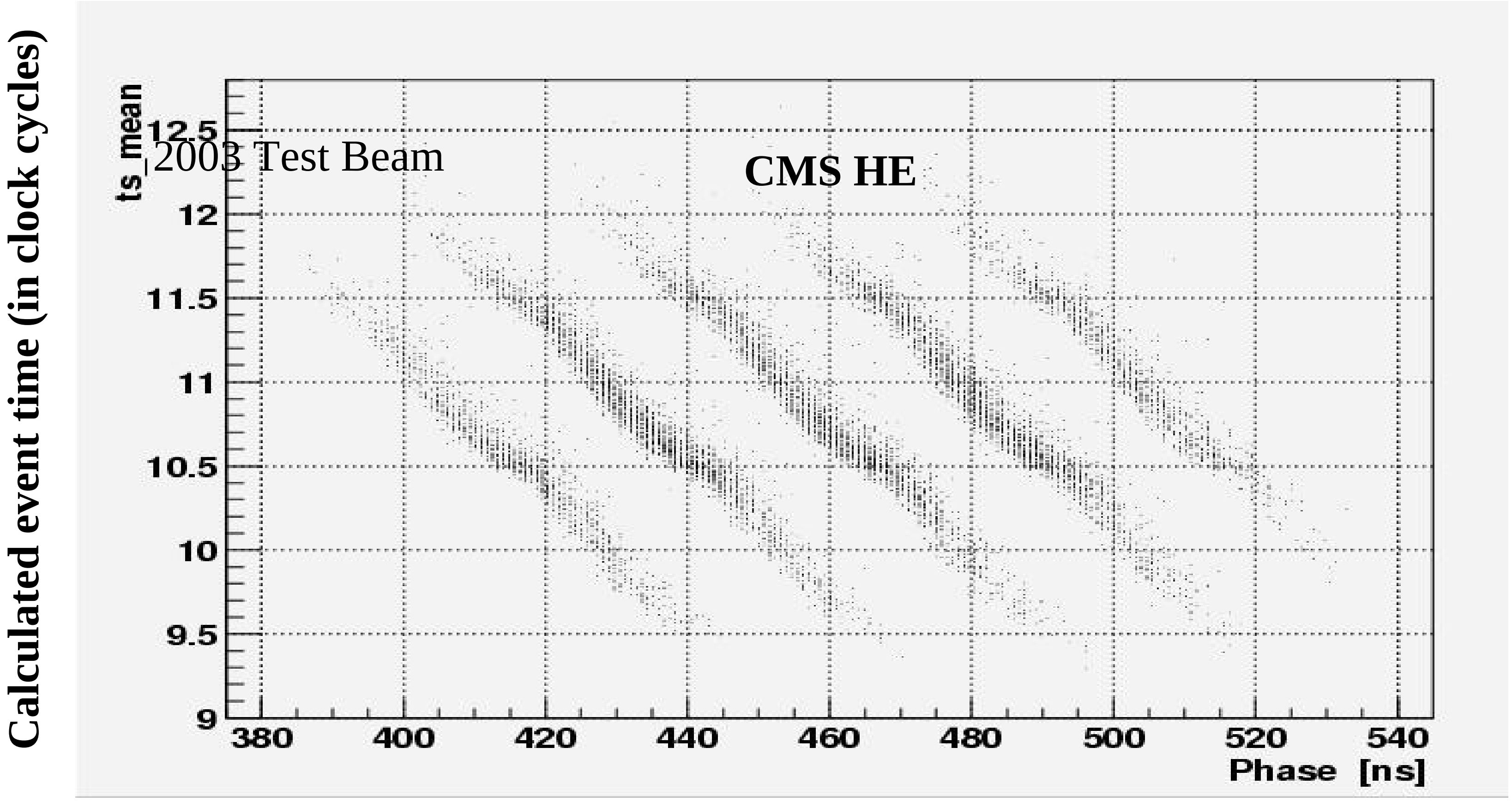
Bunch ID: CMS HB Pulse Shape

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

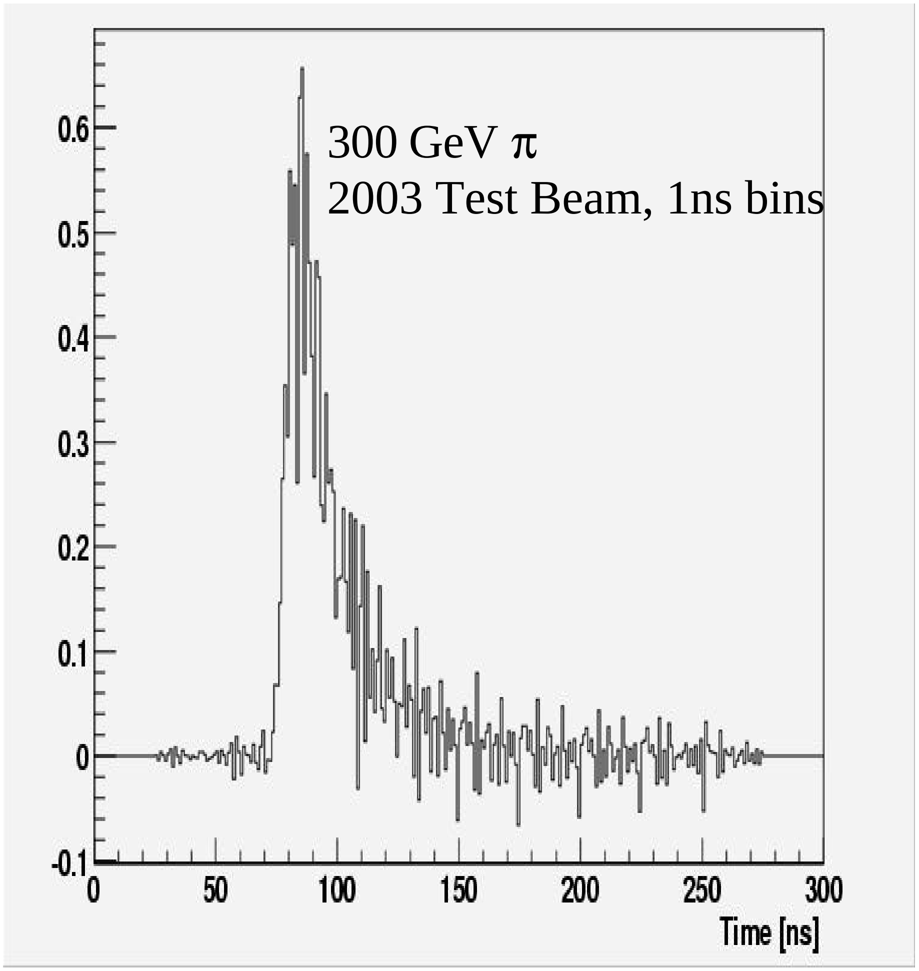
Timing using calorimeter pulse shape



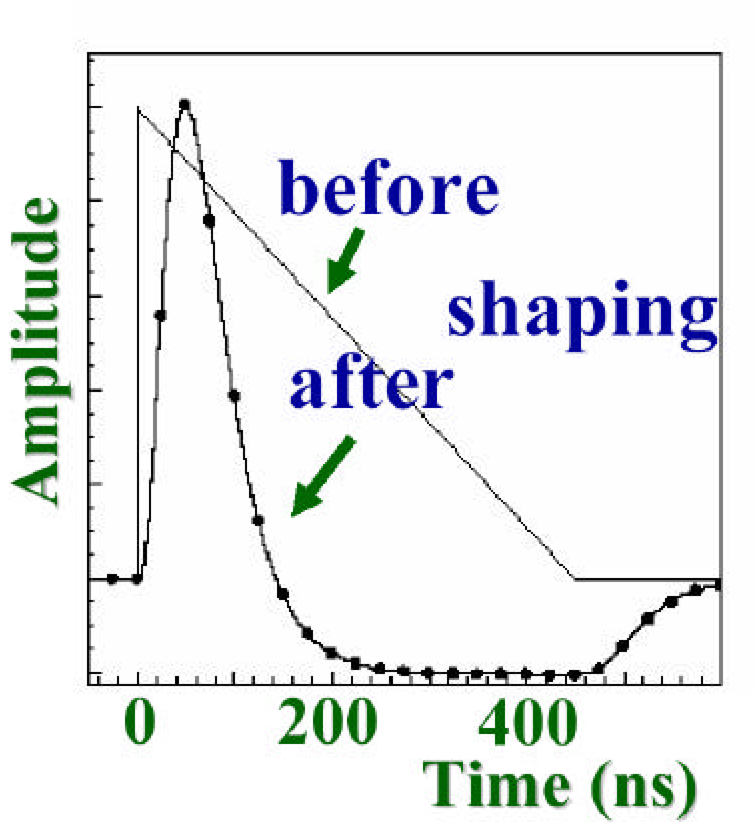
Calculated event time (vertical scale) vs actual event time. CMS HE, 100GeV pions. Also works for lAr. DO timing resolution 4ns/E (in GeV). Watch pile-up though. The faster the calorimeter, the less important pile-up will be.

What about ATLAS?

CMS HE Calorimeter

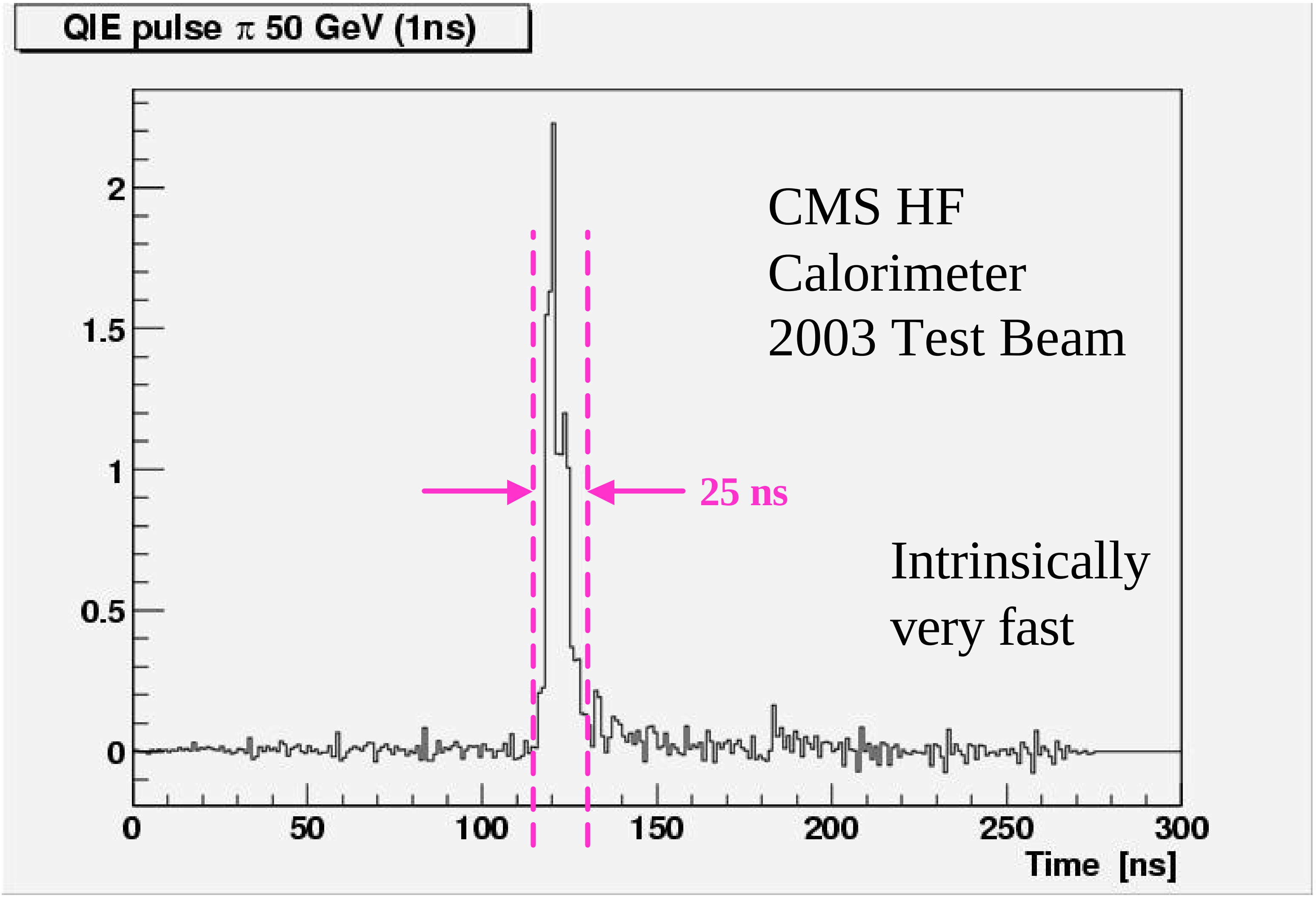


Atlas lAr EM Calorimeter



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

HF Cerenkov Calorimeter Pulse Shape



CMS HF
Calorimeter
2003 Test Beam

Intrinsically
very fast

Activation and Radiation Exposure Limits

Annual exposure from natural radioactivity ~1 mSv

CERN annual limit for radiation workers: 15 mSv

BUT

EU regulations likely to come down

Need also (safety) margin in design wrt reality

⇓

Use a limit of 5 mSv per year per person for *design* of LHC, experiments and all access scenarios

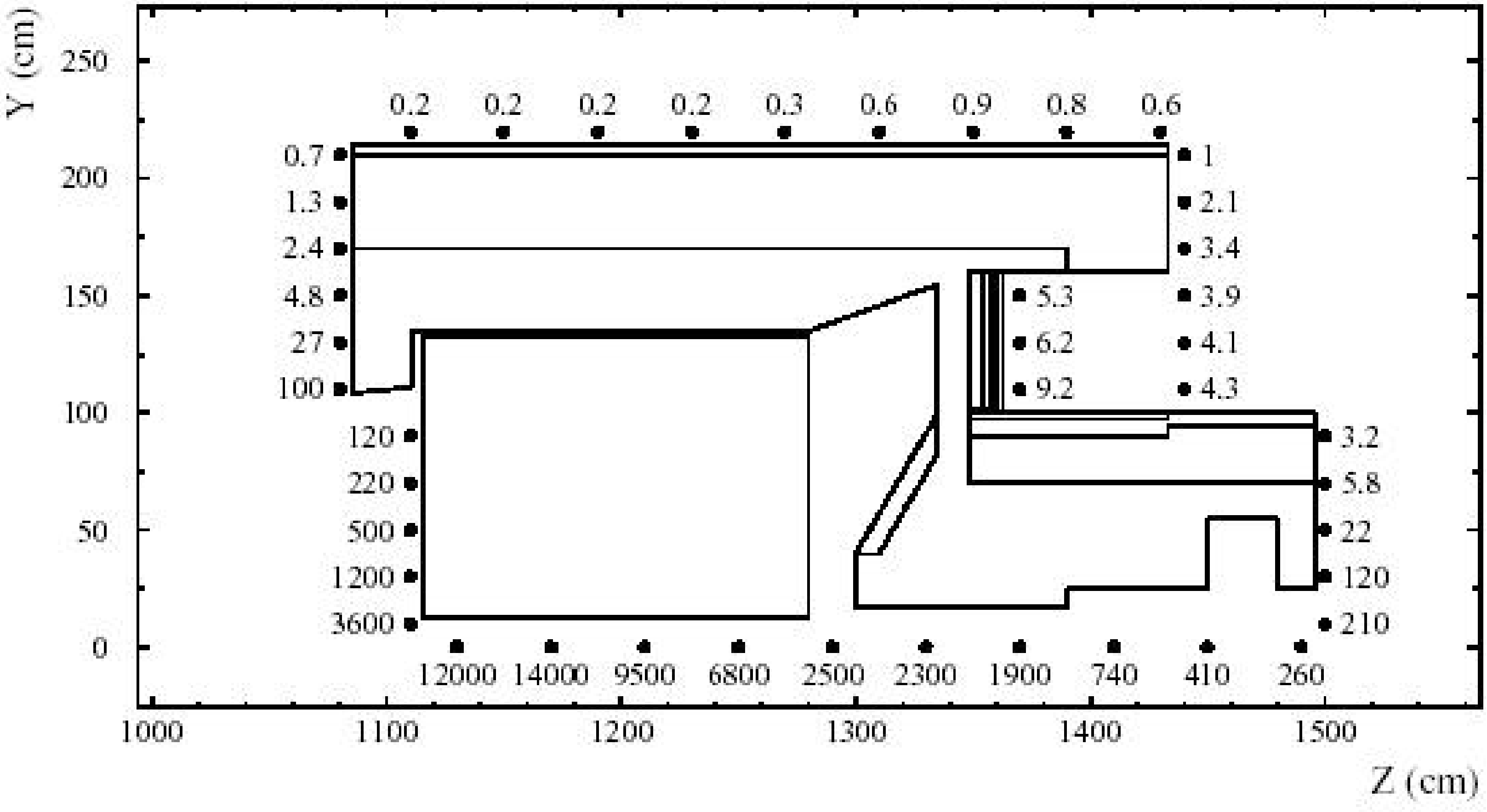
⇓

100 hours annual access time for one person in a (typical LHC/CMS) environment with 50 μSv/h

Design of all access and maintenance has to be done within the 5 mSv annual limit

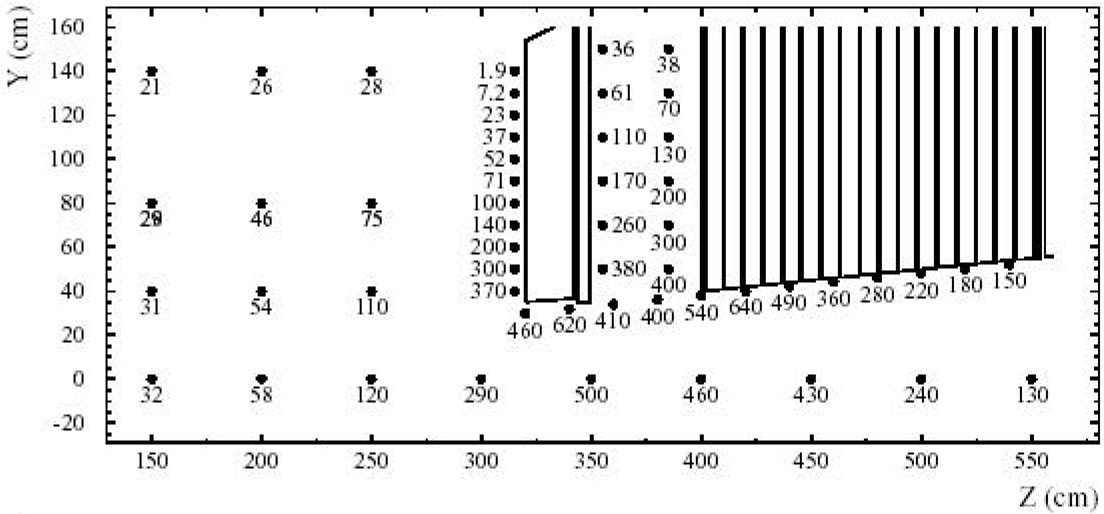
Activation in “forward” Region

Dose rates μSv/h after 10 y LHC and 1 d cooling



Activation in “endcap” Region

Dose rates μSv/h after 10 y LHC and 1 d cooling



Concentrate maintenance work on outer periphery

$\Downarrow$

Typical dose rates $<50\ \mu$Sv/h

$\Downarrow$

Design operations to be reasonably 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?
- Activation of endcap/forward calorimeters will severely limit possible maintenance. → Maintenance free?

- → New R&D

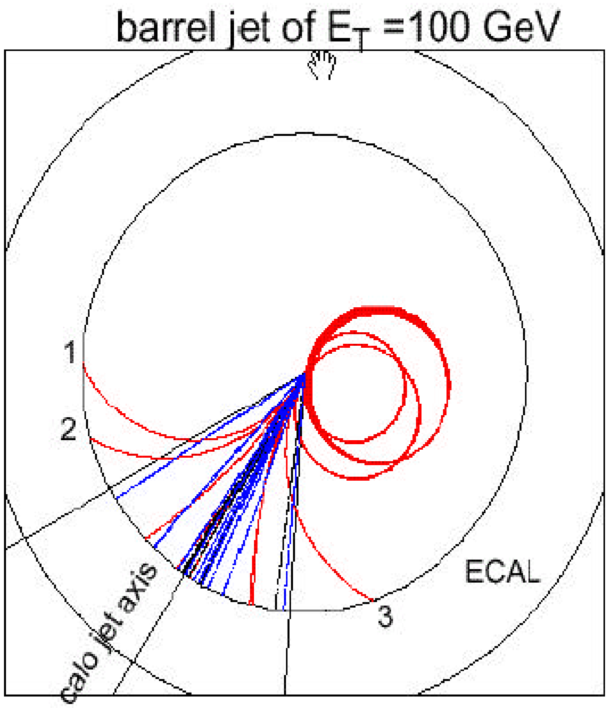
Profitable R&D Directions?

- 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?

New Calorimeter → Energy Flow

- Use tracking to improve jet response
- New calorimeters should be designed with this in mind.

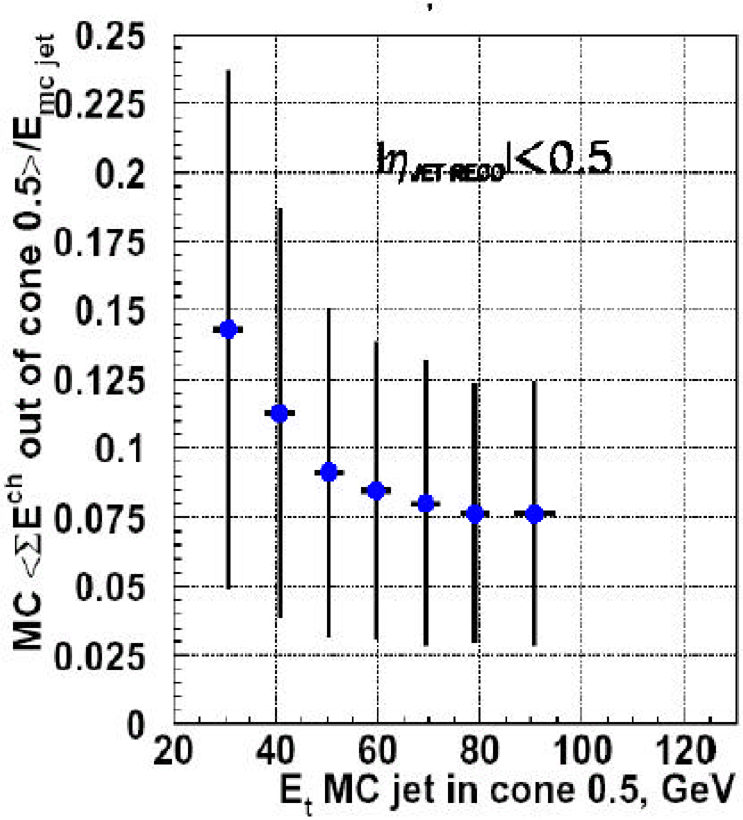
Jet Res improvement using tracking. CMS 4T B field



Radius of ECAL front ~ 1.3 meters

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

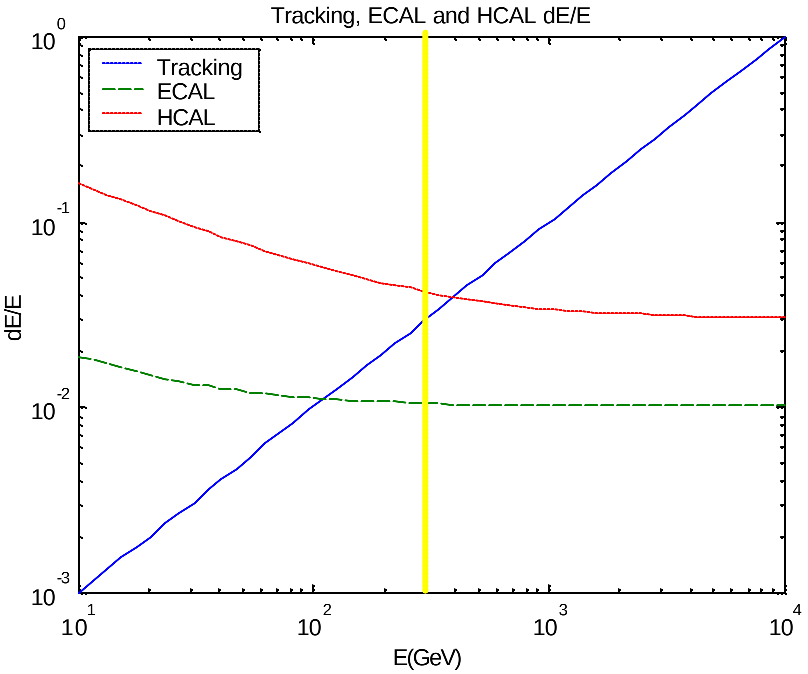
Fraction of energy escape
from a jet cone (R=0.5)
in 4T field.



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)

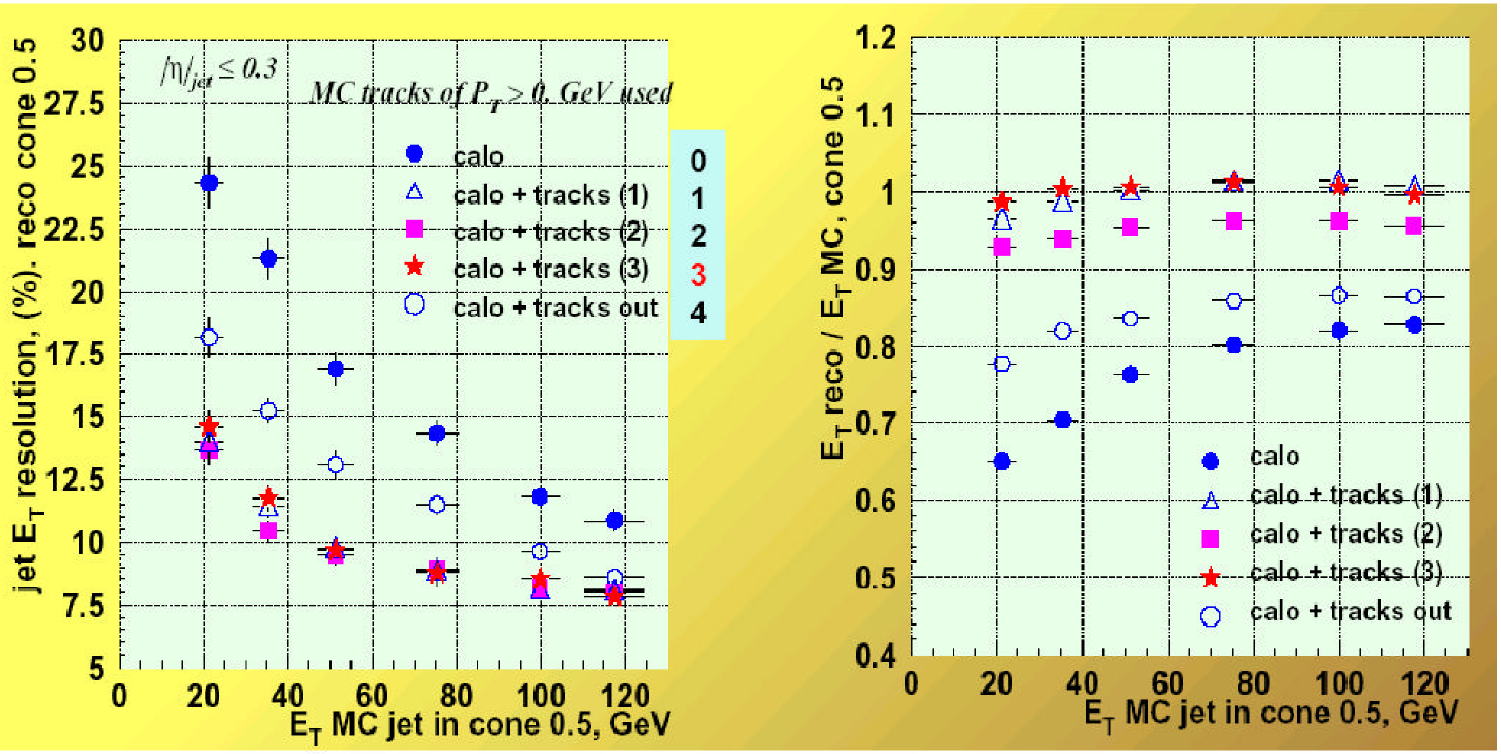
Energy Flow Jet Improvement

Resolution

20GeV 24% → 14%
100GeV 12% → 8%

E_T Scale

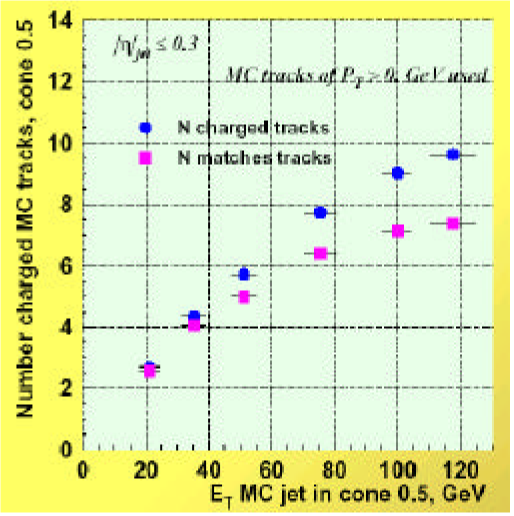
< 2% in 20-20GeV



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

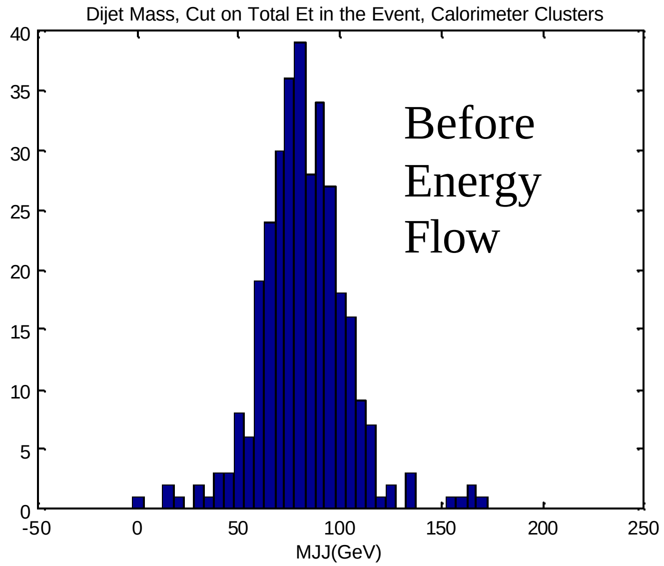
Improved Dijet Mass

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

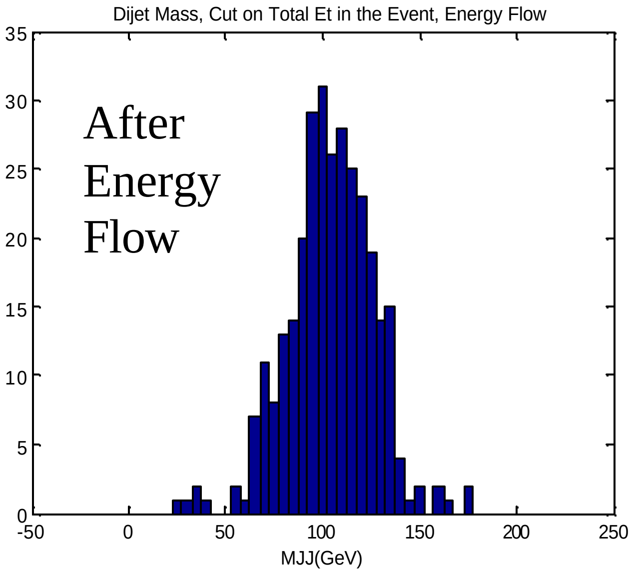


Energy Flow

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



Mean 81.7 GeV, (21%)



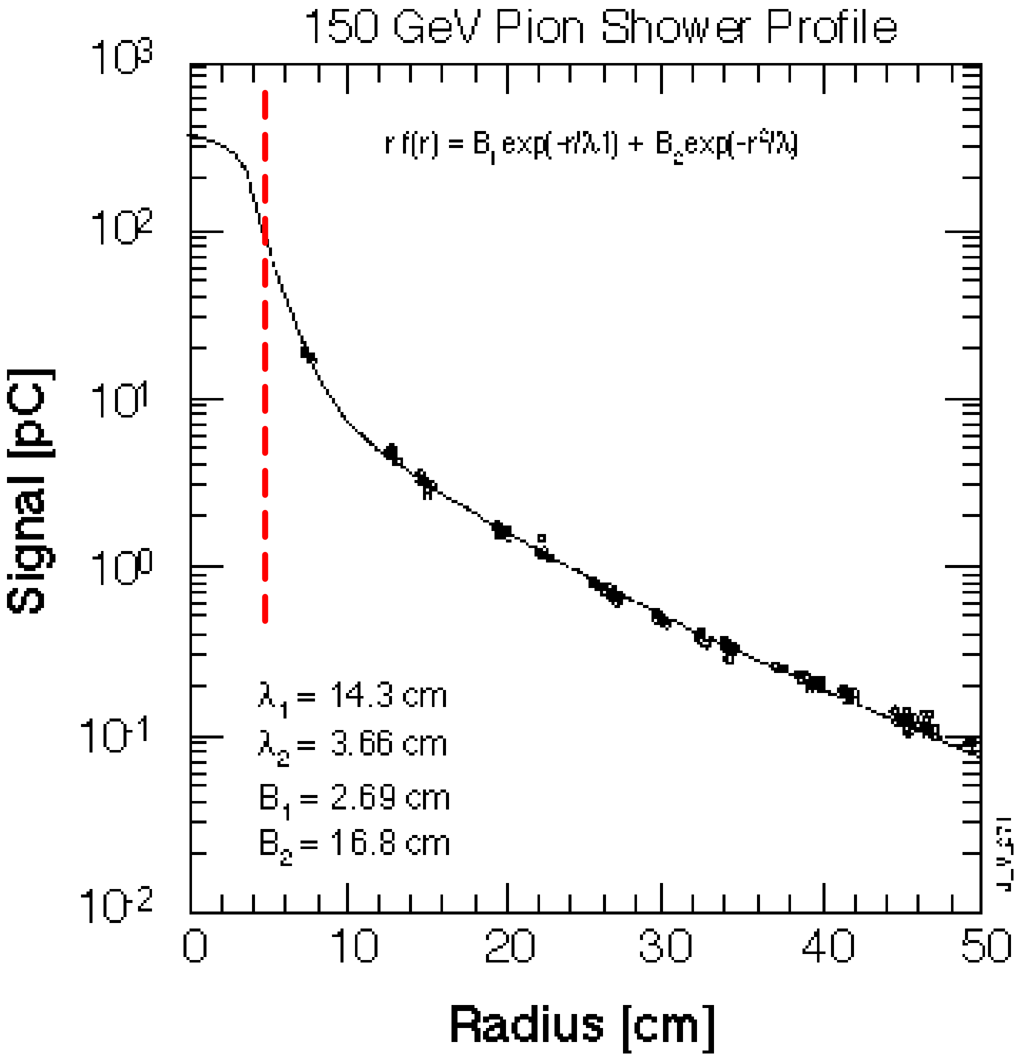
Mean 105.5 GeV, (17%)

New Calorimeter

- Issues for designing new calorimeter for VLHC
- Review the basics

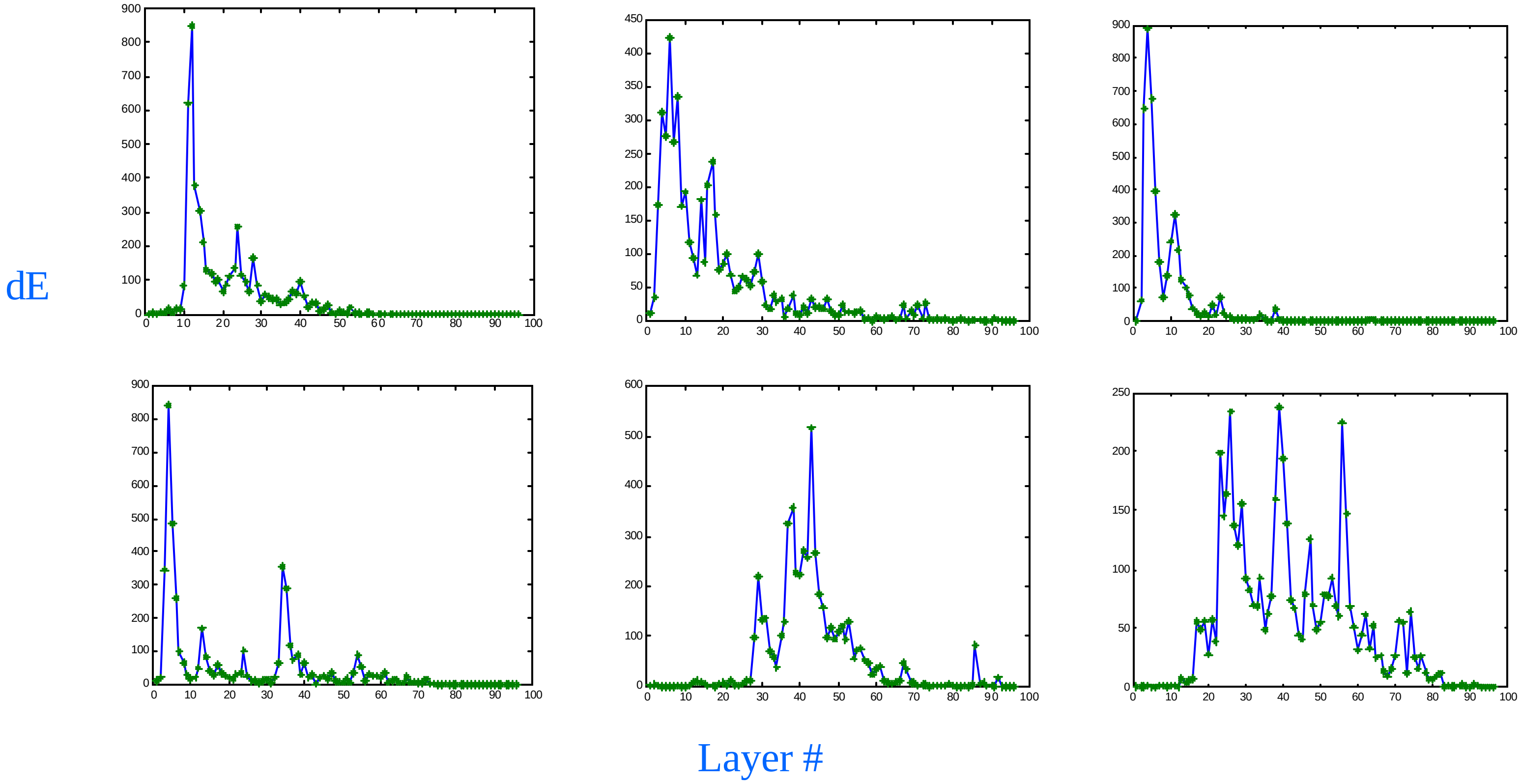
Transverse Size - HCAL

- **Shower size limits the number of resolvable “particles” in a jet, especially the dense “core” of a jet. Limits set to “energy flow” 5 cm reasonable.**



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

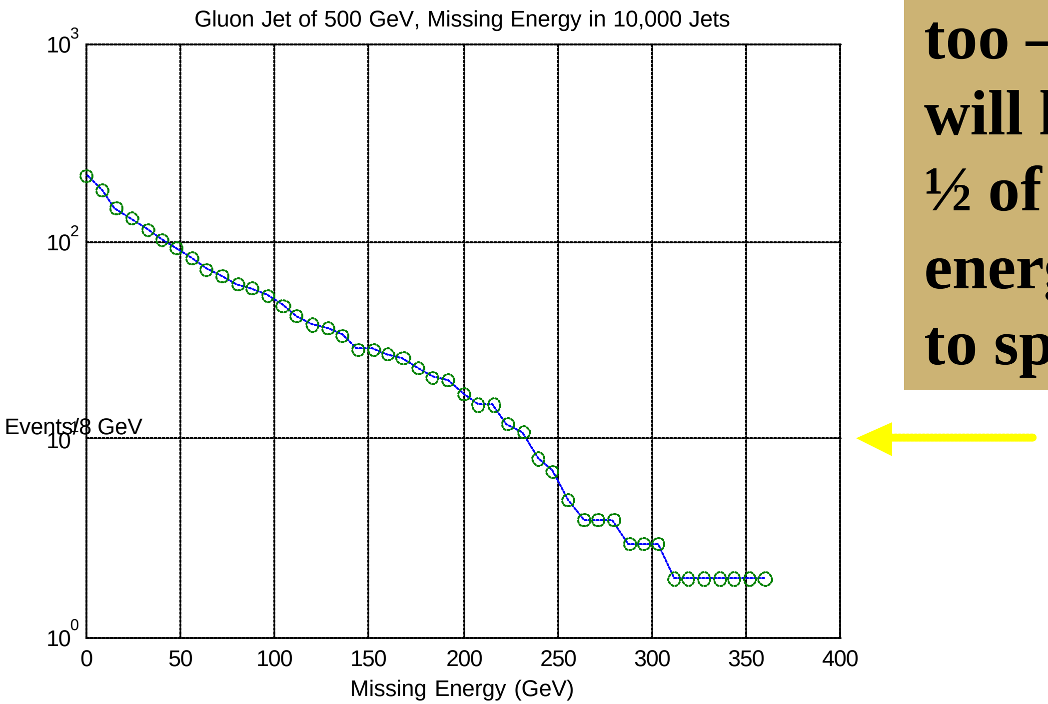


SDC Hanging File Calorimeter Data. 96 layers of scintillator, each read out with separate pmt.

Intrinsic Limitations to Containment

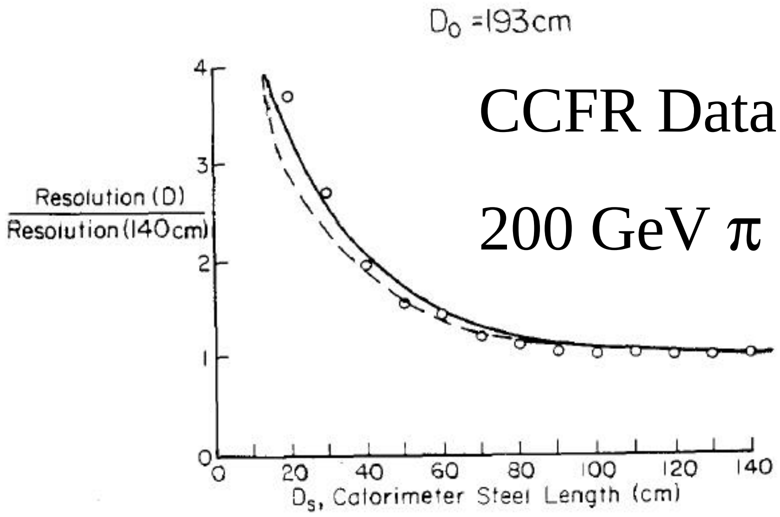
- **Jet “splitting”, g -> QQ and Q -> qlv, puts intrinsic limit on required depth. Jets themselves “leak”.**

Jets with energy > Missing ET



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

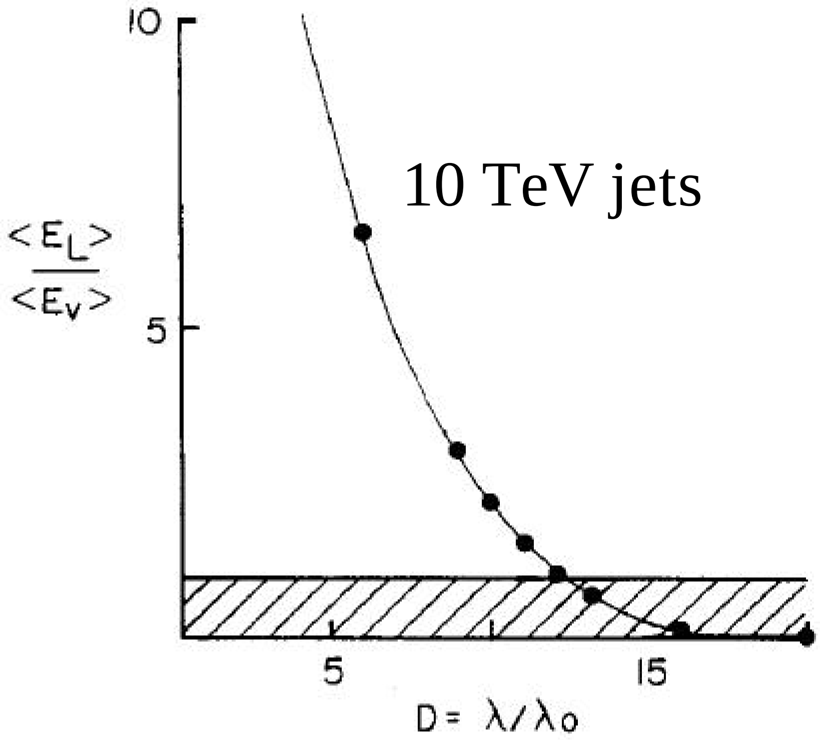
Calorimeter Depth Requirements



CCFR Data

200 GeV π

Relative Resolution vs depth

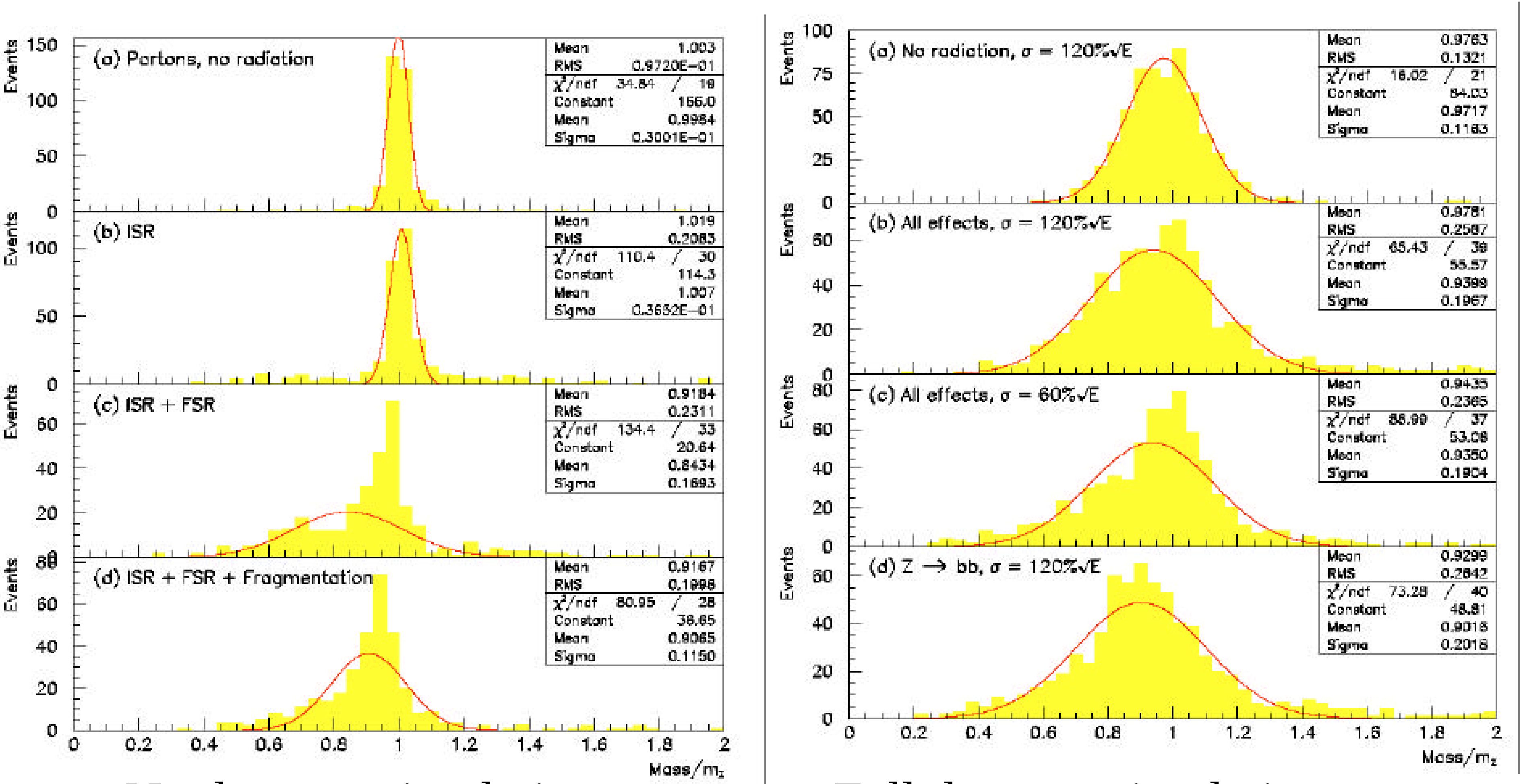


10 TeV jets

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



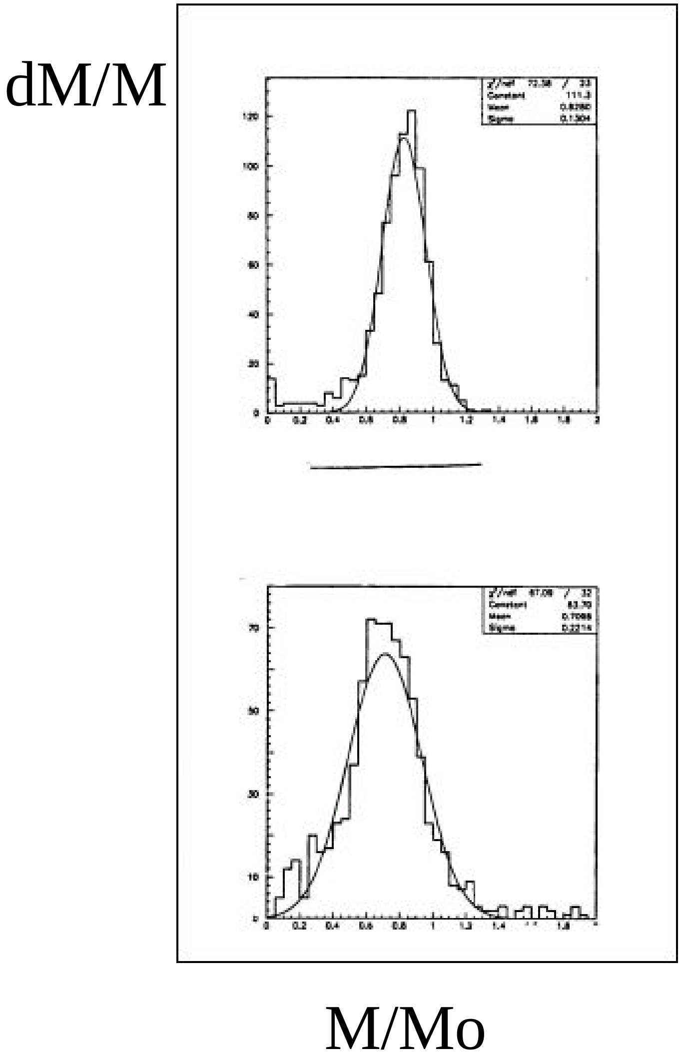
No detector simulation

Full detector simulation

Z’s at the LHC in “CMS” detector

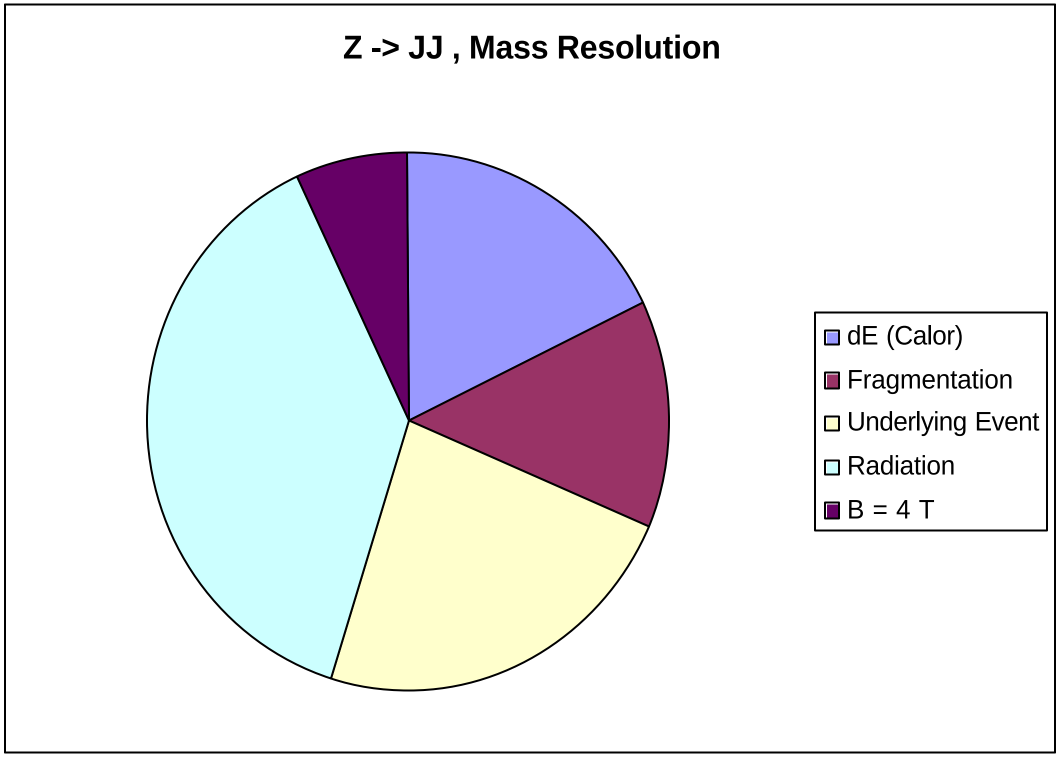
LHC – CMS Study of FSR

- 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

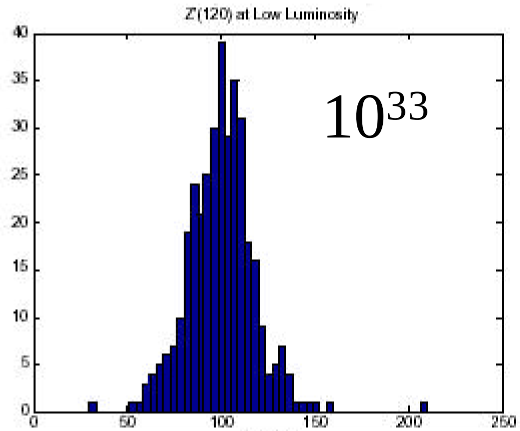
- A series of Monte Carlo studies were done in order to identify the elements contributing to the mass error. Events are low P_T, Z -> JJ. dM/M ~ 13% without FSR.

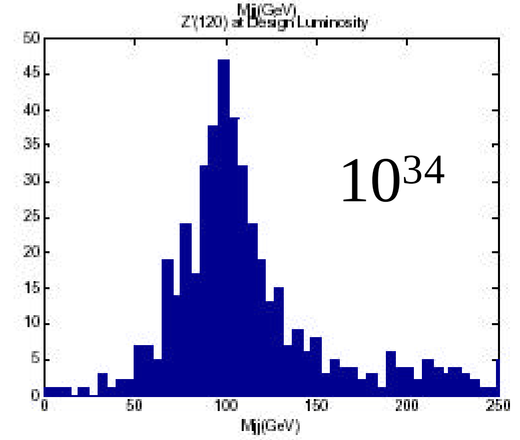


FSR is the biggest effect. The underlying event is the second largest error (if cone R ~ 0.7). Calorimeter resolution is a minor effect.

Effects of Pileup Events

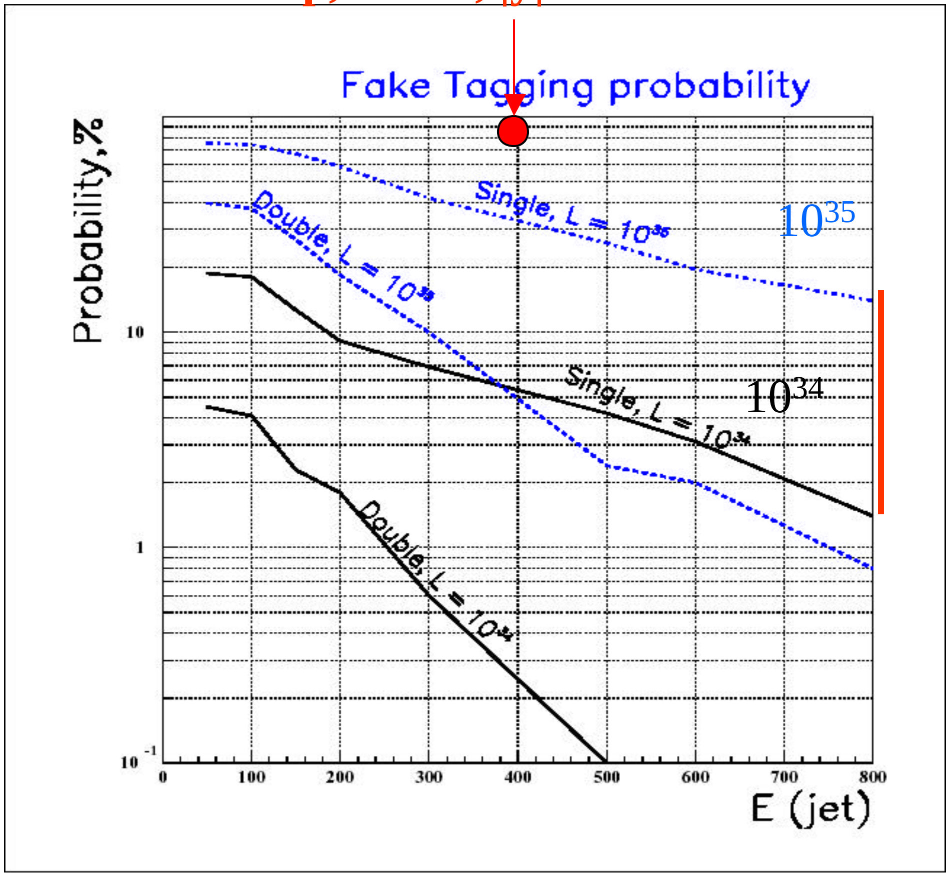
120 GeV Z'

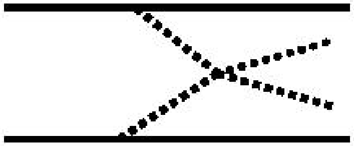




M(GeV)

Pileup, R=0.5, |y|=3 400 GeV in R=0.5 cone

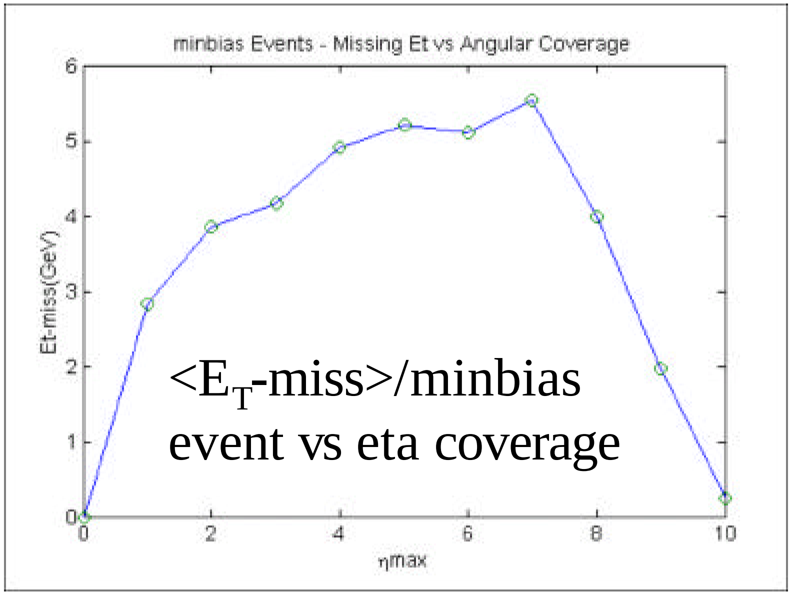




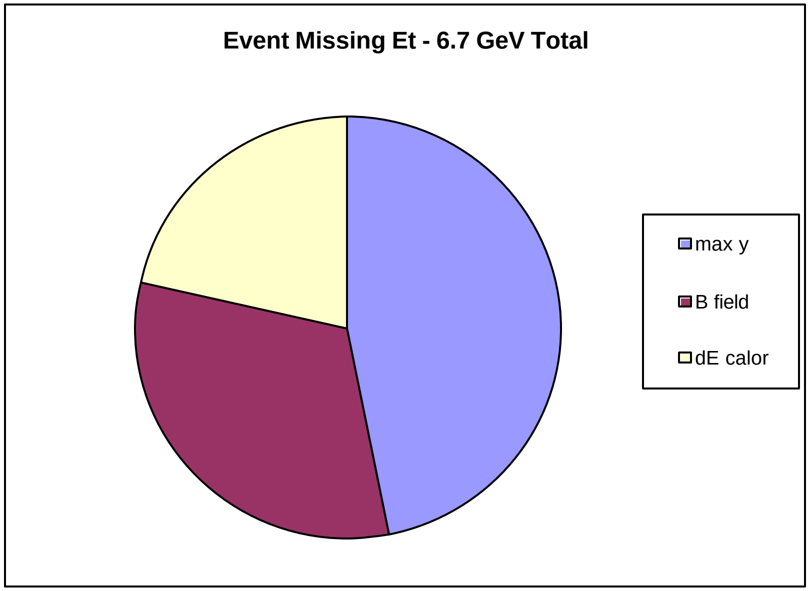
WW fusion → Forward tag jets, E_T~ 40 GeV

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 |h| = 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)**

Acknowledgements

- Thanks to Tiziano Camperisi and Dan Green.