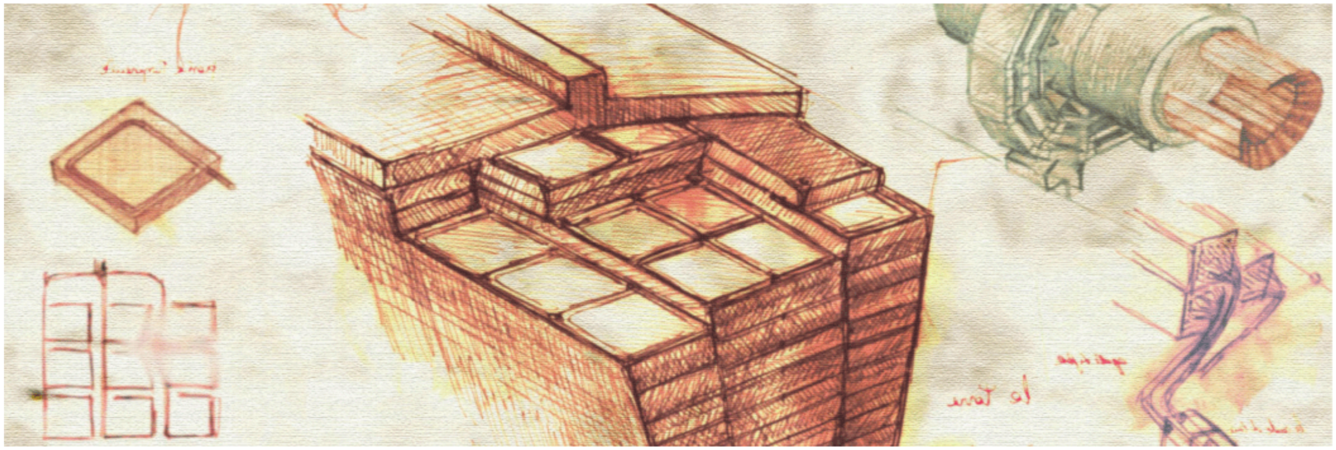
# Radiation-Hard Quartz Cerenkov Calorimeters



**Yasar Onel**

**The University of Iowa**

**(on behalf of CMS Collaboration)**

# Outline

- Introduction to Quartz Calorimetry
- Quartz as radiation hard material
- Quartz Calorimeters for the CMS Detector
  - Quartz Fiber Calorimeters
    - PPP1 -- Prototype
    - HF
  - Quartz Plate Calorimeters
    - Castor
    - QPCal Prototype
- Conclusion

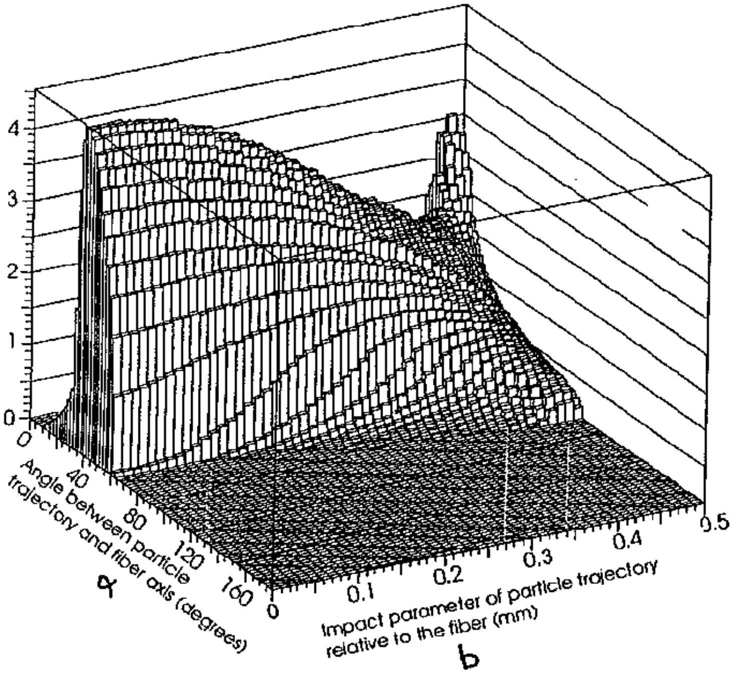
# Introduction

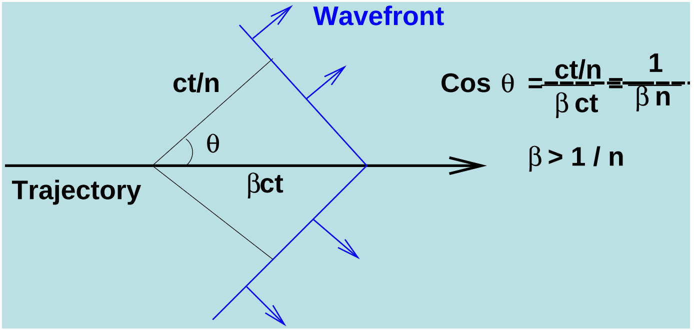
- The detector is intrinsically radiation hard at the required level (hundreds of MRads)
- The detector, for all practical purposes, is sensitive to the electromagnetic shower components ($\rho_M$)
- It is based on Cherenkov radiation and is extremely fast (< 10 ns)
- Low but sufficient light yield (<1 pe/GeV)
- The effects of induced radioactivity and neutron flux to a great exter are eliminated from the signal
- Neutron production is considerably reduced (high-Z vs low-Z)
- The detector is relatively short
- The detector is perfectly hermetic
- When high energy charged particles traverses dielectric media, a coherent wavefront is emitted by the excited atoms at a fixed angle θ called Cherenkov light.
- Light is generated by Cherenkov effect in quartz fibers
- Sensitive to relativistic charged particles (Compton electrons...)
- $d^2N/dxd\lambda=2\pi\alpha\, q^2(\sin^2\theta_c/\lambda^2)$

  $=(2\pi\alpha\, q^2/\lambda^2)[1-1/\beta^2 n^2]$

  $\beta_{min} = 1/n$

  $E_{min} \sim 200$ KeV
- Amount of collected light depends on the angle between the particle path and the fiber axis





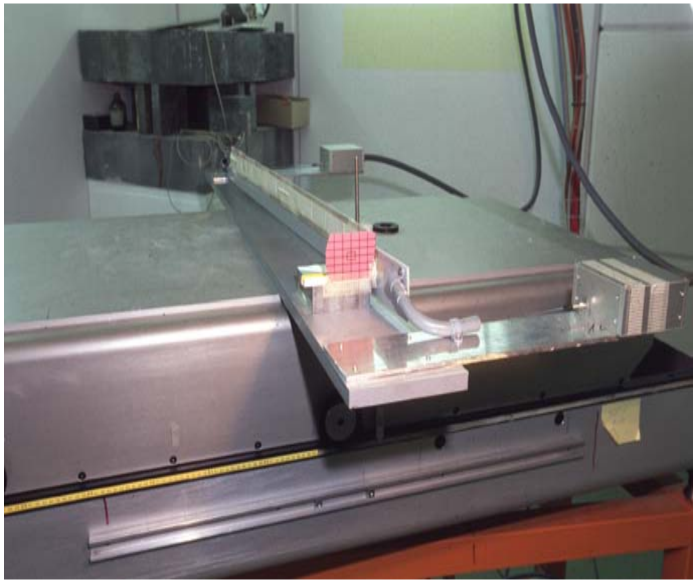
# Quartz Radiation Damage

- Scientific literature about optical characteristics of Quartz fibers is generally in the infrared band (800nm, 1300nm, 1550nm studied a lot…)
- Many of these studies conducted by $\gamma$ or **e**$^-$ irradiation
- Our studies concentrated on 325-800 nm range
  - PMT sensitivity 400-500 nm
- Three experiments were carried out
  - UTR-10 , 10 kWatt Reactor @ ISU, Ames
    - Total $\gamma$ dose ~ 22 kRad
    - Neutron Flux: 1.3x1010 n/cm2/s/kW
    - Integrated neutron fluence at the end of experiment: ~1x1015 n/cm$^2$
  - MGC-20E cyclotron of ATOMKI in Hungary
    - 18 MeV proton incident on 3 mm thick Be-target to generate neutrons, <E>=3.7 MeV
    - Eneutron ranged up to 20 MeV
    - 25.3 hours of operation, total neutron fluence ~1.02 x 1015 n/cm2 ±18%
    - Average nfluence at the cylinder ~ 0.6 x 1015 n/cm2
    - During Irradiation, the dose rate was constant ~ 1.1 x 1010 n/cm2/sec ±18%
  - The Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory
    - IPNS produces neutrons by Uranium fission induced by a proton beam
    - The fission reaction also produces gamma radiation
    - 15 uA of 450 MeV protons over 313 hours (2 weeks) produced 7.42 x $10^{17}$n/cm$^2$
    - Average fiber dose was calculated as 17.6 Mrad neutron and 91.1 Mrad gamma

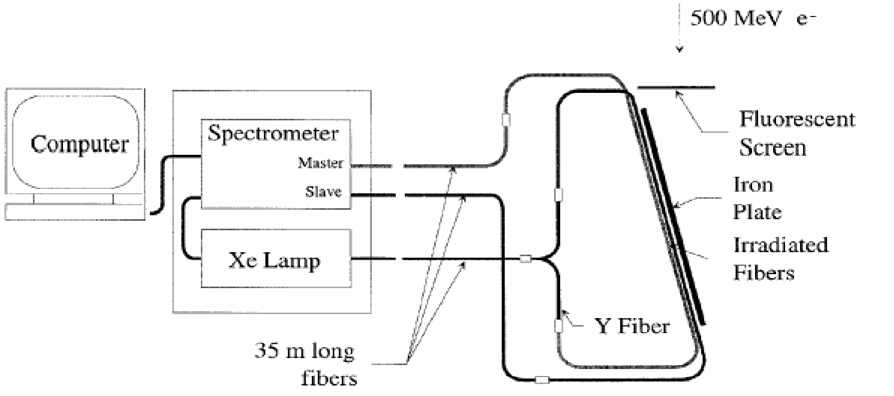
# Quartz Radiation Damage

## Test Area at LIL

- Motorized support, moved from the beam during stop. Dose rate 600rad/s.
- Beam perpendicular to fluorescent screen.
- There is effectively 5.5 cm iron in front of fiber. Fiber embedded inside the iron.
- Iron block placed @ 8% slope with respect to the beam.
- Beam scanning of 8 cm on fluorescent screen irradiates 100 cm fiber length.
- Fiber placed @ max of dE/dx of EM shower.
- Dosimeters were installed behind iron absorber in the same place with fibers.

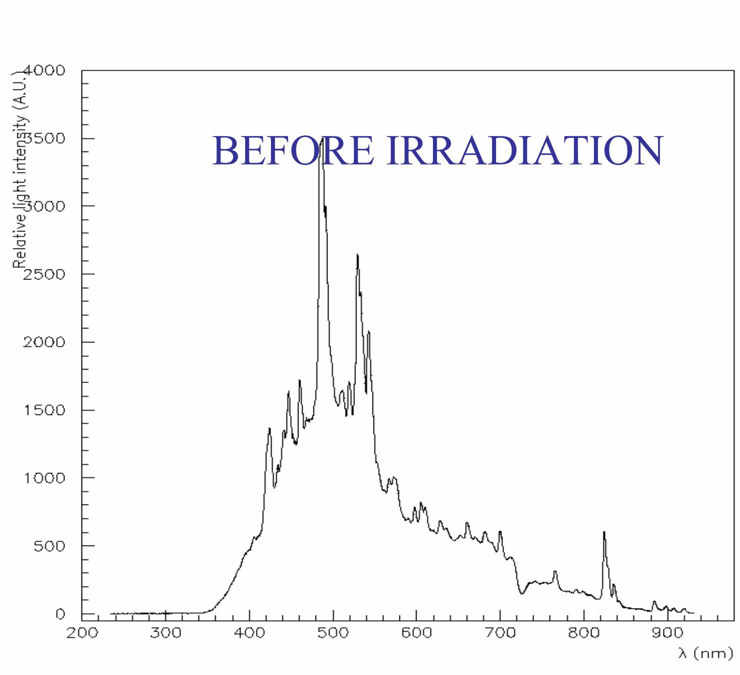


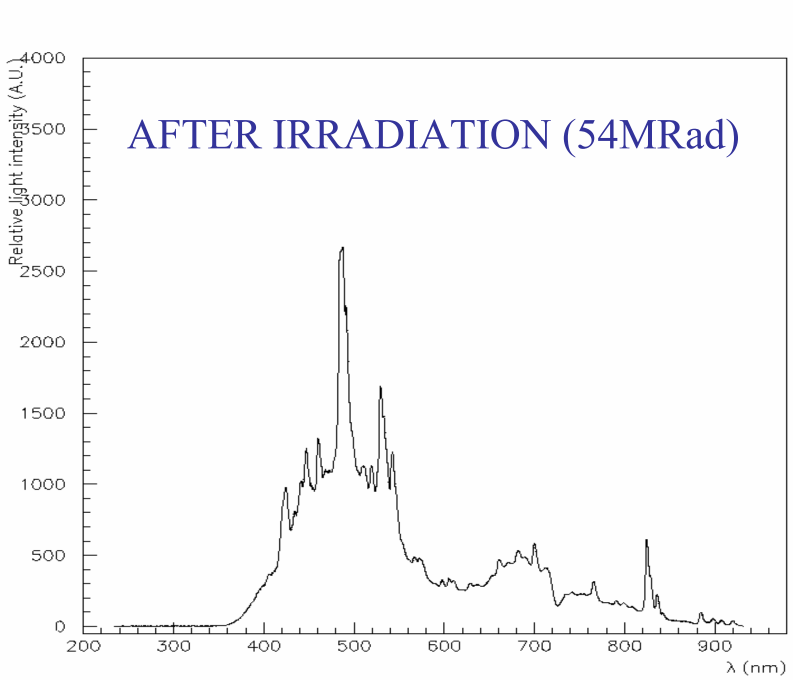
- Iowa group has tested fibers at LIL CERN 500 MeV electrons.
  - ***CMS-CR 2006/005***
  - ***NIM A490 (2002) 444***
  - ***CMS NOTE 98-056***
- Spectrometer, light source and PC were kept in temperature stabilized place.
- Irradiation place was at room temperature.
- Measurements were done *In situ.*



# Quartz Radiation Damage

## Sample Spectra (Before& After Irradiation)





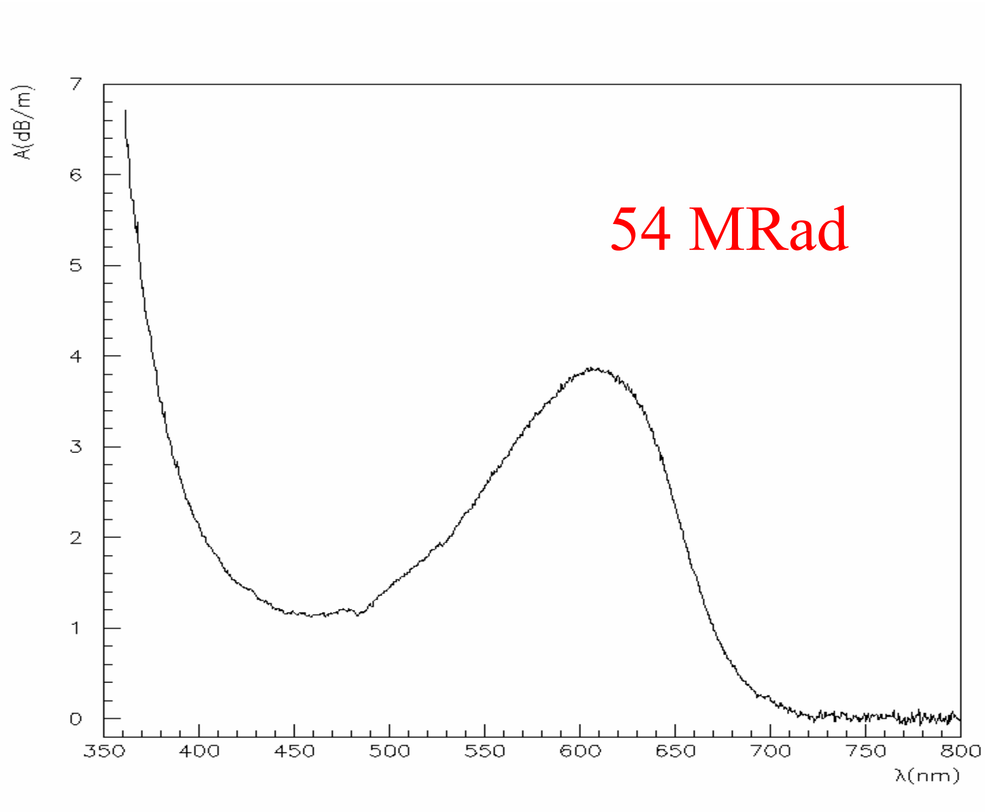
- UV light absorbed by long fibers.
- Total decrease almost for all wavelengths.
- Deep around 610 nm.
- Least effect between 700 and 800 nm.

# Quartz Radiation Damage

## Attenuation

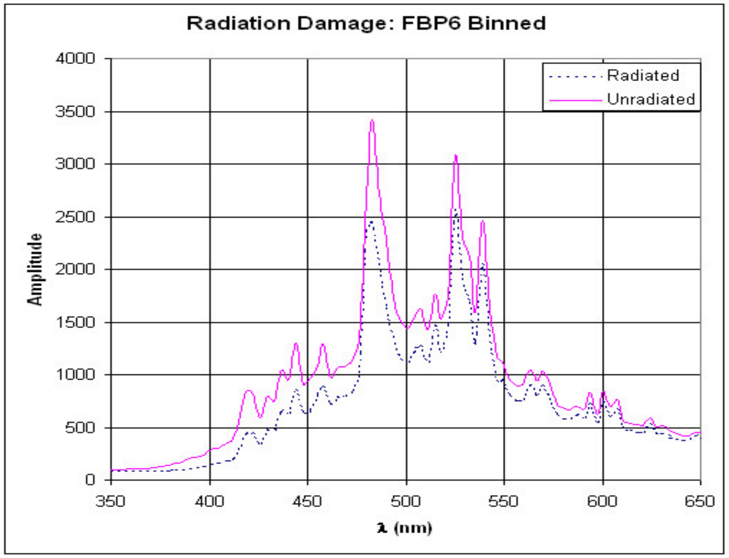
$$A(\lambda, D) = -(10/L)\log_{10}[I(\lambda, D)/I(\lambda,0)]$$

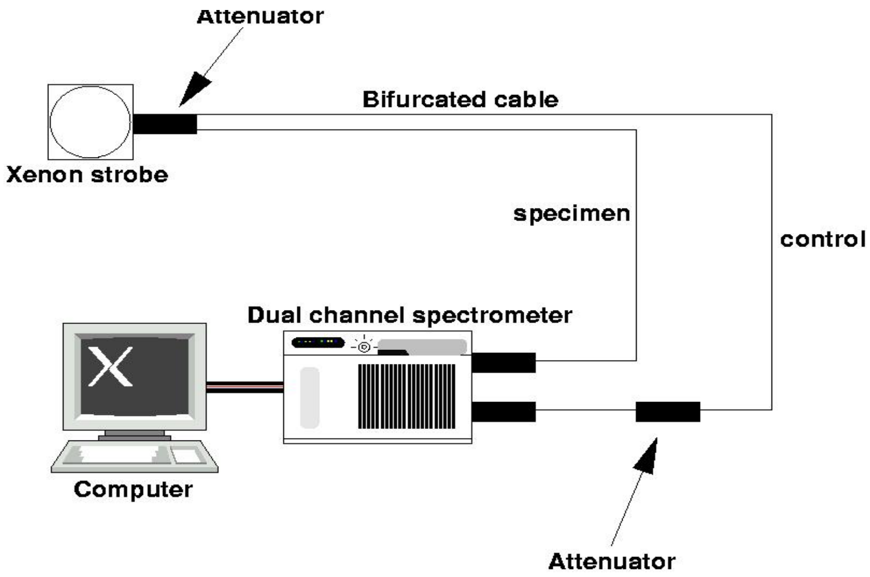
- Obtained using previous two spectrum.
- There is no transmission below 350 nm.
- Relatively bigger attenuation at 610 nm.
- No effect between 700 and 800 nm in our measurement precision.
- Relative deep around 450 nm.

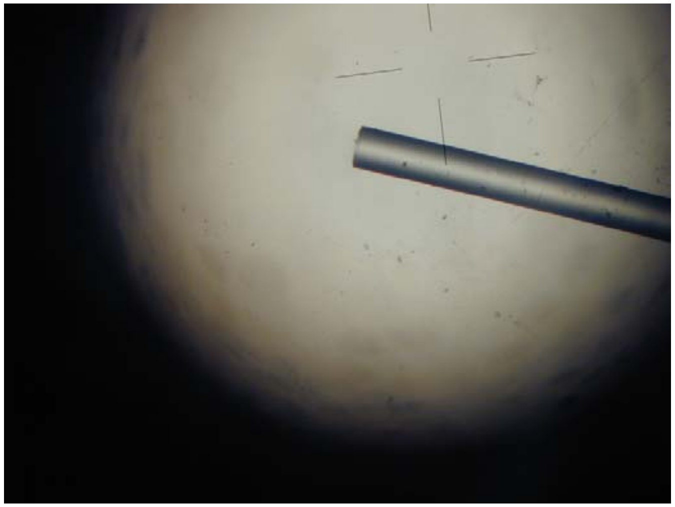


# Quartz Radiation Damage

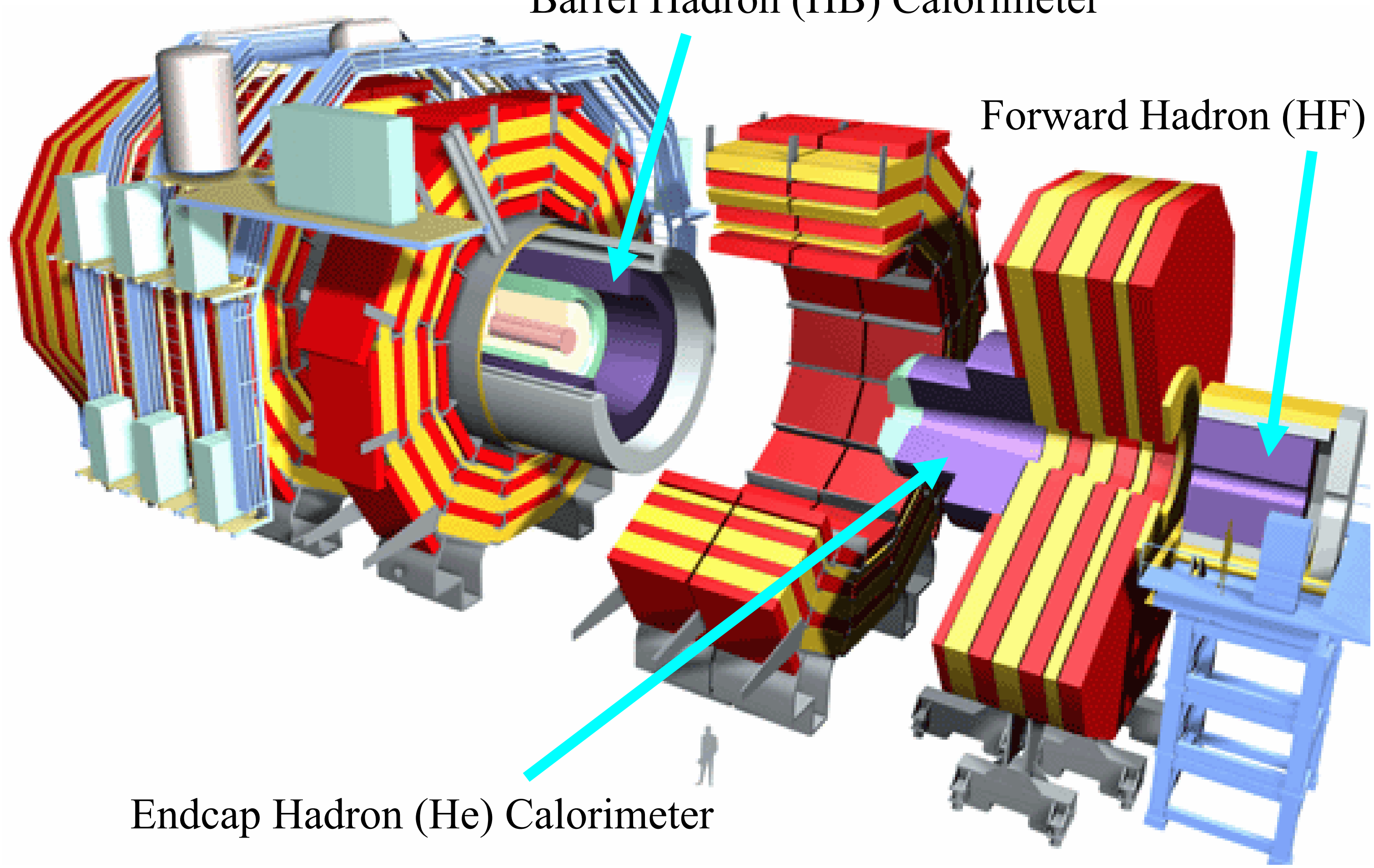
- Seven sets of quartz in the form of fiber are irradiated in **Argonne IPNS** for 313 hours.
- The fibers were tested for optical degradation before and after 17.6 Mrad of neutron and 73.5 Mrad of gamma radiation.
- Polymicro manufactured a special radiation hard solarization quartz plate.
- Seven types of quartz fibers were cleaved
- The fibers were loaded into an Ocean Optics SD2000 digital spectrometer
- ***CMS IN-2006/014***







# CMS Detector

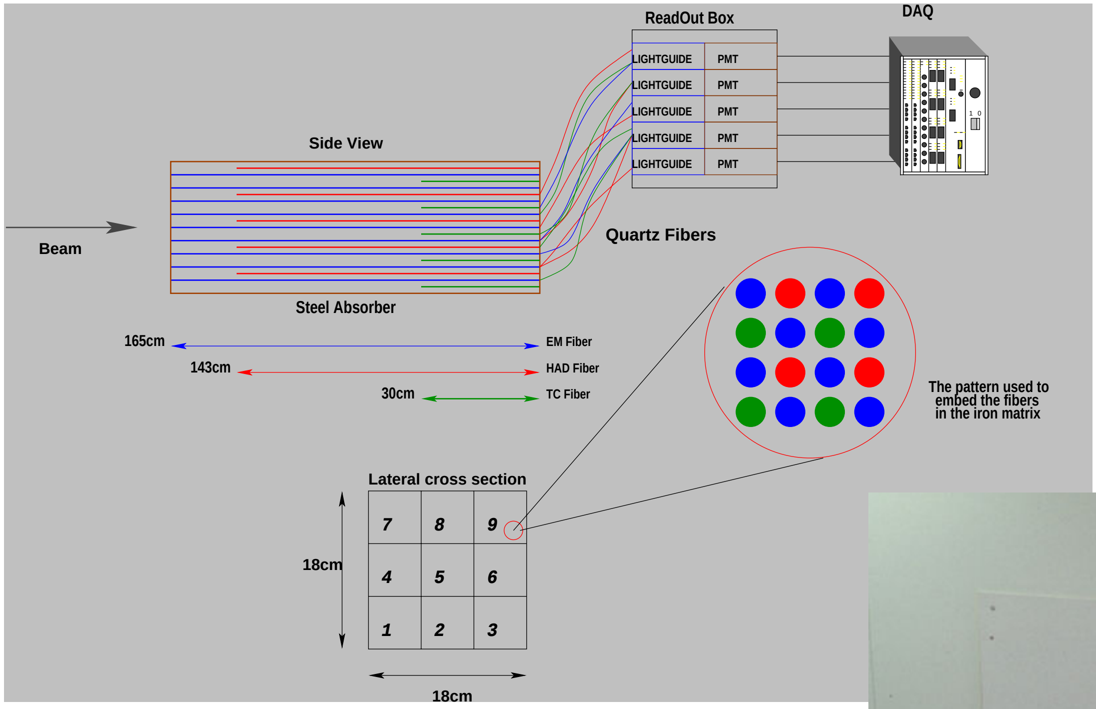


Barrel Hadron (HB) Calorimeter

Forward Hadron (HF) Calorimeter

Endcap Hadron (He) Calorimeter

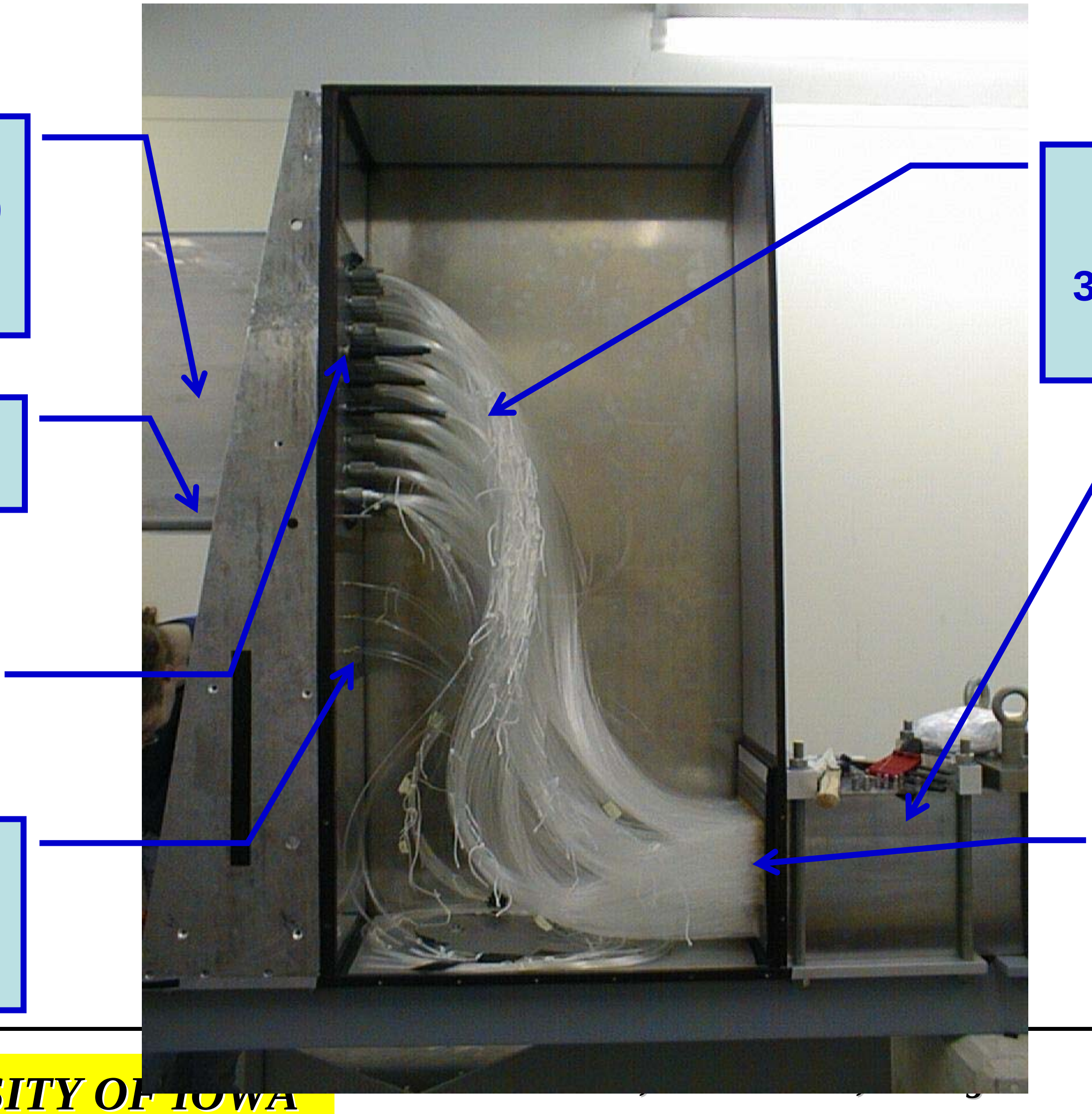
# PPP - I



PPP - I (PreProduction Prototype)
Schematic View

The Prototype

# PPP - I



**ROBox**
**( Light Guides)**
**R6425 PMTs**

**LED, Laser**
**and PIN PDs**

**Ferrules**

**Radioactive**
**Source**
**Tubes**

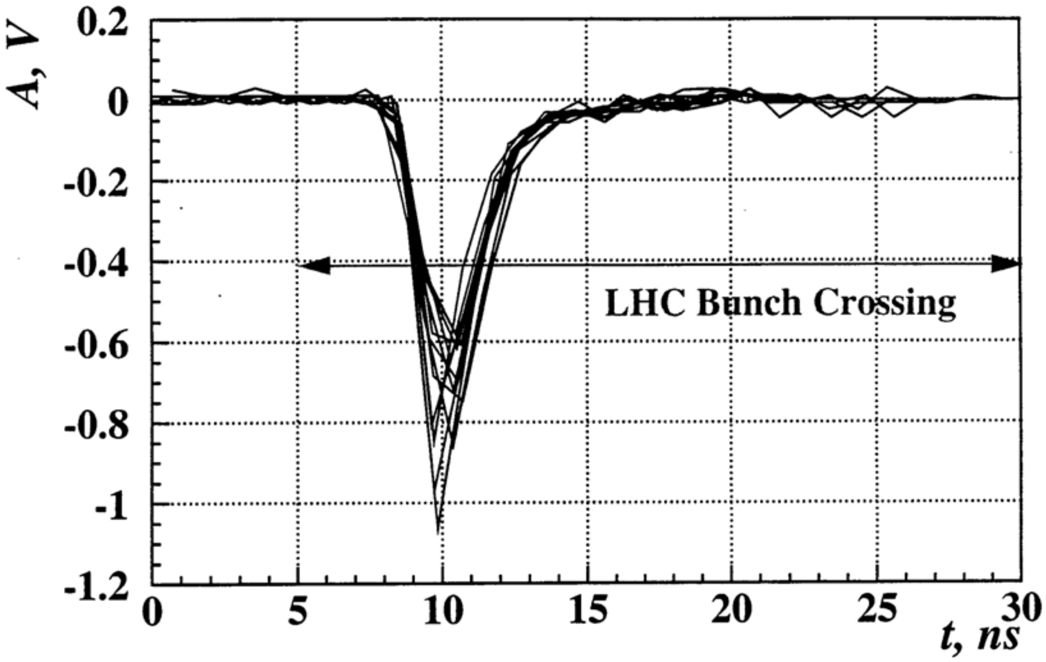
**Fiber Bundles**
**(EM, HAD and TC)**
**300-micron core QP**

**Iron**
**Absorber**
**(9.5 $\lambda_I$)**

**3 x 3 Tower**
**structure**
**(6 cm x 6 cm)**

# PPP - I

## Previous Experimental Data on Photodetectors by HF Group

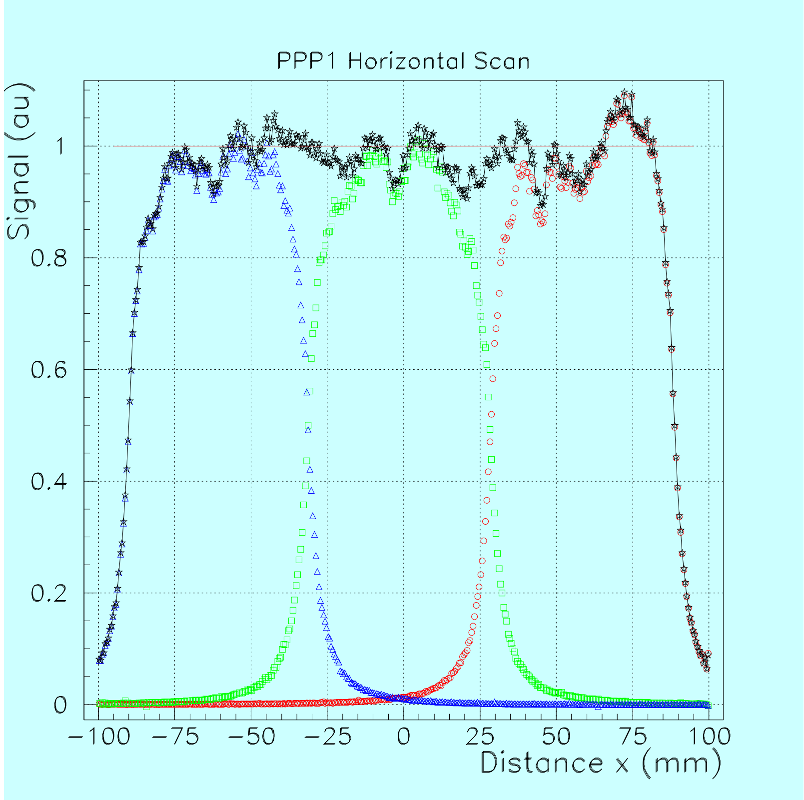


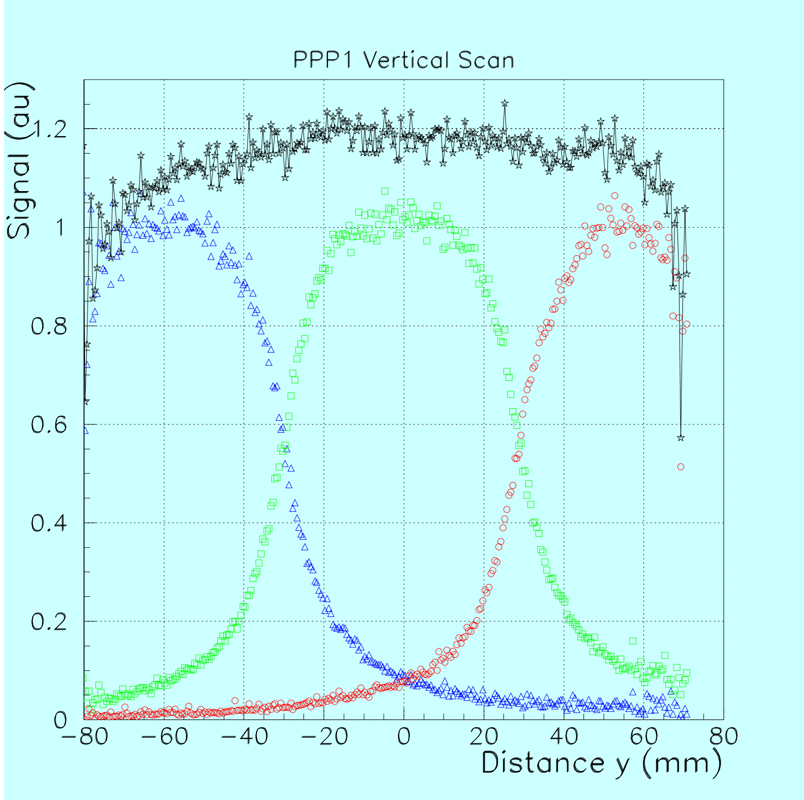
Hamamatsu R6427 at 350GeV Pion Beam

# PPP - I

## Spatial uniformity with electron and pion beams

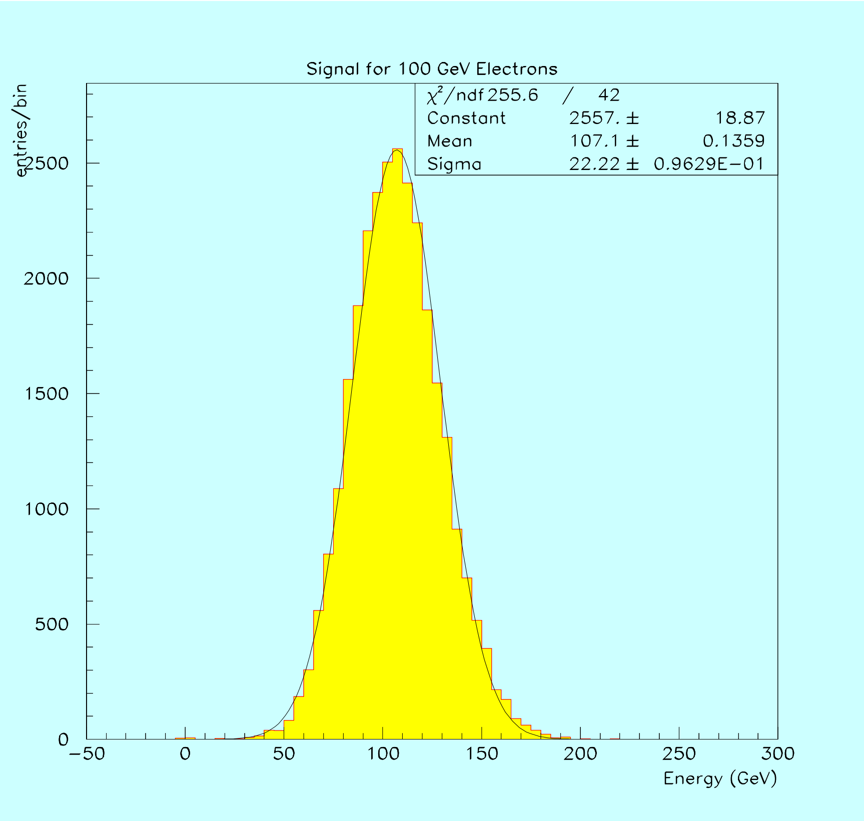
*A.S.Ayan, Ph.D. Thesis, 2004*

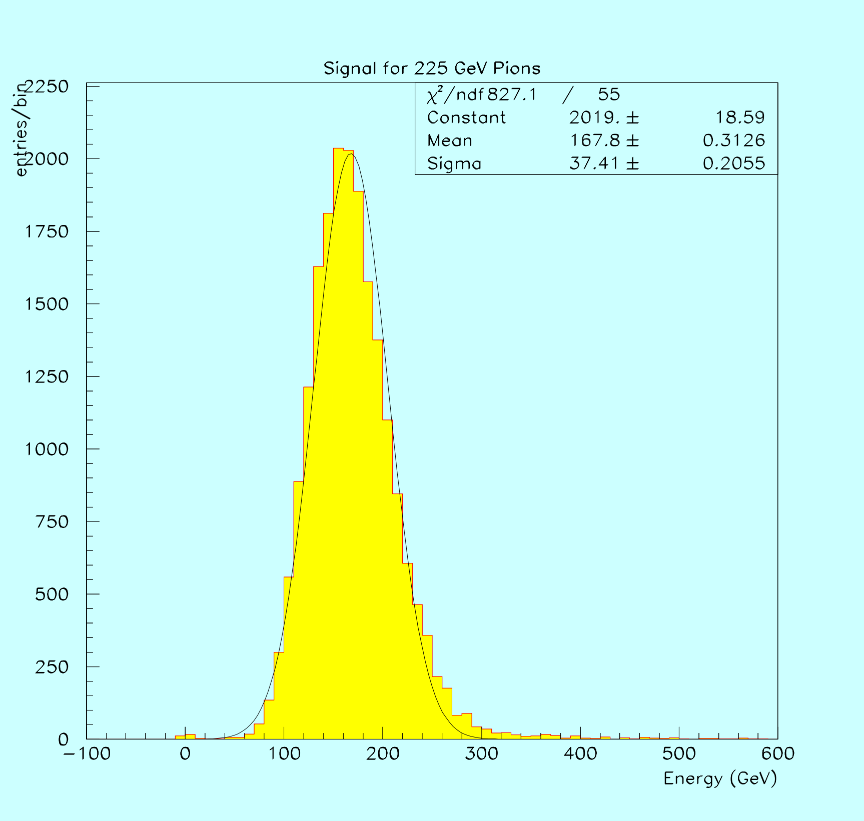




# PPP - I

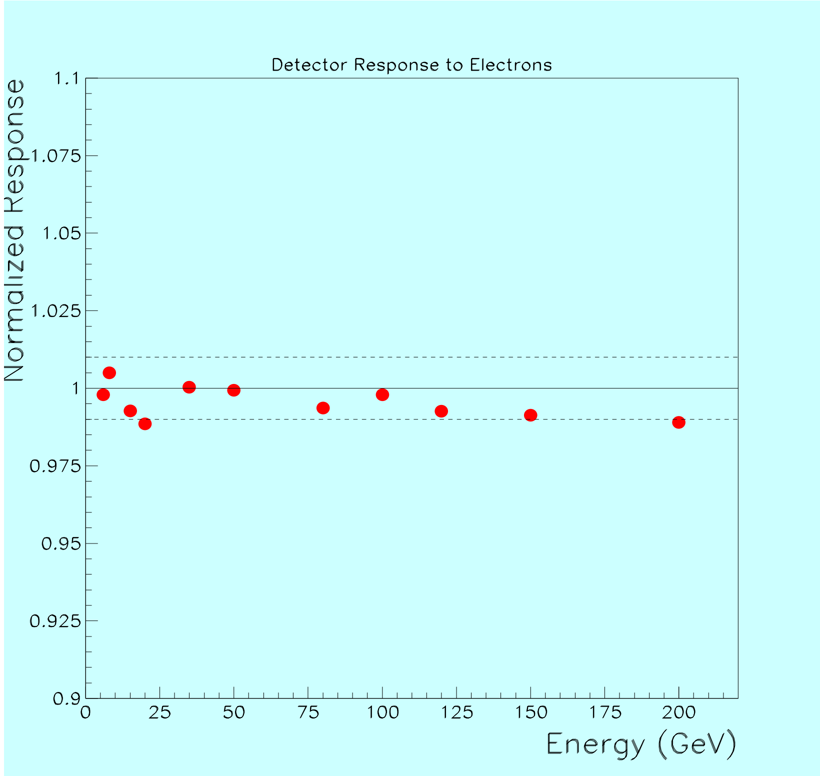
## Detector Response to 100 GeV electron and 225 GeV pion

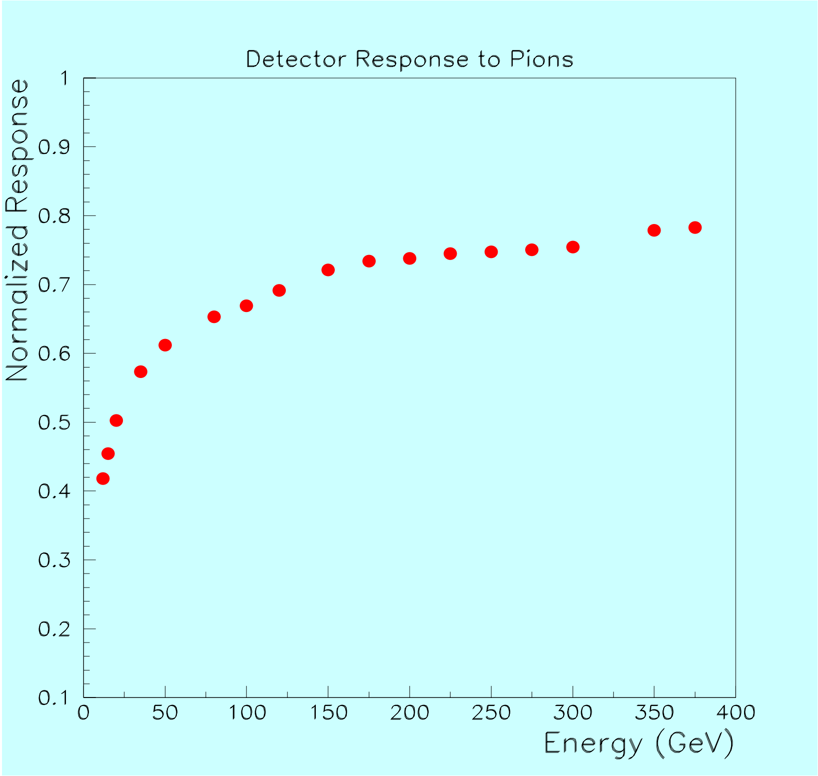




# PPP - I

## Energy Response Linearity



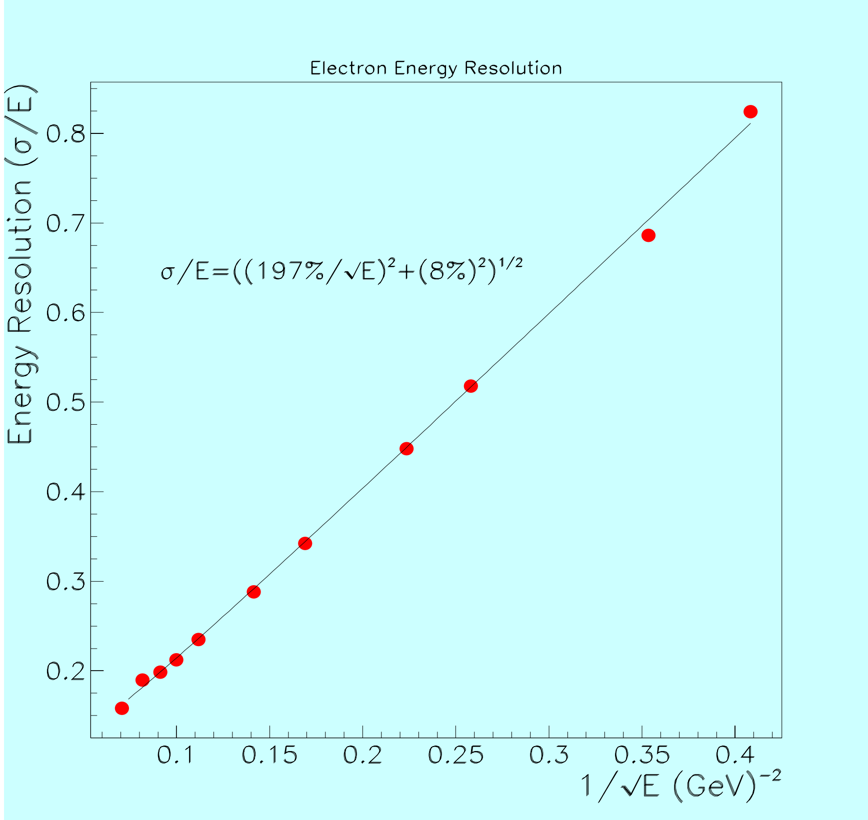


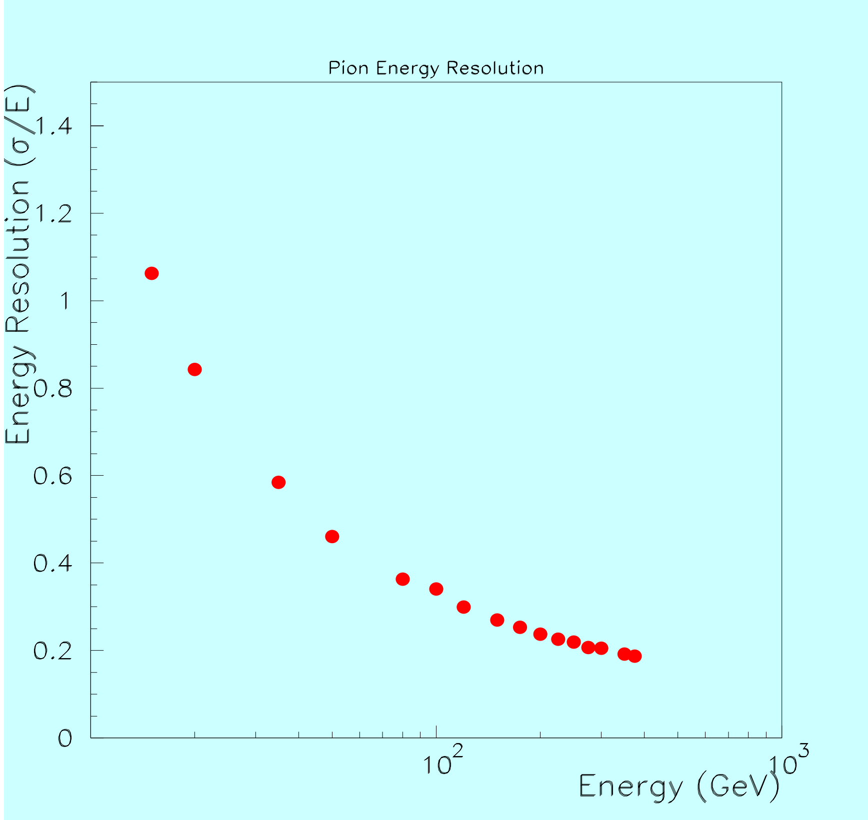
- HF PPP1 responds linearly within 1% to electrons in the energy range tested (6 - 200 GeV). The $\pi^-$ response is highly nonlinear.

***J. Phys. G: Nucl. Part. Phys. 30 N33-N44, (2004)***

# PPP - I

## Energy Resolution

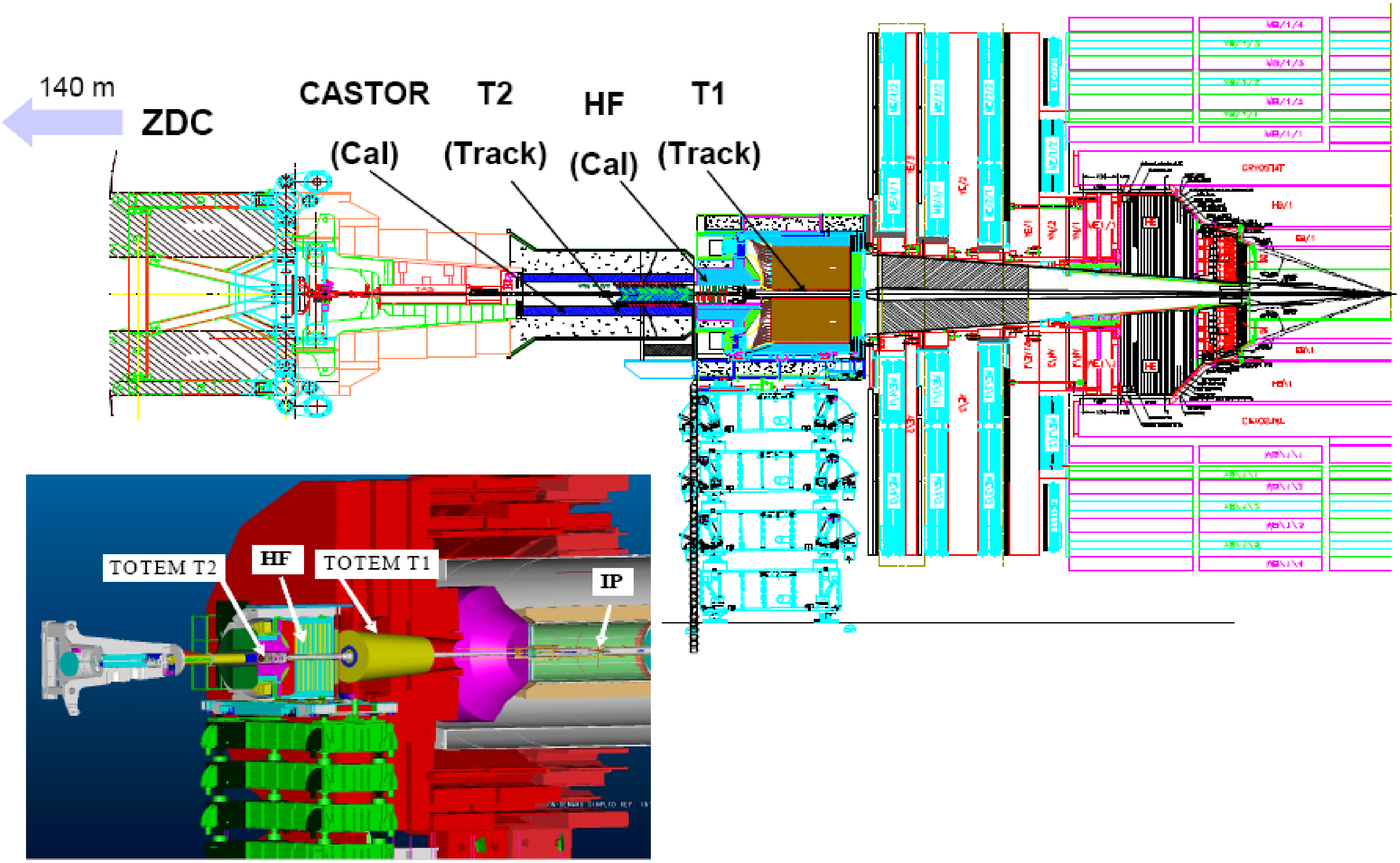




$$(\sigma/E)^2 = (a/\sqrt{E})^2 + b^2$$

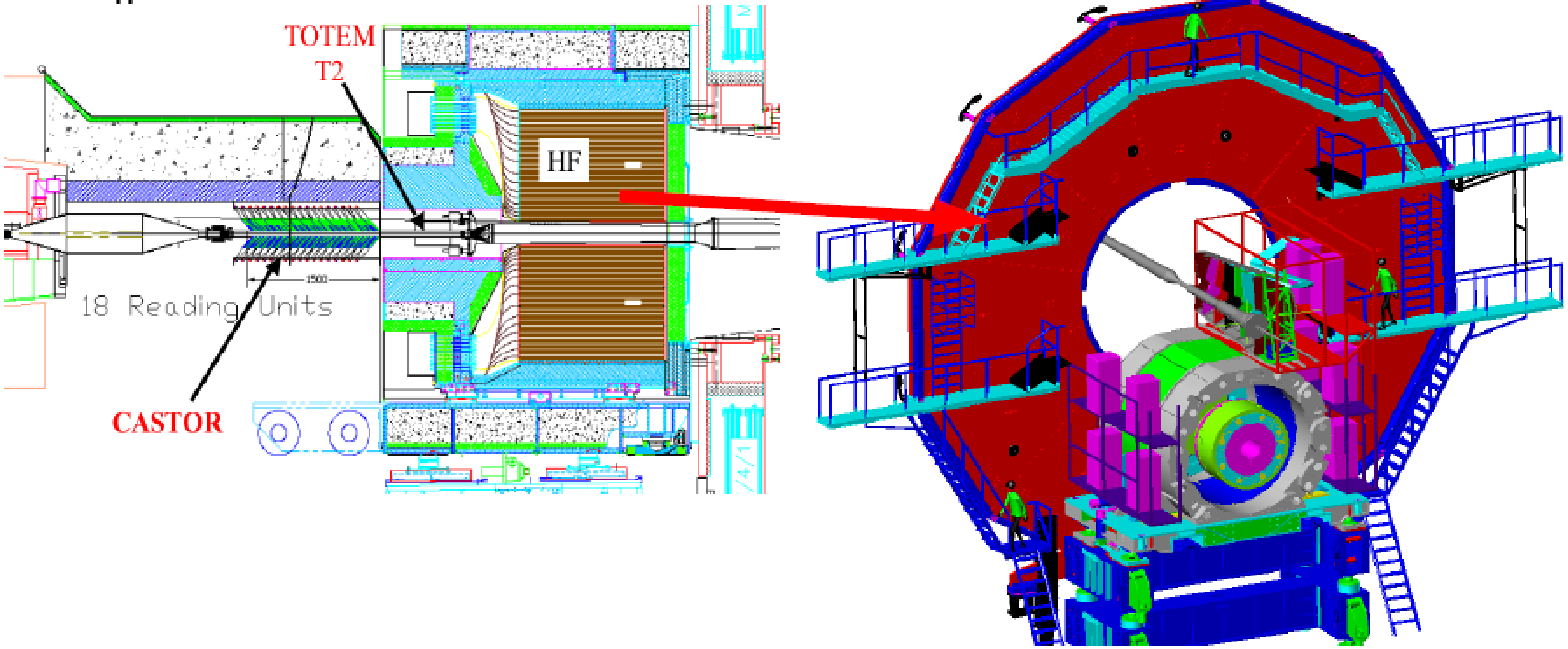
**a = 197 %  b = 8%**

# CMS Forward Detectors

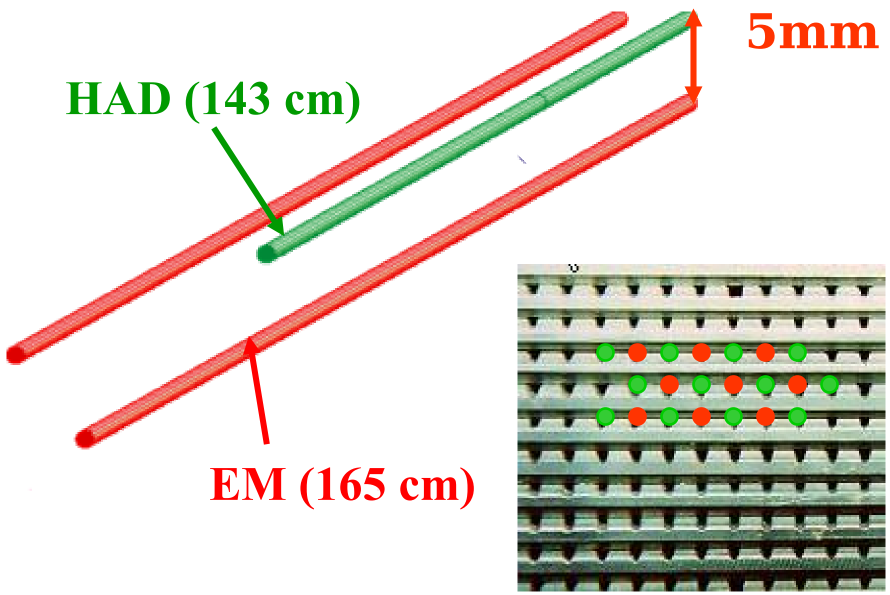


# HF Calorimeter

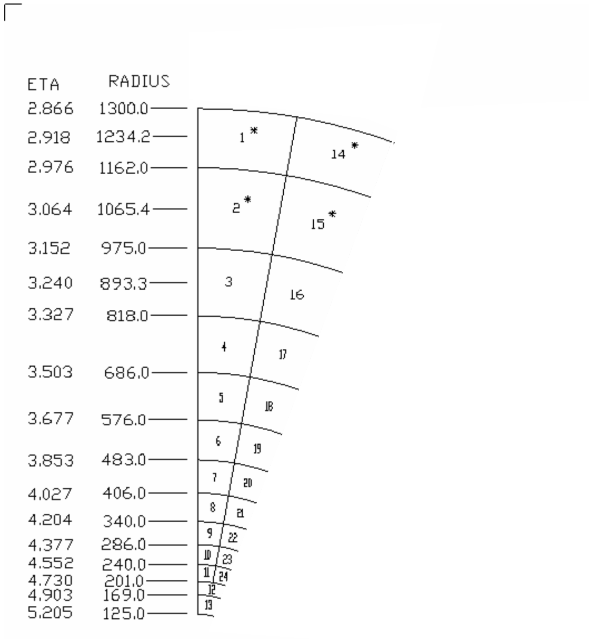
- ..



# HF Calorimeter



- 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.

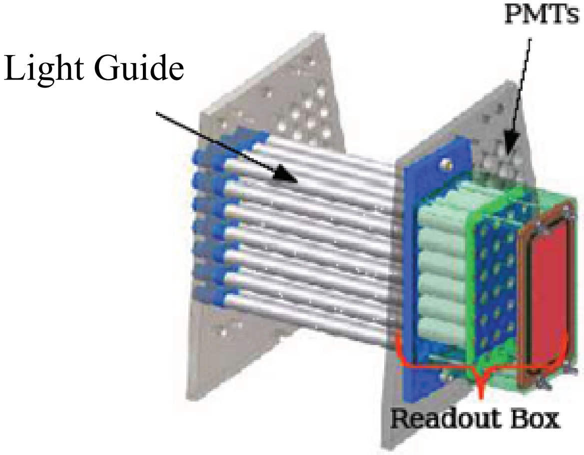


| ETA | RADIUS |
|---|---|
| 2.866 | 1300.0 |
| 2.918 | 1234.2 |
| 2.976 | 1162.0 |
| 3.064 | 1065.4 |
| 3.152 | 975.0 |
| 3.240 | 893.3 |
| 3.327 | 818.0 |
| 3.503 | 686.0 |
| 3.677 | 576.0 |
| 3.853 | 483.0 |
| 4.027 | 406.0 |
| 4.204 | 340.0 |
| 4.377 | 286.0 |
| 4.552 | 240.0 |
| 4.730 | 201.0 |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

- Iron calorimeter, composed of $20^0$ wedges
- Covers 5 > |η| > 3
- Total of 1728 towers
- 2 x 432 towers for EM and HAD
- η x φ segmentation (0.175 x 0.175)

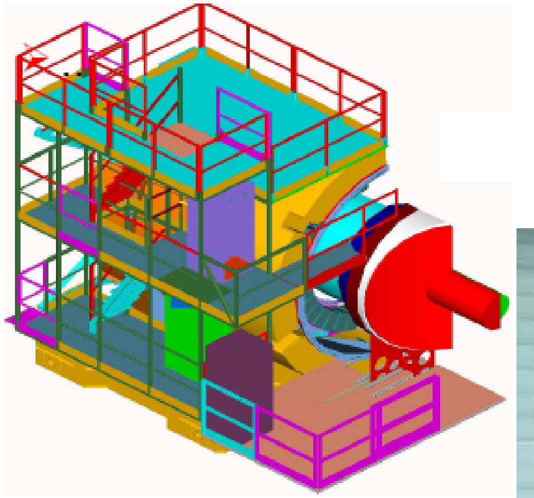
# HF Calorimeter

- Fibers inserted in all 36 wedges



- HF are first Items to be lowered in July 2006

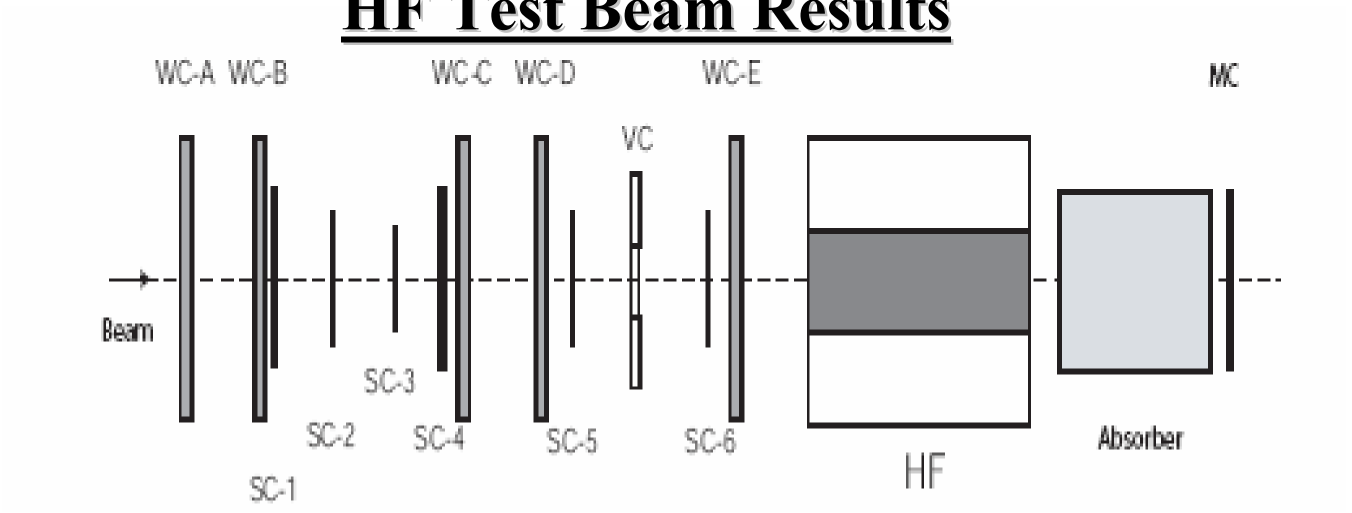
# HF Calorimeter



## HF in 186 Services

# HF Calorimeter

## HF Test Beam Results



- The beam line at the CERN H2 beam line for the HF calorimeter tests.
- A single HF wedge, mounted on a table that could be moved remotely
    - horizontal and Vertical directions
    - tilted in the vertical plane up to 6 degrees with respect to the beam direction.
- The electromagnetic energy resolution is dominated by photoelectron statistics.
    - a = 198%, b = 9%
- The hadronic energy resolution is largely determined by the fluctuations in the neutral pion production in showers,  a = 280% and b = 11%.

***CMS NOTE 2006/044***

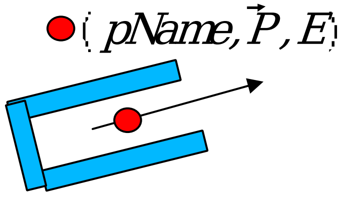
# HF Calorimeter

## Test Beam Verification via Geant4 Simulation

***T.Yetkin, Ph.D. Thesis, 2006***

### Beam Sim.

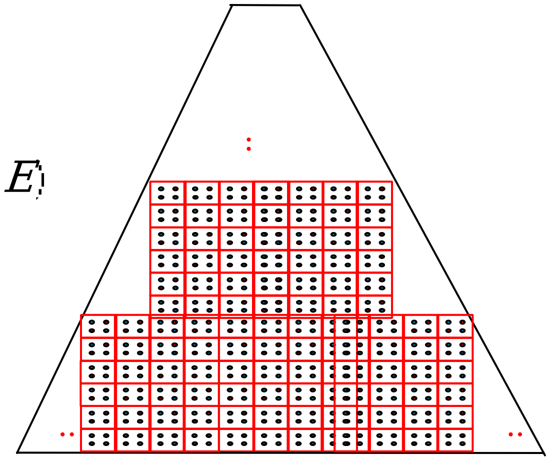
Spatially distributed (randomly to generate square, circle, spherical, etc.) or point-like beam spot. In HF beam spot is square shape.



Gun Position

### Geometry Sim.

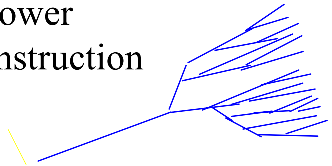
Build geometry as close as possible to the real geometry with same materials. In HF simulation passive material is iron and active material is quartz.

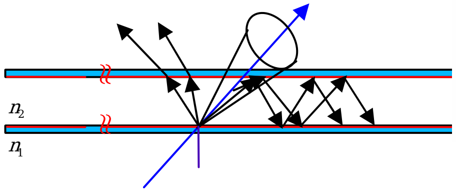


### Physics Sim.

Electromagnetic and Hadronic Physics Simulation with the interface of Physics Lists (matter-particle interactions and showering). Cherenkov process is added externally for the energy loss of charged particles inside quartz fibers.

Shower construction

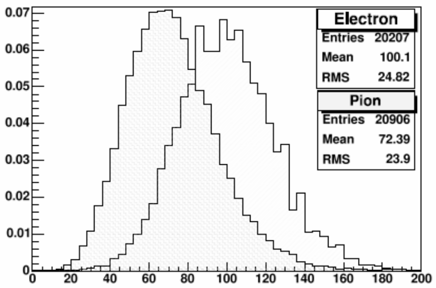




Cerenkov Process

### Analysis

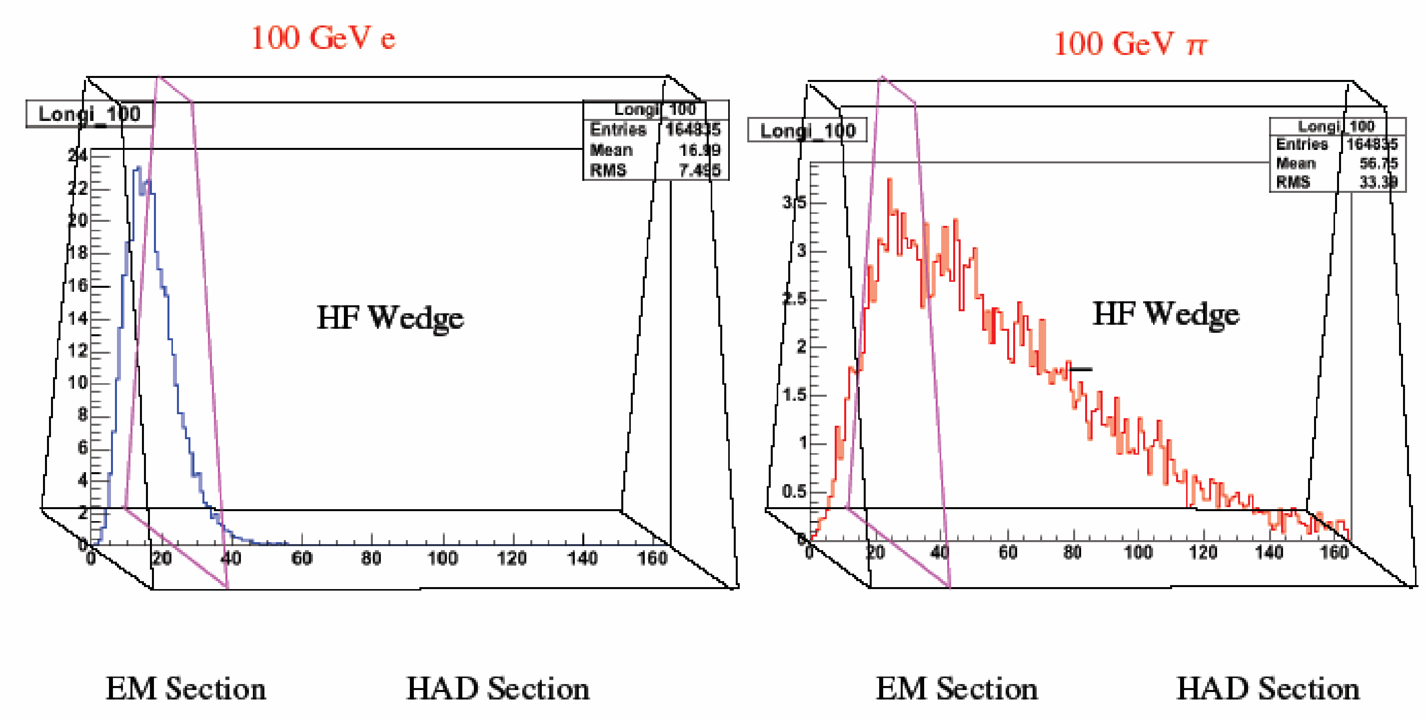
Number of photo-electrons are stored at the end of simulation. Towers are read out separately. ROOT is the package for analysis framework.

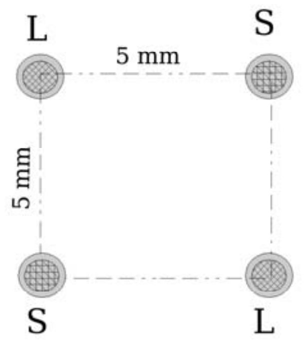


Histograms

# HF Calorimeter

- Active material is quartz fiber (~600μm diameter). Two set of fibers are embedded to the passive material which is steel: Long (165 cm) and Short (143 cm) fibers.





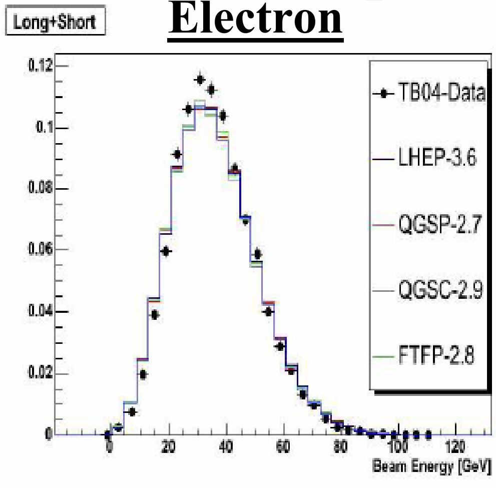
Figures from Geant4 Simulation

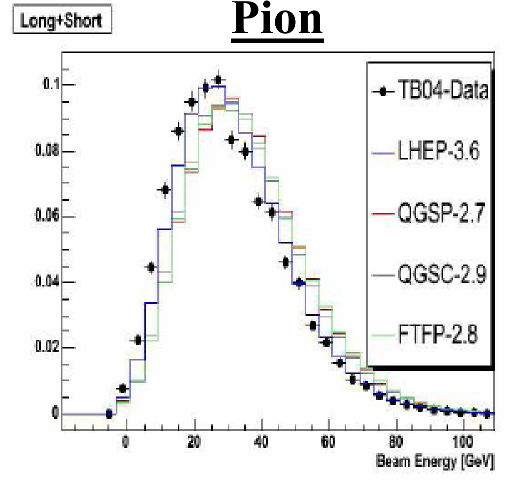
# HF Calorimeter

## Response of HF detector (L+S)

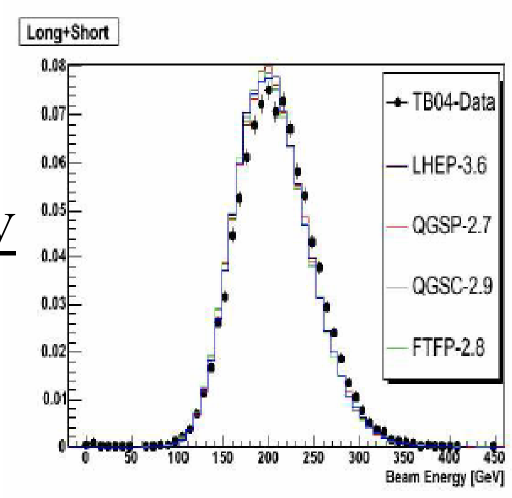
**Electron** **Pion**

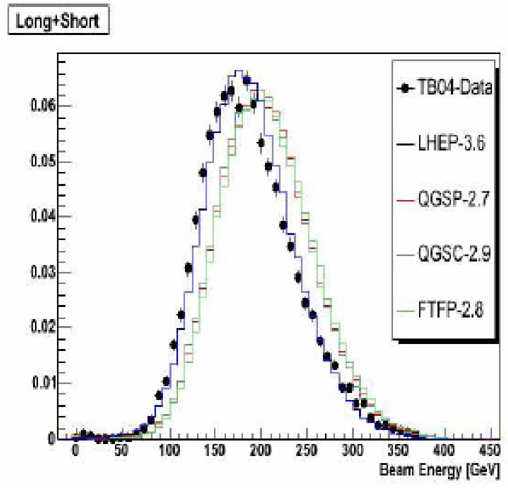
**30 GeV**





**150 GeV**

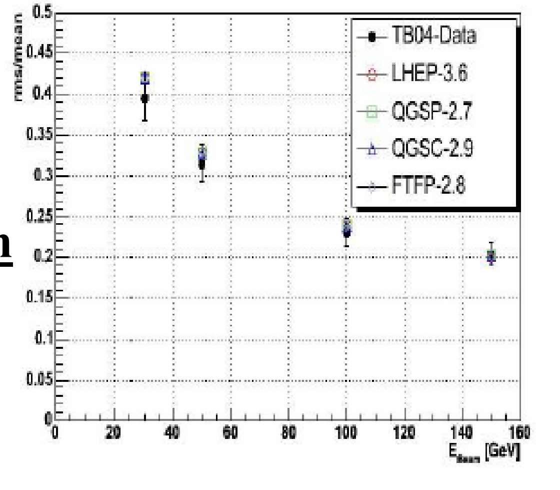




# HF Calorimeter

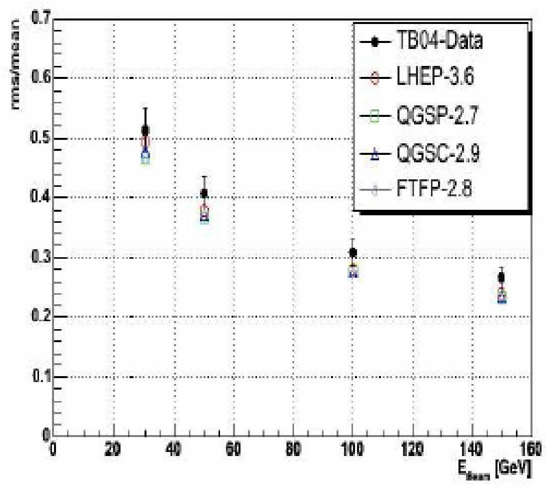
## Energy Resolution (L+S)

**Electron**



| Data | 30 GeV | 50 GeV | 100 GeV | 150 GeV |
|---|---|---|---|---|
| TB04 | 0.396±0.028 | 0.315±0.022 | 0.231±0.016 | 0.204±0.014 |
| LHEP | 0.421±0.001 | 0.329±0.001 | 0.239±0.001 | 0.201±0.001 |
| QGSP | 0.420±0.001 | 0.328±0.001 | 0.240±0.001 | 0.201±0.001 |
| QGSC | 0.421±0.001 | 0.328±0.001 | 0.239±0.001 | 0.203±0.001 |
| FTFP | 0.422±0.001 | 0.328±0.001 | 0.238±0.001 | 0.203±0.001 |

**Pion**



| Data | 30 GeV | 50 GeV | 100 GeV | 150 GeV |
|---|---|---|---|---|
| TB04 | 0.514±0.036 | 0.407±0.029 | 0.309±0.022 | 0.267±0.019 |
| LHEP | 0.495±0.001 | 0.380±0.001 | 0.280±0.001 | 0.241±0.001 |
| QGSP | 0.467±0.001 | 0.368±0.001 | 0.275±0.001 | 0.234±0.001 |
| QGSC | 0.477±0.001 | 0.373±0.001 | 0.276±0.001 | 0.236±0.001 |
| FTFP | 0.466±0.001 | 0.372±0.001 | 0.274±0.001 | 0.232±0.001 |

# HF Calorimeter

## Response Linearity

- Linearity is the measure of detector response and it is defined as the ratio of measured energy to incoming beam.

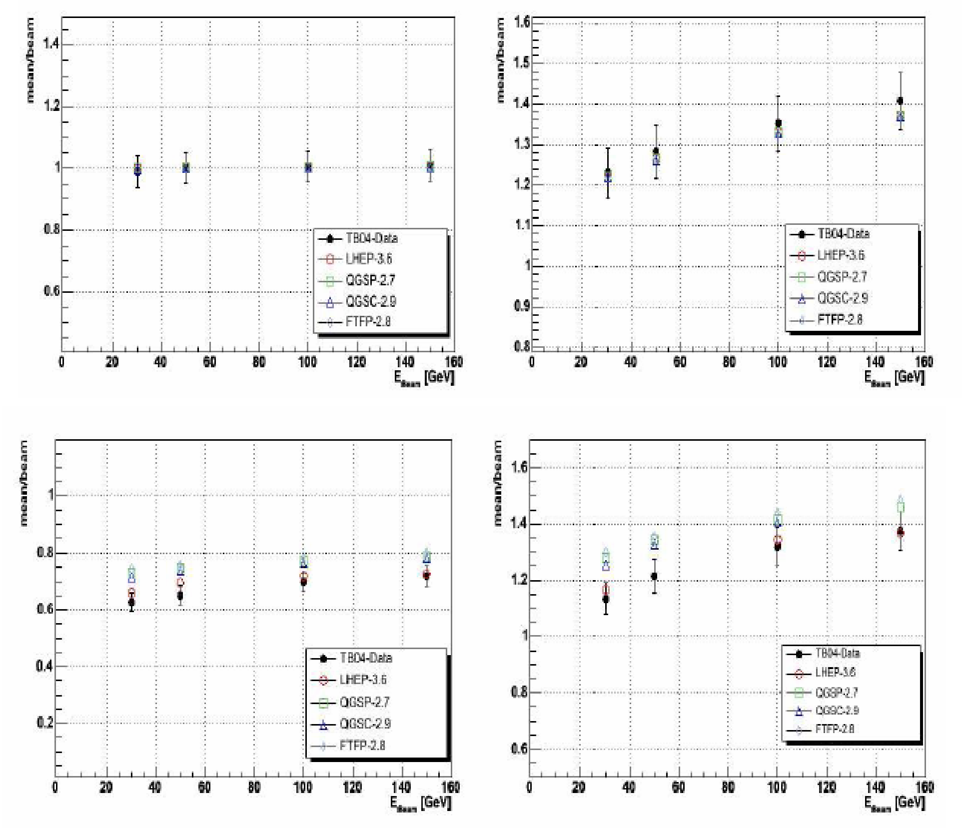
- HF response is constant when electrons are measured with the long fibers only. However with the increased energy the short fibers start to register energy and it becomes non-linear. For pions the non-linearity is seen in both cases. The simulation results are agree with the test beam data.

**Long**

**Short**

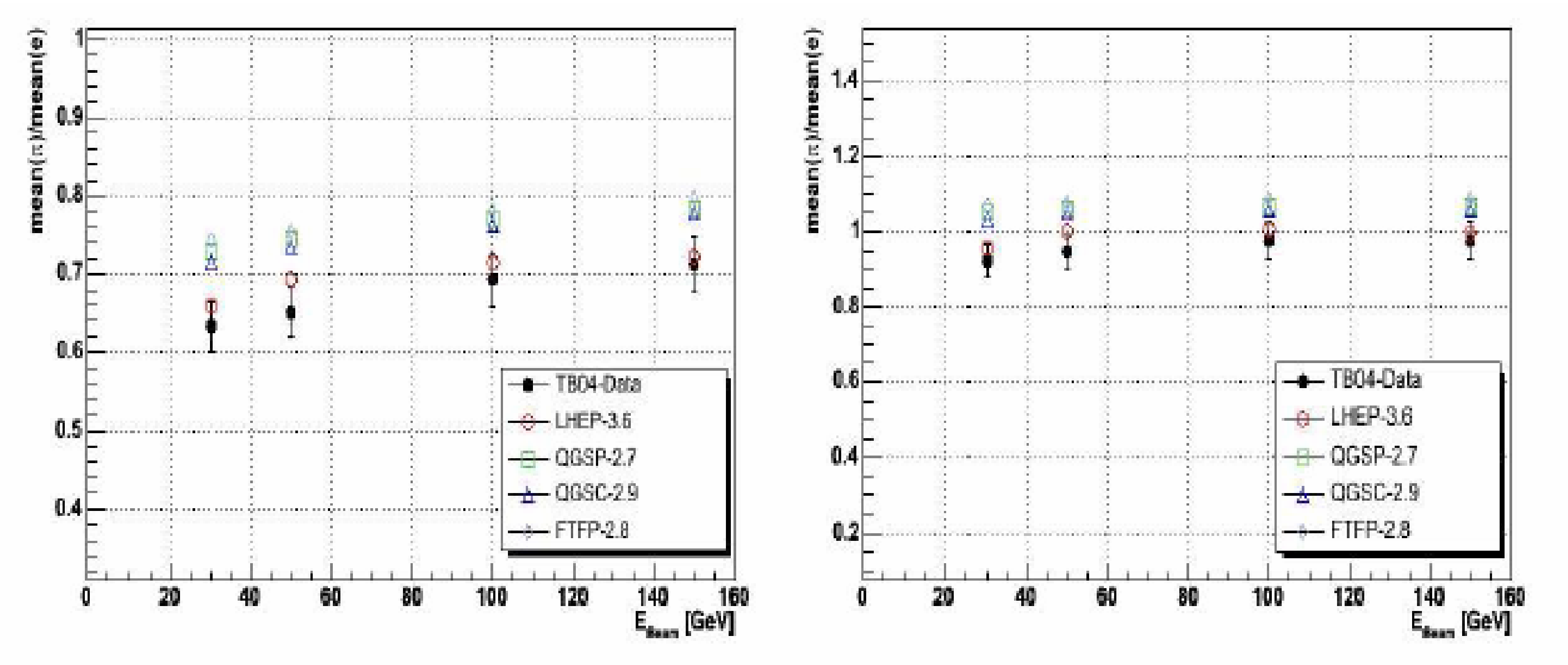
**Electron**

**Pion**



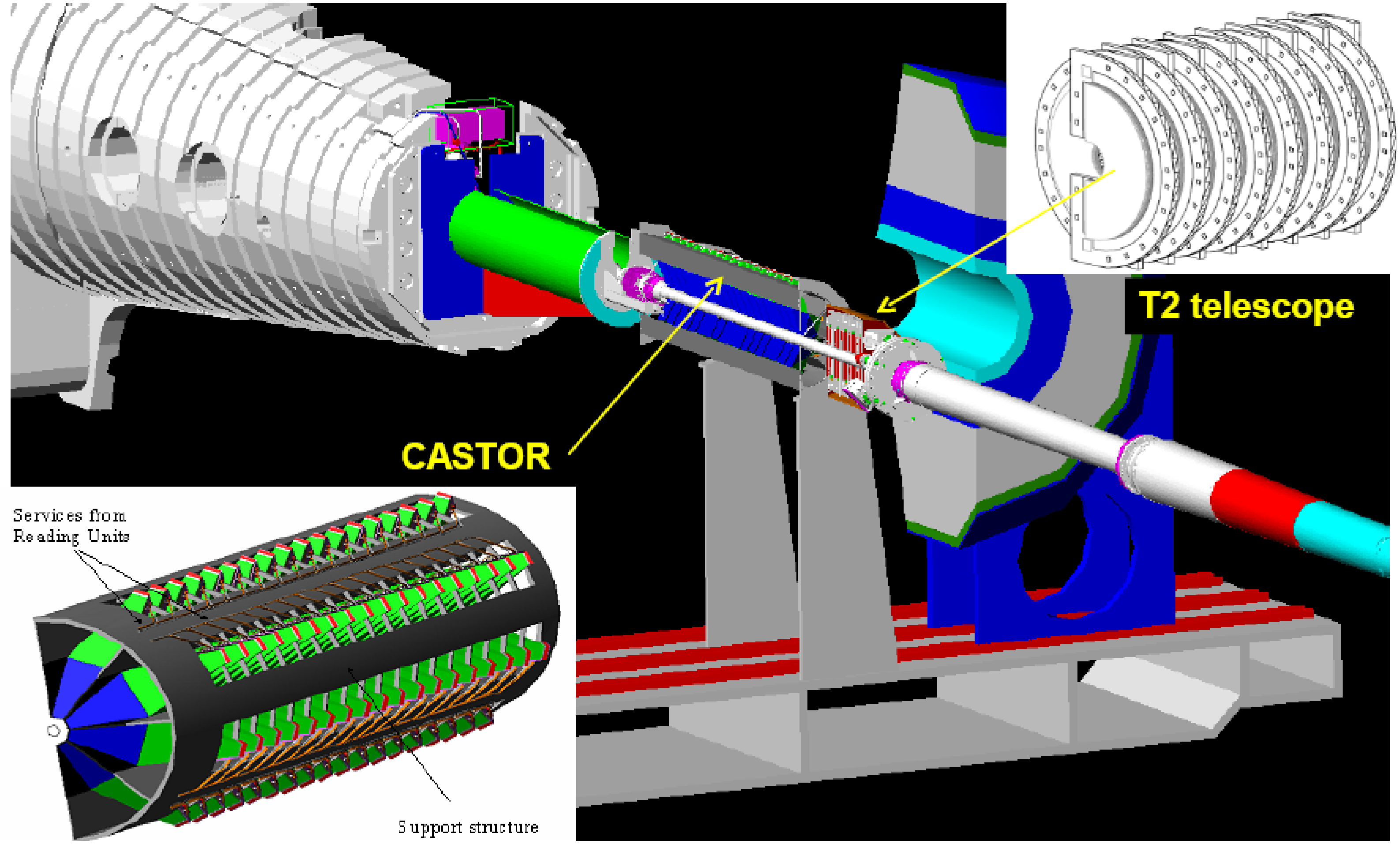
# HF Calorimeter

## pion/electron Ratio



- Taking the short fiber into account makes HF pi/e ratio independent from energy.

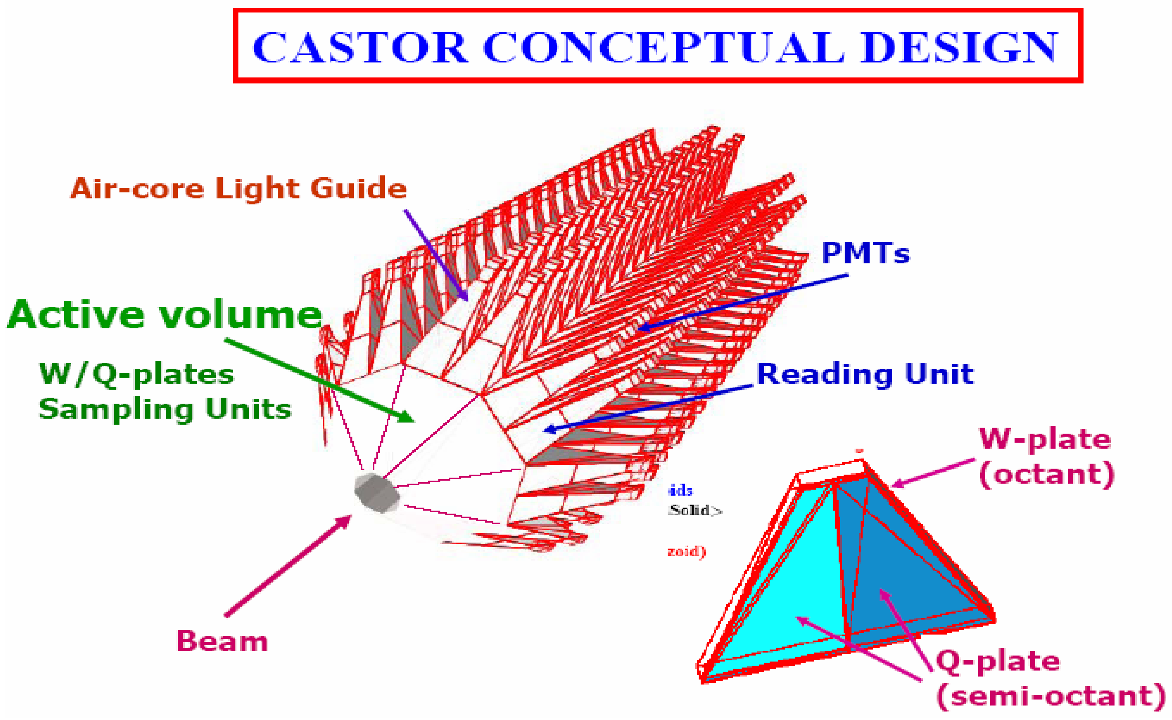
# CASTOR Calorimeter



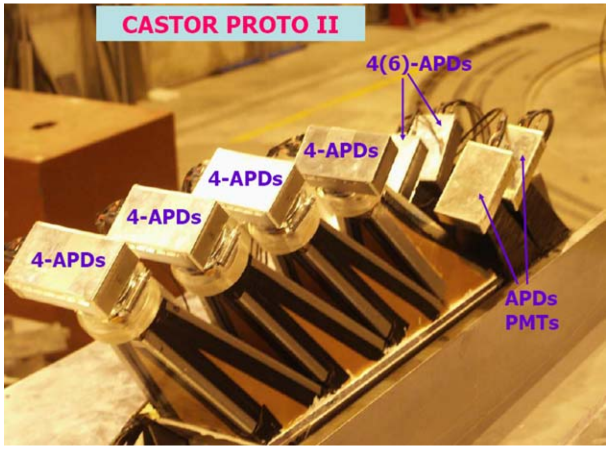
- Each set of tungsten and quartz plates covers 45$^0$ in azimuth. There are two 22.5$^0$ quartz plates for each tungsten plate. The light from 7 quartz plates collected by a light guide and directed to a PMT.

# CASTOR Calorimeter

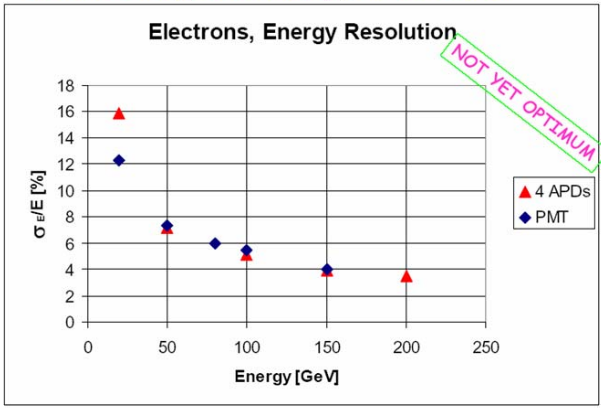
## Prototype and Test Results



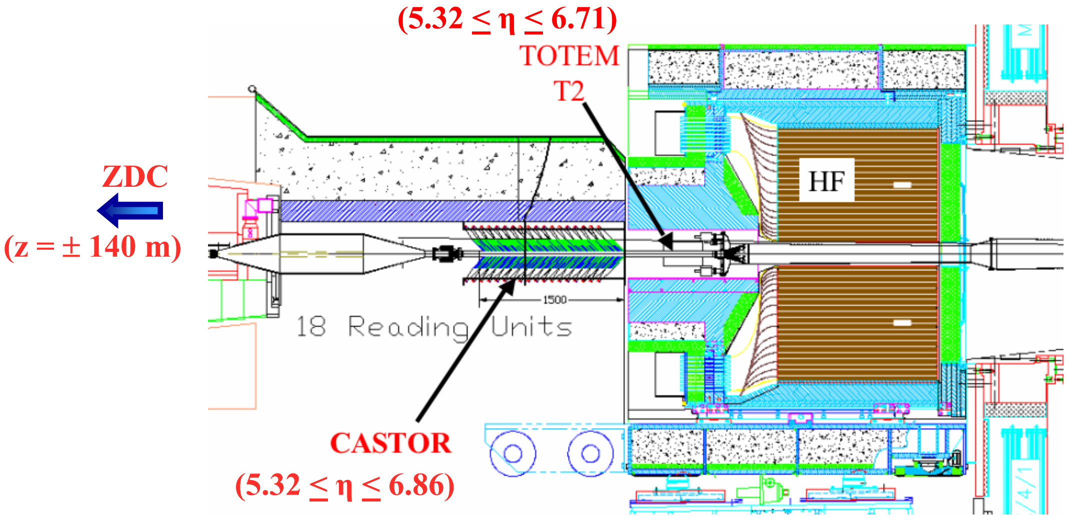
http://cms.doc.cern.ch/castor/

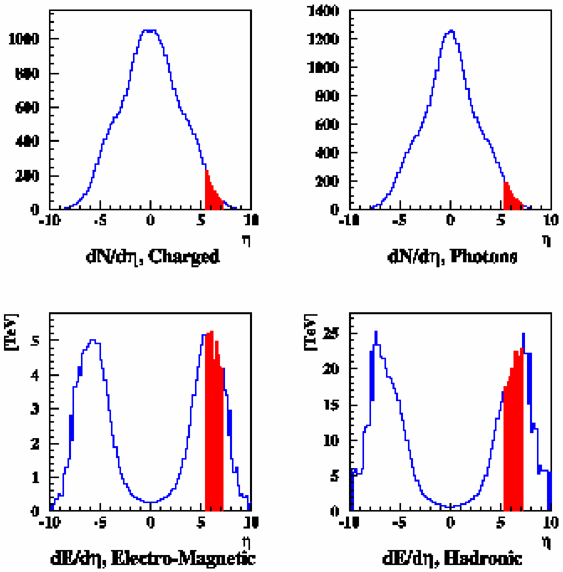


Electron Energy Resolution:(4)APDs vs PMTs



# CASTOR Calorimeter





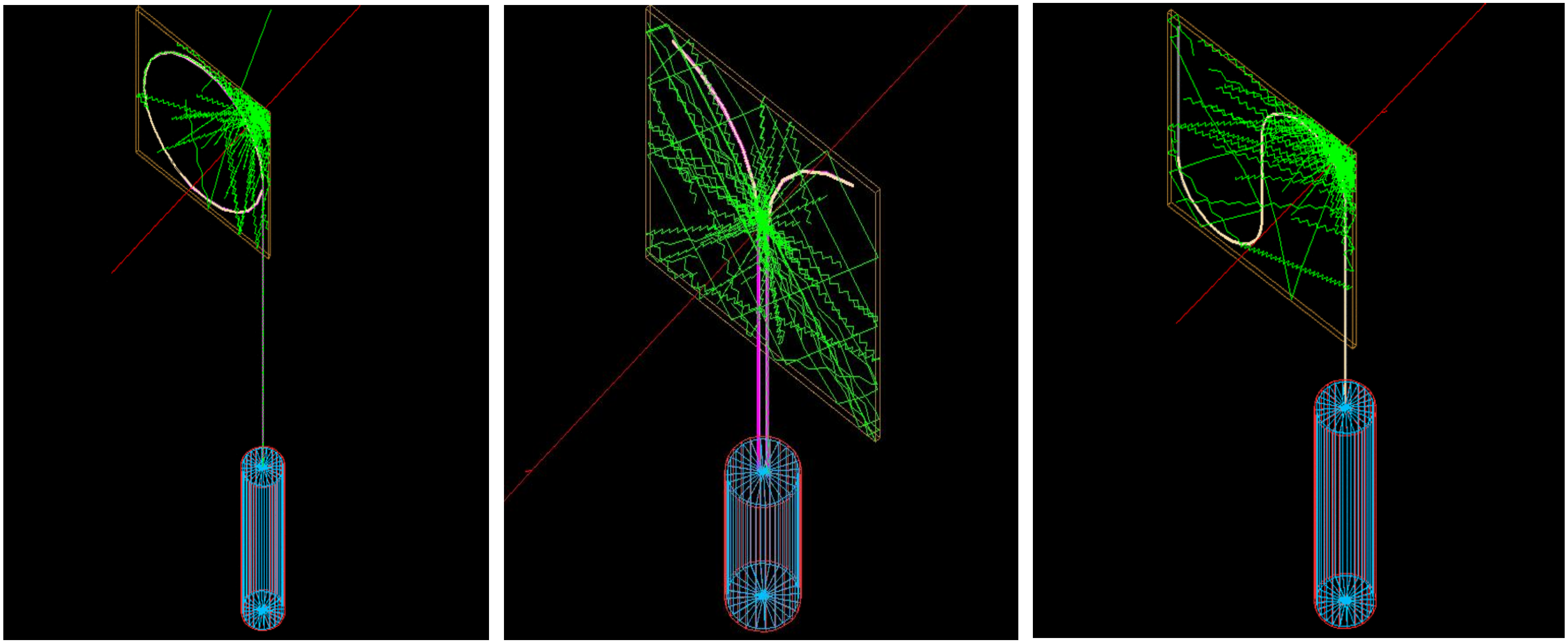
- Near Hermetic coverage (out to |η|<7 with CASTOR)
- Physics
  - Centrality
  - Nuclear PDFs - particularly gluon distributions
  - Momentum fractions x ~ $10^{-6}$ – $10^{-7}$ at scales of a few $\mathrm{GeV}^2$ in pp
  - Diffractive processes (10-20% of total cross section at high energies)
  - Limiting Fragmentation
  - Peripheral and Ultra-Peripheral collisions
  - DCC, Centauros, Strangelets ……

# HE Upgrade for SLHC

- The Super LHC scenarios requires a detector upgrade on CMS HE Calorimeter. Due to the radiation damage problem on the scintillators.
- Quartz plates are proposed as a substitute for the scintillators at the Hadronic Endcap (HE) calorimeter.
- With the quartz the light is from Cerenkov radiation. The number of Cherenkov photons created in quartz is ~1-2% of the scintillation photons in a regular HE plate.
- We have been performing some R&D studies to develop a highly efficient method for collecting Cerenkov light in quartz with wavelength shifting fibers.
- We are also constructing a prototype calorimeter, fist 6 layers have been tested at Fermilab test beam. This summer we’ll take whole prototype to Cern test beam.

# HE Upgrade for SLHC

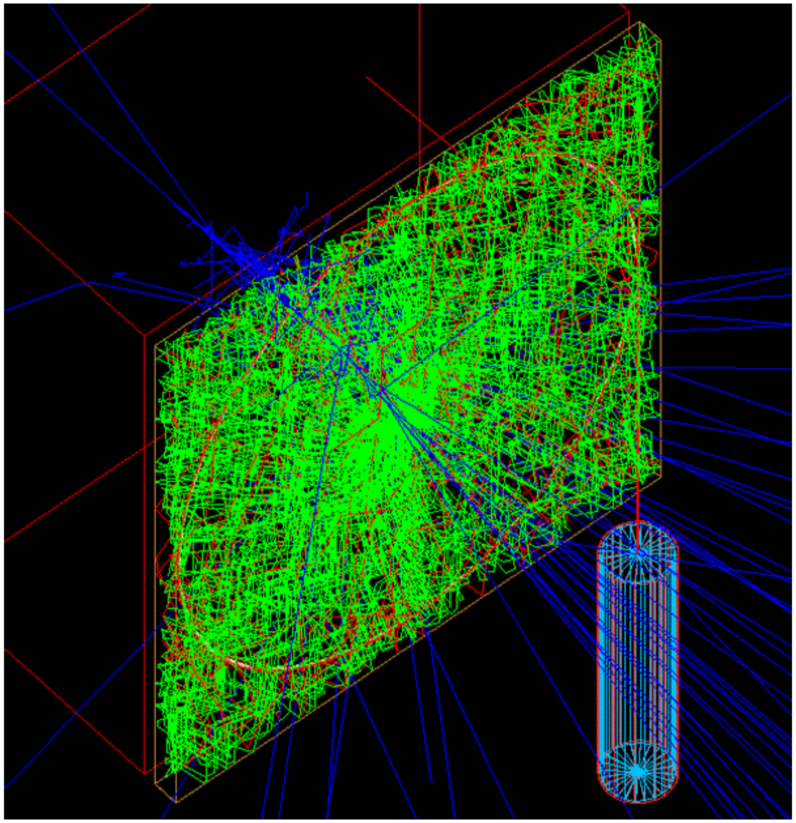
## Collecting Cerenkov Light in Quartz Plates



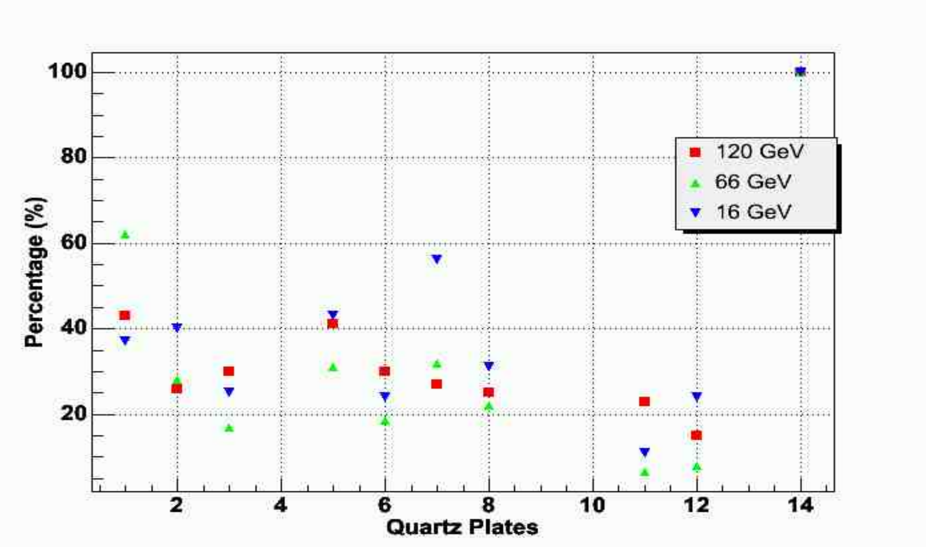
- We have tested/simulated different fiber geometries in the quartz plates, for their light collection uniformity and efficiency.

# HE Upgrade for SLHC

## Test Beam Results and Simuations



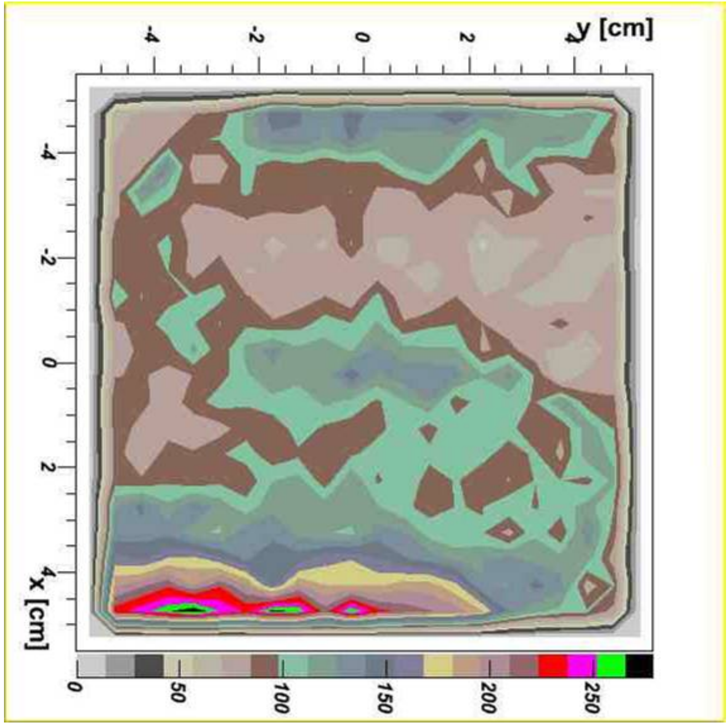
- WaveLength Shifting (WLS) fiber, Bicron 91a, is embedded in the quartz plate. Quartz plates are wrapped with reflecting material of 95 % efficiency.
- The Cerenkov photons reaching the PhotoMultiplierTube (PMT) are counted.
- Cerenkov Photons are shown in green. Photons emitted by WLS process are shown in red.
- At the test beams we compared the light collection efficiencies with that of original HE scintillators.

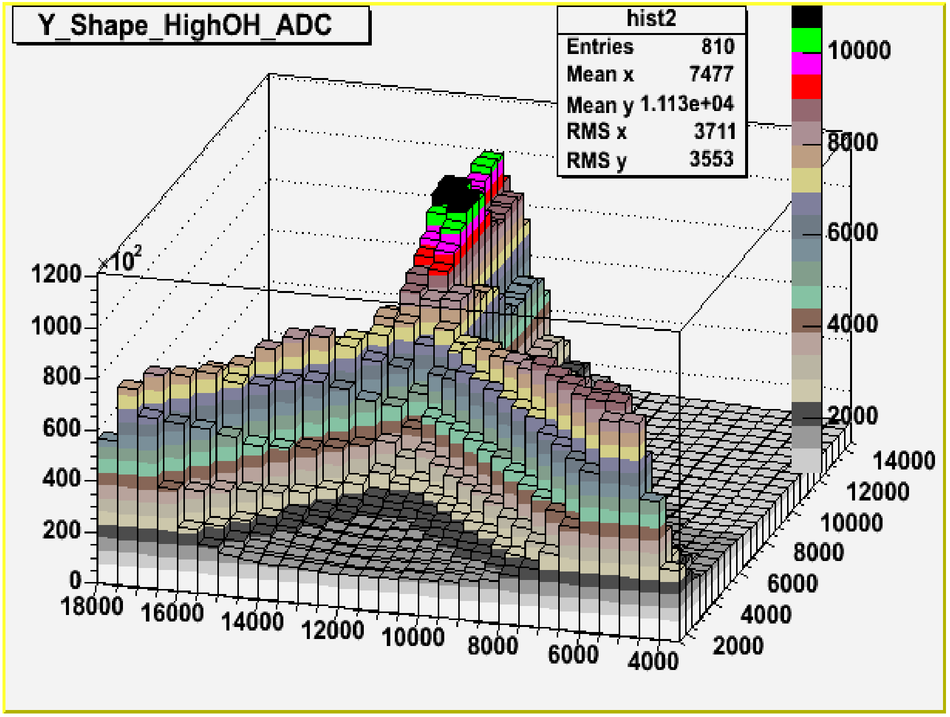


# HE Upgrade for SLHC

## Surface Uniformity Tests and Simulations

- We simulated the collected light with 4 GeV electron beam and counted the number of wavelength shifted photons reaching the PMT.
- We also performed bench tests on the light collection uniformity with different light sources.

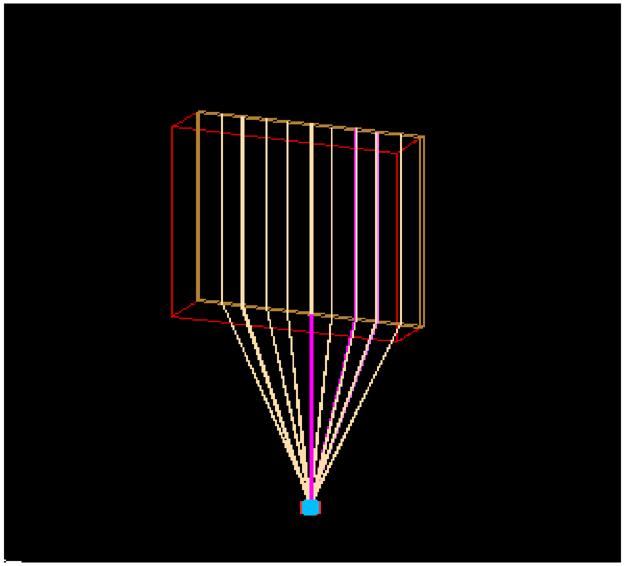




# HE Upgrade for SLHC

## The Final Fiber Geometry

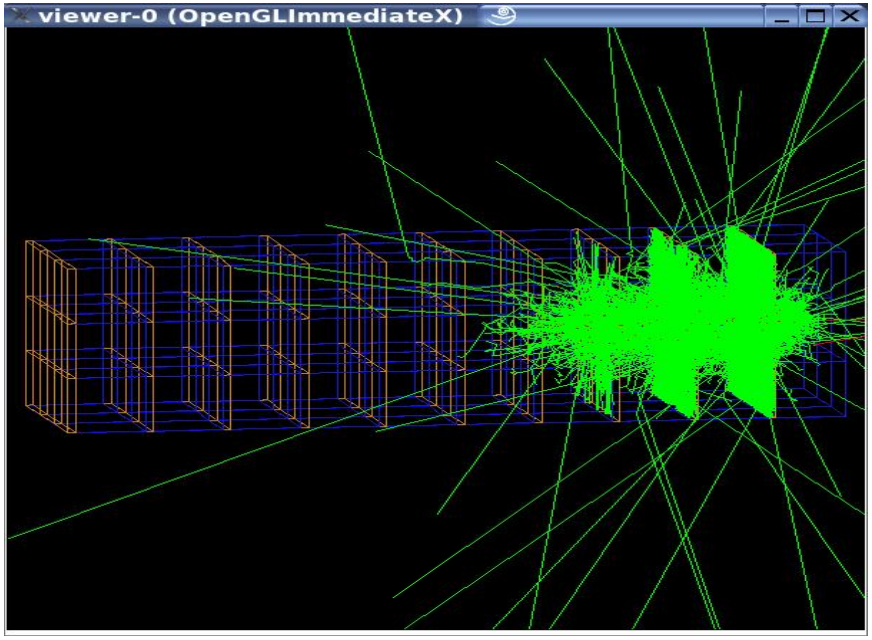
- We used the “chosen” geometry on the prototype.
- The signal is read by Hamamatsu R7525 PMTs
- The fibers are 1mm diameter Bicron wavelength shifting fibers. They absorb photons down to 280 nm, emit 435 nm.
- The fibers go ~20 cm out of the quartz.

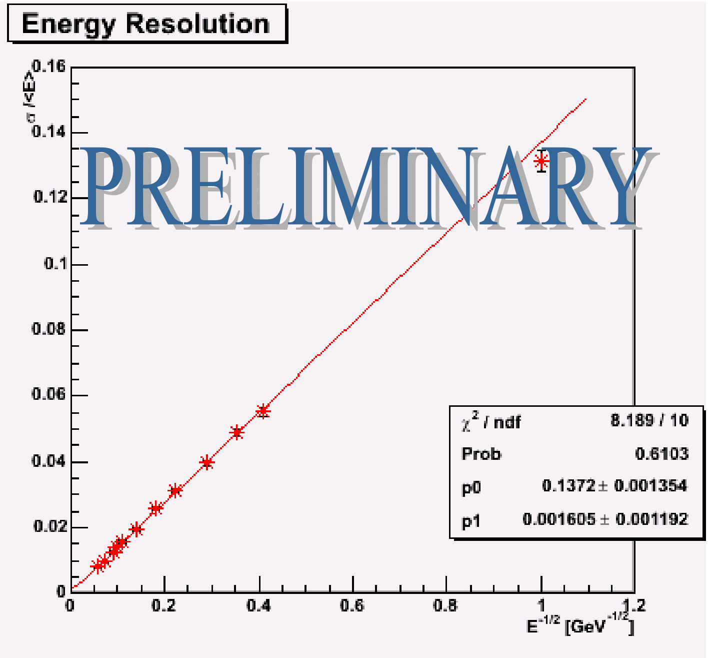


# HE Upgrade for SLHC

## The Calorimeter Prototype Design and Simulations

- R&D results and initial model shaped the prototype.
- The final design:
  - 20cm x 20cm, 20 layers 70 mm iron, 5 mm quartz
  - Should be portable for tests at CERN, Fermilab, and Iowa
  - The Cerenkov light is collected by wavelenght shfting fibers and carried to the Hamamatsu R7525 PMT.

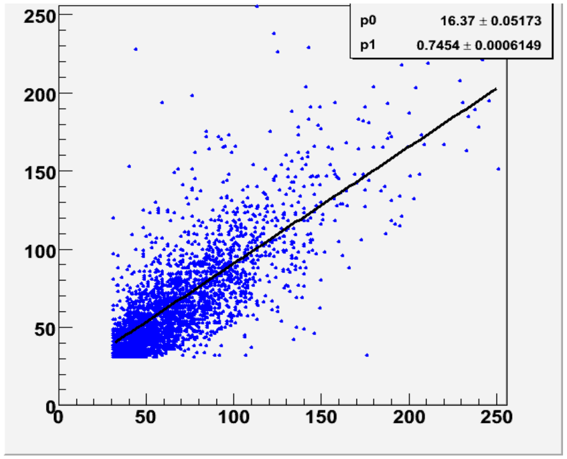


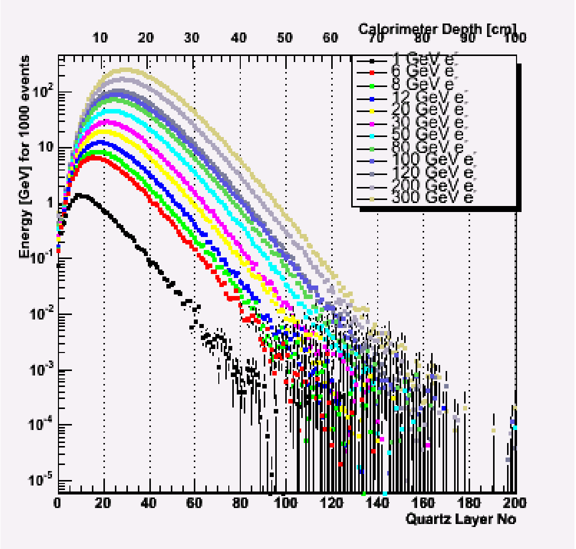


# HE Upgrade for SLHC

## Prototype Test Beam at Fermilab M-Test

- On Feb. 2006 we tested first 6 layers of the calorimeter at Fermilab M-Test.
- The preliminary results are encouraging, we collect cerenkov photons as many as 75% of the scintillation photons.
- We'll have beam time at Cern this summer for the whole calorimeter.





# Cerenkov Compensation Precision Calorimetry

- Basic Idea:
  - Cerenkov Light is most sensitive to electrons (photons)
  - Ionization sensitive to neutrons, hadrons, electrons
  - Use these 2 measurements to correct calorimeter energy – stochastic & constant terms

- Detect both Cerenkov Signal Ec and Ionization Ei on the same shower.
- For pure e-m showers, normalize the detected energies so that Ei = Ec = Eem.
- For hadrons, only when only $p^0$ are produced does Eh ~ Ei ~ Ec.
- As Eh fluctuates more into n, $p^{+-}$, etc., Ec decreases faster than Ei.
- On an Ec vs Ei scatter plot, the fluctuation is correlated/described by a straight line with slope $a<1$, from which the constant a is defined by $a = a/(1+a)$.
- The Ec vs Ei correlation yields an estimate of the compensated E as:

$$Ecomps = Ei + a(Ei-Ec),$$

where the constant a is different for each calorimeter material/design.

- For electrons, Ecomps = Ei = Ec, since (Ei-Ec) = 0
- No “suppression” needed for compensation, thus more active material can be used, up to 100%, thus reducing the stochastic term.
- Two independent measurements enable tuning the constant term to near zero.

**References:**
**D. R. Winn, W. A. Worstell, IEEE TNS, 36, 334, 1989**
**Y. Onel, D. Winn, 2004 LCRD Proposal**
**R. Wigmans et al., 2005 LCRD Proposal**
**T. Zhao, A. Para, 2006 LCRD Proposal**

# Conclusion

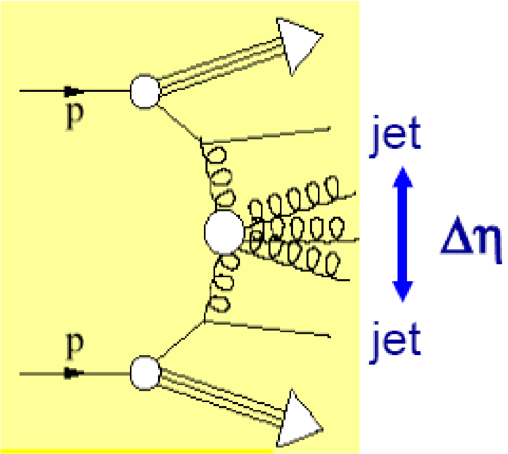
- We have developed the technology for radiation hard calorimeters using quartz fibers and quartz plates.
- Studied in detail the radiation hardness of quartz core material with proton, neutron, gamma, and electron beams.
- Built the CMS-PPP-I, CMS-HF, and also working on the CMS-ZDC, CMS-CASTOR, and CMS-HE upgrade detectors.
- We have simulated the above detectors with Geant4 and compared the results with the test beams.

# Backup Slides

# Low-x measurements with HF

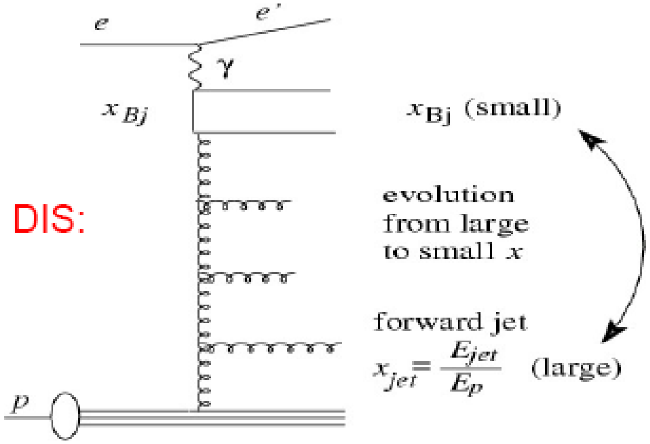
- Forward jet production (“Mueller-Navelet” BFKL jets):

hadron-hadron



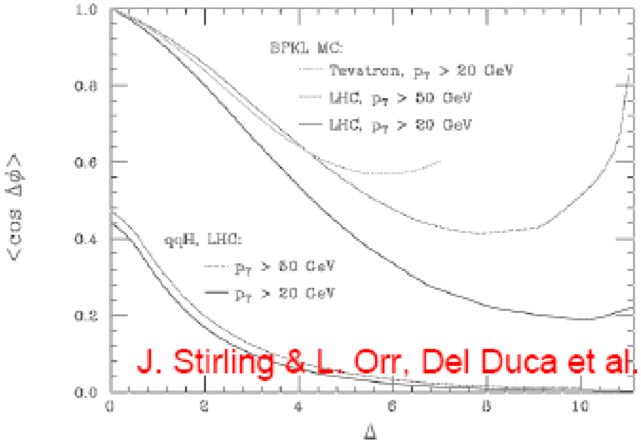
A.Roeck, Blois'03

DIS:



Azimuthal decorrelation between the 2 jets versus rapidity distance between the 2 jets:

Large Δη range required



J. Stirling & L. Orr, Del Duca et al.

# CMS Coverage

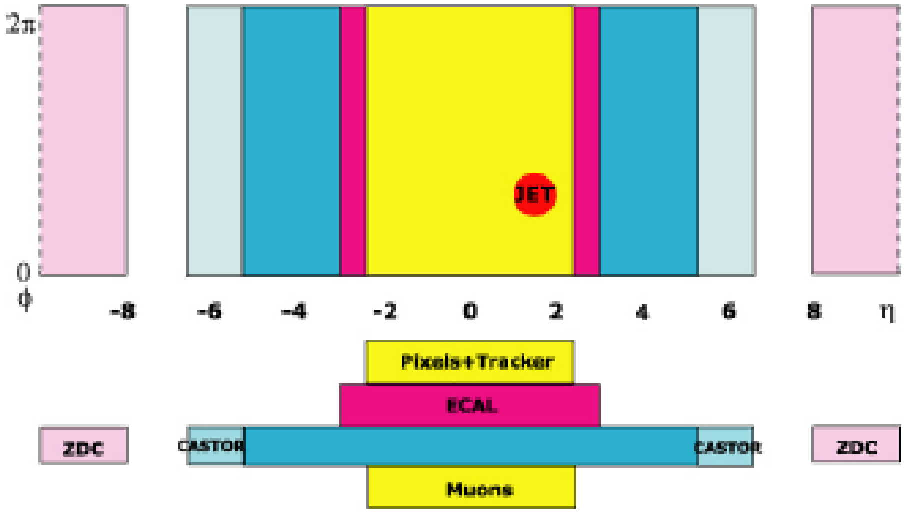


Figure 1: The coverage in pseudorapidity and azimuthal angle of the various detectors in CMS