The CMS Hadronic Calorimeters

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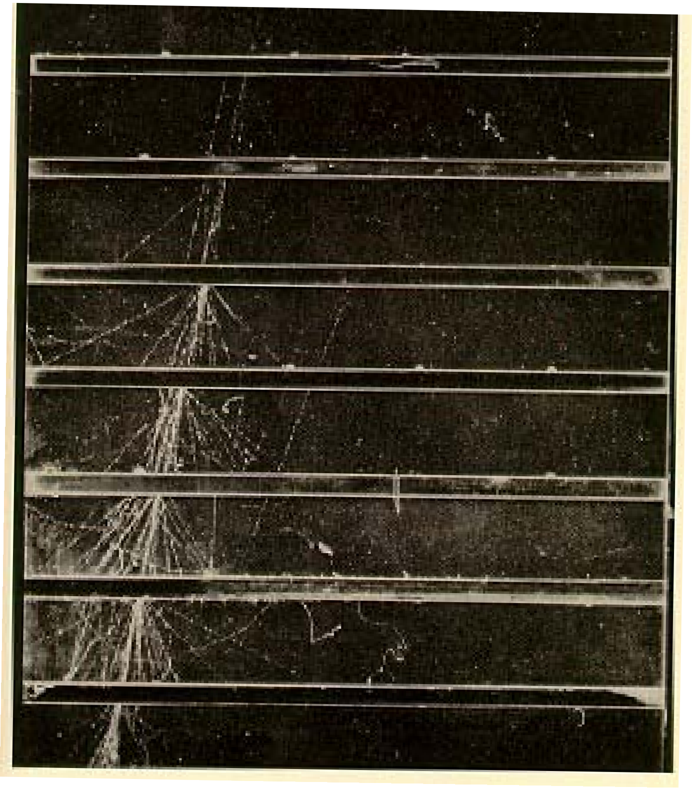
Energy Loss in Materials

Absorption of the incident energy is via a cascade process leading to *n* secondary particles, where $\langle n \rangle \propto E_{INC}$

Sampling calorimeter consists on alternating layers of "absorbers" and "active" material



- ***Electromagnetic shower energy loss through Bremstrahlung and pair production***
- ***Pair production continues until photons' energy is too low to produce pairs***
- ***Low energy particles dissipate energy through ionization***

Scintillator samples the number of particles in each layer → *energy*

Hadronic Showering

Hadronic showering is more complicated than EM showering

Involves strong and weak interactions

Shower development is characterized by the mean free path between inelastic collisions (the nuclear interaction length, λ_{Int})

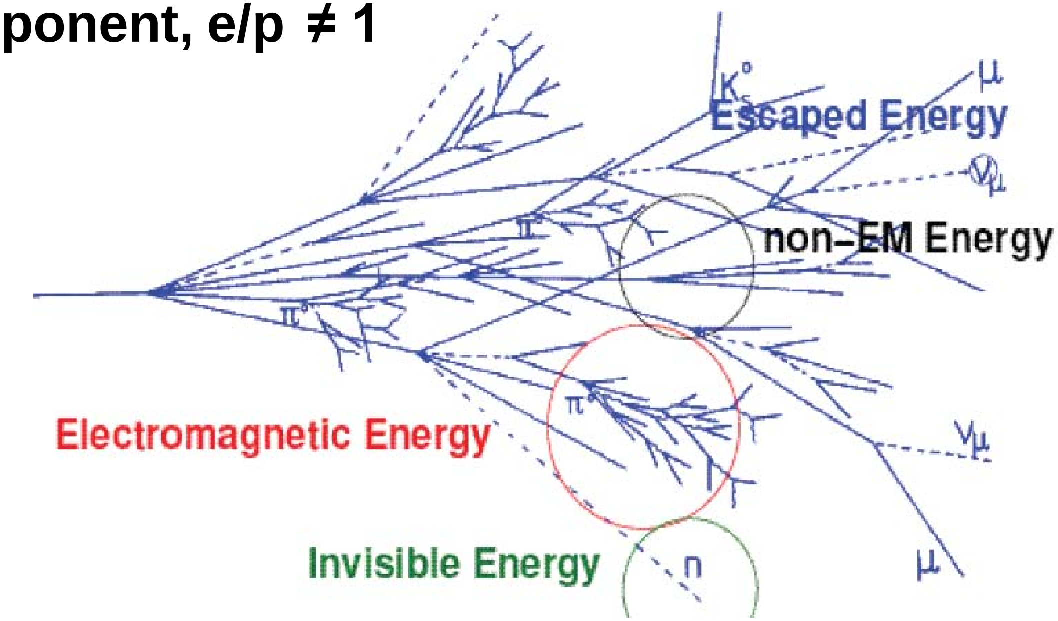
High energy hadrons interact with nuclei producing secondary particles (mostly $\pi^{\pm}, \pi^{0}$) *~1/3 of the pions produced are π^0 which decay $\pi^0 \rightarrow \gamma\gamma$*

Cascade has EM and HAD component, e/p ≠ 1

Neutrinos escape undetected

Muons unlikely to Bremstrahlung and dissipate energy

Long lived particles (KS, KL, Λ) may escape before decaying or interacting



Energy Resolution

The calorimeter energy resolution can be parameterised as:

$$\sigma_E / E = a / \sqrt{E} \oplus b / E \oplus c$$

(where ⊕ denotes a quadratic sum)

The first term is the *stochastic term* arising from fluctuations in the number of signal generating processes (includes photo-electron statistics in a photodetector)

The second term is the *noise term* and includes:

- ***Noise in the readout electronics***
- ***Fluctuations in 'pile-up'***

The third term is a *constant term* and includes:

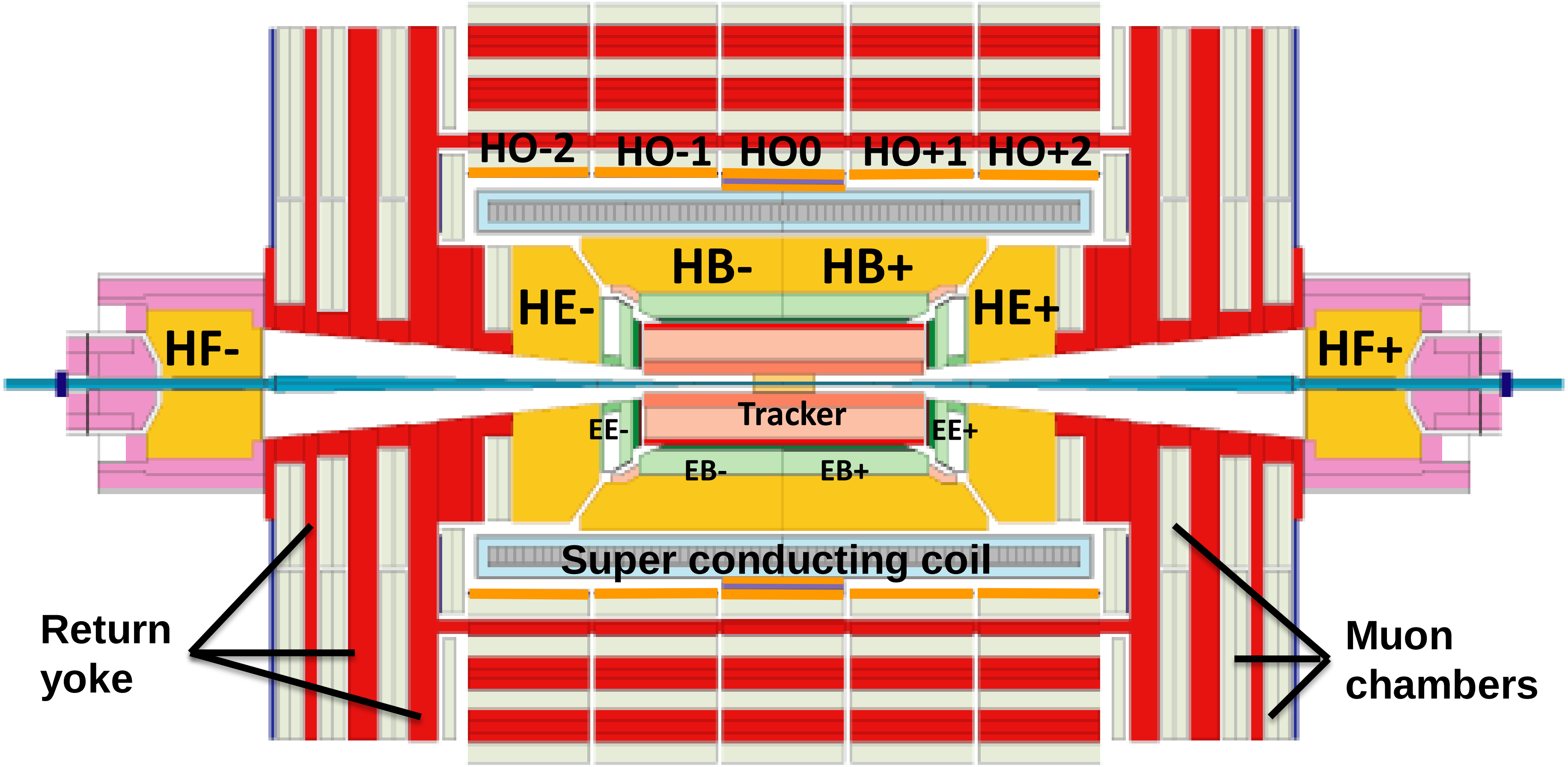
- ***Imperfections in calorimeter construction***
- ***Non-uniformities in signal collection***
- ***Channel to channel inter-calibration errors***
- ***Fluctuations in longitudinal energy containment***
- ***Fluctuations in energy lost in dead material before or within the calorimeter***

Calorimeter Resolution

Experiment	Material (HAD)	Resolution EM	Resolution HAD
ZEUS	Uranium – Scintillator	$17\%/\sqrt{E}$	$35\%/\sqrt{E}$
H1	Lead/Steel – Liquid Argon	$11\%/\sqrt{E} \oplus 1\%$	$50\%/\sqrt{E} \oplus 2\%$
CDF	Iron – Scintillator	$13.5\%/\sqrt{E} \oplus 2\%$	$50\%/\sqrt{E} \oplus 3\%$
DØ	Uranium – Liquid Argon	$15\%/\sqrt{E}$	$45\%/\sqrt{E} \oplus 4\%$
CMS	Brass - Scintillator	$2.8\%/\sqrt{E} \oplus 0.3\%$	$100\%/\sqrt{E} \oplus 4.5\%$
Atlas	Copper – Liquid Argon	$10\%/\sqrt{E} \oplus 0.2\%$	$50\%/\sqrt{E} \oplus 3\%$

CMS Calorimeter

CMS Calorimeter (ECAL+HCAL) - Very hermetic (>10λ in all η, no projective gap)



HB	Brass Absorber (5cm) + Scintillator Tiles (3.7mm)	Photo Detector (HPD)	|η| 0.0 ~ 1.4
HE	Brass Absorber (8cm) + Scintillator Tiles (3.7mm)	Photo Detector (HPD)	|η| 1.3 ~ 3.0
HO	Scintillator Tile (10mm) *outside of solenoid*	Photo Detector (HPD)	|η| 0.0 ~ 1.3
HF	Iron Absorber + Quartz Fibers	Photo Detector (PMT)	|η| 2.9 ~ 5.2

HCAL Barrel (HB)

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

Coverage: $|\eta| < 1.3$

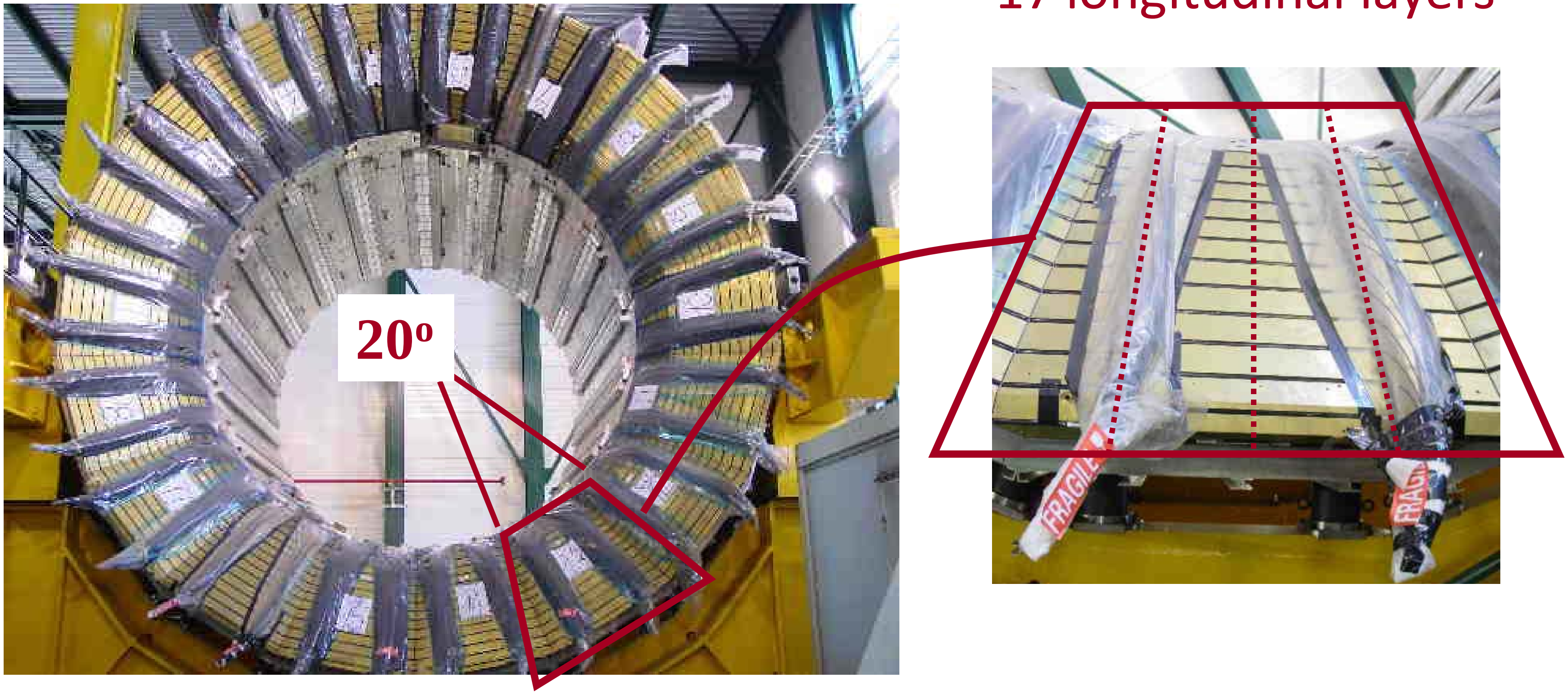
Depth: $5.8\,\lambda_{int}$ (at $\eta=0$)

π resolution: $\sim 90\ \%/\sqrt{E}$

Segmentation:

$\phi \times \eta = 0.087 \times 0.087$

17 longitudinal layers



HCAL Endcap (HE)

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

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

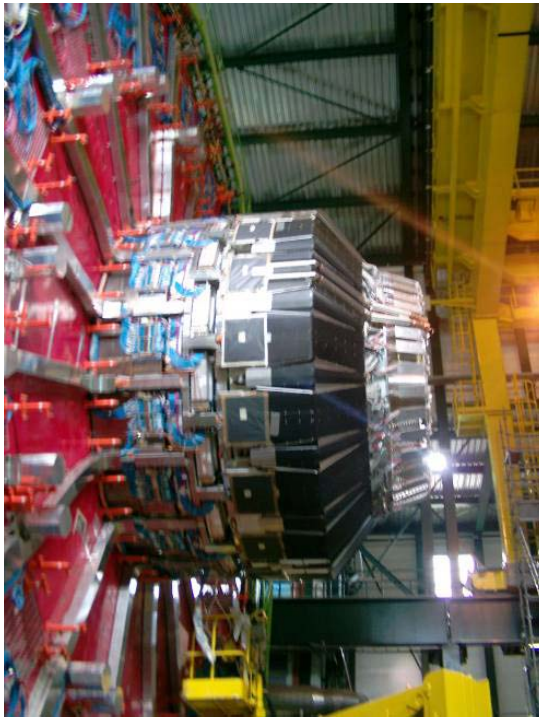
Depth: $10\ \lambda_{int}$

π resolution: $\sim 100\% / \sqrt{E}$

Segmentation:

$\phi \times \eta = 0.087 \times 0.087$

19 longitudinal layers



Barrel (HB) and Endcap (HE) Calorimeters

Similar technology used for HB and HE calorimeters

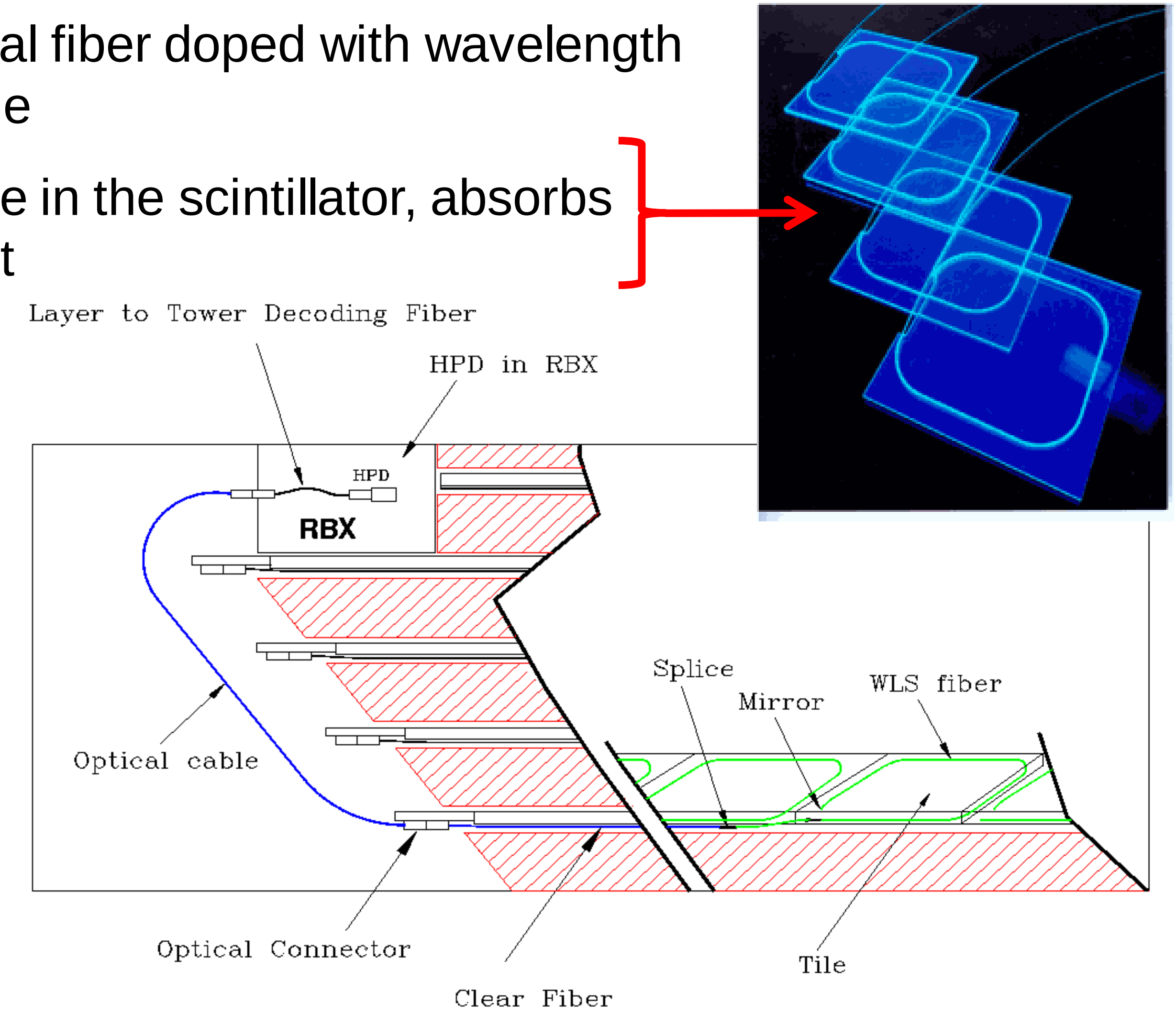
Light readout via an optical fiber doped with wavelength shifter acting as light guide

Fiber is placed in a groove in the scintillator, absorbs scintillator light, re-emits it

Passive layers of brass to induce showering

About 5% of the light is captured in the fiber

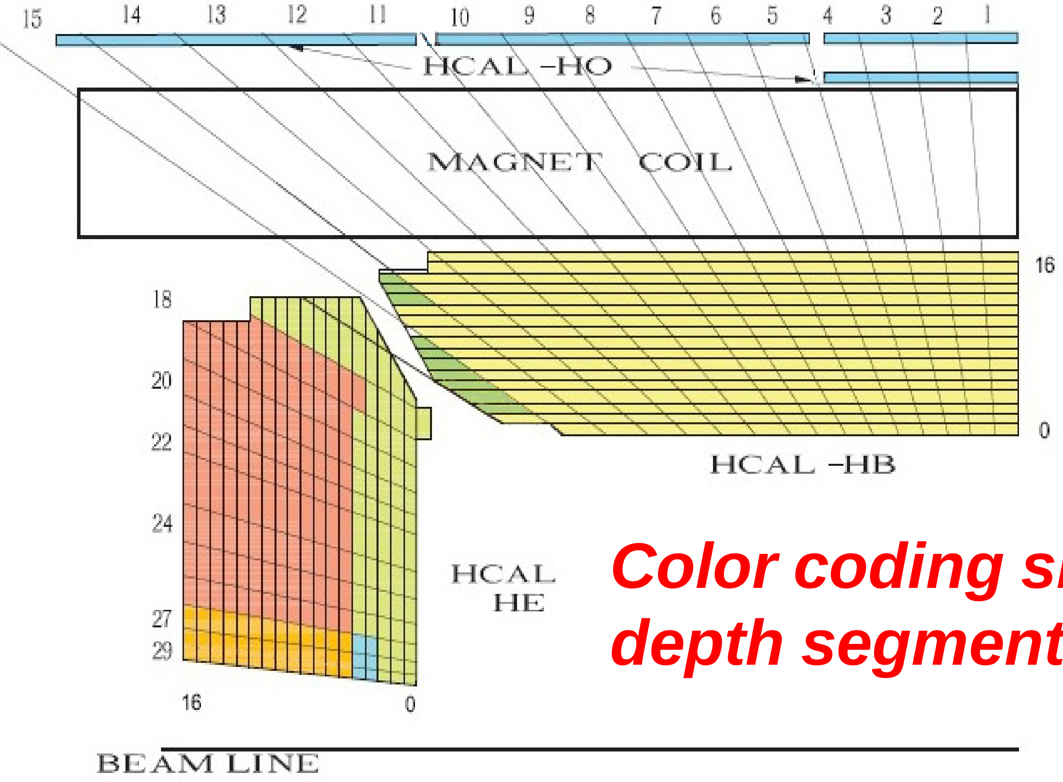
Fibers sent to a Hybrid PhotoDiode (HDP) with 19 or 73 channels/device



Outer HCAL (HO)

In the central region (|η|<1.3) HB does not fully contain very energetic hadron showers

Additional scintillator layers (HO) are located outside the solenoid *(which acts as an absorber)*



HO used to identify late starting showers and measure energy deposited after HB

Color coding shows depth segmentation

Outer HCAL (HO)

Sampling calorimeter: magnet+yoke (passive) & scintillator

Coverage: $0 < |\eta| < 1.3$

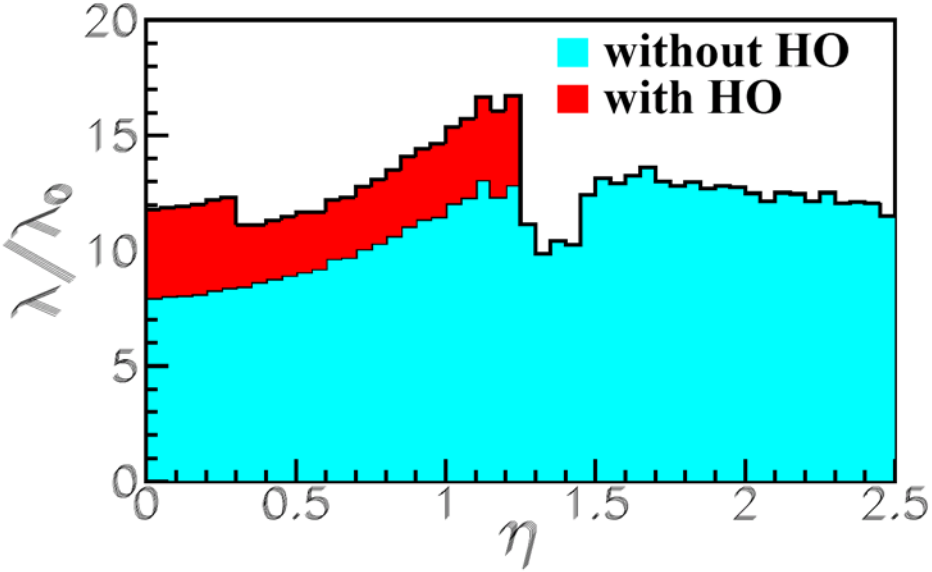
Depth: $10\ \lambda_{int}$

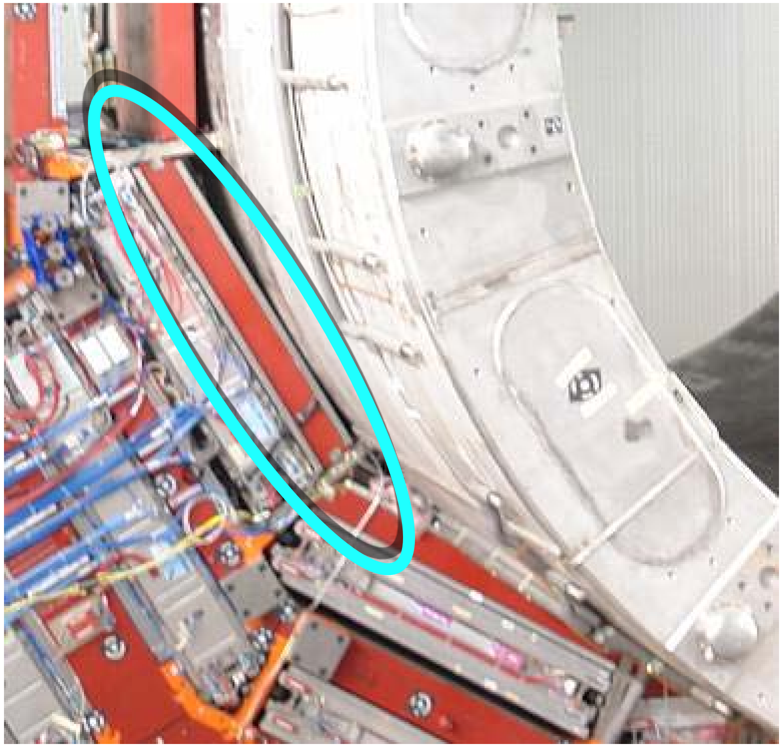
π resolution: $\sim 120\% / \sqrt{E}$

Segmentation:

$\phi \times \eta = 0.087 \times 0.087$

1 or 2 longitudinal layers

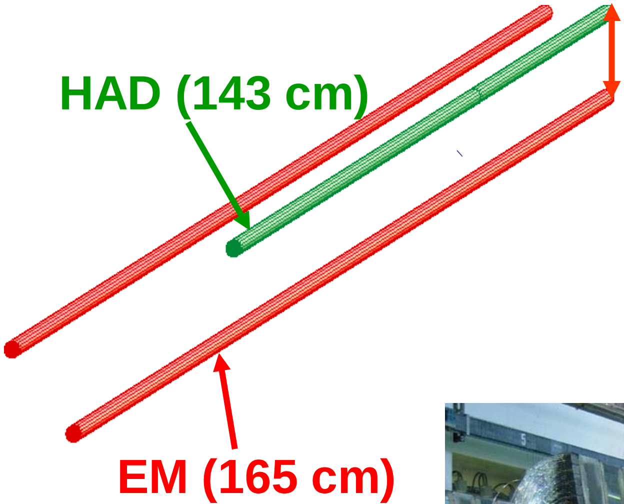


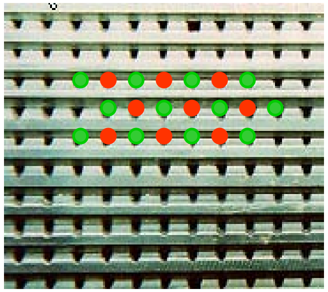


HO captures energy leakage from HB due to late showering

Forward Calorimeter (HF)

HF is located about 11 m from the interaction point, covers 3 < |η| < 5 with depth 10 λ_{int}





Choice of technology driven by the need to operate in a *very* high radiation environment

Consists of iron absorber embedded with quartz fibers parallel to the beam direction

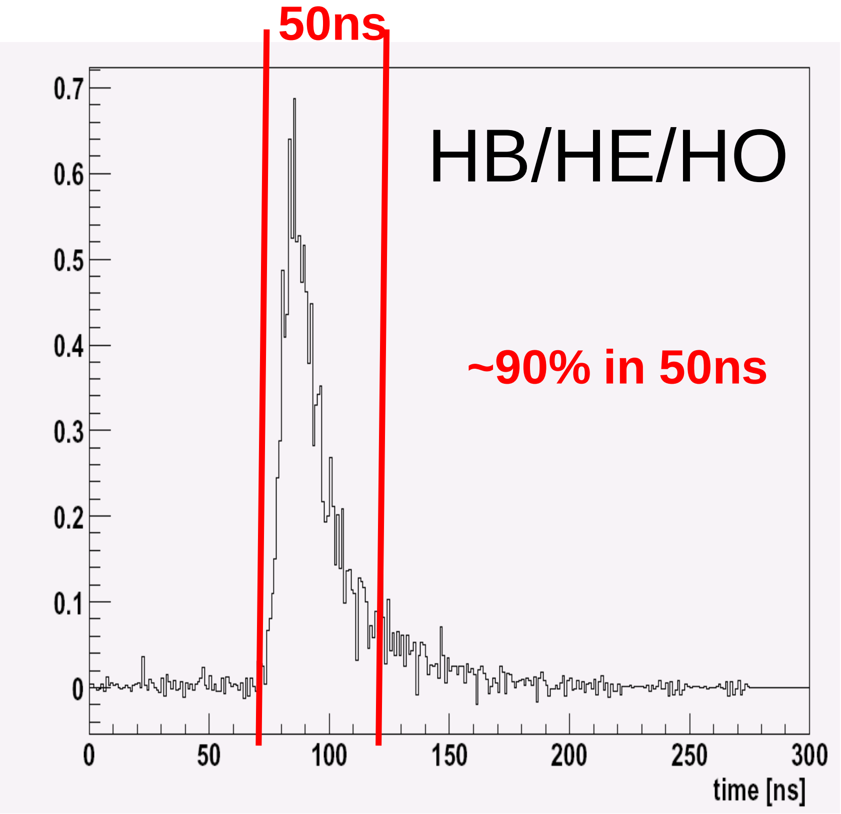
Particles incident on the front surface produce showers in the quartz/iron matrix; charged particles produce Cherenkov light. Very fast readout ~10 ns.

Fibers bundled in 0.175 x 0.175 (Δη x Δφ) towers

Pulse Shapes to QIE

LHC clock = 25ns (= 1 time sample)

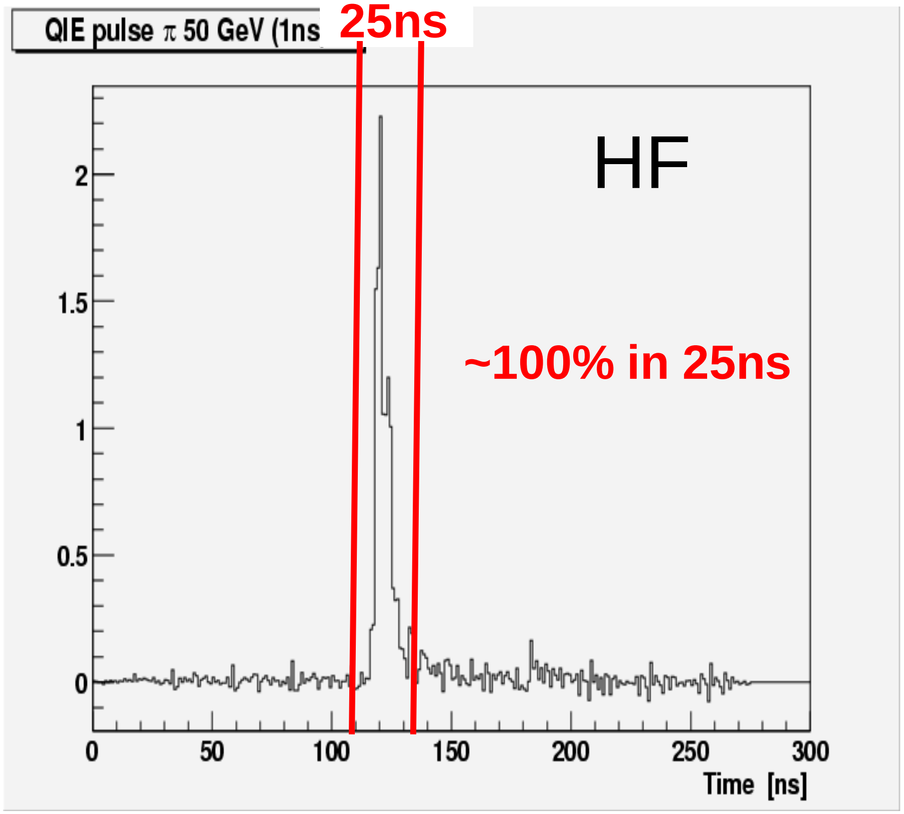
Signal is integrated over 4 TS for HB/HE/HO and 1 TS for HF



50ns

HB/HE/HO

~90% in 50ns



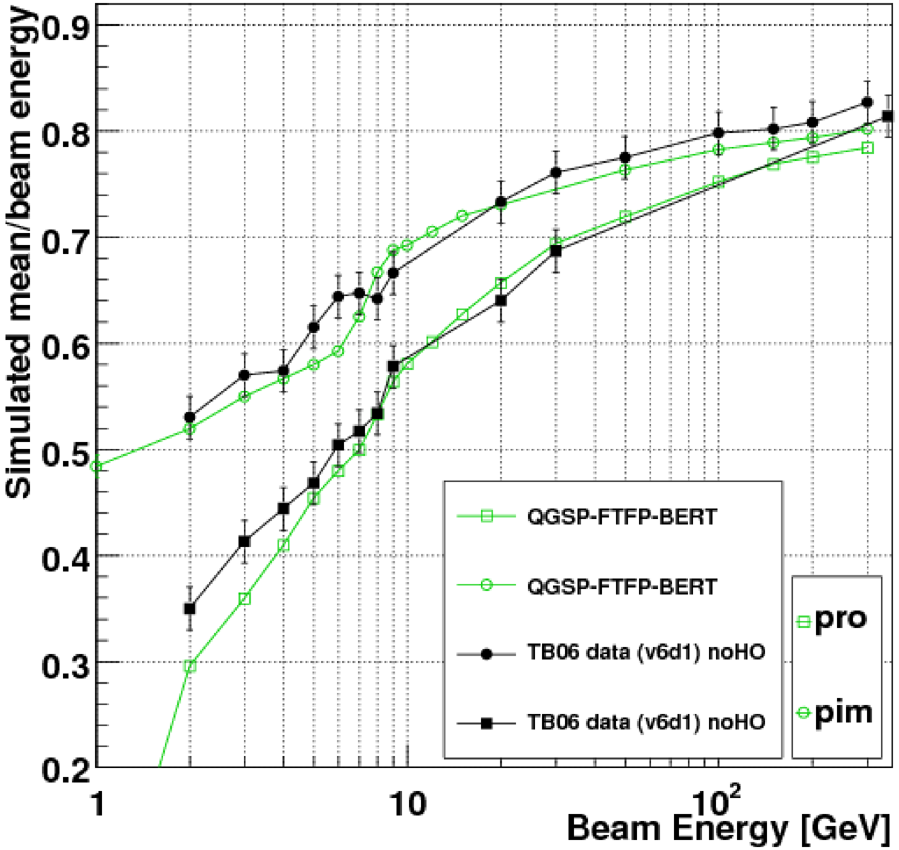
25ns

HF

~100% in 25ns

Calorimeter Response

Calorimeter response was determined in the test beam for a *few cells* then extrapolated to the rest of the calorimeter using a Co60 source → “pre-calibration”

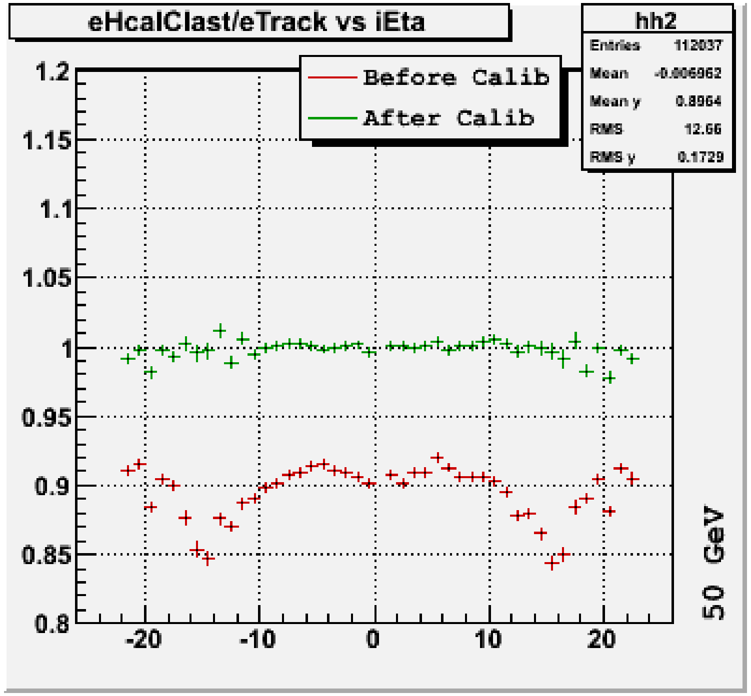


Calorimeter response is non-linear

We can only calibrate the response at one energy (50 GeV pions)

Response Corrections

Pre-calibration does not account for dead material between the surface of HCAL and the interaction point
(Tracker, cooling, and cabling between ECAL and HCAL)



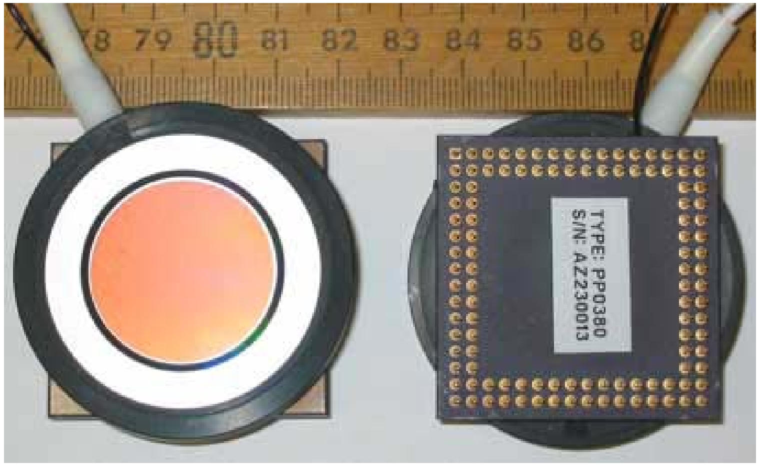
Will use collision data to provide a "response correction"

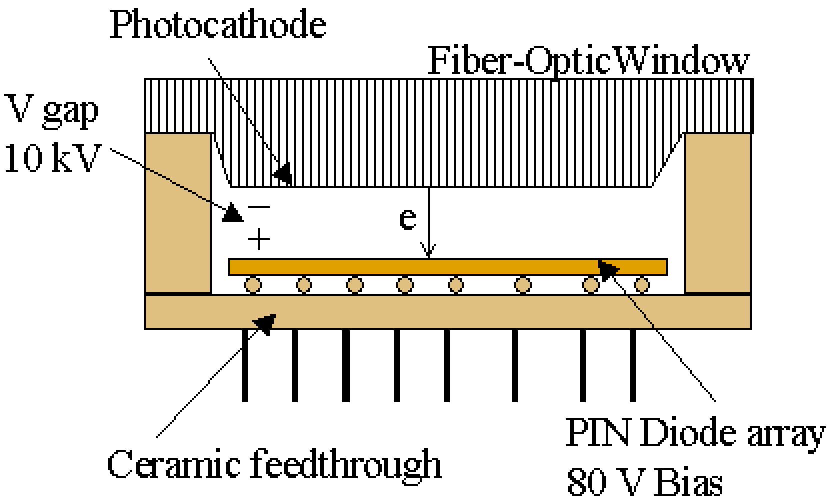
1) MinBias data for phi symmetry

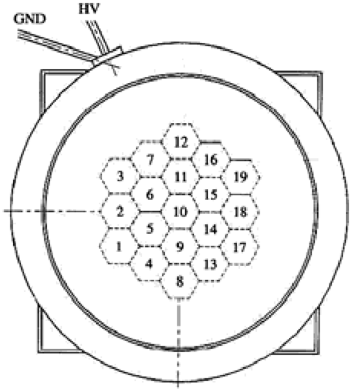
2) Isolated tracks for central region
Tracker momentum

3) Dijet balancing for forward region
p_T balance

Hybrid Photo Diode (HPD)







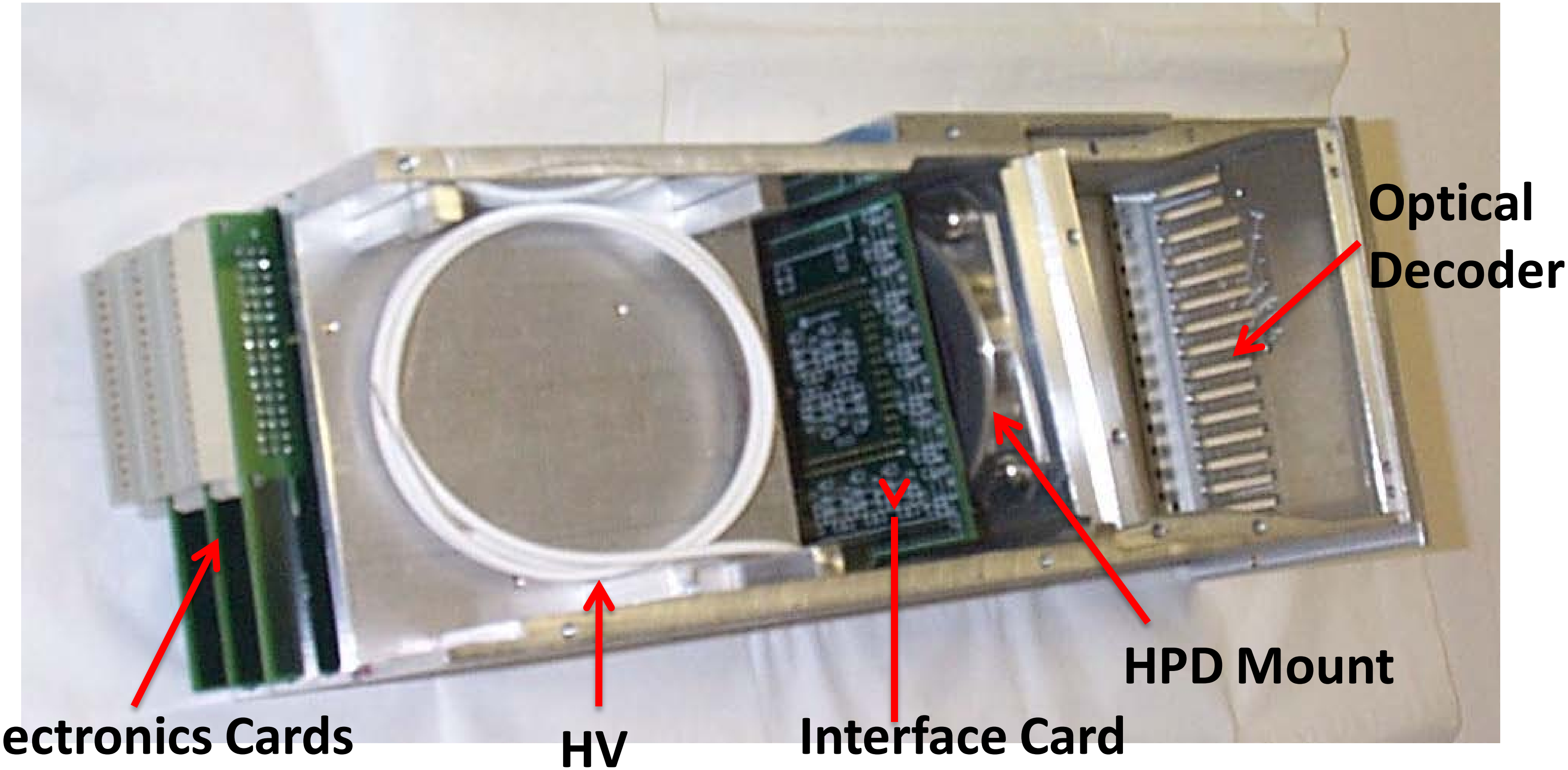
Hybrid Photo Diode photon transducer (HB, HE, HO)

19 or 73 channels/device
(one channel used for calibration)

Optical Decoder Unit
Directs light collected from the calorimeter to the HPD channel

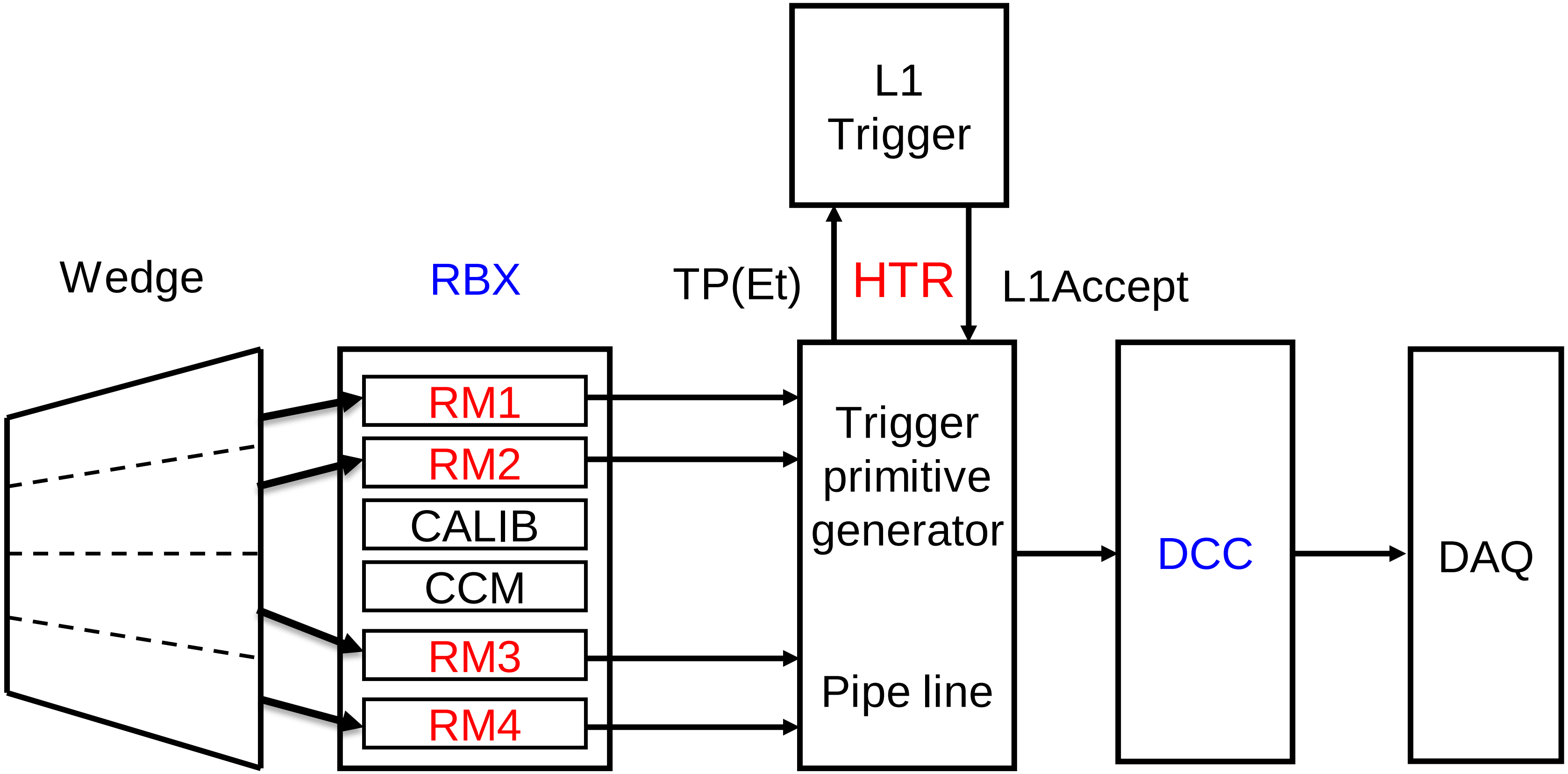
Readout Module

The readout module (RM) integrates the HPD, front end electronics, and digital optical drivers



(Charge Integrating Encoder (QIE) fC → ADC)

Schematic View of HCAL Readout



On Detector (UX5)

Counting Room (UXC55)

One wedge: 4 φ-slices, 16 η

RBX: Readout Box (one per wedge)

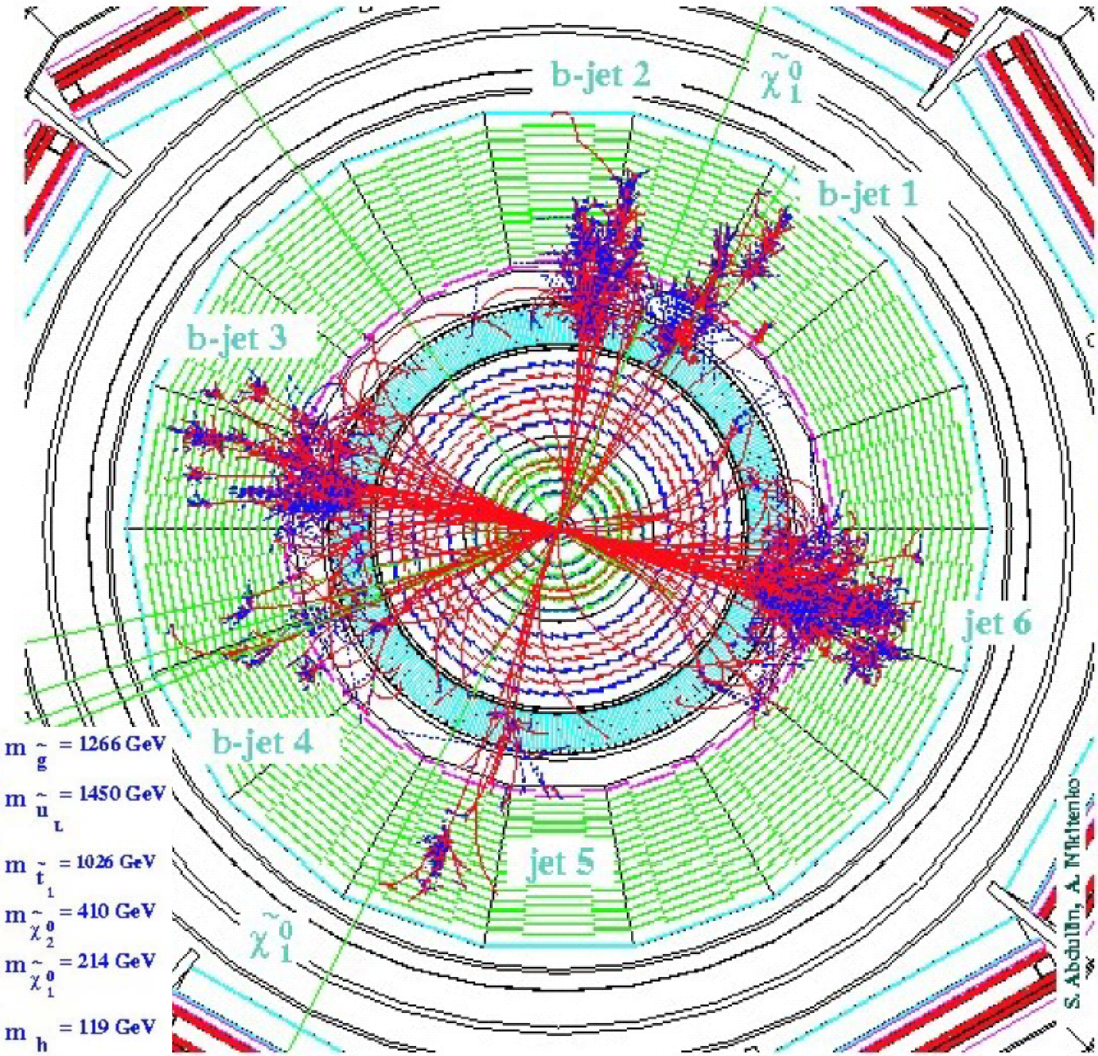
RM: Readout Module (four per RBX)
1 HPD and 18 ch QIE(ADC)

HTR: Hcal Trigger Readout module

DCC: Data Concentrator Card

Calorimetry Goals

SUSY event in CMS: *High pT jets and missing transverse energy*



Primary goals

Measure quarks and gluons
→ Jets

Measure “neutrino”s
→ Missing ET

Additional goals

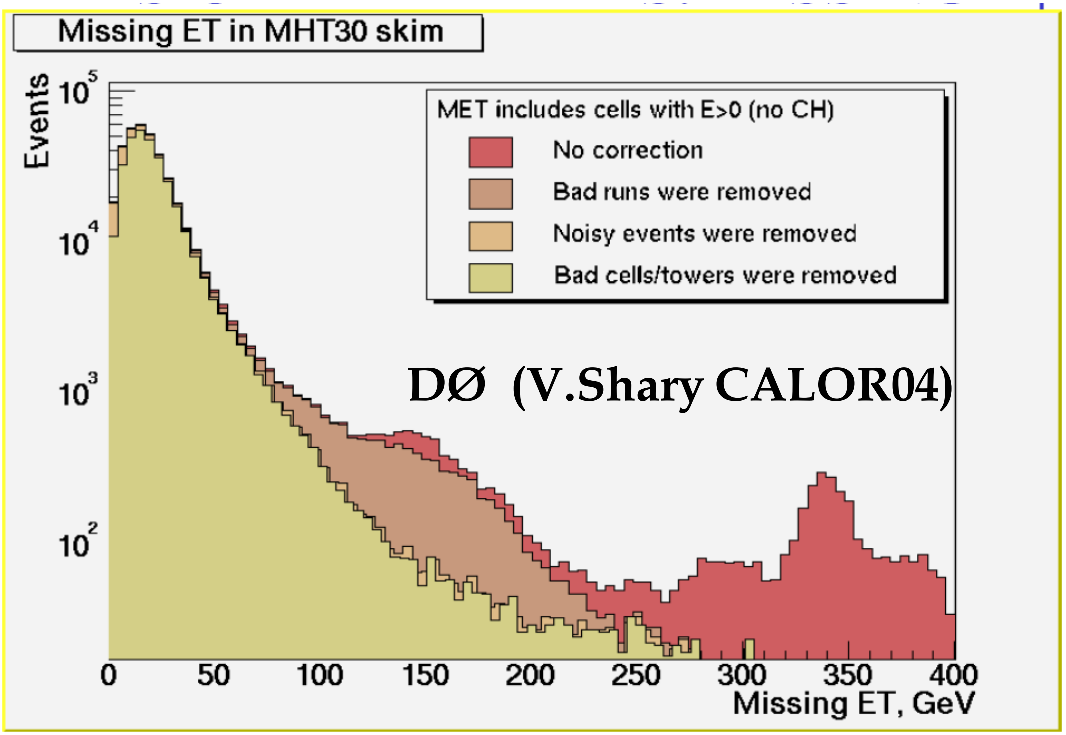
Electron/photon ID
→ energy only in ECAL, not in HCAL

Muon ID
→ MIP signal or EM shower in HCAL

Tau ID
→ very narrow jets
(for hadronic tau decay)

Understanding MET

Many important signatures involve Jets + Missing ET



DØ (V.Shary CALOR04)

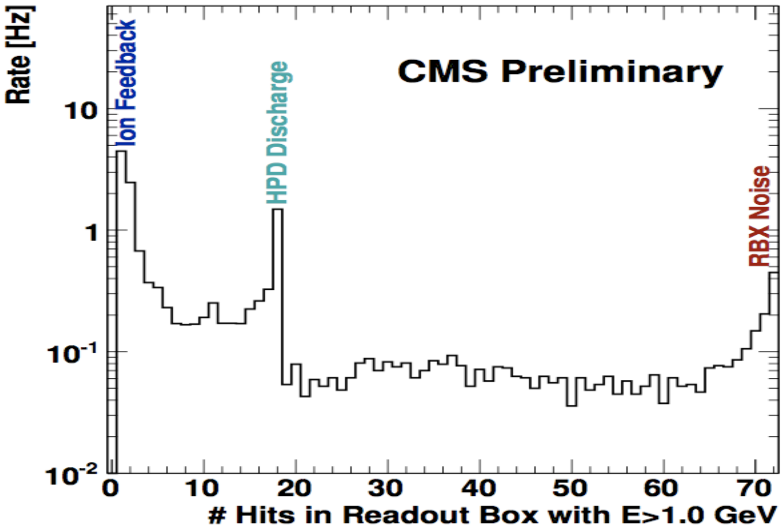
Identify and treat:

Calorimeter noise
Dead Channels
Hot Channels
HDP discharge
HDP ion feedback

Use the global run data to look at real data…

Plenty to do in the area of Data Quality Monitoring and a great place to get involved!

Calorimeter Noise

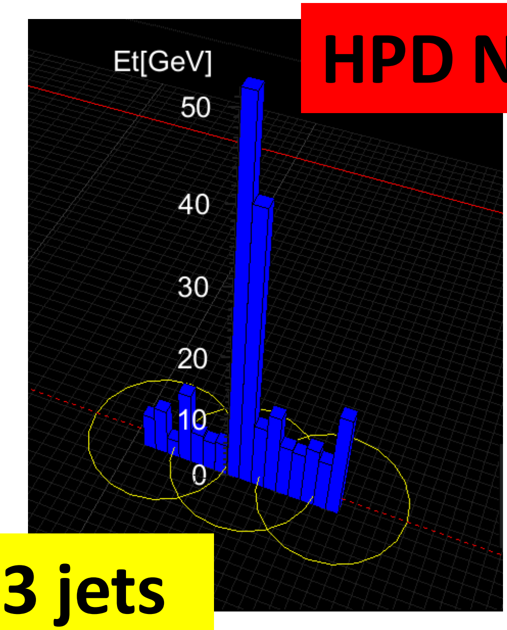


Observe hardware related noise with distinct patterns

Replaced noisy HPDs

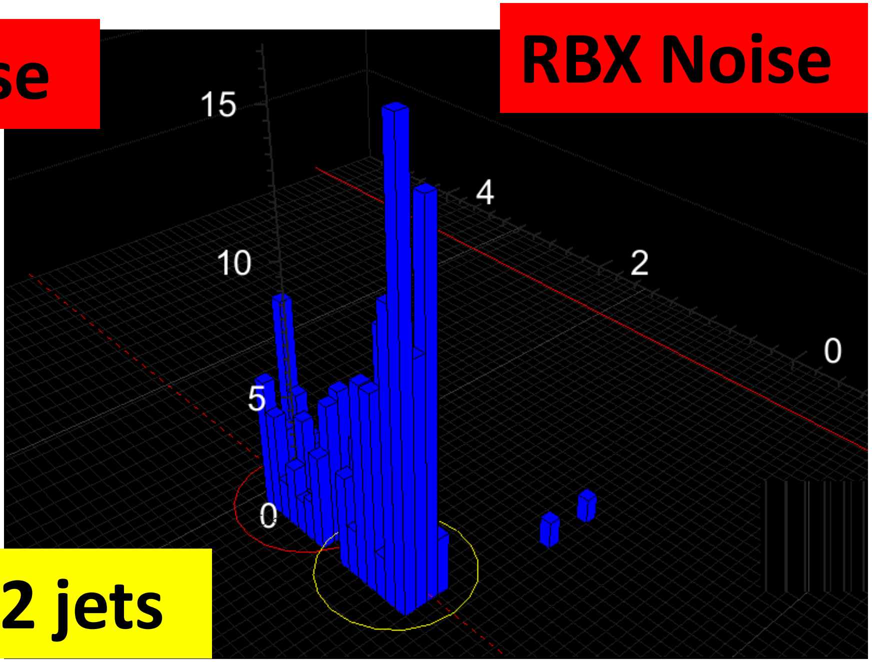
Reduced operating voltage

Jet algorithm reconstructs noise as Jets



HPD Noise

3 jets



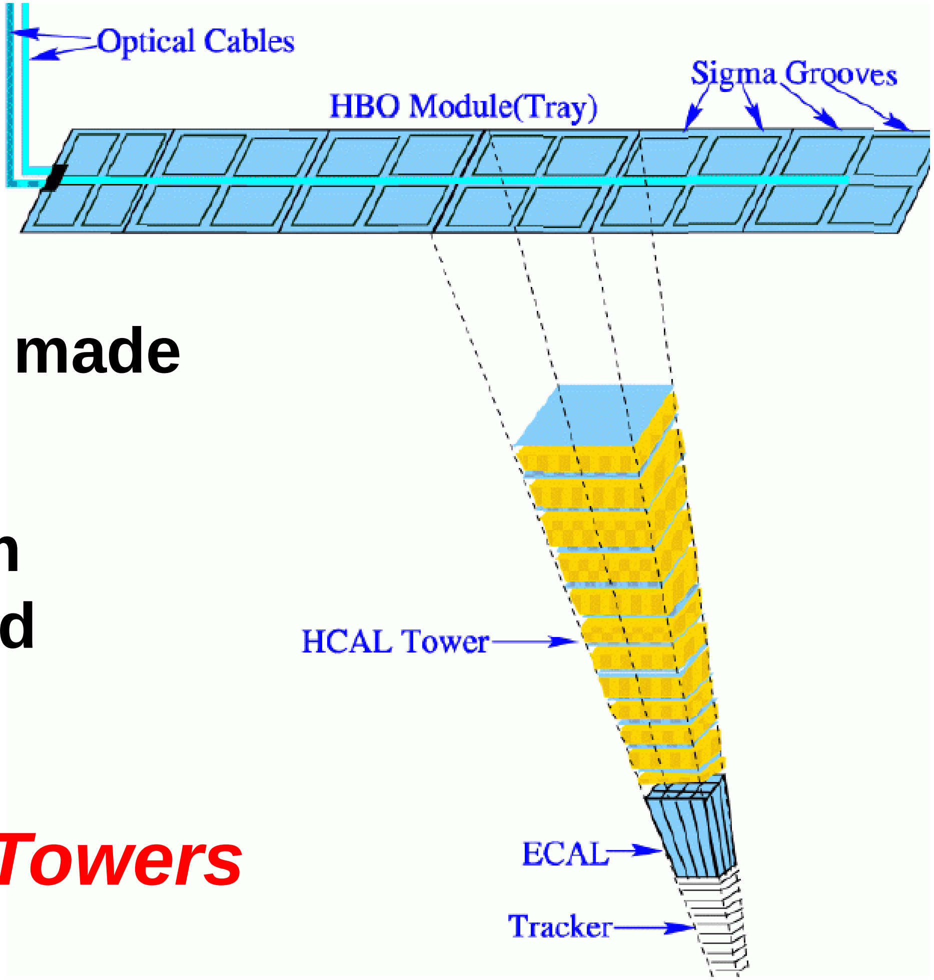
RBX Noise

2 jets

CaloTowers

Most users will access the reconstructed data

Digitized Data → Reconstructed Hits → CaloTowers



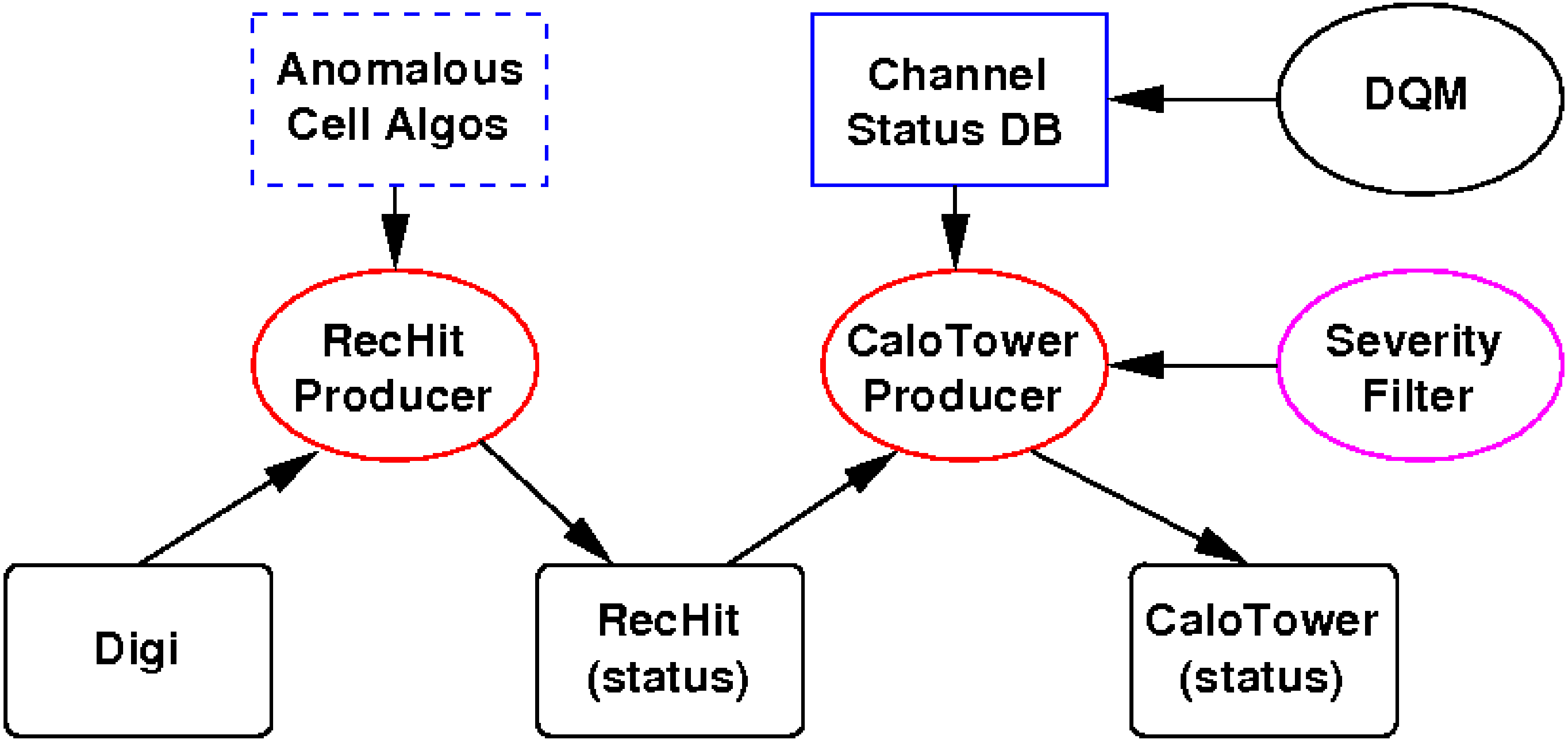
Detector/electronics related problems need to be identified *before* “rechits” are made

CaloTowers are made up from multiple EM Crystals (5x5) and several Hadron sections

Jet clustering uses CaloTowers

Flagging Corrupted Data

Anomalous cell framework



Used to flag noise and identify timing errors…
Could possibly recover corrupted data…

Silicon Photo Multipliers (SiPM)

Pros:

SiPMs are insensitive to the magnetic field and have much lower noise level compared to HPDs

SiPMs have an order of magnitude higher S/B for muons compared with HPDs
Allowing for a precise intercalibration using cosmic muons

Cons:

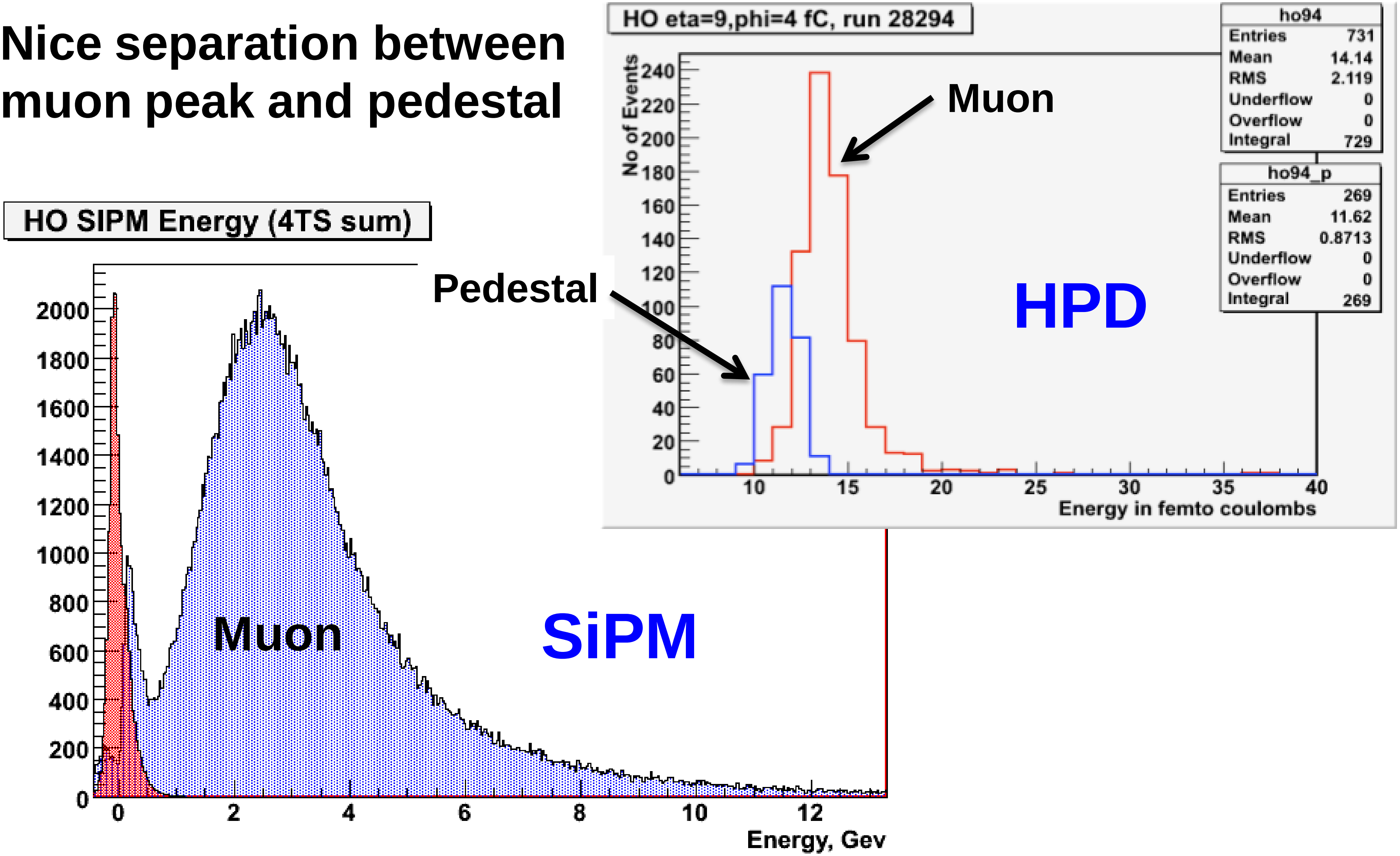
Gain is strongly dependent on temperature (8% per deg C)
Peltier coolers installed

Replace HPDs in HO with SiPMs during 2010/2011 shutdown

144 SiPMs were installed in HO to gain some operational experience

SiPM Muon Signal

Nice separation between muon peak and pedestal



Summary

Calorimetry is essential for the LHC physics program

Jets and Missing E_T are important signatures in many searches for new physics

Need to understand and suppress noise…

The CMS Calorimeters are working well

Gaining valuable operation experience during
Mid Week Global Runs and CRAFT (B=3.8T)

We have real data to look at!!!

Still plenty to do and a great opportunity to make an impact!