Outline of Lecture 3

- Optimal Use of Calorimeter Information
  - Improving the Energy Measurement
  - Complementary Strengths of Tracking and Calorimetry
- Future Developments in Calorimetry
  - Dual-Readout Paradigm
  - New Detector and Photodetector Technologies
  - Upgrading Existing Calorimeters for Beyond $10^{34}cm^{-2}s^{-1}$

Summing Energies from Different Calorimeters

- Perhaps one of the biggest challenges for calorimeter-only measurements is having to sum energies from different calorimeters
  - If calorimeters have a different e/h, then one suffers not only from non-compensating EM-fraction fluctuations within each calorimeter but also from the longitudinal fluctuations of the EM and HAD components of the shower between calorimeters
  - Many ECAL/HCAL transitions occur at ~1 λ_{int} right before the hadronic shower max (and unfortunately this is typically the location of dead material in the calorimeter)

Dual-e/h Response Compensation

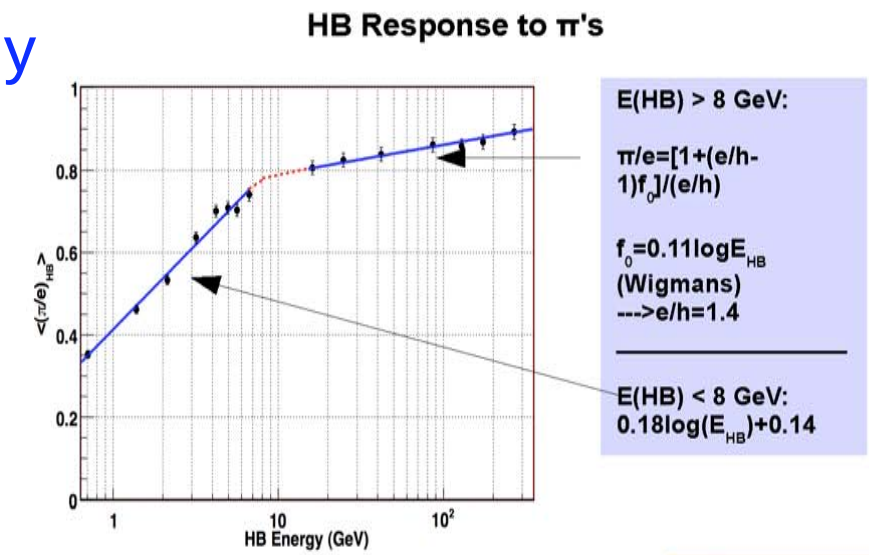
Crystals+Tile Calorimetry

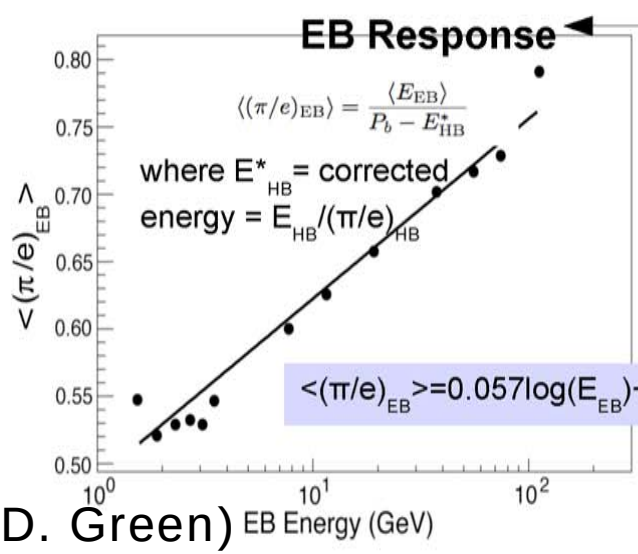
1) ECAL and HCAL clusters are matched

2) HCAL Tile Energy corrected for measured e/π in tile calorimeter (measured from HCAL only showers, MIP in ECAL)

3) ECAL Crystal Energy corrected for remaining e/π non-linearity in the beam energy minus the e/π-corrected HCAL energy

4) Corrected HCAL and ECAL energies for matched clusters are summed

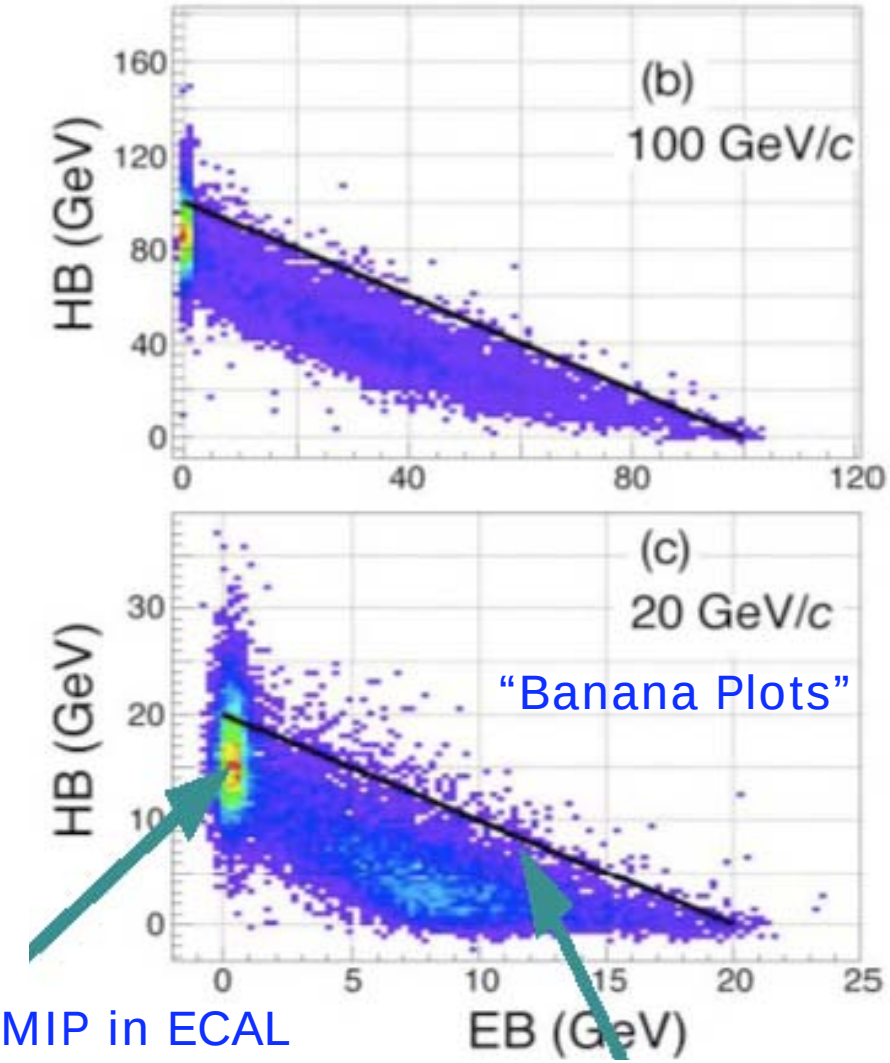


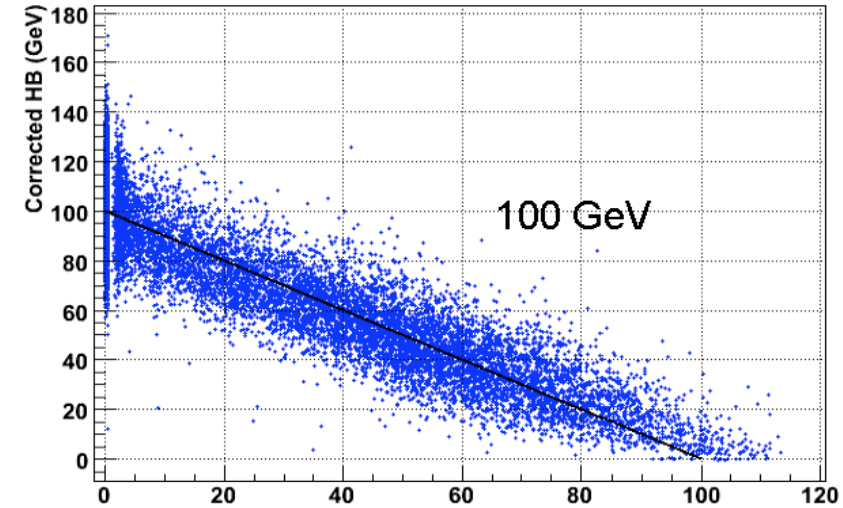


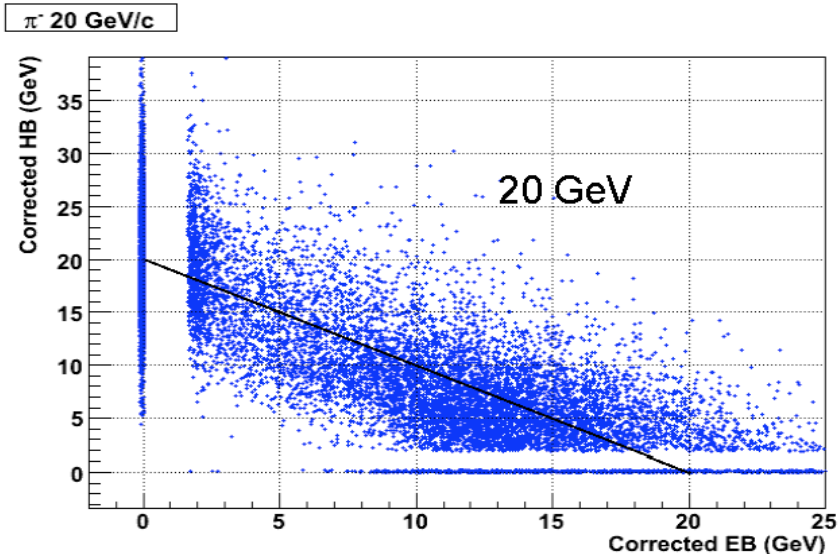
w/ events that have significant energy *both* in EB & HB.

(Courtesy of D. Green)

Dual-e/h Response Compensation

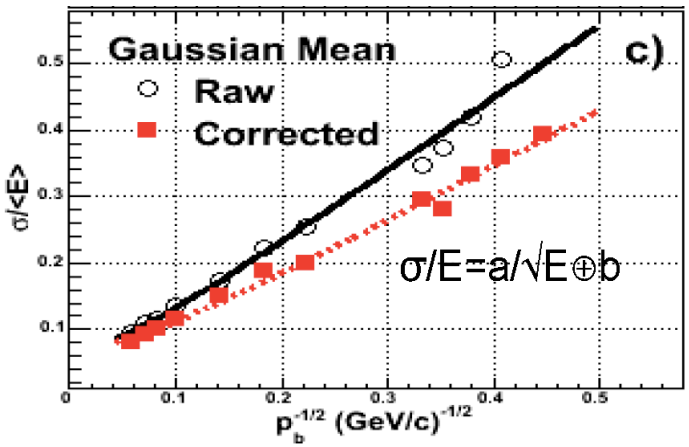


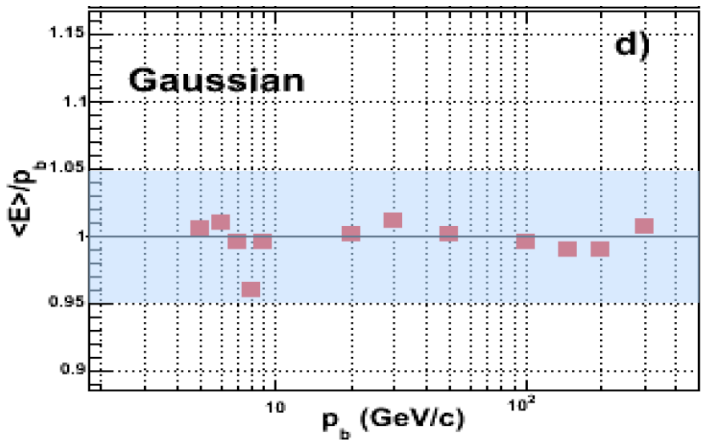




Dual-e/h Response Compensation

- Reduces stochastic term down to the level expected based on absorber thickness
  - Removes e/π response non-linearity for isolated particles





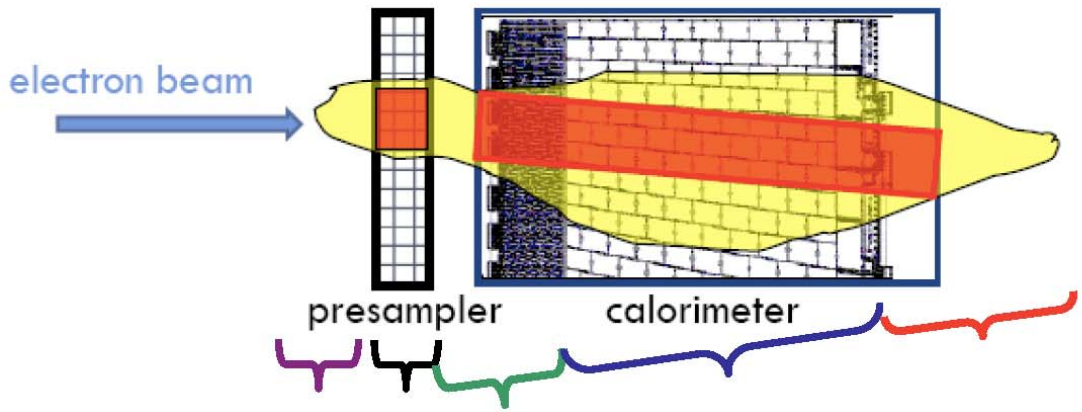
- Linearity restored within 5% for p≥5 GeV and 2-3% for p≥9 GeV.

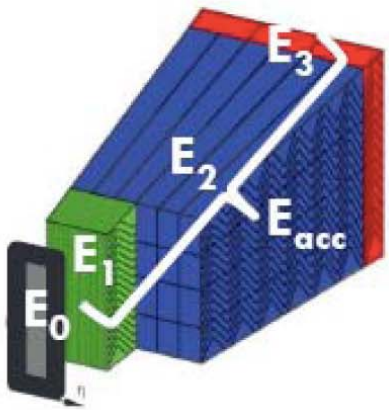
$$\sigma/E = a/\sqrt{E} \oplus b = 84\%/\sqrt{E} \oplus 7\% \text{ in } P = 5\text{-}300 \text{ GeV/c}$$

(idea developed by D. Green)

Atlas/H1 Energy Weighting Method

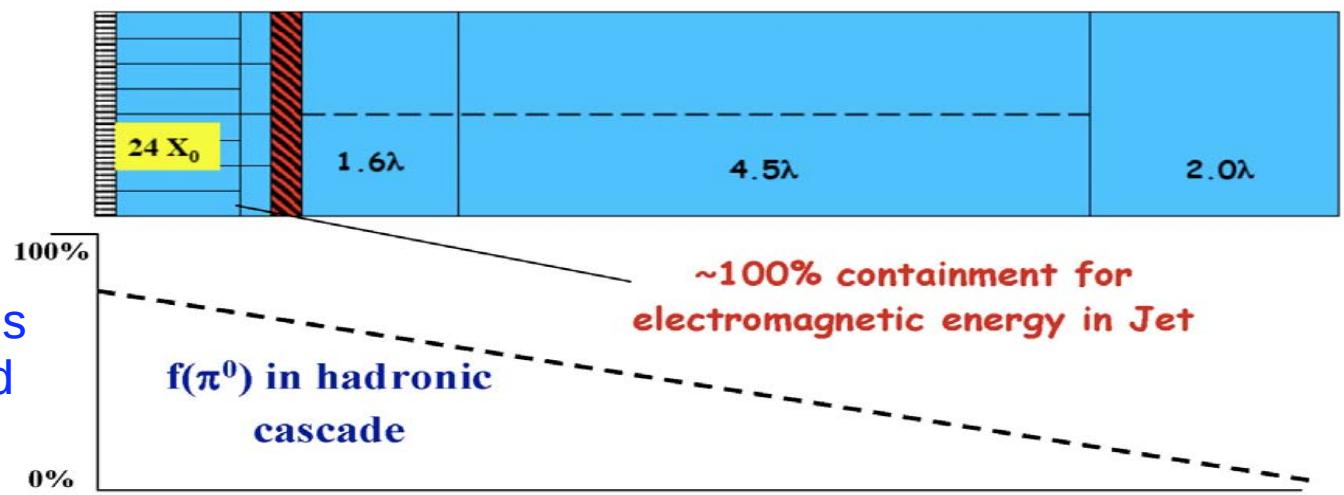
Atlas em calorimeter+preshower:





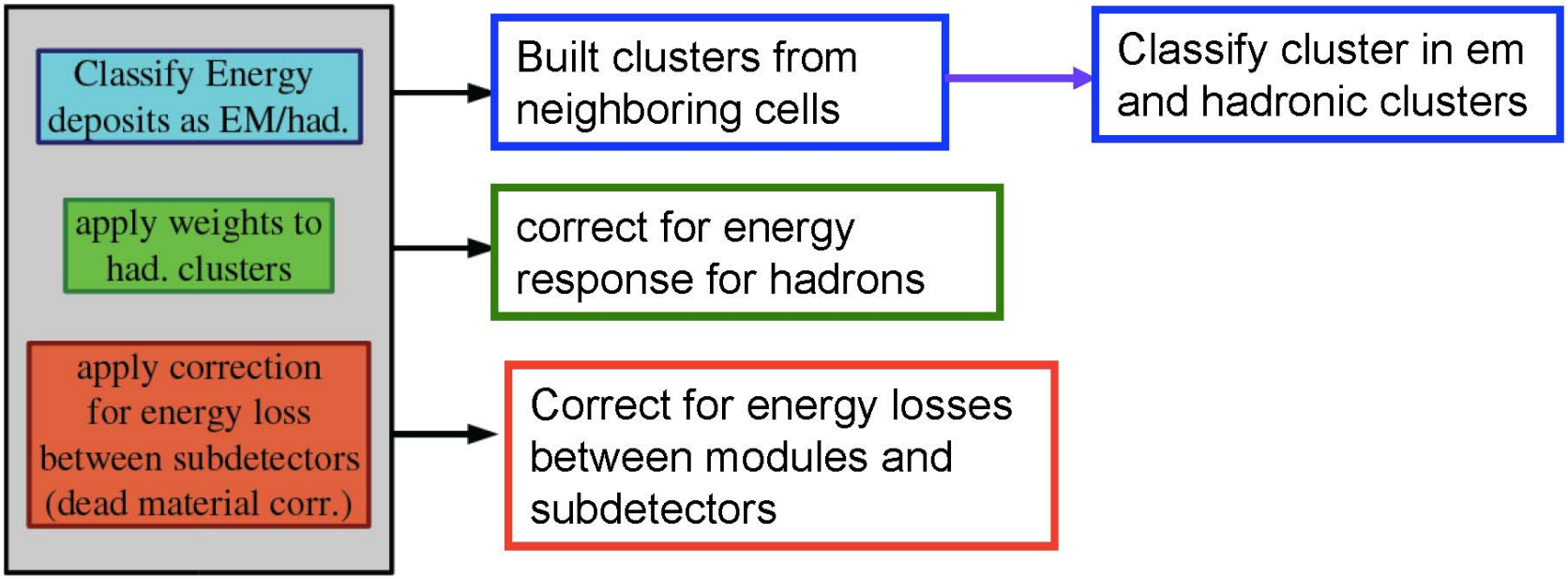
$$E_{electron} = \text{offset} + W_0E_0 + W_{01}\sqrt{E_0E_1} + \lambda E_{acc} + W_3E_3$$

Hadron Showers: Layer Weighting and E-Density Weighting methods have been studied



Topological Noise Removal

Originaly implemented in H1, now also used by Atlas

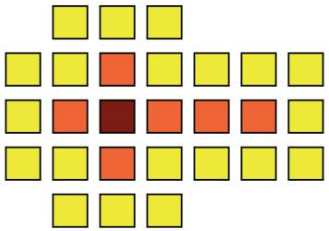


Clusters are reconstructed using "topological algorithm:

- **seeds: highest energy > 4σ**
- **neighbors: energy > 2σ**

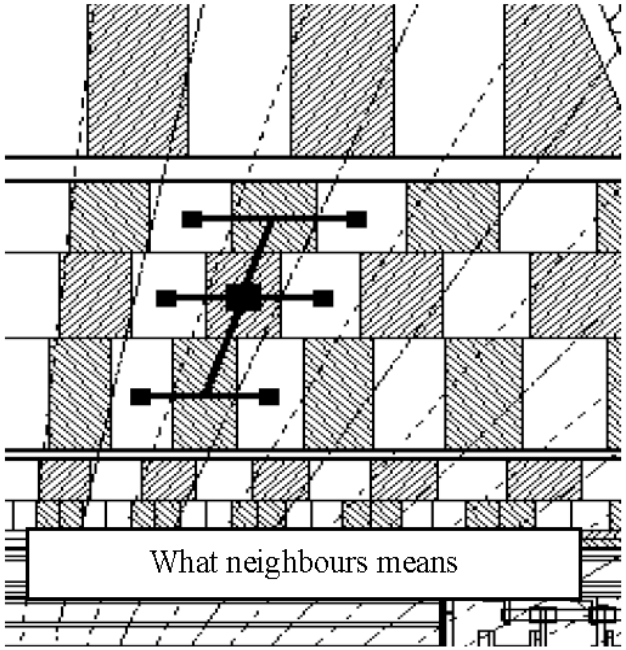
Need to take care of overlapping clusters

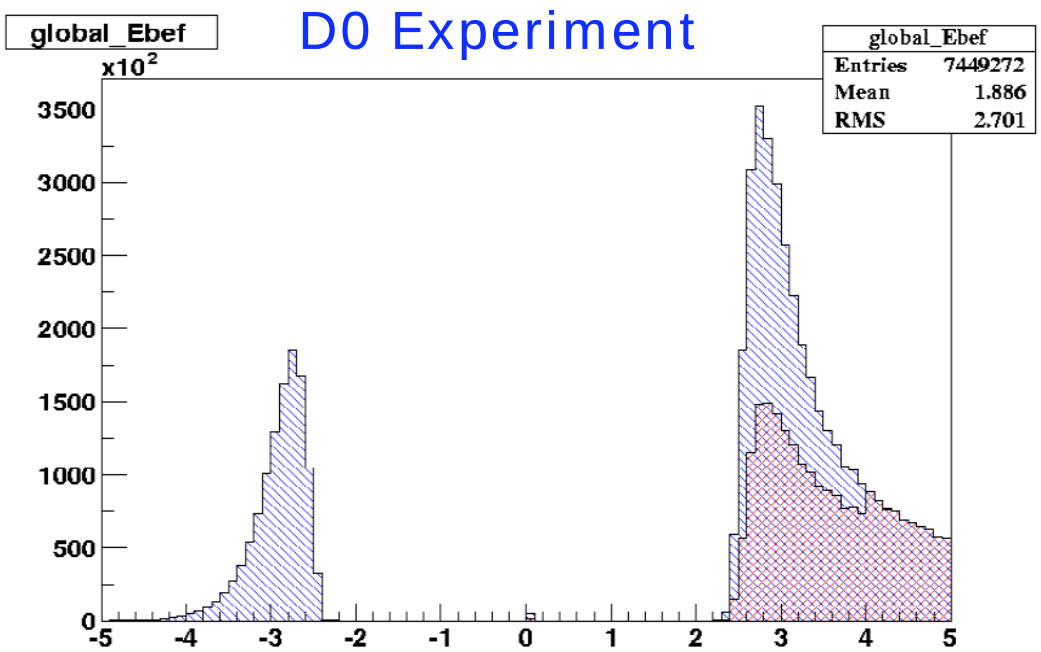
Clusters can span over subdetectors!



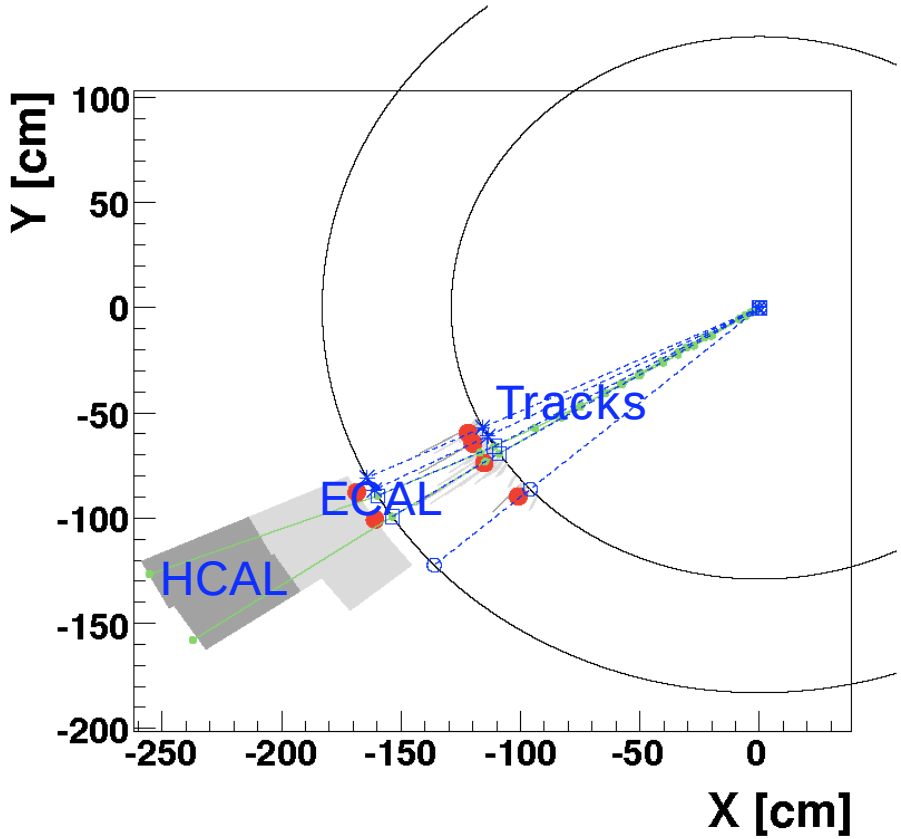
T42 Noise Suppression

- Online noise suppression: only energies |E|>1.5-2.5 σ are read out
- Offline T42 algorithm is applied:
  - All cells with E>4σ are kept
  - all cells with 2σ<E <4σ and a neighbor with E>4 σ
  - Reduction of number of cells kept: 40%

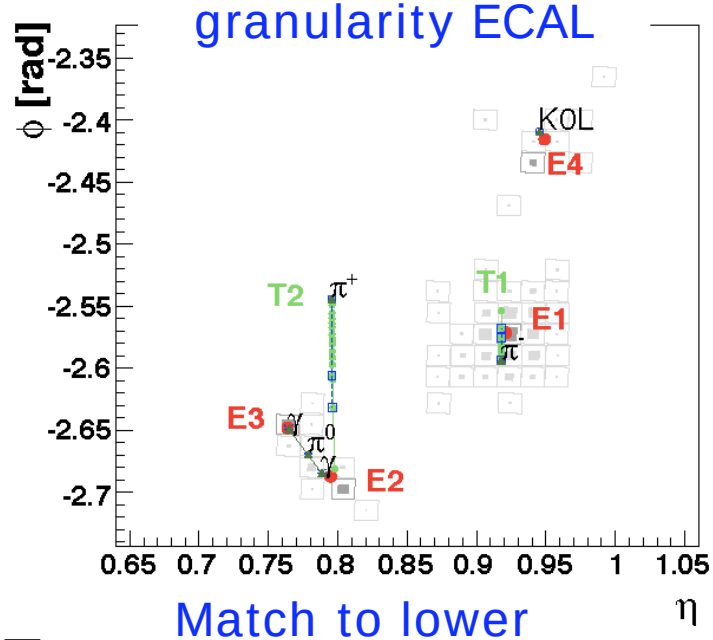




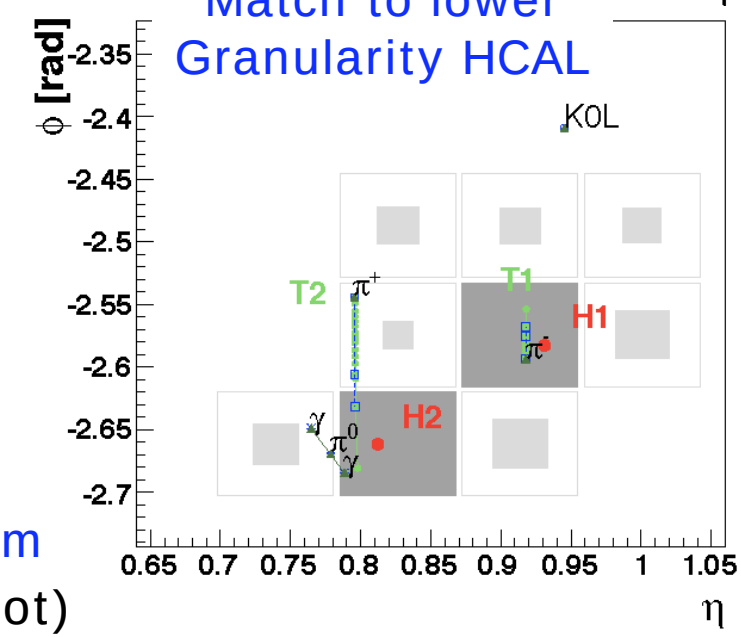
Particle Flow



Match track to high granularity ECAL



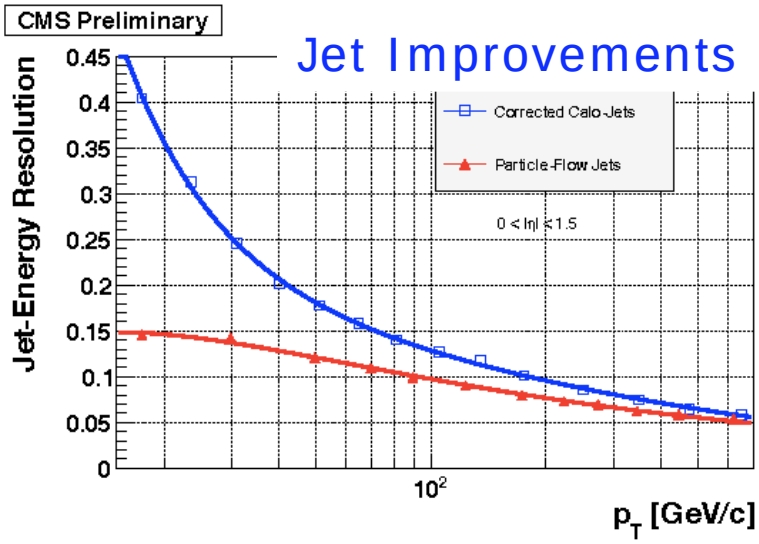
Match to lower Granularity HCAL

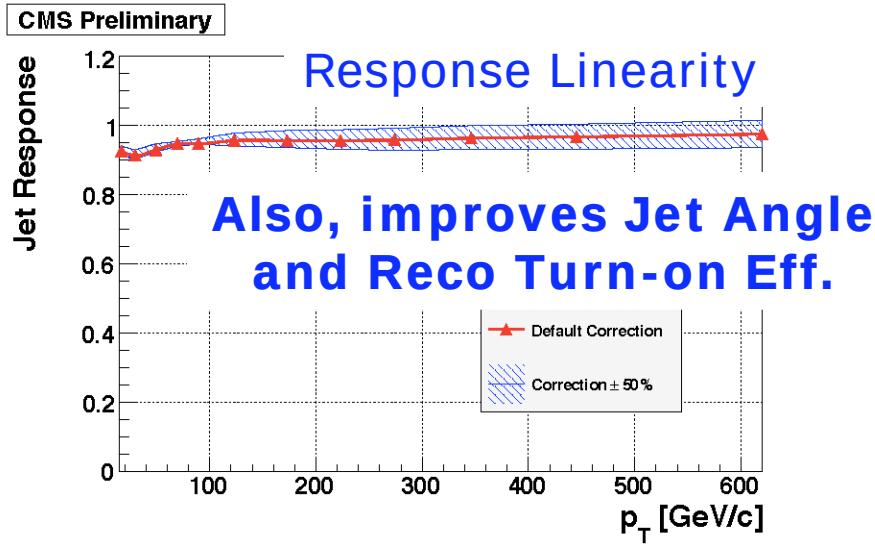


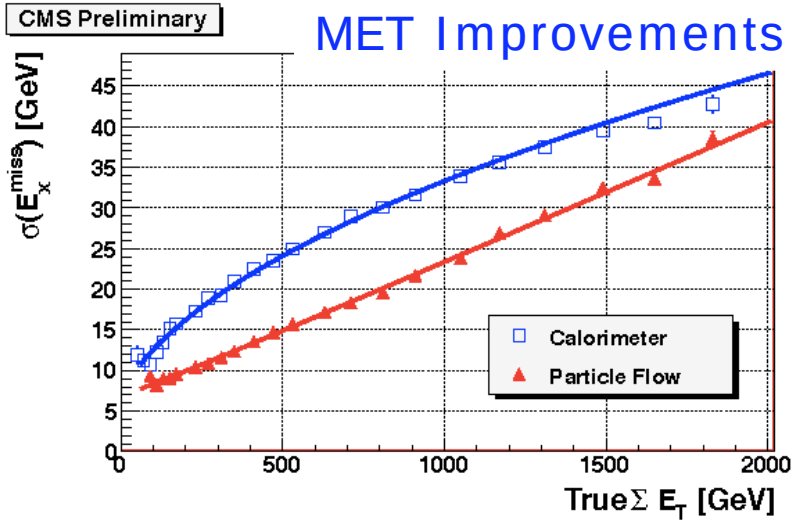
1) Leverage High Precision Tracking
2) And High Resolution ECAL EM-Showers
3) Match and Discard Charged Hadron Showers Replacing with Track Momentum

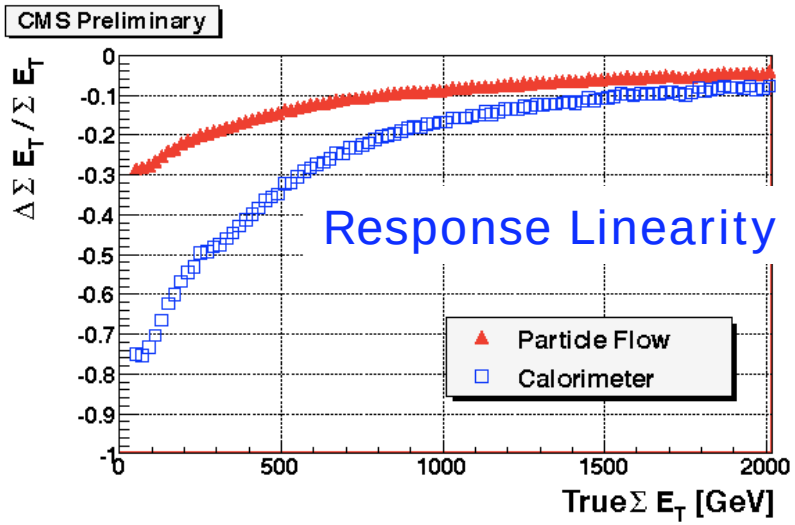
(Courtesy of P. Janot)

Particle Flow



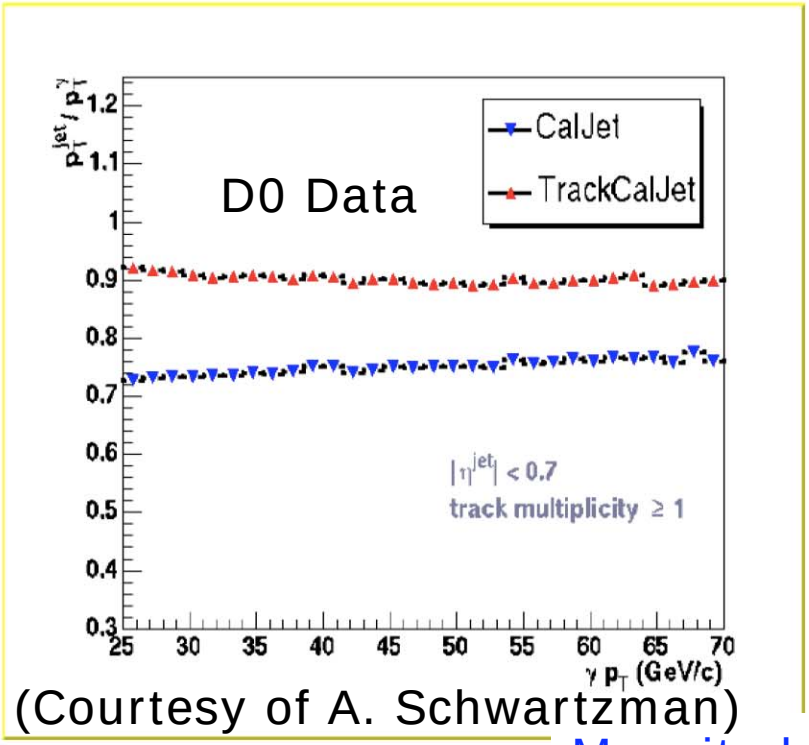






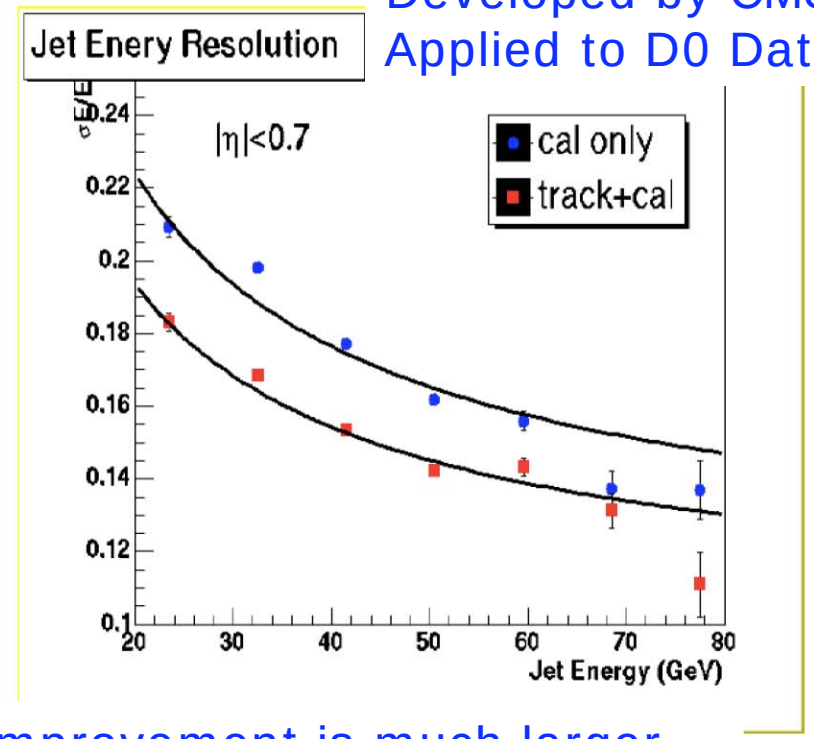
Jet Plus Track

- No track-cluster matching required
  - Expected e/π non-linearity is subtracted from calorimeter measurement and replaced with track momentum



(Courtesy of A. Schwartzman)

Developed by CMS
Applied to D0 Data



Magnitude of improvement is much larger for calorimeters with large e/π non-linearity

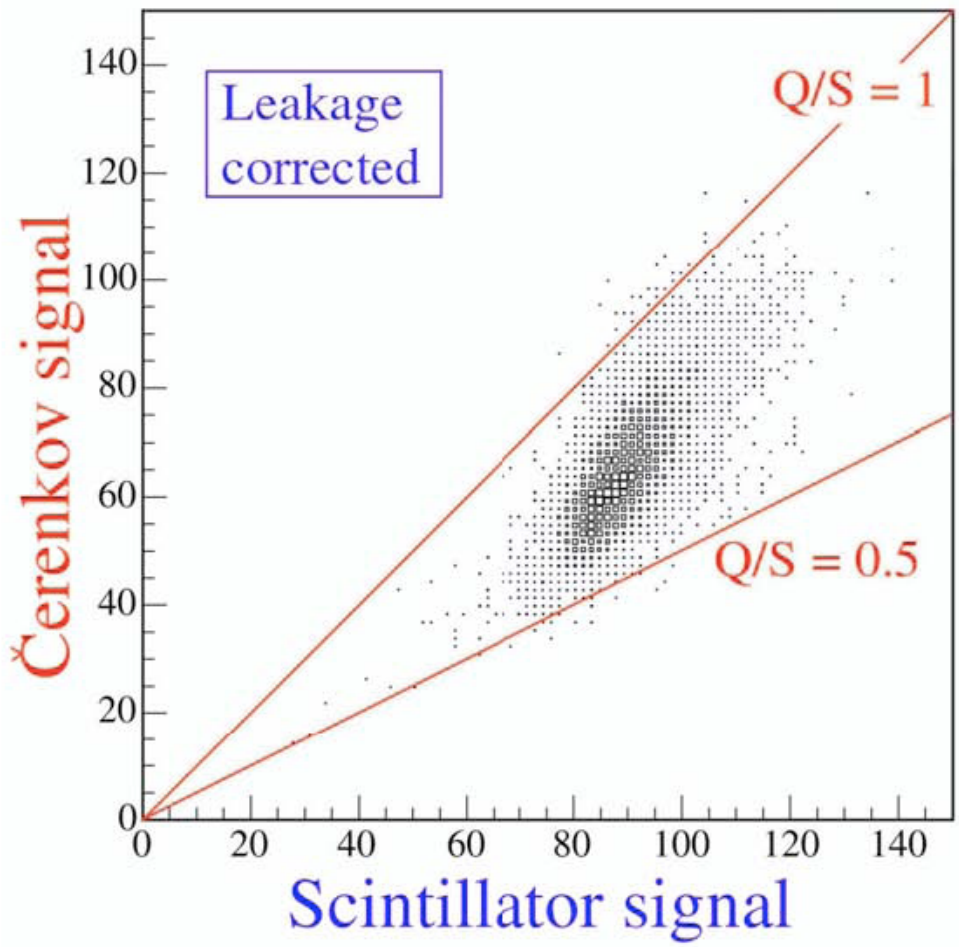
What's on the horizon?

- Dual-REAdout Method (DREAM Collaboration)
  - Measure EM fraction cell-by-cell by comparing Cherenkov and dE/dx signals
  - Densely packed SPACAL calorimeter with interleaved Quartz(Cherenkov) and Scintillating Fibers
  - What is the dream? Measure jets as accurately as electrons

$$\sigma_E / E \approx 15\% / \sqrt{E}$$

DREAM: Structure

New Method for Computing Energy



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

e.g. If $e/h = 1.3\ (S),\ 4.7\ (Q)$

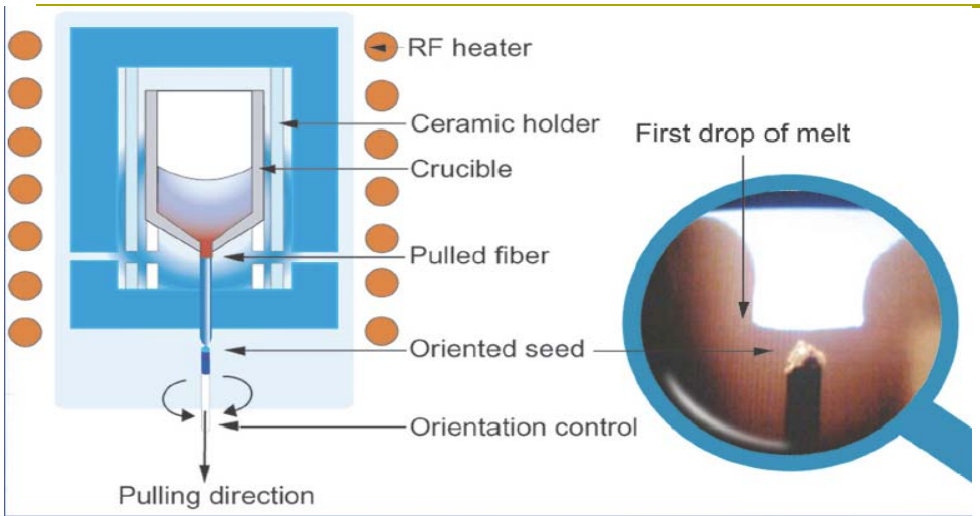
$$\boxed{\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}}$$

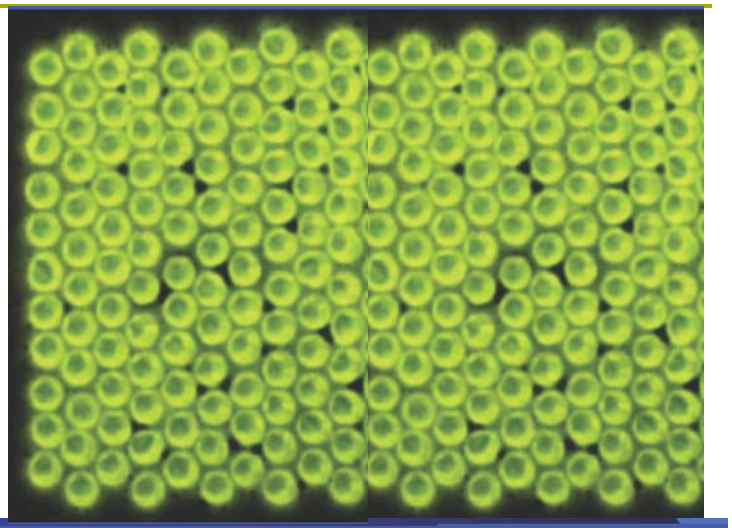
$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

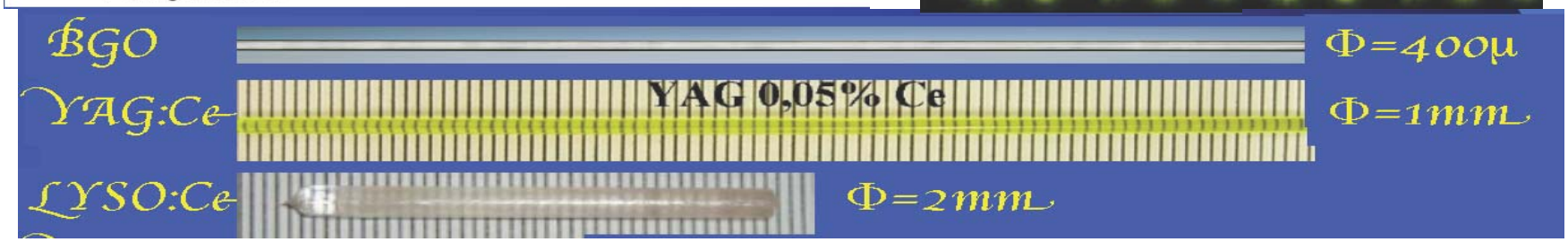
with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

(Courtesy of R. Wigmans)

New Detectors: Crystal Fibers



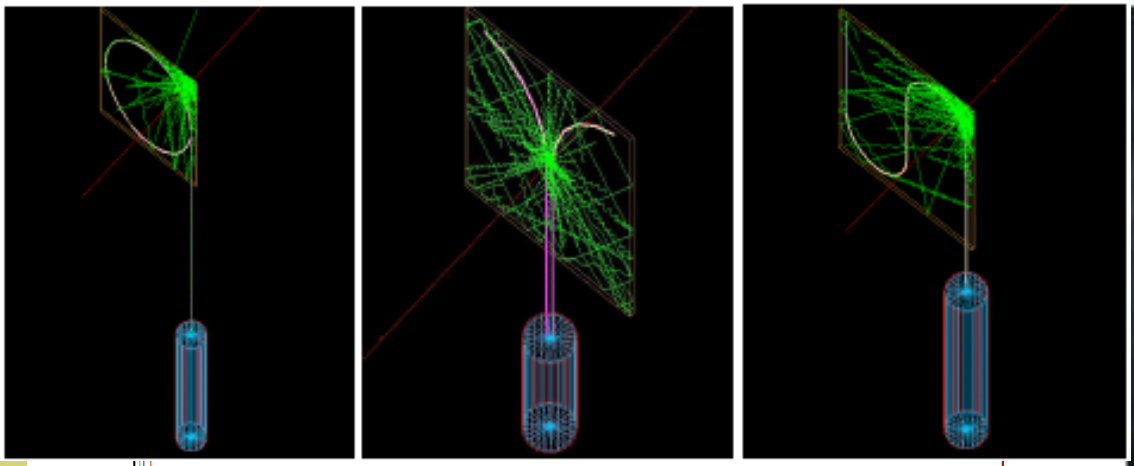


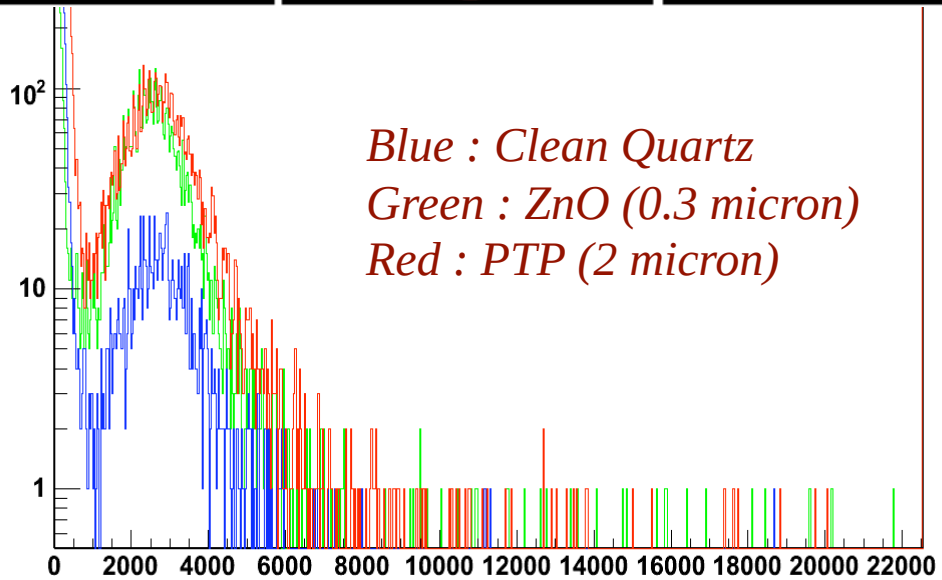


Material	Density (g/cm^3)	Radiation length X_0 (cm)	Refraction index n	Critical angle	Fondamental absorption (nm)	Cerenkov threshold e energy (KeV)	Relative photon yield*
Quartz	2.2	12.7	1.46	47°	190	190	250
LuAP	8.34	1.1	1.95	59°	146	84	501

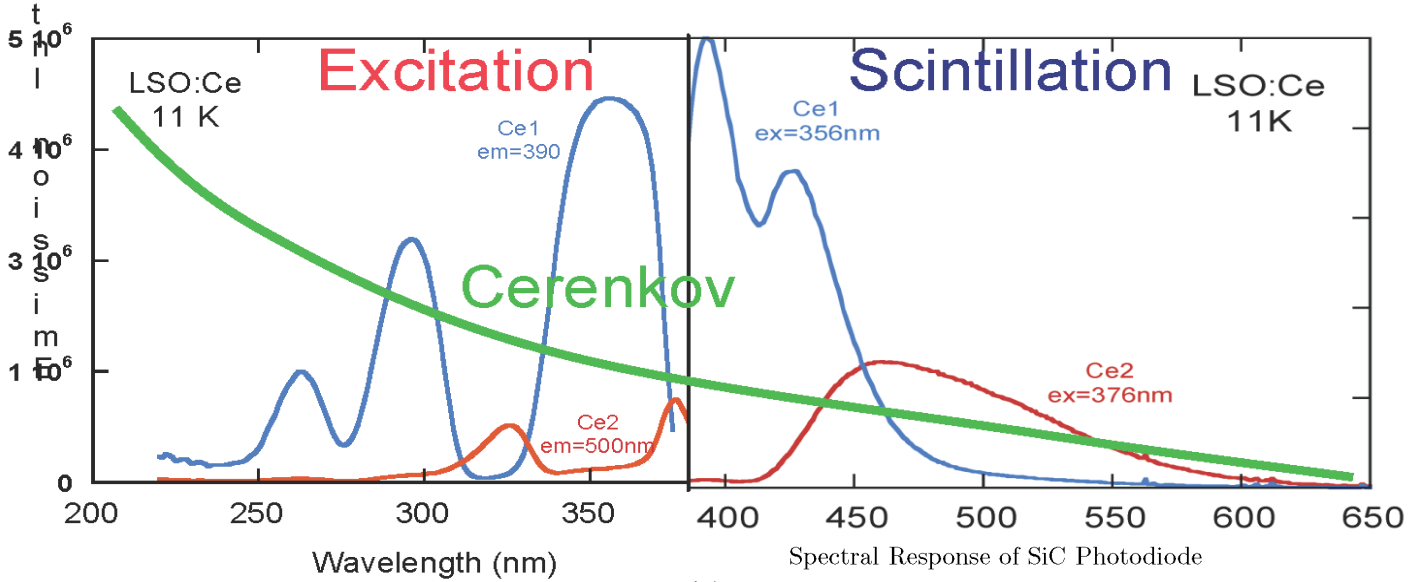
(Courtesy of P. Lecoq)

Quartz Plates

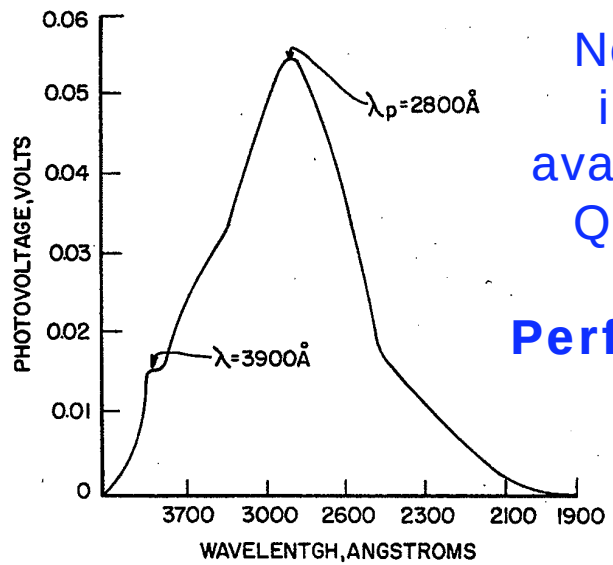




Detecting UV Light



Spectral Response of SiC Photodiode

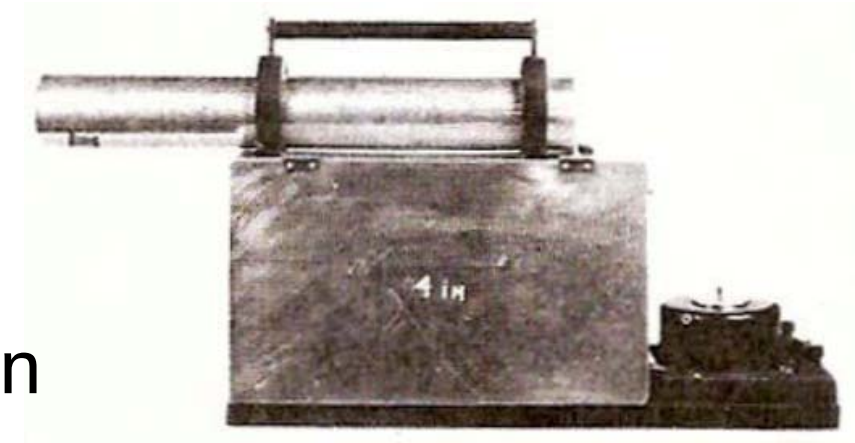


New Developments in Silicon Carbide avalanche photodiodes QE of 60% peaking at 280nm

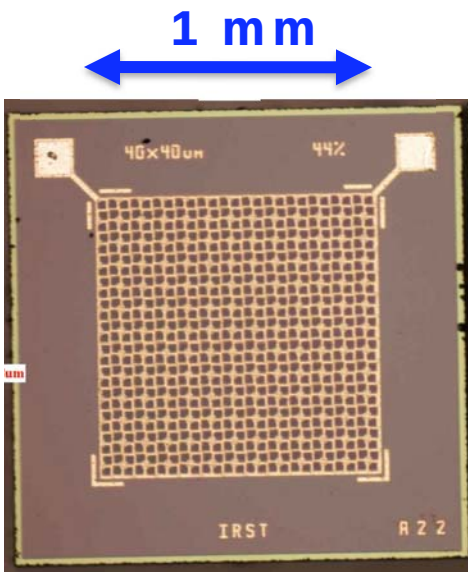
Perfect for Cherenkov

Blast from the Past

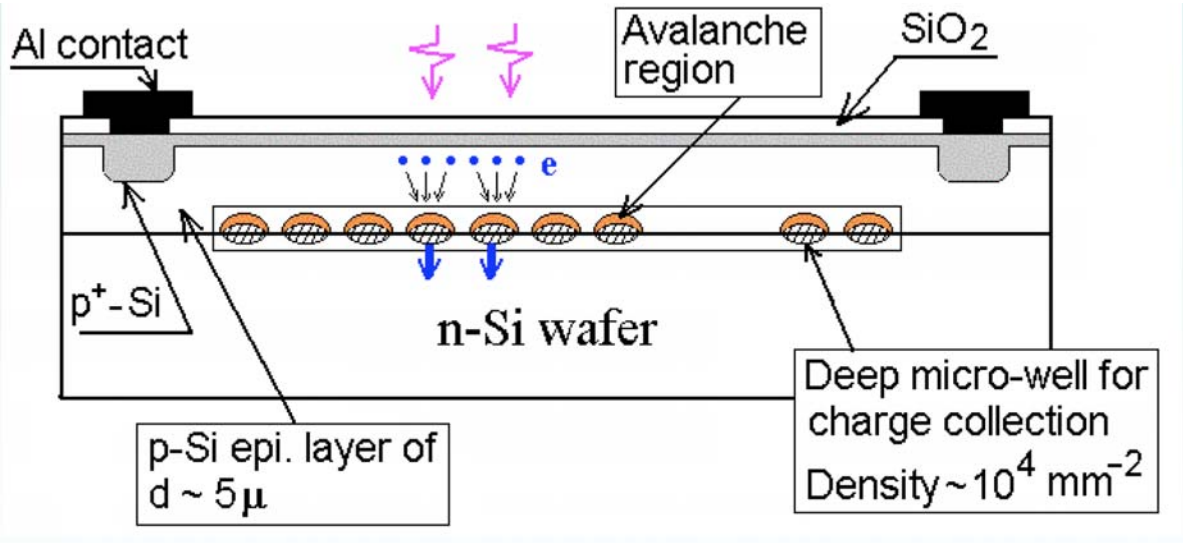
- Geiger Tube is Back!



- Reincarnated in Silicon

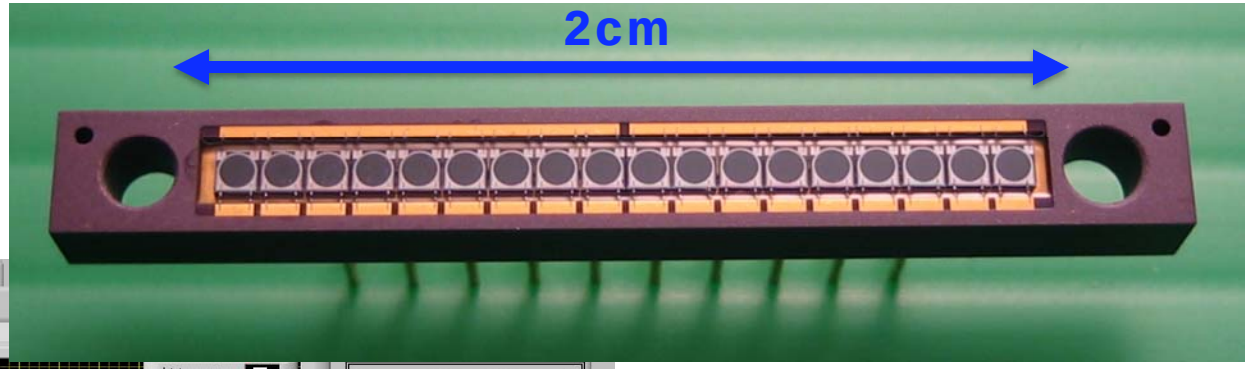


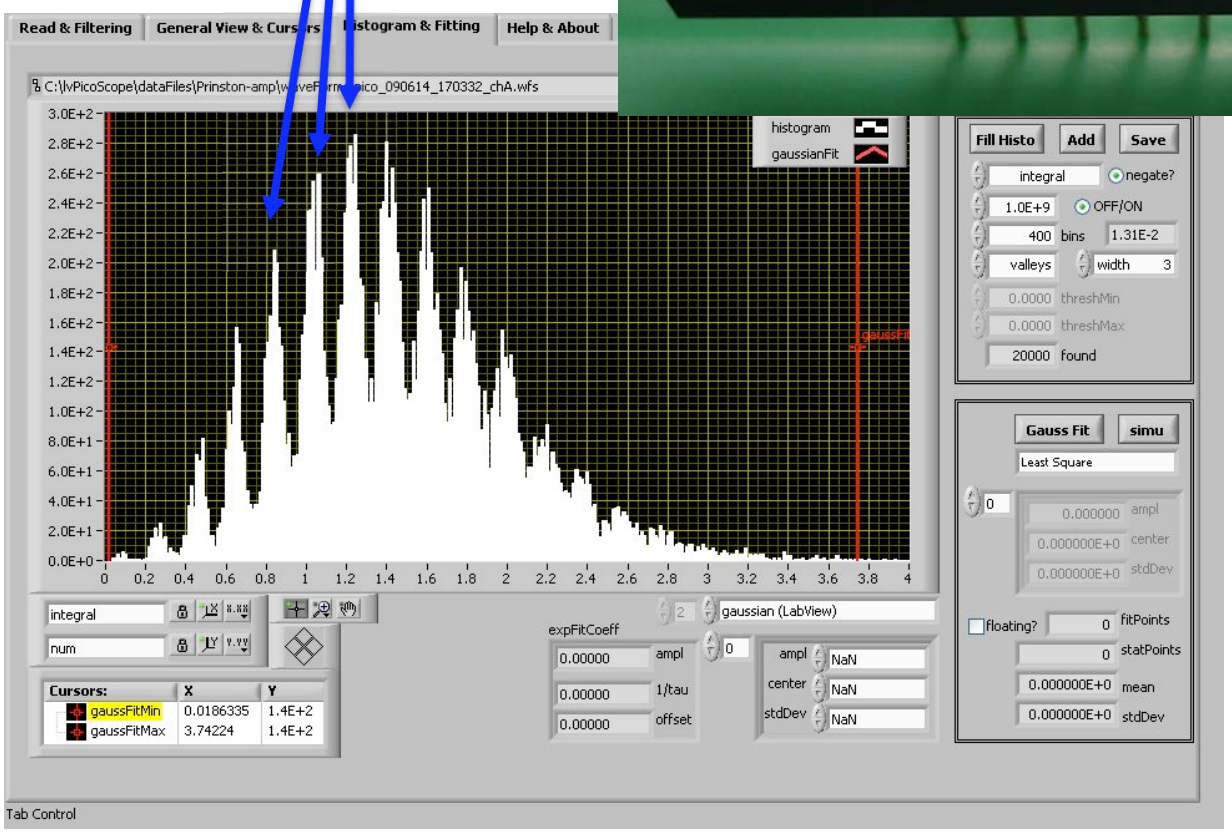
FBK: 625 Pixels



Linear Array of SiPMs(MAPD)

Photon Counting



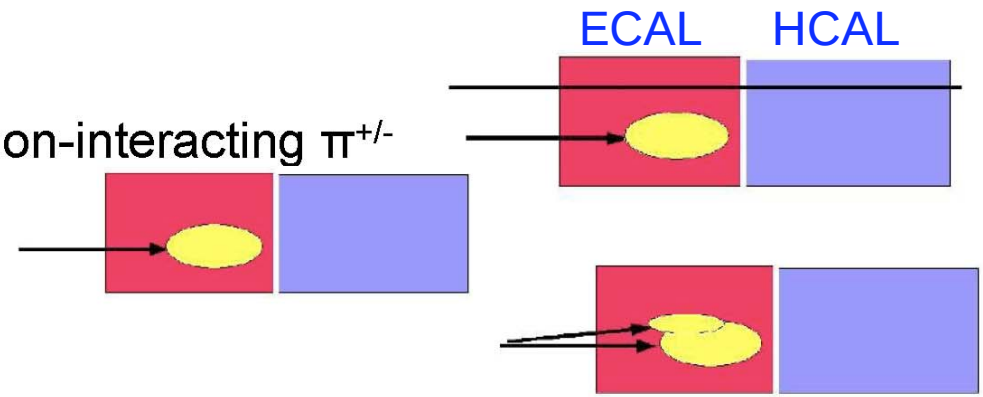


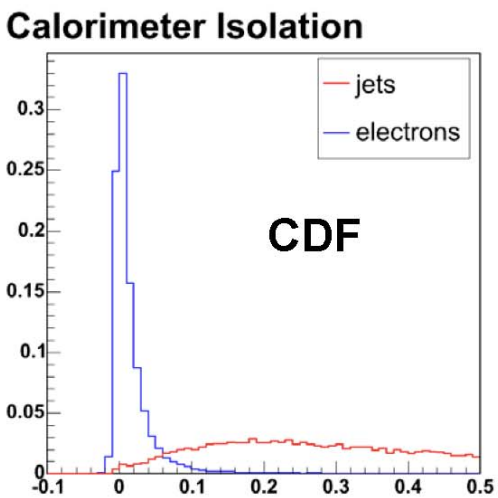
Zecotek Custom Device
15,000 pixels per mm^2
Gain per pixel ~60,000
Operating Voltage +86V

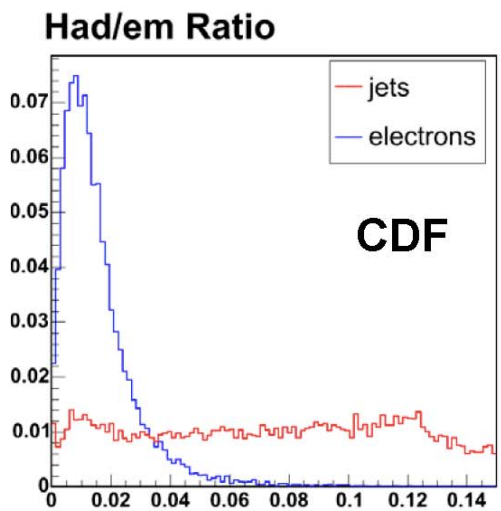
Electron ID

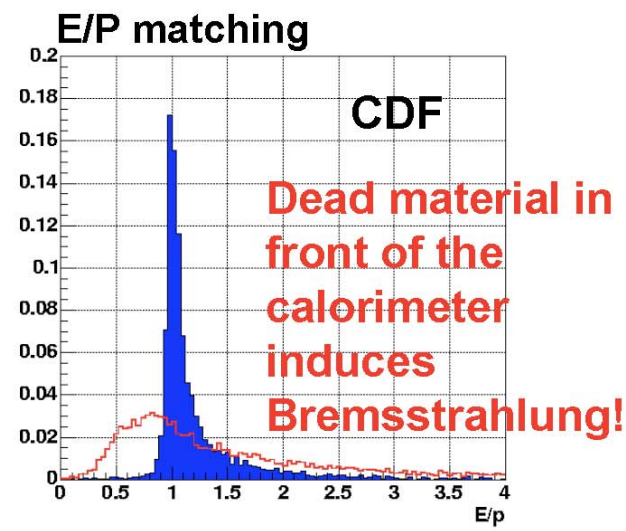
Main backgrounds:

- overlay over a π^0 and a non-interacting $\pi^{+/-}$
- early showering π+/-
- photon conversions

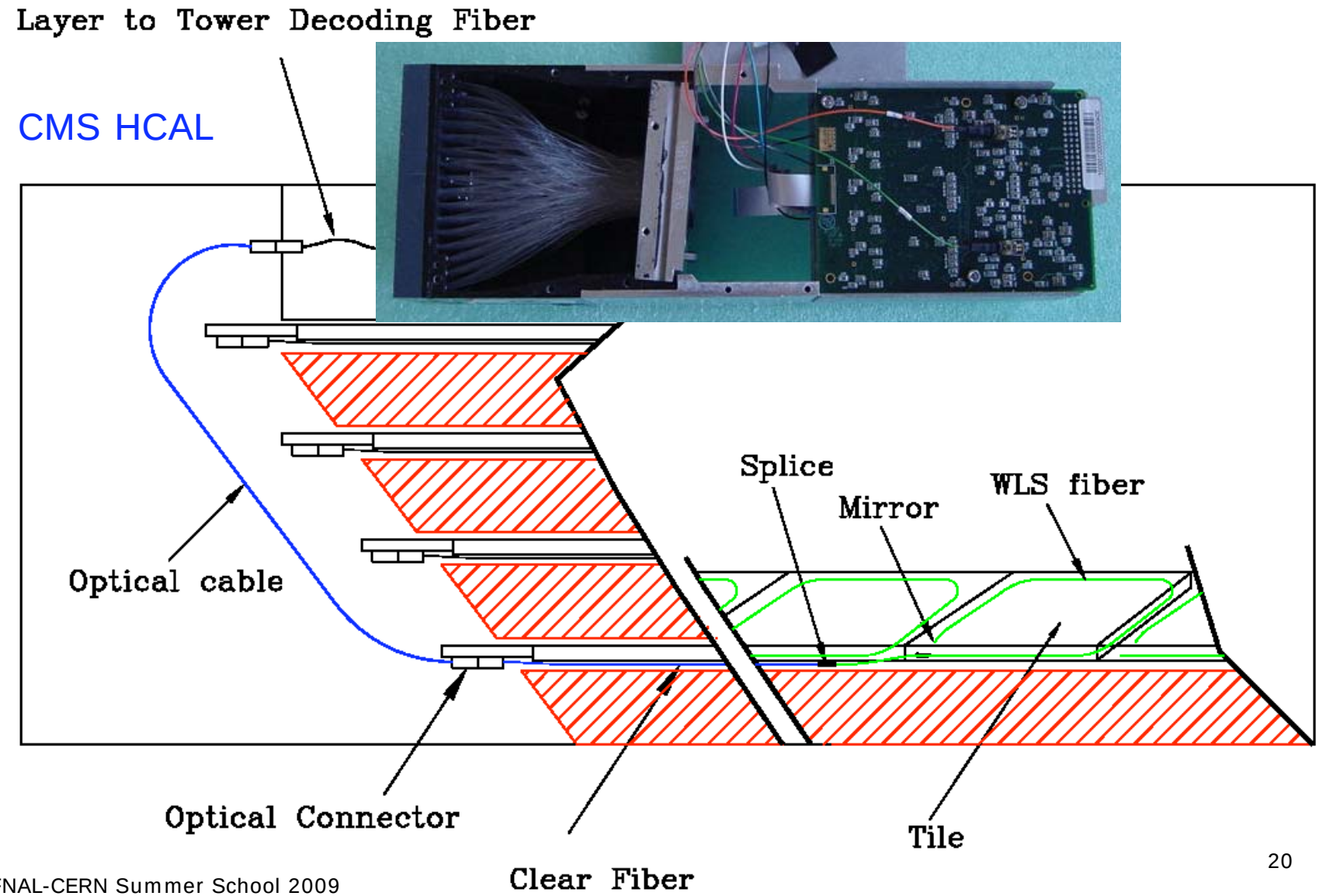






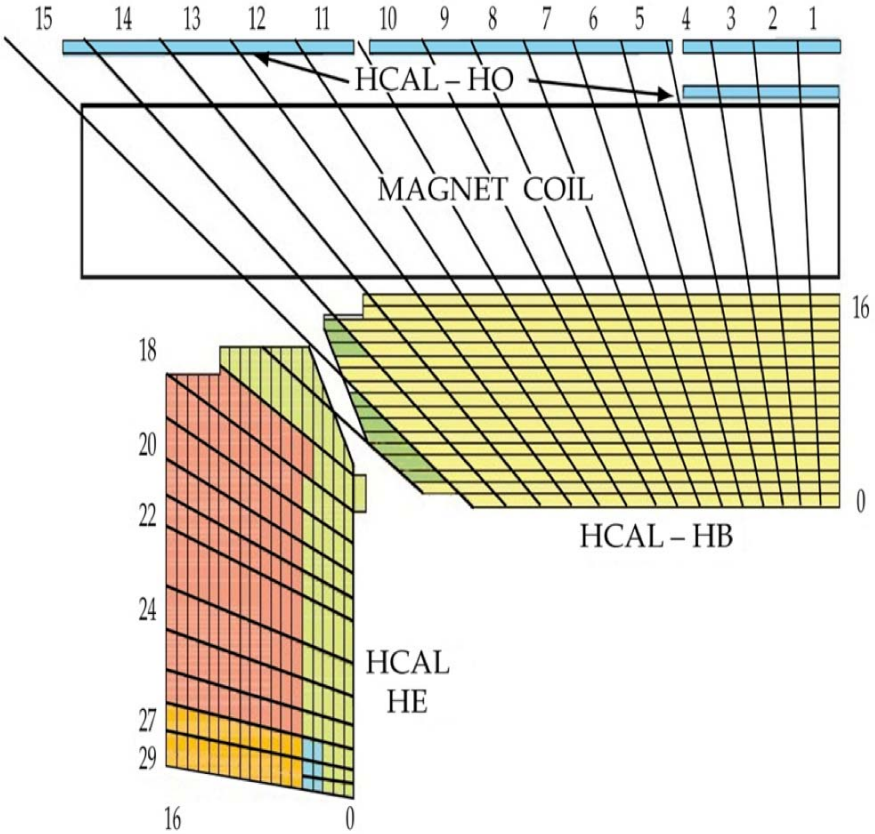


Replace Optical Addition of Layers

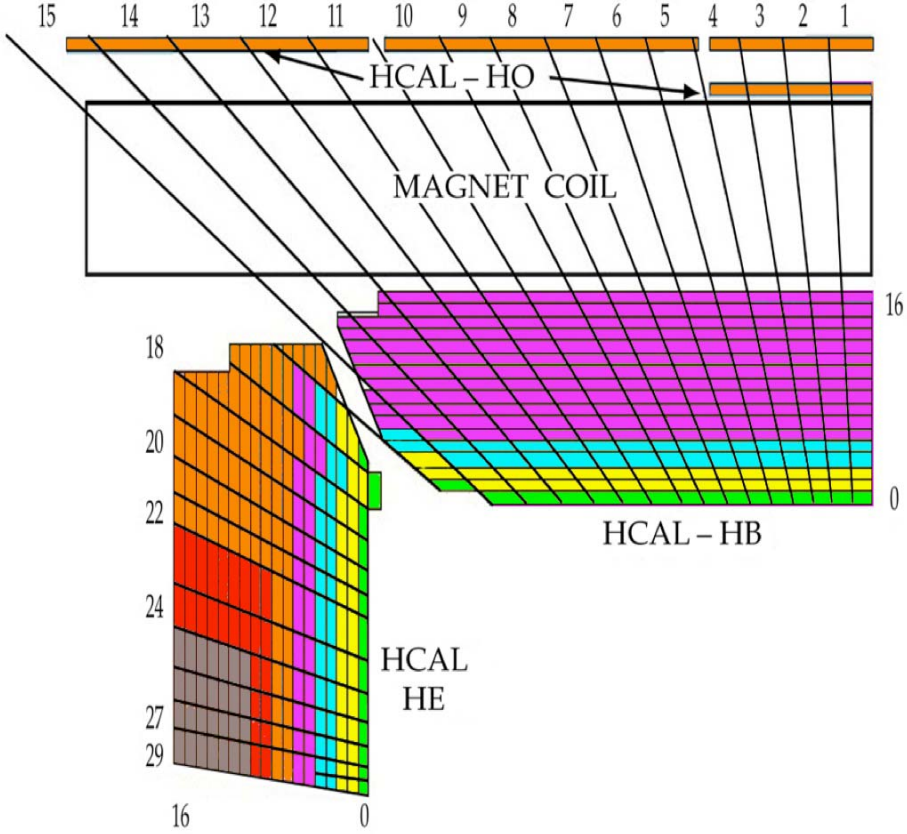


More Depth Segmentation

Current
18-Channel RMs



Upgrade
64-Channel HB RMs
48-Channel HE RMs



Radiation Damage Compensation in Endcap

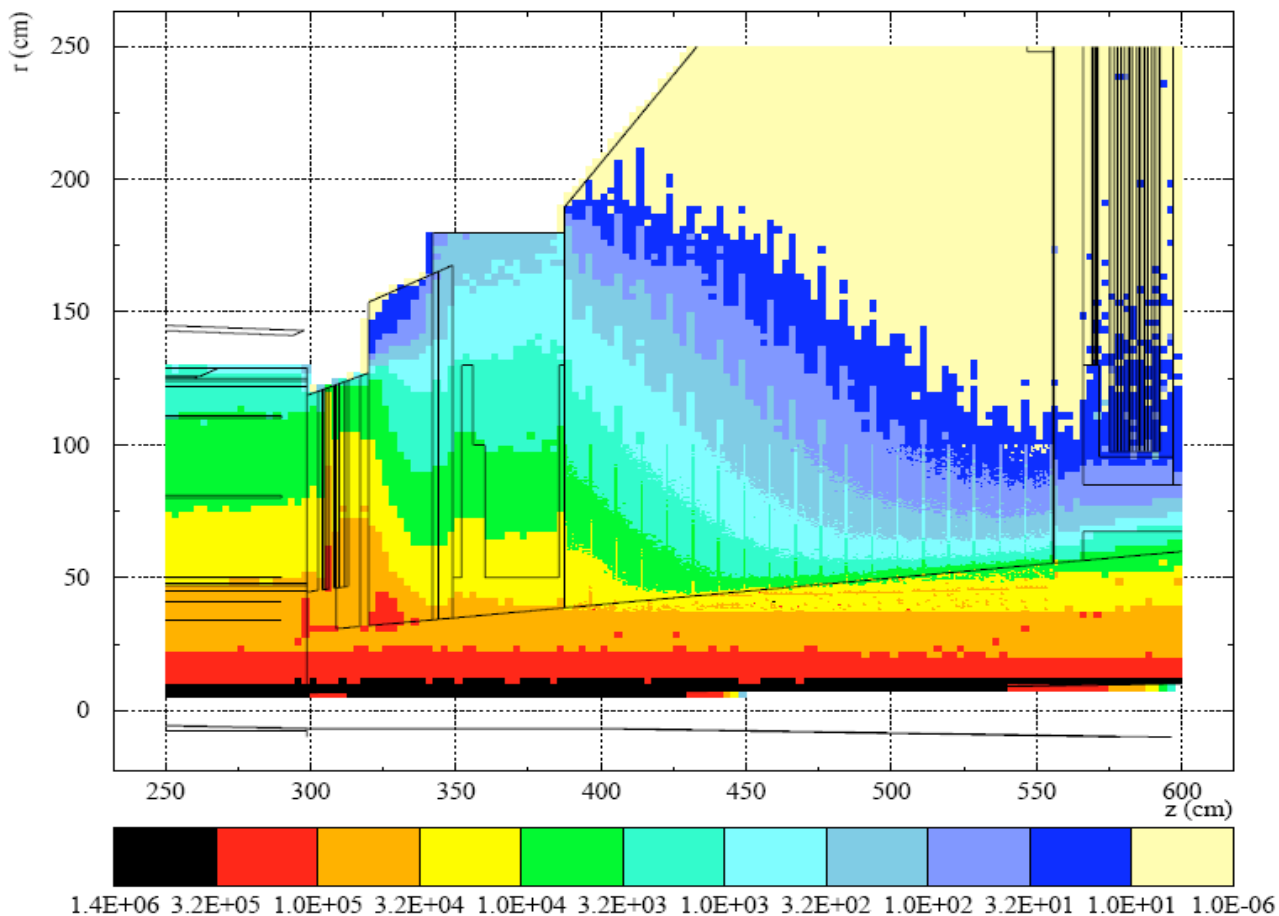


Figure 2: Dose map (Gy per 500 fb^{-1}) in the endcap calorimetry for the reproduction of the HE calculations. Note the high resolution map in the HE up R=100 cm.

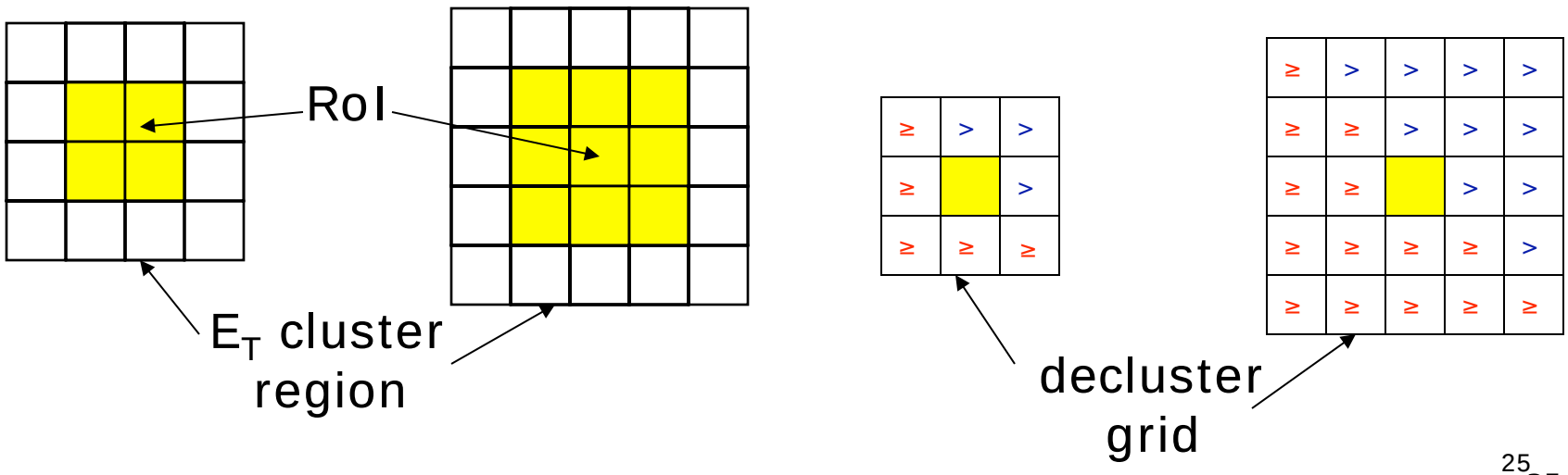
Final Remarks

- There is no great obstacle to producing physics measurements than an incomplete understanding of the detectors
  - Invest your time now and apply some of the basic principles from these and other lectures to estimate the expected behavior of the calorimeter you are using
  - Don't let the Monte Carlo do everything for you
  - Always keep in mind ways of improving the measurements and reducing systematic uncertainties – do it now, and you'll leave your mark on the experiment for years to come

SLIDE APPENDIX

Trigger "Bump Hunters"

- Some trigger algorithms are based on finding local maxima in the calorimeter with a search algorithm known as the "sliding window"
  - Despite the name, it's more akin to bump hunting than, say, an iterative cone jet algo



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