Part II: Calorimeter Technologies

- **I. Homogeneous calorimeters**
  - A. Scintillating crystals
  - B. Lead glass (Čerenkov light)
- **II. Sampling calorimeters**
  - A. Active media
    1. Plastic scintillator
    2. Ionization chambers
       - i. Noble gases
       - ii. Noble liquids
    3. Semiconductors
  - B. Passive media
    1. Choice of density
    2. Choice of Z, A

Homogeneous Calorimeters

All shower particles lose energy only via interactions with the absorber, which is also the active material, so

$$e / mip = 1$$

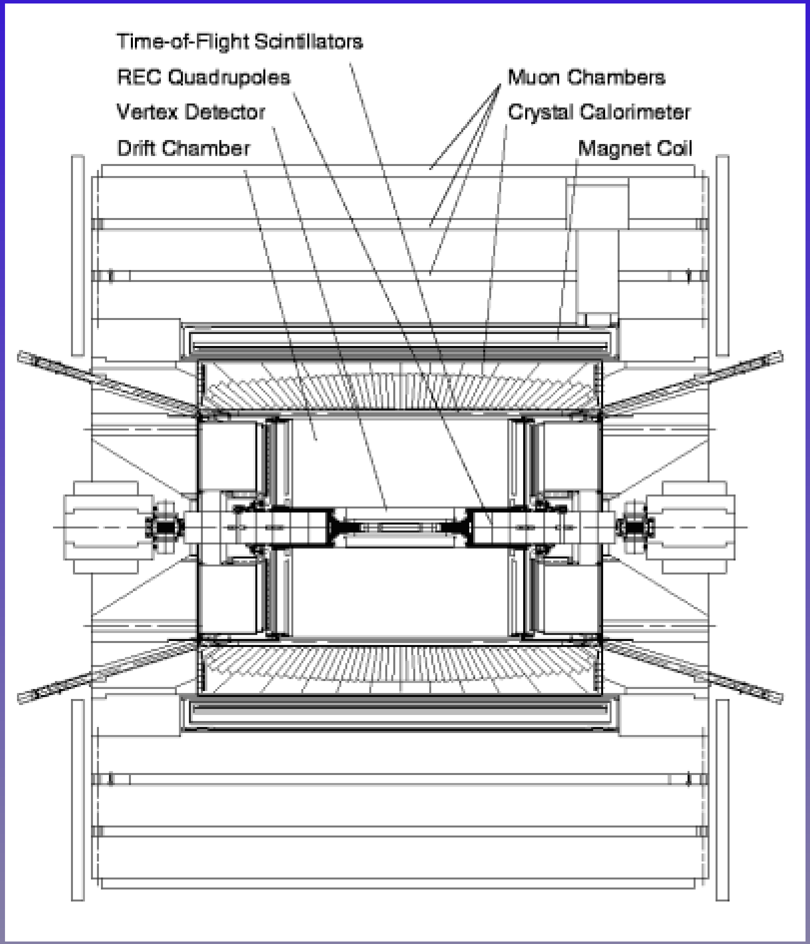
Scintillation Light

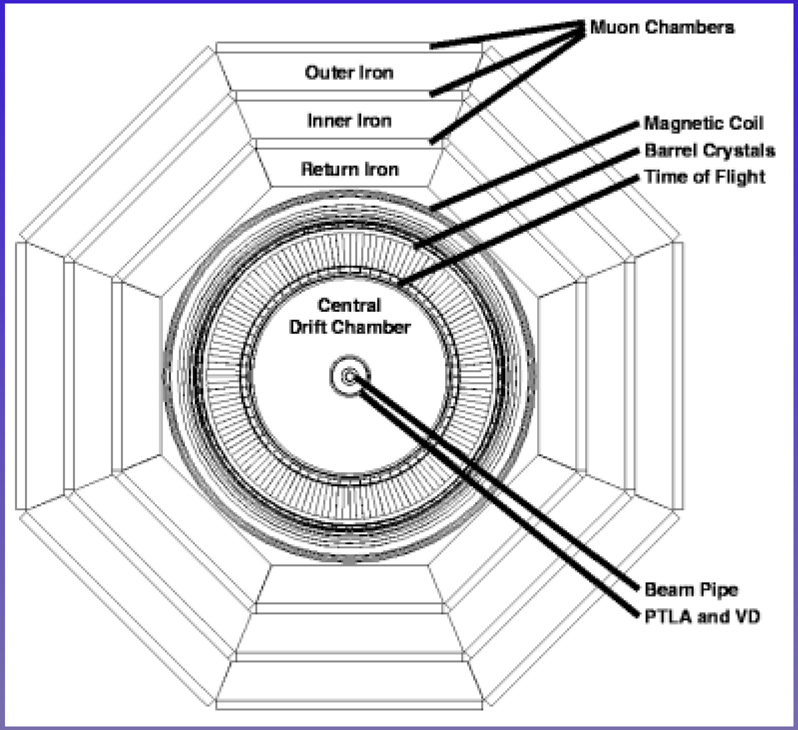
Scintillator	Density [g/cm^3]	L_R(cm)	Light Yield γ/MeV (rel. yield)	τ_1 [ns]	λ_1 [nm]	Rad. Dam. [Gy]	Comments
NaI (Tl)	3.67	2.59	4×10^4	230	415	≥10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005	565	≥10	Slightly hygroscopic
CSI pure	4.51	1.86	4×10^4 (0.04)	10 36	310 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 620	220 310	10^5	
BGO	7.13	1.13	8×10^3	300	480	10	
$PbW0_4$	8.28	0.89	≈100	10 10	≈440 ≈530	10^4	light yield =f(T)

Čerenkov Light

Material	Density [g/cm^3]	L_R(cm)	n	Light yield [p.e./GeV] (rel. p.e.)	λ_{cut} [nm]	Rad. Dam. [Gy]	Comments
SF-5 Lead glass	4.08	2.54	1.67	600 (1.5×10^{-4})	350	10^2	
SF-6 Lead glass	5.20	1.69	1.81	900 (2.3×10^{-4})	350	10^2	
PbF_2	7.66	0.95	1.82	2000 (5×10^{-4})		10^3	Not available in quantity

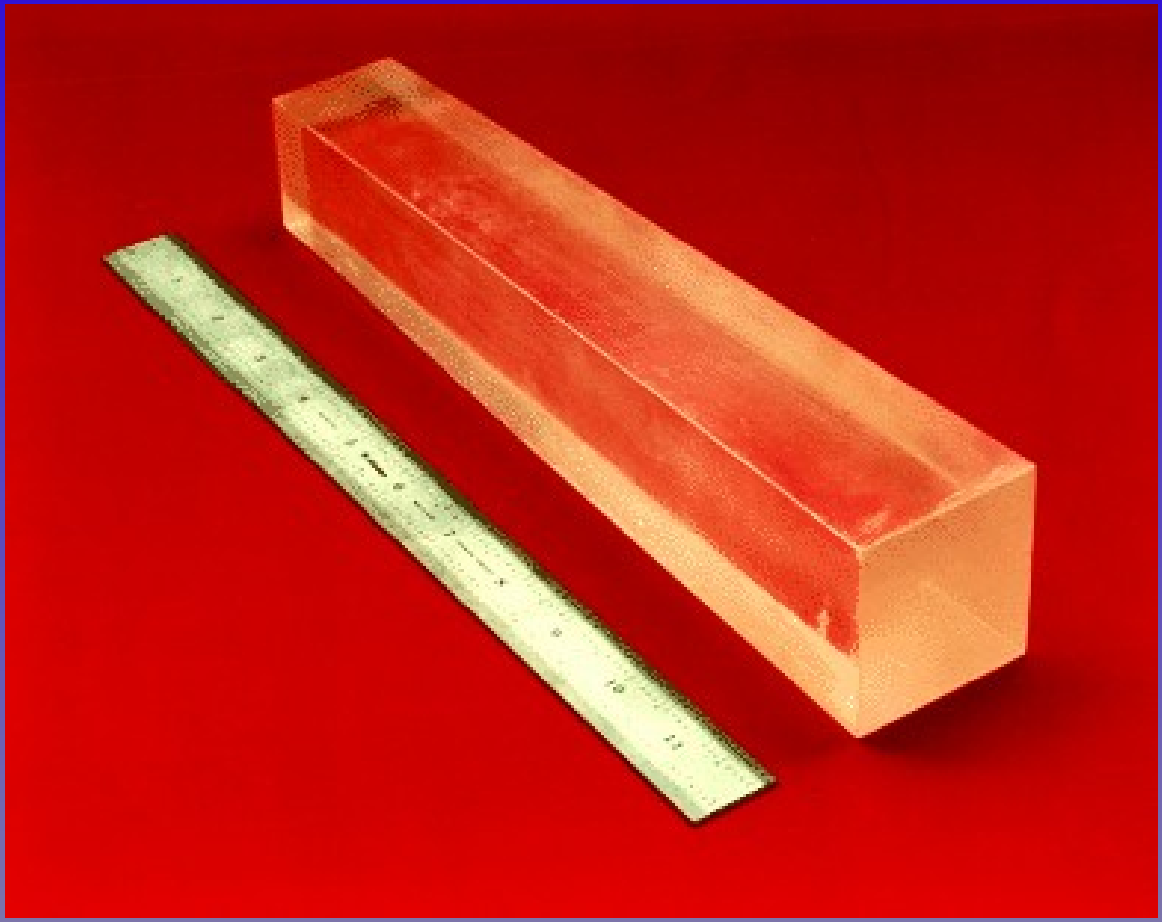
CLEO CsI Crystal Calorimeter





7800 thallium-doped CsI Crystals

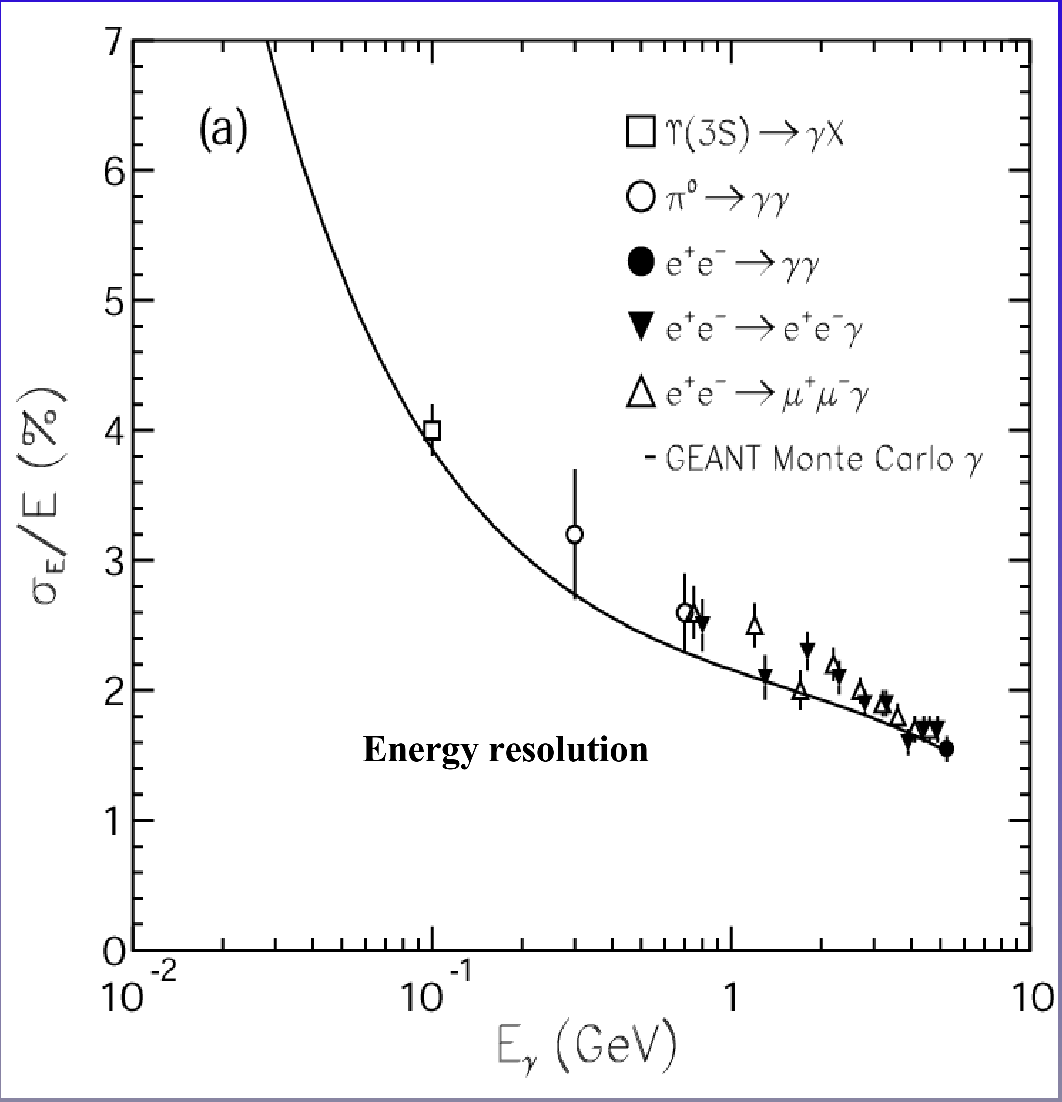
CLEO CsI Crystals



Each crystal 5 cm square by 30 cm (16 L_R) long

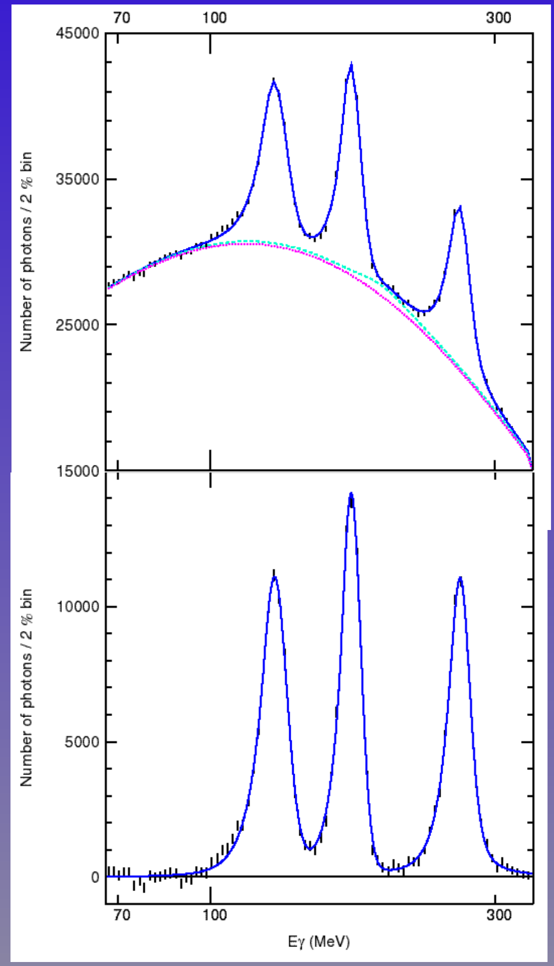
Silicon photodiode readout

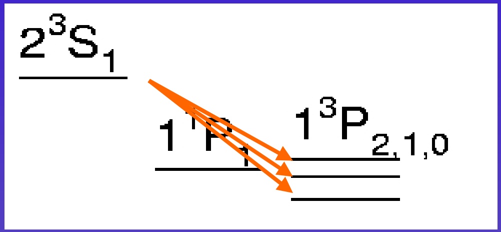
CLEO CsI Energy Resolution



CsI: QWG3 Topical School.
B Heltsley, LEPP.
Beijing, Oct 2004

Crystal Calorimeter Spectroscopy
ψ(2S) Inclusive γ Spectrum

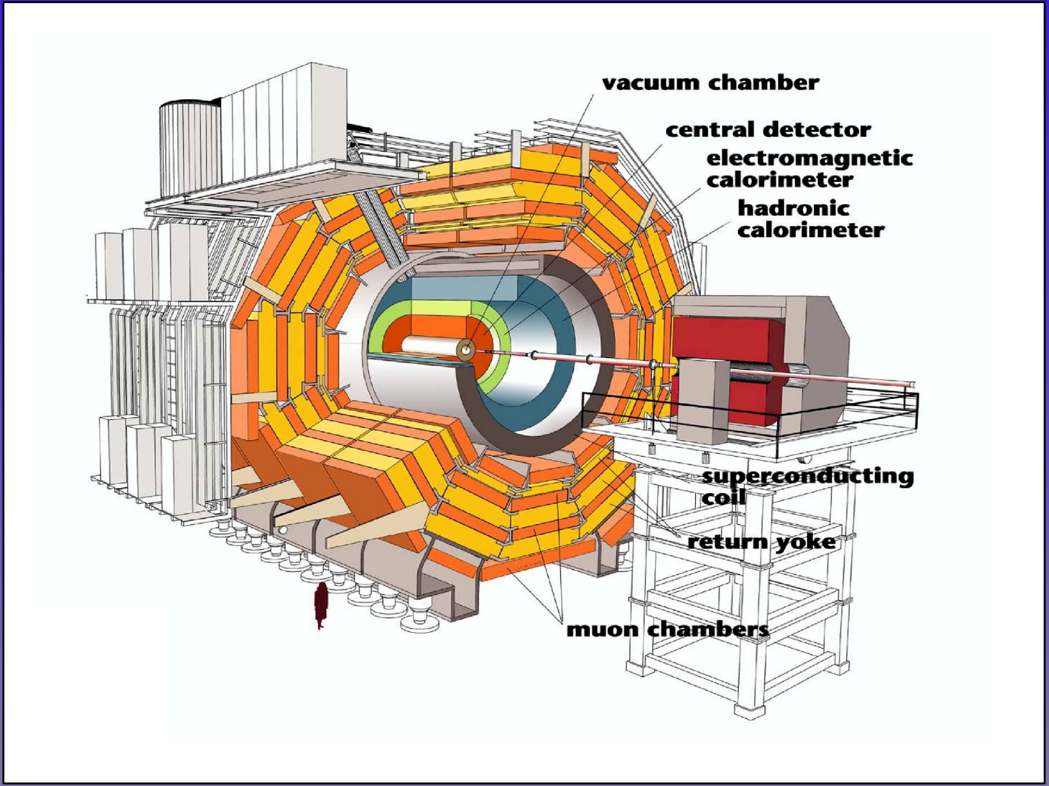




CsI: QWG3 Topical School.
B Heltsley, LEPP. Beijing, Oct 2004

CMS $PbW0_4$ EM Calorimeter

76000
Lead tungstate crystals



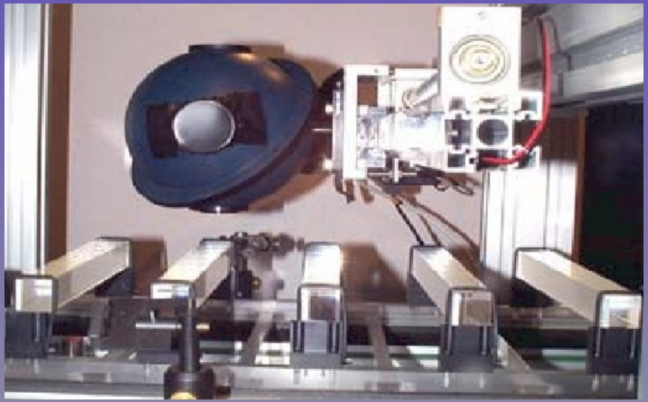
CMS Crystal Production

Automated quality control

Light yield

Light transmission

Radiation hardness



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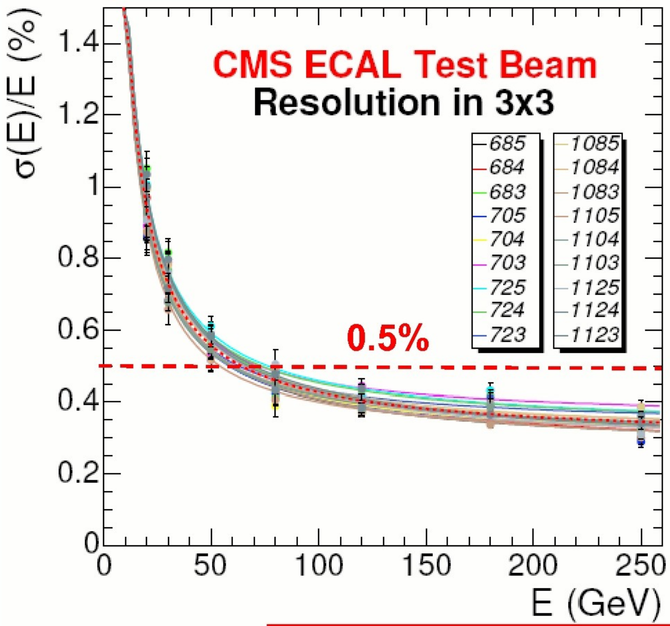
CMS $PbW0_4$ Test Beam Performance

Central impact: 18 3x3 matrices



Average resolution at each energy point:

Energy (GeV)	Resolution (%)
20	0.94 ± 0.05
30	0.74 ± 0.04
50	0.56 ± 0.03
80	0.45 ± 0.02
120	0.40 ± 0.01
180	0.38 ± 0.01
250	0.34 ± 0.01

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.9\%}{\sqrt{E}}\right)^2 + \left(\frac{125(MeV)}{E}\right)^2 + (0.30\%)^2$$

Stochastic **Noise** **Constant**

Alexandre Zabi
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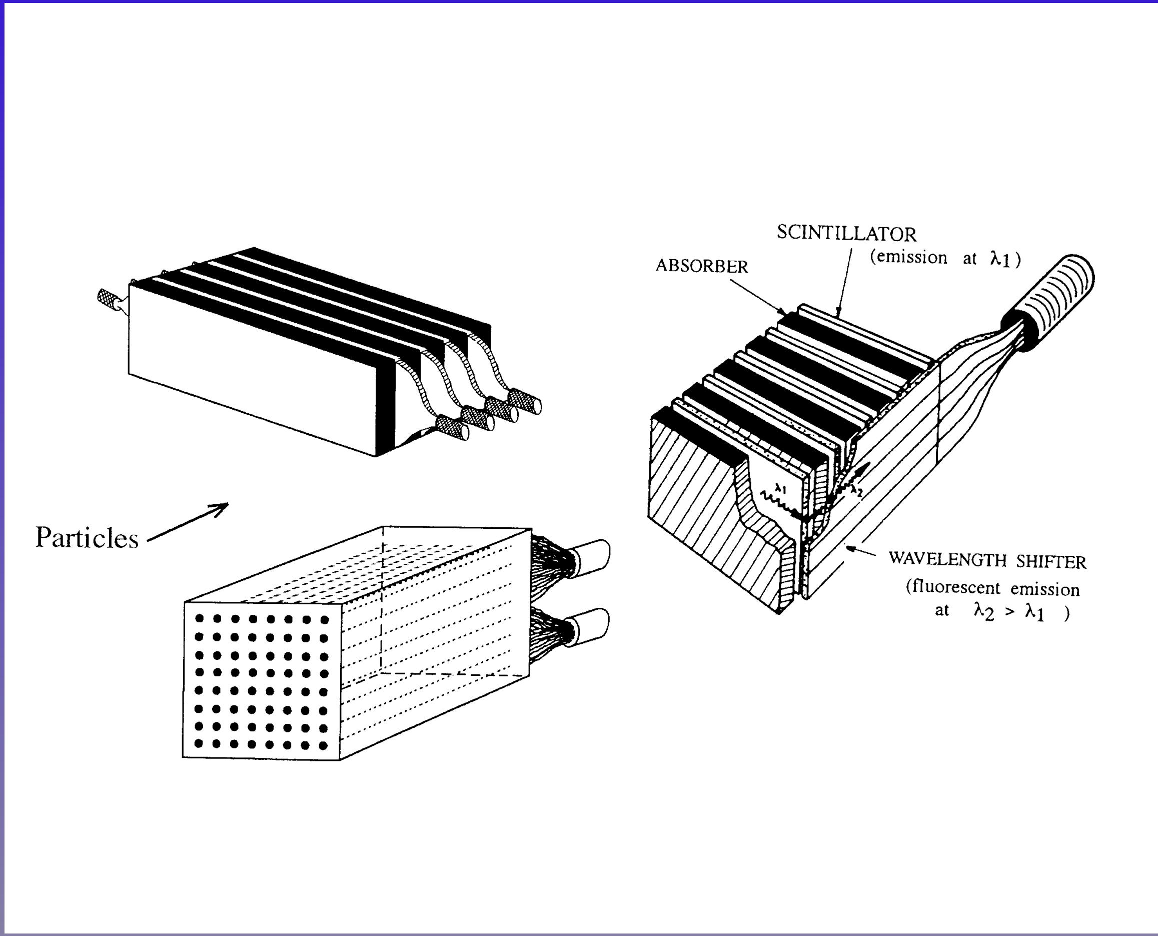
Sampling Calorimeters



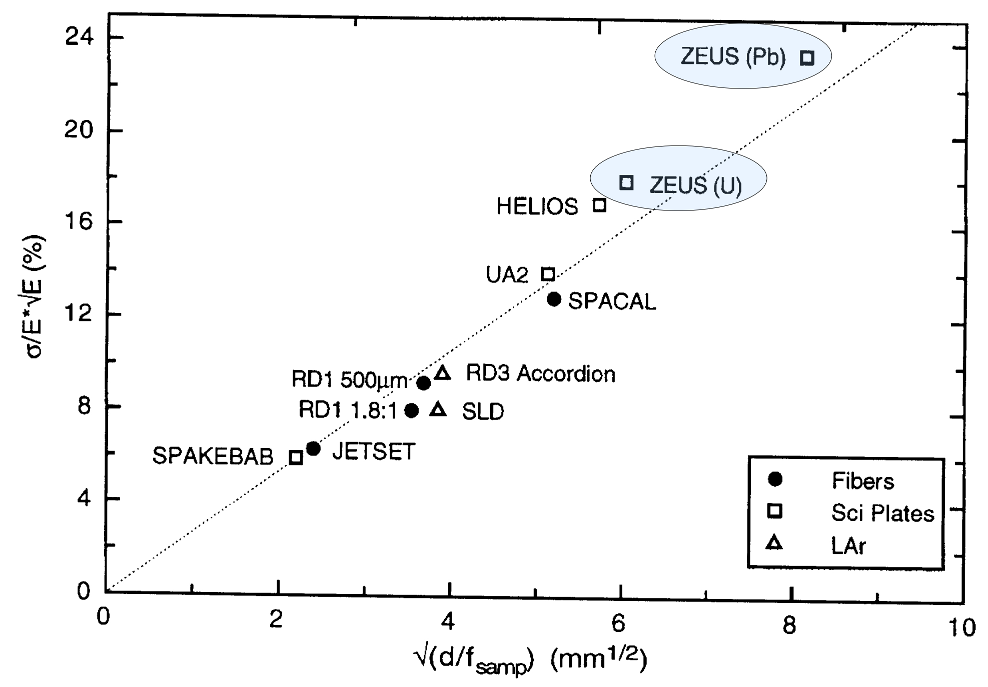
Electromagnetic Sampling Fraction

Energy resolution scales with the inverse square root of the sampling fraction.

ZEUS (U): $f_{em} = 4\%$

Compensation can be achieved in lead, but since it produces fewer neutrons than uranium, f_{em} must be reduced and so the resolution suffers.

In this case, the thickness of the absorber was doubled and the thickness of the scintillator halved.



e/h Ratio and Compensation

Rel: Ionization signal from relativistic charged pions
P: Ionization signal from spallation protons
n: Signal from evaporation neutrons
inv: energy deposited with no signal, e.g. nuclear recoil

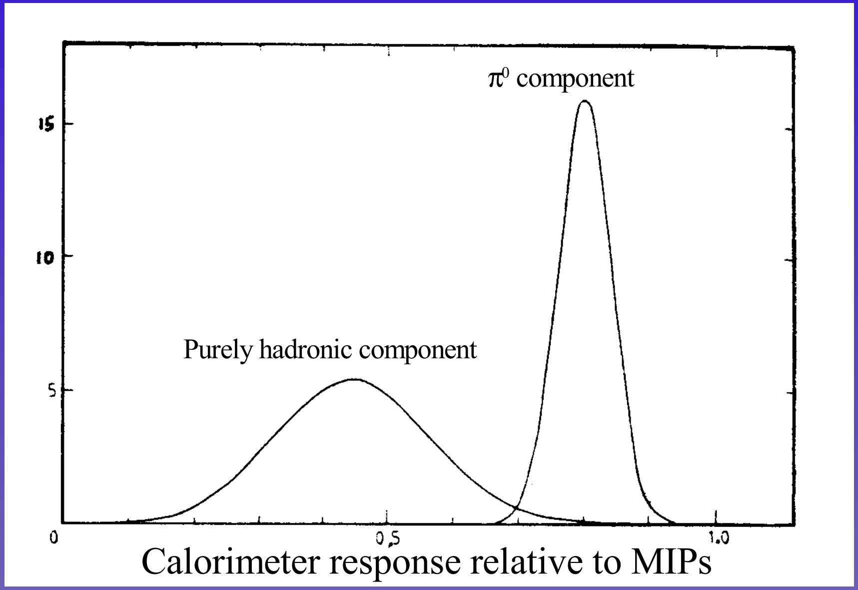
$$h = f_{\rm rel} \times rel + f_{\rm p} \times p + f_{\rm n} \times n + f_{\rm inv} \times inv$$

$$\frac{e}{h} = \frac{e/mip}{f_{\rm rel} \times rel/mip + f_{\rm p} \times p/mip + f_{\rm n} \times n/mip}$$

So e/h can be determined if the sampling fractions of these components relative to the MIP sampling fraction are known.

(ref:Wigmans)

Consequences of Differing Sampling Fractions f_{EM} and f_H

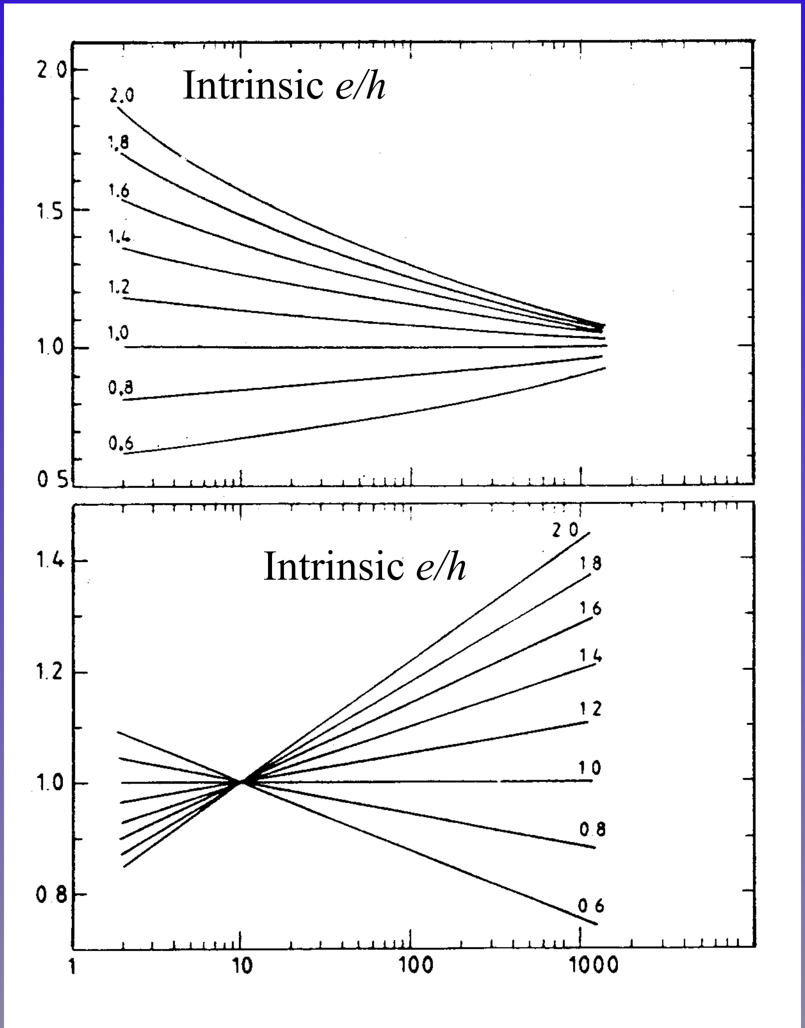


- Signal fluctuations are not gaussian
- Fluctuations in EM part affect overall resolution
- Signal is not proportional to E
- Ratio of signal for electrons and hadrons depends on energy
- Relative resolution does not scale with $E^{-1/2}$

Response Nonlinearity from Noncompensation

S_π / S_e

S_π

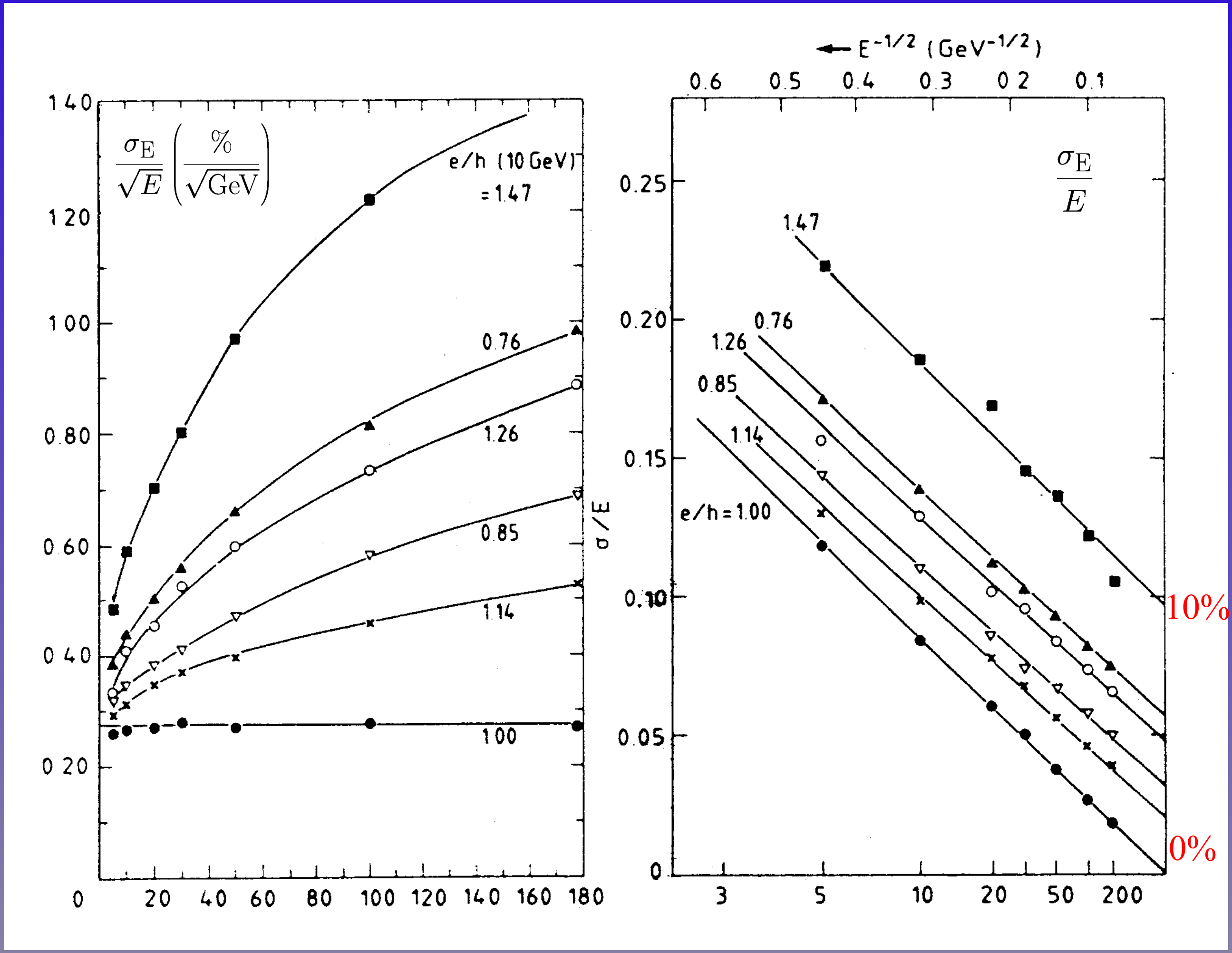


The signal from pions approaches that for electrons as the em fraction of the shower increases with energy.

The linearity of the signal from pions is poor for the same reason.

Energy Resolution for Noncompensation

Statistical term



Scale with √E

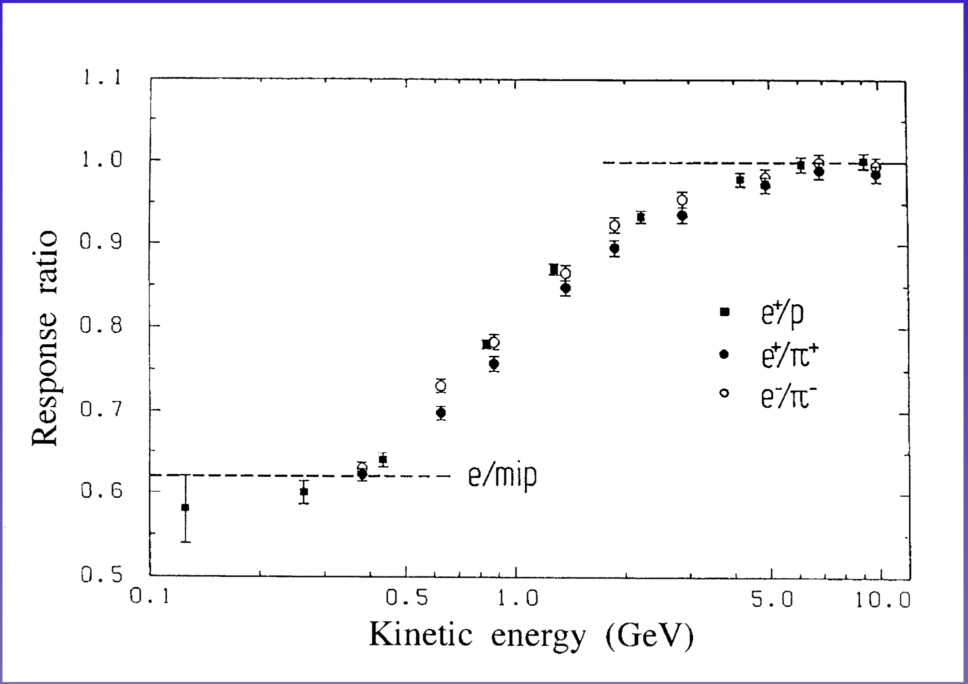
10%

0%

Energy-independent term

Low-energy hadrons and MIP's

At low energy (E<5 GeV), hadrons lose more of their energy via ionization than via shower formation and nuclear interactions. As a result, even compensating calorimeters exhibit nonlinearity at low energy. Since an essential characteristic of a compensating calorimeter is a lower sampling fraction for e and h than for mips, the sampling fraction decreases with hadron energy.



ZEUS, 1990

Ways to reduce f_{em}

I. Absorb the e+e- pairs from low energy photons in the passive material. If one uses a high-Z material, not only are more low-energy photons produced, they are also preferentially absorbed in the high-Z material (photo-effect), AND the e+e- they produce can't get out of it. For example, for 511 keV photons, f/f_{mip}=0.27 in uranium and 0.83 in steel. In this manner, the overall f_e can be reduce 30-40%.

II. Wrap the passive material in a material of lower Z. The thickness can be tuned to absorb photoelectrons and reduce their contribution. ZEUS used 0.3 mm stainless steel cladding to reduce f_e by 10%.

(ref:Wigmans)

Ways to increase f_h

I. Add hydrogenous materials to increase sensitivity to neutrons via elastic neutron-proton collisions. Note that this method is more effective for lower sampling fractions.

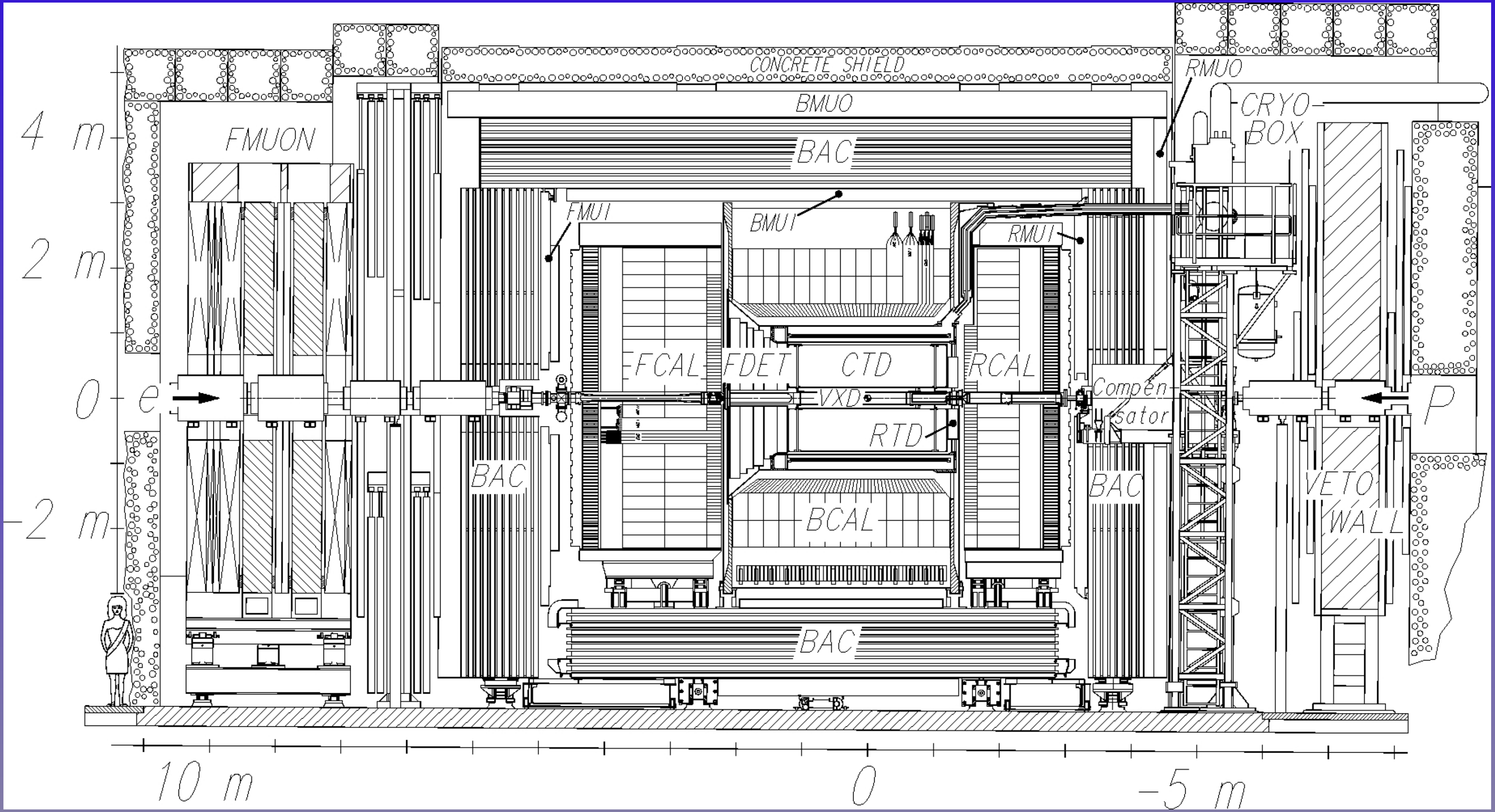
   A. Use scintillator (ZEUS, H1 spaghetti calorimeter)

   B. Add hydrogen rich gas admixture for wire chambers (L3, e.g. C_4H_{10})

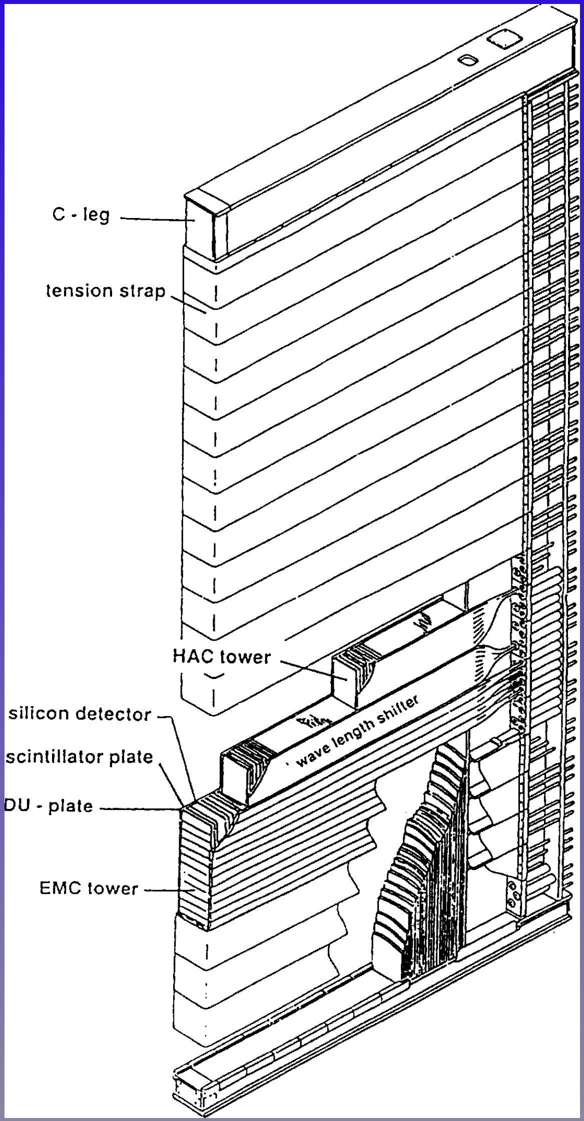
II. Increase integration time to be sensitive to slow nuclear processes (D0, ≈ 1 μs)

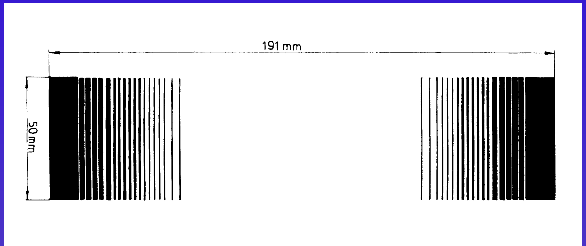
(ref: Wigmans)

The ZEUS Detector



ZEUS Uranium/Scintillator Calorimeter





3.2 mm U + 2.6 mm Sci

$$f_e = f_h = 4\%$$

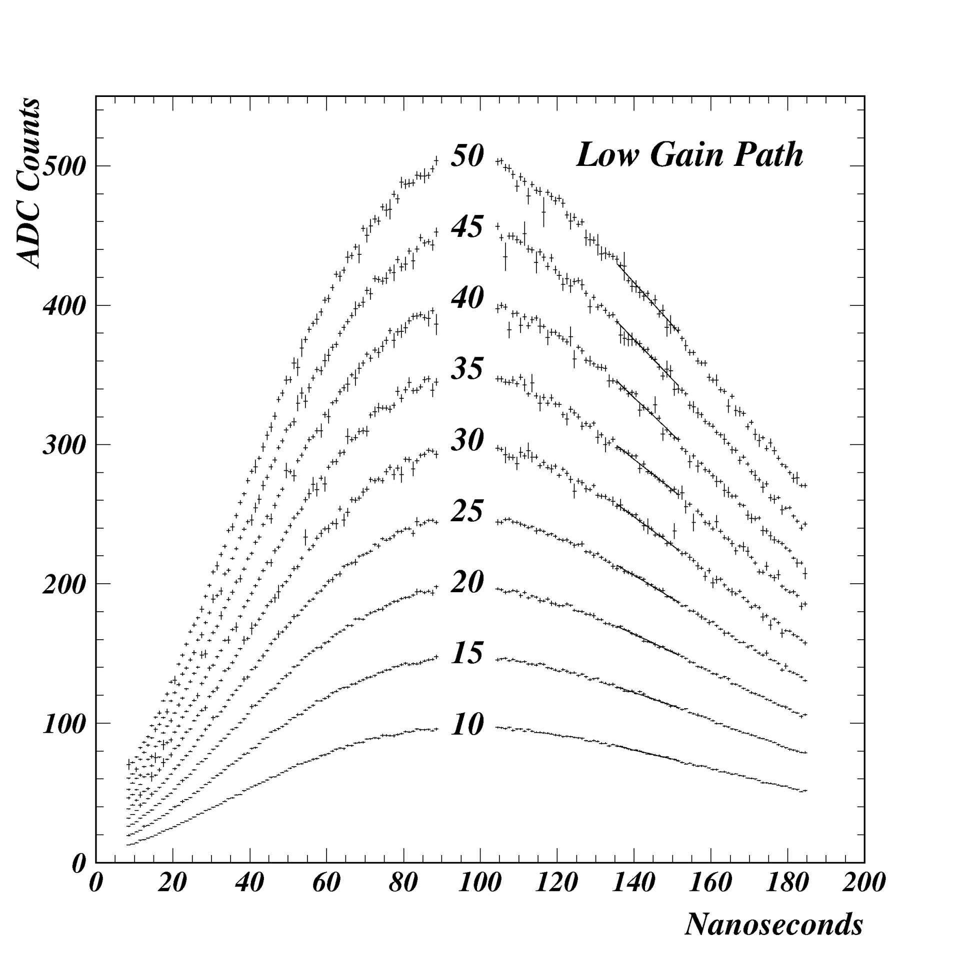
$$f_{mip} = 7\%$$

MIP sampling fraction

U: 1.09 MeV/(g/cm^2) x 18.65 g/cm^3 = 20.3 MeV/cm

Sci: 1.95 MeV/(g/cm^2) x 1.0 g/cm^3 = 1.95 MeV/cm

ZEUS Calorimeter Sampled Signal



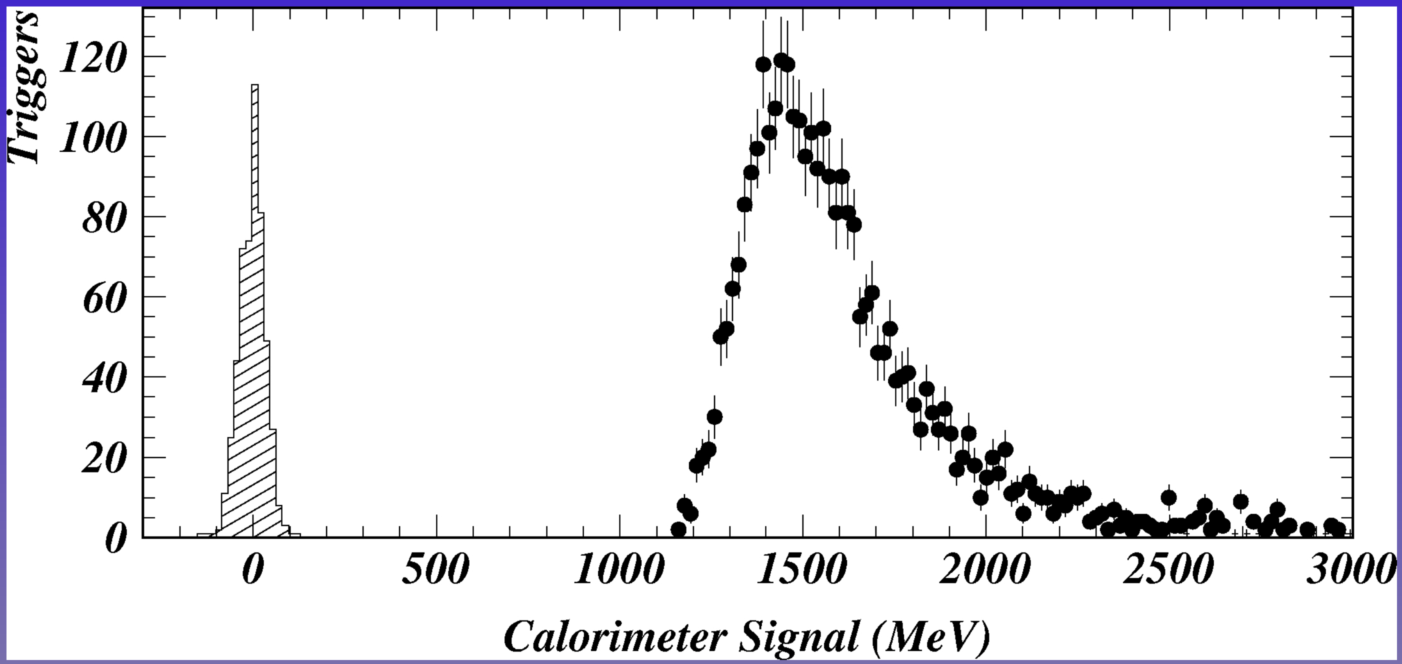
JAC, International Workshop on Calorimetry in High-Energy Physics, Brookhaven (1994)

Calibration Techniques

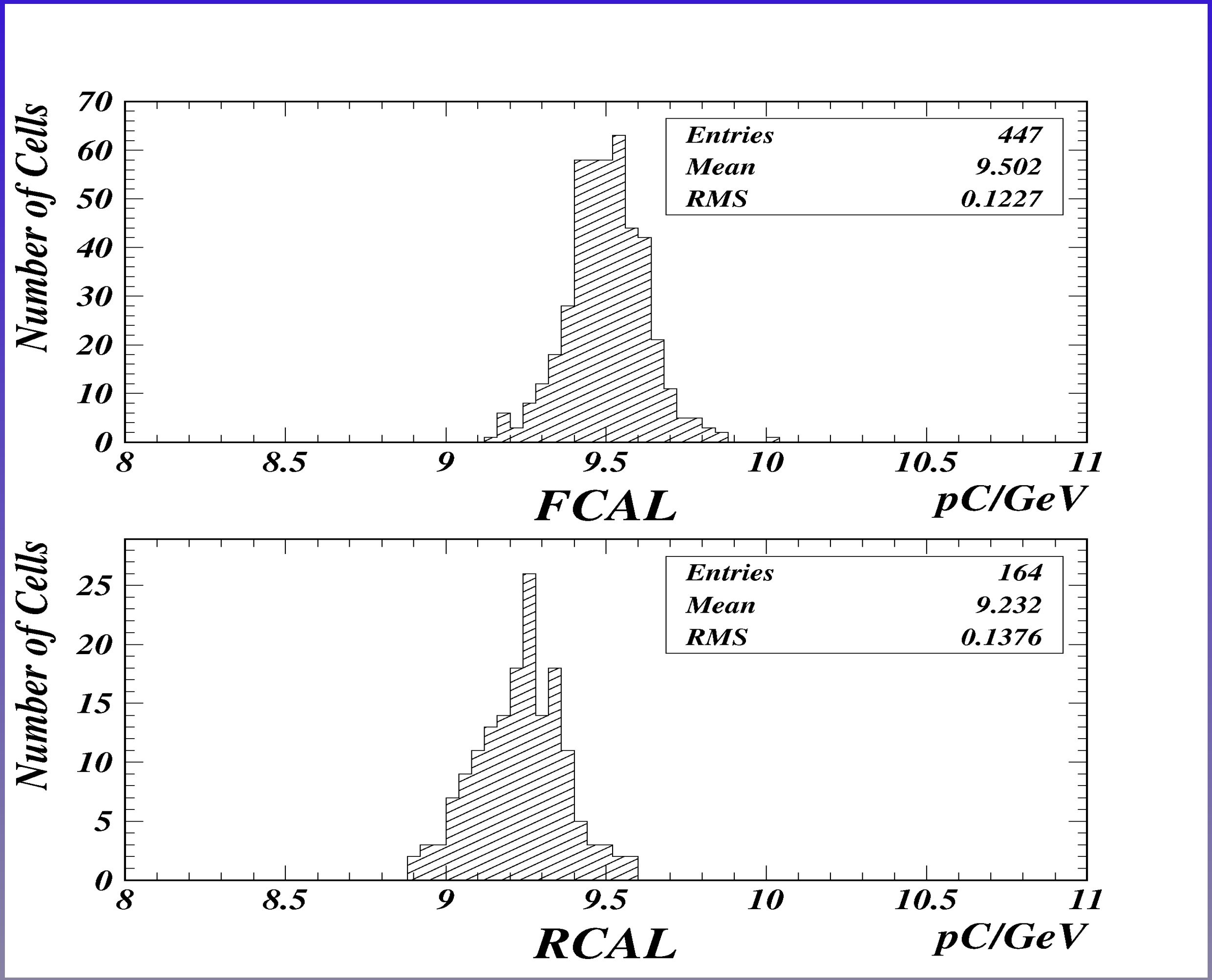
- Test Beams
- Cosmic muons
- Laser/LED Monitoring
- Guided ^{60}Co sources
- Low-level, stable radioactive background
- In situ physics ($\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $Z \rightarrow e^+e^-$, Φ-symmetry, ...)
- Cell-weighting to optimize resolution, uniformity

(ref: Wigmans)

ZEUS: Muons wrt Uranium Noise

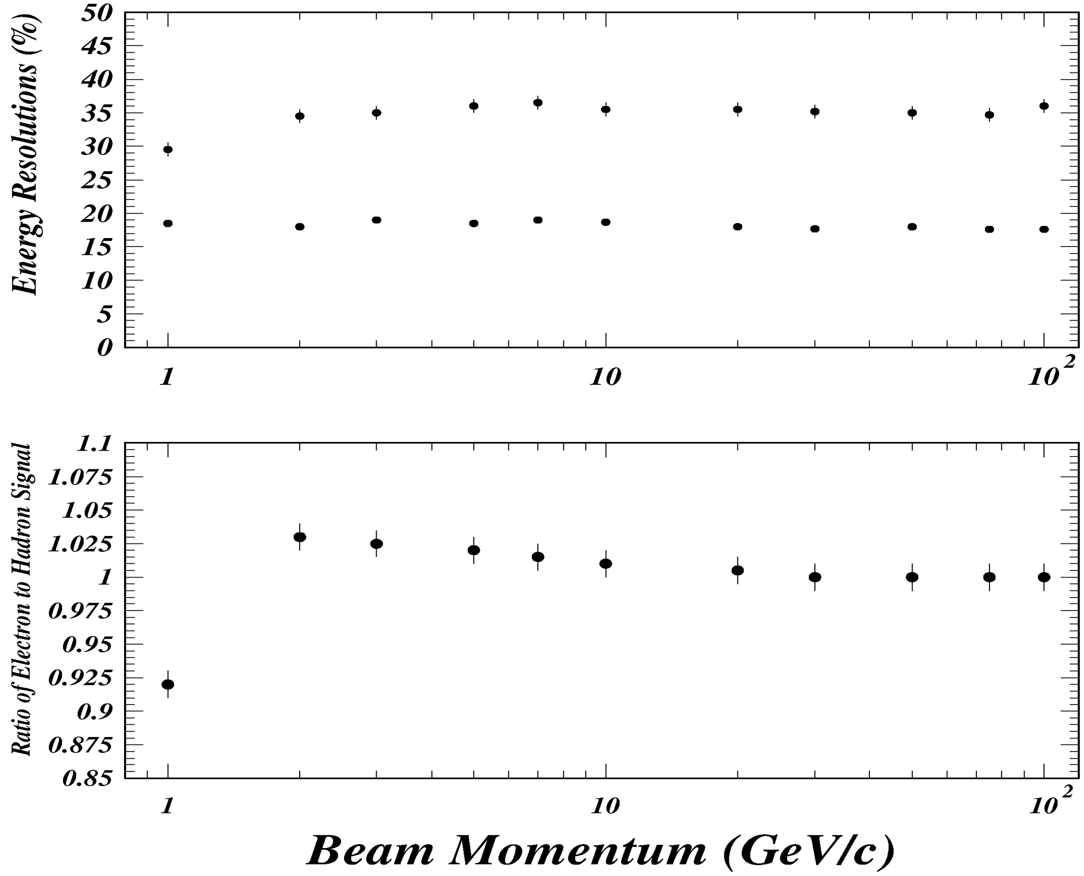


ZEUS EM Cell Test Beam Calibration Uniformity



Contribution to the energy-independent term in the resolution

ZEUS e/h and Energy Resolution

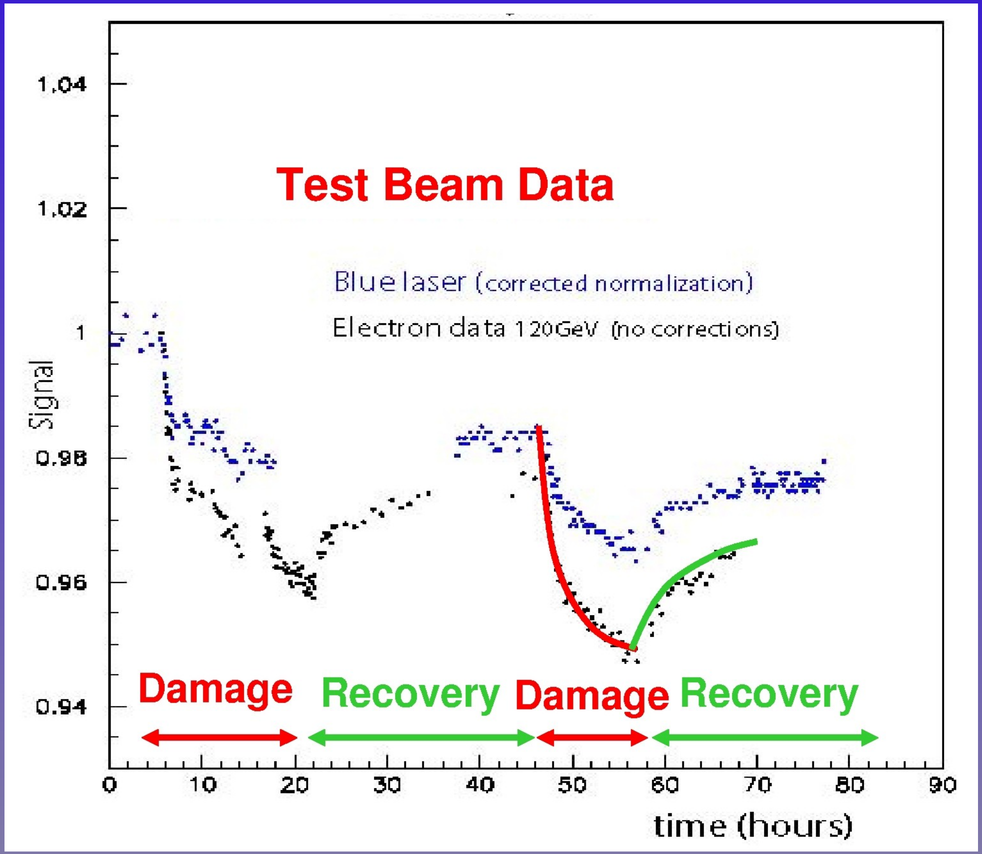


CMS Laser Monitoring of $PbW0_4$ Crystal Light Transmission

Recall goal of 0.5% systematic contribution to energy resolution, which limits dynamic range of precise measurement

Short-term radiation damage affects light transmission at a greater level than this, and varies from crystal to crystal

Laser-based monitoring system has been developed which will monitor the transmission properties of each crystal at the 0.1% level over ten years



Adi Bornheim
12th International Conference on Calorimetry in High-Energy Physics
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Concluding Remarks

Since the 1980's, calorimetric measurements have grown in importance with the expanding energy frontier in elementary-particle physics, becoming the precision instrument of choice due to their exploitation of high-statistics counting methods

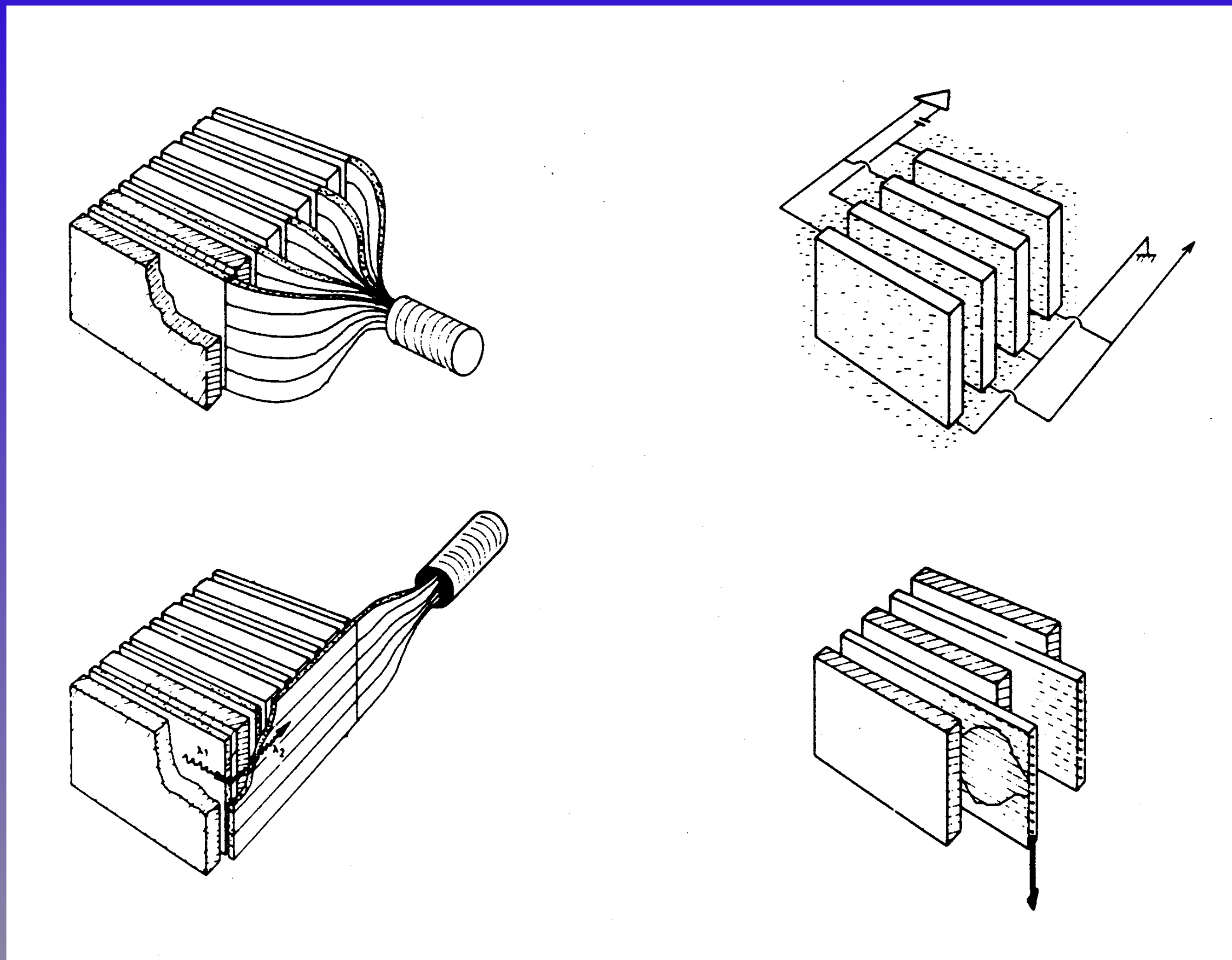
Intense R&D programs have improved quantitative understanding of the physics behind their operation (e.g. measurements of hadronic showers in the mid 1980's) and resulted in a huge variety of available calorimeter technologies

Today's applications of calorimeters extend from medical diagnostics to neutrino astrophysics, from satellites to deep-sea arrays, from mountaintops to Antarctic ice.

The experimental particle physics community has reached a consensus to expand the energy frontier as necessary to understand electro-weak symmetry breaking, entailing an enormous global effort to build a linear electron-positron collider. Present estimates of the necessary energy measurement precision exceed the capabilities of existing calorimeters by substantial factors. Extensive detector-development programs are in preparation around the world, inspiring confidence in a bright future for progress in calorimetry and further expansion of its range of applications.

End of Section
on
Calorimeter Types
and
Calibration Methods

Sampling Calorimeters



Hadronic Showers