Linear Collider Calorimetry
Summary of U.S. Activities and Results

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(for the ALCPG Calorimeter Working Group)

ALCPG/SLAC January 2004
OVERVIEW

- Physics requirements for LC calorimetry
- Calorimeter system design
- Simulations for LC calorimetry
- ECal requirements and technologies
- HCal requirements and technologies
- Issues/Conclusions
Physics examples driving calorimeter design and requirements (1)

Higgs production e.g. \( e^+ e^- \rightarrow Z h \) separate from WW, ZZ (in all jet modes)

Higgs couplings e.g.

- \( g_{tth} \) from \( e^+ e^- \rightarrow tth \rightarrow WWb\bar{b}bb \rightarrow q\bar{q}qqb\bar{b}bb \)

- \( g_{hhh} \) from \( e^+ e^- \rightarrow Z hh \)

Higgs branching ratios \( h \rightarrow bb, \ WW^*, \ cc, \ gg, \ \tau\tau \)

(all demand efficient jet reconstruction/separation and excellent jet energy + jet-jet mass resolution)
**Physics examples** driving calorimeter design and requirements (2)

**Strong WW scattering:**

separation of \( e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq \)

\( e^+e^- \rightarrow \nu\nu ZZ \rightarrow \nu\nu qqqq \)

and \( e^+e^- \rightarrow \nu\nu tt \)

(no beam constraint)

**Supersymmetry:**

- e.g. gauge-mediated SUSY with long-lived NLSP \( \rightarrow \gamma G \)
- requiring good measurement of photon(s) from secondary vertices.
Importance of good jet energy resolution

Simulation of $W, Z$ reconstructed masses in hadronic mode.

(From CALICE studies shown at ALCPG/Cornell: M. Schumacher)
Calorimeter System Design

LC Physics demands excellent jet i.d./energy resolution, and jet-jet invariant mass resolution.

Energy Flow approach holds promise of required solution and has been used in other experiments effectively.

-> Use tracker to measure Pt of dominant, charged particle energy contributions in jets; photons measured in ECal.

-> Need efficient separation of different types of energy deposition throughout calorimeter system

-> Energy measurement of only the relatively small neutral hadron contribution de-emphasizes intrinsic energy resolution, but highlights need for very efficient “pattern recognition” in calorimeter.
Calorimeter System Design

Identify and measure each jet energy component as well as possible.

Following charged particles through calorimeter demands high granularity...

Two options explored in detail:

1. **Analog ECal + Analog HCal**
   - For HCal: cost of system for required granularity?

2. **Analog ECal + Digital HCal**
   - High granularity suggests a digital HCal solution
   - Resolution (for residual neutral energy) of a purely digital calorimeter??
Fraction Energy of Particles in Jets

- Electromagnetic
- Neutral Hadrons
- Charged Hadrons

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<tr>
<th>Type</th>
<th>E/E_{tot}</th>
<th>RMS</th>
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<tr>
<td>EM</td>
<td>26.55</td>
<td>19.33</td>
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<td>CH</td>
<td>69.59</td>
<td>19.49</td>
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<tr>
<td>NH</td>
<td>3.299</td>
<td>6.632</td>
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</table>

11/24/2003

DHCal Study at UTA-A Report
Venkatesh Kaushik
Calorimeter System Design

Charged hadron/photon separation in jet:

“Figure of Merit”  ~  BR$^2$/R$_{\text{Moliere}}$

Other design issues:
- Timing reqs? Bunch i.d. ?
- Operation in a strong magnetic field.
- Hermetic - minimize intrusions, gaps, dead material
- Minimize costs - design for ease of production
- Robust, reliable design
- Inner radius of endcaps/radiation hardness?
SD Configuration

M. Breidenbach/Cornell 2003
Studying options with simulations

Studies in support of:

- general calorimeter parameters
- various detector technologies
- EFlow initial ideas

BUT need:

- EFlow algorithm development for detector optimization and detector technology comparisons.
**Analog vs Digital Energy Resolution**

**GEANT 4 Simulation of SD Detector (5 GeV $\pi^+$)**
- Sum of ECAL and HCAL analog signals - Analog
- Number of hits with 7 MeV threshold in HCAL - Digital

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**Total CAL Energy Sum**

**Analog**

- Total CAL Energy Sum
  - Mean: 3.6636
  - Gaussian:
    - Mean: 3.6194 ± 0.0188
    - Sigma: 1.0566 ± 0.0150
    - $\chi^2$: 4.4721
- Landau Tails + path length
- $E$ (GeV)

**Digital**

- Total CAL Num of Hits
  - Mean: 107.07
  - Gaussian:
    - Mean: 107.62 ± 0.351
    - Sigma: 20.930 ± 0.259
    - $\chi^2$: 1.1570
- Gaussian
- Number of Hits
Analog ECAL + Digital HCAL Reconstruction

5 GeV pion

$\sigma$/mean $\sim 26\%$

- Total CAL Energy Sum
  - Mean: 3.6773
  - RMS: 1.1038
  - Gaussian
    - Amplitude: 376.85$\pm$6.80
    - Mean: 3.6814$\pm$0.0153
    - Sigma: 0.9561$\pm$0.0096
    - $\chi^2$: 10.841

- Number of HAD Hits vs HAD ESums

- Total CAL EMA/HDigital E Sum (Mean)
  - Mean: 3.6668
  - RMS: 1.1006
  - Gaussian
    - Amplitude: 371.93$\pm$6.74
    - Mean: 3.6978$\pm$0.0156
    - Sigma: 0.95406$\pm$0.00982
    - $\chi^2$: 13.208
Particle Flow Studies at Argonne

Hadronic Z Decays at $\sqrt{s} = 91$ GeV

- Have Developed Straightforward Photon and Neutron/$K_{Long}$ Algorithms Based on Combinations of Tracking/Calorimeter Information
- Resolutions for both about x2 worse than Perfect Identification
- In addition to continued algorithm development, ready to start testing different detector designs.

Algorithm results compared to MC truth
NIU - Tiles/fibers

Single Particle Resolutions

Parameterized Jet Resolutions -Zh

3x3 works

Digital (density based clustering) EFlow

\[ \Sigma^+ \rightarrow p\pi^0 \]

Density weighted \( \theta-\phi \)

\( \sim 60\% \) worse

Calo only

Eflow
UTA-GEM Analog and Digital CAL Performances

• GEM digital and analog responses comparable
  – Large remaining Landau fluctuation in analog mode observed
  – Digital method removes large fluctuation

• GEM Energy resolutions
  – Digital method comparable to TESLA TDR
  – Analog resolution worse than GEM digital or TESLA TDR

• Performance dependence on cell sizes and absorber configuration needed
UTA-Energy Flow Studies for $\pi^-$

Pions $\langle E_{\pi^-} \rangle = 7.5$ GeV chosen for study

- Studied the energy distribution of pions in jet events $e^+e^- \rightarrow t\bar{t} \rightarrow 6\text{ jets} \quad \sqrt{s} = 1.0TeV$
- Find the centroid of the shower (HCAL) using
  - Energy weighted method
  - Hits weighted method
  - Density weighted method
- Matched the extrapolated centroid with TPC last layer hit to get $\Delta \theta$ and $\Delta \phi$ distribution
- Will use 2 Mokka single $\pi$ for EFA development
ECAL Requirements

Physics requirements emphasize segmentation/granularity (transverse AND longitudinal) over intrinsic energy resolution.

Localization of e.m. showers and e.m./hadron separation -> dense (small $X_0$) ECal with fine segmentation.

Moliere radius -> $O(1 \text{ cm.})$ - from min. charged/neutral separation.

Transverse segmentation $\approx$ Moliere radius

Tracking charged particles through ECal -> fine longitudinal segmentation and high MIP efficiency.

Excellent photon direction determination (e.g. GMSB)

Keep the cost (Si) under control!
SLAC-Oregon Si-W ECaI R&D

- Silicon-tungsten ECaI is ∼ideal realization
- Goal: **How to make it practical while maintaining performance...**
- Highly **integrated electronic readout** (reduce cost and complexity)
- Simple, robust silicon detector design (low cost)
- Flexible design relative to eventual performance optimization
  - e.g. transverse segmentation nearly independent of cost
- Initial prototypes:
  - Pixels are 5 mm x 5 mm x 0.6 X₀
  - A detector element (wafer) is ≈800 pixels with **one** full readout chip
  - Readout includes 2000 dynamic range and timing at few ns level
  - Power off when no beams ⇒ simple, passive cooling
- Technical tests of initial prototypes - thermal, noise, resolution
- Construct a full-depth module: 15cm x 15cm x 30 X₀
  - Ready for **test beam in 2005**
- First prototype silicon detectors delivered Jan/04
- Electronics design converging for initial chip order early ‘04
Wafer and readout chip

- Multi-Layer G-10
- Wire Bond
- Readout Chip
- Bump Bonds
- Silicon Wafer
- p+
- n
- n++

Dimensions:
- 300 μm
- 1 μm
Multi-layer W-Si prototype:
- 3 independent C-W alveolar structures according to the thickness of tungsten plates
- 30 detector slabs which are slit into central and bottom cells of each structure
- Active zone: 3 x 3 silicon wafers

M. Merkin, A. Savin, A. Voronin
MSU-Moscow

High quality silicon wafers
- low leakage current (<10nA/pad)
- only 3 guard rings/wafer
- good (very good?) prod. rate

Similar production will start soon in Prague
V. Vrba (IOP-ASCR)
Mechanics R&D and production

Prototype

- Structure 1 and 2 produced
- Support (type H) produced for stack 1,2
- to do
  - Structure-3 (4.2 mm)
  - Support H for stack 3

Dead area Inter-alveoli is only 0.4 mm

structure 1

- 2 active layers and one layer of tungsten
- 7 mm

M. Anduze, A. Busata
LLR

and ITEP, IHEP which make a VERY NICE production of good quality tungsten sheet

first mip measurement with a complete chain of detector slab

Expected mip position

R&D

- Thermal simulation
- Cooling design
- Large scale module CFi-W
- etc...

CALICE
Compact Sampling ECAL with High Spatial, Timing and Energy Resolution

Objective: Develop a cost and performance optimized ECAL design which retains the performance advantages of the Si-W concept, but finer sampling, excellent time resolution and cost which permits placement at larger R.

Extensive study of EM energy resolution for various longitudinal configurations which retain small Moliere radius

Position resolution for 1 GeV $\gamma$ of 300 $\mu$m, with 1 mm Si strips at conversion point.

U.Kansas: G. Wilson
Relevance to detector design/physics performance

- Improvement in the ECAL performance in terms of:
  - i) energy resolution (15%/\sqrt{E} to 10%/\sqrt{E}) – better single particle measurements and jet energy resolution.
  - ii) timing resolution – can resolve NLC bunch crossings (1.4ns separation) and reduce \gamma\gamma pile-up
  - iii) cost at fixed radius – allows placement at larger radius which improves angular resolution (and hence jet energy resolution) and allows gaseous tracking.
  - iv) position resolution – better angular resolution and jet energy measurement with particle flow algorithms

U.Kansas: G. Wilson
CU BOULDER

- **Electromagnetic/Hadronic Calorimeter**
- 5x5 cm² tile array scintillator tungsten
- Alternate layers offset (picture on left)
- Leads to improvement in spatial resolution added
- to excellent energy resolution ≈11%/E¹/₂
- Z⁰→e⁺e⁻ Mass Resolution σ = 1 GeV
- X 2 Improvement over non-offset case.
- Beginning pattern recognition of hadronic jets
- Reconstruction of photon energy and direction in middle of hadronic jet.
- Studying resolution of different structures versus cost.
Spatial Resolution

- Z0 Mass Fit after Bias Correction

U. Nauenberg
JLC-CAL: Scintillator based

- Pre-shower: 1mm, 4mm
- Shower MAX.: 10mm
- EM CAL.: 1mm, 4mm
- Hadron CAL.: 2mm, 8mm

1:4 for compensation

Strip Array EM CAL

- Strip: 1cm x 0.2cm x 20cm
- Fiber: 1mm x 20cm WLSF + Clear Fiber

Tile Fiber EM CAL

- partly constructed
- 2SL’s

- Full module with MEGA-Tile will be tested march/2004

Shower Max. detector

WLSF R/O

- improve position resolution, track matching
- and e/π separation
Lab tests for Crystal ECAL

• Lab tests of PbWO$_4$ crystals begun
  • Goal is to test suitability of crystals for ECAL: light yield, uniformity, response time etc.
  • Crystals on loan from CalTech
  • Equipment from Iowa and SLAC

• DAQ system now set up and tested by graduate on short-term attachment; a post-doc will take over soon.
Cerenkov Compensated Precision Calorimetry for LC

Y. Onel, University of Iowa - D.R. Winn, Fairfield

• 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 $E_c$ and Ionization $E_i$ on the same shower.
- No “suppression” needed for compensation, thus more active material can be used, up to 100%, thus reducing the stochastic term.

• Compensating E-M & Hadron Calorimeters
  - CMS experience: combined crystal em + compensated hadron Calorimeter: hadrons $sE/E \sim 90-100\%E^{-1/2} + 3-4\%$ - unacceptable for LC performance.
  - To correct a crystal em+hadron system, Add a 2nd wavelength filtered Cerenkov photodetector to each crystal to compensate the crystal e-m calorimeter. Combined em+hadron Resolution should reach resolution of compensated hadron alone.
  - To correct any highly non-compensated em calorimeter, add some Cerenkov (or electron-sensitive) detector.

• High Precision Sampling Hadron Calorimeter
  - MC indicates that $sE/E \sim 20\%E^{-1/2} + <1\%$ practical
  - Energy-Flow possible with Clear & Scintillating “bricks”/WLS fibers
HCAL Requirements

Physics requirements emphasize segmentation/granularity (transverse AND longitudinal) over intrinsic energy resolution.

- Depth $\geq 4\lambda$ (not including ECal $\sim 1\lambda$)

- Assuming EFlow:
  - sufficient segmentation to allow efficient charged particle tracking.
  - for “digital” approach - sufficiently fine segmentation to give linear energy vs. hits relation
  - efficient MIP detection
  - intrinsic, single (neutral) hadron energy resolution must not degrade jet energy resolution.
DHCAL with Resistive Plate Chambers

Resistive Plate Chambers

- Suited for DHCAL
  - Simple and flexible technology
  - Cheap: all materials commercially available
  - Reliable: no ageing problems ever observed with glass as resistive plates
  - Thin: detectors with t < 10 mm feasible
  - Readout can be segmented into small pads: of order 1 cm²

- R&D so far (in U.S.)
  - Built four chambers
  - Extensive tests with single pads
  - Extensive tests with multiple pads
  - Measurements with different gases
  - Measurements of geometrical acceptance
  - Design of larger chambers well advanced

Developed expertise in RPC technology

Chamber design for prototype section almost complete

Goal: construction of 1 m³ prototype section
  → validate technology
  → detailed measurements of hadronic showers
  → validate MC simulation
Electronic Readout

- Real challenge
  - 40 layers of 1 m²: 400,000 channels
  - Cost has to be kept ≤ $1/channel

- R&D so far (in U.S.)
  - Built VME based readout system
  - System works well for streamer mode (large signals)
  - Additional amplification needed for avalanche mode
  - Developed conceptual design of system for prototype
  - Based on front-end ASIC
    Handles 64 channels
    Specifications almost complete
    Design work to start soon

- Cost estimate for 1 m³ prototype section (M&S only)
  - Mechanical structure (table, absorber…) $40k
  - RPCs (120 chambers à 33 x 100 cm²) $10k
  - Front-end ASIC (need 7000) $100k
  - Remainder of electronic readout system $335k

  Grand total (without contingency) $485k

Funding to be sorted out
  → DOE, NSF, ANL, EU, Japan...

Time scales
FY2004: complete R&D
FY2005: construction of prototype
FY2006: tests in particle beams
DHCAL using GEM technology

GEM - a flexible technology - ideal for high degree of segmentation

Develop DHCAL GEM design

Prototype GEM layer

Signal Amplitude (mV)
Current status: details of GEM system construction/operation tested and understood.

- U.S. domestic foil production by 3M Corporation
- Joint electronics development with Fermilab/DHCAL-RPC
- Large scale layer construction under development
- Plans for 1m$^3$ stack for test beam (with RPC)
Tile/fiber HCal
NIU 84 ch.Layer Stack

>10 p.e. for both PMT and Si-PM

PMT Response

Efficiency and Noise Rejection

Si-PM response

Light output vs bias

ADC CHANNEL

ADC COUNTS

Ru106, Si-PMT, 51 Volts

MPh sample. Courtesy of B. Dilgsan
| Tyvek Paint VM2002 Mylar CM590 CM500 Alum Foil |
|---|---|---|---|---|---|
| 1.00 | 0.89 | 1.08 | 0.83 | 0.28 | 0.44 | 0.63 |

**Response dispersion <10%**

**Optimum cell (our current guess):**
- Square 6-9 cm²
- 1.0mm fiber
- Straight Groove
- Glued fiber and painted surface
- 4.5-5.0 mm thick scintillator
- Embedded Si-PM/MRS
CALICE HCal - MiniCAL

Main goals:
• Gain experience with larger # of channels
• Develop hardware understanding in simulations
• 27 layers
• SiPMs and APDs, MA-PMs for reference
• Cosmics and DESY electrons (1…6GeV)
• shower shapes and low E part to be worked on
Calorimetry Issues

- Which option?
  "Traditional", EFlow, or Digital + EFlow approach??
- Demonstration of full EFlow/pattern recognition algorithm (needs more work!)
- Integration of calorimetry into (SiD) detector design.
- R+D funding level vs. Test beam needs?
  Beam tests of high granularity calorimeter(s) with MC comparisons necessary before technology choice/final calorimeter system design.
Calorimetry conclusions – where do we stand?

- Requirements from physics understood.
- Emphasis on jet energy, jet-jet mass measurement.
- Energy Flow approach looks promising.
- A number of different ECal and HCal technologies being studied – need test beams!
- Simulations – need comprehensive EFlow studies!
- Much to be done, but interesting/challenging!
## Comparison of Detector Configurations

(Ray Frey)

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>SD</th>
<th>LD</th>
<th>JLC</th>
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<tr>
<td>Tracker type</td>
<td>TPC</td>
<td>Silicon</td>
<td>TPC</td>
<td>Jet-cell drift</td>
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<tr>
<td>EC al</td>
<td>Si pad/W</td>
<td>Si pad/W</td>
<td>ad. tile/Pb</td>
<td>scint. tile/Pb</td>
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<tr>
<td>$R_{\min}$ barrel (m)</td>
<td>1.68</td>
<td>1.27</td>
<td>2.00</td>
<td>1.60</td>
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<td>Type</td>
<td>$30 \times 0.4 X_0$</td>
<td>$30 \times 0.71 X_0$</td>
<td>$40 \times 0.71 X_0$</td>
<td>$2 X_0$</td>
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<tr>
<td>Sampling</td>
<td>$+10 \times 1.2 X_0$</td>
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<td></td>
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<tr>
<td>Gaps (active) (mm)</td>
<td>2.5 (0.5 Si)</td>
<td>2.5 (0.3 Si)</td>
<td>1 (scint.)</td>
<td>1 (scint.)</td>
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<td>Long. readouts</td>
<td>40</td>
<td>30</td>
<td>10</td>
<td>3</td>
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<tr>
<td>Trans. seg. (cm)</td>
<td>$\approx 1$</td>
<td>0.5</td>
<td>5.2</td>
<td>144</td>
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<tr>
<td>Channels ($\times 10^3$)</td>
<td>32000</td>
<td>50000</td>
<td>135</td>
<td>5</td>
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<tr>
<td>$z_{\min}$ endcap (m)</td>
<td>2.8</td>
<td>1.7</td>
<td>3.0</td>
<td>1.9</td>
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<td>HCal</td>
<td></td>
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<tr>
<td>$R_{\min}$ (m) barrel</td>
<td>1.91</td>
<td>1.43</td>
<td>2.50</td>
<td>2.0</td>
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<tr>
<td>Type</td>
<td>T: scint. tile/S.Steel</td>
<td>digital</td>
<td>scint. tile/Pb</td>
<td>scint. tile/Pb</td>
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<td>Sampling</td>
<td>$38 \times 0.12 \lambda$ (B), $53 \times 0.12 \lambda$ (EC)</td>
<td>$34 \times 0.12 \lambda$</td>
<td>$120 \times 0.047 \lambda$</td>
<td>$1000 \times 0.047 \lambda$</td>
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<tr>
<td>Gaps (active) (mm)</td>
<td>T: 6.5 (5 scint.)</td>
<td>1 (TBD)</td>
<td>2 (scint.)</td>
<td>2 (scint.)</td>
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<tr>
<td>Longitudinal readouts</td>
<td>T: 9(B), 12(EC)</td>
<td>34</td>
<td>3</td>
<td>4</td>
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<tr>
<td>Transverse segmentation (cm)</td>
<td>D: 38(B), 53(EC)</td>
<td>19</td>
<td>14</td>
<td>14</td>
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<td>$\theta_{\min}$ endcap</td>
<td>5$^\circ$</td>
<td>2$^\circ$</td>
<td>2$^\circ$</td>
<td>8$^\circ$</td>
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<td>Coil</td>
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<tr>
<td>$R_{\min}$ (m)</td>
<td>3.0</td>
<td>2.5</td>
<td>3.7</td>
<td>3.7</td>
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<tr>
<td>$B$ (T)</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Comment</td>
<td>Shashlik EC al option in TDR discontinued</td>
<td>option: Si pad shower max. det.</td>
<td>scint. strip (1 cm) shower max. det. (2 layers)</td>
<td></td>
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</tbody>
</table>
**HCal Location Comparison**

**Hcal Delta Cost**

- 80 M$
- 60 M$
- 40 M$
- 20 M$
- 0 M$

**HCal Lambda**

- 0 M$
- 10 M$
- 20 M$
- 30 M$

Scale - Relative to 4 $\lambda$ Inside!!

- 2$\lambda$
- 4$\lambda$
- 6$\lambda$

Quadrant View

**Hcal inside coil**

- Beam Pipe
- Tracker
- Ecal
- Hcal
- MT
- Endcap
- Endcap_Hcal
- Endcap_Ecal
- VXD
- Endcap_Trkr

**HCAL outside coil**

- Scale - Relative to 4 $\lambda$
- 0 M$
- -10 M$
- -20 M$
- -30 M$

**Coil**
Digital calorimetry - counting cells