A Calorimeter with Resistive Plate Chambers

José Repond
Argonne National Laboratory

Seminar at University of Virginia, Charlottesville, VA
October 21, 2009
Outline

I Introduction: Measuring Hadronic Jets
II Particle Flow Algorithms
III CALICE collaboration
IV Hadron Calorimeters
V Resistive Plate Chambers
VI Digital Readout System
VII Vertical Slice Test
VIII Simulations
IX Measurements with VST
X 1 m³ Physics Prototype
XI Technical Issues
XII Conclusions
I Introduction: Why do Jet Physics?

At high energy particle colliders

Observation of collimated jets of hadronic particles

Given an appropriate algorithm, particle in events can be associated to jets

\[ \{p_1, p_2, \ldots, p_n\} \rightarrow \{J_1, J_2, \ldots, J_N\} \]

with \( n \gg N \)

Reconstruct momentum of partons
study short distance QCD
heavy particles decaying into \( q\bar{q} \), e.g. \( W^\pm, Z^0 \)

Jets can be associated with partons of underlying hard scattering
Traditional Jet Measurement

Uses calorimeter alone

→ Example of CDF live event

Calorimeter: sandwich design

Used by most calorimeters at colliders

→ Alternating layers of

Absorber plates to incite shower and
Active media (detectors) to count charged particles traversing it

Energy summed up in (large) ‘Towers’

\[ E_{\text{jet}} \propto \sum N_{\text{charged}} \]
Compensation

Calorimeter measures photons and hadrons in jet

Typically with different response: e/h ≠ 1
Leads to poor jet energy resolution of > 100%/√E_{jet}

ZEUS tuned

Scintillator and Uranium thickness to achieve e/h ~ 1

→ Best single hadron energy resolution ever

35%/√E  ➔  50%/√E Jet Energy Resolution

At a future e^+e^− Linear Collider

Goal of

σ/E_{jet} = 30%/√E_{jet}

New approach
II Particle Flow Algorithms

The idea...

Charged particles measured with the Tracker
Neutral particles measured with the Calorimeter

<table>
<thead>
<tr>
<th>Particles in jets</th>
<th>Fraction of energy</th>
<th>Measured with</th>
<th>Resolution $[\sigma^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>65 %</td>
<td>Tracker</td>
<td>Negligible</td>
</tr>
<tr>
<td>Photons</td>
<td>25 %</td>
<td>ECAL with 15%/VE</td>
<td>$0.07^2 E_{\text{jet}}$</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>10 %</td>
<td>ECAL + HCAL with 50%/VE</td>
<td>$0.16^2 E_{\text{jet}}$</td>
</tr>
<tr>
<td>Confusion</td>
<td>Required for 30%/$\sqrt{E}$</td>
<td></td>
<td>$\leq 0.24^2 E_{\text{jet}}$</td>
</tr>
</tbody>
</table>

Requirements for detector

→ Need excellent tracker and high B – field
→ Large $R_l$ of calorimeter
→ Calorimeter inside coil
→ Calorimeter with **extremely fine segmentation**
→ Calorimeter as dense as possible (short $X_0$, $\lambda_i$)
PANDORA PFA

Developed by
Mark Thomson (University of Cambridge)
Based on GEANT4

Current performance

| $E_{\text{Jet}}$ | $\sigma_E/E = \alpha/\sqrt{E_{\text{jj}}}$ \[|\cos\theta|<0.7\] | $\sigma_E/E_{\text{j}}$ |
|-----------------|---------------------------------|------------------|
| 45 GeV          | 24.9 %                          | 3.7 %            |
| 100 GeV         | 30.7 %                          | 3.1 %            |
| 180 GeV         | 43.0 %                          | 3.2 %            |
| 250 GeV         | 52.2 %                          | 3.3 %            |

Leakage at high jet energies

ILC performance goal achieved

Open question
Are hadronic showers simulated properly? (see later)
Do PFAs really work?

Applied to existing detectors

ALEPH, CDF, ZEUS…

→ Significantly improved resolution

YES! But that is not the issue...

Goal for future e⁺e⁻ Linear Collider Detectors

Design a detector optimized for the application of PFAs

Huge simulation and hardware effort underway

→ Asia, Africa, America, and Europe
III CALICE Collaboration

**Goals**
Development and study of finely segmented calorimeters for PFA applications

**Strategy**
Study of physics, proof of technological approach → **physics prototypes**
Development of scalable prototypes → **technical prototypes**

**Projects**

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>Technology</th>
<th>Detector R&amp;D</th>
<th>Physics Prototype</th>
<th>Technical Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECALs</td>
<td>Silicon - Tungsten</td>
<td>Well advanced</td>
<td>Exposed to beam</td>
<td>Design ~ completed</td>
</tr>
<tr>
<td></td>
<td>MAPS - Tungsten</td>
<td>Started</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scintillator - Lead</td>
<td>Well advanced</td>
<td>Exposed to beam</td>
<td></td>
</tr>
<tr>
<td>HCALs</td>
<td>Scintillator - Steel</td>
<td>Well advanced</td>
<td>Exposed to beam</td>
<td>Design ~ completed</td>
</tr>
<tr>
<td></td>
<td>RPCs - Steel</td>
<td>Well advanced</td>
<td>Being constructed</td>
<td>(Design started)</td>
</tr>
<tr>
<td></td>
<td>GEMs - Steel</td>
<td>Ongoing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MicroMegas - Steel</td>
<td>Started</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCMTs</td>
<td>Scintillator - Steel</td>
<td>Well advanced</td>
<td>Exposed to beam</td>
<td>?</td>
</tr>
</tbody>
</table>

4 regions
14 countries
51 institutes
> 300 physicists
IV Hadron Calorimeters

Within the PFA paradigm

HCAL’s role is to measure neutral hadrons (n, K_L^0)

Fine segmentation is important → 1 x 1 cm^2

Short interaction length \( \lambda_I \)

Absorber choices

<table>
<thead>
<tr>
<th>Material</th>
<th>A/Z</th>
<th>( \lambda_I ) [cm]</th>
<th>( X_0 ) [cm]</th>
<th>( \lambda_I/X_0 )</th>
<th>( t_{\text{passive}}/4\lambda_I ) [cm]</th>
<th>( \equiv )</th>
<th>Number of layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>56/26</td>
<td>16.8</td>
<td>1.8</td>
<td>9.3</td>
<td>67</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>64/29</td>
<td>15.1</td>
<td>1.4</td>
<td>10.8</td>
<td>42</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>184/74</td>
<td>9.6</td>
<td>0.35</td>
<td>27.4</td>
<td>38</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>207/82</td>
<td>17.1</td>
<td>0.56</td>
<td>30.5</td>
<td>68</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>238/92</td>
<td>10.5</td>
<td>0.32</td>
<td>32.8</td>
<td>42</td>
<td>181</td>
<td></td>
</tr>
</tbody>
</table>

With 1 \( X_0 \) sampling

With > 1 \( X_0 \) sampling
**Active Media**

**Multi-bit readout (AHCAL)**
(analog)

- Scintillator pads
  
  3 x 3 cm$^2$ cells
  SiPM or MPPC readout

**Single-bit readout (DHCAL)**
(digital)

- Resistive Plate Chambers (RPCs)
- Gas Electron Multipliers (GEMs)
- Micromegas
  
  1 x 1 cm$^2$ pads

DHCAL trades the high-resolution readout of a small number of towers with 1-bit readout of a large number of pads
## Comparison of HCAL active media

<table>
<thead>
<tr>
<th></th>
<th>Scintillator</th>
<th>GEMs/Micromegas</th>
<th>RPCs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>Proven (SiPM?)</td>
<td>Relatively new</td>
<td>Relatively old</td>
</tr>
<tr>
<td><strong>Electronic readout</strong></td>
<td>Analog (multi-bit) or Semi-digital (few-bit)</td>
<td>Digital (single-bit)</td>
<td>Digital (single-bit)</td>
</tr>
<tr>
<td><strong>Thickness (total)</strong></td>
<td>~ 8mm</td>
<td>~8 mm</td>
<td>~ 8 mm</td>
</tr>
<tr>
<td><strong>Segmentation</strong></td>
<td>3 x 3 cm²</td>
<td>1 x 1 cm²</td>
<td>1 x 1 cm²</td>
</tr>
<tr>
<td><strong>Pad multiplicity for MIPs</strong></td>
<td>Small cross talk</td>
<td>~ 1.0</td>
<td>Measured at 1.4/1.0</td>
</tr>
<tr>
<td><strong>Sensitivity to neutrons (low energy)</strong></td>
<td>Yes</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td><strong>Recharging time</strong></td>
<td>Fast</td>
<td>Fast</td>
<td>Slow (&lt; 100 Hz/cm²)</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Proven</td>
<td>Sensitive</td>
<td>Proven (glass)</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>Challenge</td>
<td>?</td>
<td>Expected to be straightforward</td>
</tr>
<tr>
<td><strong>Assembly</strong></td>
<td>Labor intensive</td>
<td>Somewhat labor intensive</td>
<td>Somewhat labor intensive</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Not cheap (SiPM?)</td>
<td>Expensive foils</td>
<td>Cheap</td>
</tr>
</tbody>
</table>

**Areas of concern**
### Sensitivity to slow neutrons

<table>
<thead>
<tr>
<th></th>
<th>Scintillator</th>
<th>RPC Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Molecule</strong></td>
<td>C₆H₅CH=CH₂</td>
<td>C₂H₂F₄</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>1.032 g/cm³</td>
<td>4.3 x 10⁻³ g/cm³</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>5 mm</td>
<td>1.2 mm</td>
</tr>
<tr>
<td><strong>Sensitivity to slow neutrons</strong></td>
<td>small</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Hadronic shower radius</strong></td>
<td>larger</td>
<td>smaller</td>
</tr>
<tr>
<td><strong>Single particle resolution</strong></td>
<td>better</td>
<td>worse</td>
</tr>
</tbody>
</table>

#### Momentum [GeV/c]

<table>
<thead>
<tr>
<th>K_L⁰</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ = x√E Scintillator</td>
<td>(54.2)</td>
<td>(55.5)</td>
<td></td>
</tr>
<tr>
<td>σ = x√E RPC</td>
<td>0.57</td>
<td>0.66</td>
<td>0.64</td>
</tr>
</tbody>
</table>

#### Tradeoff...
V Resistive Plate Chambers

Developed in the 1980’s

Many applications

ATLAS and CMS (muon system)
ALICE (TOF, muon system)
Belle and BaBar (muon system)
Phenix, STAR (TOF, muon system)
OPERA (neutrino detection)

Operation

at higher HV: Streamer mode (large signal ~ 10’s of pC)
at lower HV: Avalanche mode (smaller signal 0.1 – 10 pC)

Readout

Strips
Our RPC Designs

- Multigap – RPC (mostly used for Time-of-Flight)

- Standard 2-glass Design

- ‘Exotic’ 1-glass Design (our own invention)
Measurements with an Analog Readout

Published as G.Drake et al., N.I.M. 3 A578, 88 (2007)

Used CDF’s RABBIT system with 14-bit resolution
Utilized cosmic rays (readout triggered by scintillators)
Chambers flushed with typical mixture for avalanche mode

Freon R-134A : Isobutane : Sulfur Hexafluoride = 94.5 : 5.0 : 0.5

Readout with single pad of 16 x 16 cm²

2-glass design

Avalanche signal charges 0.1 – 10 pC
Readout with single pad of 16 x 16 cm$^2$

2-glass RPC

~ Linear increase of signal charge with high voltage

Streamers develop at higher HV
Wide plateau with high efficiency and few streamers

Plateau with $\varepsilon > 90\% + F_{\text{streamer}} < 5\%$
Readout with multiple 1 x 1 cm$^2$ pads

Only take events where highest Q in central 3 x 3 array
‘Hit pad’ defined as pad with highest Q

Charged contained within ~ 1.5 cm Independent of HV
2-glass RPC

Higher surface resistivity decreases Pad multiplicity

$R_\text{pl} \sim 0.1 \, \text{M}\Omega$

$R_\text{pl} \sim 50 \, \text{M}\Omega$
VI Digital Readout System

Centered around the DCAL front-end chip

Readout board consists of a pad- and a front-end board

→ Avoid cross talk from digital lines into analog inputs
→ No costly blind or buried vias
→ Connection via conductive glue

1 Data Concentrator per Readout Board

1 Data Collector per 12 Data Concentrators

1 Timing and trigger module per system

→ provides clocks and resets to front-end
→ distributes trigger signals to front-end
The DCAL Chip

Developed by

FNAL and Argonne

Input

64 channels
High gain (GEMs, micromegas…) with minimum threshold ~ 5 fC
Low gain (RPCs) with minimum threshold ~ 30 fC

Threshold

Set by 8 – bit DAC (up to ~600 fC)
Common to 64 channels

Readout

Triggerless (noise measurements)
Triggered (cosmic, test beam)

Versions

DCAL I: initial round (analog circuitry not optimized)
DCAL II: some minor problems (used in vertical slice test)
DCAL III: no identified problems (final production)
VII  Vertical Slice Test

Small prototype calorimeter

20 x 20 cm² RPCs (based on two different designs)
Up to 10 chambers → 2560 readout channels

Electronic readout

Complete chain as for larger system

Tests with

Cosmic rays at Argonne
Fermilab test beam
(\(\mu, 120\) GeV p, 1 – 16 GeV \(\pi^+, e^+\))

Very successful → Extrapolation to larger system
A few nice events from the testbeam....

A perfect $\mu$

A $e^+$ shower

2 perfect $\mu$'s

$\pi^+$ showers
Monte Carlo Simulation = Integration of current knowledge of the experiment

Perfect knowledge $\rightarrow$ Perfect agreement with data

Missing knowledge $\rightarrow$ Not necessarily disagreement with data

Disagreement with data $\rightarrow$ Missing knowledge, misunderstanding of experiment

Perfect agreement with data $\rightarrow$ Not necessarily perfect knowledge
Simulation Strategy

- Experimental set-up
  - Beam (E, particle, x, y, x', y')
  - GEANT4
  - Points (E depositions in gas gap: x, y, z)
- Measured signal Q distribution
  - RPC response simulation
  - Hits
  - Comparison
  - Parameters
    - Exponential slope $a$
    - Threshold $T$
    - Distance cut $d_{\text{cut}}$
    - Charge adjustment $Q_0$

With muons – tune $a$, $T$, $(d_{\text{cut}})$, and $Q_0$
With positrons – tune $d_{\text{cut}}$
Pions – no additional tuning
Measured charge distribution for HV = 6.2 kV

Measured charge distribution as function of y in the pick-up plane

Generated charge distributions for different HV settings

Throw 10,000 points in x,y plane, calculate charge \( Q(r) \), sum up charge on 1 x 1 cm\(^2\) pads

Overall reconstructed charge with 10,000 throws
IX Measurements with the VST

Rate dependence of RPCs – published in JINST

Unique contribution to understanding of RPCs, essential for operation of DHCAL

Calibration with muons – published in JINST

Measurement of efficiencies, pad multiplicities and noise rates

Response to Positrons – published in JINST

First showers in a DHCAL, validity of concept, understanding of DHCAL response

Hadron showers in a DHCAL – published in JINST

Including predictions for larger prototype calorimeters

Environmental dependence paper – draft exists, plots (almost) finalized

Essential information for operation of DHCAL
Measuring and Calculating the Rate Capability

Developed analytical model to calculate drop in efficiency

Based on assumption of voltage drop due to current through RPC

Measurements in FNAL test beam

Published in 2009 JINST 4 P06003

Fits theoretically motivated

Analytical prediction

Effect not (yet) implemented in simulation
Measuring the Muon Response

Broadband muons

from FNAL testbeam (with 3 m Fe blocker)

Used to measure efficiency and pad multiplicity of RPCs → calibration constants

Tuned

slope $a$
threshold $T$
charge adjustment $Q_0$

→ reproduce the distributions of the sum of hits and hits/layer

Data

Monte Carlo simulations after tuning
Measuring Positrons Showers

Positrons at 1, 2, 4, 8, 16, GeV

from FNAL testbeam (with Čerenkov requirement)

Tuned

distance cut $d_{\text{cut}}$

→ reproduce distributions in individual layers (8 GeV data)

Published as B.Bilki et al., 2009 JINST 4 P04006
Data
Monte Carlo simulations – 6 layers
Monte Carlo simulations – Infinite stack

Published as B.Bilki et al., 2009 JINST 4 P04006
Lateral shower shape for 2GeV $e^+$

Longitudinal shower shape

Published as B.Bilki et al., 2009 JINST 4 P04006
# Measuring Pion Showers

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>Stack of iron bricks</th>
<th>Number of events</th>
<th>Beam intensity [Hz]</th>
<th>Fraction of events without veto from the Čerenkov counters [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>1378</td>
<td>547</td>
<td>6.0</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>5642</td>
<td>273</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>1068</td>
<td>80</td>
<td>57.3</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>5941</td>
<td>294</td>
<td>15.5</td>
</tr>
<tr>
<td>8</td>
<td>No</td>
<td>30657</td>
<td>230</td>
<td>24.6</td>
</tr>
<tr>
<td>16</td>
<td>No</td>
<td>29889</td>
<td>262</td>
<td>28.0</td>
</tr>
</tbody>
</table>

Trigger =

Coincidence of 2 scintillator paddles + veto from either Čerenkov counter

6 layer stack corresponding to 0.7 $\lambda_I$

Published as B.Bilki et al., 2009 JINST 4 P10008
# Event Selection

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least 3 layers with hits</td>
<td>Rejects spurious triggers</td>
</tr>
<tr>
<td>Exactly 1 cluster in the first layer</td>
<td>Removed upstream showers, multiple particles</td>
</tr>
<tr>
<td>No more than 4 hits in first layer</td>
<td>Removed upstream showers</td>
</tr>
<tr>
<td>Fiducial cut away from edges of readout</td>
<td>Better lateral containment</td>
</tr>
<tr>
<td>Second layer</td>
<td></td>
</tr>
<tr>
<td>At most 4 hits</td>
<td>MIP selection</td>
</tr>
<tr>
<td>At least 5 hits</td>
<td>Shower selection</td>
</tr>
</tbody>
</table>

Published as B.Bilki et al., 2009 JINST 4 P10008
**Brick data**

**Secondary beam with +2 GeV/c selection**

**Fe blocks in front of RPCs**

~ 50 cm deep corresponding to 3 $\lambda_I$

→ 97% of $\pi$ interact

→ $\Delta E_{\mu} \sim 600$ MeV

Calibration close to expected values

→ no corrections applied

In the following this will be our $\mu$ signal shape

\[ y = \alpha e^{-\frac{1}{2} \left( \frac{x - \bar{x}}{\gamma} \right)^2} + \delta (x - x_0) e^{\phi(x_0 - x)} \]
MIP Selection

Fit to 3 components

- **Muons** (from brick data)
- **Pions** (from MC, not shown)
- **Positrons** (from MC)

(red line sum of 3 components)

MC curves = absolute predictions, apart from general scaling due to efficiency problems (rate)
Shower Selection

Fit to 2 components
- Pions (from MC)
- Positrons (from MC)

MC curves = absolute predictions, apart from general scaling due to efficiency problems (rate) at 16 GeV (-9%)

Reasonable description by simulation

Positron contamination at low energies

Not many pions at low energies

Published as B.Bilki et al., 2009 JINST 4 P10008
Environmental Dependence of the Performance of RPCs

Understanding of noise/role of gas
Why do we need to flush the gas?
What goes wrong in old gas?

Understanding of the stability/calibration of the system
Corrections for environmental conditions?
Sample of the data collected over ~ 1 month

Fluctuations in the performance as well as in the environmental conditions
Linear correction for the environment

\[ F_i(T,p,H) = F_{i,0} + b_{T,i}\Delta T + b_{p,i}\Delta p + b_{H,i}\Delta H \]

with \( i = N, \varepsilon, \mu \)

Corrections work well for \( \varepsilon, \mu \)

Width of noise rate still above statistical error
Sample of slopes of environmental dependence

P=100kPa

T=22.5°C
Slopes of environmental dependence

More or less consistent slopes for different chambers

If effects entirely due to changes in mean free path in gas

\[ b_T / b_p \sim 338 \text{ Pa/K} \]

Roughly correct for \( \epsilon, \mu \)

Much larger for N

(Other factors contribute to noise rate)

<table>
<thead>
<tr>
<th>Performance variable</th>
<th>Changes for ( \Delta T = 1 \degree C )</th>
<th>Changes for ( \Delta p = 100 \text{ Pa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPC design</td>
<td>2-glass</td>
<td>1-glass</td>
</tr>
<tr>
<td></td>
<td>Good(%)</td>
<td>Damaged(%)</td>
</tr>
<tr>
<td>Noise rate</td>
<td>14 ± 1.6</td>
<td>42 ± 1.2</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.26 ± 0.051</td>
<td>0.28 ± 0.0559</td>
</tr>
<tr>
<td>Pad multiplicity</td>
<td>2.0 ± 0.09</td>
<td>2.0 ± 0.09</td>
</tr>
</tbody>
</table>
Dependence on gas flow

Noise rate and pad multiplicity rise dramatically for flow rates below 0.3 cc/min

→ **Corresponds to 8 volume changes/day**

This data is without beam activity

(better understanding of the underlying mechanism for accidental noise hits would be very useful)
The 1 m$^3$ Physics Prototype

Description

38 layers each 1 x 1 m$^2$
Interleaved with 20 mm thick steel plates
Re-use of CALICE absorber structure and stage

RPCs

Area = 32 x 96 cm$^2$ (3 per layer)
Mostly 2-glass design (some 1-glass design)
Thickness

Glass = 1.15 (Cathode) and 0.85 mm (Anode)
Gas gap = 1.15 mm

Motivation for 1 m$^3$ prototype

- Validate our technical approach
- Gain experience with larger system
- Make precision measurements of hadronic showers (helpful for further developments of GEANT4)
- Provide test bed for further technical developments

Readout

350,208 individual channels (~ NOvA)
1-bit readout
RPC Construction

Chambers

114 + spares needed
So far 8 built

Spraying of resistive paint

Challenge to achieve \( R_{\square} = 1 - 5 \text{ M}\Omega/\square \)
Assembled (automated) spraying booth

\[
y = -0.205x + 1.817
\]

1.11 – 3.08 M\( \Omega/\square \)
Quality Assurance

Currently

Use old electronics to check out chambers

Future

A) Will measure each chamber with new electronics and VST (for tracking)

B) Will measure cosmic rays with completed cassettes in hanging file structure
Electronics for the 1 m³

**ASICS**

Need 5472 DCAL III chips

→ Robot testing at Fermilab
   (over half done)

**Front-end board**

Redesigned
1\(^{st}\) prototype works (few small glitches)
2\(^{nd}\) prototype begin assembled

→ Production soon

**Remainder of system**

Data collectors are built and being tested
Timing and trigger modules being redesigned
Gluing of the Pad- and Front-end boards

Need to make 1536 connections
Glue starts to harden after 3 – 4 hours

→ built x – y table and dispenser

First board glued successfully
First Noise Run and Cosmic Rays

Geometrical Distribution of Noise with Large FEB

[Diagram showing noise distribution with fishing lines highlighted]

Higher rates around fishing lines

Used tracking with VST chambers

Later: will use self-contained system with large chambers
Peripherals

Gas

Mixing – done
Distributing – almost done

Low Voltage

7 Wiener power supplies in hand
1st distribution box built and being tested

High Voltage

Units in hand
Computer control programs commissioned
Simulating Larger Systems

Reasonable Gaussian fits for $E > 2$ GeV
Discontinuity at $E \sim 8$ GeV (surprising, changes with physics list)
Non-linearity above $E \sim 20$ GeV (saturation)
Resolution $\sim 58\%/\sqrt{E(\text{GeV})}$ (for $E < 28$ GeV)
Resolution degrades above 28 GeV (saturation)
Resolution of $1\text{m}^3$ with containment cut somewhat better than for extended calorimeter
Study of different extended RPC-based calorimeters

Efficiency and pad multiplicity have only minor effect on resolution (Small $\mu$ might be desirable for PFAs)

However values need to be known

Linear calibration corrections for $\epsilon, \mu$ will work ($P_1 \sim 0$)
Study with different GEANT4 physics lists

Physics list

List of processes included in the shower simulation

Different approaches (data, parametrizations, calculations…)

Clearly something fishy around 4 – 8 GeV
Tests with the 1 m³ calorimeter

Cosmic ray tests

Each chamber will be tested in the cosmic ray test stand
Each completed layer will be inserted in hanging file structure
and will be tested with cosmic rays

Fermilab test beam

Tests with $\mu$, $\pi^\pm$, $e^\pm$
Comparison with various MC models of hadronic showers
Comparison with scintillator – analog HCAL (CALICE)

Time scale

First layer to be inserted soon
Construction completed in early 2010
Data analysis in 2010 - 2012

Expect 4 – 5 papers
## XI  Further Technical Issues

### Preparation for Technical Prototype

<table>
<thead>
<tr>
<th>Connection</th>
<th>Physics prototype</th>
<th>Technical prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RPC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas inlet</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>Gas outlet</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>High-voltage supply</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>High-voltage computer control</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td><strong>Front-end electronics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-voltage</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Cooling water inlet</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>Cooling water outlet</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>Data cables</td>
<td>240</td>
<td>1</td>
</tr>
</tbody>
</table>
R&D Topics for a technical prototype calorimeter

RPCs – mechanical, 1-glass design
(New RPC design invented in and developed by us)

Gas system – recycling, distribution

High Voltage – distribution, monitoring

Low Voltage – distribution, monitoring

Front-end – token ring passing, power consumption, channel count, thickness, reliability…
XII  Conclusions

For a future Lepton Collider we propose a novel way based on Particle Flow Algorithms (PFAs) for measuring the energy of jets

PFAs require calorimeters with extremely fine segmentation of the readout

We have developed an RPC – based hadron calorimeter with $1 \times 1 \text{ cm}^2$ readout pads

Initial tests with a small size calorimeter were quite successful

Currently we are constructing a $1 \text{ m}^3$ physics prototype

→ To be tested in Fermilab test beam in 2010/2011

Further R&D issues remain for a Technical prototype

→ We have started to look into some of them…

(We are always looking for new collaborators with graduate students: Excellent thesis topics)
## Responsibilities and collaborators

<table>
<thead>
<tr>
<th>Task</th>
<th>Responsible institutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project coordination</td>
<td>Argonne</td>
</tr>
<tr>
<td>RPC construction</td>
<td>Argonne</td>
</tr>
<tr>
<td>Cassette structure</td>
<td>Argonne</td>
</tr>
<tr>
<td>Mechanical structure (prototype section)</td>
<td>DESY</td>
</tr>
<tr>
<td>Overall electronic design</td>
<td>Argonne</td>
</tr>
<tr>
<td>ASIC design and testing</td>
<td>FNAL, Argonne</td>
</tr>
<tr>
<td>Front-end and Pad board design &amp; testing</td>
<td>Argonne</td>
</tr>
<tr>
<td>Data concentrator design &amp; testing</td>
<td>Argonne</td>
</tr>
<tr>
<td>Data collector design &amp; testing</td>
<td>Boston, Argonne</td>
</tr>
<tr>
<td>Timing and trigger module design and testing</td>
<td>FNAL</td>
</tr>
<tr>
<td>DAQ Software</td>
<td>Argonne, CALICE</td>
</tr>
<tr>
<td>Data analysis</td>
<td>Argonne, FNAL, Iowa, (UTA)</td>
</tr>
<tr>
<td>High Voltage system</td>
<td>Iowa</td>
</tr>
<tr>
<td>Low voltage system</td>
<td>Argonne</td>
</tr>
<tr>
<td>Gas mixing and distribution</td>
<td>Iowa</td>
</tr>
</tbody>
</table>