Dual-readout calorimetry and 4th for $\mu^+\mu^-$ and $\nu$ physics

John Hauptman
University of Mississippi, Oxford, NFMCC meeting
January 13-18, 2010

4th began as a small attempt to encourage the ILC detector community to look again at its calorimetry. At that time (August 2005) there were three concepts (SiD, LDC, and GLD) with identical calorimeters, simulated by the same code, and all of it based on one idea, Particle Flow Analysis (PFA). I suggested “a fourth” concept on encouragement from GP Yeh and Barry Barish. I am now writing a book for Wiley-Berlin on this subject.
Quickly, a small number of excellent collaborators joined:

- Alexander Mikhailichenko (LNS, Cornell) - machine, MDI, dual solenoids
- Richard Wigmans (DREAM, TTU) - calorimetry
- Franco Grancagnolo (INFN, Lecce) - tracking, software Corrado Gatto (Emi Cavallo, Vito Di Benedetto, Anna Mazzacane, Giusi Terracciano, Gianfranco Tassielli: 4 PhD theses)

Four major innovations (& many particle identification measurements)

1. dual-readout calorimeters, both fiber and crystal;
2. low-mass cluster-timing tracking chamber; go to pixels (C. Damerell);
3. dual-solenoid to return the flux without iron; and,
4. single final-focus structure for detector+QF1+QD0

Letter of Intent:  [http://www.4thconcept.org/4LoI.pdf](http://www.4thconcept.org/4LoI.pdf) (140 people, 33 institutes/universities, 15 countries, 4 regions)

June’09: I asked Vito Di Benedetto to stay at Fermilab to work with Nikolai Mokhov on MARS+ILCroot.

Next form an “executive board” to lead this detector & machine effort:

Alan Bross, Alexander Mikhailichenko, Nural Akchurin, Timofey Zolkin(?), John Hauptman, Nikolai Mokhov, Steve Kahn, & send an email to us if you are interested in joining this board.
In the beginning, there were three ...
4th detector

- Final Focus beam delivery on one frame
- QF1+QD0
- Solenoids outer & inner
- High-precision muon tracking after calorimeter
- End-coils
- Dual-readout calorimeters
- Cluster-timing tracking chamber & pixel vertex chamber
Dual-solenoids (completely new in HEP)
Dual-solenoids  (A. Mikhailichenko, Cornell)

Muon measured with precision in every system:

- $p_{\text{trk}}$ in central tracker
- $dE$ bremsstrahlung in calorimeter
- $p_{\mu}$ in muon spectrometer
Dual-readout calorimetry (new in high energy physics)

- Electrons and photons (EM “electromagnetic” particles) are easy.

- Hadrons (protons, pions “strongly interacting” particles) are difficult due to large stochastic fluctuations between
  
  1. the EM part (“e”) from pi-zero and eta decays to photons
  
  2. the non-EM part (“h”) consisting of everything else

and the fact that “e” response is larger than “h”.

measure both ... “dual”

Relativistic electrons ($v > c/n$) generate Cerenkov light inside the clear fibers and the crystals; most other particles do not.
Fiber DREAM module: *proof-of-principle*

**Some characteristics of the DREAM detector**

- **Depth** 200 cm (10.0 $\lambda_{int}$)
- Effective **radius** 16.2 cm (0.81 $\lambda_{int}$, 8.0 $\rho_M$)
- **Mass** instrumented volume 1030 kg
- Number of **fibers** 35910, diameter 0.8 mm, total length $\approx$ 90 km
- Hexagonal **towers** (19), each read out by 2 PMTs

$S =$ scintillating fibers  
$Q =$ quartz (clear) fibers
Simply built, inexpensive, proof-of-principle DREAM module

(built by Korean housewives with silk gloves in Lubbock, Texas)
Calibrate both signals with 40 GeV electrons

**Scintillator**
- Mean: 40.66
- Sigma: 2.02
- $\chi^2/\text{ndf}$: 80/35

**Čerenkov**
- Mean: 40.52
- Sigma: 2.66
- $\chi^2/\text{ndf}$: 211/49
Response to 100 GeV negative pions: asymmetric, non-Gaussian, and the wrong energy

DREAM
Raw signals
(100 GeV $\pi^-$)

Scintillator

Čerenkov

![Graph images](image-url)

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

\[ \frac{Q}{S} = \frac{f_{em} + 0.21 (1 - f_{em})}{f_{em} + 0.77 (1 - f_{em})} \]

\[ E = \frac{S - \chi Q}{1 - \chi} \]

with \( \chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3 \)
The asymmetric, non-Gaussian, broad, off-energy response function is the sum of narrow Gaussians.

100 GeV π⁻ Čerenkov signal
Hadronic response linearity

From: NIM A537 (2005) 537
4th dual-readout simulation performance up to 1 TeV

Single $\pi$

\[ \sigma_E / E = 25.6\% / \sqrt{E} \pm 1.5\% \]

Di-jets (total energy)

\[ \sigma_E / E = 29\% / \sqrt{E} \pm 1.2\% \]
Dual-readout of BGO crystals
BGO crystal in its housing and in the beam before DREAM.

Seven papers in NIM on crystal measurements.
Crystal DREAM: one PMT/crystal with time-history readout

Cerenkov

L3 BGO crystal

Scintillation
CERN beam test of BGO array + DREAM module (surrounded by large scintillators to catch neutrons)
BGO+fiber calorimeter at 200 GeV

DREAM data

Run 1724 200 GeV pi+

Entries 38382
Mean 204.3
RMS 11.46
\( \chi^2 / \text{ndf} \) 514.7 / 67
Constant 5296 ± 35.2
Mean 204.8 ± 0.0
Sigma 8.557 ± 0.036

\( \pi^+ \) at 200 GeV

4th simulation

hh

Entries 13330
Mean 196.3
RMS 10.05
\( \chi^2 / \text{ndf} \) 839.9 / 405
Constant 288.1 ± 3.4
Mean 197.5 ± 0.0
Sigma 5.17 ± 0.04
Cluster-timing of *every* electron cluster

(new, beyond Charpak)

Ultra-low-mass chamber, expect ~50 µm spatial resolution on each of 150 points on a track.
$H^0Z^0$ event

(tracking & calorimeters)
Neutrino near detector: just make DREAM 100 meters long, segmented to include periodic magnetic momentum measurement volumes

Learn from KLOE and SPACAL!

Figure 25: The pattern according to which the two types of fibers will be distributed inside the detector volume \((a)\) and the tower structure of the proposed fiber calorimeter \((b)\).
Particle Identification

(most of these are completely new in high energy physics)

- **uds** quarks  (jet energy resolution)
- **c,b** quarks  (vertex tagging)
- **t** quark  (reconstruction)
- **electron**  (dual-readout)
- **muon**  (dual-readout and iron-free field)
- **tau**  (reconstruction)
- **neutrino**  (by subtraction; resolution)
- **W,Z**  (hadronic jet reconstruction)
- **photon**  (BGO dual readout)
- **gluon**  (jet energy resolution)
DREAM data

$\pi^-$ 50 GeV

$e^-$ 40 GeV

4th simulation (45 GeV)
Fluctuations in \((S-C)\) among the channels of a shower

\[
\chi^2 = \sum_{k}^{N} \left[ \frac{(S_k - C_k)}{\sigma_k} \right]^2 \sim 0 \text{ for } e^\pm, \text{ large for } \pi^\pm
\]
Time-history $S(t)$ scintillating fibers

$e/\gamma - \pi^{\pm}/\text{hadrons}$

duration of pulse above $1/5$-maximum
Time-history $S(t)$ scintillating fibers

- MeV neutrons, and neutron fraction, $f_n$
- improve energy resolution, and ID “hadronic” showers

$C_{pe}$ vs $f_n$ (4th simulation)

$\frac{f_n}{f_{EM}}$ (DREAM data)

200 GeV “jets”

Tail absent for electron showers

Thursday, January 14, 2010
Time-of-flight
(Cerenkov fibers)
$\sigma \sim 0.3$ ns

Muon tagging
$S-C \sim dE/dx$ (muons)
$(S+C)/2 \sim E_{\text{brems}}$
Cluster-timing

dN/dx is Poisson, no Landau tail: better specific ionization resolution ~3%

CluCou data (two different tubes)

dE/dx resolution TPC LBL/PEP4 (data using truncated mean, resolution~6%)

Thursday, January 14, 2010
\( \tau^\pm \) ID

(for polarization)

\( \tau^- \rightarrow \rho^- \nu \)
\( \rightarrow \pi^- \pi^0 \)
\( \rightarrow \pi^- \gamma \gamma \)
b,c quark tagging (by lifetime of B,D mesons)

vertex impact parameter
W and Z mass measurement and discrimination

From the SUSY pt. 5 analysis by Anna Mazzacane
top quark

(all hadronic channel)

\[ e^+ e^- \rightarrow t\bar{t} \rightarrow bW^+ \bar{b}W^- \rightarrow 6 \text{ jets} \]
Physics processes
Flagship physics process: putative Higgs production

\[ \mu^+ \mu^- \rightarrow Z^0 H^0 \rightarrow \ell^+ \ell^- X \] at \( \sqrt{s} = 250 \text{ GeV} \)

\begin{align*}
\chi^2 / \text{ndf} & = 56.9612 / 117 \\
\text{Constant} & = 217.733 \pm 10.928 \\
M_H & = 120.284 \pm 0.050 \\
\alpha_{\mu,i} & = 0.678781 \pm 0.044998 \\
\beta & = 0.613722 \pm 0.072172 \\
\kappa & = 0.168354 \pm 0.032078 \\
bkg p0 & = 1912.55 \pm 40.57 \\
bkg p1 & = -40.0986 \pm 0.3438 \\
bkg p2 & = 0.292591 \pm 0.002017 \\
bkg p3 & = -0.000727034 \pm 0.000016761
\end{align*}

\( \mu^+ \mu^- \)

Mass of X

\( \sqrt{s} \) = 250 GeV
$e^+e^-$ (using tracking only)

$e^+e^-$ (tracking and calorimetry)
SUSY (supersymmetry):

\[ e^+ e^- \rightarrow \chi_1^+ \chi_1^- \rightarrow \chi_1^0 \chi_1^0 W^+ W^- \]

\[ e^+ e^- \rightarrow \chi_2^0 \chi_2^0 \rightarrow \chi_1^0 \chi_1^0 Z^0 Z^0 \]

chargino \( \sigma_M \approx 2.8 \text{ GeV/c}^2 \)
neutralino \( \sigma_M \approx 2.5 \text{ GeV/c}^2 \)

chargino \( \rightarrow W \)
neutralino \( \rightarrow Z \)
Bethe-Heitler background rejection (in time domain)
Time-history of scintillating fibers: 1-5 GHz

(DRS4, Grancagnolo ASIC)
BH $\mu$ rejection in time-domain

$S_{pe}(t)$

$\mu^+$
BH $\mu$ rejection in time-domain

$S_{pe}(t)$
BH $\mu$ rejection in time-domain

$S_{pe}(t)$

$\mu^+$

Thursday, January 14, 2010
Time-history is very powerful: every volume in 4th is clocked out at 1 GHz, or faster

- particle IDs
- background rejections (plural)
- one $t_0$ and one pedestal (or baseline)
- depth segmentation is 5-10 cm

Far better than a physical segmentation, which is expensive, with many $t_0$’s and pedestals, and is difficult to calibrate.

```latex
\begin{align*}
N_1 & \quad 163.5 \pm 19.4 \\
\tau_1 & \quad 1.941e-08 \pm 1.549e-09 \\
N_2 & \quad 7.568 \pm 1.011 \\
\tau_2 & \quad 2.953e-07 \pm 5.175e-08
\end{align*}
```
Summary

• 4th is a novel detector, we will publish it, and optimize & design for the Muon Collider. It is perfectly OK as a strawman detector.

• multi-TeV objects demands higher spatial precision and smaller measurement volumes, i.e., pixels for tracking (Chris Damerell). This is *terra incognita*.

• R&D for (1) large solenoids, (2) more dual-readout tests including a “99% containment module” to be tested at CERN in ~ 2 years, and (3) fast digitizers.

• we need an “executive board” of machine physicists, detector people, and others to lead 4th.
Spares
14 mrad crossing angle optics fragment

Each quad could be moved mechanically + trim coils
Valves for push-pull disconnect

QD0, QC0, SD0, QDEX1

Kicker

QF1, SF1, QC1, QFEX2

FINAL DOUBLET (IN/OUT), Sextupoles for 14 mrad CROSSING ANGLE
DREAM readout

Shine light through module

Channel structure defined by bundled scintillation and Cerenkov fibers
The DREAM collaboration has tested several crystals:

- PbWO$_4$ (“too fast, too blue, and too luminous”)
- PbWO$_4$:Pr
- PbWO$_4$:Mo
- BGO
- BSO (Bismuth sulfate)

all work well (good reference: Silvia Franchino talk at TIPP09)
After the easy success with the DREAM module, we immediately began to think of improvements

- Cerenkov fiber pe statistics (~8pe/GeV) ... try crystals

- next largest fluctuation is the BE losses in nuclear break-up, proportional to the MeV neutrons liberated in the shower ... measure $S_{pe}(t)$.

- leakage is only suppressed by more mass (and $\gamma$), so make crude measurement of leakage (mostly neutrons).
"Scintillation"  

We can now do dual-readout in a single crystal ==> EM precision

BGO borrowed from L3

by time and wavelength

UV filter

PMT

PMT

Alessandro Cardini, INFN, Cagliari

(100 ns/div)
Dual-readout in the BGO+DREAM configuration for 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves “compensation”.

---

**Run 1724 200 GeV pi+**

- **S+SB vs C+CB**
  - Entries: 38563
  - Mean x: 124.1
  - Mean y: 147.9
  - RMS x: 23.06
  - RMS y: 23.7

- **SS’ vs CC’**
  - Entries: 38563
  - Mean x: 110
  - Mean y: 204.2
  - RMS x: 29.2
  - RMS y: 11.43
Energy resolution of DREAM module improved by 10-15% when simple leakage counters are included.
Cluster timing tracking chamber: (measure every cluster)

KLOE is a very well understood chamber

KLOE data
(vi) Neutron fraction vs. electromagnetic fraction: “hadronic” ID tag

Expected anti-correlation of

\( f_n \) (hadronic content) and

\( f_{EM} \) (electromagnetic content)
(ix) $Z \rightarrow jj$ mass resolution

(x) $b,c$ quark tagging
Summary of 4th:

- many ideas, data, beam tests, calculations and detailed simulations of physics performance;

- excellent particle ID;

- funding $155K;

- Letter of Intent is finished (with appendices) at www.4thconcept.org/4LoI.pdf;

- we are actually ready for an EDR, primarily because we have multiple successful beam tests and have made our scientific and technical decisions; and,

- book contract with Wiley on the design, physics and building of big experiments.