Advances in Detector Technology

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2009 EPS HEP Conference
July 21, 2009
Introduction

* Discoveries are limited by detector advances
  - Must keep pace with moving scientific frontiers, and accelerators
  - Detectors can rejuvenate accelerator programs

* Large challenges posed by future scientific opportunities
  - sLHC
  - ILC
  - Super B
  - Neutrinos
  - Dark Matter
  - Astro

* Many promising technologies advancing
  - Impossible to do justice - apologies for biases and omissions
Challenges

- Precision - energy, momentum, time, space
- Speed/Occupancy
- Radiation Hardness/Background Rejection
- Power/Cooling
- Cost

- Progress presented in several recent major conferences
  - IEEE Nuclear Science Symposium, Dresden, October, 2008
  - TIPP09, Tsukuba, March, 2009
  - 11th Pisa Meeting, May, 2009
Enabling Advances

- **Segmentation**
  - 10-300 µm Si pixels, Si Cal, MPGDs

- **Speed & Power**
  - Faster electronics, lower noise

- **Integration**
  - Microelectronics, mechanics

- **Materials**
  - Sensor, rad hard, robust, thin

- **Radiation immunity**
  - Understanding, design, annealing

307 Mpixel SLD vxd3
LC - Maintain segmentation with increased speed

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The Enterprise

Applications
- Colliders
  - Vertex
  - Tracker
  - Calorimeter
  - PID, incl. muon
- Dark Matter Detectors
- Neutrinos
- Ground-based
  - Particle Astro
- Space

Core Technologies
- Silicon
- Gas
- Crystals
- Liquids
- Readout, Electronics
- Services, Power, Cooling, Support, Materials
- Metrology
- Trigger, DAQ

Parallel Advances
ATLAS and CMS

- Successful Construction & Commissioning established critical lessons for future
- Upgrades for increased LHC luminosity
  - $10^{35}$ for sLHC at end of decade (shutdown ~2017)
- Inner trackers
  - Complete replacement (even for lower luminosity due to accumulated radiation)
  - Radiation damage limits
  - Increased rate (eg. ATLAS TRT)
  - Improved granularity - for pattern recognition
- Other systems will need some upgrades, esp. electronics
Linear Collider Detectors

- Goals - exceptional precision and time stamping
  - Bunch train is ~3000 bunches over 1 msec (ILC)
- Vertex detectors
  - < 4 µm precision w/ ~20 µm pixels
- Trackers
  - \( \sigma(1/p) \sim \text{few} \times 10^{-5} \)
- Calorimeter
  - 3-4% \( \sigma(E_{\text{jet}})/E_{\text{jet}} \) for \( E_{\text{jet}} > 100 \text{ GeV} \)
Heavy Flavor Experiments

- LHC-b
  - Radiation - rad-hard vertex locator
- Super B
  - Reduce scattering in tracker - thinner
  - Endcap crystals - radiation
  - Endcap PID
- NA62 ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)
  - giga-tracker
  - RICH
- MEG ($\mu \rightarrow e \gamma$)
  - Liquid Xe Calorimeter
    - purity, cal response, calibration
Neutrinos

* Current and recent advances
  - MPPC (SiPMs) at T2K
  - NOvA (seg. Liquid Scintillator)

* Future (toward the ~MegaTon detector)
  - Large liquid argon - tracking
  - New PMTs (low cost) - H$_2$O Ch
Direct Dark Matter Detection

- large mass
- low energy threshold (a few keV)
- background suppression
  - deep underground
  - passive shield
  - low intrinsic radioactivity
  - gamma background discrimination

- Signatures
  - Ionization
  - Scintillation
  - Phonons

See Elena Aprile’s talk for R&D on Nobel liquids
Silicon

• Construction/commission experience of LHC and Fermi

• Future challenges
  – Increased rate and radiation at sLHC
  – Increase precision for ILC and B factories
  – Specialize applications, such as NA62 Gigatracker
sLHC Tracking

* Intense Radiation Levels
  - $10^{16} /\text{cm}^2$ @ 5 cm (~400 MRad)
  - $10^{15} /\text{cm}^2$ @ 20 cm (~40 MRad)
  - $2 \times 10^{14} /\text{cm}^2$ @ 50 cm (~10 MR)
  (dictates technology for tracker)
* R > 20 cm
  - Silicon Strips (> 60 cm)
  - Pixels (20 - 60 cm)
* R < 20 cm
  - New technologies

- 300-400 events/crossing
- ~10000 particles in $|\eta| \leq 3.2$
- mostly low $p_T$ tracks
sLHC Inner Tracking (R<20cm)

* ATLAS Candidates:
  - Planar
  - 3D-silicon
  - Diamond
  - GOSSIP (Gas Pixel)

<table>
<thead>
<tr>
<th>technology</th>
<th>Planar silicon</th>
<th>3D silicon</th>
<th>Diamond</th>
<th>GOSSIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>possible pos resolution (um)</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>~14 (polycryst)</td>
<td>~20</td>
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<tr>
<td>resolution for inclined tracks</td>
<td>reasonable</td>
<td>reasonable</td>
<td>reasonable</td>
<td>mediocre</td>
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<tr>
<td>charge collection time (ns)</td>
<td>&lt;6</td>
<td>20-35</td>
<td>2</td>
<td>20-80</td>
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<tr>
<td>mass including cooling</td>
<td>pretty high</td>
<td>pretty high</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>life time in SLHC (3000 fb^-1)</td>
<td>20-50%</td>
<td>~50%</td>
<td>~50%</td>
<td>&gt;100% pos</td>
</tr>
<tr>
<td>production technology</td>
<td>well known</td>
<td>difficult</td>
<td>difficult</td>
<td>much R&amp;D</td>
</tr>
<tr>
<td>bias voltage control</td>
<td>easy</td>
<td>easy</td>
<td>easy</td>
<td>critical</td>
</tr>
<tr>
<td>ease of operation</td>
<td>reasonable</td>
<td>reasonable</td>
<td>relaxed</td>
<td>critical</td>
</tr>
<tr>
<td>cooling</td>
<td>critical</td>
<td>less critical</td>
<td>relaxed</td>
<td>relaxed</td>
</tr>
<tr>
<td>additional services</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>HV + gas</td>
</tr>
<tr>
<td>additional DAQ channels</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>probably</td>
</tr>
<tr>
<td>track efficiency</td>
<td>100%</td>
<td>&gt;95%</td>
<td>98-100%</td>
<td>98%</td>
</tr>
<tr>
<td>costs</td>
<td>75-300 €/cm²</td>
<td>150-300 €/cm²</td>
<td>≤1000 €/cm²</td>
<td>20-30 €/cm²</td>
</tr>
<tr>
<td>size of coll. (ATLAS institutes)</td>
<td>&gt;10</td>
<td>10</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>approved R&amp;D?</td>
<td>yes</td>
<td>yes</td>
<td>Yes</td>
<td>near submit</td>
</tr>
</tbody>
</table>

ATLAS F. Hartjes

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EPS HEP 09 talks - S. Palestini, C. Civinini, G. Pellegrini

GOSSIP

100-700 V mm

Amplification gap 10 kV/mm

50 µm

Pixel chip

3D- Double Type Columns
Silicon for Linear Collider
vertex sensors

- Excellent spacepoint precision ( < 4 microns )
- Superb impact parameter resolution ( 5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta) )
- Transparency ( \sim 0.1\% X_0 per layer )
- Track reconstruction ( find tracks in VXD alone )
- Sensitive to minimal bunch crossings ( <150 = 45 \mu sec for ILC)
- EMI immunity
- Power Constraint ( < 100 Watts)

Concepts under Development
- Charge-Coupled Devices (CCDs)
  - Build on 307Mpx of SLD \Rightarrow Column Parallel CCDs, FPCCD (slow!)
- Monolithic Active Pixels – CMOS
  - MAPs, FAPs, Chronopixels, 3D-SOI
- DEpleted P-channel Field Effect Transistor (DEPFET)
- Silicon on Insulator (SoI)
- Image Sensor with In-Situ Storage (ISIS)
- HAPS (Hybrid Pixel Sensors)
Silicon for Linear Collider tracker

- Superb resolution allows small tracking volume
  - <1% $\sigma_p/p$ at 100 GeV
- Fast - robust to backgrounds
- Requires very low mass support (passive cooling)

Also - SiLC - Silicon envelope for TPC

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NA62 Gigatracker

- Three silicon pixel sensors
  - Precise direction & timing
  - ~ GHz rate
  - 1.5 MHz/mm² maximum
  - In vacuum

- Two readout options
  - Constant Fraction Discriminator (CFD) with complex pixel circuitry
  - Time Over Threshold (TOT) with simple, low power pixel circuitry

- Prototypes of analog for options in CMOS 0.13 μm passed tests
Diamond

- Advantages over silicon
  - Larger bandgap
  - Smaller dielectric constant
- Single Crystal (> 12 cm, 2 cm thick)
  - polycrystalline (few cm²)
- Experience as radiation monitors
- Candidate for LHC inner tracking

16 chip ATLAS Module of single crystal
Gas Detectors

* ALICE TPC
  - Largest - 2466 mm Rout,
    2 x 2500 mm drift
* Micro Pattern Gas Detectors (MPGDs)
  - GEMs
  - MicroMegas
  - Timepix(CMOS)/Ingrid
* T2K Near Detector
  - Largest TPC equipped with MPGDs
Linear Collider TPC w/MGPDs

MicroPatternGasDetector (MPGD) not limited by $E \times B$ effects

Gas Electron Multiplier GEM

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Linear Collider TPC

* DESY Beam Test

- Resolution at z=0: $\sigma_0 = 54.8 \pm 1.6 \mu m$ with 2.7-3.2 mm pads ($w_{pad}/65$)
- Effective number of electrons: $N_{eff} = 31.8 \pm 1.4$ consistent with expectations

$\sigma_x = \sqrt{\sigma_0^2 + \frac{C_D^2}{N_{eff}}} \cdot z$

MicroMeGas
5 GeV electrons, 1 Tesla

$B=1T$

$C_D = 101.6 \pm 0.4 [\mu m/\sqrt{cm}]$

$\frac{C_D}{\sqrt{N_{eff}}} = 22.6 \pm 0.7 [\mu m/\sqrt{cm}]$

$N_{eff} \sim 20 \pm 1$

Double GEMs

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Krakow

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20
Linear Collider TPC

* Triple GEM structure with Timepix readout

Readout: 2 quadboards (4 TimePix Chips each)

J. Kaminiski, Univ. of Bonn

J. Kaminiski, Univ. of Bonn
The T2K/TPCs: the largest TPCs equipped with MPGDs

72 modules for ~9 m² active area, ~120k electronic channels

FEE based on the ASIC AFTER
6 FECs + 1 FEM per module
Total of 1728 ASICs
432 FECs
72 FEMs

With On-detector FEE cooling, mechanicals

EPS HEP 09 talk - Claudio Giganti

A. Delbart
Calorimetry

- Electromagnetic Calorimetry
  - Silicon-Tungsten
  - Scintillator strips
  - Crystals
  - Liquid Xe (MEG)

- Hadron Calorimetry
  - Particle Flow
  - Dual Readout
Electromagnetic Calorimetry
Silicon-Tungsten for Linear Collider

* High granularity needed for Particle Flow Analysis

EPS HEP 09 talk - C. Carloganu

Test Beam Program
2006 - DESY/CERN 2007 - CERN 2008 - FNAL

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Electromagnetic Calorimetry
Scintillator Strips w/ MPPC* for Linear Collider

- 3-5 mm strips for high granularity needed for Particle Flow
- Tested at DESY & Fermilab

* Multi-Pixel Photon Counters
# Electromagnetic Calorimetry

## Crystals

### Crystal Calorimeters in HEP

<table>
<thead>
<tr>
<th>Date</th>
<th>75-85</th>
<th>80-00</th>
<th>80-00</th>
<th>80-00</th>
<th>90-10</th>
<th>94-10</th>
<th>94-10</th>
<th>95-20</th>
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<tr>
<td><strong>Experiment</strong></td>
<td>C. Ball</td>
<td>L3</td>
<td>CLEO II</td>
<td>C. Barrel</td>
<td>KTeV</td>
<td>BaBar</td>
<td>BELLE</td>
<td>CMS</td>
</tr>
<tr>
<td><strong>Accelerator</strong></td>
<td>SPEAR</td>
<td>LEP</td>
<td>CESR</td>
<td>LEAR</td>
<td>FNAL</td>
<td>SLAC</td>
<td>KEK</td>
<td>CERN</td>
</tr>
<tr>
<td><strong>Crystal Type</strong></td>
<td>NaI(Tl)</td>
<td>BGO</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>CsI</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>PbWO$_4$</td>
</tr>
<tr>
<td><strong>B-Field (T)</strong></td>
<td>-</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>$\gamma_{\text{inner}}$ (m)</strong></td>
<td>0.254</td>
<td>0.55</td>
<td>1.0</td>
<td>0.27</td>
<td>-</td>
<td>1.0</td>
<td>1.25</td>
<td>1.29</td>
</tr>
<tr>
<td><strong>Number of Crystals</strong></td>
<td>672</td>
<td>11,400</td>
<td>7,800</td>
<td>1,400</td>
<td>3,300</td>
<td>6,580</td>
<td>8,800</td>
<td>76,000</td>
</tr>
<tr>
<td><strong>Crystal Depth ($X_0$)</strong></td>
<td>16</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>27</td>
<td>16 to 17.5</td>
<td>16.2</td>
<td>25</td>
</tr>
<tr>
<td><strong>Crystal Volume (m$^3$)</strong></td>
<td>1</td>
<td>1.5</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>5.9</td>
<td>9.5</td>
<td>11</td>
</tr>
<tr>
<td><strong>Light Output (p.e./MeV)</strong></td>
<td>350</td>
<td>1,400</td>
<td>5,000</td>
<td>2,000</td>
<td>40</td>
<td>5,000</td>
<td>5,000</td>
<td>2</td>
</tr>
<tr>
<td><strong>Photosensor</strong></td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>WS$^a$+Si PD</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>APD$^a$</td>
</tr>
<tr>
<td><strong>Gain of Photosensor</strong></td>
<td>Large</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4,000</td>
<td>1</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td><strong>$\sigma_N$/Channel (MeV)</strong></td>
<td>0.05</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>small</td>
<td>0.15</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td><strong>Dynamic Range</strong></td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

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**Future crystal calorimeters in HEP:**

- PWO for PANDA at GSI
- LYSO for a Super B Factory, Mu2e and CMS Endcap Upgrade
- PbF$_2$, BGO, PWO for HHCAL

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Electromagnetic Calorimetry

Crystals

* Rad Hard for SuperB, Mu2e, CMS
  - Endcap upgrade
  - LYSO favored
  - Large light, low noise

* Recent Application -
  Homogenous HCAL -dual readout
  - For large volume, cost-effective
  - UV transparent material crucial.
  - Three candidates evaluated.
  - Initial investigation favors scintillating PbF$_2$.

(Lu$_2$(1–x)Y$_x$SiO$_5$: Ce -
Cerium doped Lutetium Yttrium Orthosilicate)
Electromagnetic Calorimetry
Liquid Xenon - MEG

* 800 liters of LXe
  - 846 PMTs
* Nearing start of new run with improved performance

Table 1. Summary of liquid xenon detector resolution

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Resolution (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ Energy (on 55 MeV)</td>
<td>4.8</td>
</tr>
<tr>
<td>γ Position (mm)</td>
<td>15.0</td>
</tr>
<tr>
<td>γ Time (nanosecond)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

giovanni.gallucci@pi.infn.it, CALOR 2008

World's Highest Intensity Muon Beam at PSI
Hadronic Calorimetry
Particle Flow for Linear Collider

* Particle Flow demands high granularity
* Intense test beam program

- Scintillator w/SiPM
- One of 38 layers of the prototype
- GEMs
- MicroMeGas

Small RPC calorimeter in the Fermilab test beam
Fully containing Hcal under construction

DESY, CERN, & Fermilab tests

EPS HEP 09 talk - J. Cvach
**CALICE Scintillator Tests**

**Particle Flow for Linear Collider**

- **CERN 2006-07, FNAL 2008-09**

38 steel layers (2cm), $4.5\lambda$
7608 tiles with SiPMs

W/ ECAL and TCMT
common readout electronics

**CALICE’s conclusions:**

- The SiPM technology has proven to be robust and stable
- The calibration is well under control
- The performance is as expected and understood
- Strong support for predicted PFLOW performance
CALICE Digital HCAL Tests
Particle Flow for Linear Collider

* Small glass RPC module tested in Fermilab beam

20 x 20 cm² RPCs (based on two different designs)
1 x 1 cm² readout pads
Up to 10 chambers → 2560 readout channels
Complete readout chain as for larger system
Detailed tests with cosmic rays & in Fermilab beam
(µ, 120 GeV p, 1 – 16 GeV π⁺, e⁺)

* 1m³ prototype under construction

Cosmic ray tests for each chamber
Fermilab test beam with µ, π±, e±
hadronic shower MC model comparison
analog HCAL (CALICE) comparison
Construction completed in CY 2009
Data analysis in 2010/2011
Fluctuations in hadronic shower
- Nuclear binding energy losses & $\pi^0$ energy variations

Measure separately the EM shower component
- DREAM Collaboration measured in HE calorimeter
- Correct for EM fraction event by event (Q/S method)

What resolution with combined signals?
- DREAM leakage limited
sLHC Calorimetry
Confronting the Radiation Challenge

* ATLAS Forward Calorimeter
  - LAr boiling, inter-electrode ion build-up, HV resistor voltage drop
  - Two possible solutions
    - Warm calorimeter in front of current FCAL
    - New FCAL - smaller gaps and increased cooling

FCAL module (FCalcHik) on the Protvino testbeam

FCalcHik with cooling loops
Particle ID

 Crucial role in many experiments
  – BaBar, Belle, LHC-b

 Future Needs
  – Belle II, INFN SuperB, NA62

 Key Technologies
  – Radiators
    • Quartz (fused Silica) - polishing
    • Silica aerogel - improved transmission, mult-index tiling
  – Photodetectors
    • Hybrid PD
    • MCP-PMT
    • MPPC

n1=1.046
n2=1.041
n3=1.037

Novosibirsk Aerogel

144ch HAPD

EPS HEP 09 talk - Z. Dolezal
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MPPCs, SiPMs

- Single photon sensitive devices built from an avalanche photodiode (APD) array on common Silicon substrate.
- Many attractive properties
  - Extremely compact
  - B-field immune
  - Good timing
  - Gain and QE competitive with PMT
- Many investigations
Megaton Detectors for Neutrinos

- SuperK proves performance of water Cherenkov
- Future goal - 1 MTon
- Challenges
  - Costs
  - PMTs (increased QE)
  - Readout Electronics
  - New photosensors
  - Harden against accident
- T2K develops MPPC (SiPM)
* ICARUS demonstrated potential
* Promising technique for future experiments
  – Low threshold
* Goal - scale up to ~100kTon
* Challenges
  – Purification
  – Cold, low noise electronics, signal mplex
  – Vessel - design, design, materials, insulation
  – Siting
  – Costs
Neutrinoless Double Beta Decay

Several 100-200 kg detectors being developed

- Challenge to minimize backgrounds
- CUORE
  - 203 kg $^{130}$Te
  - 988 TeO$_2$ bolometers
  - Follows 11 kg $^{130}$Te CUORICINO
- EXO-200
  - 200 Kg $^{136}$Xe
  - Measure ionization and scintillation plus Ba tag
- Majorana
  - Goal: 120 kg of $^{76}$Ge

EXO-200
LXe Field Cage & Readout Planes

R&D - Ionization & Scintillation:
$\sigma(E)/E = 3.0\%$ @ 570 keV
or $1.4\%$ @ $Q_{\beta\beta}$

Will add Ba tagging
Dark Matter
Direct Detection Techniques

COUPP
PICASSO

Tracking:
Drift, DM-TPC

Phonons

CDMS
EDELWEISS

CRESST
ROSEBUD

Charge

GERDA
MAJORANA
ConGeNT

XENON
LUX, ZEPLIN
WARP, ArDM

Light

DEAP/CLEAN
DAMA, KIMS
XMASS

M. Schumann

H. Sobel
Bolometers for DM Detection

**CDMS**

- **Phonon/Charge detection with ZIP detectors**
  - Electric field pulls charge to sensitive amplifier
  - Phonons break Cooper pairs in thin superconducting Al layer, heating transition-edge sensor & causing change in resistance.
  - Readout elements highly segmented, and relative timing of ionization and phonon signals provide good event localization.

- **Operated 5 kg in Soudan**
- **Planning 25 kg in SNOLAB (SuperCDMS)**
Bolometers, cont.

- **EDELWEISS**
  - Ge/NTD
  - Ge/NbSi
  - Ge/Interdigit
    - 30 kg operating

- **CRESST-II**
  - ~300 g CaWO$_4$ crystal
    - Gran Sasso

- **ROSEBUD**
  - BGO
  - LiF (n-mon)
  - Sapphire
Warm Liquid
Dark Matter Detector

* COUPP
  - Room Temp Bubble Chamber, CF$_3$I, 2 kg tested

A CCD camera takes pictures at 50 Hz. Chamber triggers on appearance of bubble in the frame.

Single bubble DM signature.

- New 20 and 60 kg chambers will go underground in 2010
Directional Dark Matter Detectors

- Low pressure TPCs favored
  - CS$_2$ - spin-dependent interactions
  - CF$_4$ and $^3$He - spin-independent interactions

- Wire chamber readout
  - DRIFT-II
  - Two 1m$^3$ (CS$_2$) modules underground

- MPGDs
  - NEWAGE, MIMAC

- PMT and CCD readout
  - DMTPC (CF$_4$)
Noble Liquid
Dark Matter Detectors

Many Attractive Features

- Low cost, easy to obtain, dense target material.
- Easily purified due to freeze out of contaminants at cryogenic temperatures.
- Very small electron attachment probability.
- Large electron mobility (Large drift velocity for small E-field).
- High scintillation efficiency.
- Possibility for large, homogenous detectors.

Problem - $^{39}\text{Ar}$, $^{85}\text{Kr}$.

- See Elena Aprile’s talk for R&D on noble liquids.
Test Beams

- Needed for detector development as well as in many other phases of HEP experiment eg. prototype testing, calibrations, etc.

- Laboratory support of test beams very important
Conclusion

- Discoveries in HEP vitally depend on advances in detector technology
- Challenges are huge
  - speed, granularity, radiation, exotic materials, etc.
- Many efforts confronting these challenges
- Critical that the efforts are well funded
- Technology will continue to advance, with important emerging capabilities critical to future discoveries
  - with timescales dependent on the level of financial support

Don’t forget the test beams
Acknowledgements