The Detector R&D Program at Fermilab

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U.S. Detector Workshop

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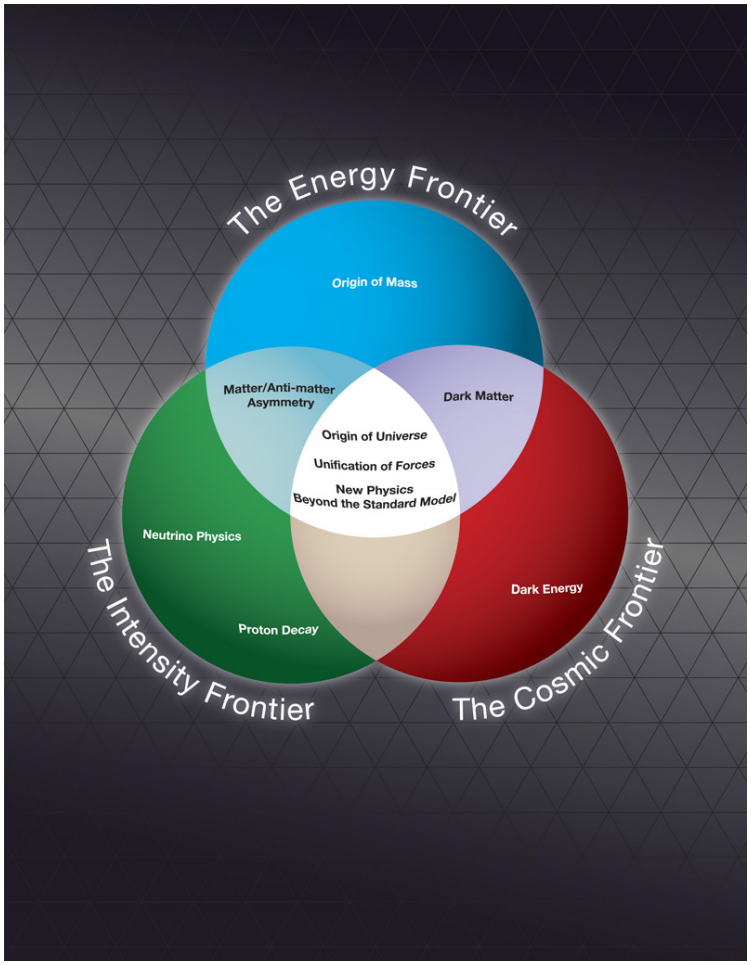
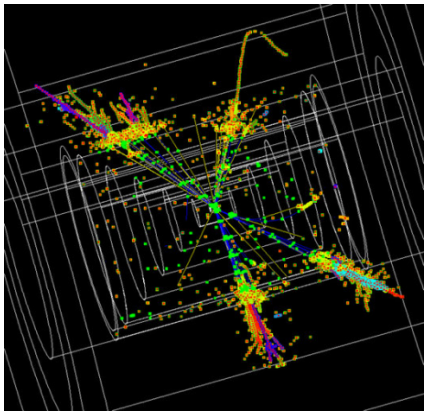
What are the major challenges in the Frontiers of HEP?

- The '3 frontiers' outline the major thrusts of high energy physics
- In each area, the physics is advancing rapidly. It is crucial that the detector technology keep pace.



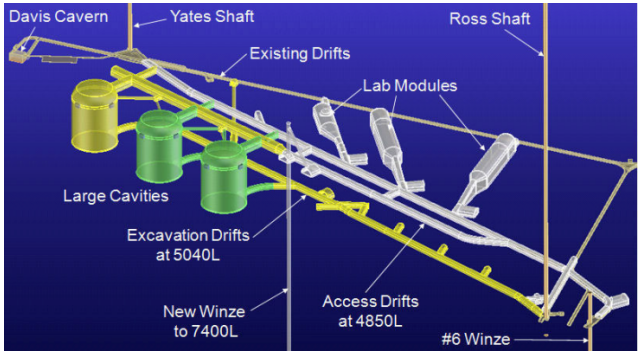
The Energy Frontier

- Vertex sensors that can withstand a fluence of 10^{16} particles/cm^2
- Triggering that can keep pace with x10 luminosity
- 4 micron point precision tracking at a lepton collider
- Hadronic jet energy resolutions of 30%/sqrt(E)



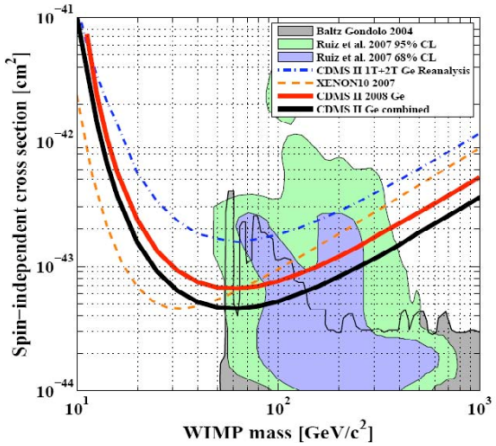
The Intensity Frontier

- Finding a low-cost, efficient photodetector that can tile a water tank of 300 kton (150,000 PMT's !)
- Developing a 20 kton liquid Argon TPC detector that can be filled easily, be purified, and with robust electronic readout
- Developing psec level Time-of-Flight techniques for rare decay tagging



The Cosmic Frontier

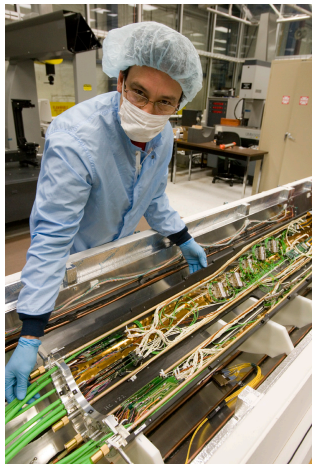
- Reducing background rates in dark matter detectors down to a level of 1 nuclear recoil per ton per year
- Expanding the depth of observation of galaxy clusters to probe Dark Energy equation of state
- Probe the Planck scale of space-time



Fermilab's Emphasis in Detector R&D

- Detector R&D at Fermilab is geared towards our strengths as a national lab, meaning that our institutional capabilities come into play. These are
  - Presence of large facilities like the Test Beam Facility or Silicon Detector Facility
  - Experienced, well established engineering groups, such as ASIC development, cryogenics engineering, and software
  - Managing large projects that may require substantial investments of manpower, time or money
- We encourage, and thrive on, a high degree of collaboration with the university community and other (inter)national labs.

Liquid Argon purity tank



CMS Pixel detector at SiDet

CALICE at the test beam

Fermilab Connects with the Community by:

- Providing facilities for use by universities and other laboratories
- Supporting visiting guest scientists
- This Workshop on the U.S. Detector R&D program
- Co-organizing new EDIT Detector School
  - "Excellence in Detectors and Instrumentation Technologies"
  - Goal is to train young researchers in detector techniques
  - At CERN, 31 January - 10 February 2011
  - At Fermilab a year later
- Co-Hosting 2nd TIPP Workshop:
  - Technology and Instrumentation in Particle Physics, 9-14, June, 2011
  - A follow-on to the very successful workshop in Japan in 2009
- Significant leadership in focused workshops on individual technologies (e.g. 3-D ASICS, homogenous hadron calorimetry, optical DAQ, etc.)

Coordinated Planning for a Lepton Collider

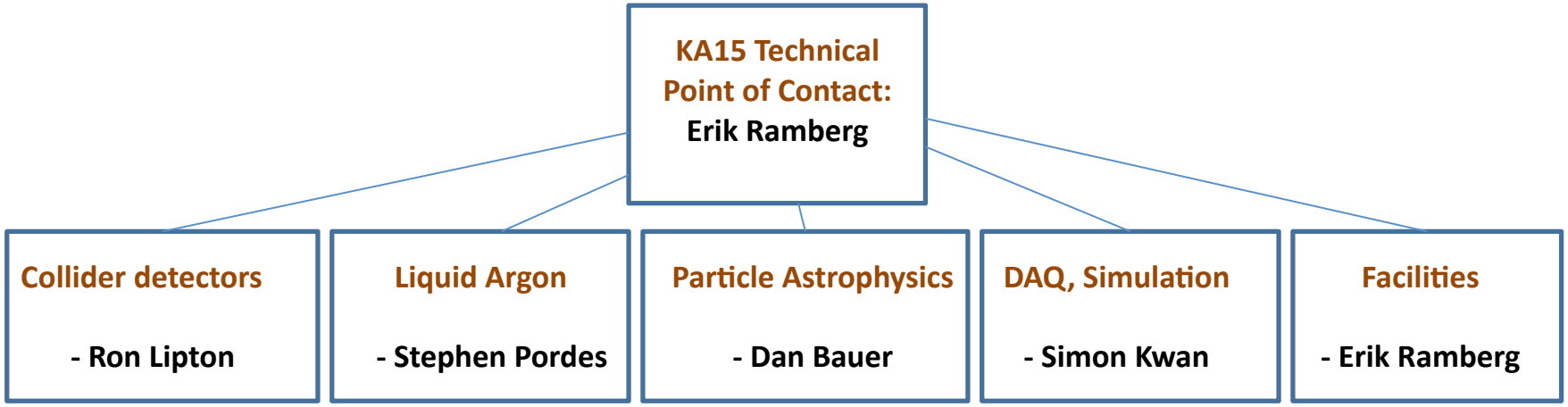
- Fermilab, along with 4 other national labs and the DPF, released a white paper on lepton collider detector R&D.
- It envisions a coordinated research program to:
  - Establish the physics capability of lepton colliders.
  - Establish the requirements of detector systems so the physics can be extracted, taking into account the very different operating conditions at each machine.
  - Provide feedback to the machine design to further optimize the physics potential.
  - Propose necessary detector and other R&D to verify detector technologies.
  - Compare the physics potential of these machines and carry out a cost-benefit analysis.
  - Coordinate the detector and physics program.

Generic Detector R&D Thrusts at Fermilab

DOE funds generic detector R&D through its KA15 budget

The KA15 portfolio at Fermilab is organized into 5 major thrusts, each with an advisor, as shown below.

The Detector R&D advisory group works with the Particle Physics and Computing Divisions and the various Centers to establish R&D priorities.



A Snapshot of our Work in Progress

- A large number of scientists, engineers and technicians at Fermilab work on detector related problems, both for established experiments, and for basic research.
- What follows is a description of some of the generic detector R&D we perform, organized by thrust (lead institution indicated by star). Many detector efforts are not reported here.
- Because of time considerations, no results are presented.
- For further information, see our web site:

http://detectors.fnal.gov

Collider Detector Research:

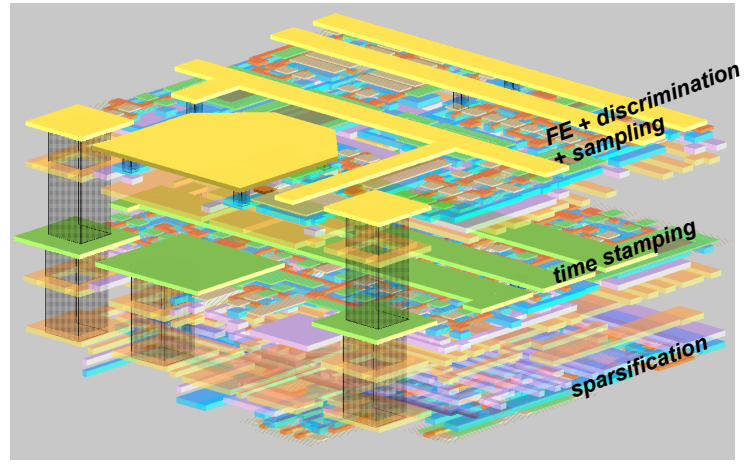
- Thinning, annealing and bonding of sensors *
- 3D ASIC development
- Silicon-on-Insulator
- Intelligent tracking systems
- Serial powering of vertex detectors *
- Total absorption crystal hadron calorimetry *
- SiPM Characterization
- Fast Timing detectors

* not discussed in this talk

3D Integrated Circuits

The aggressive requirements for ILC vertex detectors led us to explore very high density circuit integration technologies, including the development of the first 3D circuits for HEP

- VIP1 and VIP2 – 3 layer ILC vertex chip using the MIT-LL process

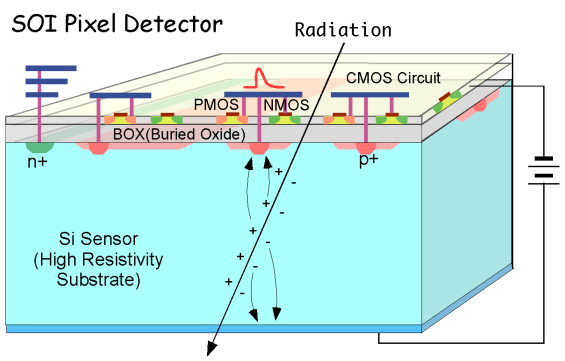


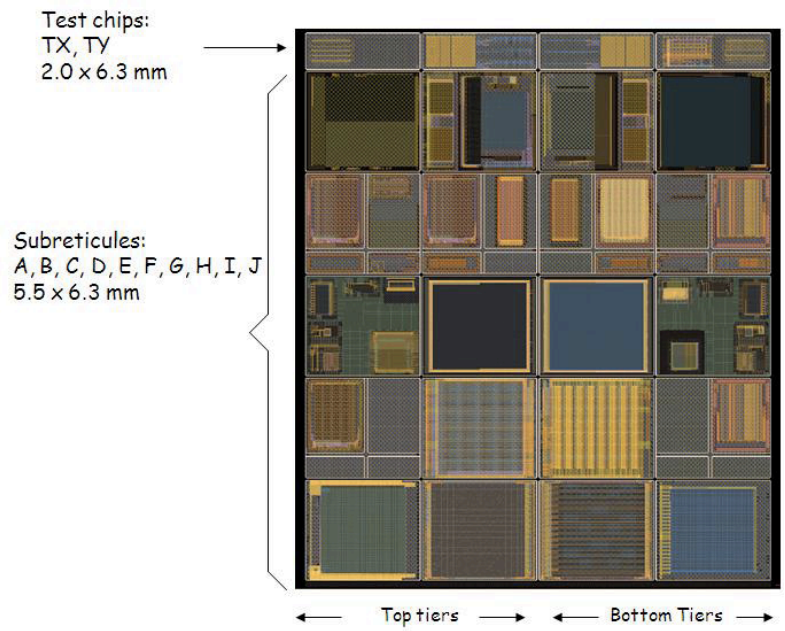
We organized a 3D multiproject run with Tezzaron. Consortium established in late 2008 with

- 15 members (BNL & LBNL)
- 5 countries

Others have since joined

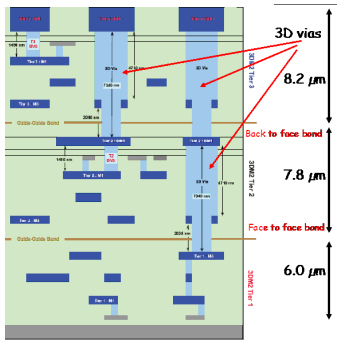
In addition, we are collaborating with KEK/OKI and American Semiconductor to develop SOI-based detectors





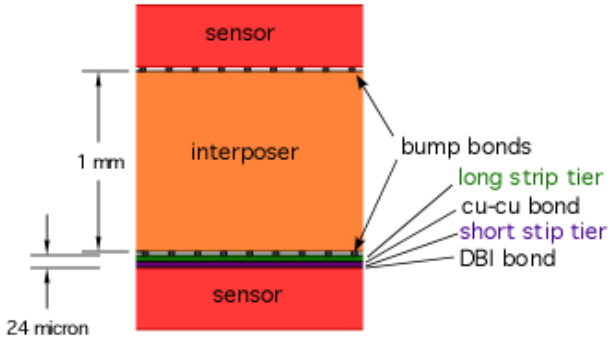
Projects in the 3D Realm

- VIP1 and VIP2 - demonstrated increased circuit density by integrating 3 circuit tiers, with extreme circuit thinning (7um) and small vias (~1.5 um). Has data sparsification, 5-bit digital and analog time stamp, high speed token passing

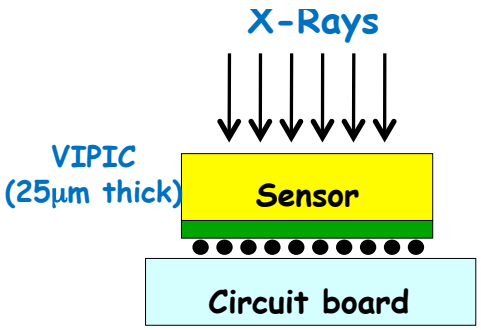


MIT LL 3 Tier Assembly

- VICTR - R&D proposal (Boston, Brown, Cornell, Davis, Riverside, Rochester, Santa Barbara, Texas A&M, Vanderbilt) for sLHC track triggering. The top tier: bond to sensor with long strips to provide phi information. The bottom tier: bond to sensor with short strips to provide z information.



- VIPIC - Evaluating application for X-ray photon correlation spectroscopy (XPCS) in collaboration with BNL to calculate autocorrelation function per pixel

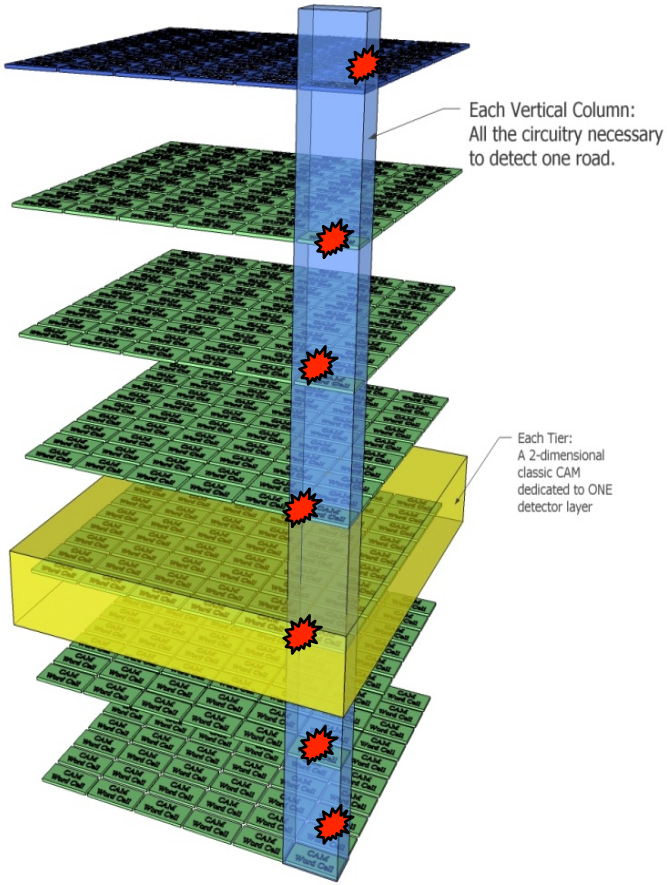


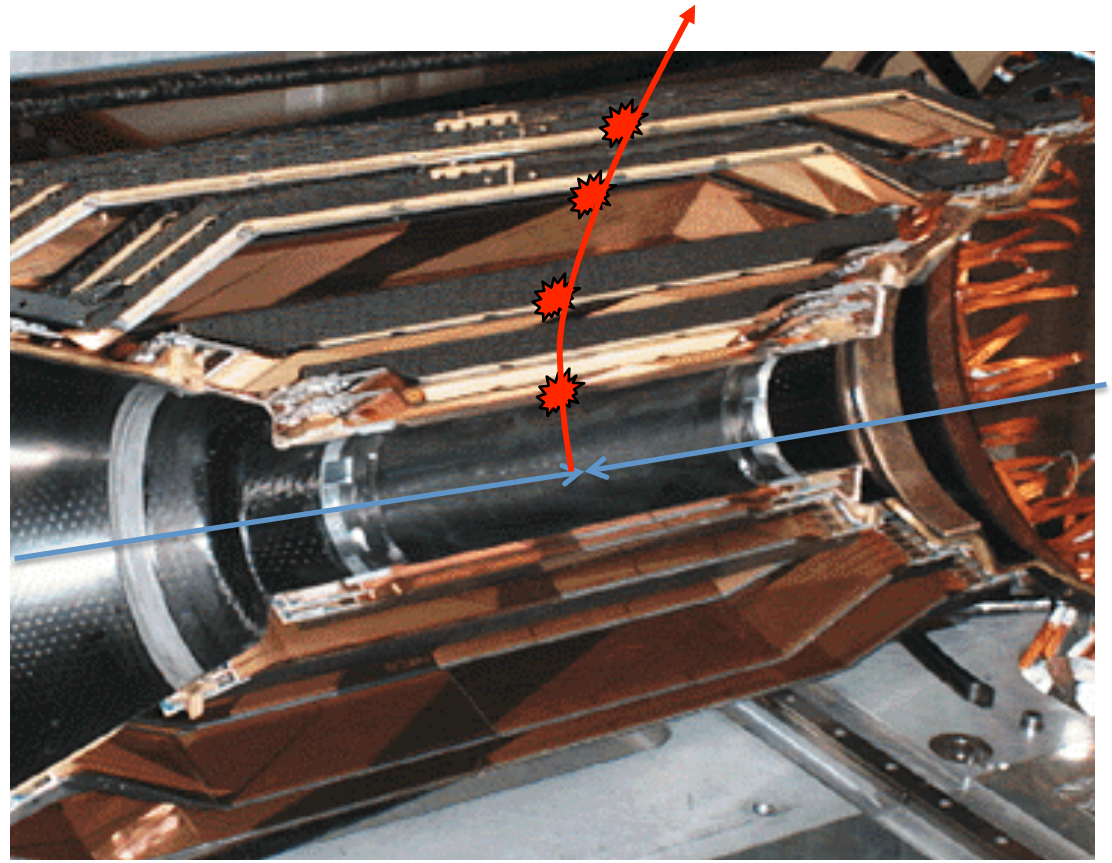
New proposal developing at FNAL: VIPRAM

(Argonne, U. Chicago)

(Vertically Integrated Pattern Recognition Associative Memory)

- **Novel design for pattern recognition using 3D technology with associated memories;**
- **To address LHC tracking trigger challenges at high luminosity;**
- **Generic enough, beyond tracking trigger, within & outside HEP**
- **Pattern recognition for tracking is naturally a task in 3D**



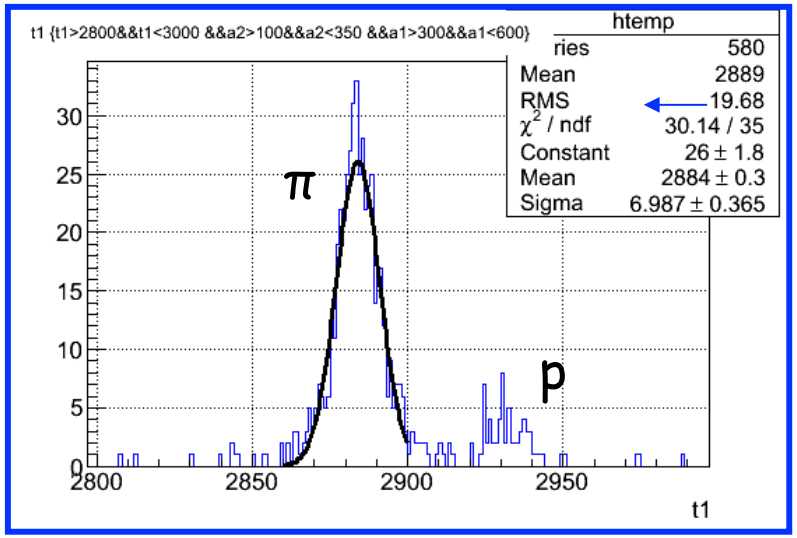


Psec Level Time-of-Flight

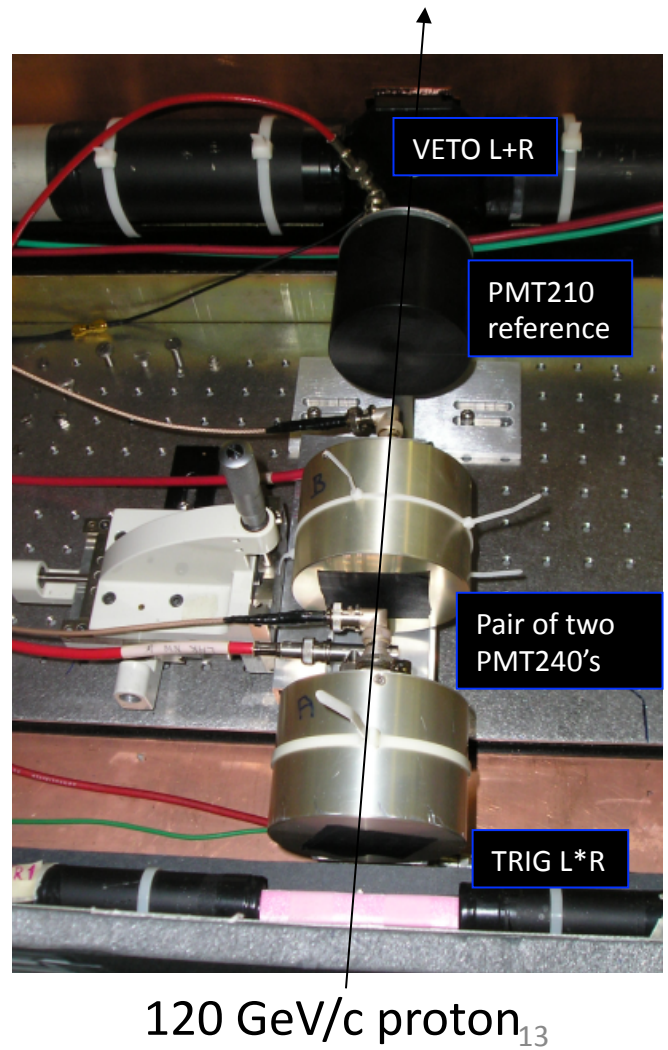
(Partners are: U.Chicago*, Argonne*, SLAC)

Microchannel Plate Photomultipliers have proven themselves as exquisite TOF detectors, with < 8 psec intrinsic timing resolution shown in the lab. Fermilab has shown almost as good timing resolution (13 psec) for SiPM.

In addition to lab tests, we've performed real TOF particle i.d. in the test beam at 22 psec level.

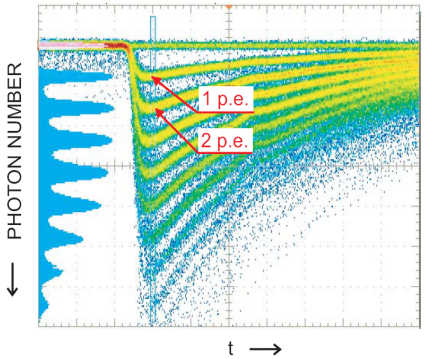


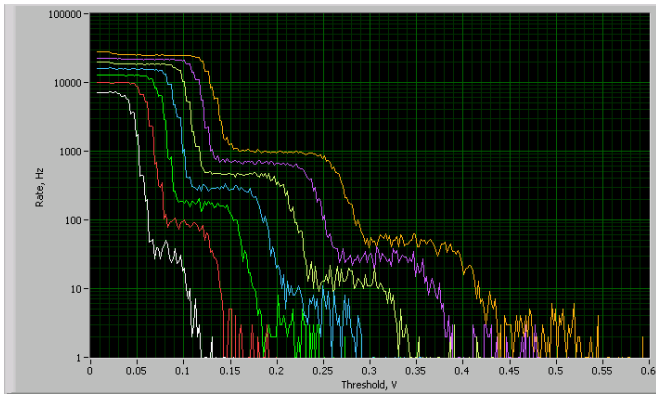
σ = 7 ch = 21.7 ps at 8 GeV with 7 m separation

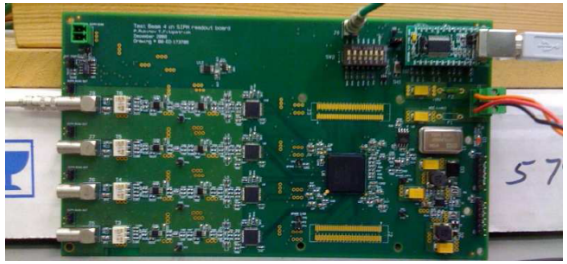


SiPM Characterization and Readout

- Fermilab has developed a general facility for characterization of SiPMs
  - Dark current and photo response
  - Cross talk
  - Temperature dependence
  - Four channel readout board (TB4) with waveform digitization
- Developing plans for dedicated ASIC for SiPM readout. With 3D ASIC readout, you can conceive of reading out each pixel separately, and realize a truly digital photon detector.

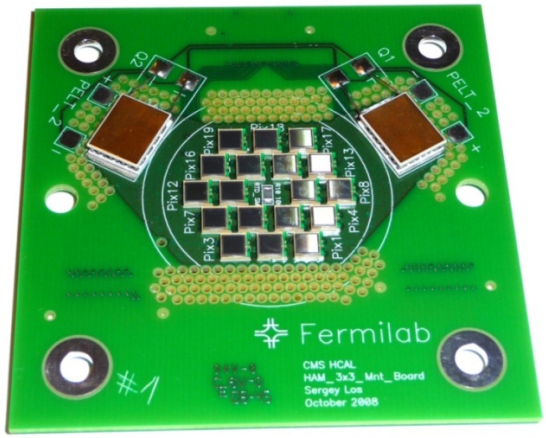




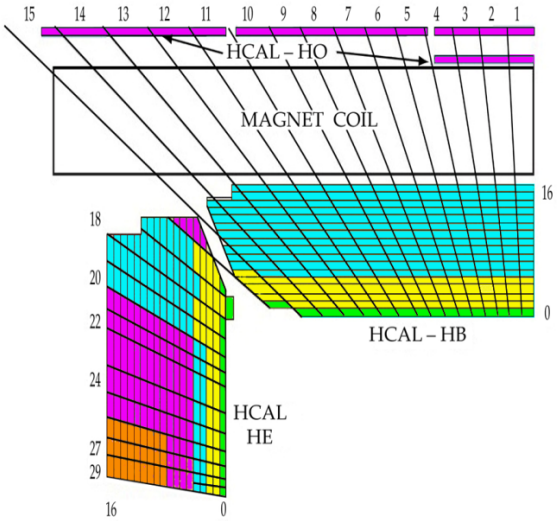


CMS Synergy for SiPM: HCAL

- CMS HPD replacement step 1: Outer Calorimeter (~2012)
  - ~3,000 SiPMs
  - Each fiber in bundle (18) guided to its own SiPM
  - Readout by QIE ASIC (Fermilab)



- CMS HPD replacement step 2: Whole calorimeter (Phase I)
  - ~110,000 SiPMs
  - Allows for longitudinal segmentation
  - SIPM tailored to HCAL
  - New ADC = new ASIC (QIE10)



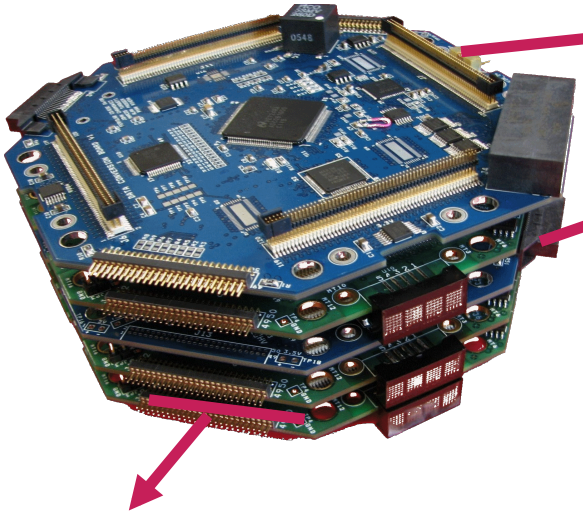
CMS

DAQ Development and Simulation:

- Versatile, high speed DAQ for detector R&D
- Free Space Optical DAQ
- Simulation for dual readout calorimetry

The CAPTAN DAQ System

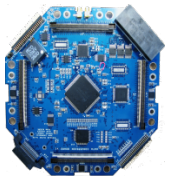
- The CAPTAN DAQ system has been developed as a versatile readout for the detector R&D community. (Users include Brown, Purdue, IIT, INFN, IHEP) There are 3 basic concepts behind the system:



1) Vertical standard bus

2) A set of core boards:

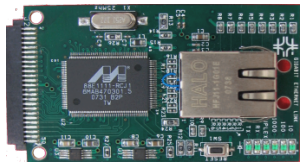
NPCB – Node Processing and Control Board



DCB – Data Conversion Board

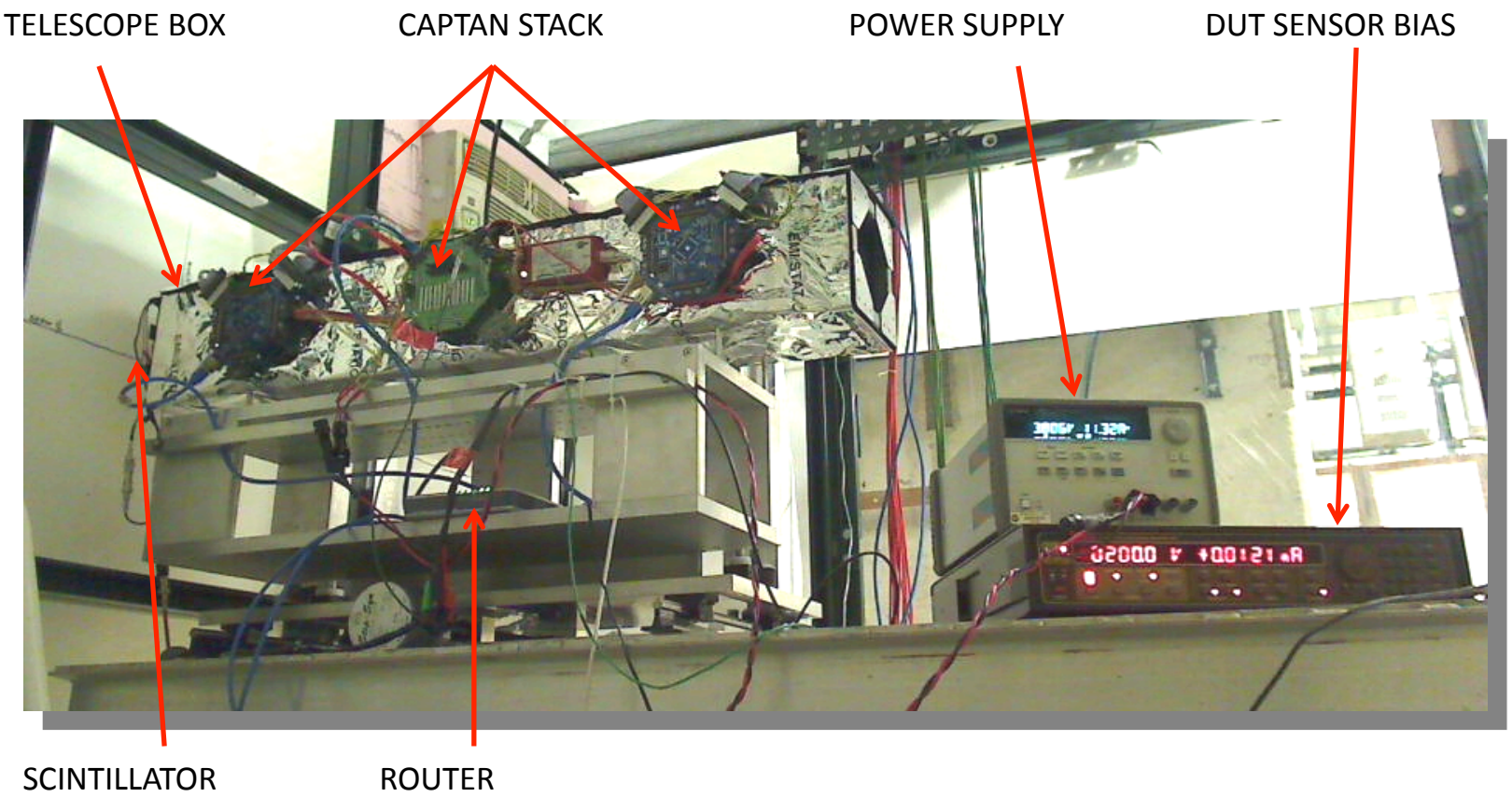
3) Horizontal connectivity

- **Gigabit Ethernet Link**
- **Interface Boards**
- **Level Translator**
- **USB**



- The software is a multithreaded application running on windows

Test Beam Pixel Telescope Overview

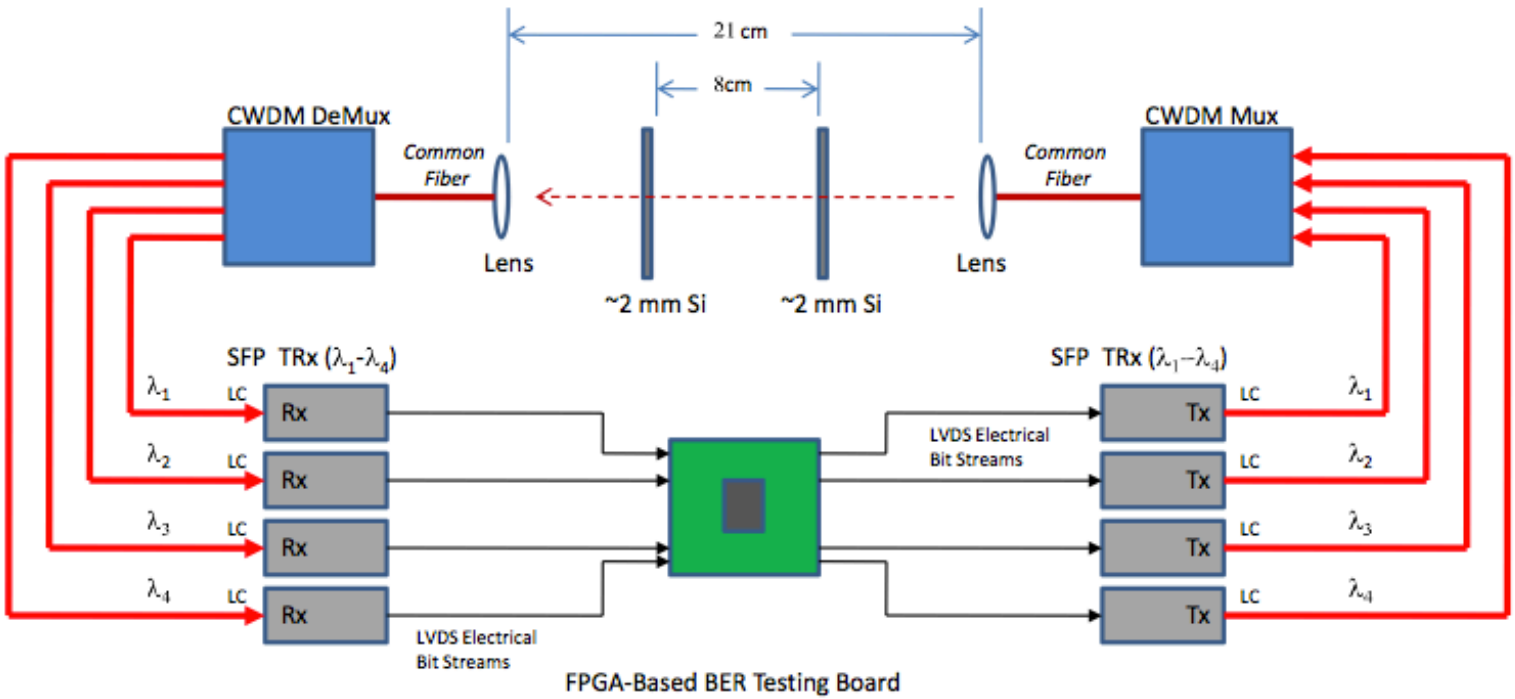


A great example of the interplay between detector development, Fermilab's unique facilities (test beam, in this case) and the User community, which now benefits from this added capability.

Multi-wavelength Free Space Data Transmission Results Shown at Optical DAQ Workshop at Fermilab (partnership with VegaWave*)

Fermilab

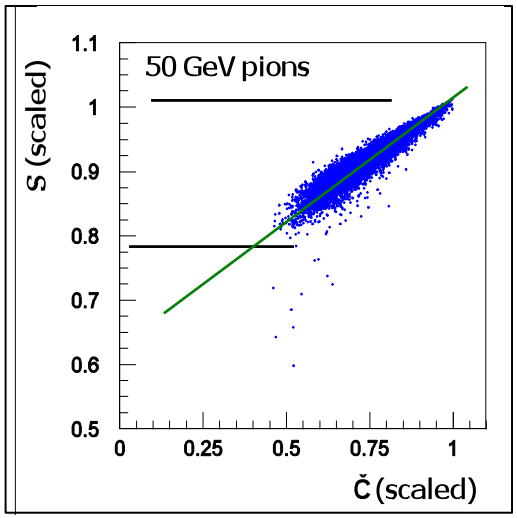
CWDM/Free-Space Bit Error Rate Testing

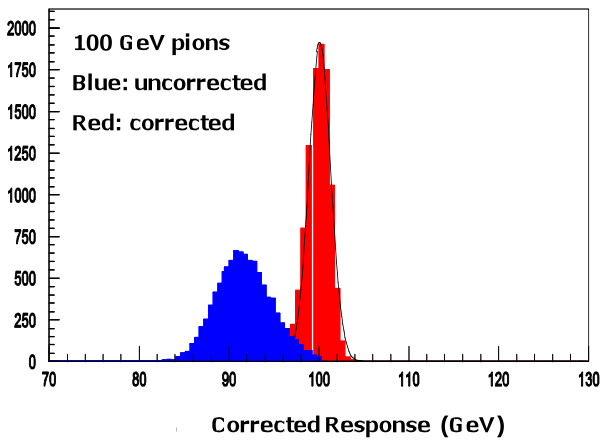


λ_1 = 1470 nm
λ_2 = 1490 nm
λ_3 = 1510 nm
λ_4 = 1530 nm

Dual Readout Calorimetry Simulation

(Partners are: Argonne, SLAC, U.Iowa, CalTech)





- Dual-readout calorimetry: measure every shower twice
  - Scintillation light: from all charged particles
  - Čerenkov light: b=1 particles, mainly EM
- Correct on a shower-by-shower basis using the correlation of the total observed ionization (S) and Čerenkov (Č) ligh
- From Monte Carlo studies:
  - Energy resolution (0.2-0.25)/√E (Gaussian)
  - No constant term up to 200 GeV
- The enabling technology is thin profile pixelated photon detectors. This would not be possible with normal phototubes
- We need to compare simulation with data – especially in a large crystal array

Liquid Argon R&D:

- Filtration systems *
- Digital electronics for TPC readout *
- Test stands for purity investigations
- Successful operation of a LAr TPC - ArgoNeut
- 20 ton LAr demonstrator
- Distillation column for low background Ar

A Working Liquid Argon TPC in a neutrino beam

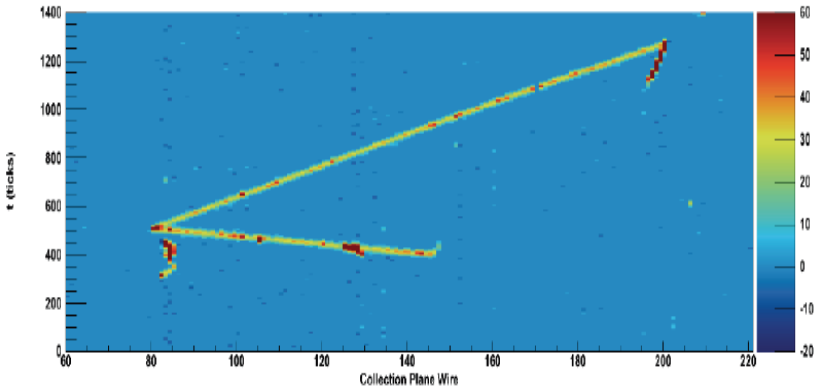
(Partners are: Kansas State, Michigan State, U.T. Austin, Yale*,Syracuse)

ArgoNeut succeeds in capturing and analyzing a large number of low energy neutrinos (<10 GeV) in a liquid Argon TPC.

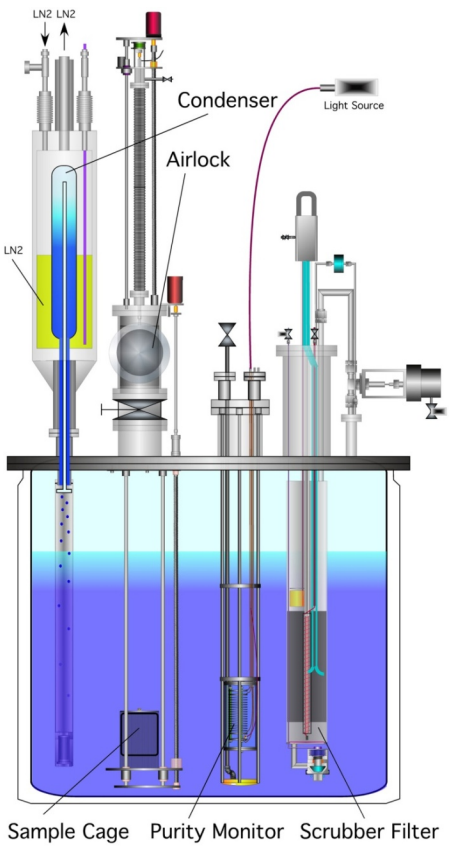
We worked with MSU to develop the readout electronics.

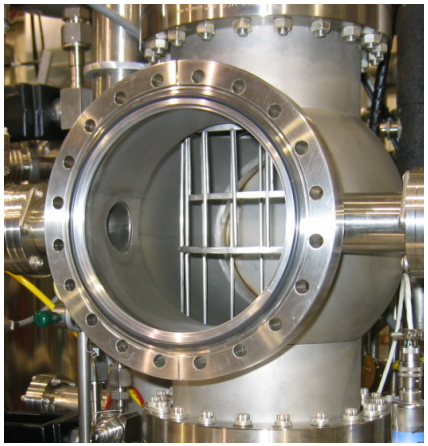
Developed methods to clean Argon, rather than use commercial filters

Can this be scaled up for long baseline neutrino detection?



Liquid Argon Testing





Isolation Valve (below photo)

A unique system ('Luke') for testing Argon purity

- Put materials in Sample Cage in the Argon Lock
- Seal the Argon Lock (open in photograph).
- [Evacuate the Argon Lock (or not).]
- Purge with pure argon gas (available from the cryostat).

An additional system ('Bo') is used for testing TPC electronic systems at liquid Argon temperatures. Note the 50 kV feedthrough.

"LAPD" = Liquid Argon Purity Demonstrator

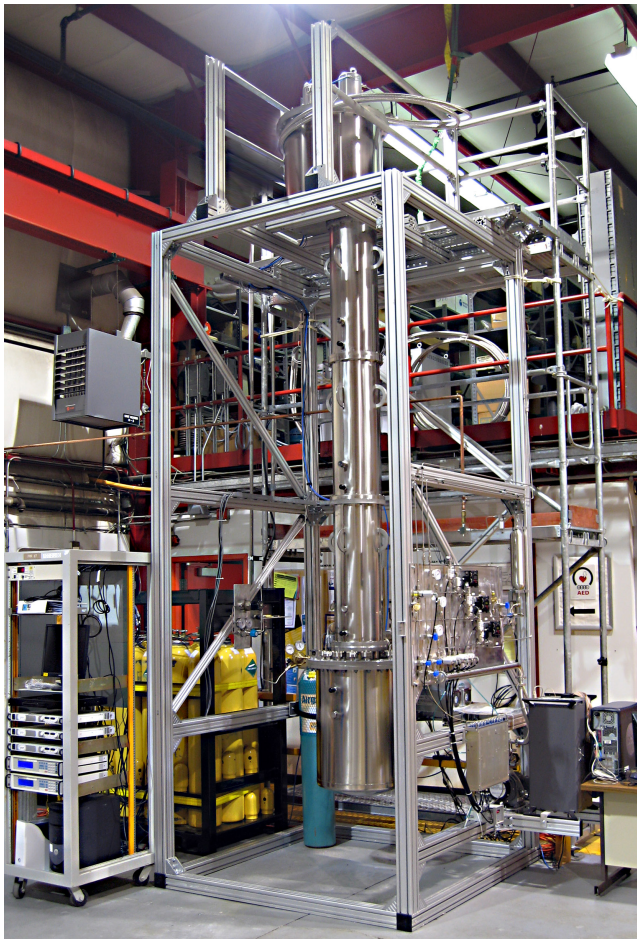
- Primary goal is to show that required electron lifetimes can be achieved without evacuation in an empty (20 ton) vessel - Phase I

- Will also monitor temperature gradients, concentrations of water, O2, and N2

- Phase II will place materials that would be used in a TPC into the volume and show that the lifetime can still be achieved

A Whopping Big Research Distillation Column

(Partners are: Princeton*, Augustana, S.D.)



Atmospheric Argon has activity of 1 Bq/kg from ^{39}Ar, which is a source of background and pile-up in multi-ton Argon based Dark Matter detectors.

Underground Argon has been shown to be depleted in ^{39}Ar by at least a factor of 25.

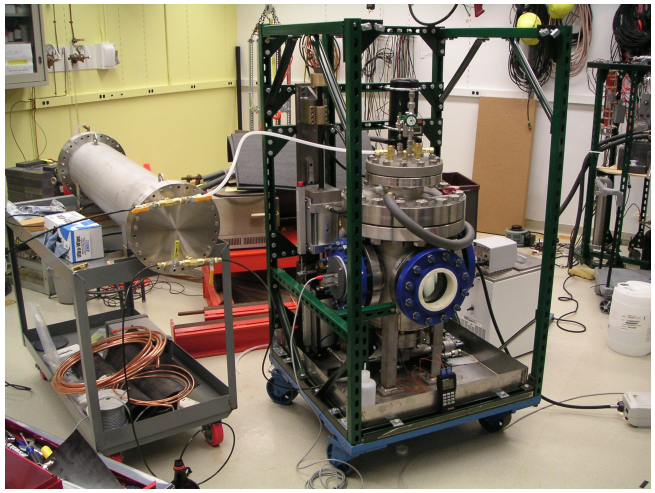
Distillation Column was designed at Princeton and assembled at Fermilab, for the separation of underground Argon from the accompanying Nitrogen and Helium.

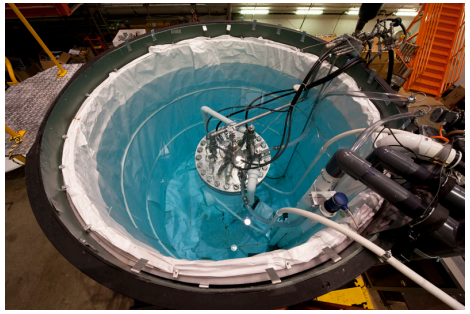
Astrophysics R&D:

- Particle identification in a bubble chamber
- Solid Xenon research
- CCD's used as dark matter detectors
- Planck scale structure of space-time *
- 21 cm line Radio Telescope *
- Optimizing CMB detectors *

Bubble Chamber Detection of Dark Matter

(Partners are: IUSB, U. Chicago*)





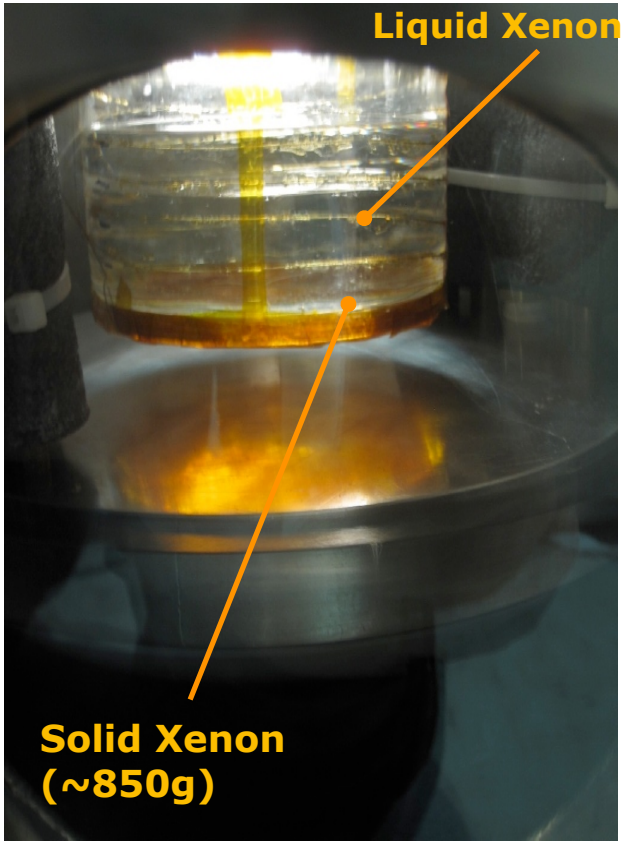
- An excellent example of how detector R&D grows into experiments.
- Test tube work at U.of C. eventually led to their delivery to Fermilab of a 2 kg device, for use in the MINOS underground facility here.
- As we learned techniques, a 4 kg upgrade was constructed to test purity and background issues, resulting in a physics result, and eventual deployment to SNOLAB.
- The R&D effort has confirmed that we can use sound to do particle i.d. in the chamber.
- The COUPP 60 kg chamber (experiment E961) has recently seen its first bubbles underground at MINOS.

Solid Xenon Detector R&D Project

(Partners are: U. Florida, Texas A&M)

Low Background Science

- Solar axion search
- Dark matter search
- Neutrinoless double beta decay



Why Xenon?

- No long-lived Xe radio isotope
- High yield of scintillation light
- Easy purification (distillation, etc)
- Self shielding : Z=54

Why Solid Xenon?

- Bragg scattering enhancement for axions
- Simple crystal structure : fcc
- More scintillation light (solid > liquid)
- Drifting electrons faster
- No further background contamination through circulation loop

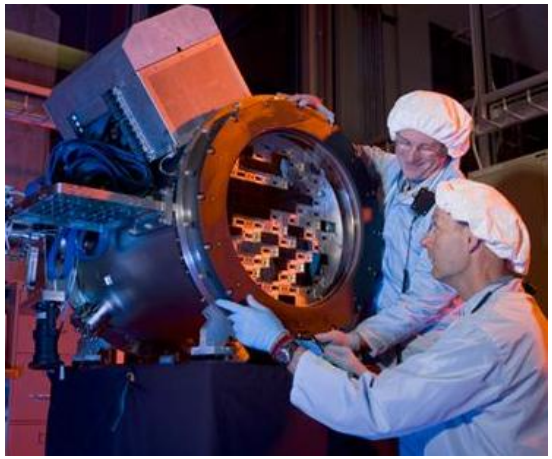
R&D Phase-1 Completed

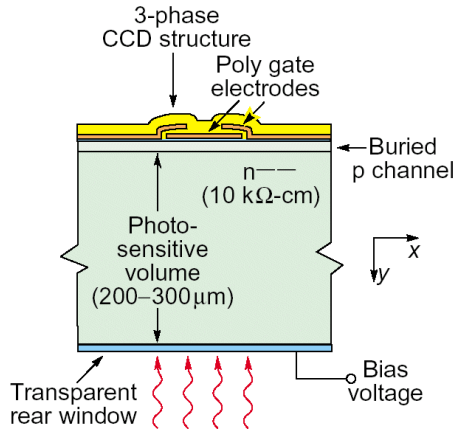
- Collaboration with U.Florida and TAMU
- Build optically transparent solid xenon
- Detailed recipes ready

R&D Phase-2: Scintillation Light Readout (Now)

Low Noise CCD Readout

DECam: wide field imager

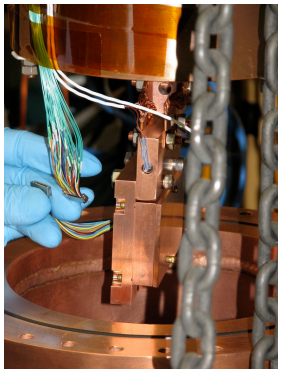




To improve the efficiency in the near-IR, the detectors are extraordinarily thick (250um instead of the typical 30 um for astronomical CCDs).

CCDs are readout serially (2 outputs for 8 million pixels). When read out slow, these detectors have a noise below 2e- (RMS). This means an <u>RMS noise of 7.2 eV in ionization energy!</u>

The DAMIC detector was built out of several spare DECAM CCD's and is investigating their use as a low-mass dark matter detector.

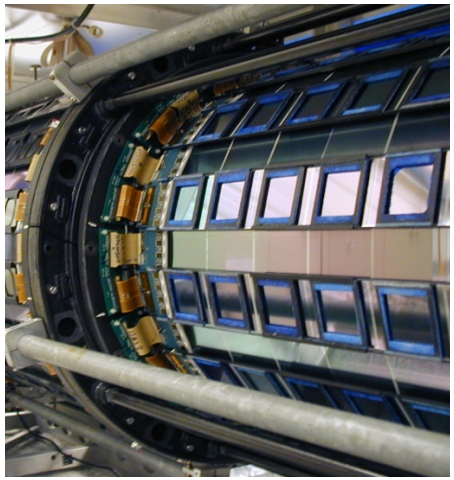


Facilities:

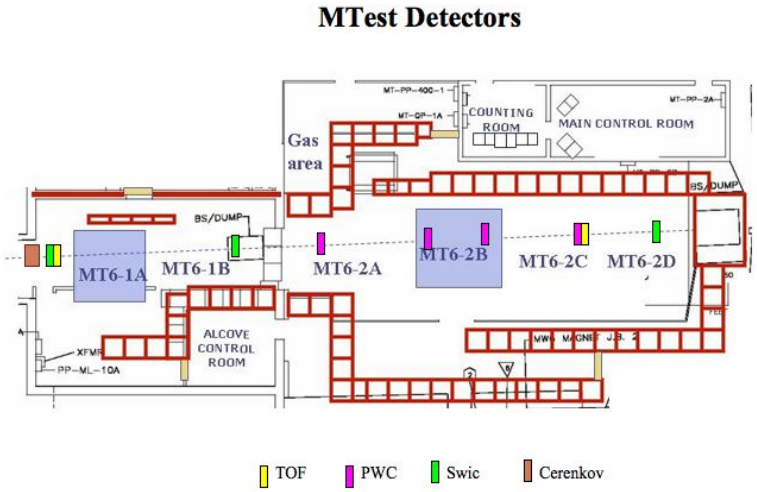
- **MINOS underground area**
- **Particle test beam facilities**
- **Computing hardware and software support**
- **Technical Centers:**
  - > Silicon Detector Facility
  - > Vacuum Deposition
  - > Detector Mechanical Support
  - > PMT and SiPM Test Benches
  - > Carbon Fiber Fabrications
  - > Wire Winding
  - > Scintillator Extrusion

SiDet has:

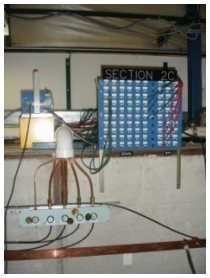
- Team of talented, experienced engineers, designers and technicians
- Extensive experience with:
  - Micron precision assembly
  - Engineering of low-mass, stiff structures
  - Thermal management issues
- Extensive equipment and resources
  - >7000 ft^2 of high-quality clean room space
    - 6000 ft^2 operated as class 10000
    - 1000 ft^2 operated as class 5000
  - 17 CMMs of various accuracies and measurement ranges
  - 1 automated optical measurement system (OGP)
  - 2600 ft^2 of burn-in space
  - 6 Kulicke & Soffa wire bonding machines



Fermilab's Test Beam Facilities



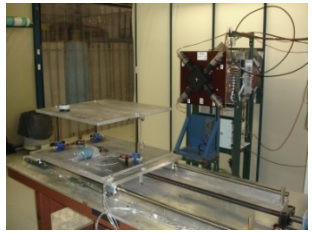
Spacious control room



Signal and HV cables

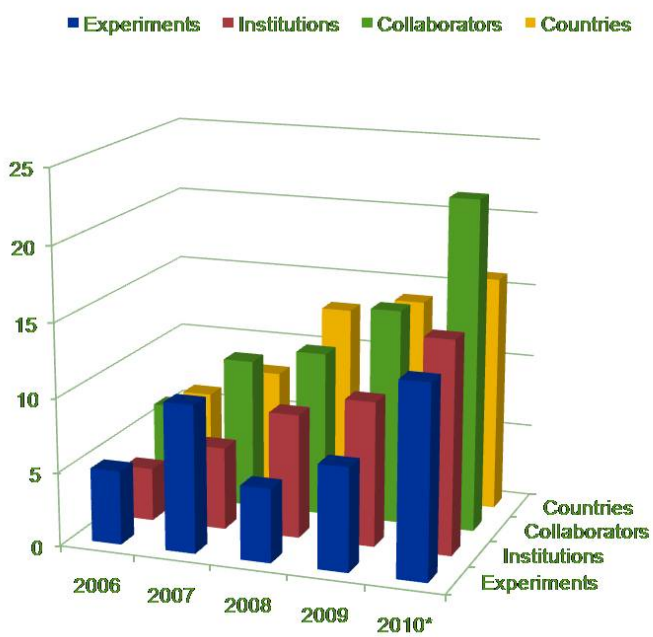
Gas delivery to 6 locations

4 station MWPC spectrometer



Two motion tables

The Test Beam Facility is a notable example of HEP community support by Fermilab:

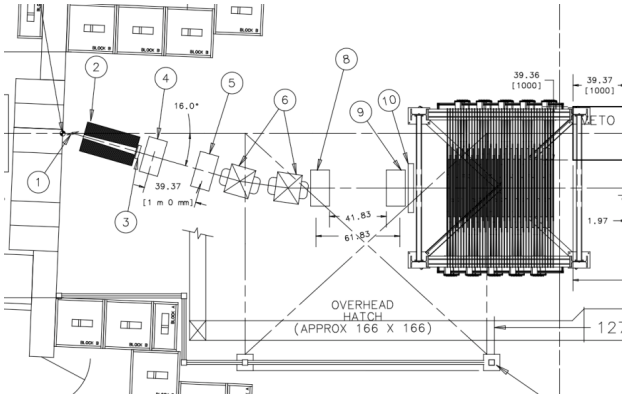


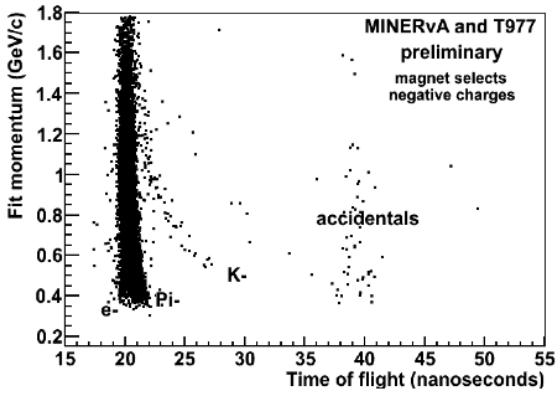
TBF Performance

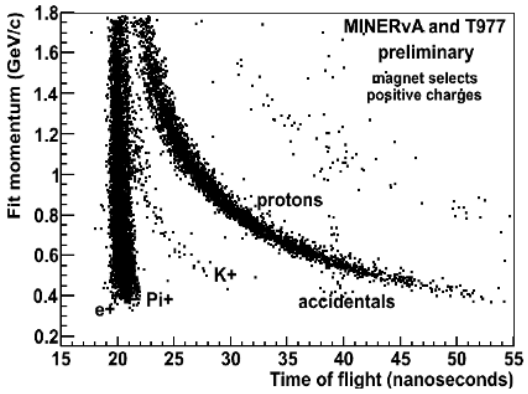
Year	Expts.	Inst.	Collab.	Countries
2006	5	18	65	6
2007	10	28	102	8
2008	5	42	112	13
2009	7	49	146	14
2010	13	72	224	16

New Tertiary 400 MeV/c Beamline

- The MINERVA experiment requested that we create a new tertiary beamline that could deliver particles down to 400 MeV/c momentum.
- The Particle Physics Division and Accelerator Division cooperated on delivering this beamline.
- Full tracking and TOF allows for momentum measurement and particle i.d.
- This new facility is now open for users.







A View to the Future

- **In the Energy frontier:**
  - Advance silicon devices into a new 3D realm, using this technology for a diverse set of problems.
  - Continue work on understanding how to build a dual readout calorimeter
  - Establish a comprehensive center for mass SiPM characterization
  - Investigate optical data transmission for vertex detectors

- **In the Intensity frontier:**
  - Begin testing of a 20 ton Liquid Argon prototype detector
  - Develop in liquid Argon electronics
  - Develop ASIC readout for SiPM's in a time-of-flight system

Fermilab will continue its focused program on detector R&D, emphasizing partnerships. It is backed up by a stronger management structure and increased involvement in national level planning.

- **In the Cosmic frontier:**
  - Calibrate acoustic response to backgrounds in a bubble chamber, for dark matter detection
  - Look for scintillation and ionization signals in solid Xenon crystals for axion and rare neutrino interactions.
  - Probe Planck scale physics in a high finesse, high power holographic interferometer
  - Operate new distillation apparatus to create radiopure liquid Argon for dark matter detectors

- **Improve our facilities:**
  - New MCenter test beam facility
  - Enhance silicon sensor and ASIC testing capabilities