Repurposing MINOS Scintillator Modules for the Short-Baseline Neutrino Program Far Detector (ICARUS) Cosmic Ray Tagger

Chris Hilgenberg*, Tyler Boone*, Simone Marcocci†, Anne Schukraft†, David Warner*, Robert Wilson*

New Perspectives 2018

June 19, 2018
Fermilab

* Colorado State University

† Fermilab

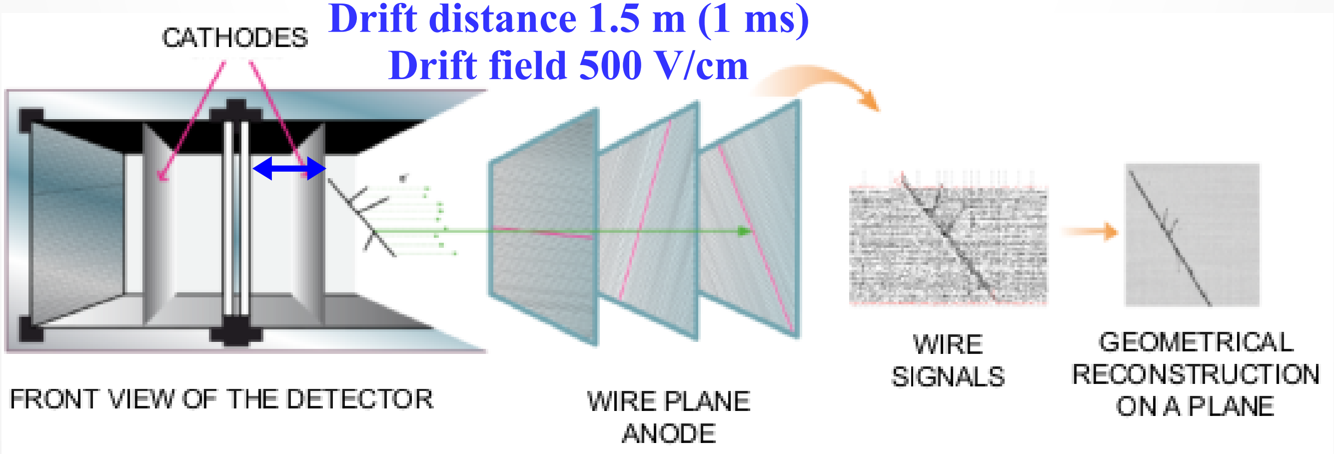
Imaging Cosmic And Rare Underground Signals

U.S. Department of Energy

SBN Program

Sterile ν Search with ICARUS

- Science goals
  - ν_μ disappearance
  - ν_e appearance
  - Address low-E excess anomaly
  - Sterile ν('s) with $\Delta m^2 \sim 1 eV^2$
- Largest liquid argon time projection chambers (LAr TPCs) ever realized w/476t active LAr
- Far detector in Short-Baseline Neutrino Program (SBN), first data expected early 2019



ν's in a LArTPC

- μ's relatively easily to reconstruct
- γ's and e's look similar
  - x2 difference in dE/dx
  - Large fraction of γ's have visible conversion gap

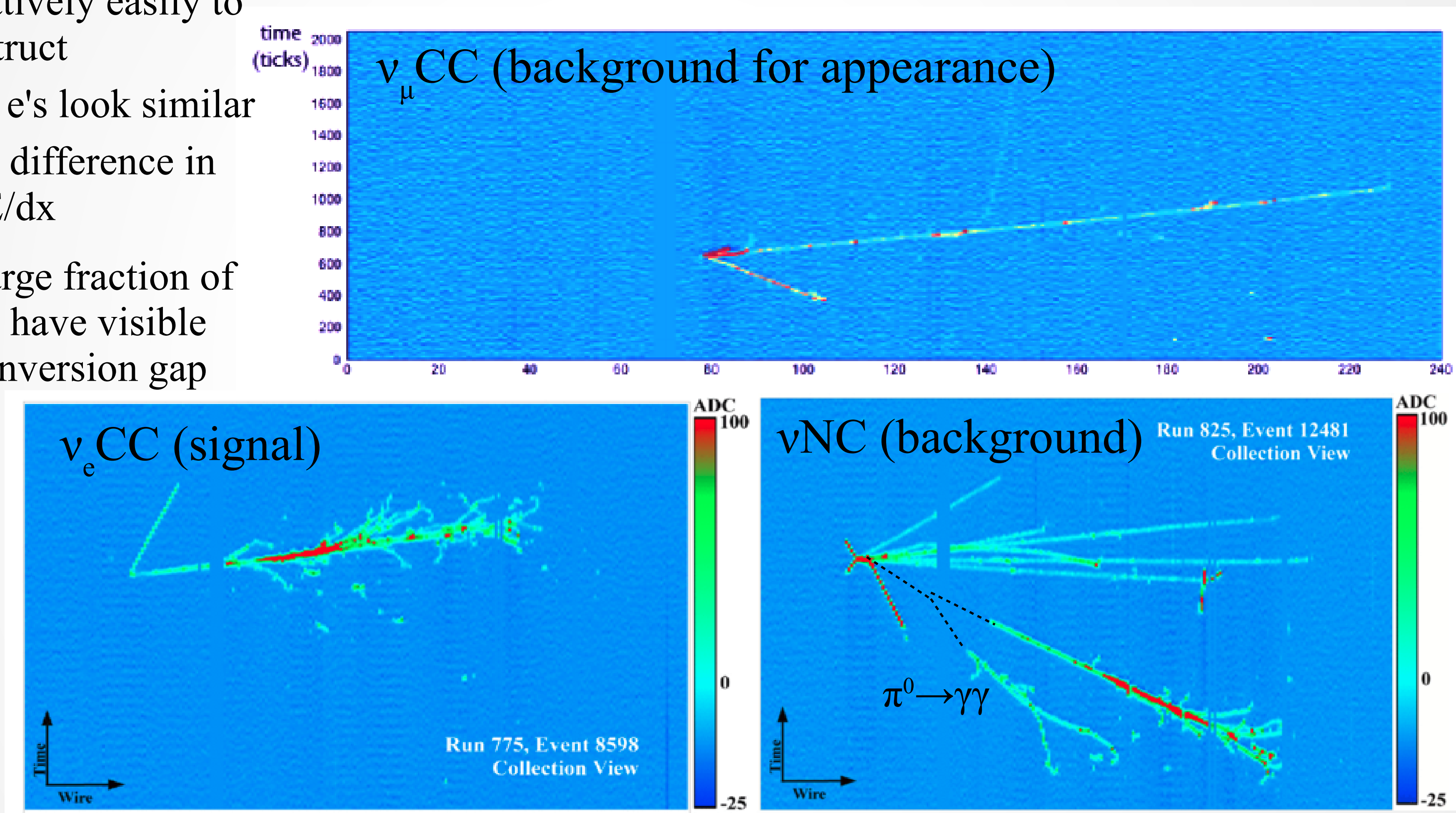
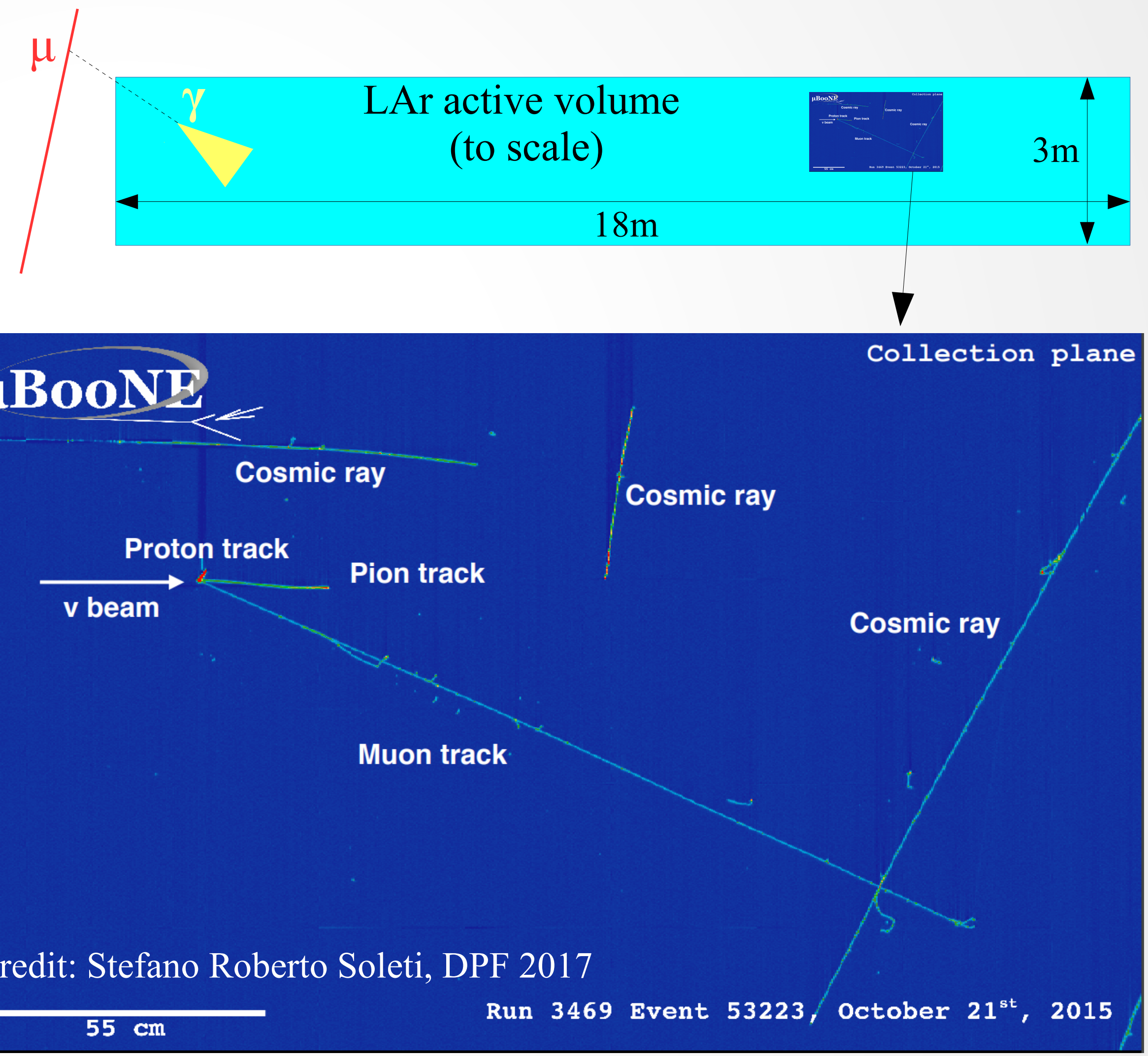


Image credit: Argoneut (2017) Phys. Rev. D 95, 072005

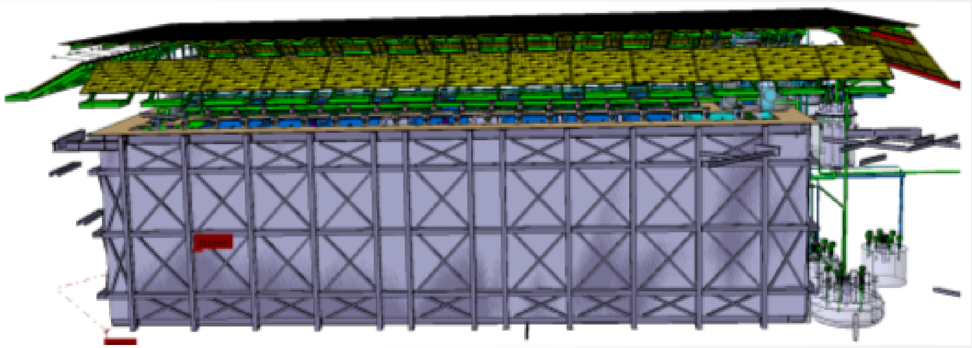
Operating a LAr TPC on the Surface

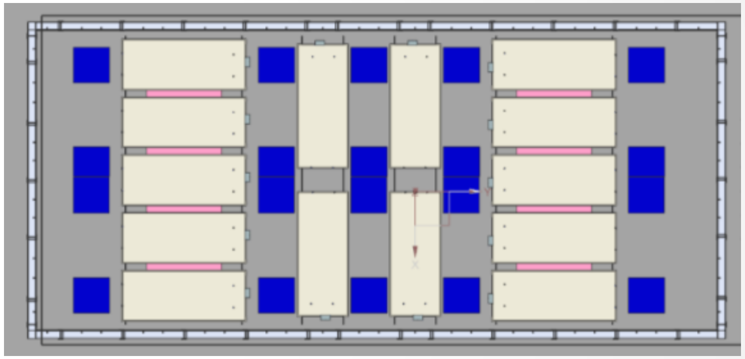
- MC predicts ~12 cosmic μ's pass through LAr per TPC readout (1ms)
- μ's passing through/near LAr produce γ's that mimic ν_e CCQE topology
- 99% background rejection possible w/TPC alone ...but not enough!
- Tracker external to TPC volume
  - Tags μ's not seen by TPC
  - Provide point and time of entry
  - Enhance background rejection by ~95% to reach 5σ significance in sterile ν search

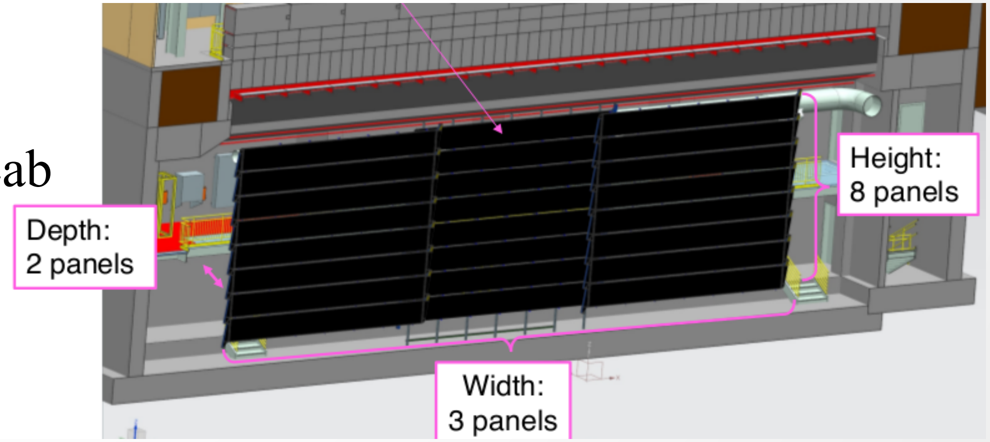


ICARUS Cosmic Ray Tagger

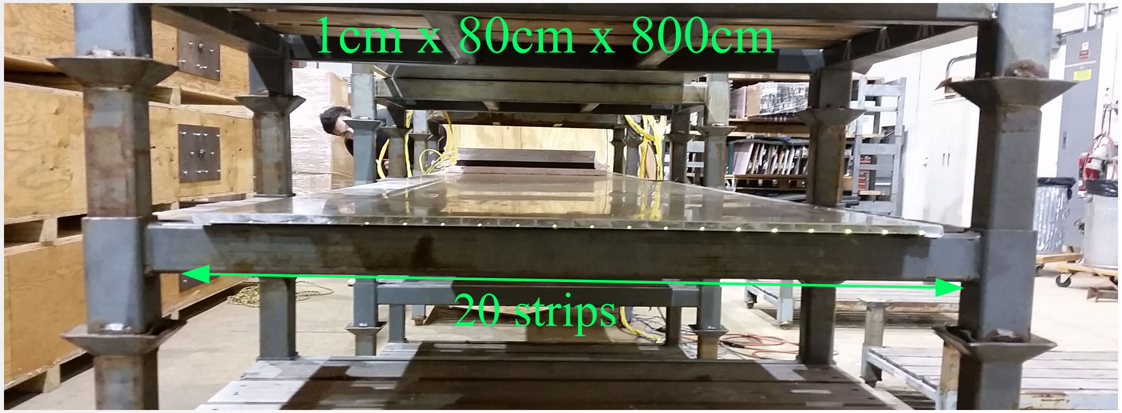
- Three subsystems based on two layers of plastic scintillator
- Cost saving solution for ICARUS' large surface area (~1000 m²)
- Collaborative effort between Europe and US
  - Top: new construction (CERN)
  - Bottom: Double Chooz veto modules (FNAL, UChicago and VT)
  - Sides: MINOS scintillator modules retrieved from Sudan Underground Lab (CSU, FNAL)



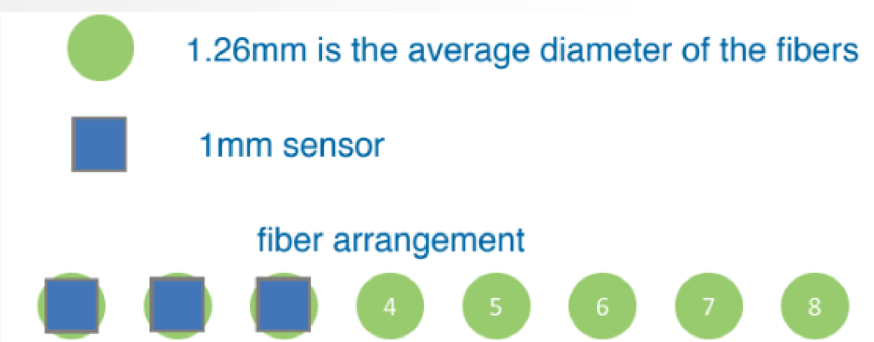


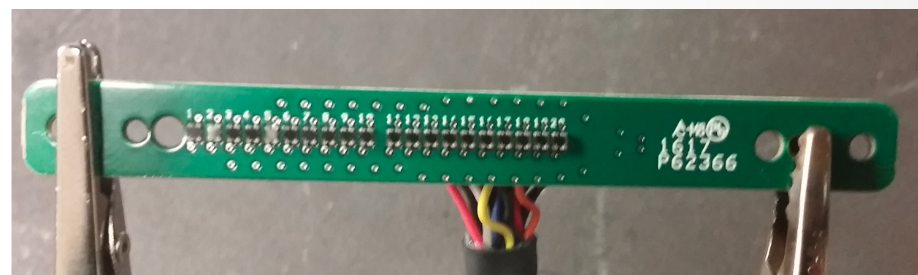


Readout Development



- SiPMs offer > 3x photon detection efficiency w.r.t. PMTs used in MINOS
- 2mm fiber spacing not ideal for existing SiPMs
- $1mm^2$ active area SiPMs allow single fiber readout

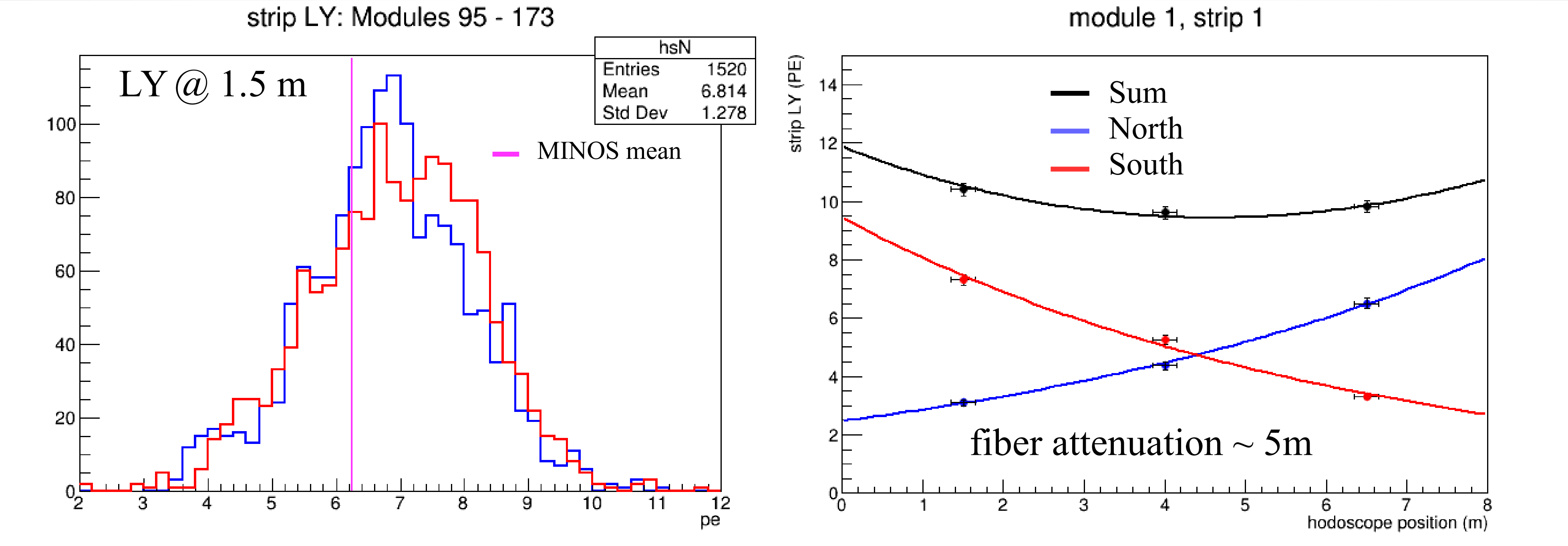




Design and fabrication performed at CSU

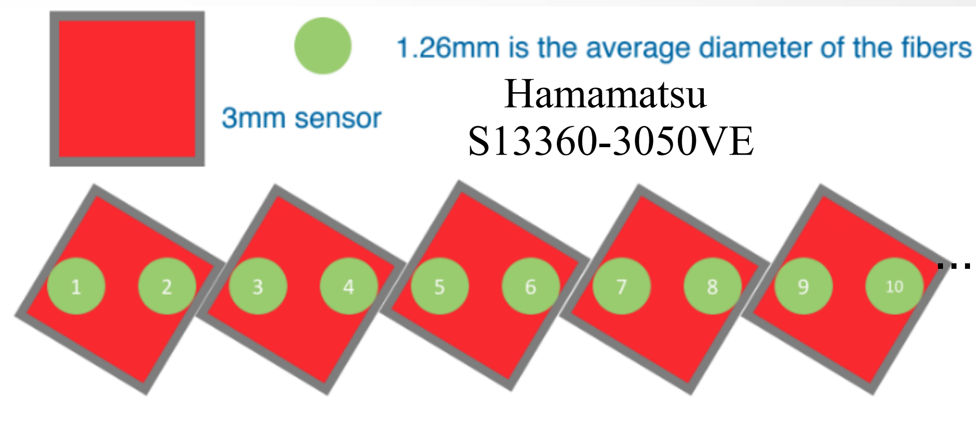
Module Characterization

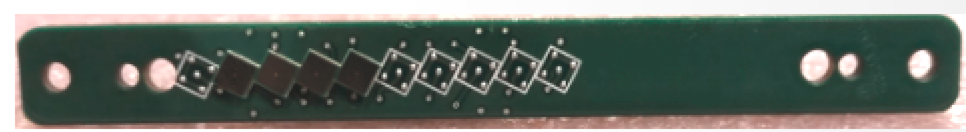
- We tested and characterized 173 modules
- We identified enough good modules for the CRT!
- We observed similar light yield (LY) as MINOS
- Reproduced MINOS attenuation curves

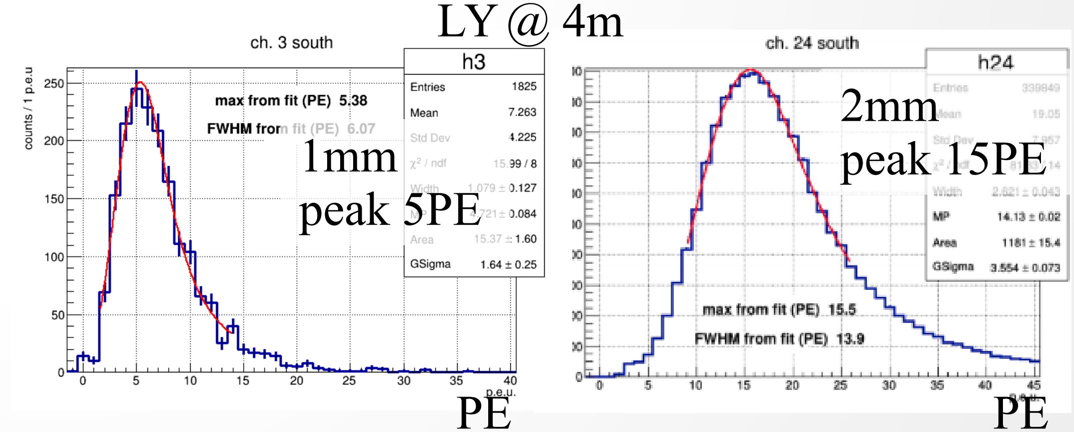


Improving the Readout

- 1mm SiPMs insufficient to meet tagging efficiency requirement (>98% / module)
  - Light loss from incomplete fiber coverage
  - Dark rate too high
- Geometry compatible w/2 fibers on 3x3mm^2 SiPM
  - Reduces channel count by 50%
  - Increases granularity from 4cm → 8cm
  - 3x LY (compared to MINOS) more than compensates for higher dark rate
  - Surpasses efficiency requirement

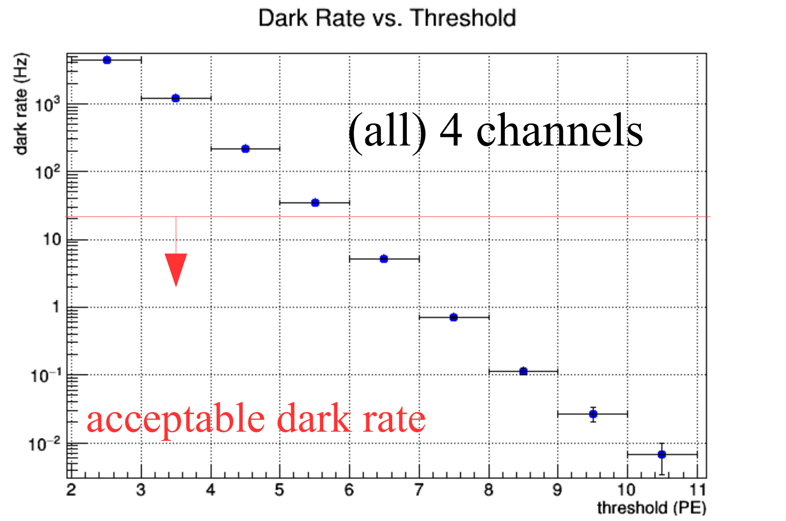


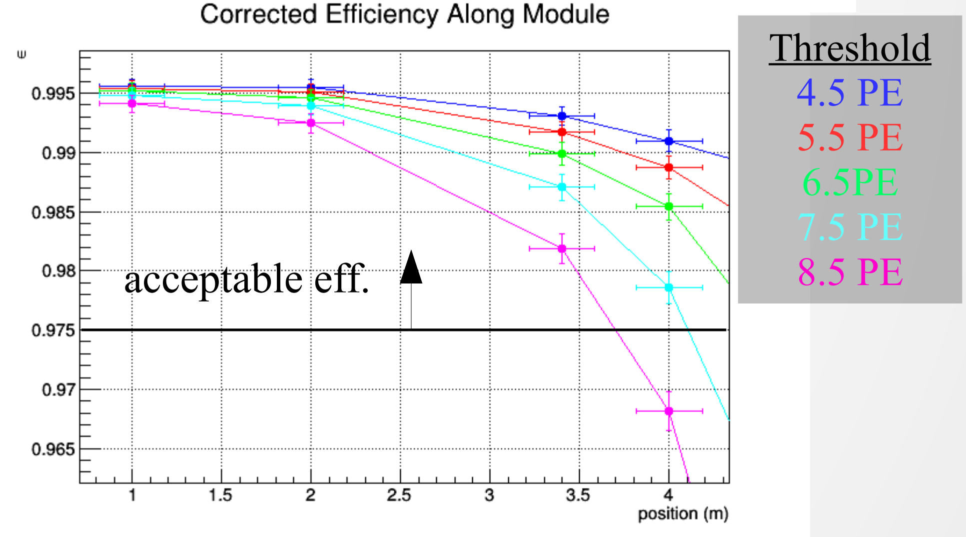


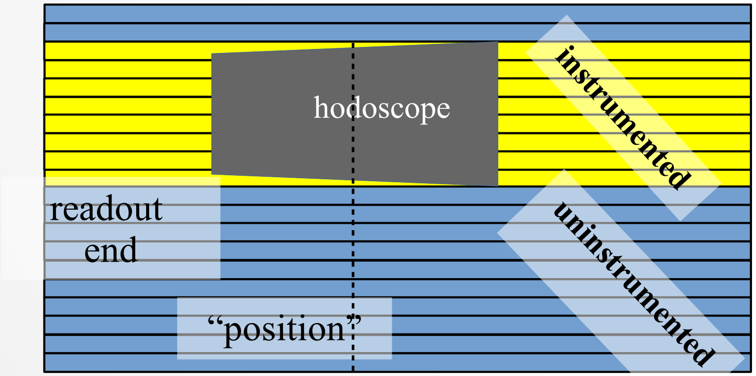


Efficiency Measurement

- Use hodoscope to provide external trigger at several positions along module
- Module instrumented at both ends
  → worst position @ 4m
- With 6.5PE threshold
  - Dark rate: 1Hz/channel
  - Efficiency @ 4m: 98.5%
  - Integrated efficiency over 4m: 99.3%





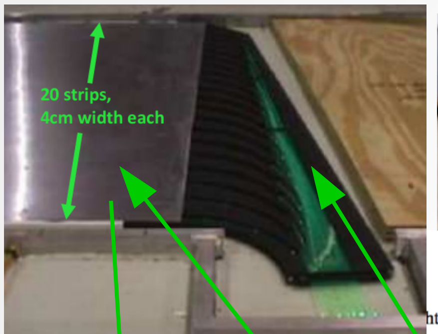


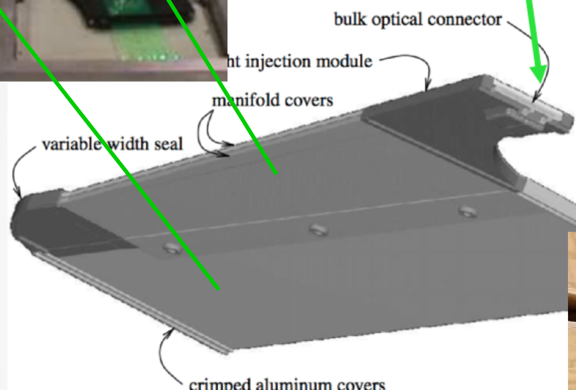
Summary

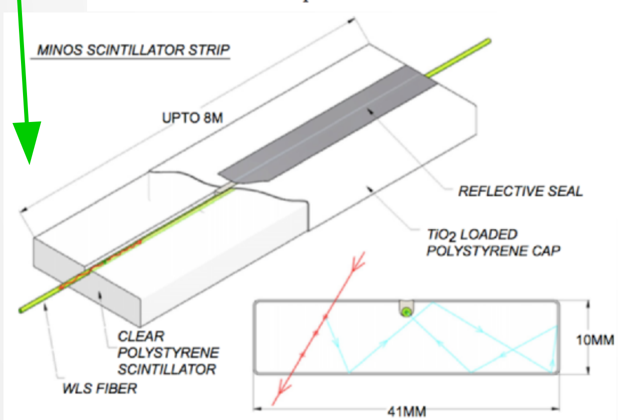
- We are repurposing MINOS scintillator modules for the ICARUS cosmic ray tagging system
- We tested 173 modules in one summer and identified enough with sufficient performance for our needs
- We have proposed a readout scheme for production based on 3mm Hamamatsu SiPMs
- Our solution yields > 3x the light yield measured in MINOS
- We have achieved >98.5% muon tagging efficiency per layer (target was 97.5%)

BEGIN BACKUP SLIDES

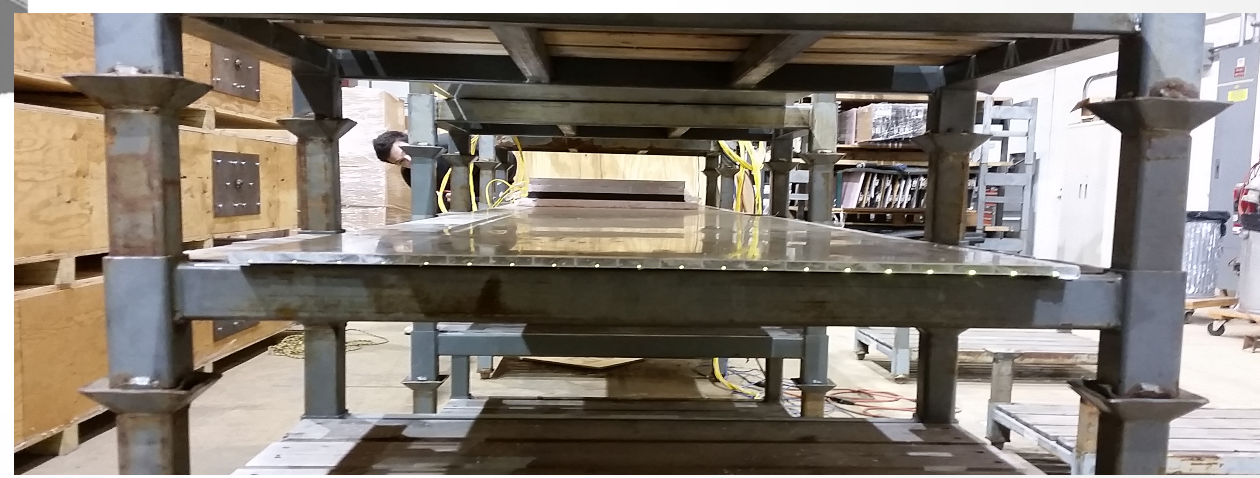
Sides: MINOS Modules







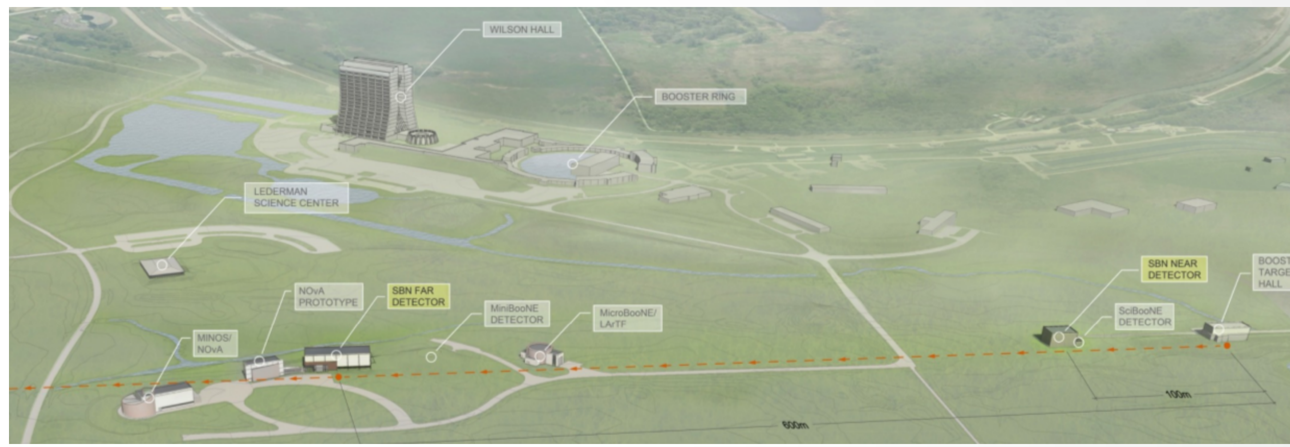
- 1cm x (20 x 4cm) x 800cm
- Fibers read out at both ends
- Clear fiber cable → PMTs
- Front-end electronics throughput ~1 Hz
- Age ~ 15 yr
- Aging induced efficiency loss ~ 2% / 15 yr



See Nuclear Instruments and Methods in Physics Research A 596 (2008) 190-228

Short-Baseline Neutrino Program

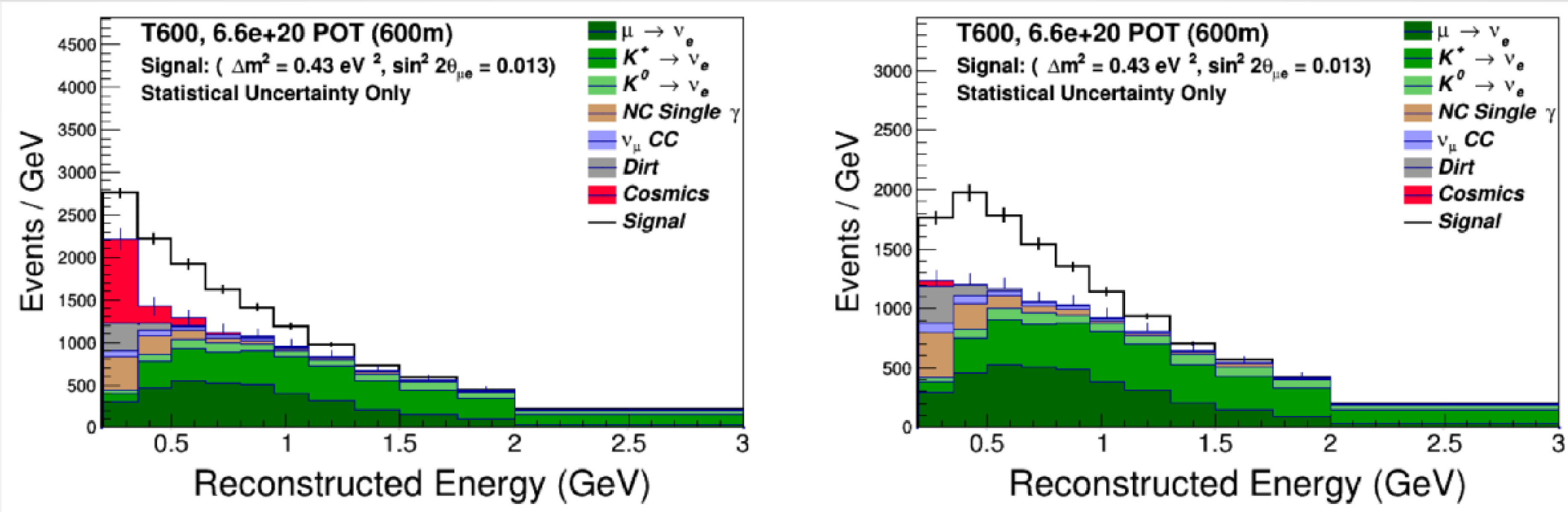
- 3 liquid argon time projection chambers (LAr TPCs) at FNAL
  - SBND (110m)
  - μBooNE (470m)
  - ICARUS (600m)

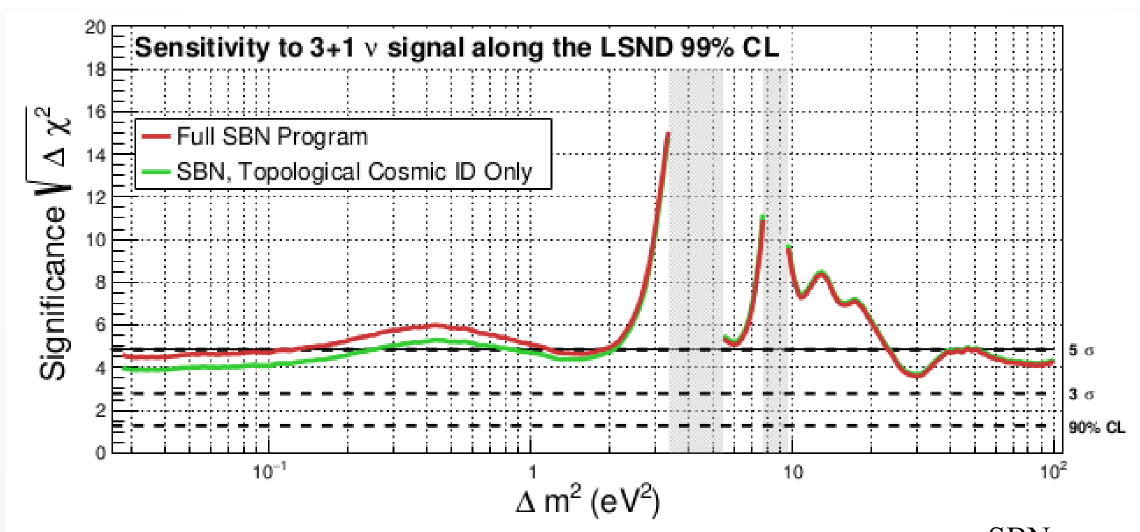


- Primary goals
  - Oscillation search:
    - $\nu_\mu \rightarrow \nu_e$ appearance
    - $\nu_\mu \rightarrow \nu_x$ disappearance
    - Sensitive to oscillations w/$\Delta m^2 \sim 1 eV^2$
  - R&D for next generation LAr TPCs, DUNE

SBN Program

ICARUS ν_e Appearance Sensitivity

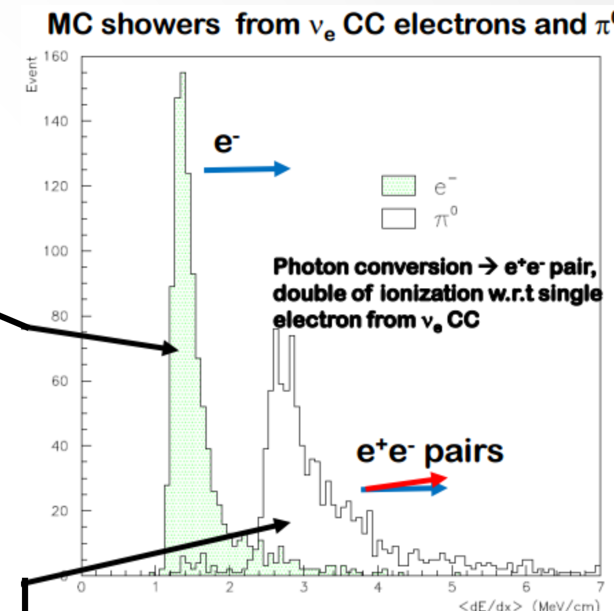


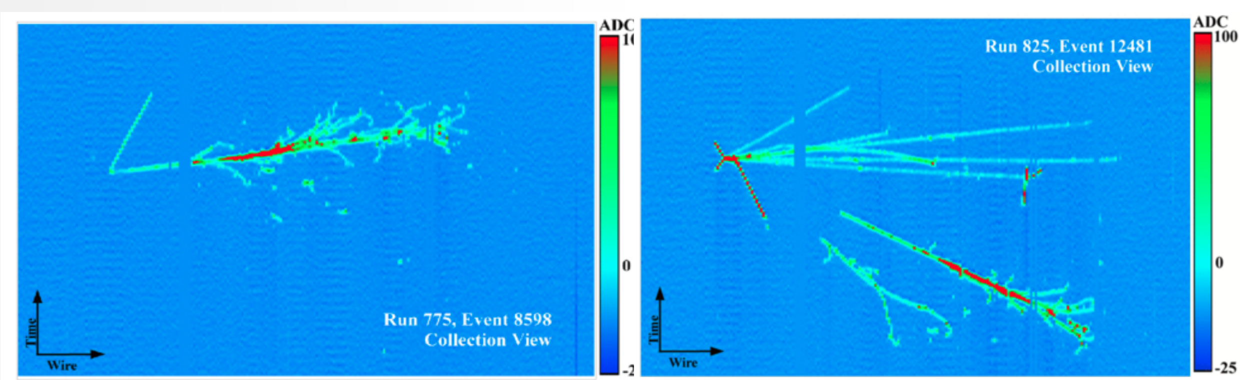


SBN proposal arXiv:1503.01520

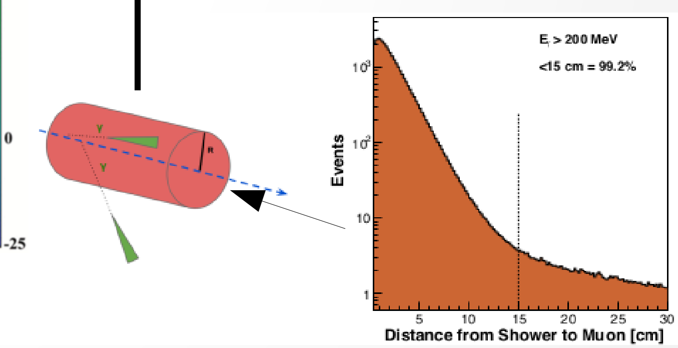
Cosmogenic Background Mitigation

- Several methods to remove background w/TPC
  - dE/dx in initial part of shower (94% rej.)
  - Distance of vertex from μ track
  - Use time structure of BNB



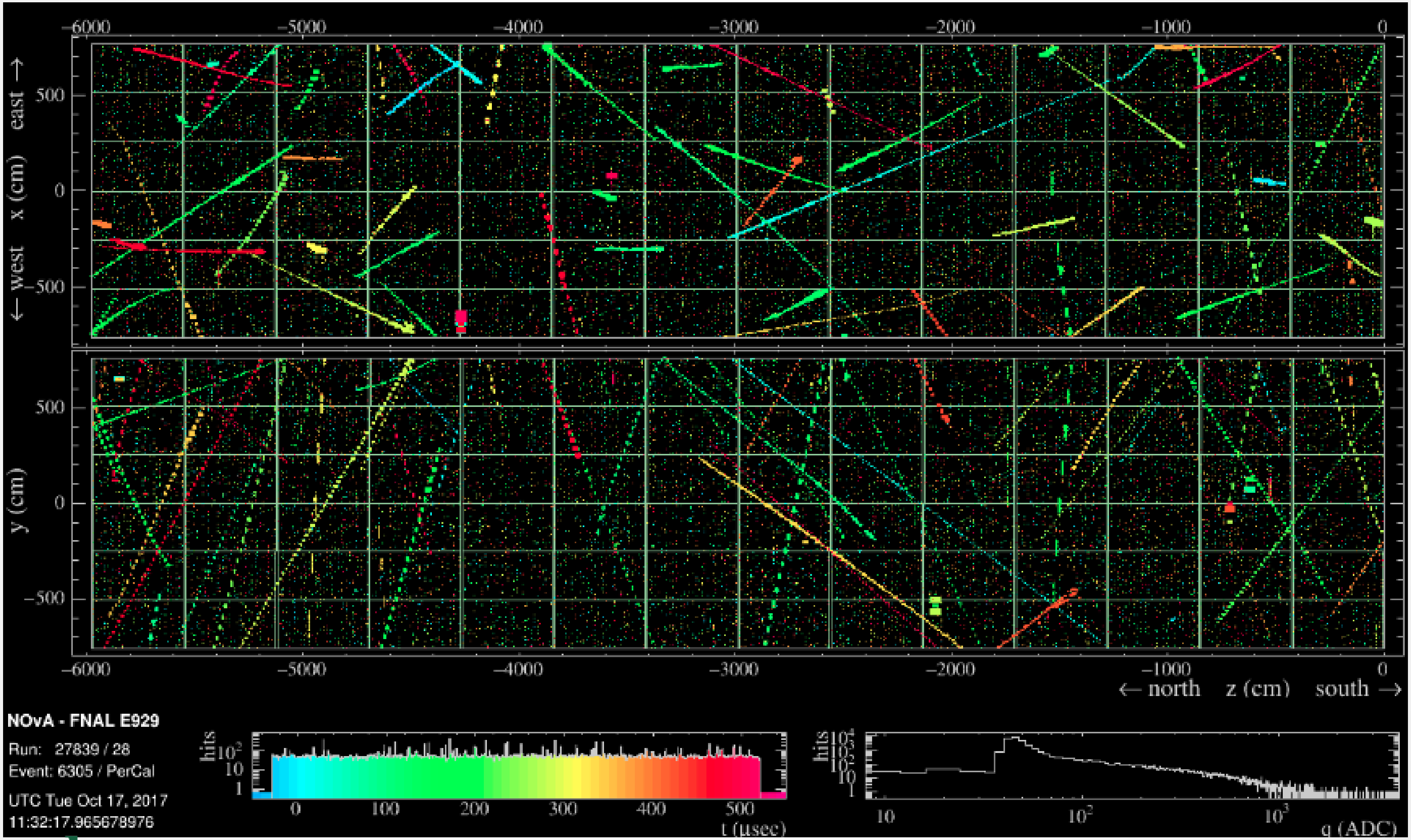


Argoneut (2017)
Phys. Rev. D 95, 072005

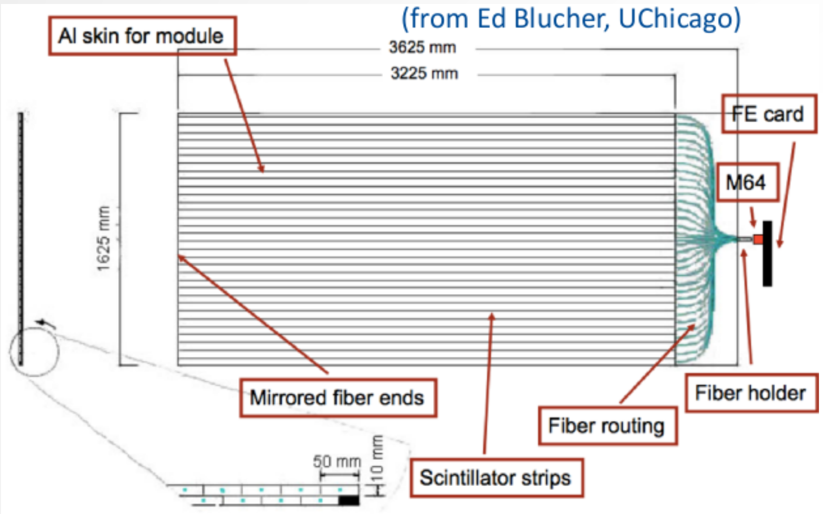


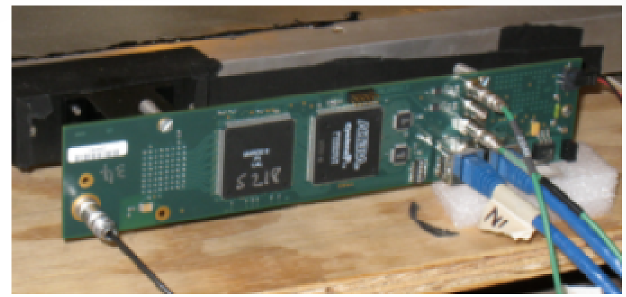
*Credit (top): indico.in2p3.fr/event/11794/contributions/6953/attachments/5681/7083/JRJC_03_dcaiulo.pdf
*Credit (bot): SBN proposal arXiv:1503.01520

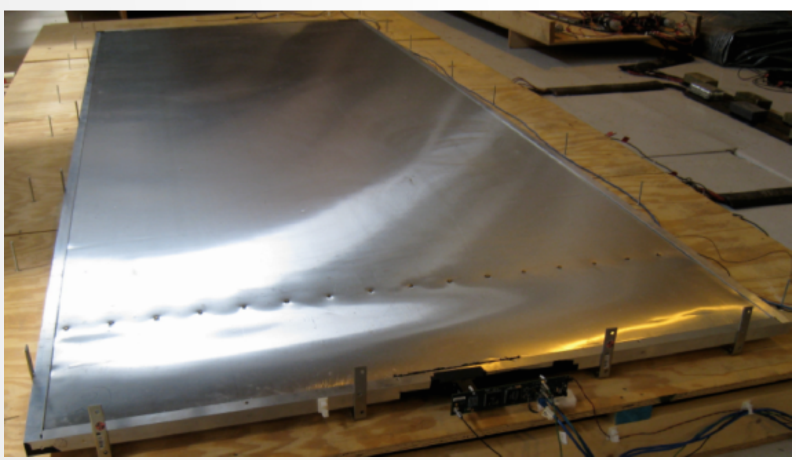
NOvA Event Display



Bottom: Double Chooz Modules





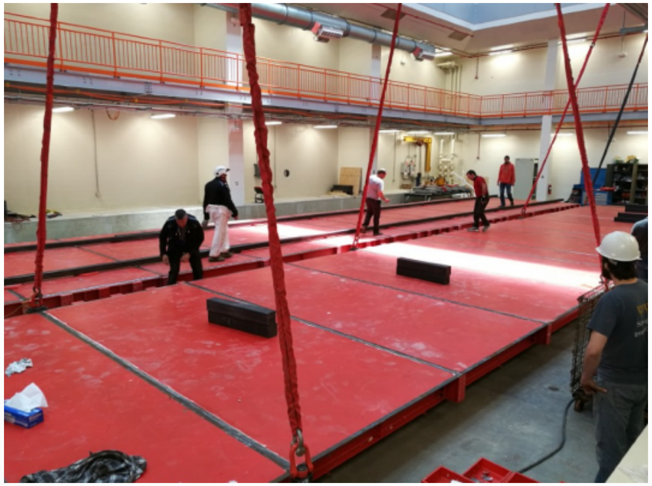


- 2cm x 1.7 m x 4m
- Single strips read out by multi-anode PMT
- Scintillator modules designed and constructed by University of Chicago
- In collaboration with Virginia Tech
- All readout electronics custom design by NEVIS/Columbia

Bottom: Installation

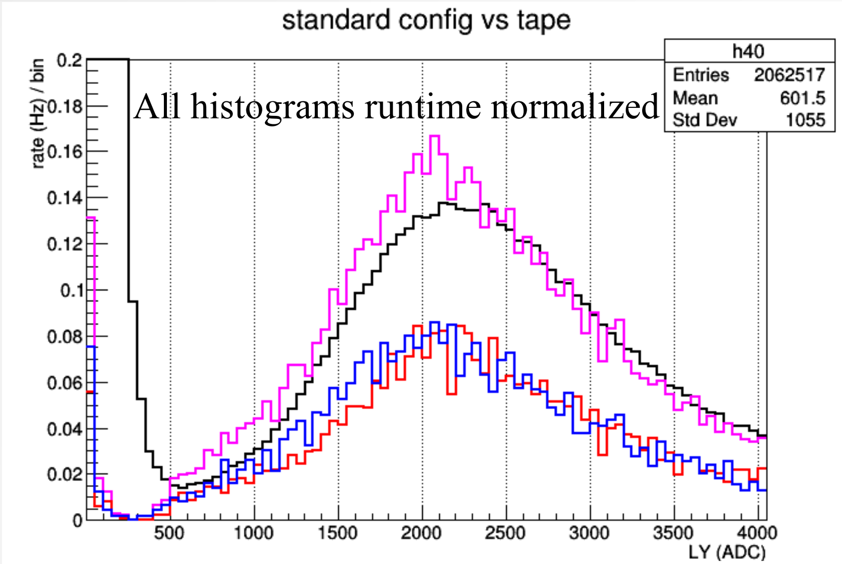
*Photo credit: Simone Marcocci

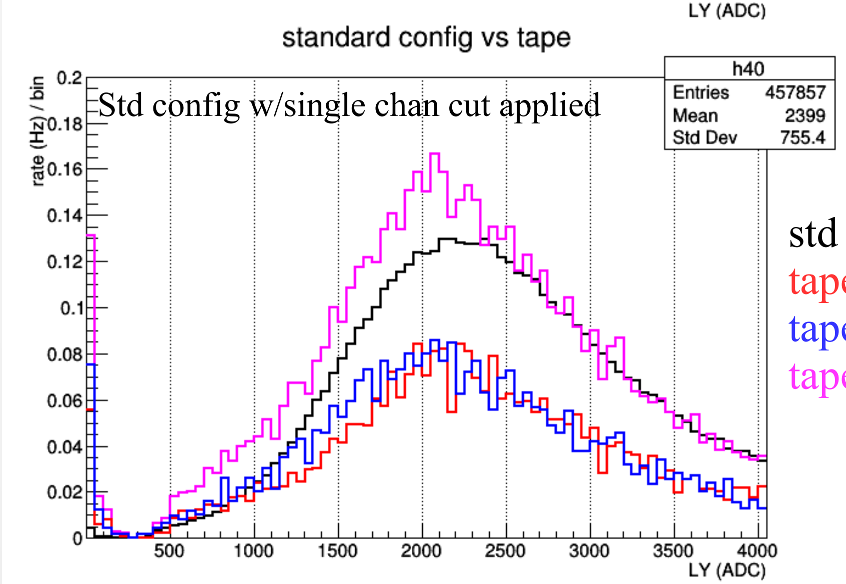


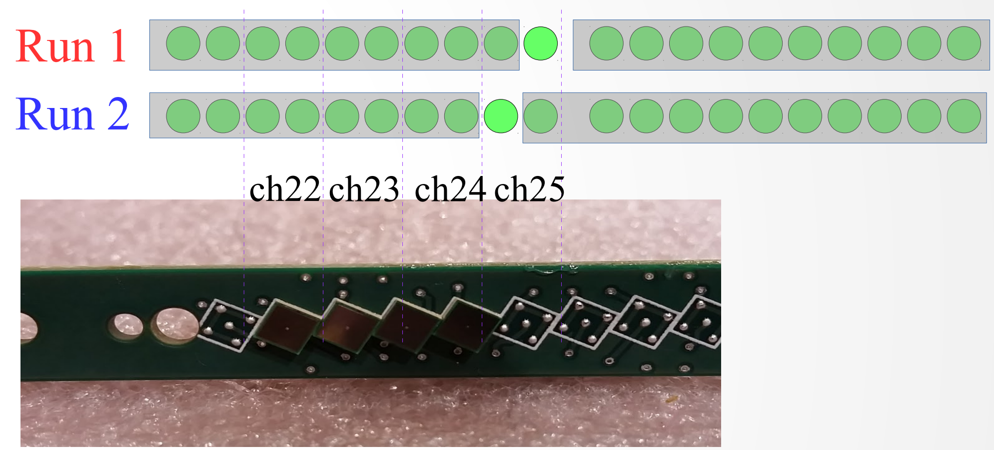
- 4 spare modules from Uchicago
  - Much help from V. Pandey (VT)
  - tested for light leaks
  - source tested for broken fibers
- Installation went smoothly ahead of schedule on 8 May

Optical X-Talk?: Single Fiber LY





Block light from all but one fiber w/black electrical tape



std config w/4 chan trig
tape run 1
tape run 2
tape runs sum

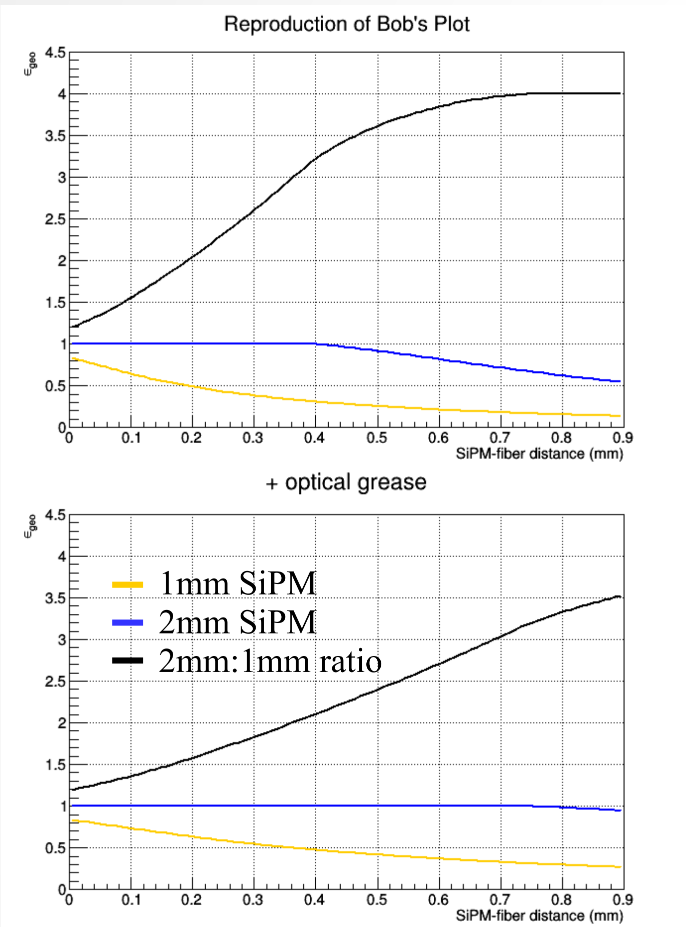
For single fiber mode relative to standard config, we observe

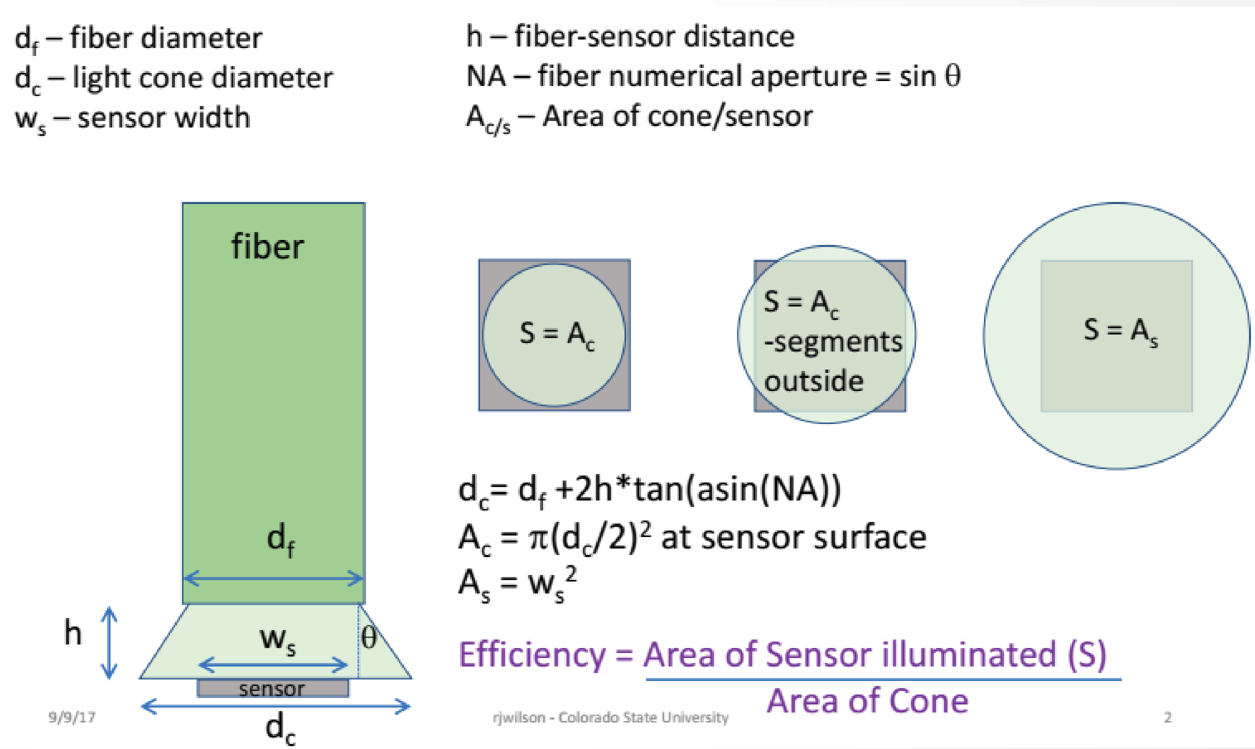
1. small excess below std. config. peak
2. peak position ~1PE lower

Could this hint at small optical X-talk effect?

Fiber-SiPM Distance Impact

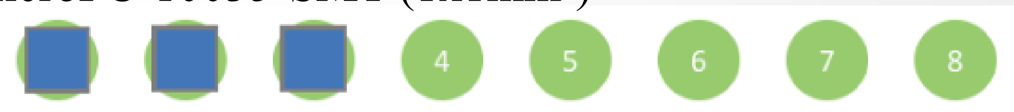
*n for silicone optical coupling compound ~1.5 → exit angle is ~38% smaller





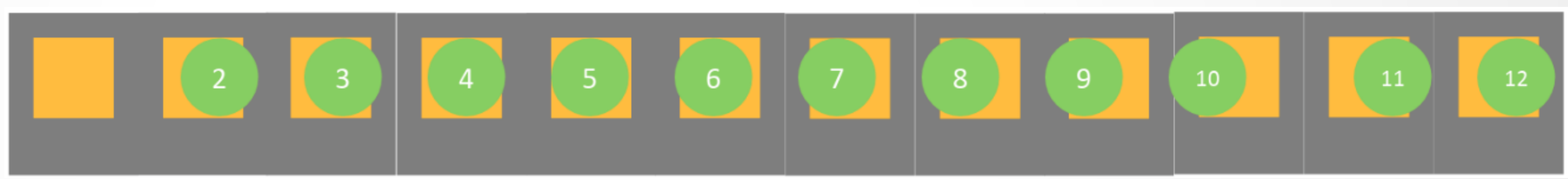
MINOS Module Snout Geometry

SensL MicroFC-10035-SMT (1x1mm^2)

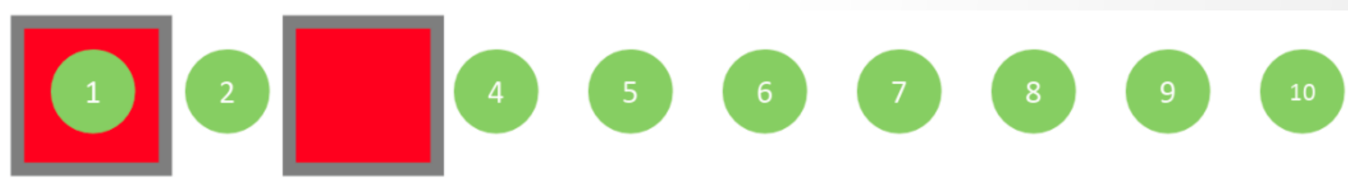


Fiber hole diameter 1.26mm

Hamamatsu S13360-1350PE (1.3x1.3mm^2)



Hamamatsu S13360-2050VE (2x2mm^2)

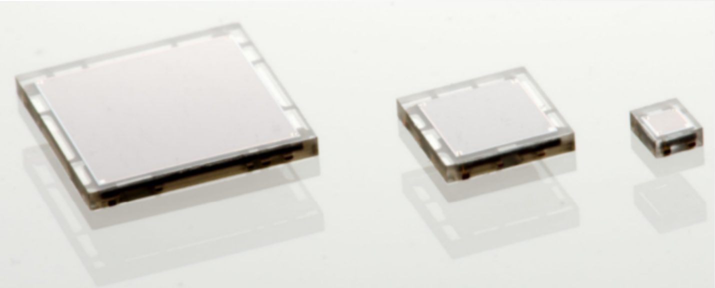


Optimal (existing) SiPM geometry enabling single fiber (scintillator strip) readout is 1x1mm^2

More on Hamamatsu SiPMs and candidates for production in Simone's talk

SensL C-Series

- Lots of experience with these at CSU
  - 6x6mm^2 used for prototype photon detectors for DUNE
  - 3x3mm^2 used in R&D for proposed all new ICARUS CRT (pre-MINOS availability)
- During start of development for MINOS readout, Hamamatsu didn't produce 1x1mm^2 SiPMs needed for single fiber readout so we decided on the SensL 1mm w/35μm pitch



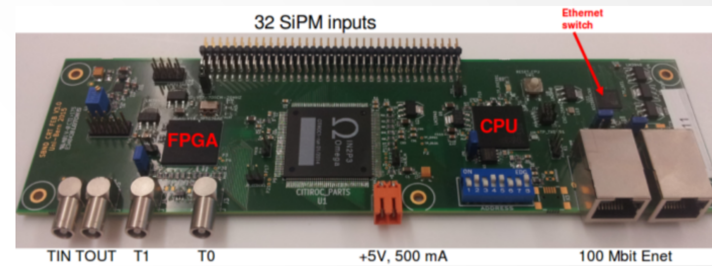
Specs from Data Sheet for 1x1mm^2 w/35μm Pitch

Overvoltage (V)	Dark Rate (kHz)	Cross-talk (%)	Efficiency (%)	Gain (x10^6)
2.5	25	7	31	3

"nominal" configuration used for summer tests

Front-End Electronics

- Same Front-End Boards (FEBs) used for uBooNE and SBND Cosmic Ray Taggers (CRTs)
  - Design has been purchased by CAEN and will produce all FEBs for top and side CRT modules
  - Bern and CAEN FEBs are functionally identical
  - Early measurements used both FEBs, no difference in results observed
  - For summer testing and beyond, CAEN FEB used with “standard” firmware
- FEBs accommodate 32 SiPM channels, generate bias voltage, and perform analog signal readout/digitization
- Some of the functionality of the FEB can be modified with a firmware change – this is done for the top and will probably also be done for the sides
- Much assistance from Igor Kreslo in understanding how to best operate the FEBs

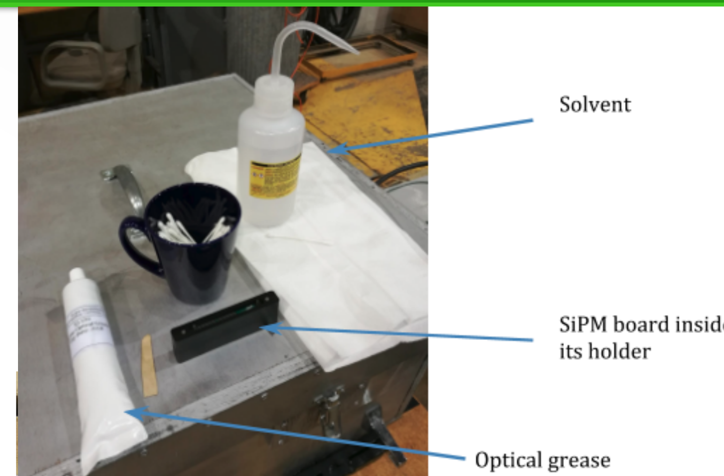


Test Stand at Wideband

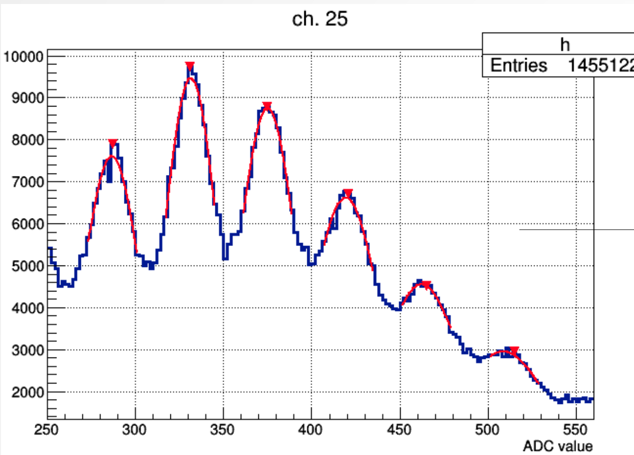
- 173 MINOS scintillator modules recovered from veto shield at far-detector, delivered to Wideband building (adjacent to Grid Computing Center)
- Test stand built (and reviewed/granted Operational Readiness Clearance) in preparation for testing all of the modules
- Capacity to read and control up to ~10 FEBs, generate external trigger from hodoscope (counters kindly provided by CDF)
- Two CAEN FEBs used for all testing, denoted by module readout end: North and South

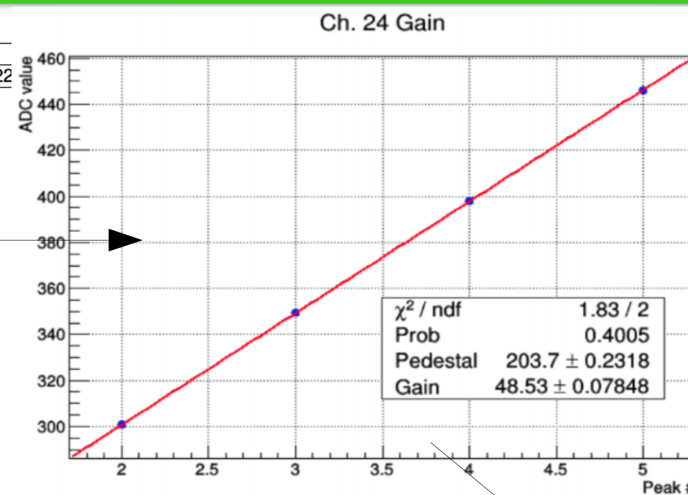
SiPM Mounting

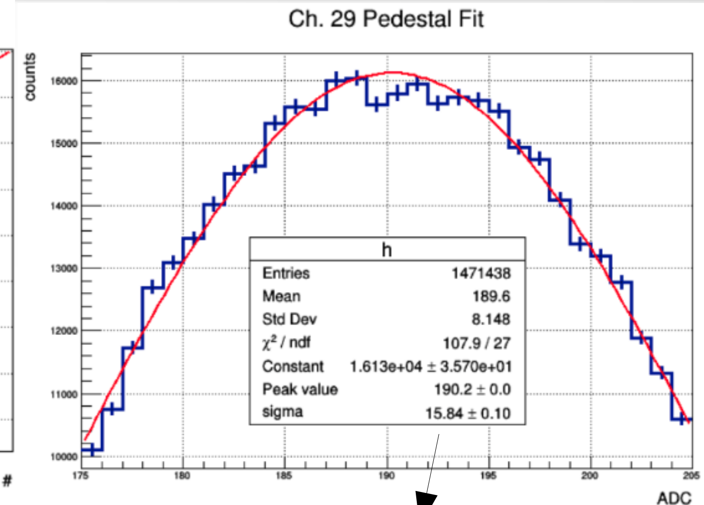
1) Clean module snouts (and SiPMs as needed) with ethyl alcohol and cotton swabs
2) Apply thin layer of optical grease
3) Alignment pins → holes
4) Secure box with tape (early on) or screws (later)
5) Secure cables with zip ties
6) Enclose in light tight bag with lots of black tape



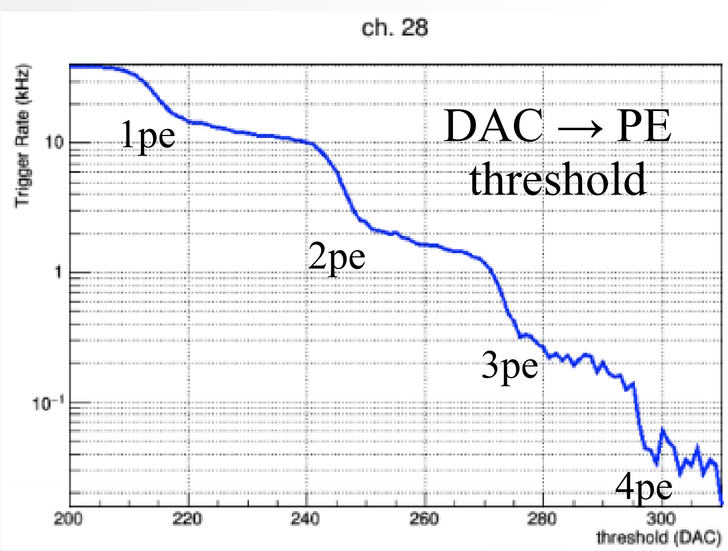
Calibration







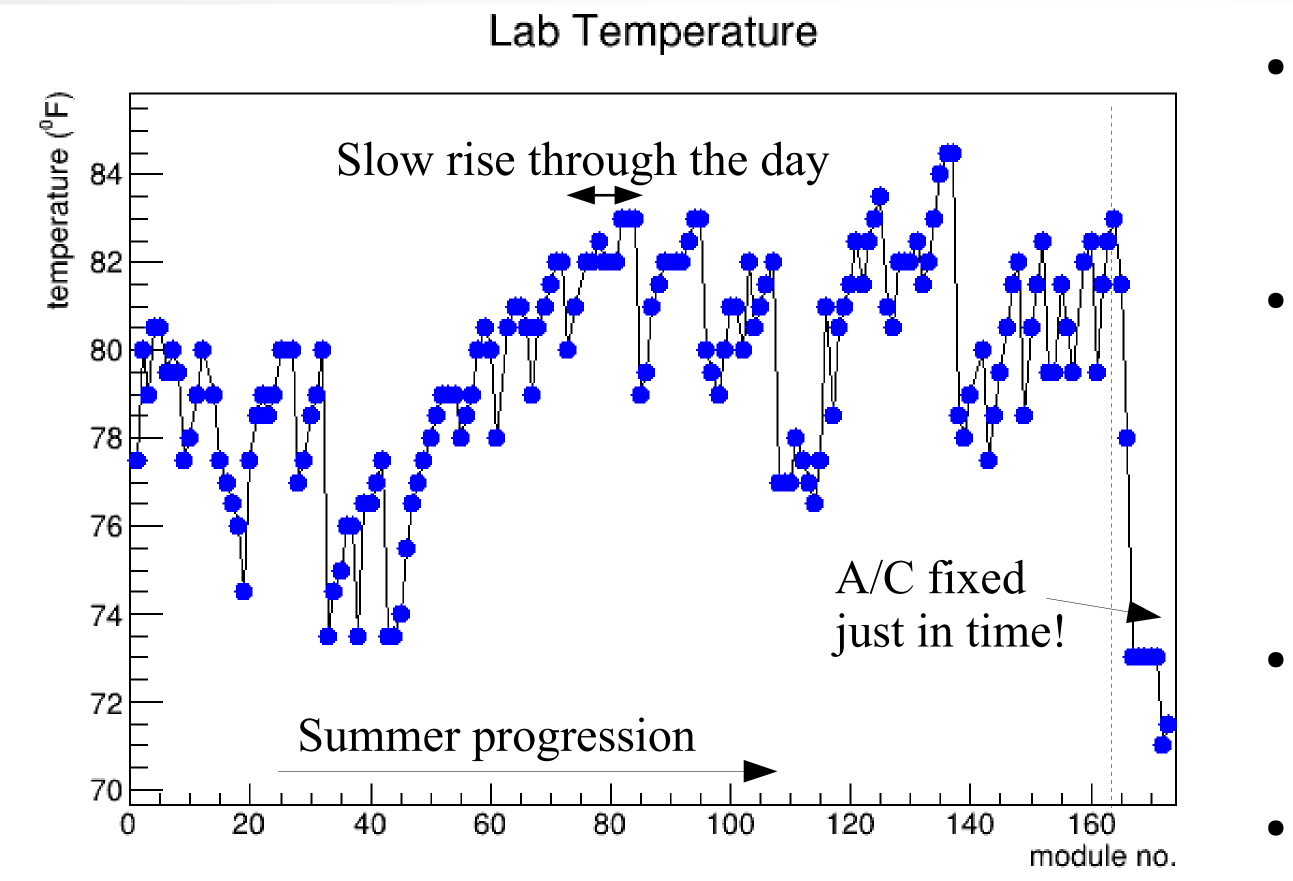
$$Amplitude(PE) = \frac{Amplitude(ADC) - Mean\,Pedestal(ADC)}{Gain(ADC/PE)}$$



- A low-level (~few PE) signal works best for calibration
- For each module, FEB, and channel, the spectra are calibrated from hodoscope data at 6.5m
- Analysis code developed to perform the pedestal and gain extraction automatically for each module's 40 channels
- Quality cuts attempt to ensure a good calibration, after several iterations, the gain and/or pedestal values are set to values obtained in most recent verified data

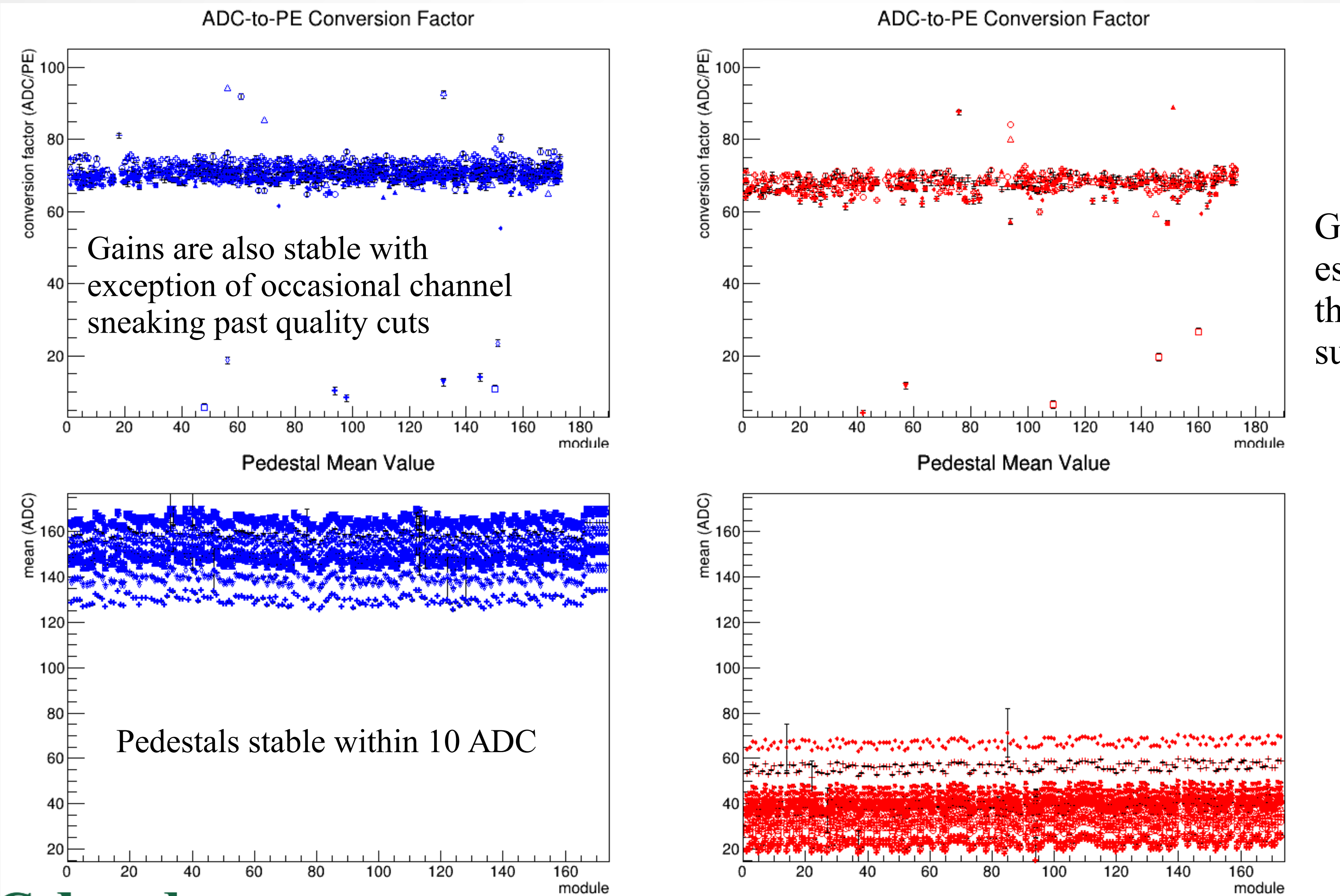
Colorado State University

Lab Temperature



- Gain and breakdown voltage are temperature dependent
- For these SensL SiPMs
  - gain varies as -0.8 %/^{0}C
  - breakdown voltage varies as 21.5 mV/^{0}C
- Typical daily variation < 2^{0}C
- Total range for testing 8^{0}C

Calibration Stability



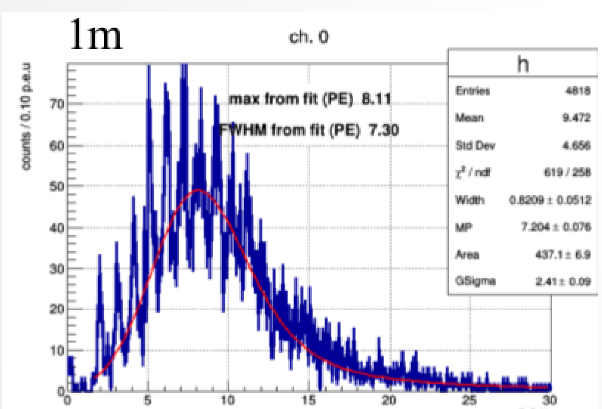
Gains are also stable with exception of occasional channel sneaking past quality cuts

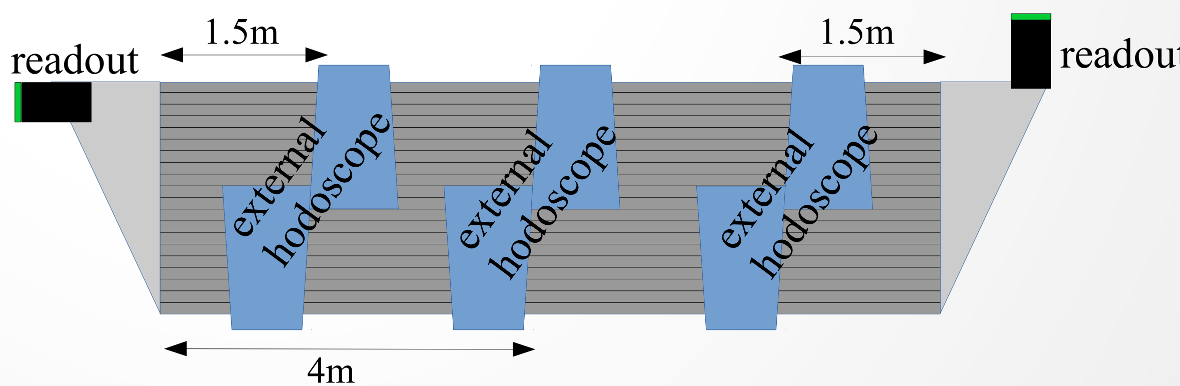
Pedestals stable within 10 ADC

Gain essentially flat through summer

Testing

- 173 modules tested
- Test rate of 5-7 / day
  - Light leaks patched
  - Individual strip response verified w/source
  - Cosmic muon light yield measured at 3 positions from both ends
- Fun fact: > 20,000 spectra were analyzed!

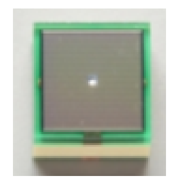


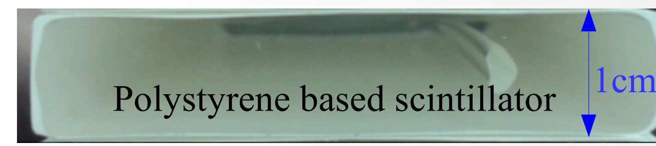


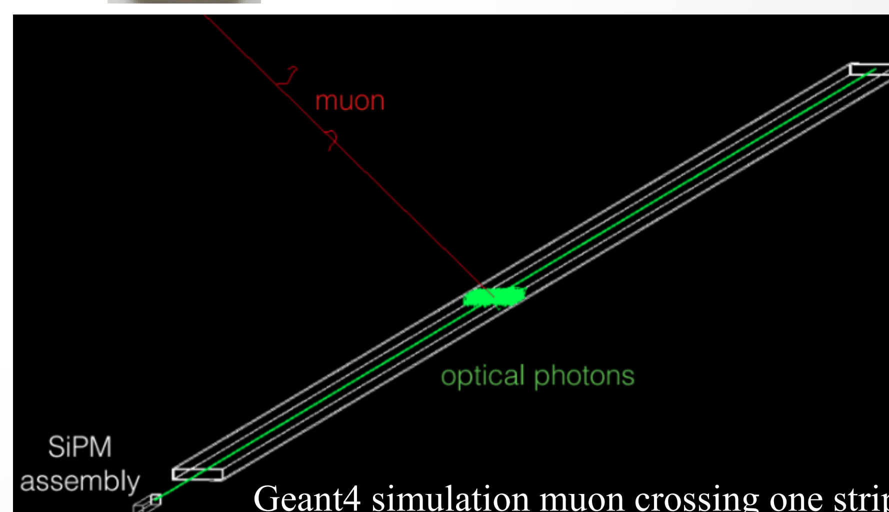
Cosmic Ray Tagger Conceptual Design

- Surround cryostat w/two layers of plastic scintillator strips
- Capture/guide light in each strip w/wavelength shifting (WLS) fiber
- Measure scintillation light intensity with photomultiplier tube or silicon photomultiplier (SiPM)
- Adjacent layer coincidence suppresses radiogenic background
- Hit matching CRT ↔ TPC

Hamamatsu SiPM



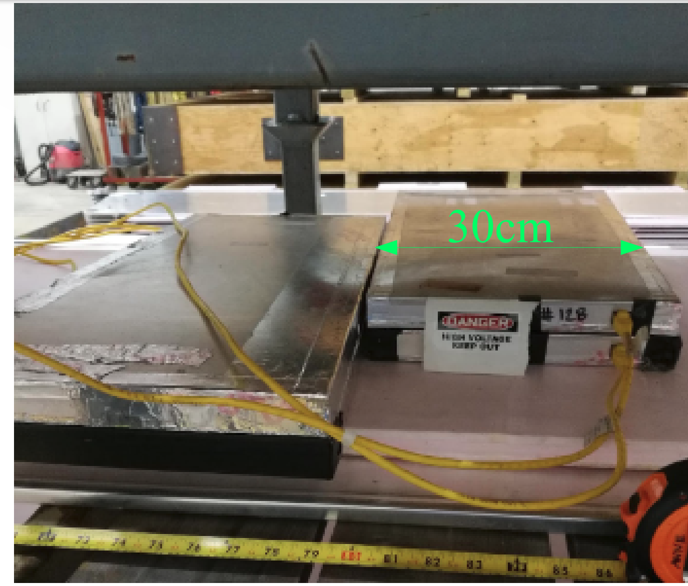


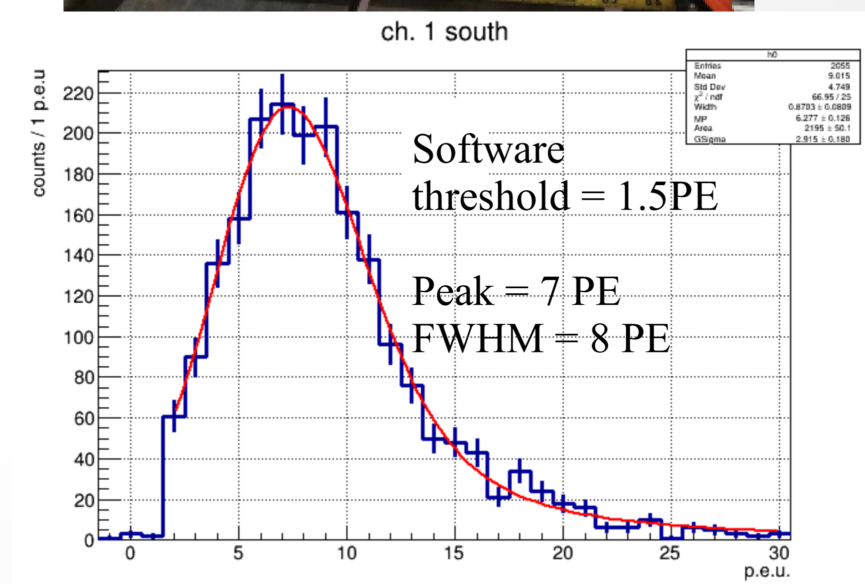


Geant4 simulation muon crossing one strip

Light Yield (LY) Measurement

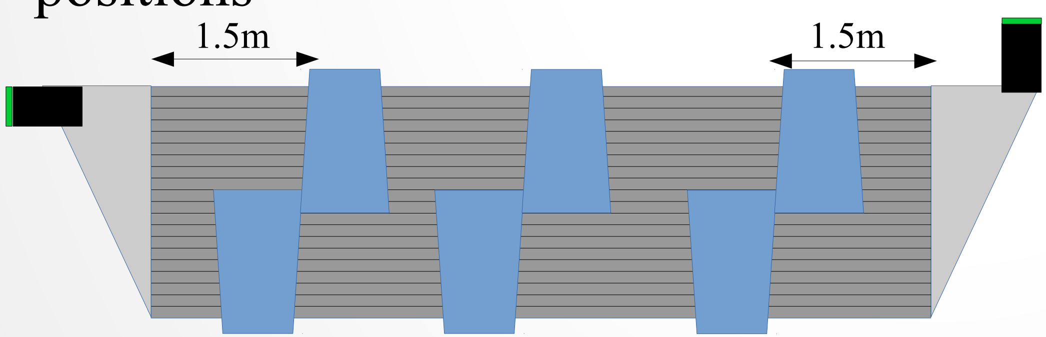
- Use 2 stacks of CDF counters with NIM logic to generate trigger from throughgoing muons (rate ~ 32Hz)
- FEB does not tell you which channel provided the trigger
  - Attempt to select events in software for each channel
  - Require only channel of interest is above given threshold, all others are below
- Fit resulting distribution with Gaussian * Landau and take fit peak (most probable response) as *LY* (which includes cross-talk and after-pulsing effects)
- This definition is good for calculating efficiency and comparing measurements with the same SiPM, bias voltage but care must be taken when comparing different devices, bias voltages
- The cross-talk and after-pulsing contribution can be estimated with dedicated dark and LED measurements (see Simone's talk)

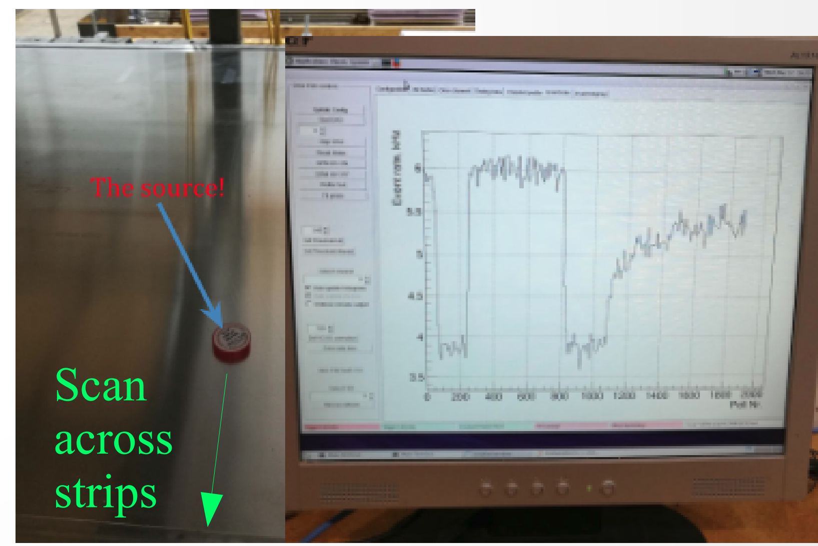




Procedure

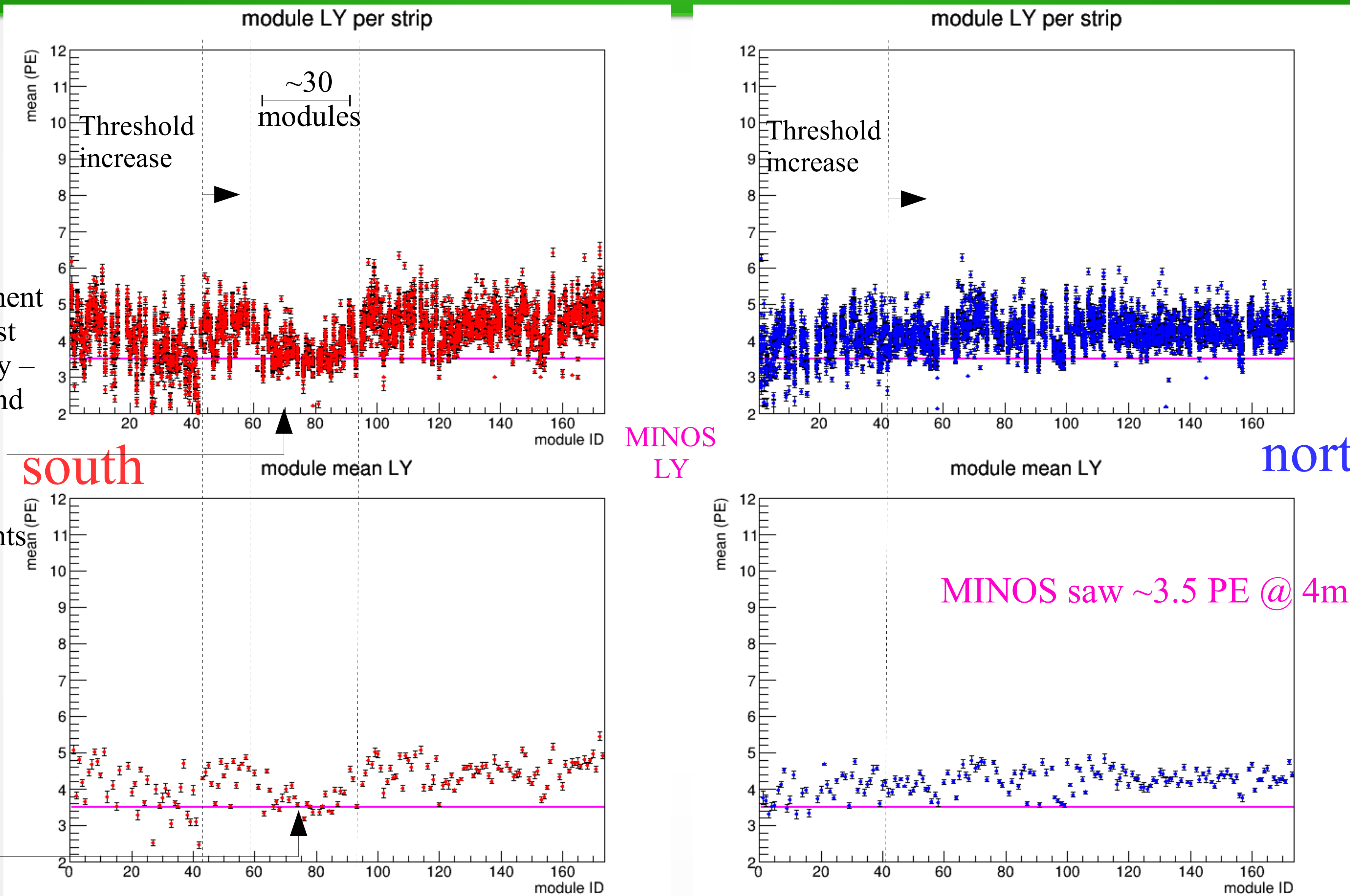
1) Mount SiPM boards and setup FEBs
2) With bright LED flashlight, scan across entire module surface, check for damage, light leaks
3) With uncollimated ^{60}Co source, trigger on one channel at a time, check for response in each scintillator strip
4) Use hodoscope to provide external trigger, measure light yield from cosmic muons at 3 positions





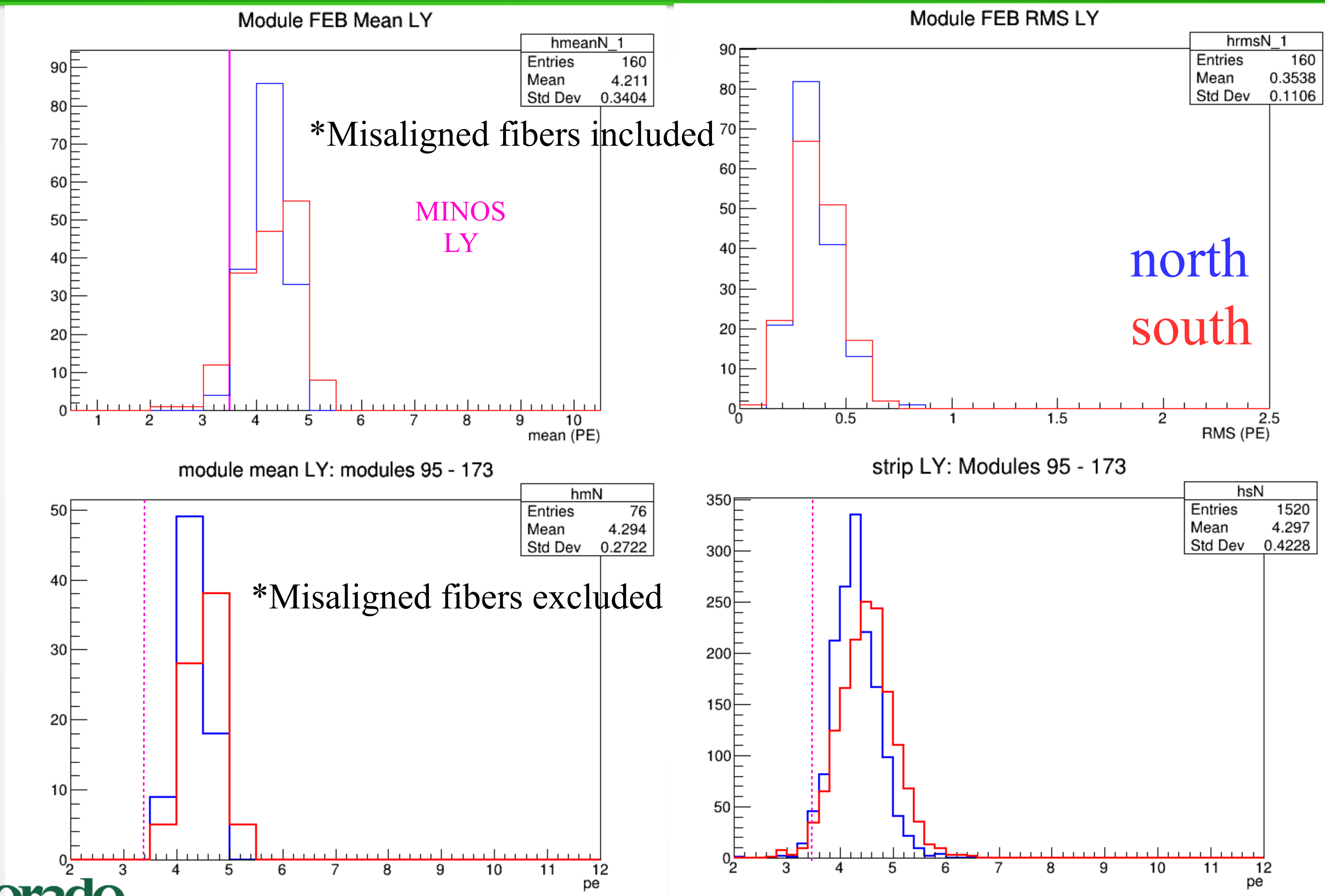
Module LY/Module Summary: 4 m

Alignment pins lost stability – wear and tear of ~60 mount/ remounts



Colorado State University

Module LY/Module Summary: 4.0 m



Test Statistics

- Damage
  - 14 modules w/damage to Al skin, mostly from corrosion, causing light leaks that were repaired with tape
  - Half of one module heavily corroded on one half – used for cutting (more on this in a few slides)
  - 5 modules w/1 or 2 damaged optical fibers, 167 with no damage
- Light yield (lower than our proposed solution – more in Simone's talk)

Number of modules with N strips' LY above threshold*

Threshold (pe)	South FEB Only			North FEB Only			Both Ends		
	20	**19**	**18**	**20**	**19**	**18**	**20**	**19**	**18**
2.5	153	6	2	153	7	2	143	12	2
3.5	93	14	9	104	20	6	60	24	12
4.5	4	3	6	0	0	0	0	0	0

strips >thresh

*misaligned measurements not corrected,
it is likely larger fraction above threshold than shown here