Liquid Argon Detectors and Readout Electronics: From R&D to Physics Discovery

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Physics Department Colloquium
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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

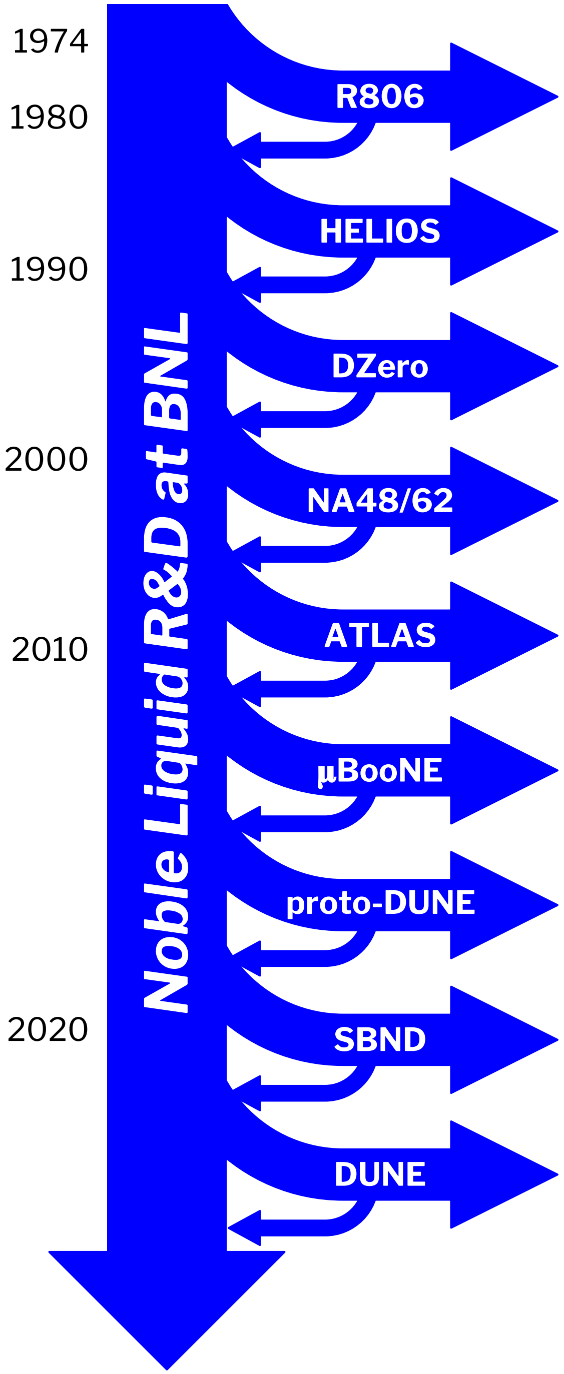
- ***Introduction***
- ***Noble Liquid Detector R&D at BNL***
  - ***Higgs Boson and Exploring the Unknown**: HEP Energy Frontier*
  - ***Neutrino Oscillations**: HEP Intensity Frontier*
  - ***Future Prospects**: Generic Detector R&D for HEP, NP, BES, …*
- ***Concluding Remarks***

Why are Noble Liquid Detectors Interesting?

	He	Ne	Ar	Kr	Xe
Atomic Number	2	10	18	36	54
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm^3]	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost ($/kg)	52	330	5	330	1200

- ***Noble liquid, particularly Liquid Argon, has many important features***
  - ***High density medium, reasonably high-Z with good uniformity***
  - ***High electron and light yield, good electron transport***
  - ***Radiation hard and low cost***

Long History of Noble Liquid Detector R&D at BNL



Discovery

Top Quark in 1995

Higgs Boson in 2012

- ***BNL pioneered Liquid Argon based detector technology in 1974***
  - ***Unique experience in cryogenic electronics and low-noise microelectronics***
- ***R&D → Experiments → R&D***
  - ***Readout electronics*** has always been an ***integral*** part of detector R&D effort for ***precision measurement*** with noble liquid detector

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

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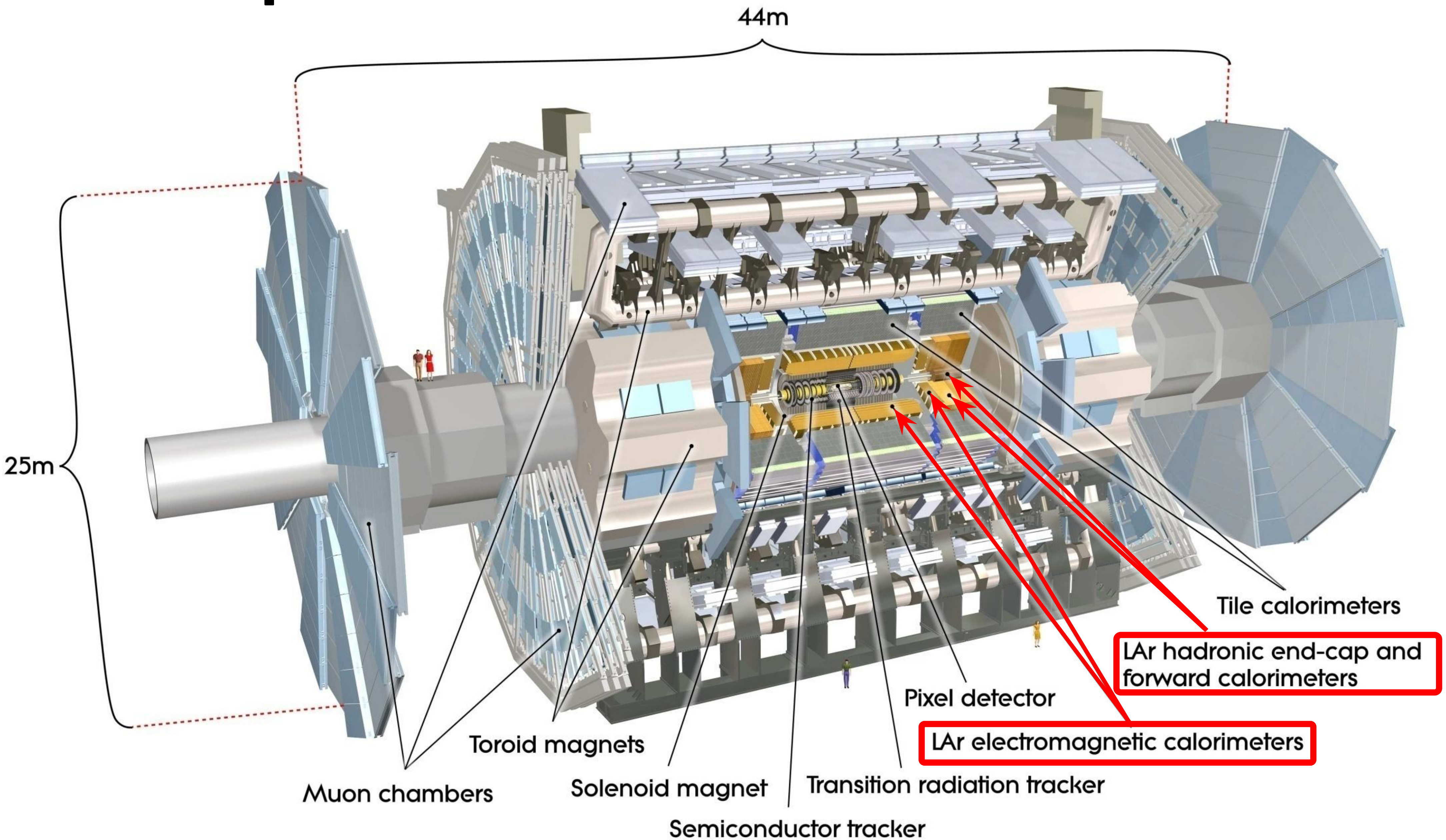
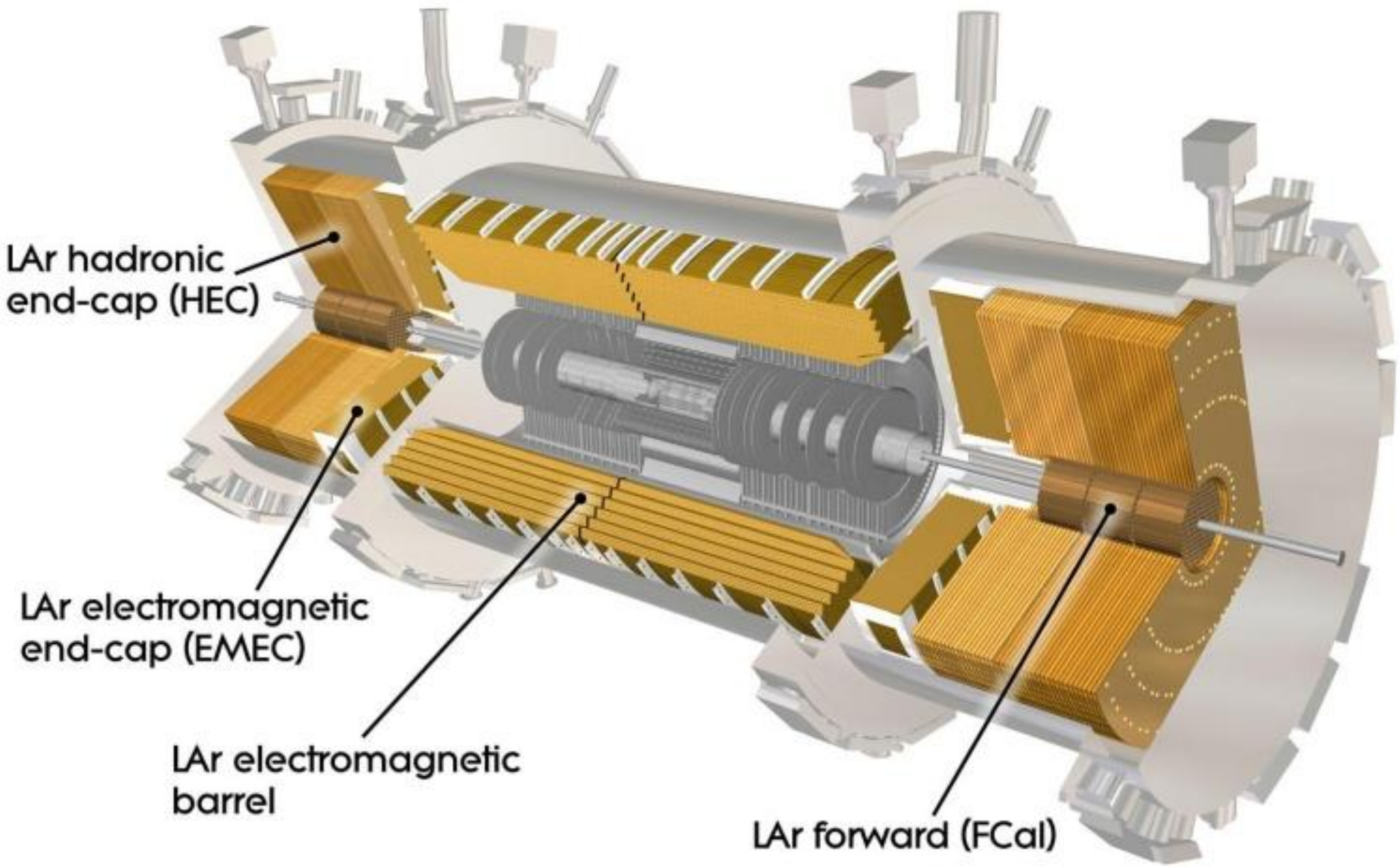
Received 14 May 1974

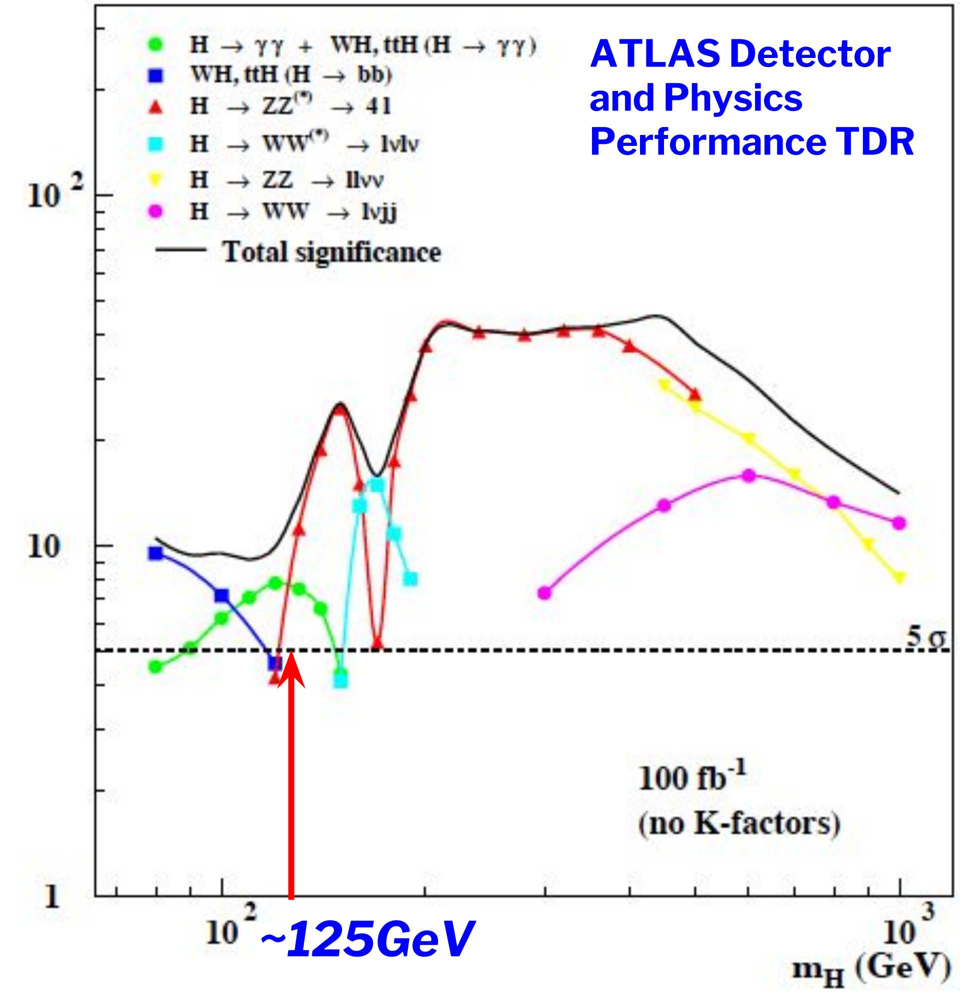
ATLAS Experiment on LHC



- ***ATLAS is one of two general purpose detectors on the Large Hadron Collider (LHC) with one of the main goals to discover the Higgs***

ATLAS Liquid Argon Calorimeter

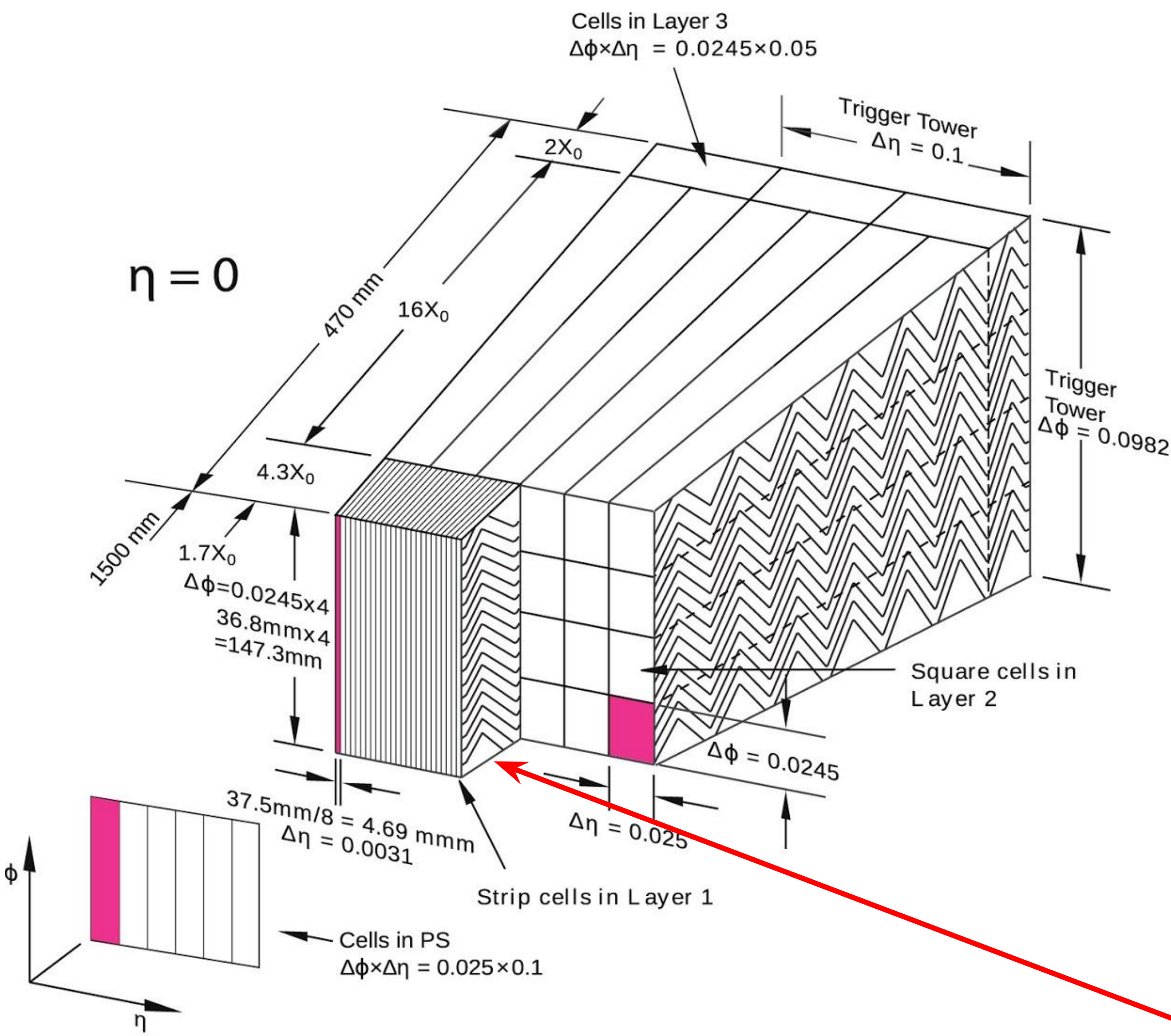




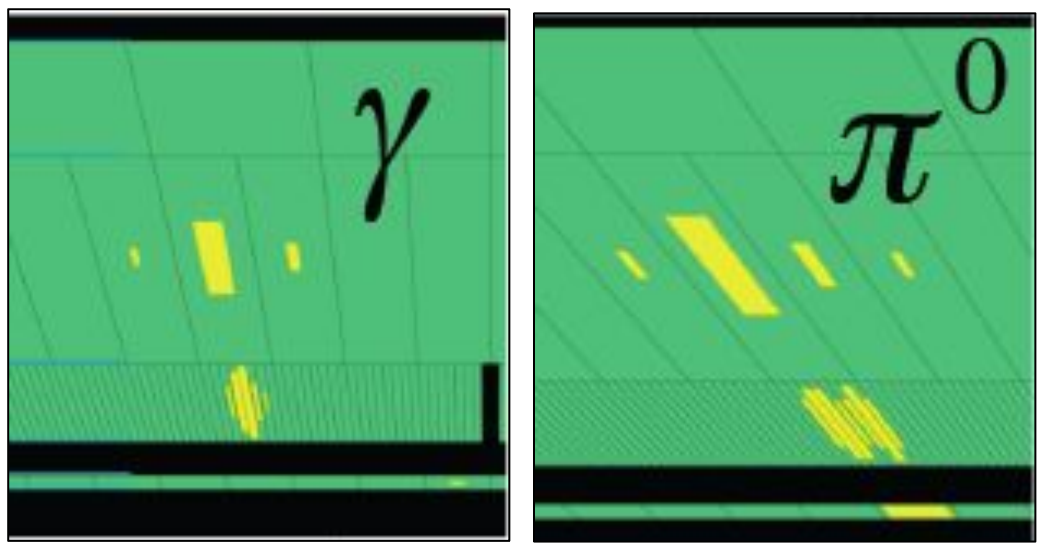
- ***Electromagnetic Barrel (EMB)***
- ***Electromagnetic End-cap (EMEC)***
- ***Hadronic End-cap (HEC)***
- ***Forward Calorimeter (FCAL)***

- ***Liquid Argon (LAr) Calorimeter is crucial for measurements of H→ γγ and H→ZZ→ee(ee) channels***

Design of LAr Calorimeter

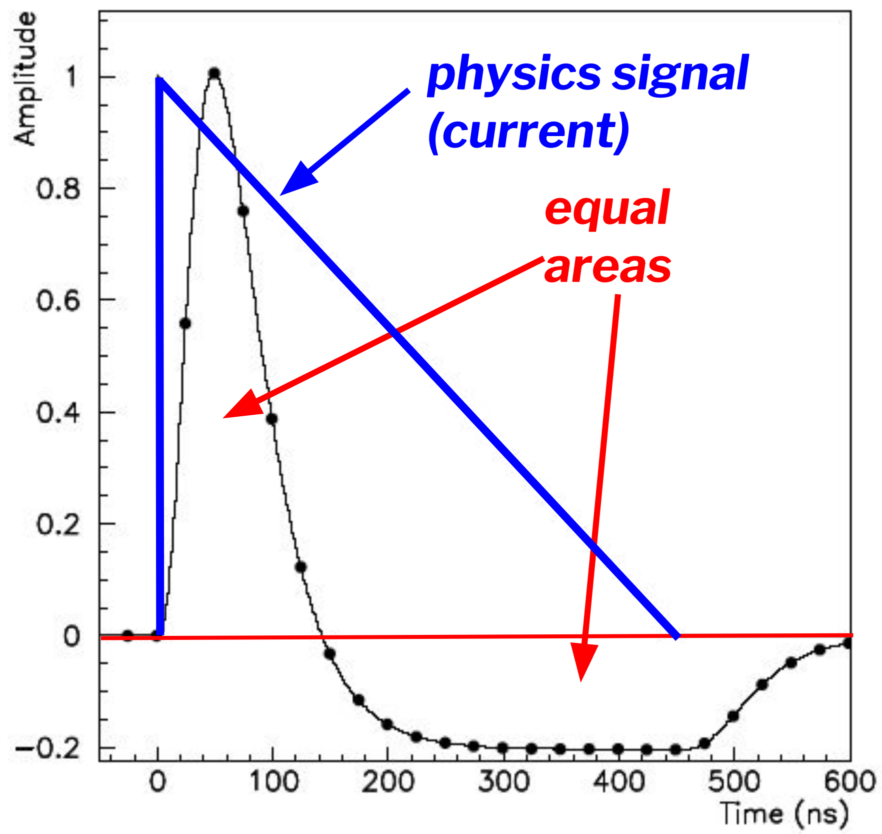


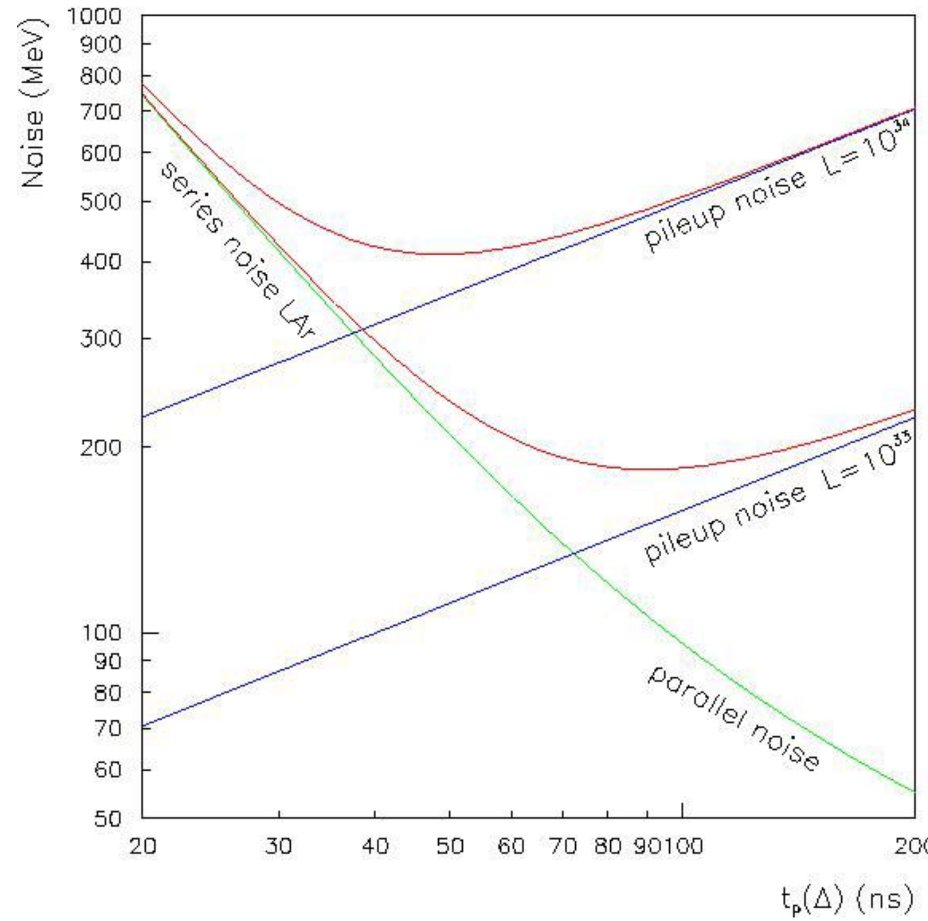
- ***Accordion-shaped electrodes with pointing feature to ease segmentation***
- ***Nearly hermetic coverage with 2π azimuthal angle***
- ***Excellent energy resolution in large dynamic range (~50MeV to ~3TeV) and precision calibration (< 0.25%)***



- ***Trigger Tower: Δη x Δφ = 0.1x0.1, sum of 60 cells → stringent noise requirement***
- ***Fine strip layer to allow efficient π^0 rejection or high γγ purity***

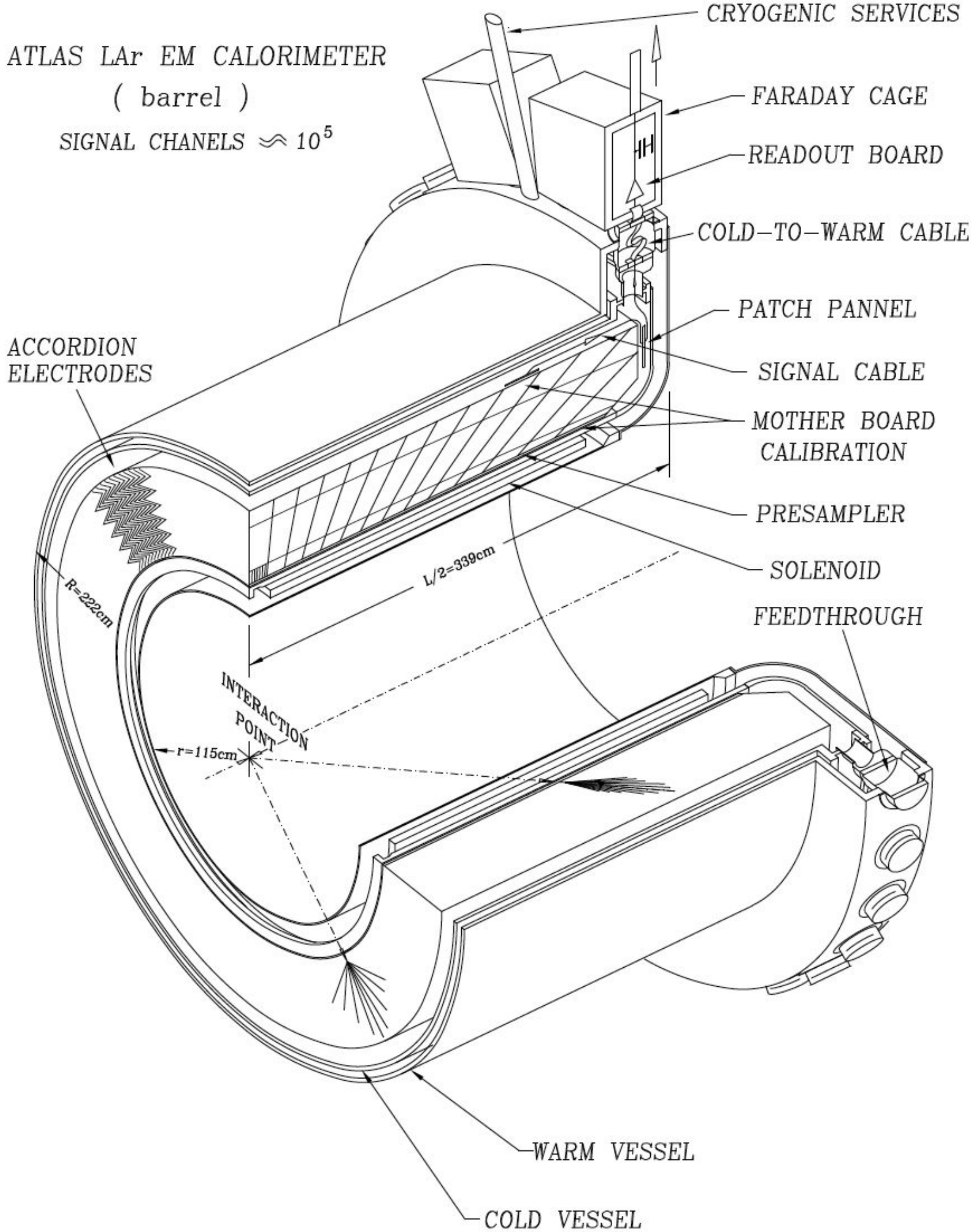
LAr Calorimeter Front End Signal Processing





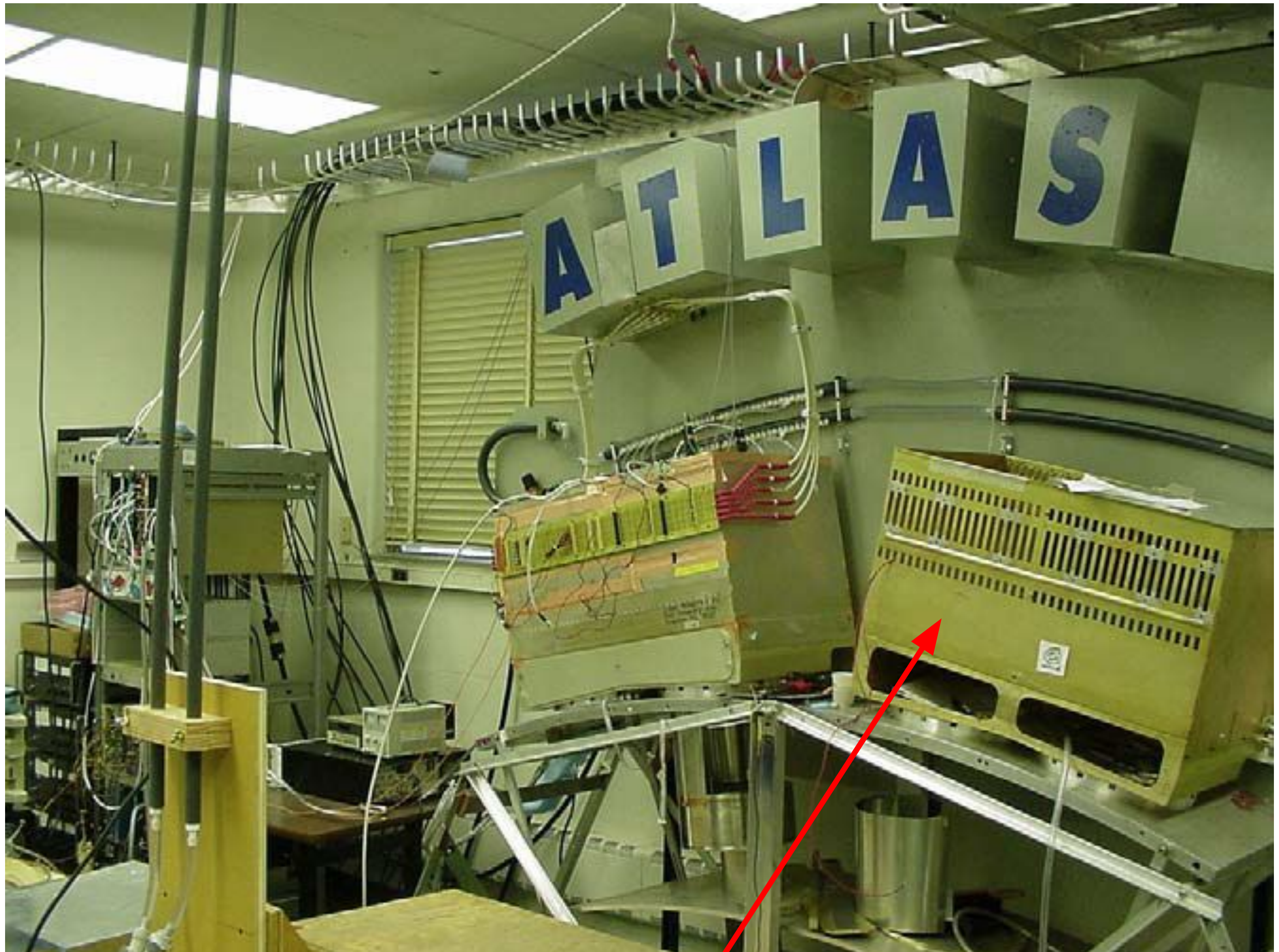
- ***Fast** signal pulse shaping to allow precision energy measurement with first part of current*
- ***Area balanced** **bipolar shaping** to minimize baseline shift in high rate operation*
- ***Careful** optimization of shaping time for designed luminosity → minimal sum for **electronics and pile-up noise***

LAr Calorimeter Readout → Faraday Cage with Cryostat



- ***BNL was leading the LAr calorimeter detector readout system design***
- ***Electrodes***
  - Motherboards (cold electronics)
- ***System crate: on detector electronics***
  - Preamplifier
  - Monitoring Board
  - Warm Cables
  - Baseplane – Analog Trigger Sums
  - Pedestal and Front End Crate
  - Cooling System
  - FEB Final Assembly and Testing
  - Radiation Hard Power Supply
- ***An integral system design approach - from detector electrode to readout electronics, plus system integration test***

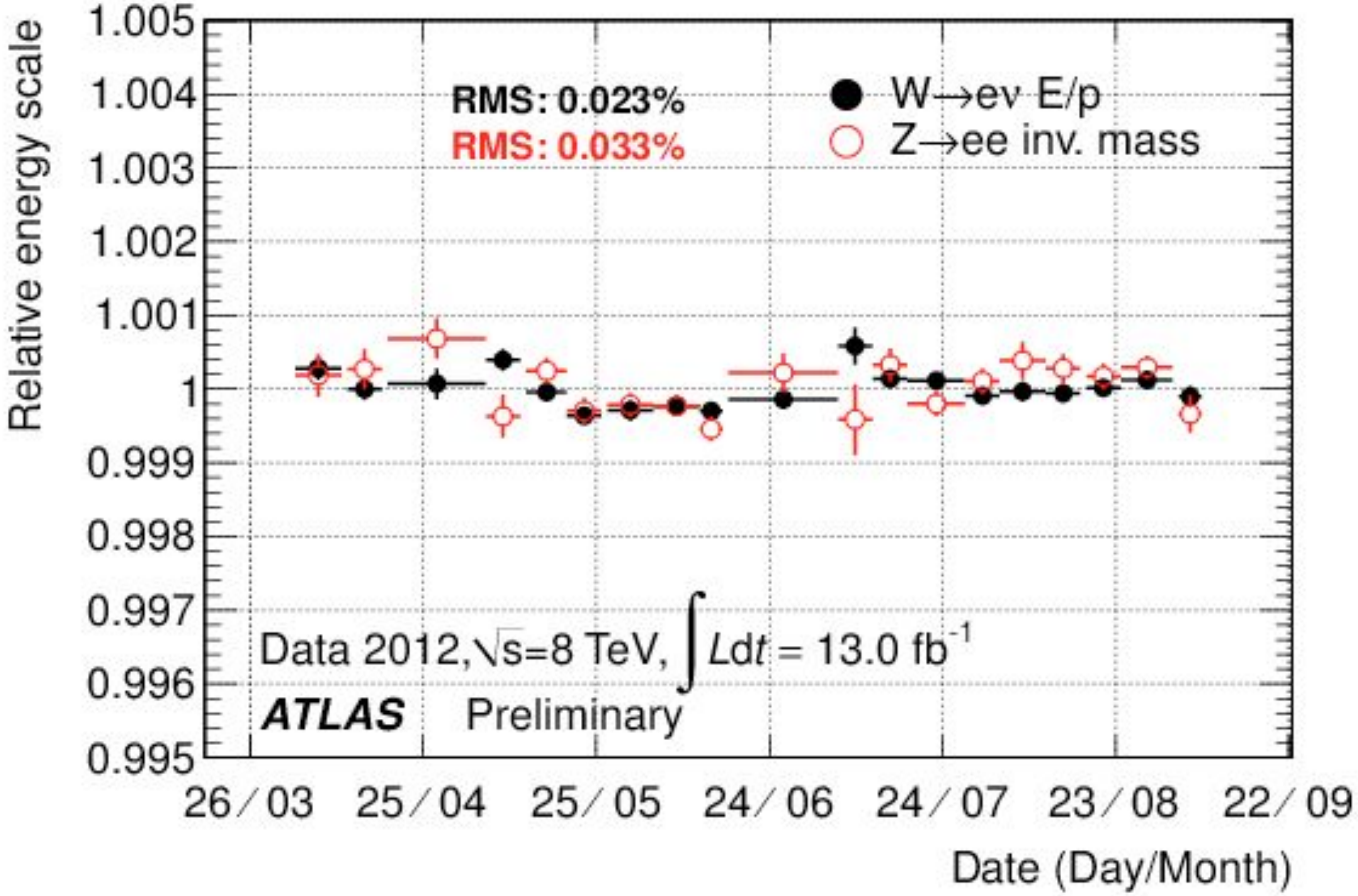
LAr Calorimeter Front End System Test



Front End Crate → an extension of cryostat as Faraday Cage

- ***LAr front end system test at BNL before final electronics production***
  - Full readout chain, only such system outside CERN
  - Used for FEB production tests
- ***Critical integration test for system performance and FEB production***
  - Studied system performance and identified a key issue of clock quality before FEB production
  - Qualified ~800 FEBs or ~100,000 channels
  - Resolved design flaws of radiation hard low voltage power supply system
- ***Test stand is being used in the LAr Phase-I and Phase-II upgrades***

Excellent Stability and Performance of LAr Calorimeter

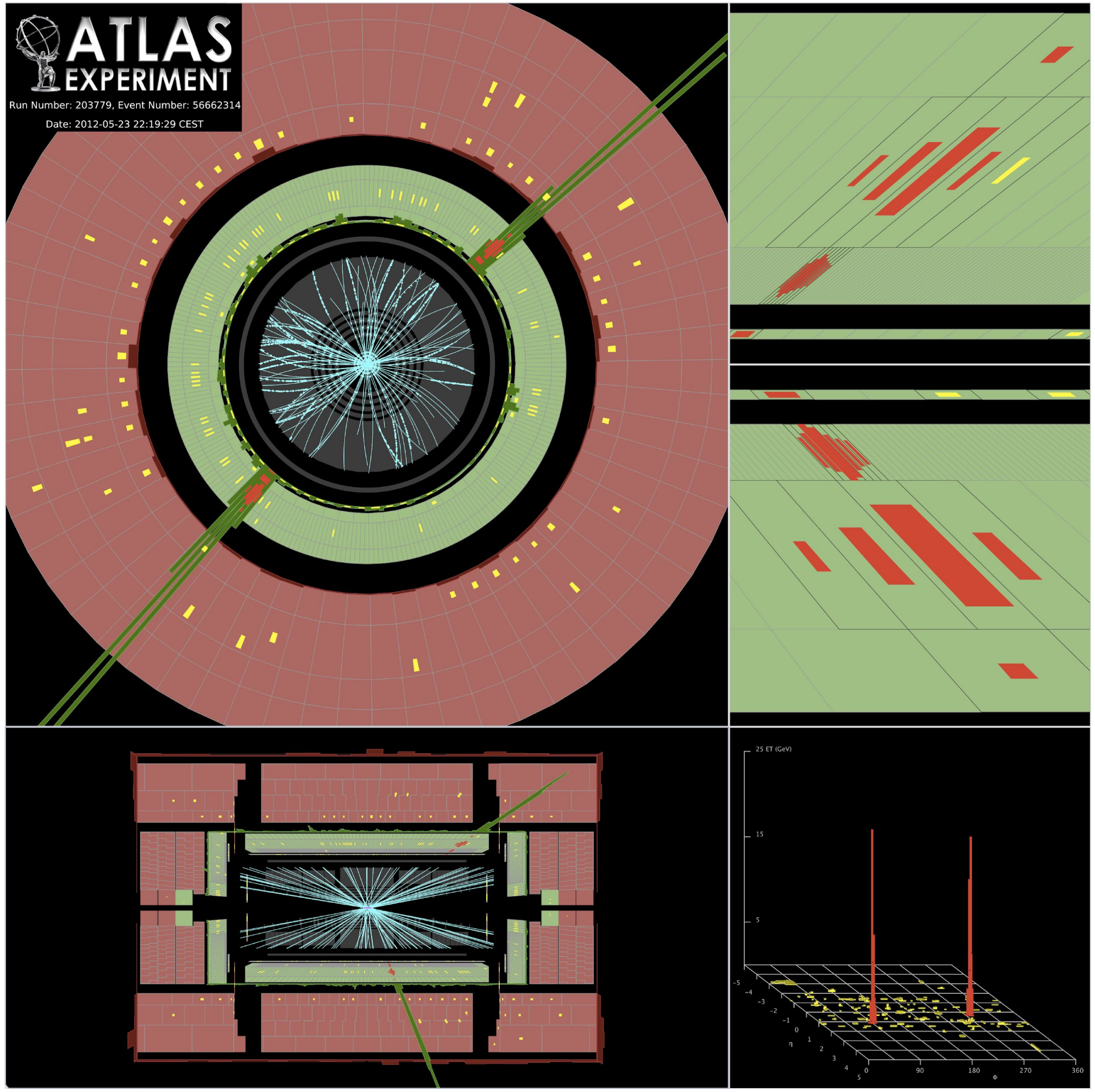


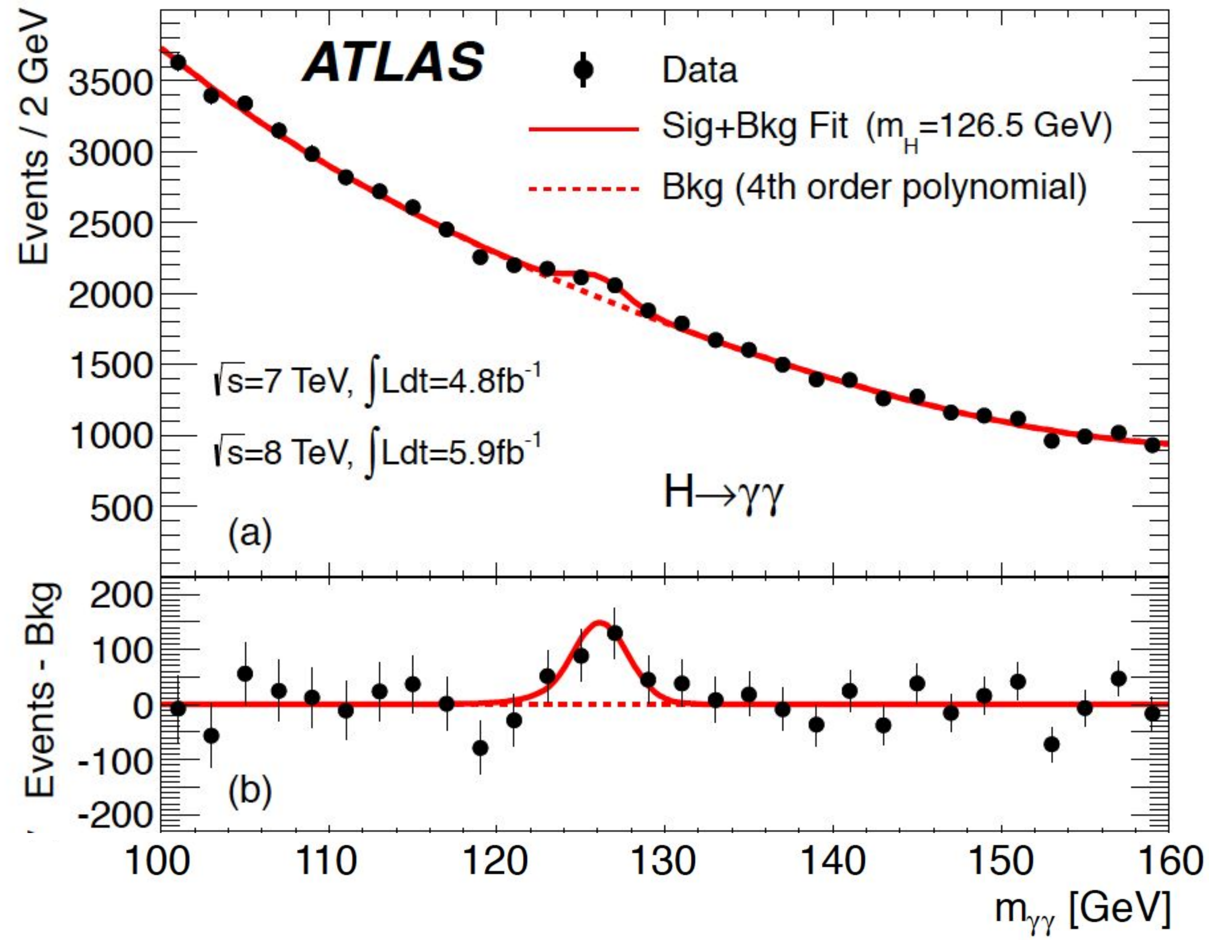
- ***Temperature stability***
  - ***~5mK***
- ***Electronic calibration***
  - ***A few per mil***
- ***Energy scale stable***
  - ***~ per mil, vs. time and pileup***
- ***Excellent energy resolution***
  - ***Allows a mass resolution of ~1% for the Higgs between 100 and 200 GeV***

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{170MeV}{E} \oplus 0.7\%$$

- ***BNL designed and constructed a LAr calorimeter capable of achieving and exceeding the requirements.***
  - This work resulted in the ***Higgs discovery*** with strong BNL leadership

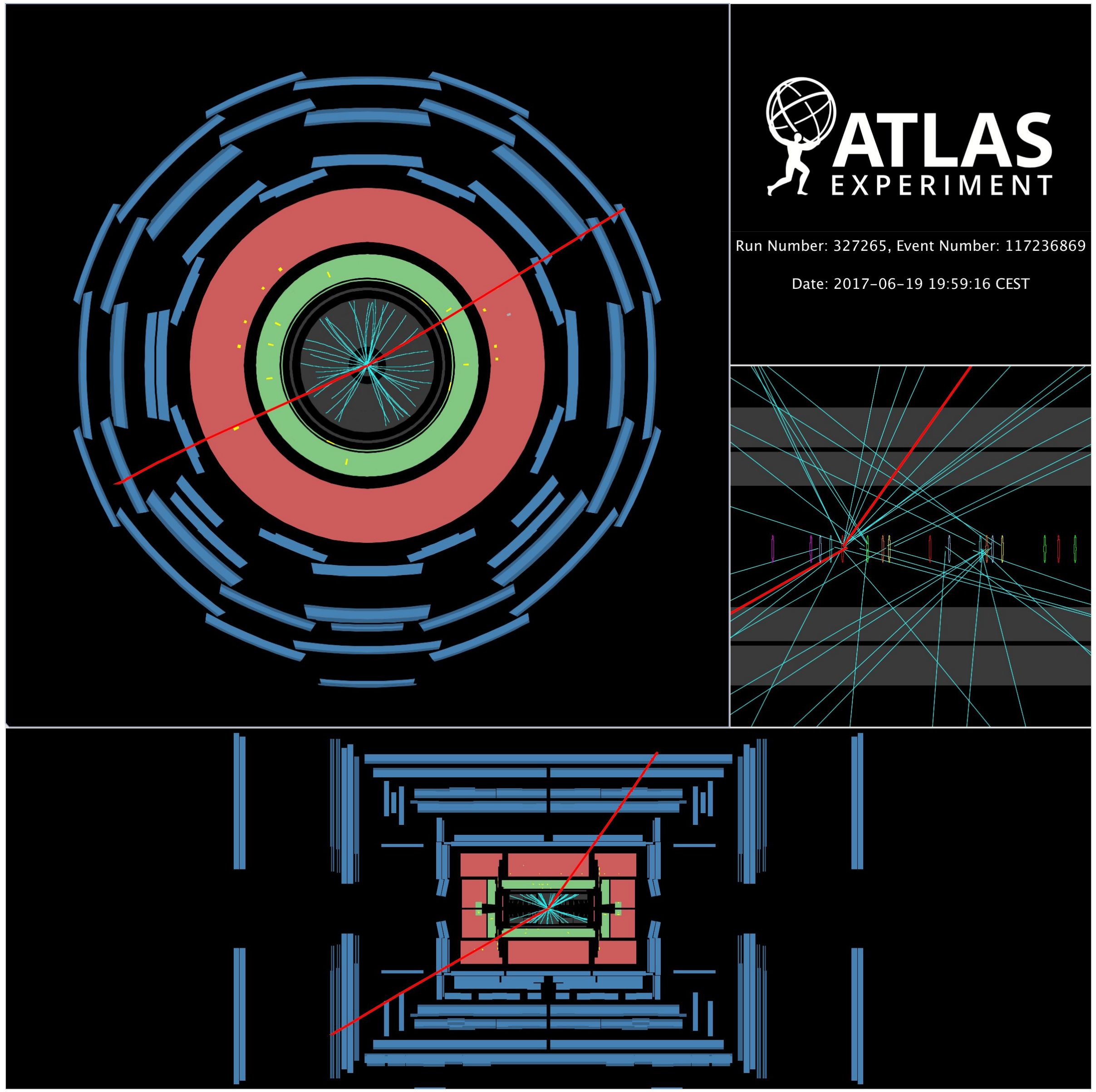
Higgs Discovery in 2012

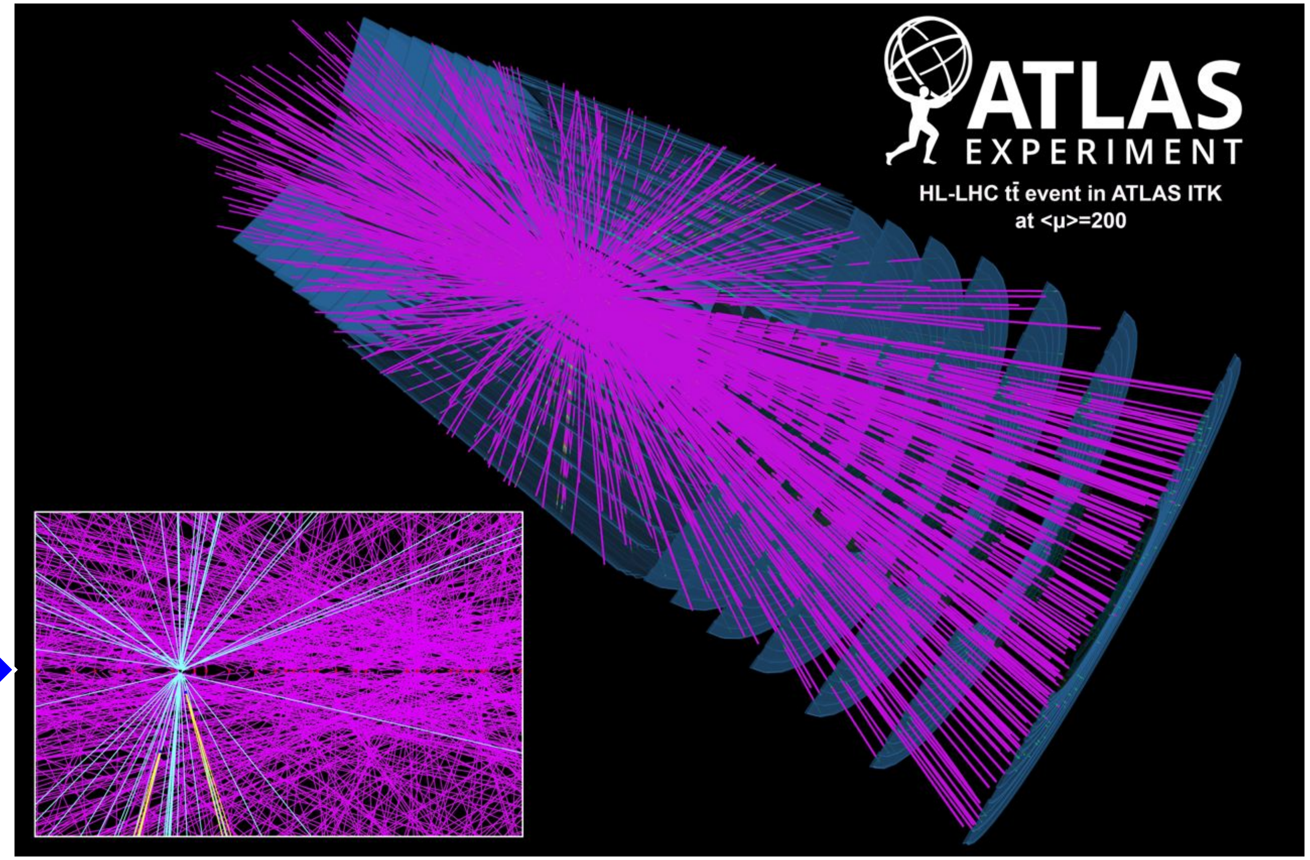




- ***2012: ATLAS and CMS find evidence of Higgs-like events***
- ***ATLAS LAr calorimeter provides more than 5σ confidence level***

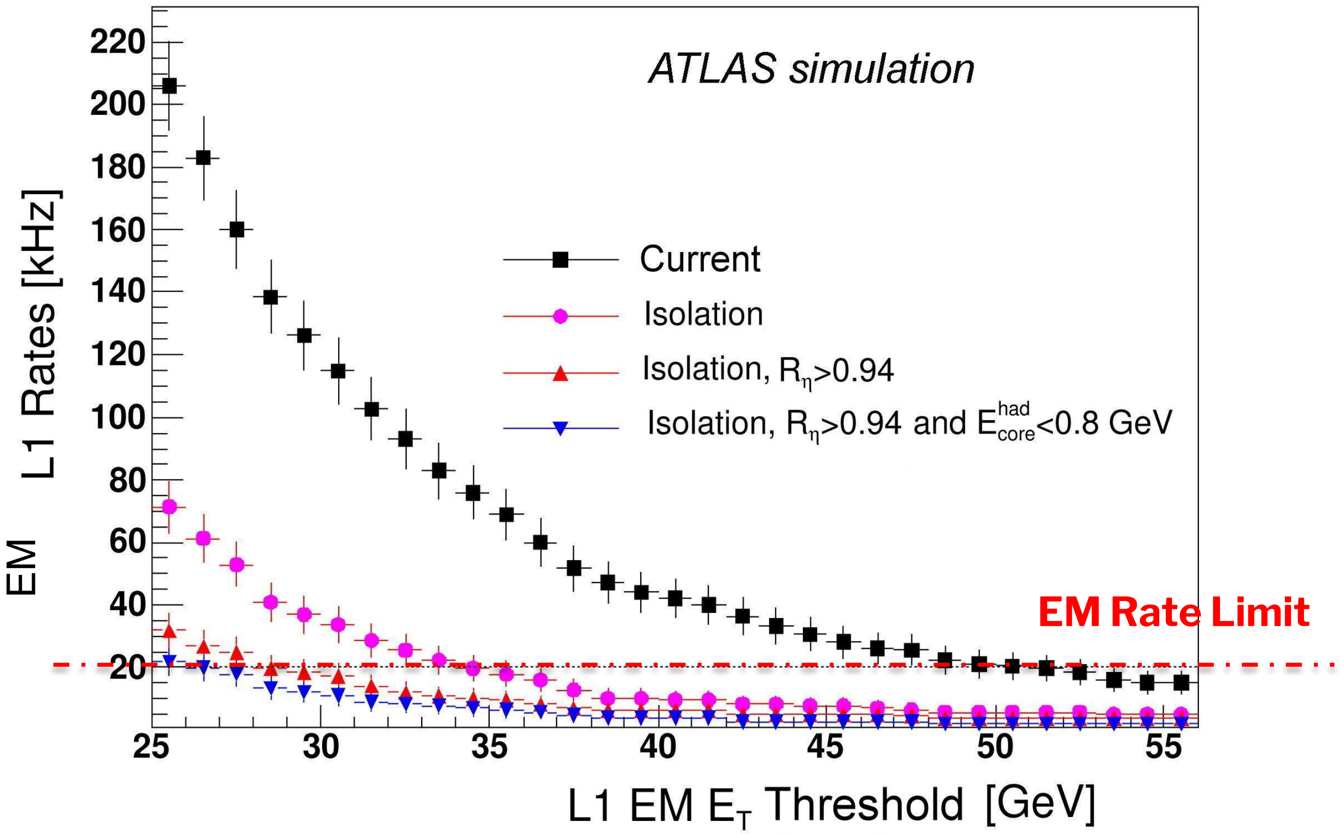
From LHC to HL-LHC





- ***Pile-up events in ATLAS ~ 20 in Run2***
  → ~80 in Phase-I Upgrade
  → ~200 in Phase-II Upgrade
- ***LAr calorimeter noise will be increased by factor of x2~3 → trigger and readout challenge!***

Phase-I Upgrade Physics Motivation



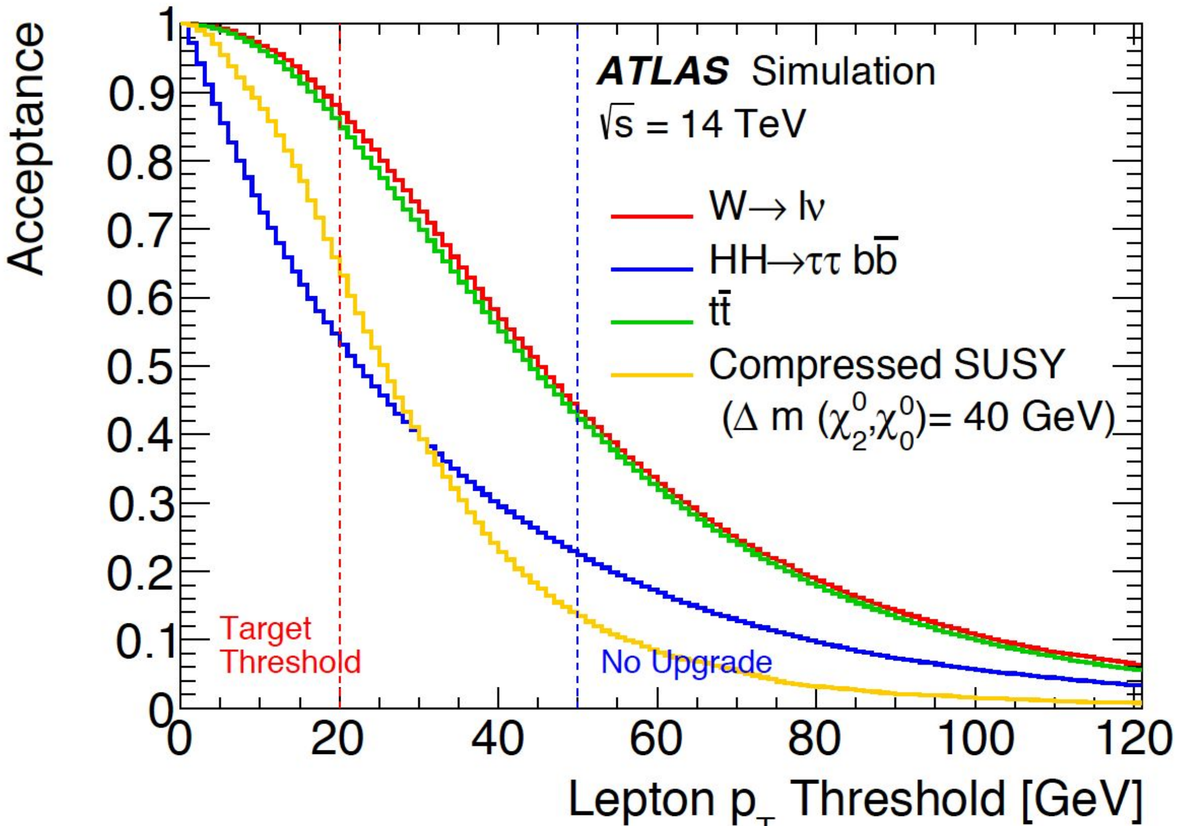
Level-1 trigger	Relative Efficiency $WH \to \ell\nu b\bar{b}$	Trigger Rate (kHz)
Electron channel		
$E_T^{EM} > 35$ GeV	73	54
$E_T^{EM} > 35$ GeV, and isolation	71	16
$E_T^{EM} > 35$ GeV, isolation and $rCore_{L1} > 0.93$	71	6.5
Muon channel		
$E_T^{\mu} > 20$ GeV for current small wheel	82	40
$E_T^{\mu} > 40$ GeV for current small wheel	50	18
$E_T^{\mu} > 20$ GeV for new small wheel	78	18

- ***Enhance rejection* while retaining high p_T relative efficiencies**
- ***Benchmark*: without upgrades, changing thresholds in order to contain rates results in *significant (~50%) loss* of efficiency for events triggered on massive-object, single-lepton decay. Impacts W, WH, ttbar, top, SUSY, etc.**

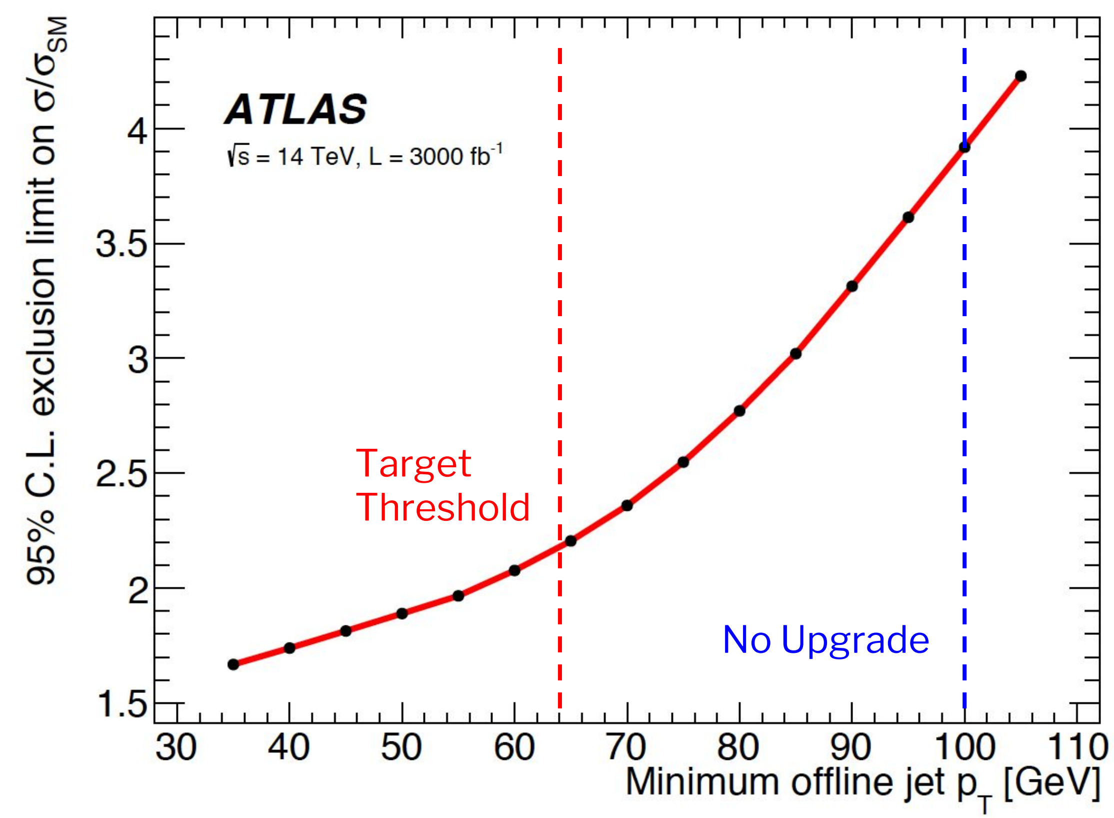
HL-LHC Upgrade Physics Motivation

- ***ATLAS will continue direct searches for Physics Beyond the Standard Model at the highest energies on HL-LHC***
  - ***Exploration of the Higgs sector***, and ***Precision Measurements***
- ***Physics Gains from Trigger/DAQ Improvements***
  - *Offline-like algorithms at lowest level*
  - *Increased bandwidth to permanent storage*

} *Low thresholds at L0 (hardware) & HLT (software) level*

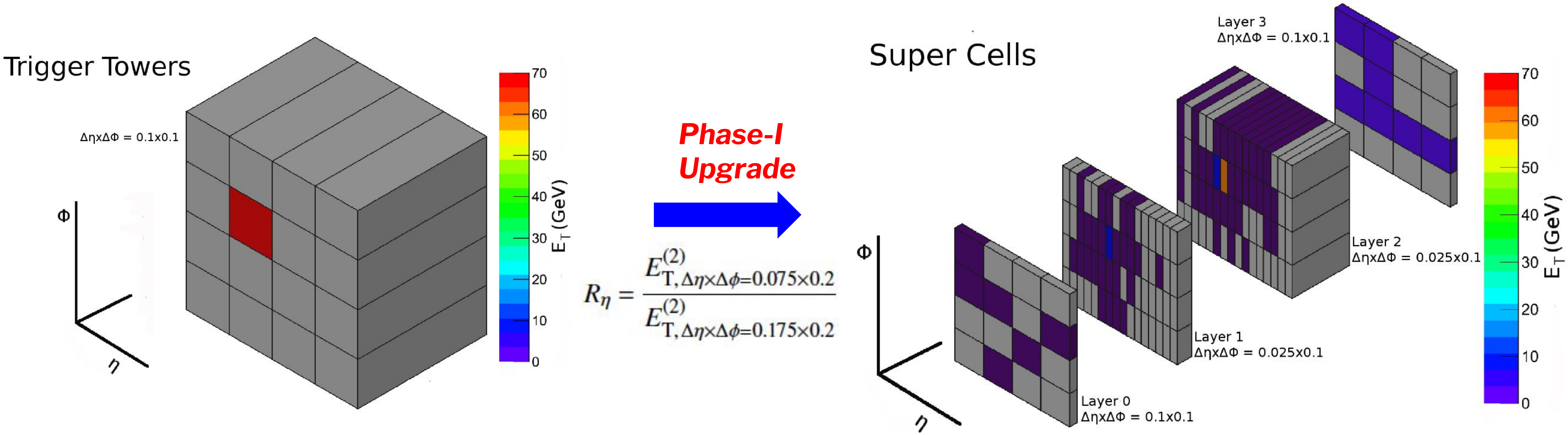


Lepton Trigger Thresholds



Multi-Jet Triggers: HH → 4b

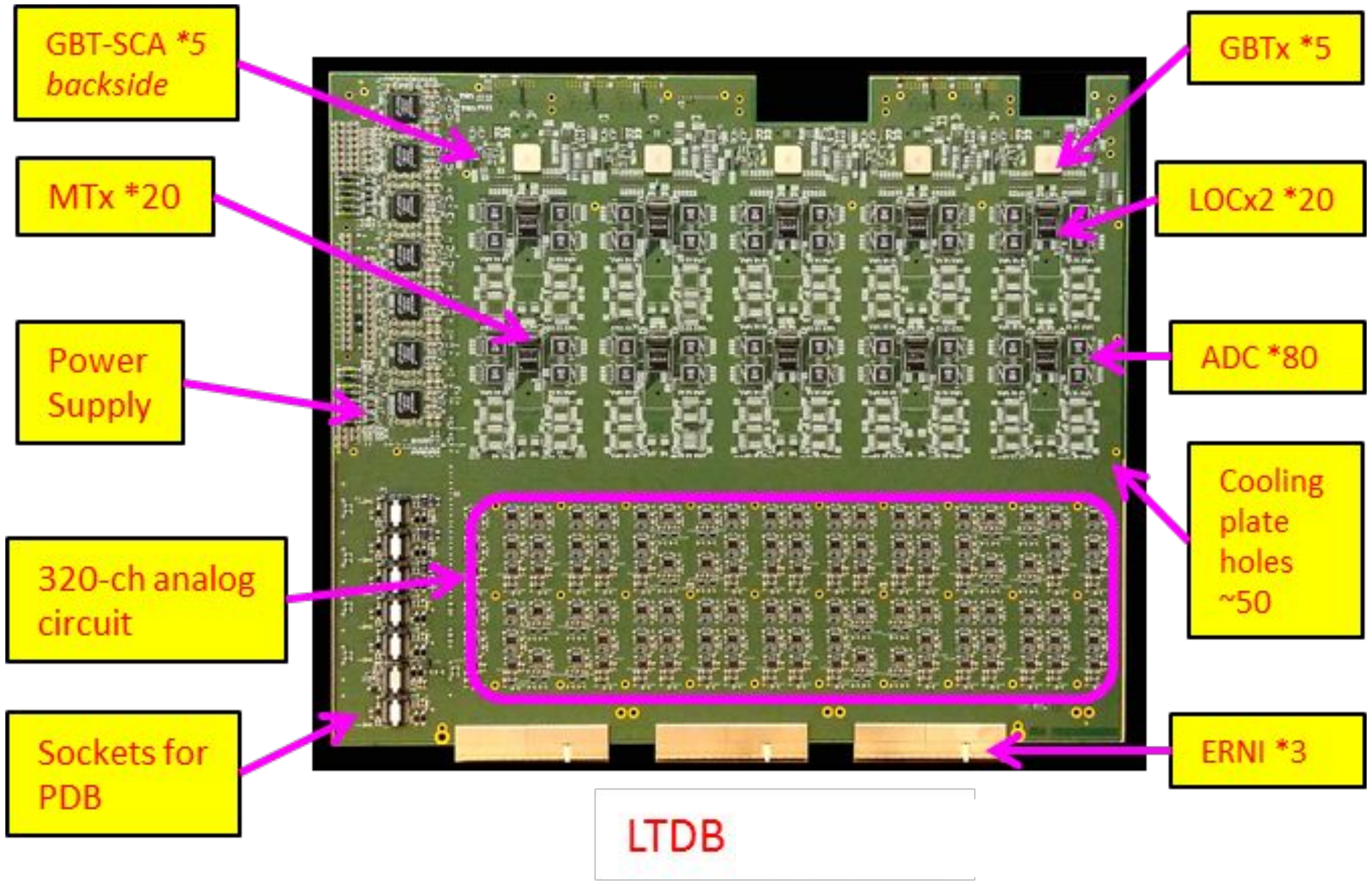
LAr Calorimeter Phase-I Upgrade



- ***LAr Phase-I upgrade will have new calorimeter trigger electronics with increased granularity and functionality for LAr calorimeter level 1 trigger***
  - Fine lateral and longitudinal LAr Super Cells
  - Increasing granularity ***10 times*** by changing from Trigger Tower to Super Cell readout
- ***Given that the Higgs boson is light, maintaining low trigger thresholds on the physics objects is mandatory for precision measurement***

Front End Signal Processing

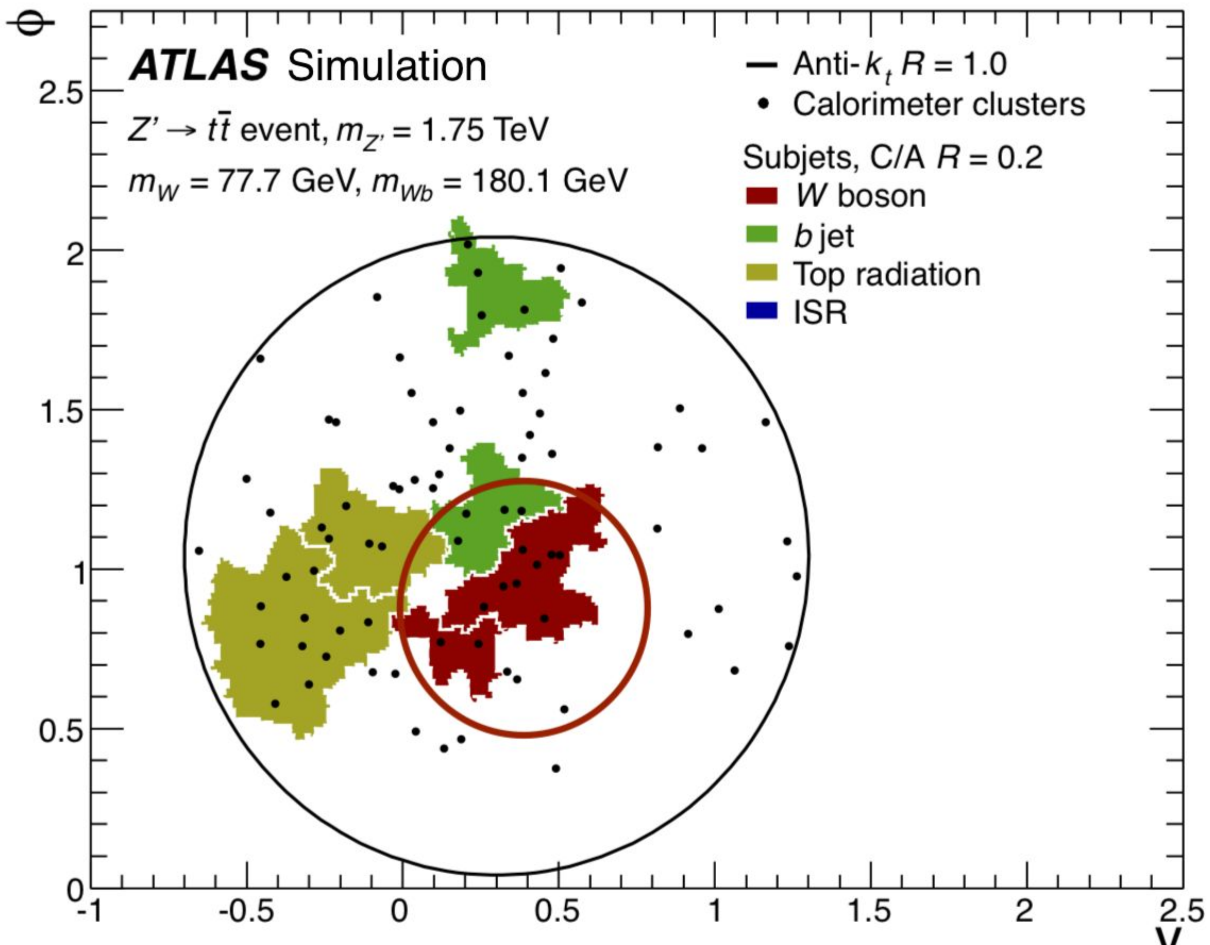
- ***BNL is leading the LAr Trigger Digitizer Board (LTDB) development***
  - ATLAS Phase-I LAr Calorimeter Front End

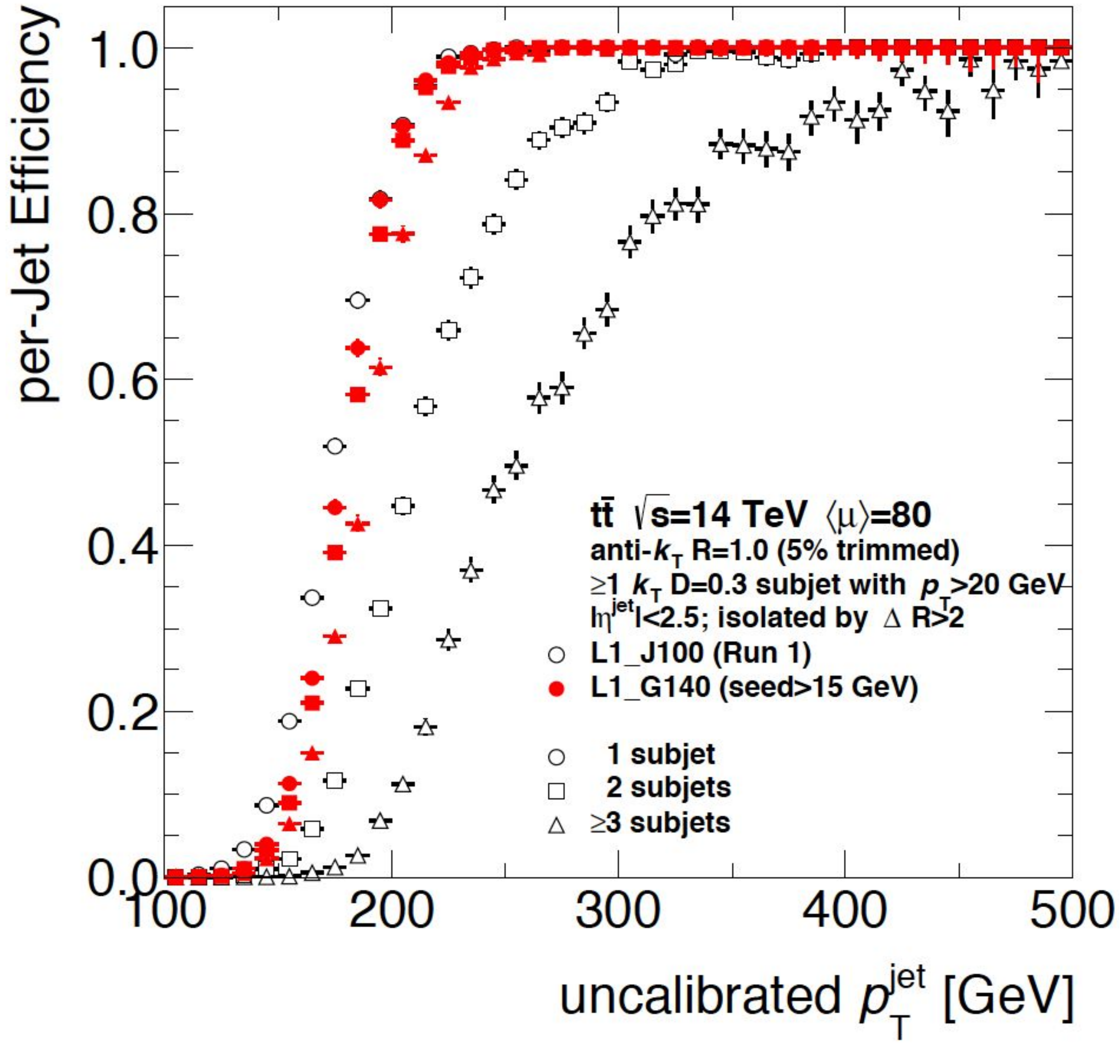


- **Combined analog & digital board on detector**
  - Analog and digital parts designed by different institutes
  - BNL leads architectural design
  - Collaboration with Saclay, Milan, Columbia and SMU
- **320 calorimeter signals** (supercells)
  - 80 custom 12-bit ADCs @ **40 MSPS** digitization
  - 20 custom MTx devices for data processing
  - 5 GBTx/GBT-SCA for clock distribution, control & monitoring
  - **40 optical links @ 5 Gb/s ⇒ 200 Gb/s output**

- ***Successful data taking with LTDB demonstrator in Run2 from 2015-2018***

Calorimeter Trigger Phase-I Upgrade

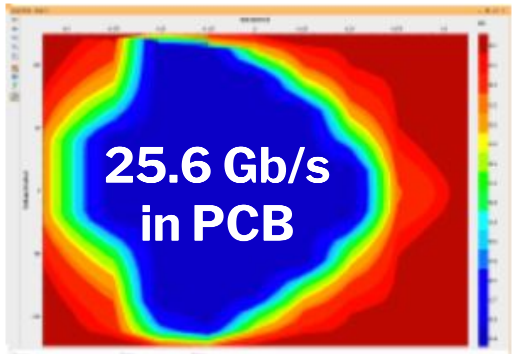


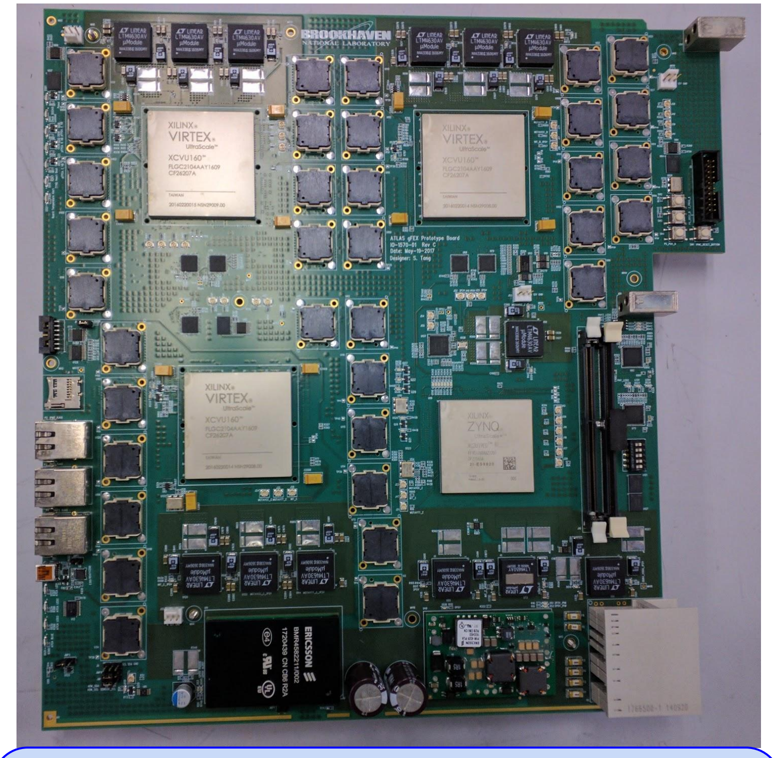


- ***High p_T bosons and fermions key part of ATLAS physics program***
  - ***W, Z, & H bosons, top quarks***, and exotic particles
- ***Analyses use large-R jets with R = 1.0 or larger***
  - Isolated lepton and small-R jet triggers inefficient → ***requires large-R jet triggers***

gFEX - Global Feature Extractor for Large-R Trigger

- ***BNL is designing electronics that maximizes throughput while also running fast trigger algorithms***
  - FPGA with many transceivers satisfies high-bandwidth, fixed-latency & processing requirements
- ***Global Feature Extractor Module (gFEX)***
  - ATLAS Phase-I Level-1 Calorimeter Trigger Module
    - **single board system receives data from full calorimeter**
    - hardware designed by BNL
  - **ATCA blade**
    - 30 layer Megtron-6 PCB
    - 3 VU9P FPGA and 1 ZU19 MPSoC
    - 128 Gb DDR4 RAM
    - 420 optical fibers in 35 miniPODs
  - Throughput
    - **input: 3.5 Tb/s on 312 fibers**
    - output: 1.4 Tb/s on 108 fibers
    - inter-FPGA: 1.6 Tb/s (high-speed & low-speed)

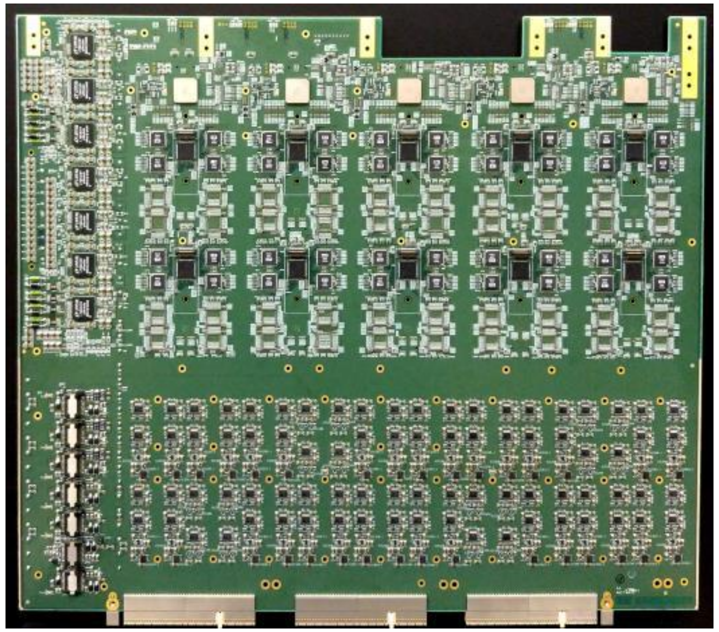




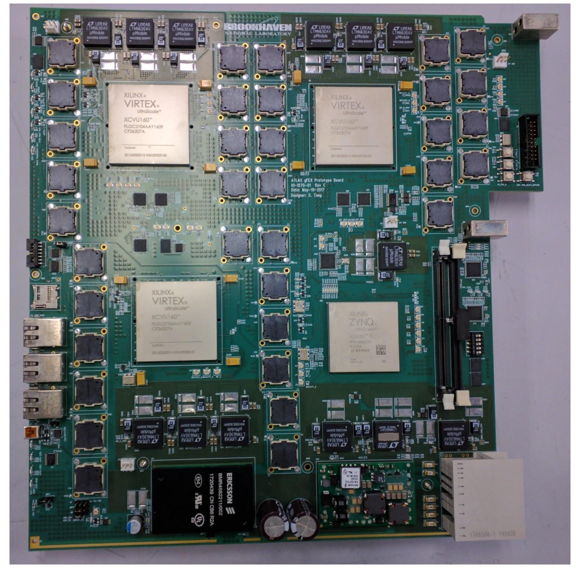
Collaboration between BNL and Chicago, Indiana, Lund, Oregon, Pittsburgh, Stockholm

- ***Production module installed in ATLAS for data taking in summer 2018***

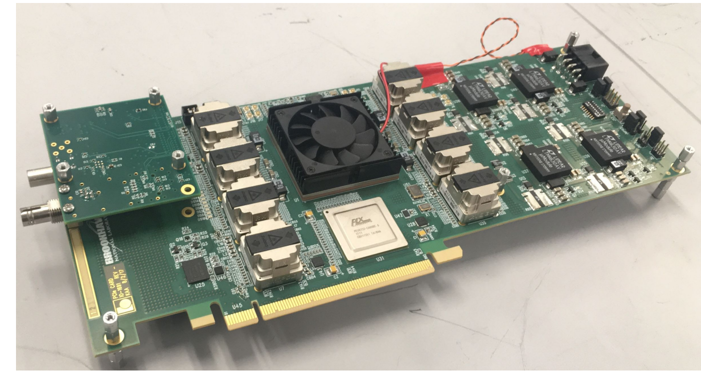
Phase-I Calorimeter and Trigger Readout Electronics



LTDB - Liquid Argon Trigger Digitizer Board



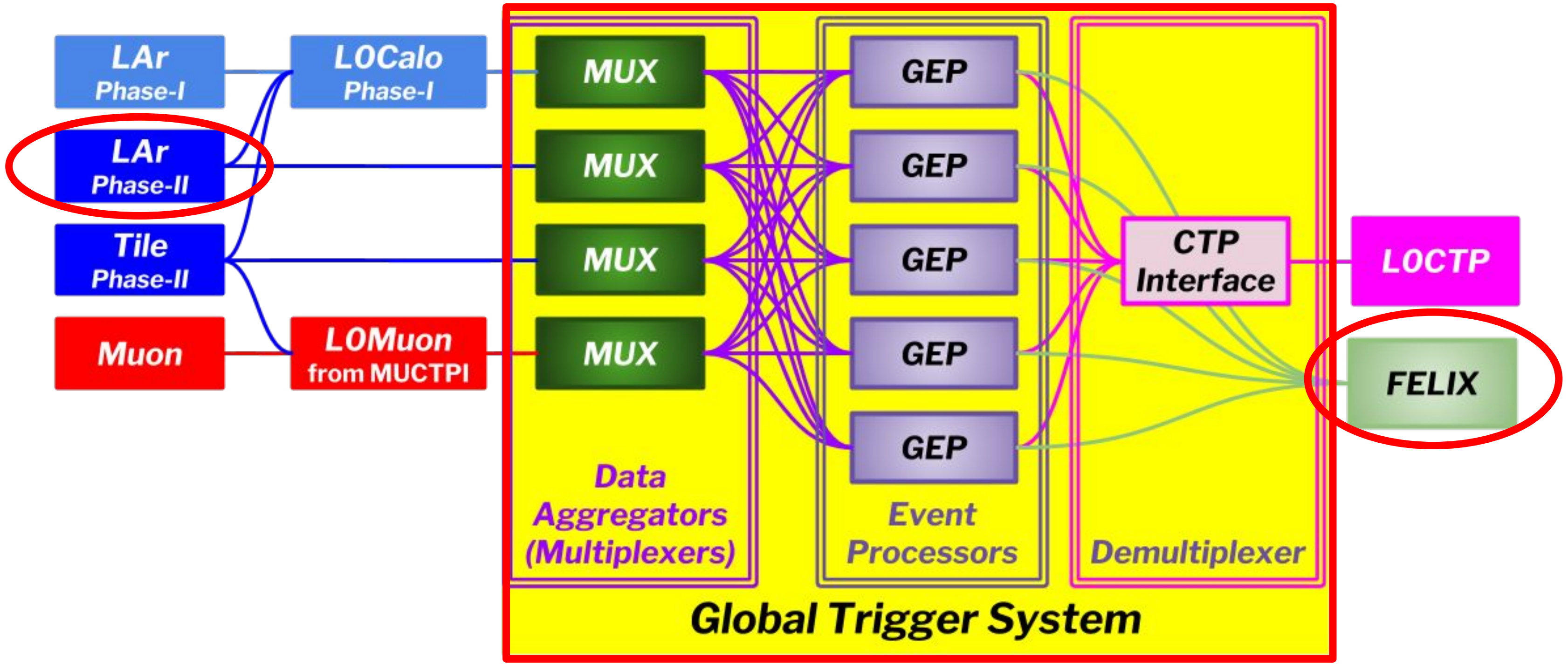
gFEX - Global Feature Extractor



FELIX - Front End LInk eXchange

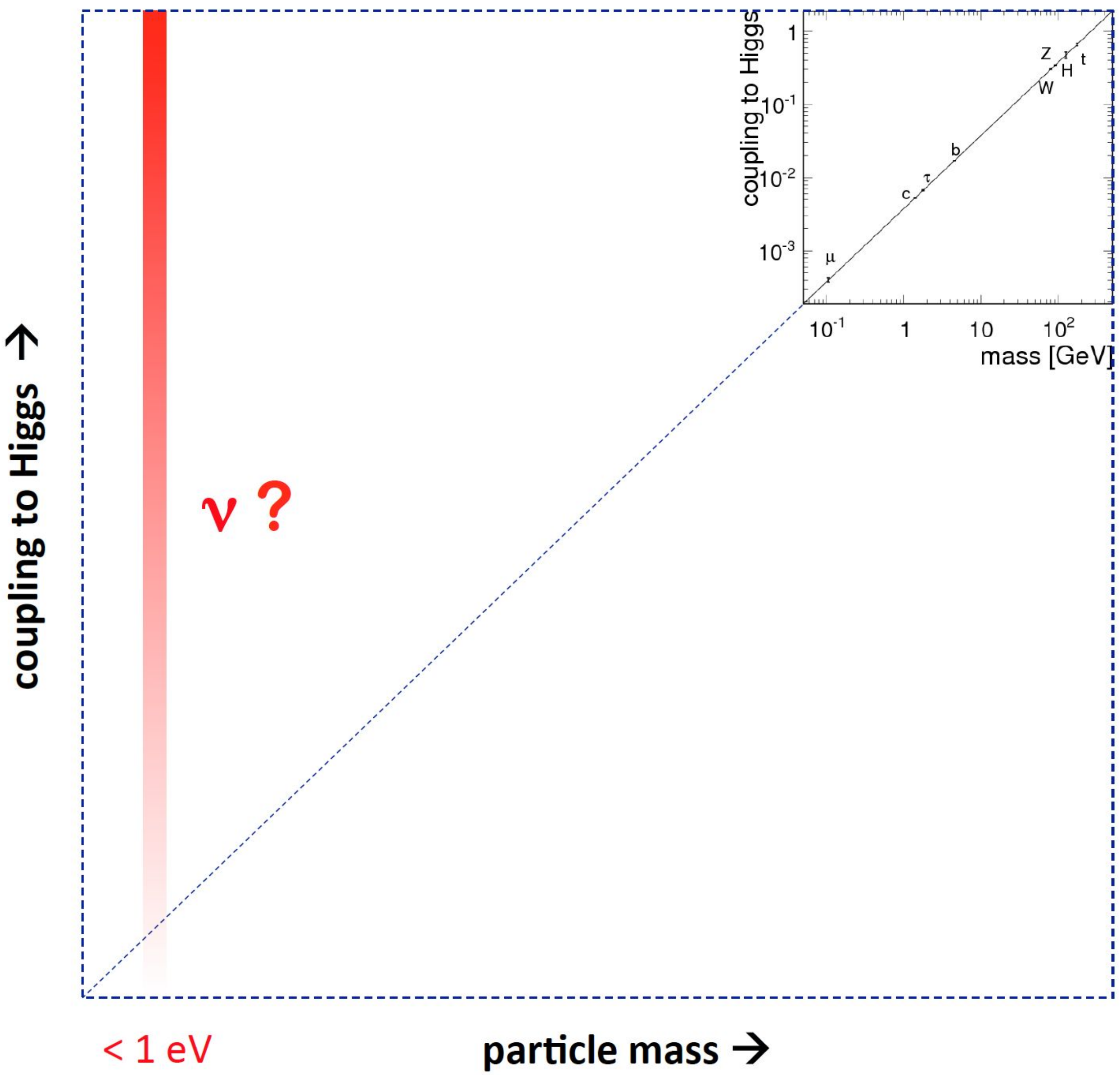
- ***The increasing luminosity of LHC threatens our ability to continue to explore the mechanisms behind Electroweak Symmetry Breaking***
- ***We are upgrading the calorimeter and trigger readout electronics (LTDB, gFEX, FELIX) to maintain our physics acceptance and to expand our reach in the search for new physical phenomena in Phase-I Upgrade***
    - ***gFEX*** - ***Patent*** (BSA18-02/IP2018-003-01) pending “High Data Throughput Reconfigurable Computing Platform"
    - ***FELIX*** - Being adopted in various particle physics experiments in ***worldwide***, ***a new thrust of generic detector R&D***

Phase-II Calorimeter and Trigger Readout Electronics



- ***We are upgrading the calorimeter and trigger readout electronics (FEB2, Global Trigger, FELIX) to maintain our physics acceptance and to expand our reach in the search for new physical phenomena in HL-LHC Upgrade***
  - ***LAr readout electronics*** upgrade to match new trigger and DAQ scheme, eliminate aging and radiation damage, **improve readout performance** in two gain system for better **H→γγ** photon calibration
  - ***Global trigger*** based on ***gFEX*** design concentrates **data for a full event** from detector & trigger systems onto a **single processor** for analysis, enables a low-p_T electron trigger, low thresholds for multi-jet and E^T_{miss} triggers at Level-0
  - ***FELIX*** based DAQ system with new Ultrascale+ FPGA, an ***leveraged R&D*** with ***DUNE far detector***

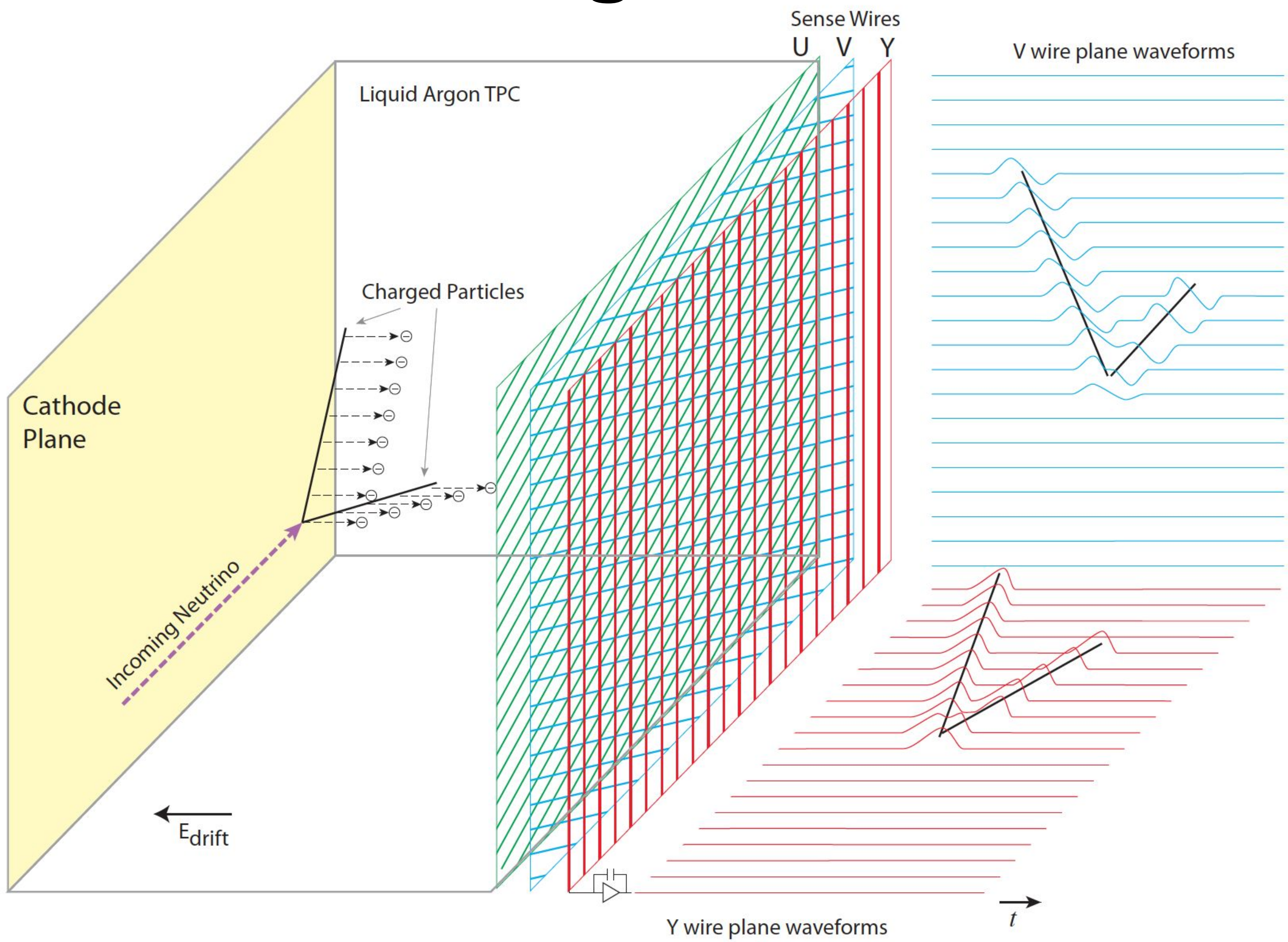
From Energy to Intensity Frontier → Liquid Argon TPC



Where are the ν's on this plot?
Why are they so light?

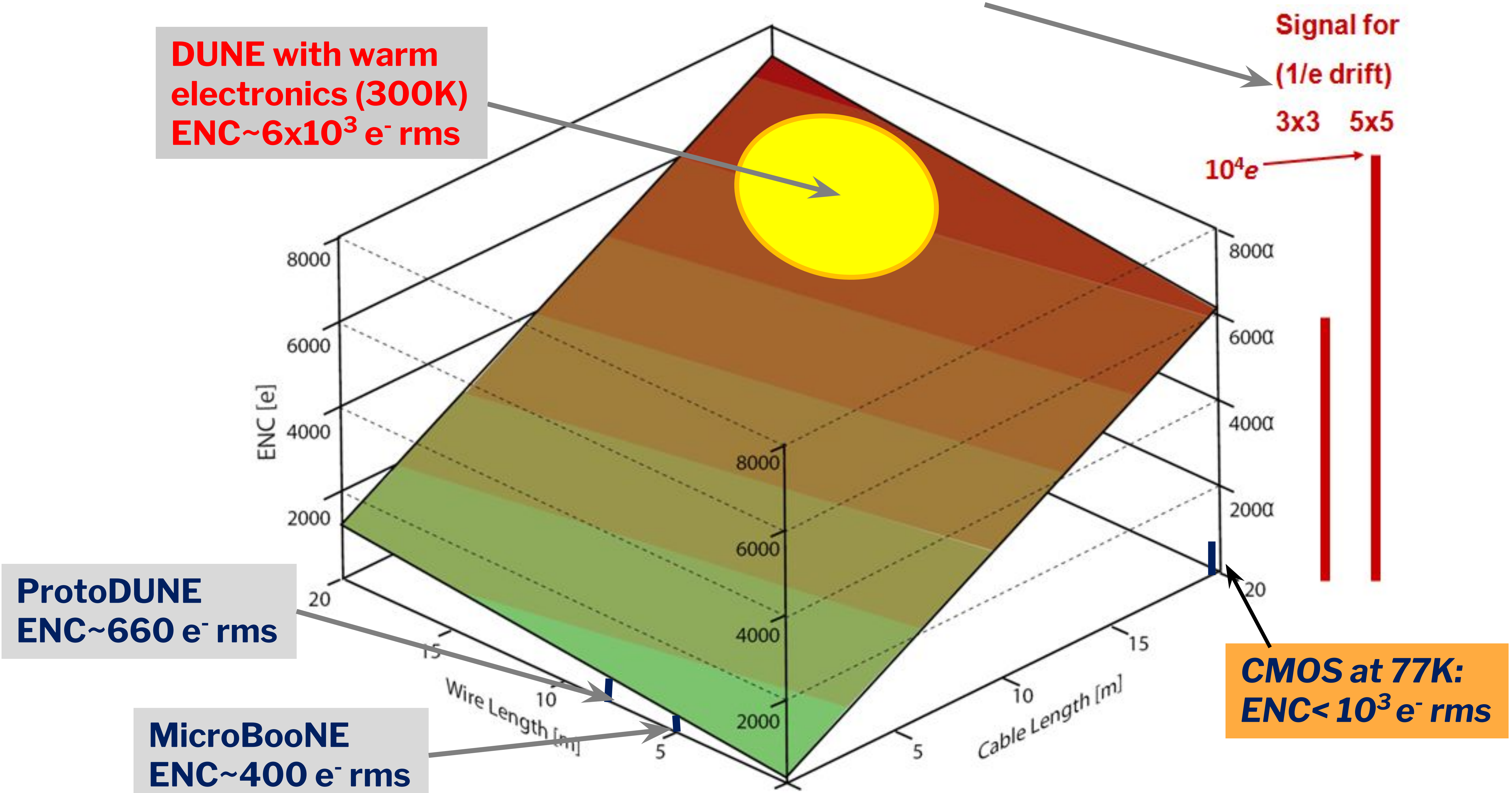
- ***LAr technologies are also at the heart of BNL efforts to explore the neutrino sector - the other unfinished piece of the Standard Model***
- ***BNL has engaged in a series of accelerator based neutrino experiments:***
  - ***MicroBooNE → ProtoDUNE → SBND → DUNE***
  - Great ***synergy*** with the technical developments made for ATLAS and prior experiments
- ***Neutrino physics requires a world-class neutrino observatory and nucleon decay detector with large mass (> 10kt) - LAr TPC***
- ***Cold electronics developed at BNL is an enabling technology, which makes giant LAr TPC realizable, and makes it possible to reconstruct neutrino interactions with image-like precision and unprecedented resolution***

How Does LAr TPC Work? Detecting Signals Induced by Drifting Electrons

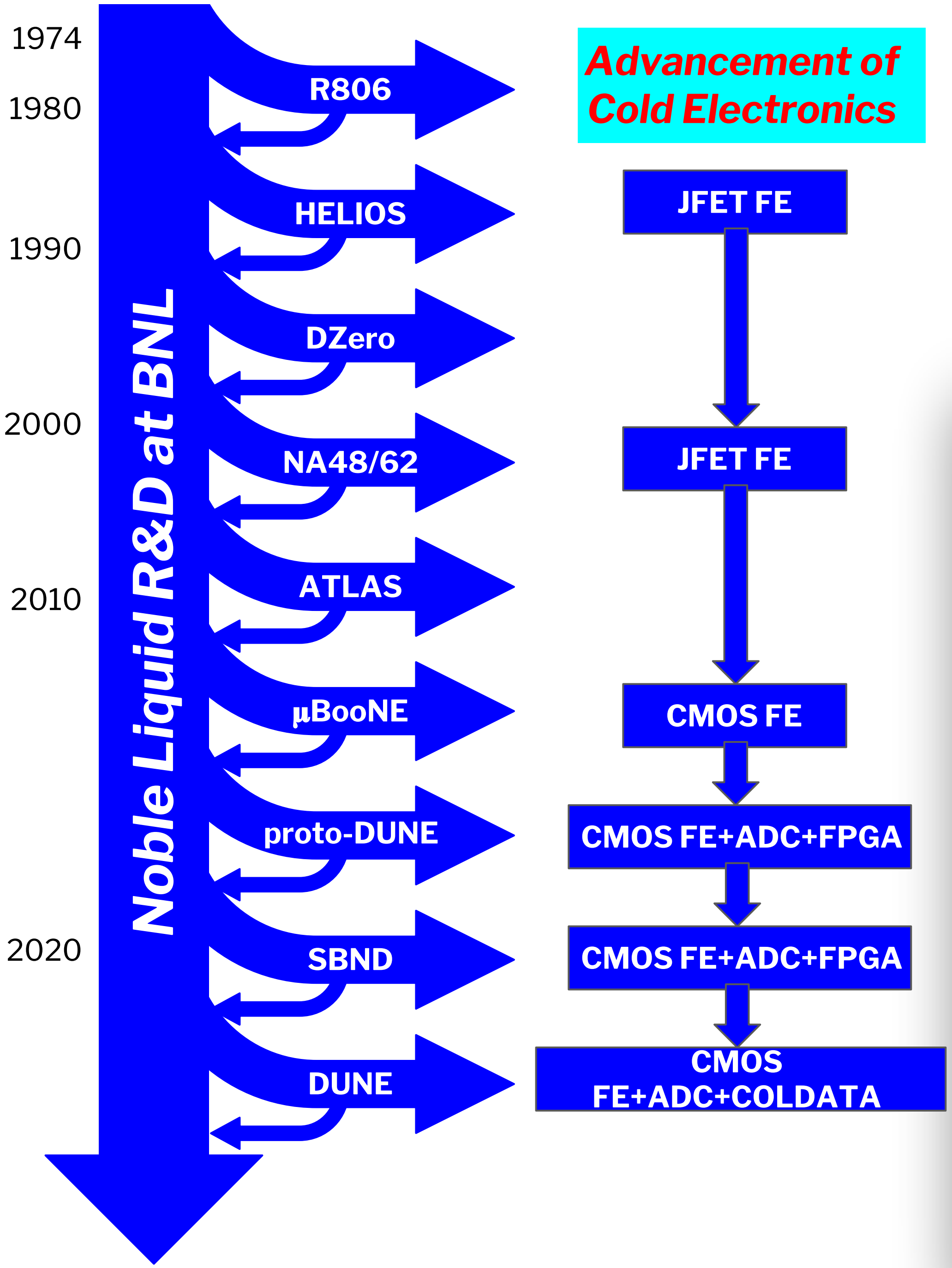


Noise (ENC) *vs* TPC Sense Wire and Signal Cable Length for CMOS at 300K and 89K

MIP Signal for 3x3 and 5x5 mm Sense Wire Spacing



Long History of Noble Liquid Detector R&D at BNL



- ***Cold electronics* decouples the electrode and cryostat design from the readout design**
- ***Signal multiplexing* results in large reduction in the quantity of cables (less outgassing) and the number of feedthroughs/cryostat penetrations**

1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment IOP Publishing
Journal of Physics: Conference Series **308** (2011) 012021 doi:10.1088/1742-6596/308/1/012021

Cold electronics for "Giant" Liquid Argon Time Projection Chambers

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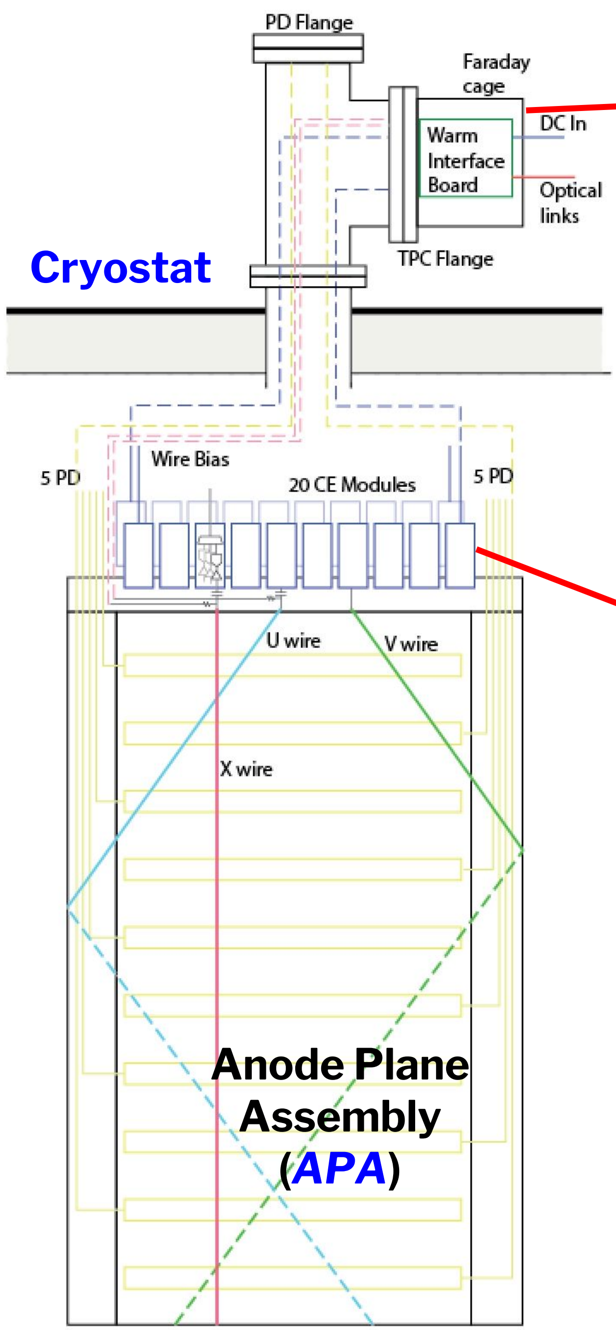
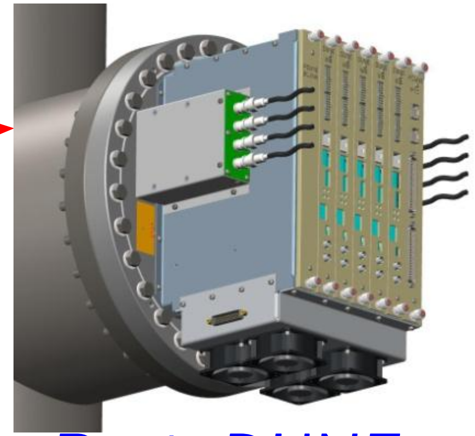
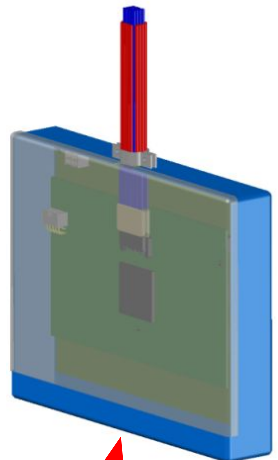
Abstract. The choice between cold and warm electronics (inside or outside the cryostat) in very large LAr TPCs (>5-10 ktons) is not an electronics issue, but it is rather a major cryostat design issue. This is because the location of the signal processing electronics has a direct and far reaching effect on the cryostat design, an indirect effect on the TPC electrode design (sense wire spacing, wire length and drift distance), and a significant effect on the TPC performance. All these factors weigh so overwhelmingly in favor of the cold electronics that it remains an optimal solution for very large TPCs.

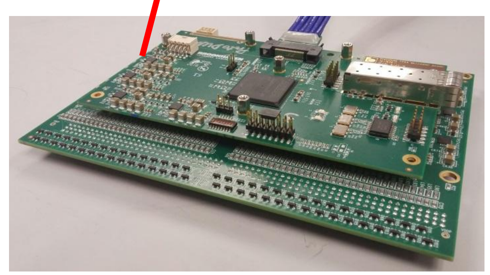
Integral System Design Concept



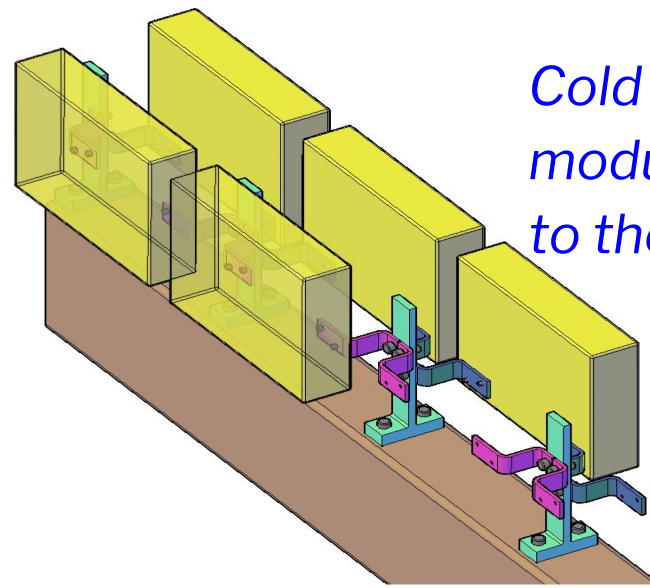


ProtoDUNE



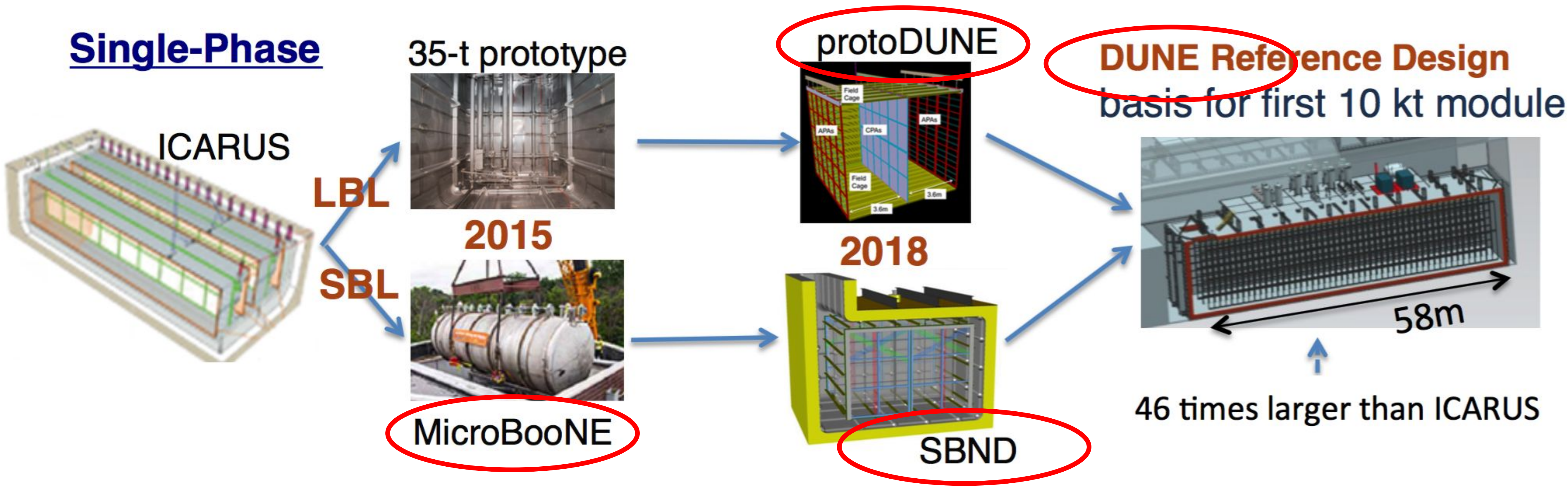


A necessary (but not sufficient!) condition to achieve a good system performance, **the integral design concept** of APA + CE + Feed-through, plus Warm Interface Electronics with **local diagnostics** and strict isolation and **grounding rules** will have to be followed



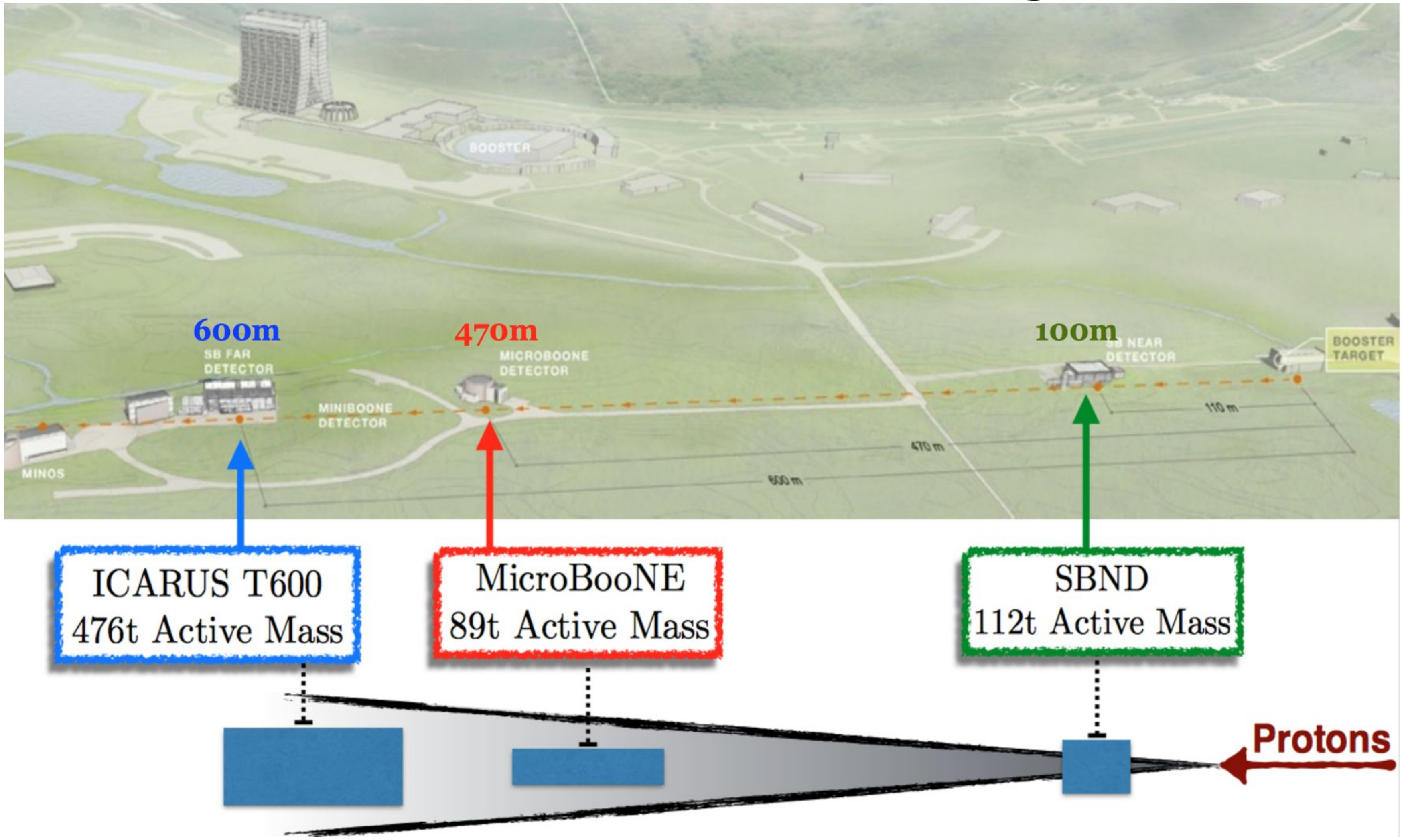
Cold electronics (CE) module and its attachment to the APA frame

LAr TPC Development towards DUNE



BNL is leading TPC readout electronics System Design for MicroBooNE, SBND, ProtoDUNE and DUNE far detector

Short Baseline Neutrino (SBN) Program at Fermilab

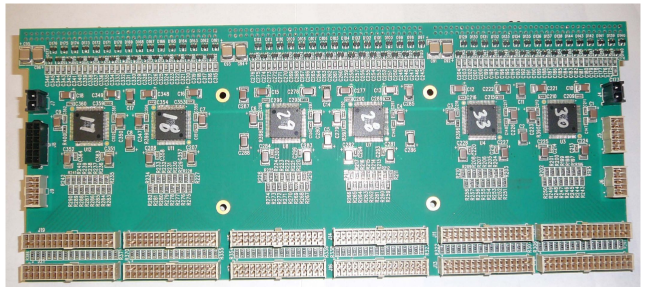


- ***Three detectors with one technology: Liquid Argon TPC to study ν-Argon interaction physics***
- ***MiniBooNE neutrino anomaly study in MicroBooNE Phase-I***
- ***Sterile neutrino oscillation study in SBN Phase-II***

MicroBooNE Experiment

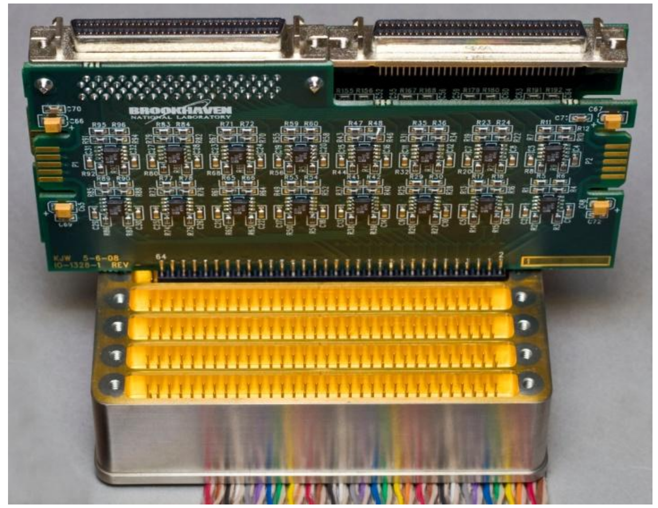
- ***170 ton LAr TPC in the Fermilab Booster Neutrino Beamline***
- ***Technical advances:***
  - Argon fill without evacuation
  - ***Cold front-end electronics***
  - Long drift (2.5m)
  - Near surface operation
  - Automated reconstruction
- ***MicroBooNE is also an important first step in the SBN program***

MicroBooNE Front End Electronics

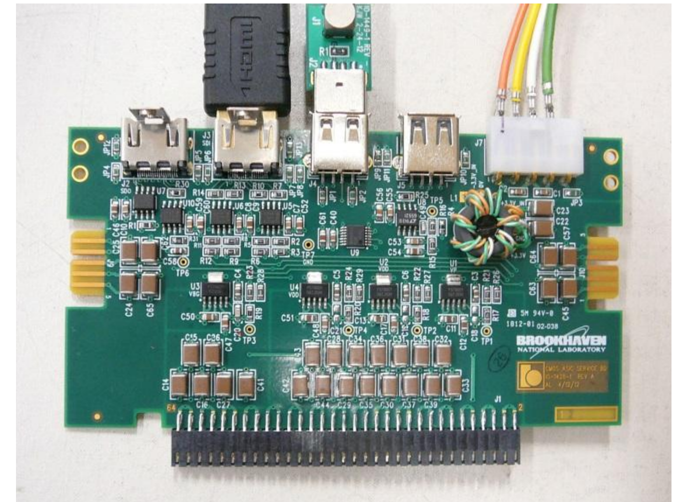


H. Cold Mother Board

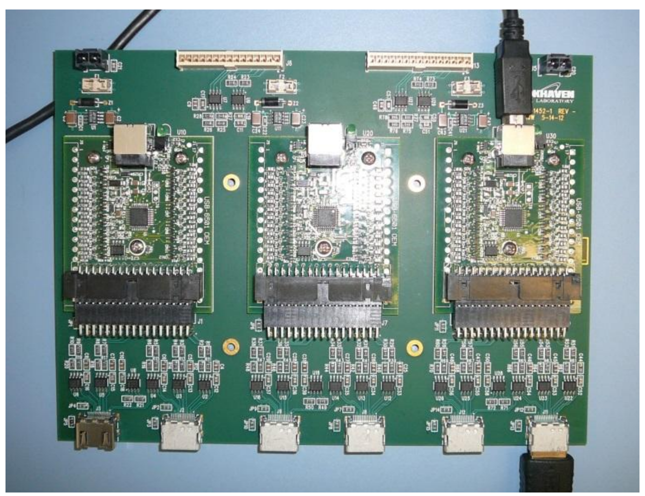
V. Cold Mother Board



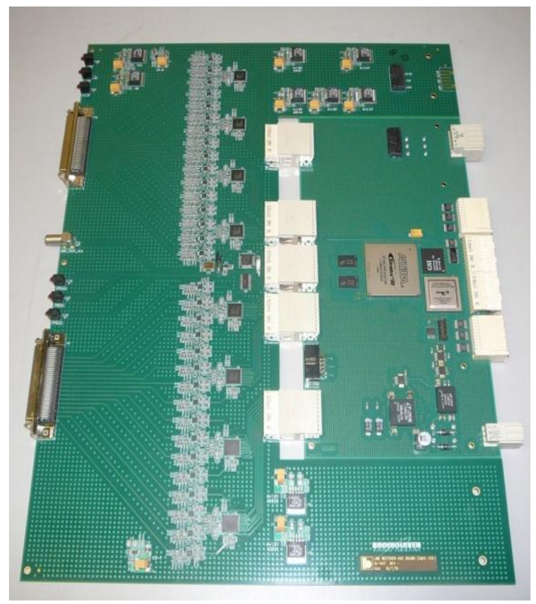
Intermediate Amplifier



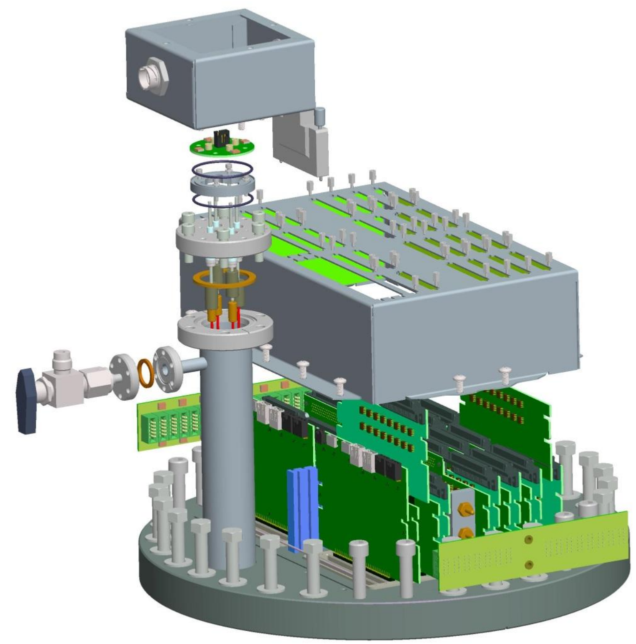
Service Board



ASIC Configuration Board

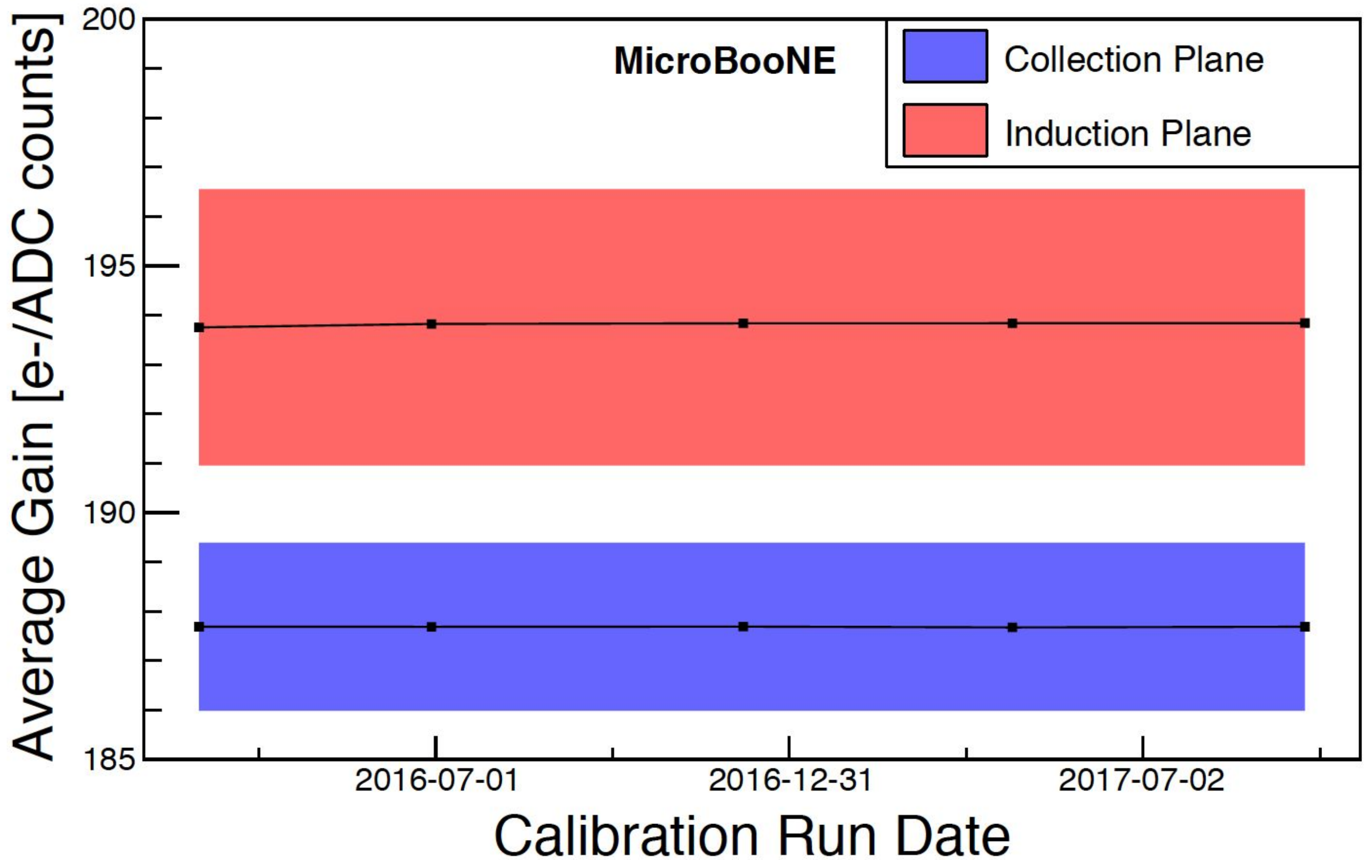


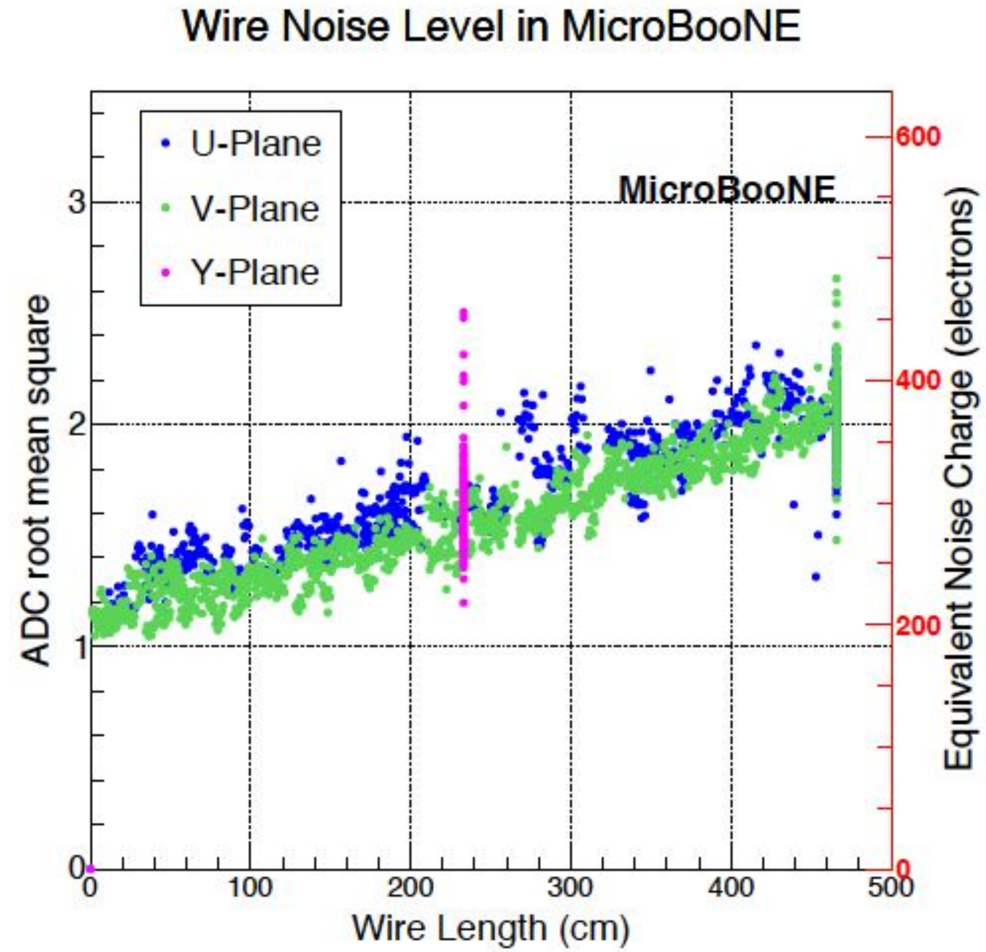
Receiver ADC Board



Signal Feed-through Assembly

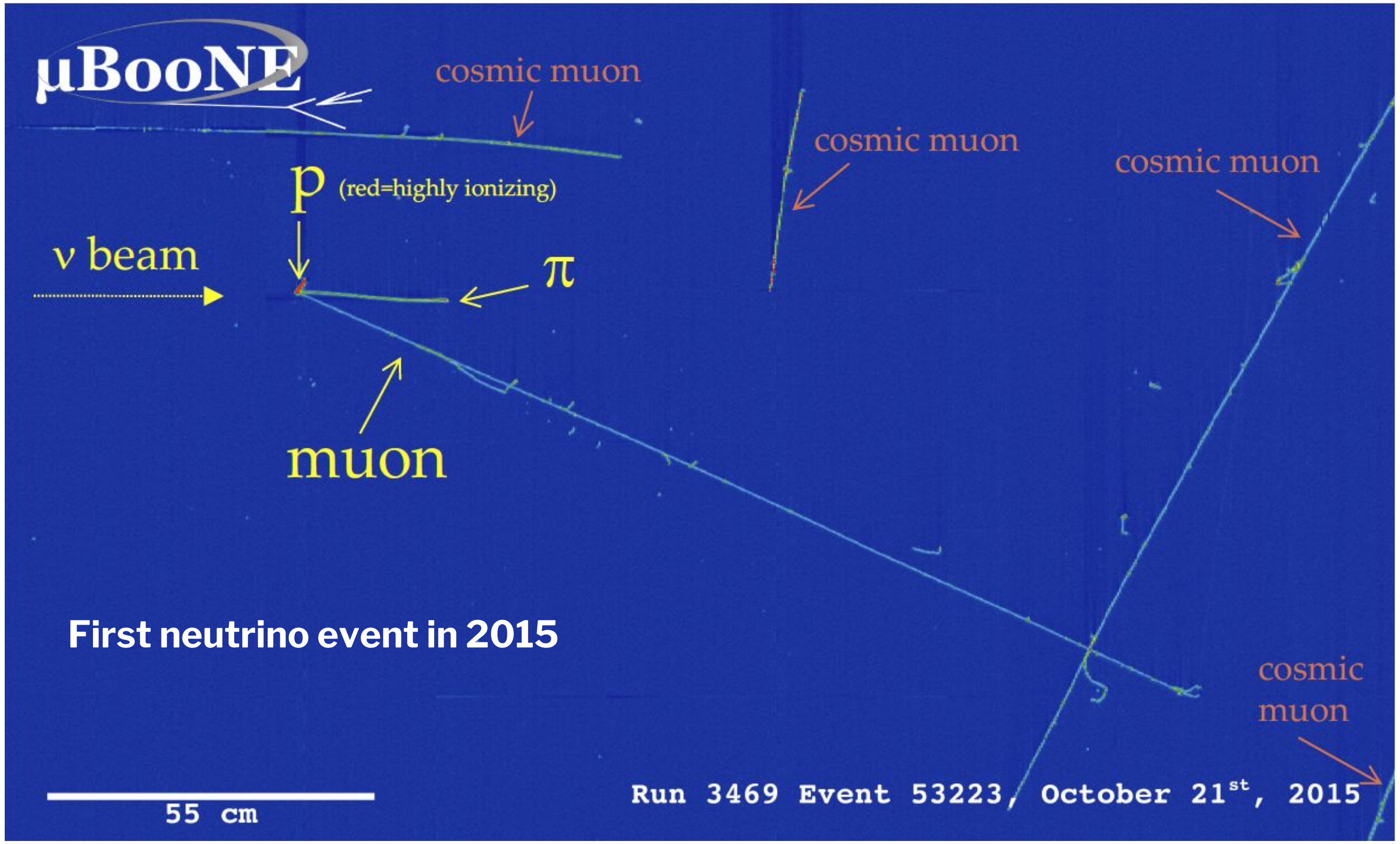
Excellent Stability and Performance of MicroBooNE TPC

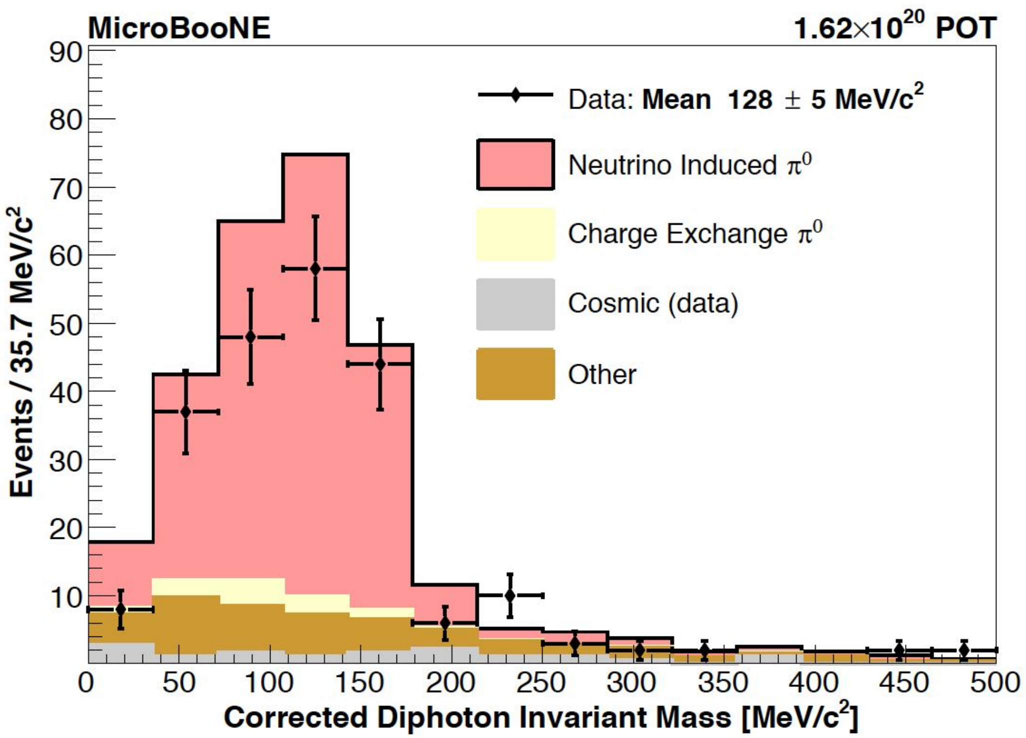




- ***Electronic calibration***
  - Cold electronics gain stable over two year period, ***variation ~0.2%***
- ***Excellent noise performance***
  - ENC after noise filtering is < **400 e^-** for 85% of channels, in agreement with bench tests of FE ASIC

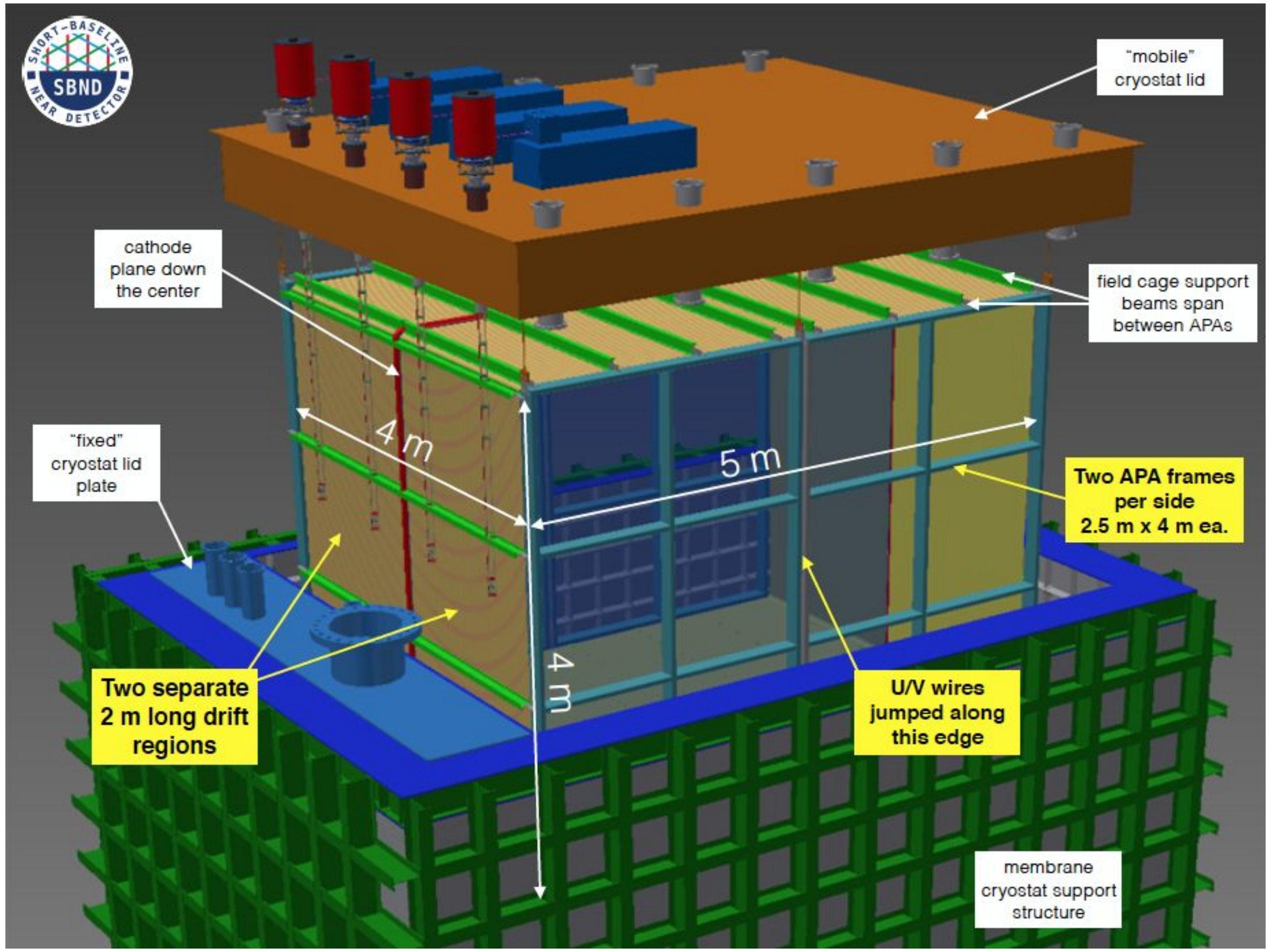
One of the First MicroBooNE Events and Physics Results

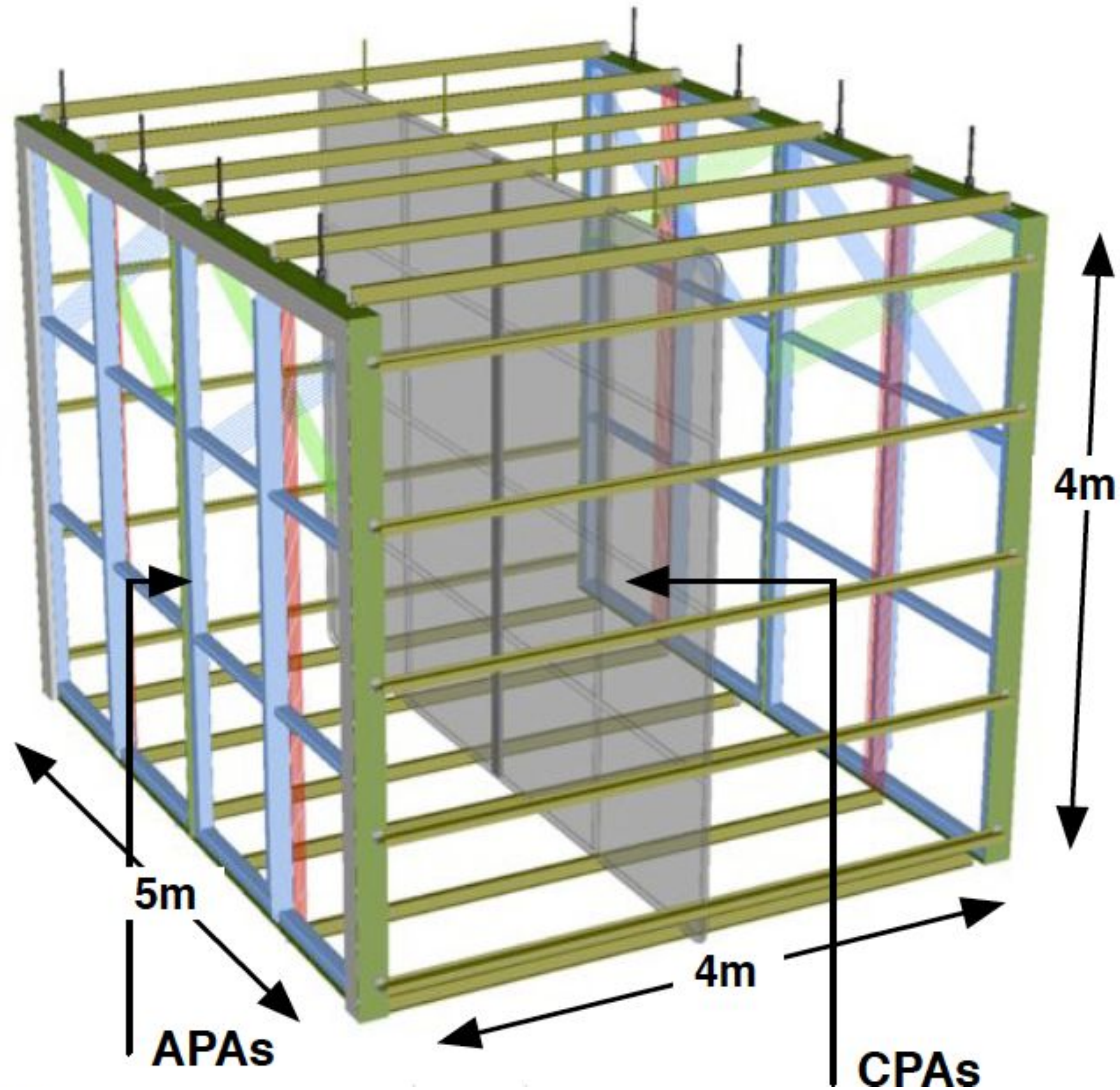




- ***MicroBooNE is the first experiment instrumented with cold CMOS ASICs, total 8,256 channels***
  - S/N is improved by more than **factor of 3** compared to previous large scale LArTPC experiment (e.g ICARUS)
- ***First physic results submitted to PRL***
  - "First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE LAr TPC", arXiv:1811.02700

SBND Experiment

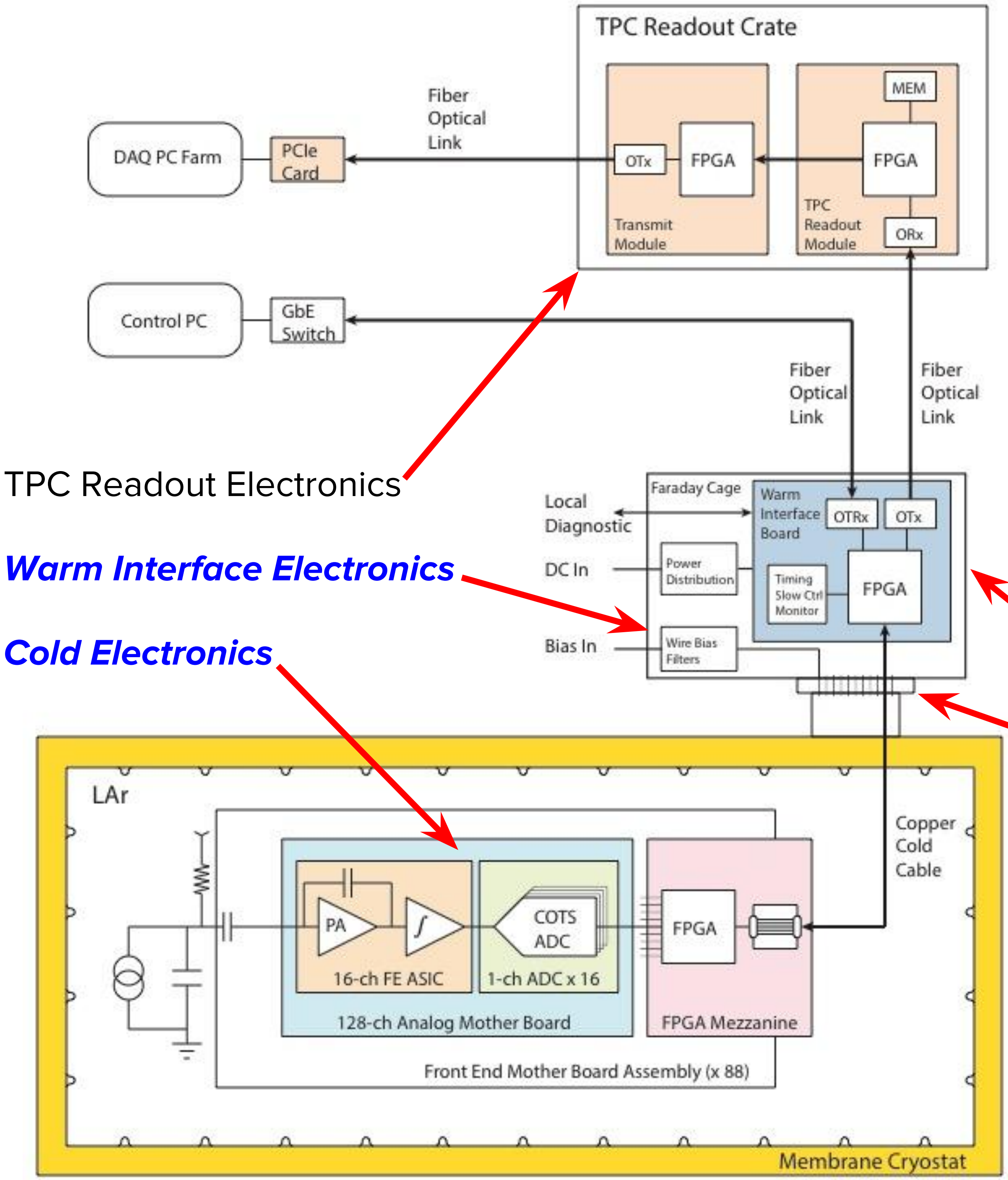




- ***260 ton LAr TPC as near detector in SBN program, started with current DUNE design***
  - Central **cathode plane assembly (CPA)**, two **anode plane assemblies (APA)** on either side w/ 2m drift distance each.

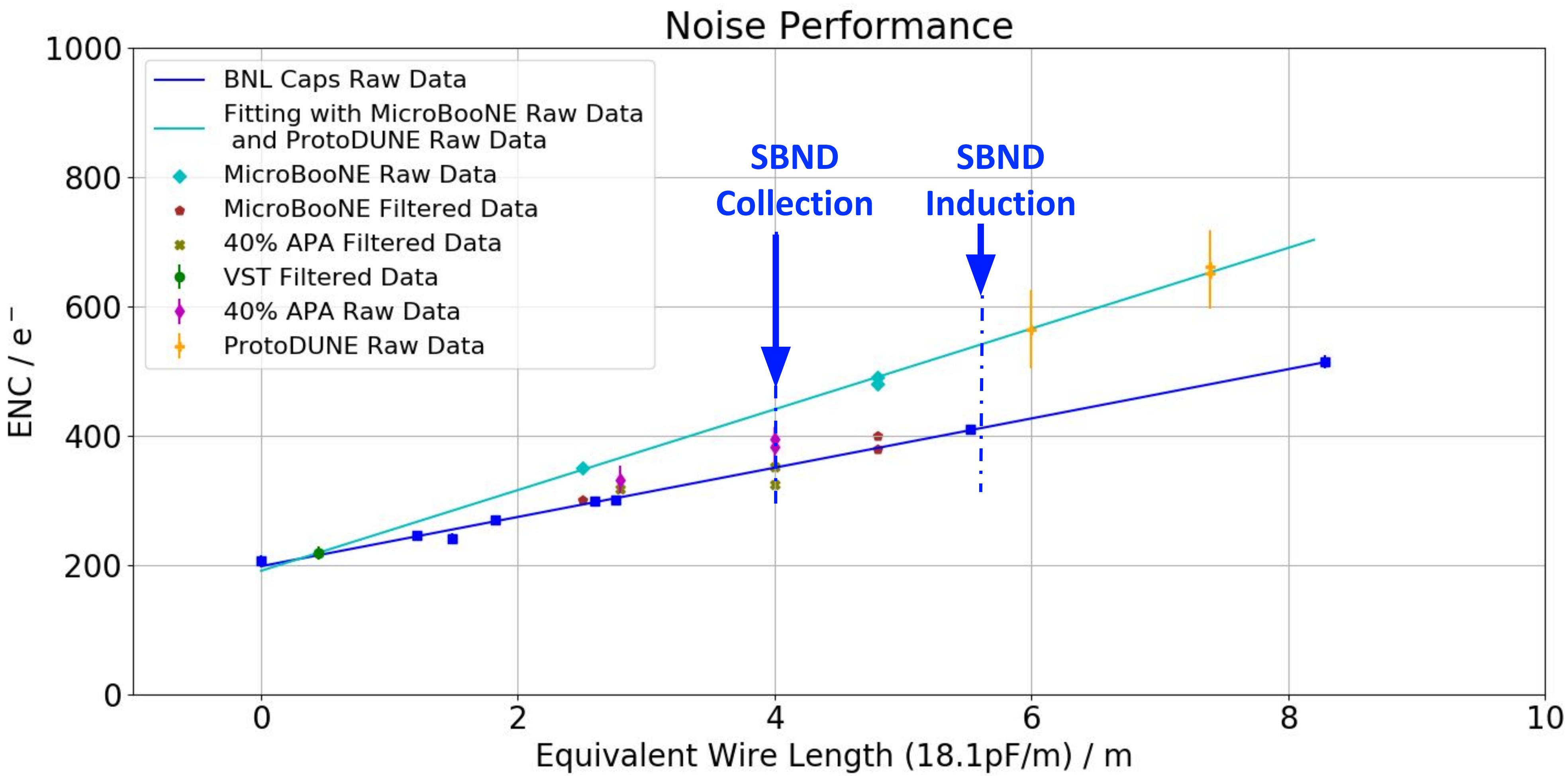
SBND Front End Electronics System

- ***Total: 11,264 channels***
- ***88 Front End Mother Board assemblies***
  - 704 FE ASICs, 11,264 COTS ADCs, 88 Cold FPGAs
  - 4 sets of cold cable bundles, 4 sets of signal feed-throughs
- ***28 warm interface boards with local diagnostics***



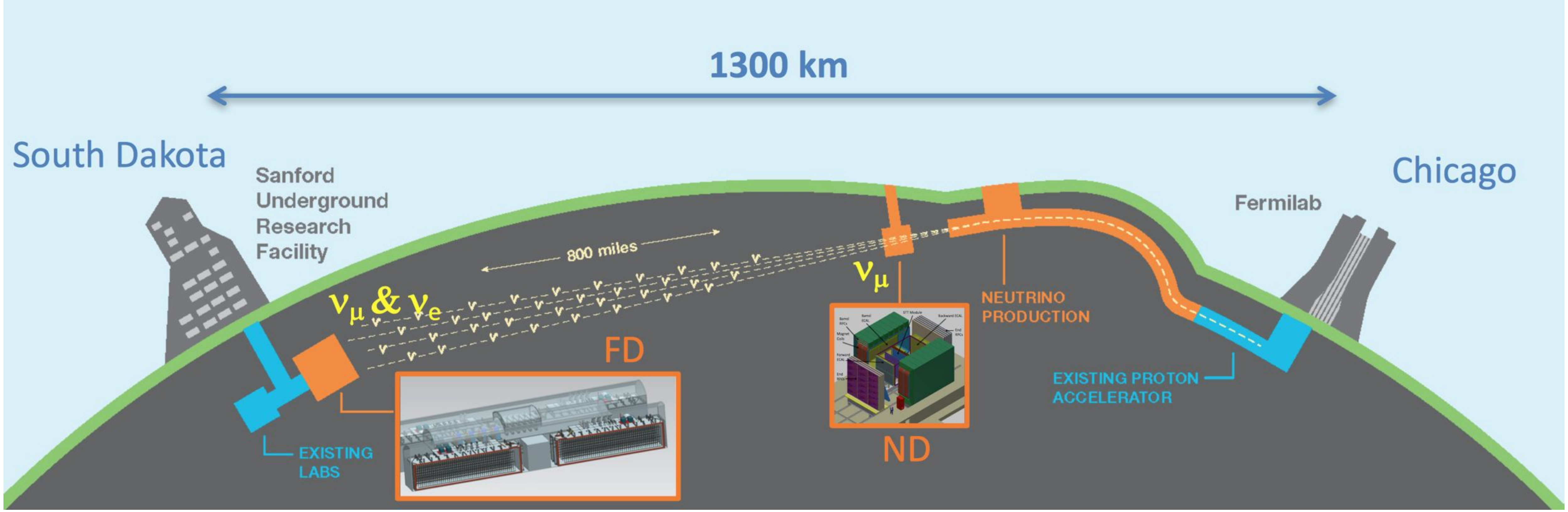
Faraday Cage

Noise (ENC) Projection for SBND



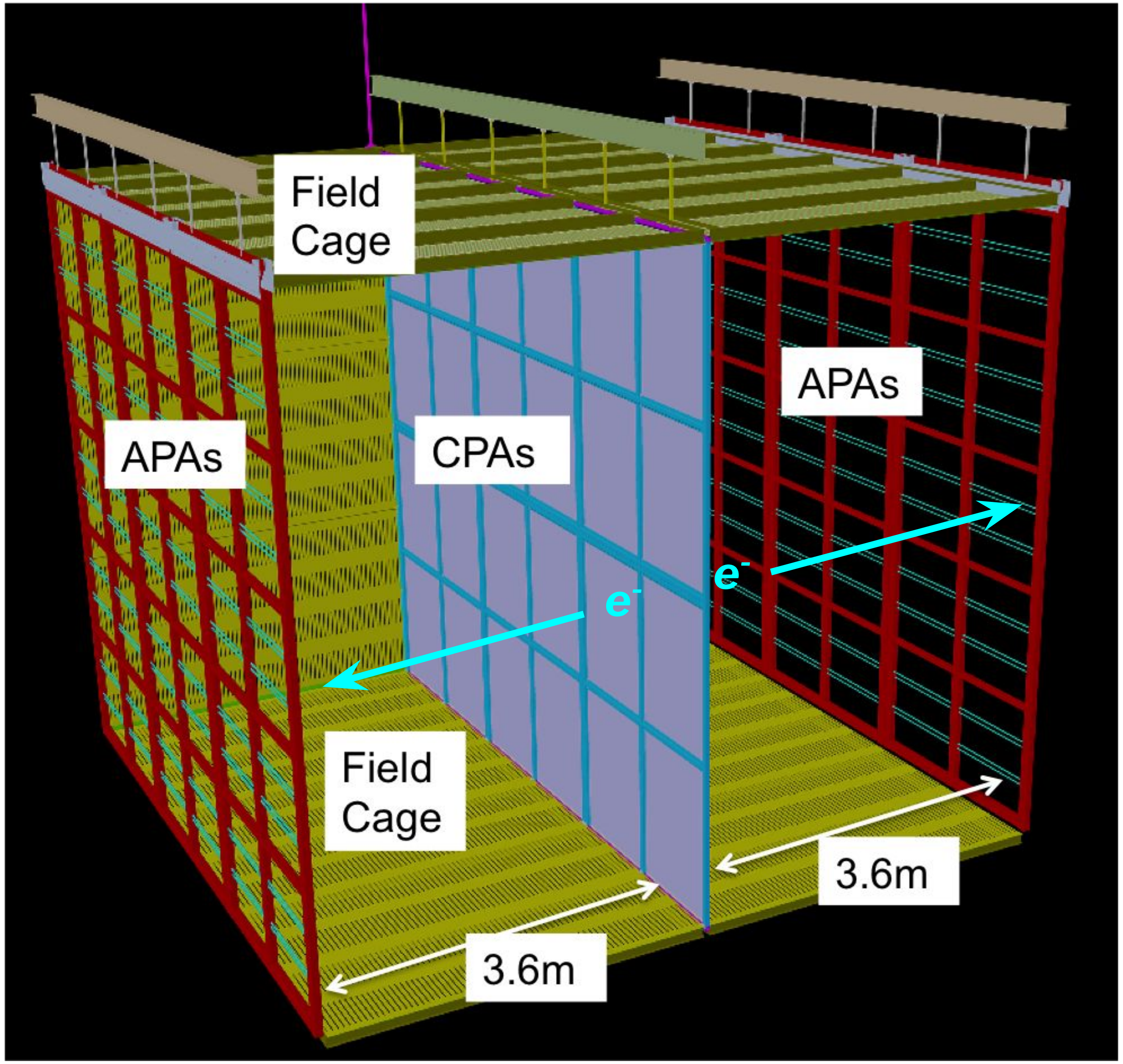
- ***Expected SBND noise performance***
  - Induction plane (5.77m) < **600 e⁻**, collection plane (4.0m) < **500 e⁻**
- ***Expected SBND noise performance after offline filtering***
  - Induction plane (5.77m) ~ **450 e⁻**, collection plane (4.0m) ~ **350 e⁻**

Long Baseline Neutrino Program: LBNF/DUNE



- ***Neutrino beam from FNAL to Homestake: 1,300 km long baseline***
  - Muon neutrinos/anti-antineutrinos from high-power proton beam: 1.07 MW (→ 2.14 MW)
  - Two parallel caverns each have two 10 kt detector pits with a laydown space in between
- ***DUNE primary science program***
  - ***Neutrino Oscillation Physics***: Discover CP Violation in the leptonic sector; Mass Hierarchy; Precision Oscillation Physics
  - ***Nucleon Decay***: e.g. targeting SUSY-favored modes, $p \rightarrow K^{+}\bar{\nu}$
  - ***Supernova burst physics & astrophysics***: Galactic core collapse supernova, sensitivity to ν_e

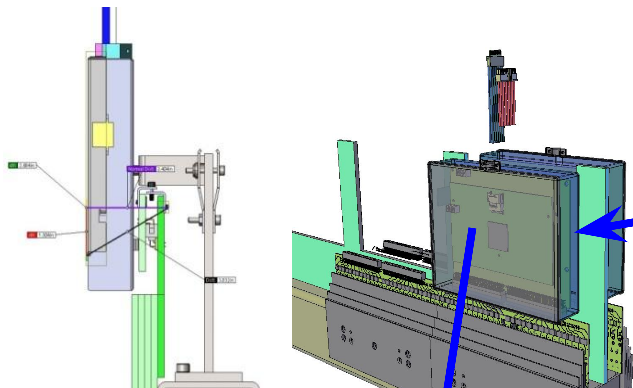
ProtoDUNE Experiment:
Verifying LAr TPC Technologies for DUNE



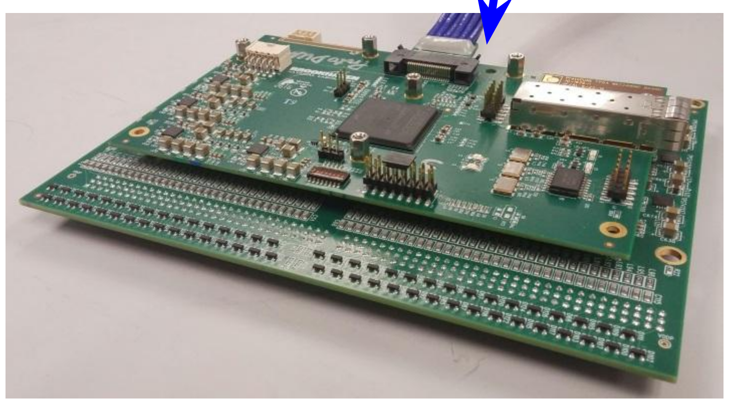
- ***Single-phase LAr TPC prototype***
  - Sit in H4 beam line in EHN1 @ CERN
  - Consisting of 6 full-size APA's plus CPA's → 2 x 3.6m drift regions
  - Total ***15,360*** TPC channels
  - Use photon detectors of different fabrication methods
  - ***Successful operation*** with beam data taking in 2018
- ***A key test platform for DUNE FD:***
  - Components
  - Construction methods
  - Installation procedures
  - Commissioning
  - Detector response to particles

ProtoDUNE Front End Electronics

7m Cold Cables

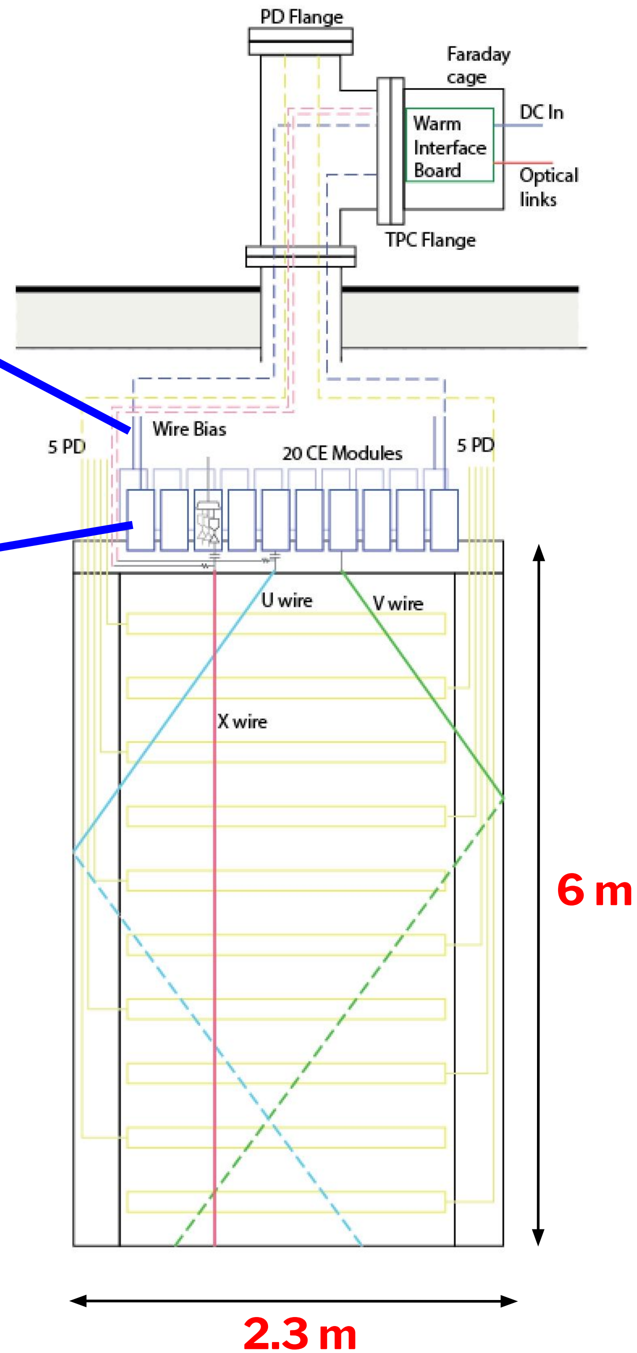


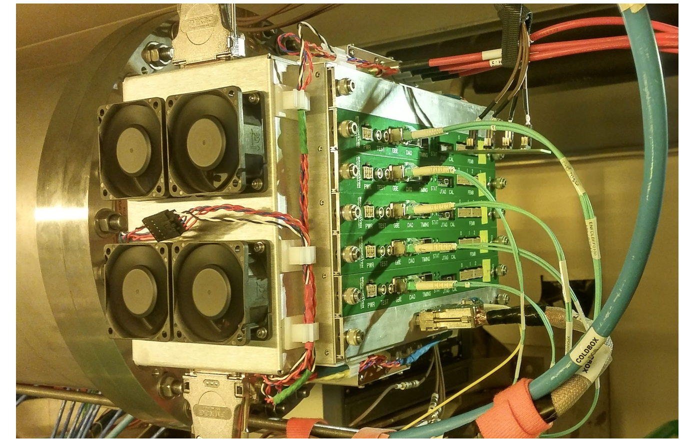
20 CE boxes on APA



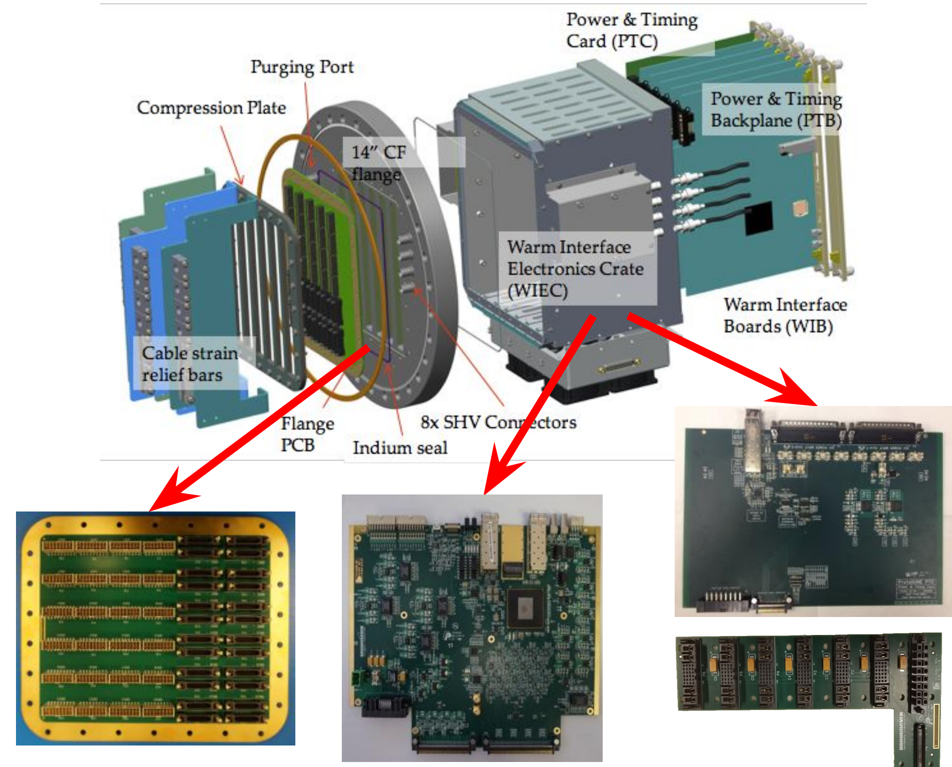
FEMB (inside CE box)

Cold Side



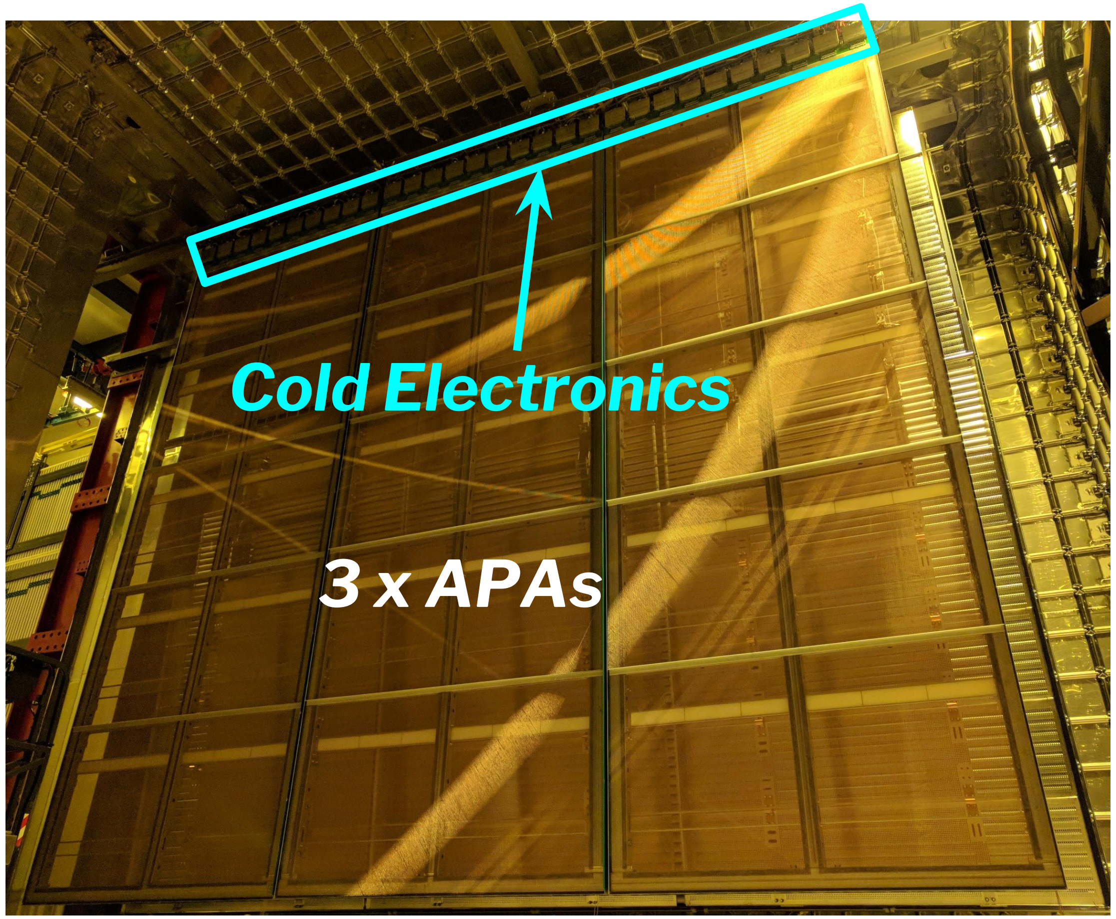


Signal Feed-through Assembly



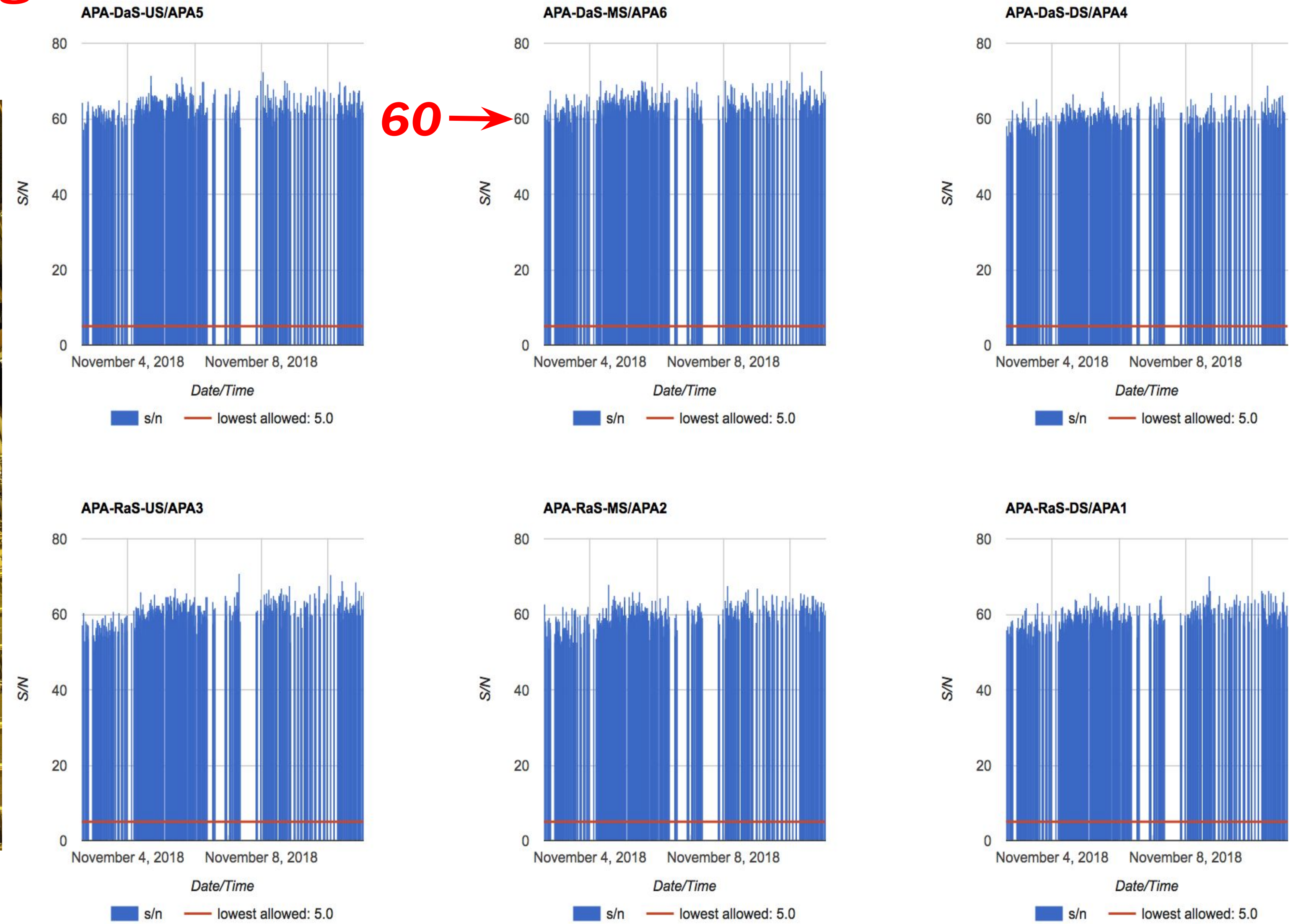
Warm Side

Excellent Performance of ProtoDUNE TPC



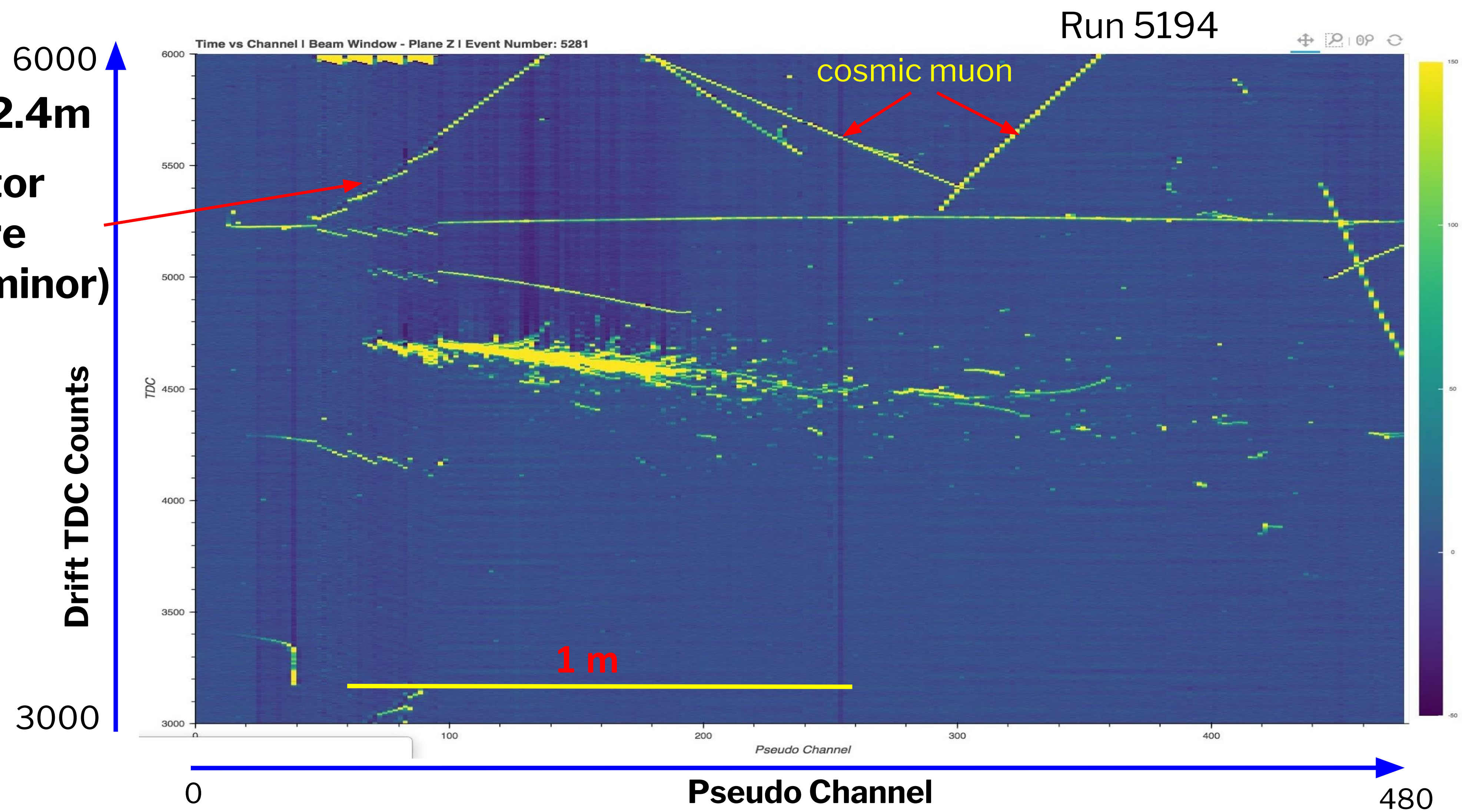
Signal to Noise Ratio

protoDUNE DQM: sn timeline



- ***Noise performance with 180V drift HV and bias on***
  - ENC of collection plane ~**565 e$^-$** , induction planes ~**660 e$^-$**
- ***S/N is ~60:1 for all 6 APAs during ProtoDUNE operation***

An Example of EM Shower in ProtoDUNE

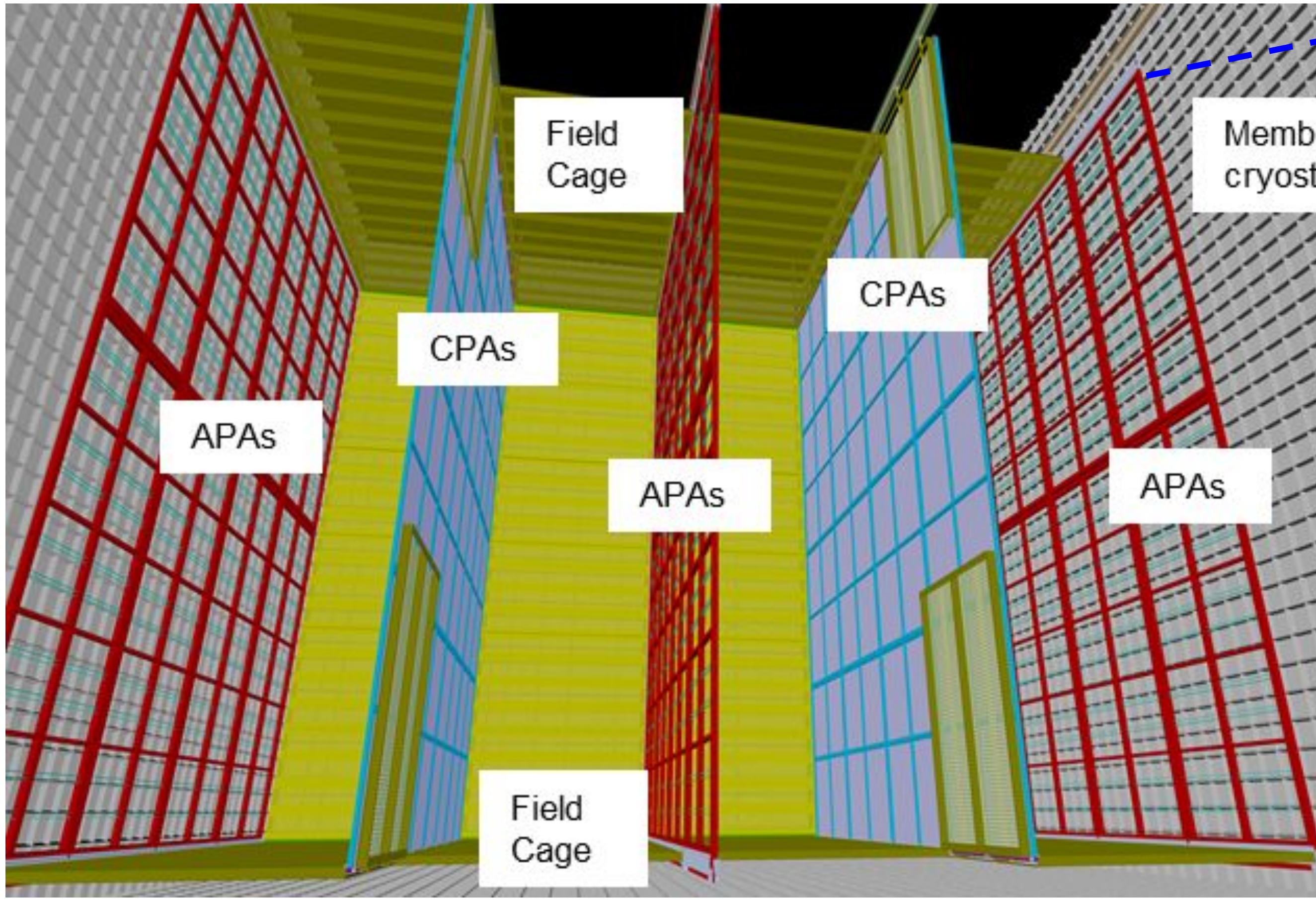


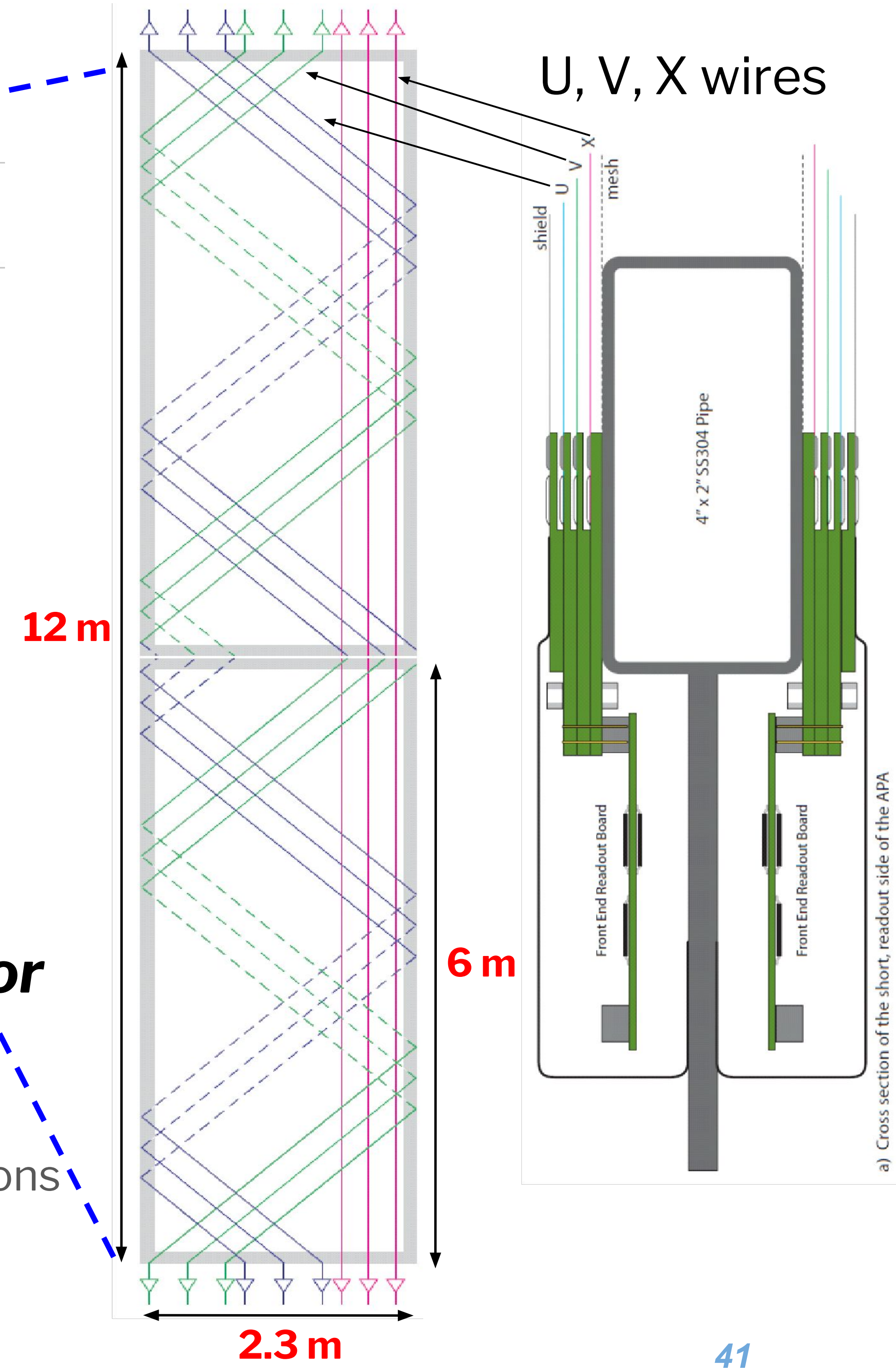
A monitor software glitch (minor)

Charge scale limited to "yellow"~ 3fC for monitoring

From Online Monitoring (Raw Data)

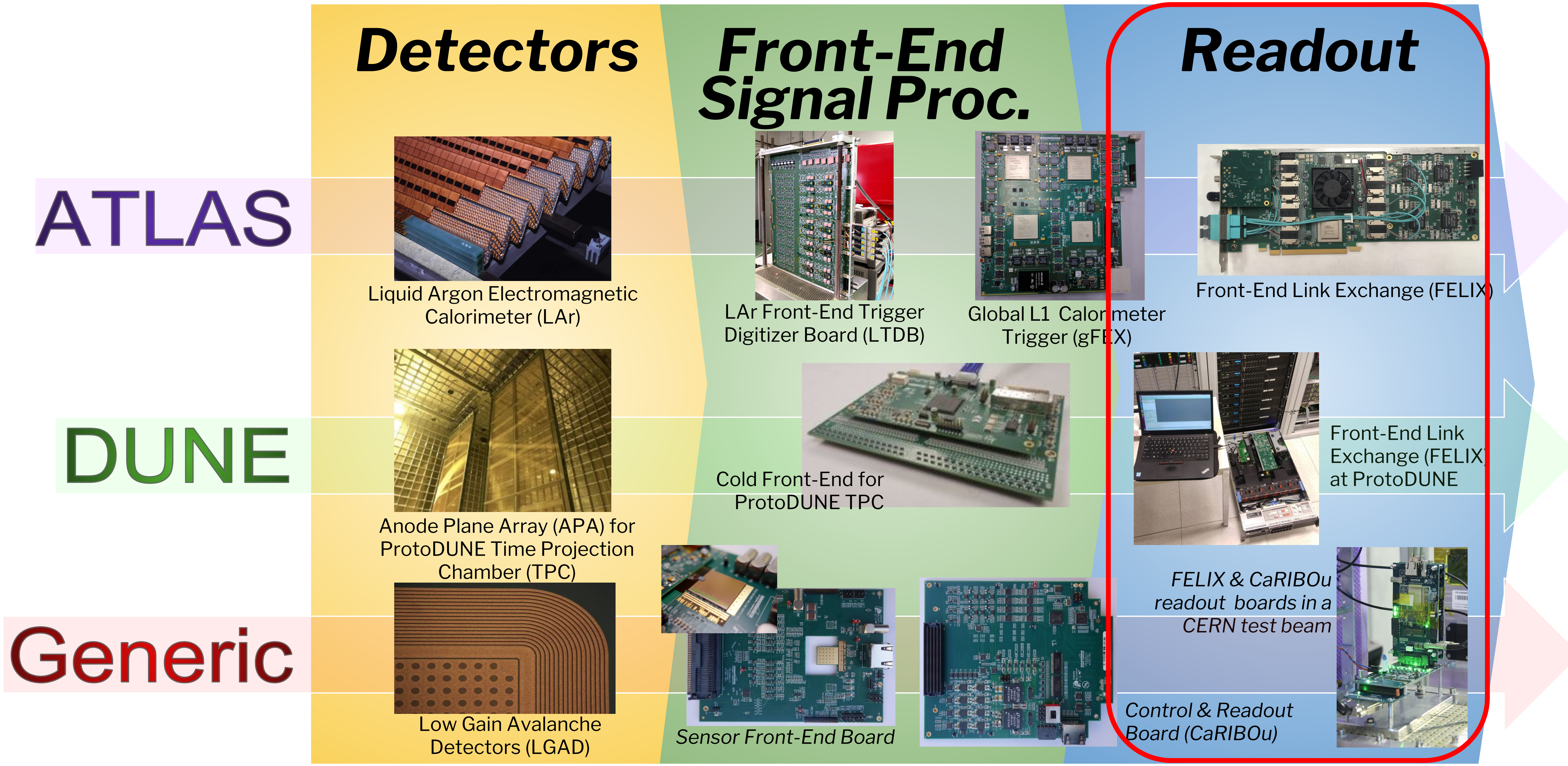
DUNE Far Detector





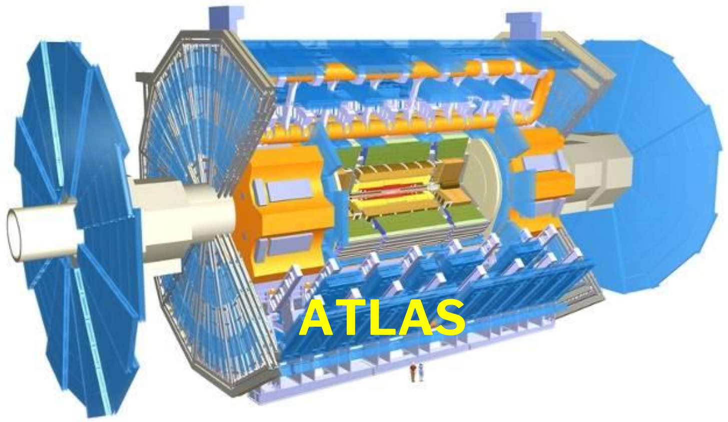
- ***APA, CPA & front end cold electronics system for DUNE far detector***
- ***DUNE 10 kt Far Detector***
  - Consisting of 150 APA's plus 200 CPA's → 4 x 3.6m drift regions
  - Active volume: 12m x 14m x 58m
  - Total ***384,000*** TPC channels

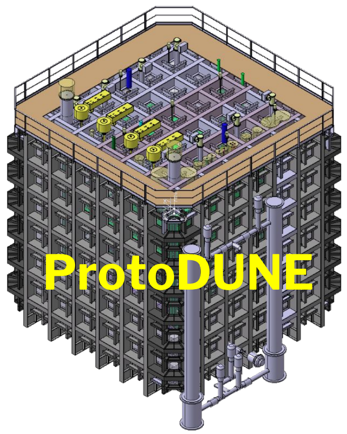
R&D Goal: address challenges in select detectors and electronics technologies to provide integrated solutions for future experiments

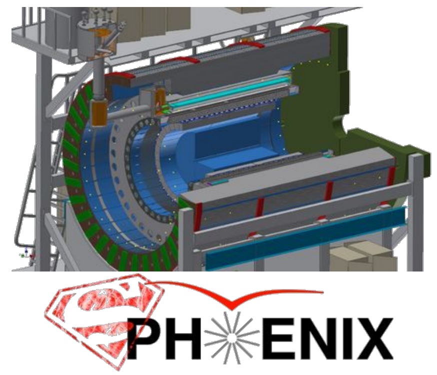


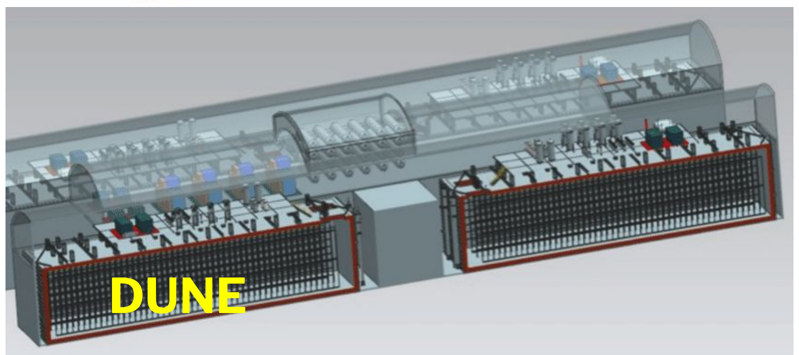
LAr Calorimeter and TPCs → Data Rate Challenge → High-Bandwidth Readout

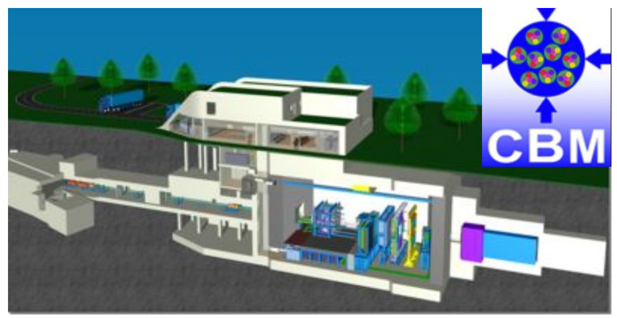
- ***BNL developing electronics for high-bandwidth detector readout***
  - **Front End LInk eXchange** (**FELIX**): A fast elegant interface to DAQ, based on state-of-the-art COTs technology

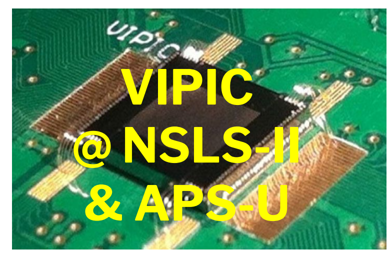


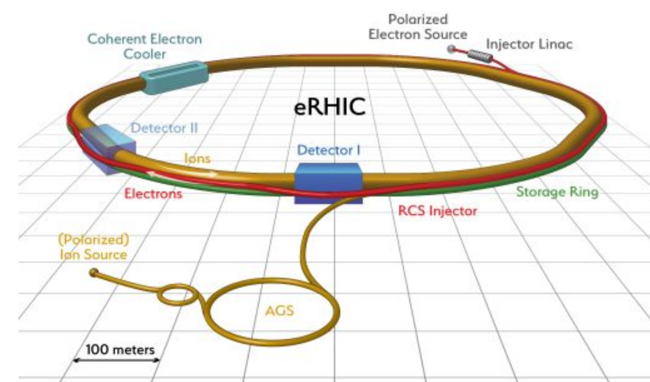


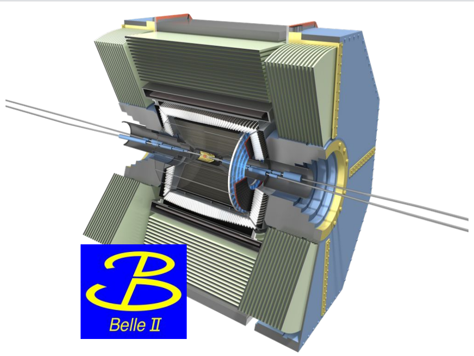


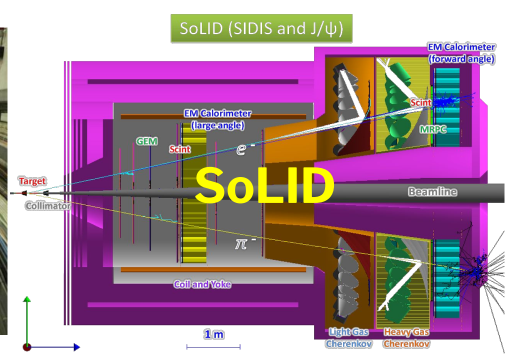


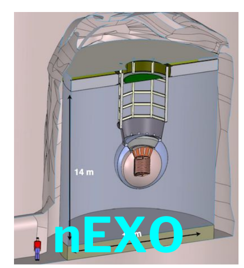


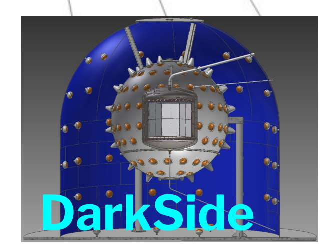




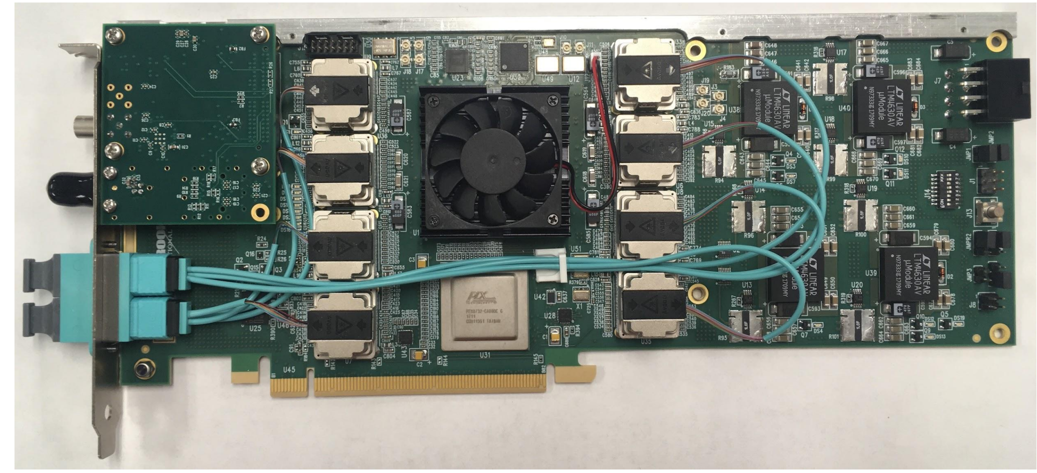








High-Bandwidth Readout - FELIX

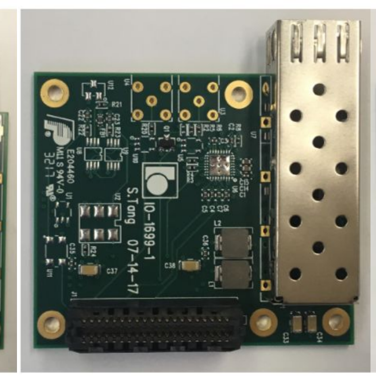


- ***Front End LInk eXchange (FELIX)***
  - BNL designed hardware & co-developed firmware
  - **Generic PCIe card** with Kintex Ultrascale FPGA
    - 48-channels Tx & Rx links in 8 miniPODs
    - PCIe Gen3 x16 lanes interface to host
    - **Supports versatile line rates & timing systems**
  - Throughput:
    - **460 Gb/s** input/output via optical fiber
    - Up to **128 Gb/s** to host PC

Collaboration between BNL, ANL, Bologna, CERN, FNAL, Irvine, Nikhef, UCL and Weizmann

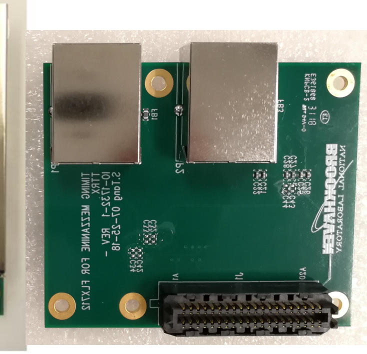
- ***Planned upgrades for ATLAS on HL-LHC and DUNE***
  - Xilinx Virtex Ultrascale+ FPGA
  - **PCIe Gen4 x16 lanes**
  - **48x 25Gb/s** fiber optical links
  - **24x 25Gb/s** serial links to FMC+ mezzanine

TTC



TTC-PON

White Rabbit



TTD

Concluding Remarks (1)

- ***BNL plays a leading role, defining readout architecture, in the ATLAS LAr calorimeter construction and upgrades***
  - This work resulted in the 2012 ***Higgs discovery*** with strong BNL leadership
  - Upgrades will expand our reach in the search for ***new physical phenomena***
- ***Readout electronics developed at BNL for low temperatures (77K-300K) is an enabling technology for noble liquid detectors for neutrino experiments***
  - ***To capture exciting physics*** from both short baseline and long baseline neutrino programs
- ***Generic detector R&D at BNL will address challenges in select detectors and electronics technologies***
  - ***Noble liquid detector*** for both energy and intensity frontiers, and ***FELIX*** based detector readout, in addition to ***silicon*** detectors
  - To provide ***integrated solutions*** for future experiments and get ready for ***new physics discoveries***

Concluding Remarks (2)

- ***2014 P5 report identified five science drivers***
  - ***Use of the Higgs boson as a tool for further inquiry***
  - ***Investigation of the physics of dark matter***
  - ***Exploration of new particles, interactions, and physics principles***
  - ***Investigation of the physics of neutrino mass***
  - ***Investigation of the physics of dark energy and cosmic inflation***

ATLAS, Phase-I and HL-LHC Upgrades (first three drivers)

MicroBooNE, SBND ProtoDUNE, DUNE (new particles; neutrino mass)

LDRD on 21-cm Readout (dark energy and cosmic inflation)

- ***BNL is leading the design and realization of large physical scale LAr detectors in HEP experiments for high precision measurements***
  - These detectors have ***excellent uniformity and stability, high precision calibration and low noise***
  - Developments of these two LAr detector techniques have made BNL particle physics program more ***competitive***
- ***I have been privileged to have the opportunity to work with many colleagues on LAr detectors and readout electronics systems***
  - Focusing on the overall system optimization for ***integrated detector and readout***, inspired by experimental requirements and our physics interest
  - Found common approaches and techniques in implementation of ***LAr detectors in different frontiers*** to satisfy these requirements