Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Dual Calorimetry and 6-D Tracking with LArTPC for Physics Discovery

PI: Chao Zhang (PO), Bo Yu (IO)

Other Investigators: Shanshan Gao (PO), Xin Qian (PO), Hucheng Chen (PO), Steve Kettell (PO), Sergio Rescia (IO), Thomas Tsang (IO), Veljko Radeka (IO)

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FY2023 NPP LDRD Type A Proposal

Proposal title: Dual Calorimetry and 6-D Tracking with LArTPC for Physics Discovery

Primary Investigator: Chao Zhang (PO), Bo Yu (IO)

Other Investigators: Shanshan Gao (PO), Xin Qian (PO), Hucheng Chen (PO), Steve Kettell (PO), Sergio Rescia (IO), Thomas Tsang (IO), Veljko Radeka (IO)

Indicate if this is a cross-directorate proposal. Yes _X__ No___

If yes, identify other directorates/organizations: IO

Program: HEP

Proposal Term: 3 years From: 10/2022 To: 9/2025

Total funding per year in FY23, FY24 and FY25: $500K/y

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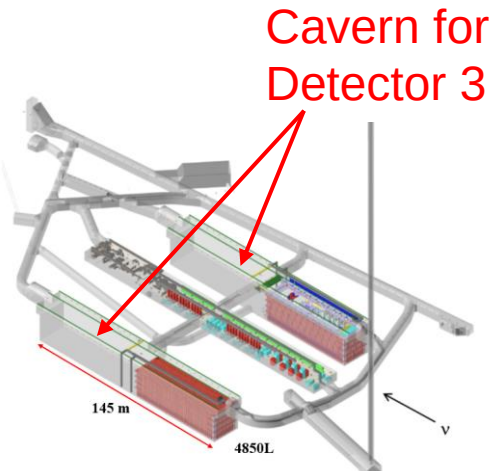
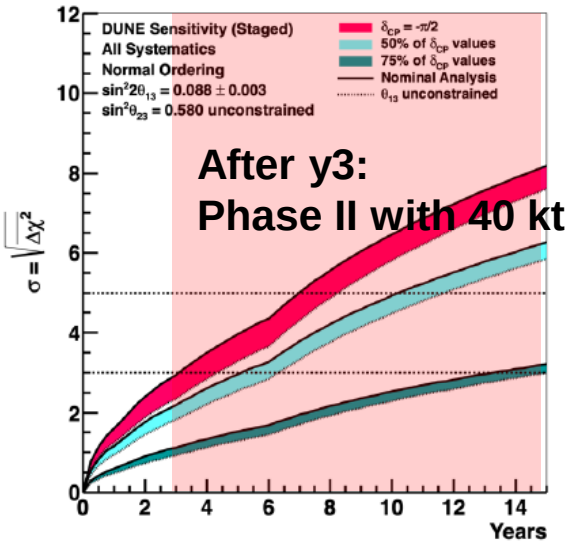
Motivation: DUNE Phase-II FD3&4

- 2014 P5 goals for DUNE:
  - Discover leptonic CP-violation at 5σ for >50% of δ_{CP} values
  - ν mass ordering, PMNS mixing matrix unitary test (θ_{23}, θ_{13}), proton decay, supernova ν, etc.
- Phase I: two 10-kt LArTPC far detectors
  - FD1: horizontal drift (large BNL contribution)
  - FD2: vertical drift (BNL-led project)
- Phase II: two more 10-kt FDs
  - Required to fully reach original P5 goal
  - Upcoming SNOWMASS process is crucial to endorse this vision of full scope of DUNE in the updated P5
  - Opportunities to improve technology and reduce cost
  - Position BNL for leadership of FD3&4



DUNE Far Site

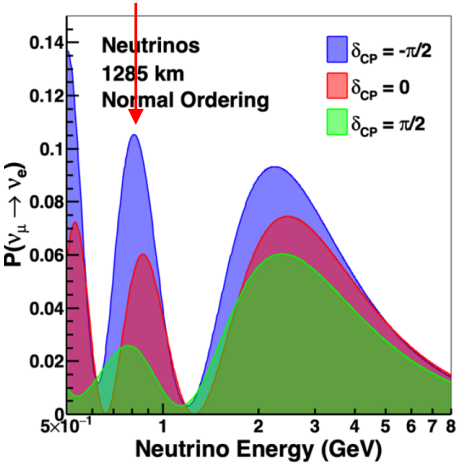


CP Violation Sensitivity

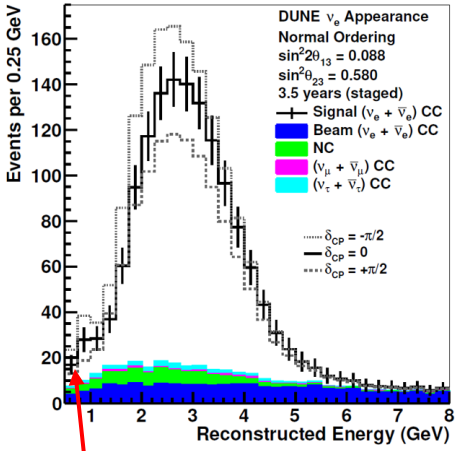
Improve neutrino energy resolution with DUNE FD3&4

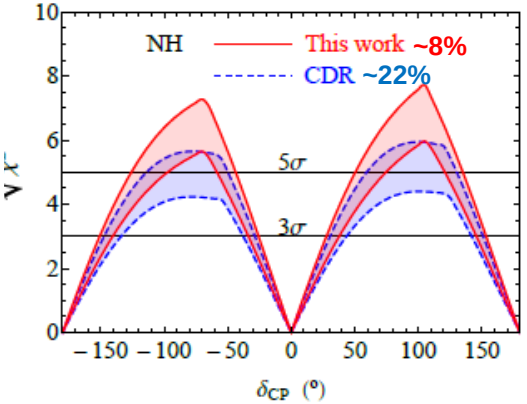
- Improve ν_e energy resolution from ~13% (TDR) to <8% will have a huge implication
  - Significant improvement of 5σ coverage of δ_{CP} phase space and the resolution of δ_{CP} (<10º)
  - Bigger gain than PIP III 3MW beam (*PRD 103:116003, 2021*)
- Proposed methods to improve neutrino energy resolution
  - **Reduce e^- recombination dispersion**: dual calorimetry using both charge and light (anti-correlation)
  - **Improve hadronic energy resolution**: 6-D tracking (3-D spacial trajectory, time, dQ/dx, and dL/dx) to achieve better PID
- Other benefits from the proposed work
  - Significantly improve proton decay $p \rightarrow K^+\bar{\nu}$ detection efficiency (TDR 30% → 90%)
  - Much more capable low energy physics program (supernova ν, solar ν, etc.)

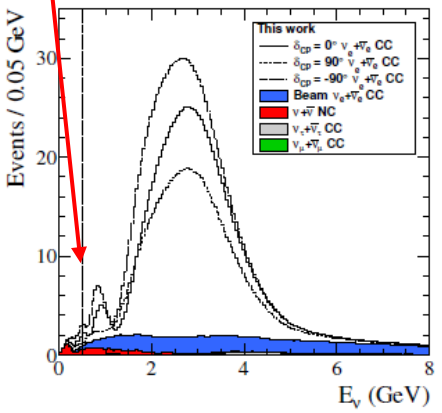
Larger CP effect at 2nd oscillation maxima



TDR: δE~13%

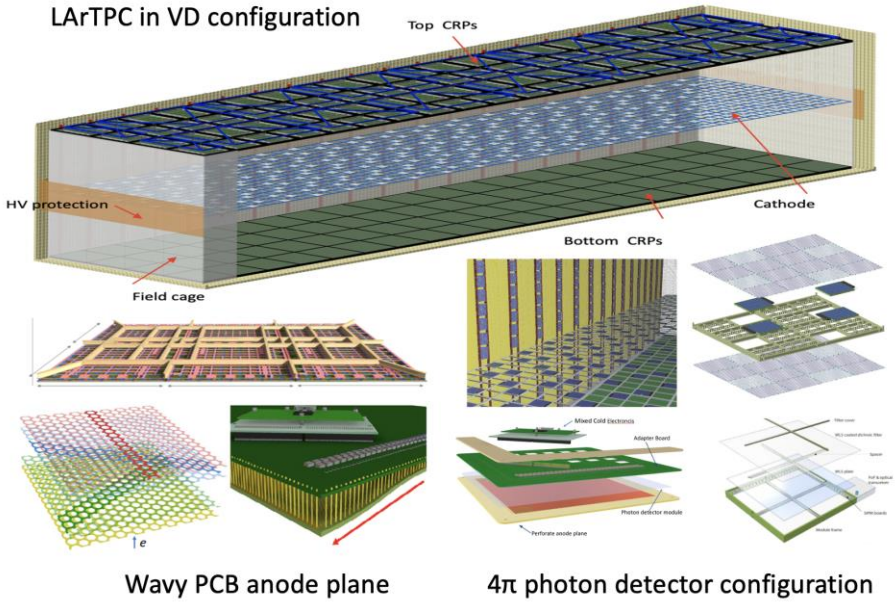






JHEP 09 (2016) 030: δE~8%

Dual Calorimetry: Improving Light Collection and Charge Resolution



Experiment	PD for each TPC	# of Face	Face Coverage	Surface Coverage
MicroBooNE	8-inch PMT	1	4.3%	~0.9%
ICARUS	8-inch PMT (cathode half transparent)	1	5.1%	~1.6%
SBND	8-inch PMT + X-ARAPUCA, (reflector)	1	16.5%	~4.4%
DUNE-HD	X-ARAPUCA	1	8.4%	~3%
DUNE-VD	X-ARAPUCA	3 (cathode and two long walls)	14.8% cathode, 7.4% long walls * 2	~5%
Proposed based on VD concept	**X-ARAPUCA, (reflector)**	**6**	**30% long walls, 30% short walls, 25-30% cathode, 1% anode,**	**~25%**

- R&D to reach 25% surface 4π coverage of photon detectors: x8 larger than FD1 (x5 larger than FD2)
  - bottleneck: power and data throughput of PD electronics readout
- R&D of “wavy” PCB anode plane to resolve topological ambiguities with projective charge readout

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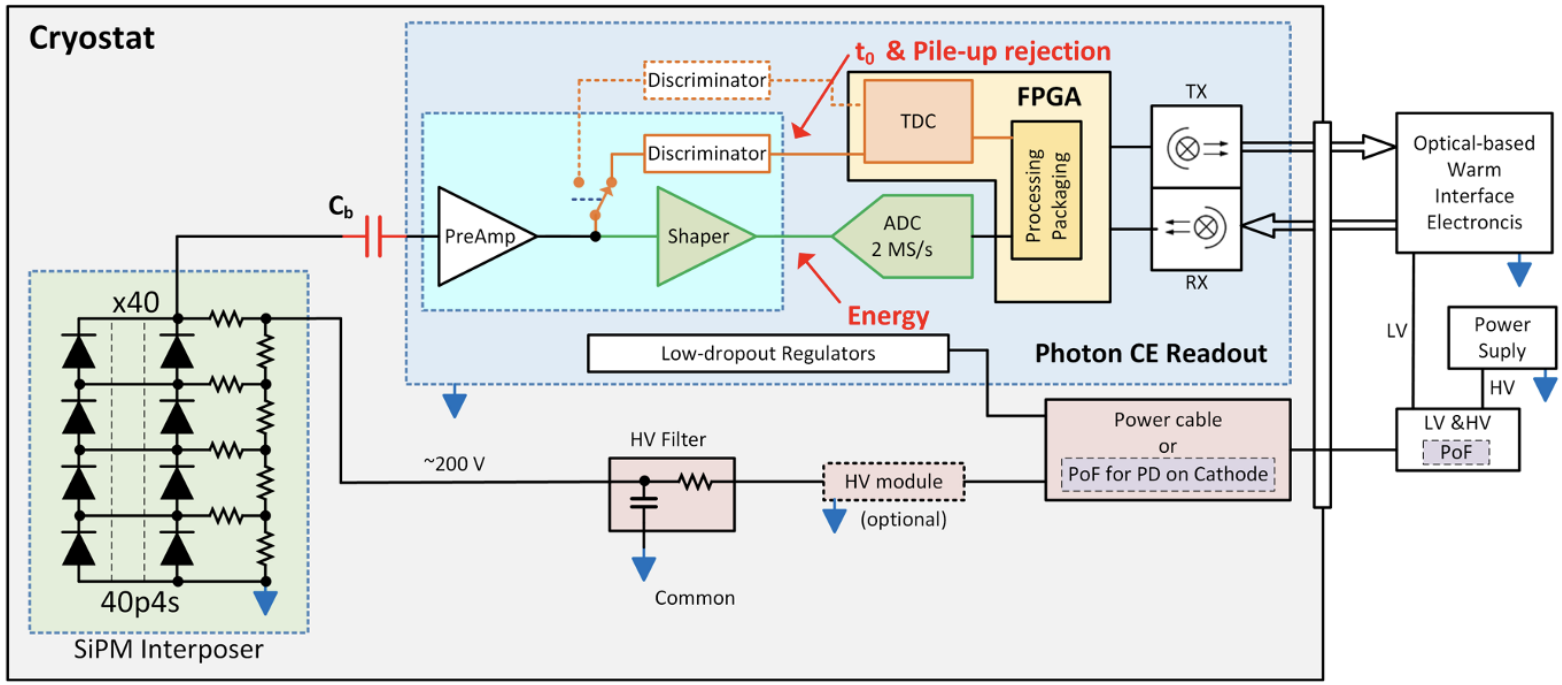
R&D: Evolving Cold Electronics for PD Readout

Proposed PD readout design with BNL cold electronics (LArASIC)



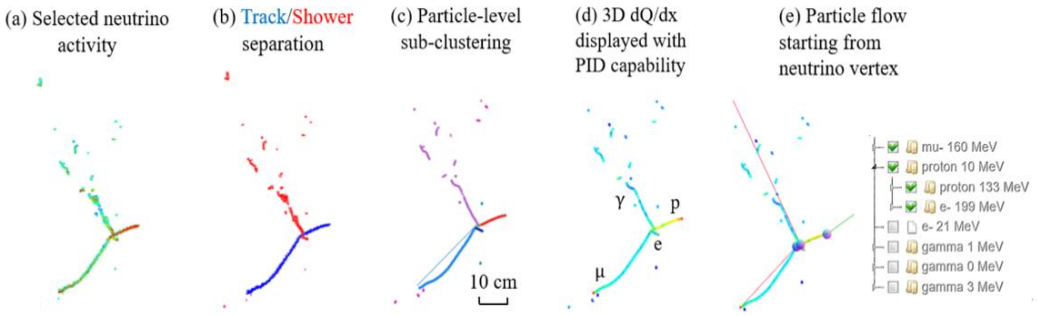
- Amplified SiPM signal split into two paths for digitization in cold:
  - energy path: 2 MHz sampling waveform after shaping, O(10) ns timing resolution
  - time path: discriminated signal with TDC, O(1) ns timing resolution
  - optical-based warm interface electronics to further reduce noise and cost (potential application for charge readout too)

- A factor of 20 reduction in power consumption and data throughput compared with FD2 reference design
  - Enable significantly more channels with better performance and lower cost

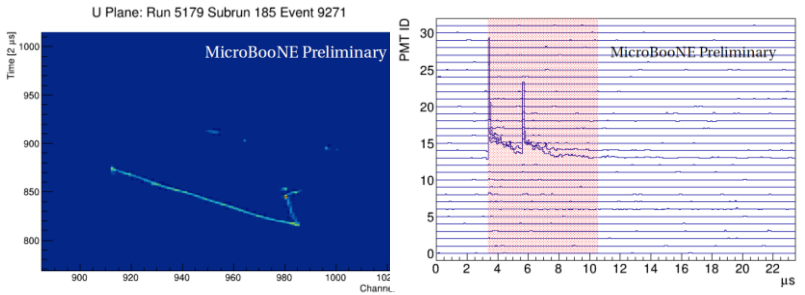
6-D Tracking Enabled

- For each particle sub-cluster, reconstruct:
  - In traditional LArTPC: trajectory (3D) + dQ/dx (charge per unit length)
  - This proposal: + time + dL/dx (light per unit length)
- Will enable:
  - Identification of decay products ($\mu^{\pm}$, $K^{\pm}$)
  - Identification of neutrons through TOF
  - Separation of low-E neutrons from γ's

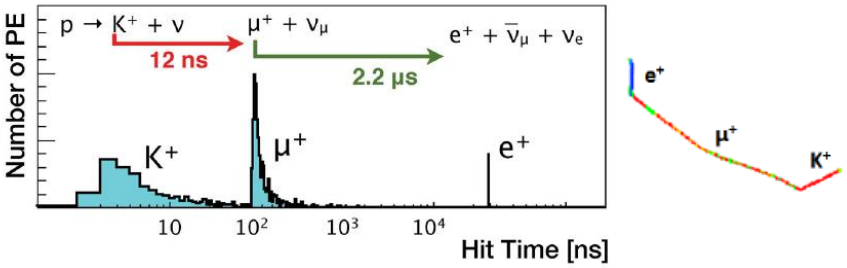
  ✓Improved energy resolution through better PID of final state particles
- Proposed algorithm development:
  - Based on current BNL-led Wire-Cell software reconstruction
  - Incorporate charge & light information into a holistic pattern recognition and 6-D track fitting framework
  - Study the improved sensitivity and new physics opportunities enabled by this technology



Traditional particle track reconstruction flow (example from Wire-Cell reconstruction in MicroBooNE)



Identification of Michel electron using charge and light signal (example from MicroBooNE)



An example of proton decay identification

Summary I

- Proposed work in this LDRD
  1. Develop an economical solution of low-power and highly-multiplexed cold electronic readout for photon detectors with excellent energy and timing resolution, enabling 4π light readout with >25% surface coverage.
  2. Develop and test a novel wavy PCB anode plane design to resolve topological ambiguities with projective charge readout.
  3. Algorithm development and physics study to achieve dual calorimetry and 6-D tracking reconstruction with improved energy resolution and particle identification capabilities.
- Estimated total effort
  - Post-doc: 2.0 FTE
  - Scientific staff: 0.5 FTE
  - Engineers & Technicians: 0.2 FTE

Summary II

- Intellectual merit
  - Will significantly improve DUNE's energy resolution and PID capability for Phase II FD 3&4. These improvements are crucial toward achieving the scientific goals of DUNE and enhance its discovery potential.
- Return on Investment
  - Will position BNL for leading roles in DUNE FD3&4 (>$100M) for the next decades, including project management, cold electronics, photon detector, and physics analysis.
  - Excellent platform to build future ECA, AI/ML, SciDAC, and other DOE proposals
- Broader impacts
  - Will continue to maintain and advance BNL's international leadership in LArTPC design, cold electronics development, photon detector R&D, algorithm development, and physics analysis in neutrino and other HEP experiments.

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