Develop Next-generation LArTPCs with 4D Tracking and Dual Calorimetry Capability

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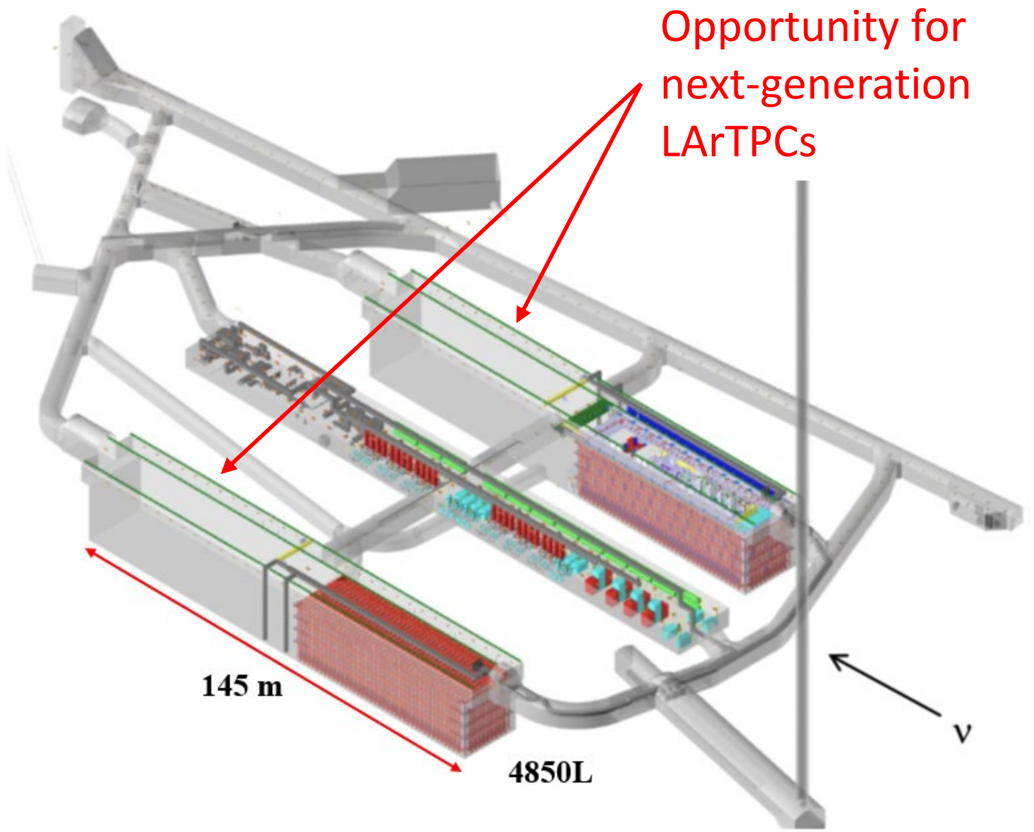
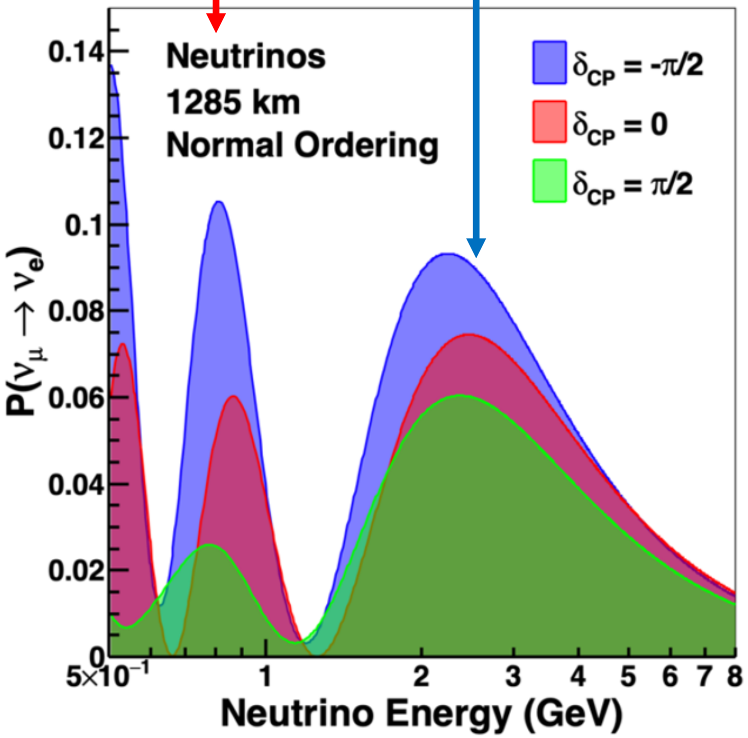


Motivation: Better Energy Resolution and Larger Target Mass → Improved Physics Reach

- CP effect is much larger at 2^{nd} osc. maximum than that at 1^{st} osc. maximum
  - Separation between 1^{st} and 2^{nd} oscillation maxima is clear in the true neutrino energy
  - Separation is not as clear in the reconstructed neutrino energy, which is limited by the **finite energy resolution**

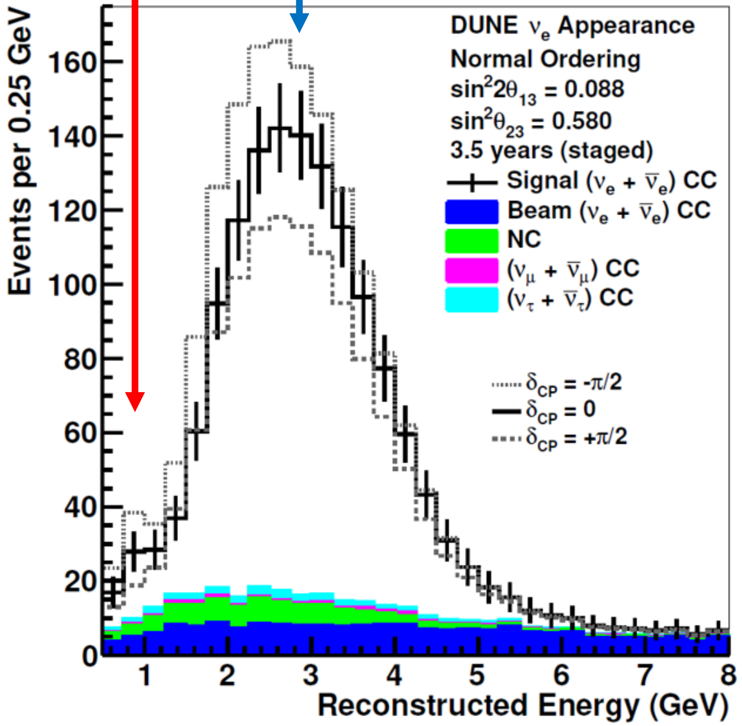
1^{st} osc. maximum

2^{nd} osc. maximum



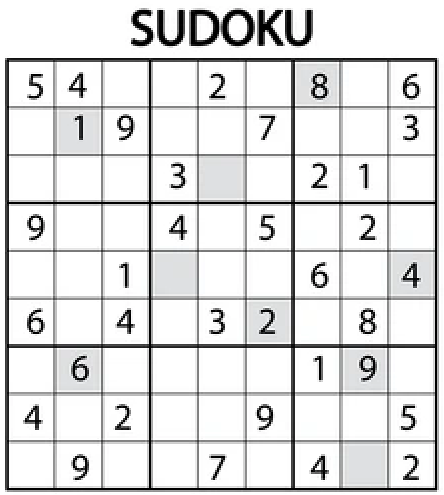
1^{st} osc. maximum

2^{nd} osc. maximum



"The improved energy resolution would lead to a significant improvement in the fraction of values of δ_{CP} for which a 5σ discovery of leptonic CP-violation would be possible!" JHEP 9, 30

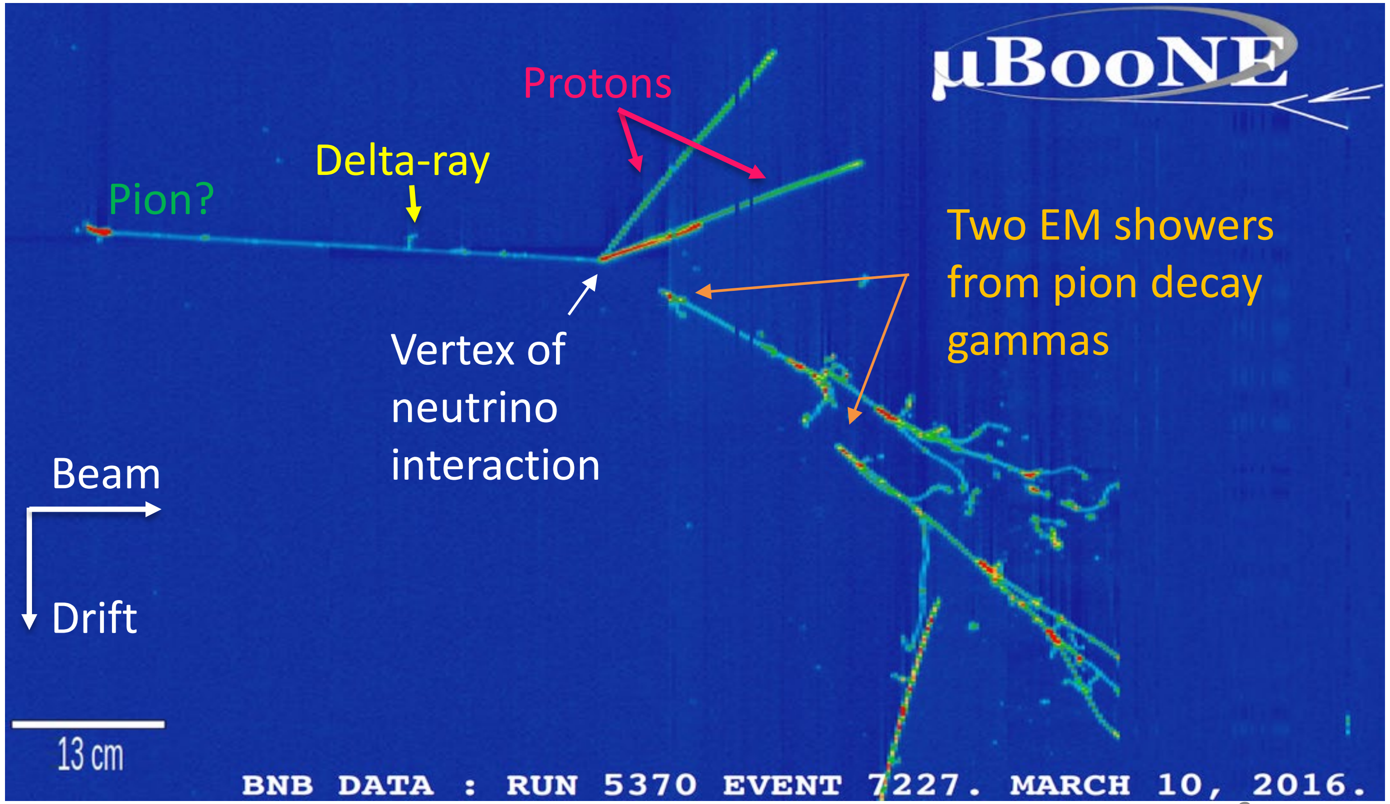
Neutrino Energy Reconstruction in LArTPC



- Event reconstruction in LArTPC is like solving SUDOKO
    - Some particles are well identified, and some particles are not
    - The particle flow follows the physics rules

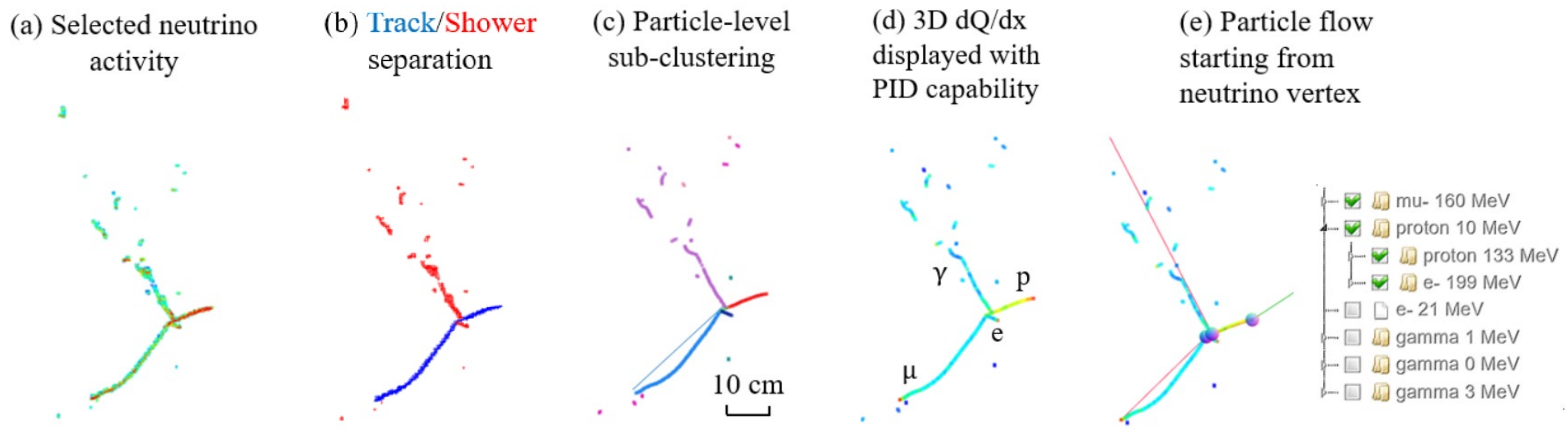
- A better neutrino energy resolution thus requires better particle identification capability → **4D tracking and dual calorimetry!**

- Calorimetry energy reconstruction with particle mass or binding energy included if PID can be done (arXiv:2110.13961)
    - Track: Range, dQ/dx → dE/dx correction
        - Calibrated by stopped muons/protons
    - EM shower: scaling of charge
        - Calibrated by π^0 invariance mass



MicroBooNE (2016): probably a neutral current interaction of ν_μ

4D Tracking and Dual Calorimetry

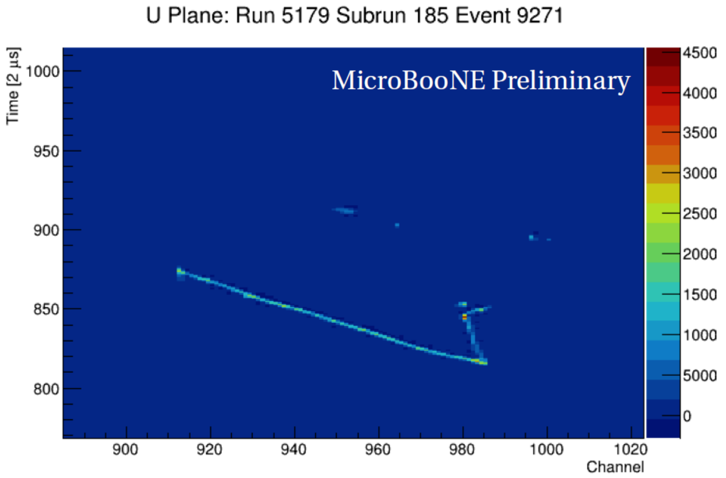


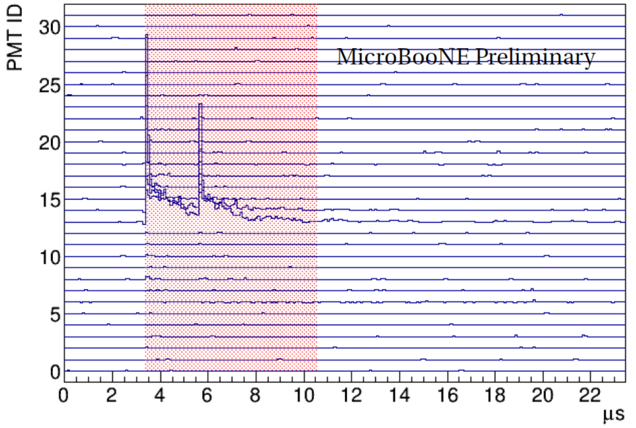
- 4D tracking: for each particle sub-cluster, know its time (1D) in addition to its trajectory (3D)
  - Identification of Michel electron from muon decay, kaon decays, neutrons through TOF …
- Dual calorimetry: for each particle track trajectory point, know dL/dx (light per unit length) in addition to dQ/dx (charge per unit length)
  - Separation of low-energy gamma from neutron, better energy resolution for non-stopped charged particles …

4D tracking

- Many-to-many charge-light matching algorithm developed by Wire-Cell in MicroBooNE is effectively a 4D tracking with event clusters
  - Foundation of 99.999% cosmic-ray muon background rejection
- 4D tracking with particle sub-clusters requires
  - Particle-level sub-clusters (3D pattern recognition)
  - An improved light reconstruction separating flashes within O(1) us
    - **A capable light detector with excellent timing resolution**

Identification of Michel electron using light signal





Wire-Cell Many-to-many charge-light matching in MicroBooNE

Dual Calorimetry

- The current track trajectory and dQ/dx fitting algorithm fits three 2D projective charge measurements with pattern recognition results as inputs
  - Test statistics are shown on the right
- The proposed dL/dx (light) fitting algorithm will fit the light measurements with track trajectory and dQ/dx results as inputs
  - Regularization w.r.t. dQ/dx can be added given anti-correlation between charge and light
  - **A capable light detector with excellent timing resolution is required**

Trajectory fit:

$$\mathrm{T}_{U/V/W} = \sum_j \sum_i \frac{q_i^2}{\delta q_i^2} \cdot dis(U/V/W)_{ij}^2$$

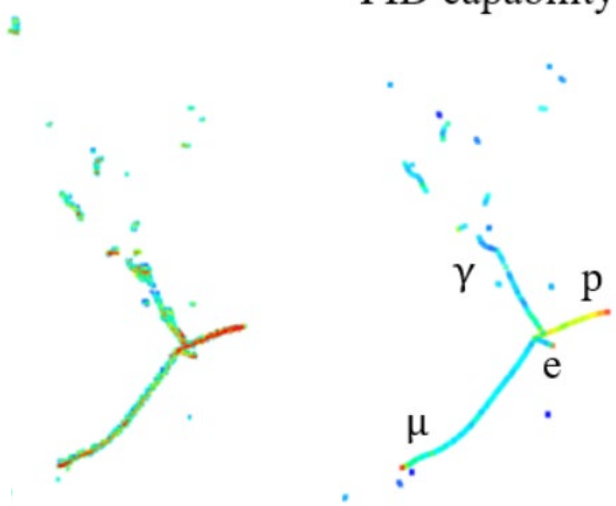
i: pixel in 2D projection j : 3D trajectory point

$$dis(U)_{ij}^2 = \Delta U^2 \cdot \left(U_i - U_j\left(x_j, y_j, z_j\right)\right)^2 + \Delta x^2 \cdot \left(t_i - t_j\left(x_j, y_j, z_j\right)\right)^2$$

ΔU: bin size in U view, Δx : bin siz in drift time t

(a) Selected neutrino activity

(d) 3D dQ/dx displayed with PID capability



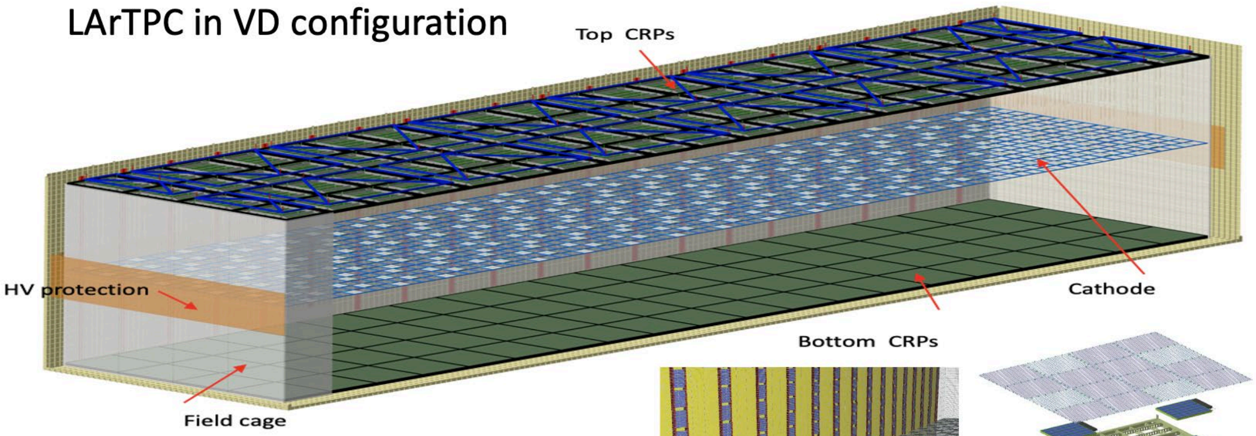
dQ/dx fit:

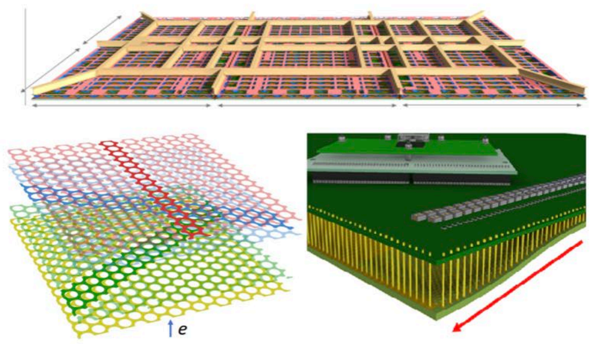
$$T_U = \sum_{i=U,T} \frac{\left(q_i - \sum_j R_{Uij} Q_j\right)^2}{\delta q_i^2},$$

R_{Uij} : smearing coefficients calculated with a fixed trajectory

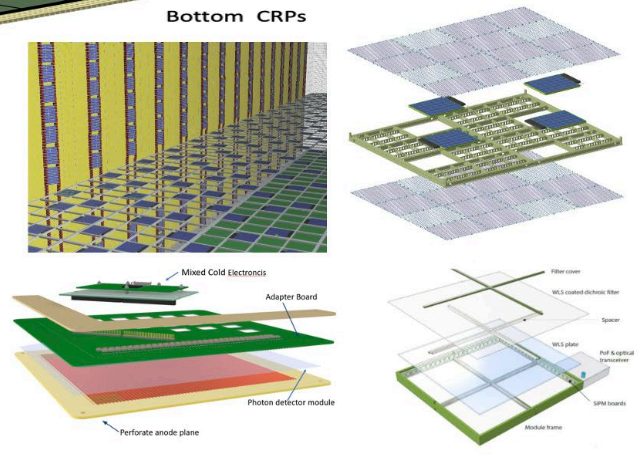
Next-generation LArTPC with 4π Light Coverage

LArTPC in VD configuration





Wavy PCB anode plane



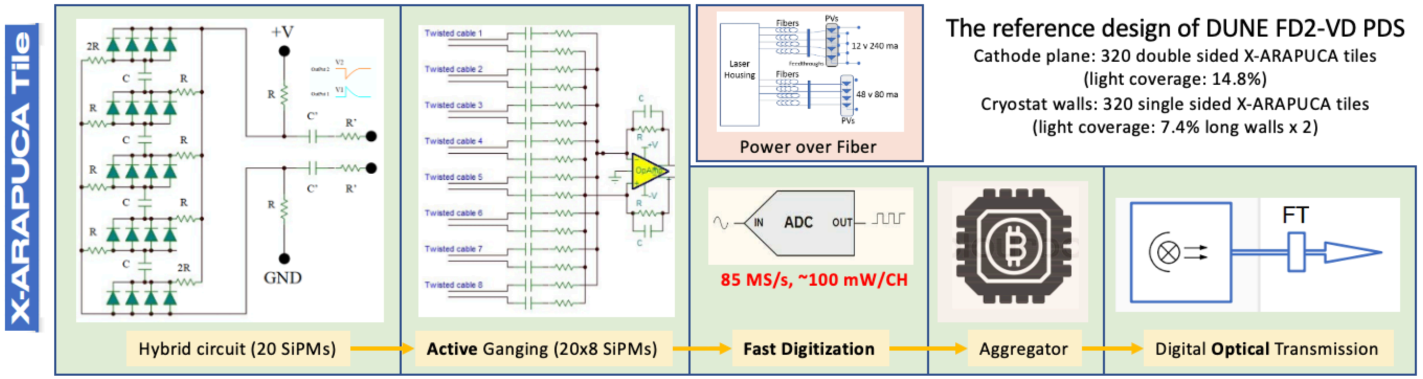
4π photon detector configuration

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%**

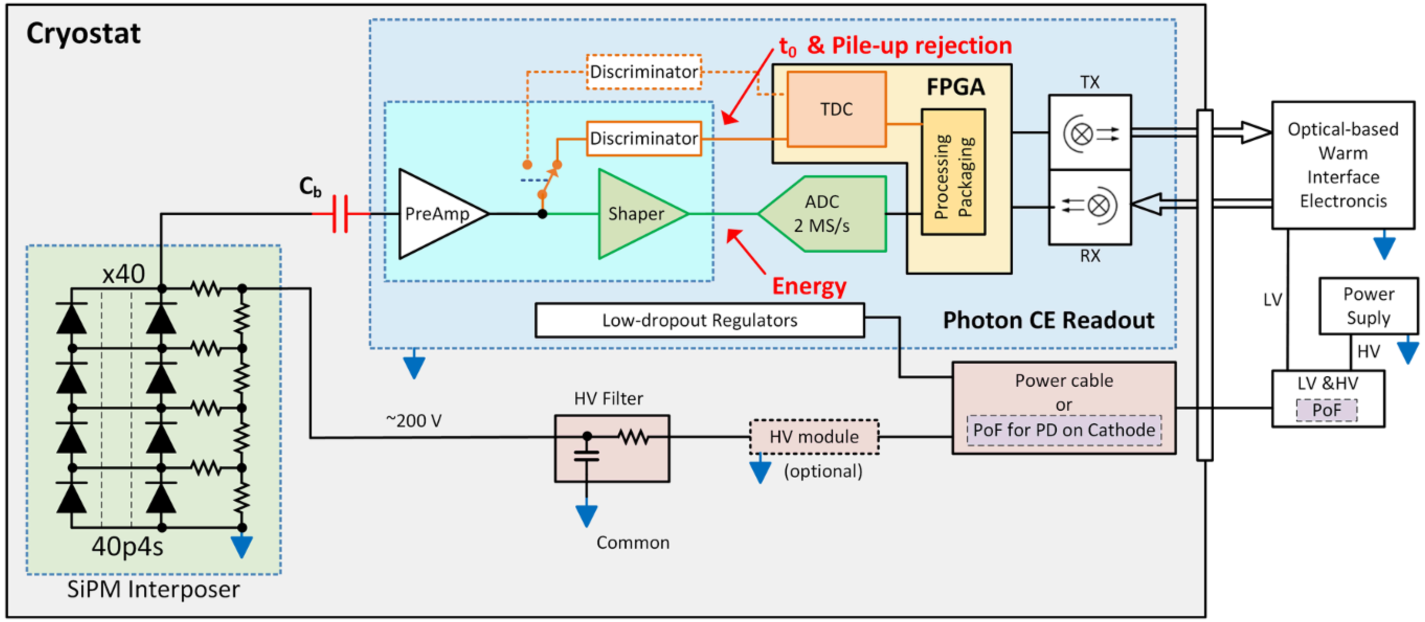
- We propose next-generation LArTPC with 4π light coverage with about one order of magnitude improvement in the photon surface coverage
  - R&D on photon detector (PD) readout electronics, integration of PD on anode …

R&D: Evolve LArASIC for PD SiPM Readout

- Readout SiPM arrays with "electrostatic transformer"
- PreAmp is weakly capacitive coupled with SiPM array
- Amplified signal in LArASIC is split into two paths:
  - (Regular) energy path: record the waveform after shaping
  - (New) time path: Discriminated signal is recorded with a TDC for timing information for O(1) ns timing resolution
- Lower-power consumption and smaller data volume w.r.t. reference design will enable significant larger photon surface coverage



a (top), b(bottom)



Proposed design with BNL cold electronics (LArASIC)

Summary

- We propose next-generation LArTPCs with 4D tracking and dual calorimetry capabilities
  - Development on algorithm → Improved particle identification and reduced energy resolution that significantly enhance the physics reach of DUNE
  - R&D on electronics readout for photon detector: evolve LArASIC for SiPM readout with electrostatic transformer → 4π and ~25% photon surface coverage