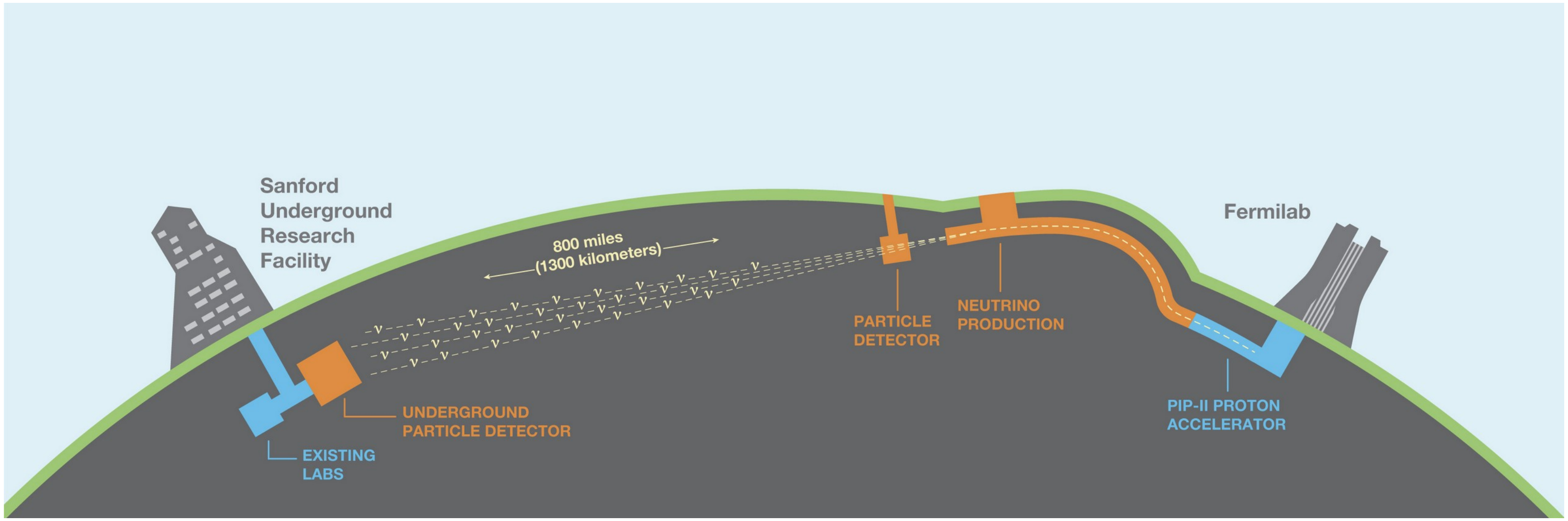
APEX: Optimized vertical drift PDS for DUNE FD3

F. Marinho on behalf of the DUNE collaboration

LIDINE 2024 – 26-28th August 2024 – São Paulo

27/08/2024

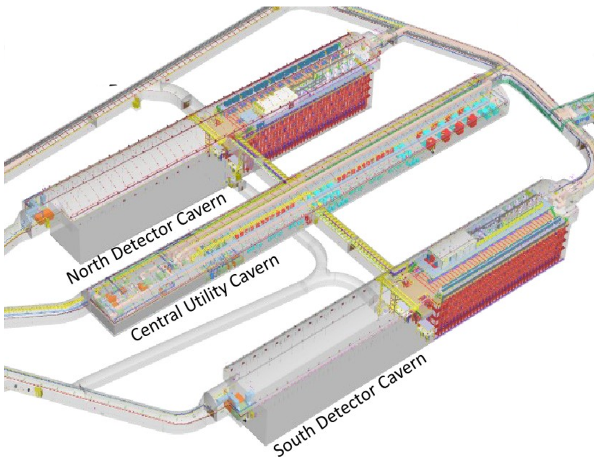
DUNE Experiment

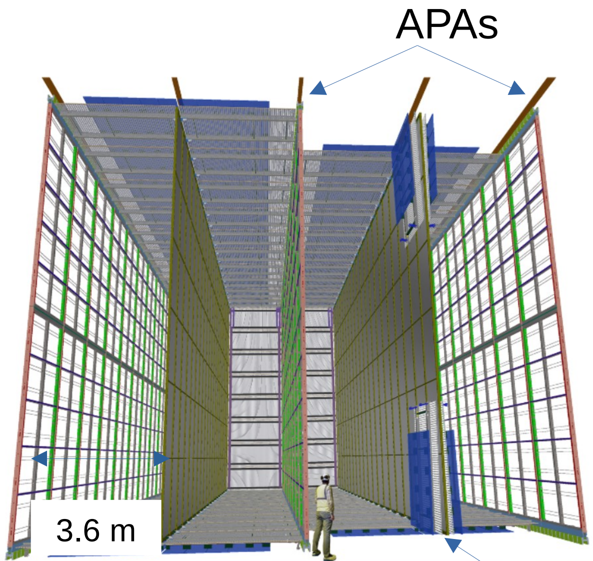


- Intense neutrino beam: 1.2 MW → 2.3 MW
- Near Detector system including a LAr TPC
- 4 Far Detector LArTPC modules (70 kton total mass)
  - 1300 km source distance, 1,5 km under surface
- Physics goals
  - Precise neutrino oscillations parameters determination
  - Detection:
    - Galactic core colapse supernovae neutrinos
    - Solar neutrinos
  - Searches:
    - Nucleon decay, Non standard interactions

DUNE FD1 & 2

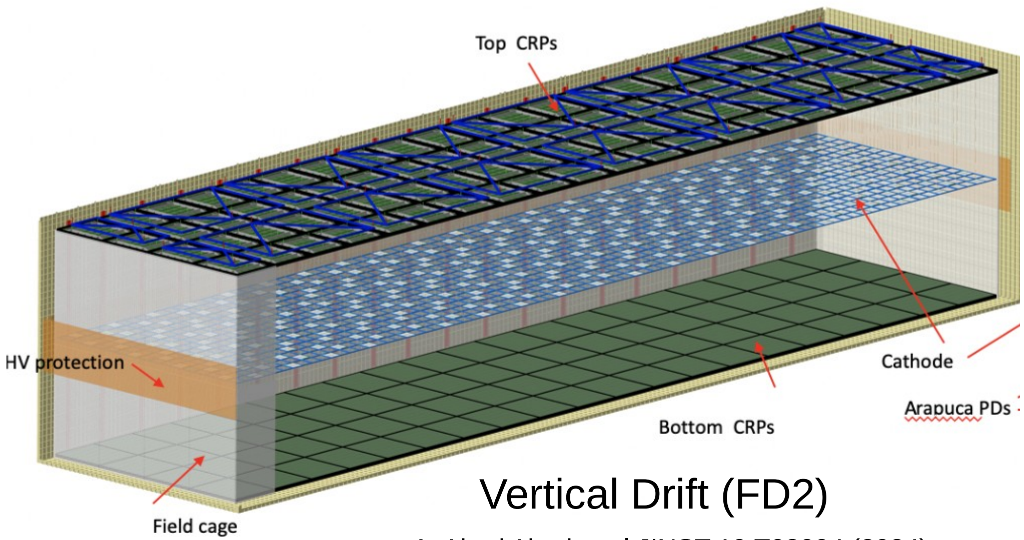
Far detector modules built in phases.
Phase I: First two modules





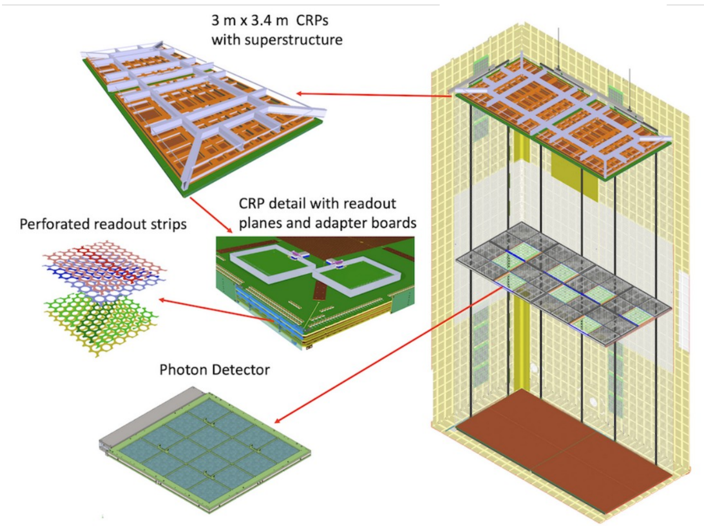
Horizontal Drift (FD1)

- APAs (FD1) and CRPs (FD2)
  - Readout: induction (2) and collection (1) planes
  - High res. tracking (~mm)
- PDS sensors for timing
  - (T_0, non-beam events trigger & calorimetry)



Vertical Drift (FD2)

A. Abed Abud et al JINST 19 T08004 (2024)



*see G. Botoske talk

DUNE Phase II

- Extend frontiers of neutrino physics and astroparticle physics
- Consists of:
  - Third and fourth far detector (FD) modules/fiducial volume increase
  - Upgraded near detector complex
  - Beam power enhancement

Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	Up to 2.3 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

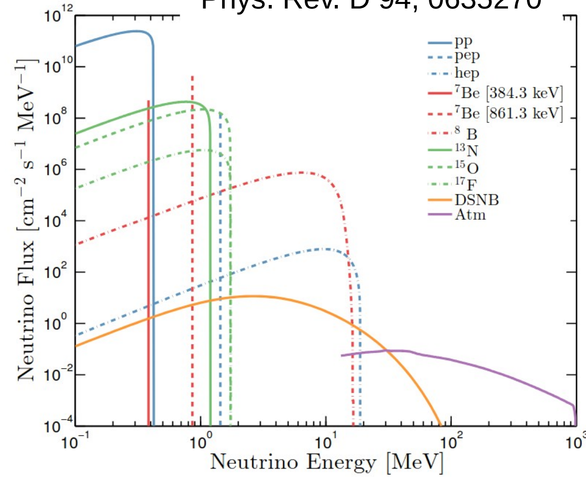
- Optimized photon readouts for Phase II VD FD modules
  - Further development of proven solutions from Phase I
    - Performance enhancement, cost-effectiviness

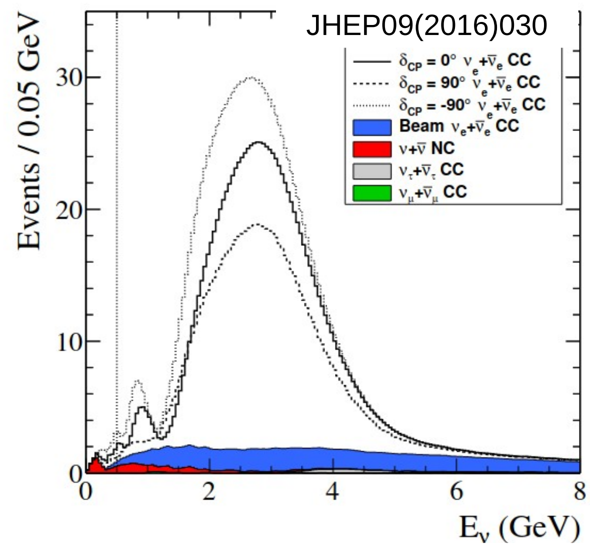
White Paper: arXiv:2312.03130
DUNE Phase II: Scientific Opportunities, Detector Concepts, Technological Solutions

DUNE Phase II: FD3

- Extend frontiers of neutrino physics and astroparticle physics
- Low-energy physics (1-10s MeV)
  - Background rejection and lower thresholds
  - Supernova core colapse burts
  - Solar neutrinos
  - Diffused supernova neutrino background
- Beam neutrinos (GeV)
  - Light: Independent energy measurements, timing and position (auxiliary to PID)
  - Energy reconstruction strategies and improved resolutions
  - Potential to improve resolving of 2nd oscillation peak and shape-only sensitivity

Phys. Rev. D 94, 0635270



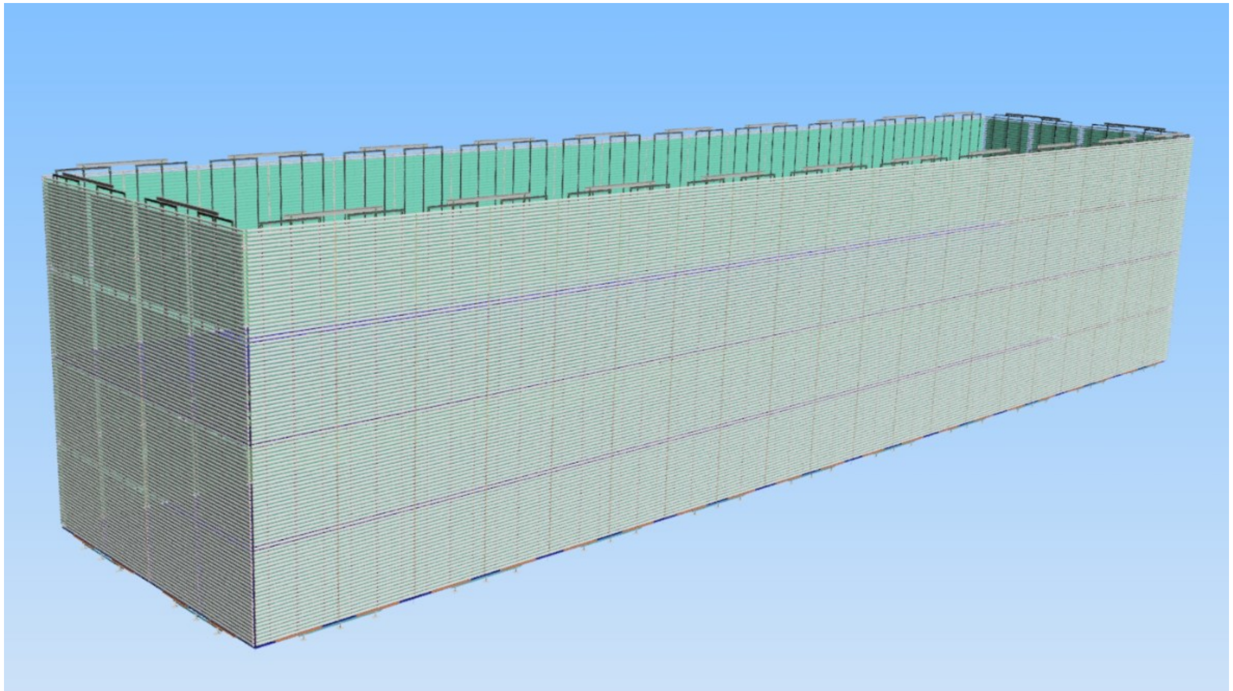


APEX: Aluminum profiles with embedded X-ARAPUCA

- Optical coverage >55% with light trap technology
  - Enhanced light yield (LY) and uniformity of PDS response

* see S. Manthey’s talk

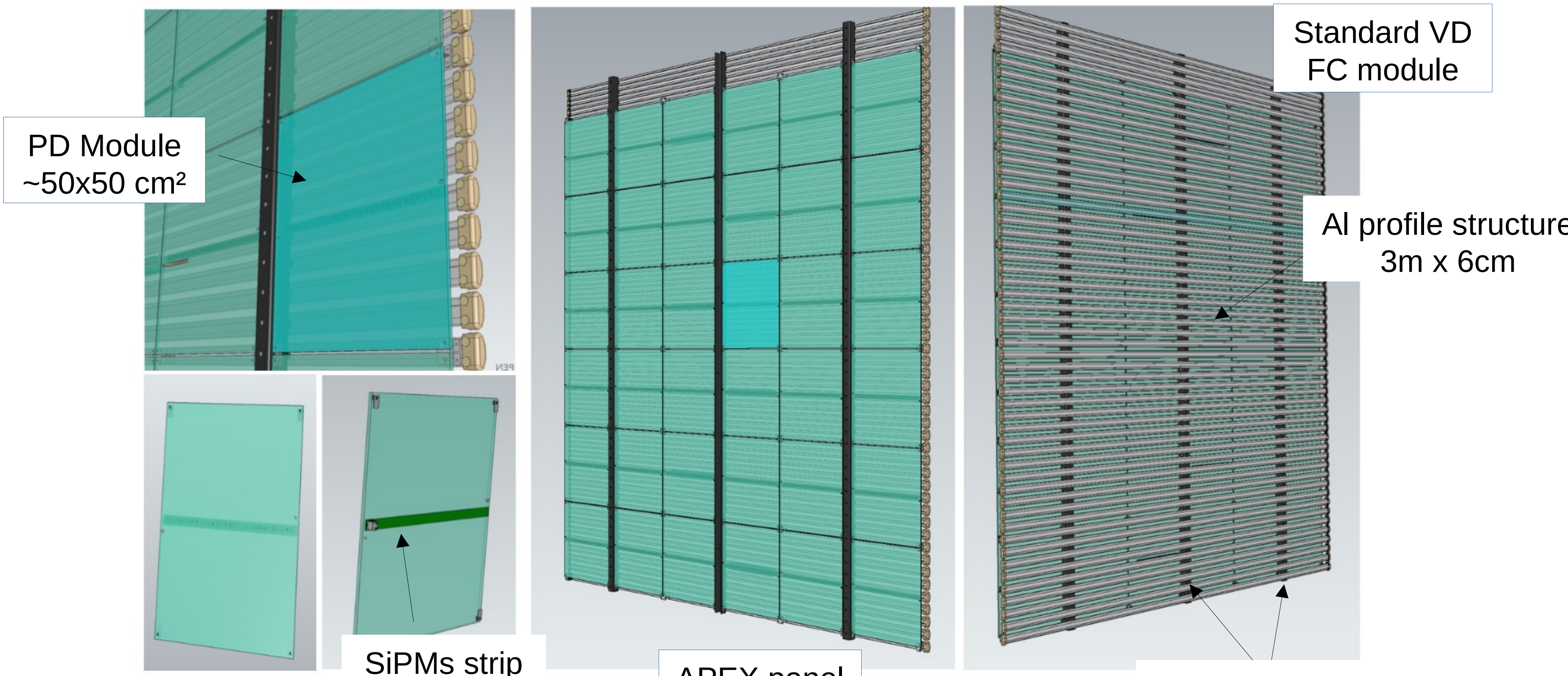
- Integrated VD TPC Field Cage + Photon Detector System
- P(S)oF technology for power and signal in/out of the field cage
  - Non-conductive optical fibers, readout electronics on HV surface
- Fully compatible with any VD LArTPC charge readout



arXiv:2312.03130

APEX: Aluminum profiles with embedded X-ARAPUCA

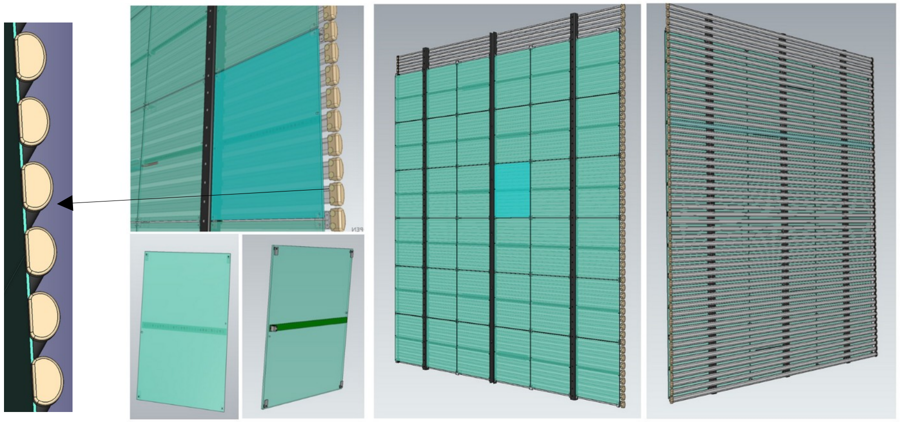
- Simplified, lightweight, and low(er)-cost photodetector
- Optimized photon readout with increased active coverage
- Bulk materials with low-radioactive content

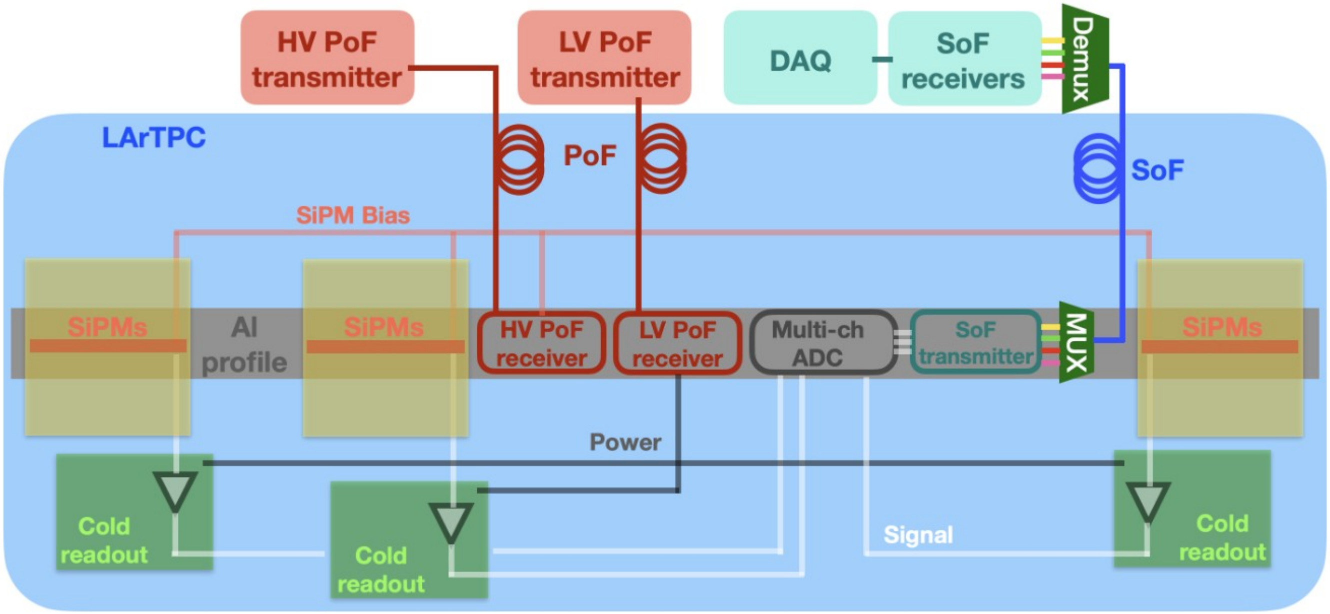


arXiv:2312.03130

APEX: Aluminum profiles with embedded X-ARAPUCA

- Each row of 6 PD modules in an APEX panel is a electrically isolated system
- 1 PD module/9 profiles
  - 5th profile: mechanical fastening and electrical reference
    - C-shaped profile: Faraday cage shielding for CE readout boards for the 6 module on horizontal row
  - PoF transmitter and SoF receivers (driver and laser diode) to the PDs via fibers

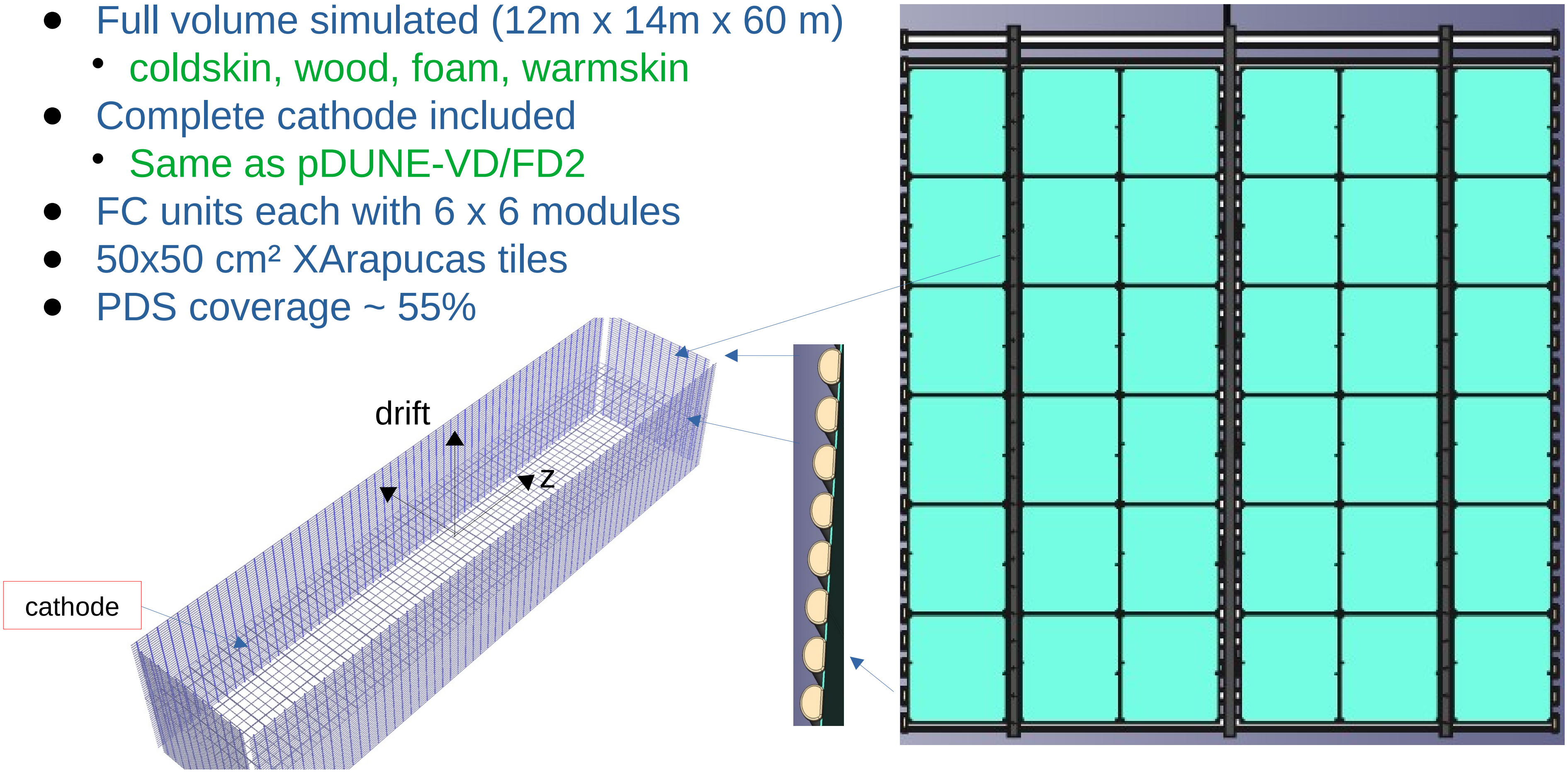




arXiv:2312.03130

APEX: Simulation geometry

- Full volume simulated (12m x 14m x 60 m)
  - coldskin, wood, foam, warmskin
- Complete cathode included
  - Same as pDUNE-VD/FD2
- FC units each with 6 x 6 modules
- 50x50 cm² XArapucas tiles
- PDS coverage ~ 55%



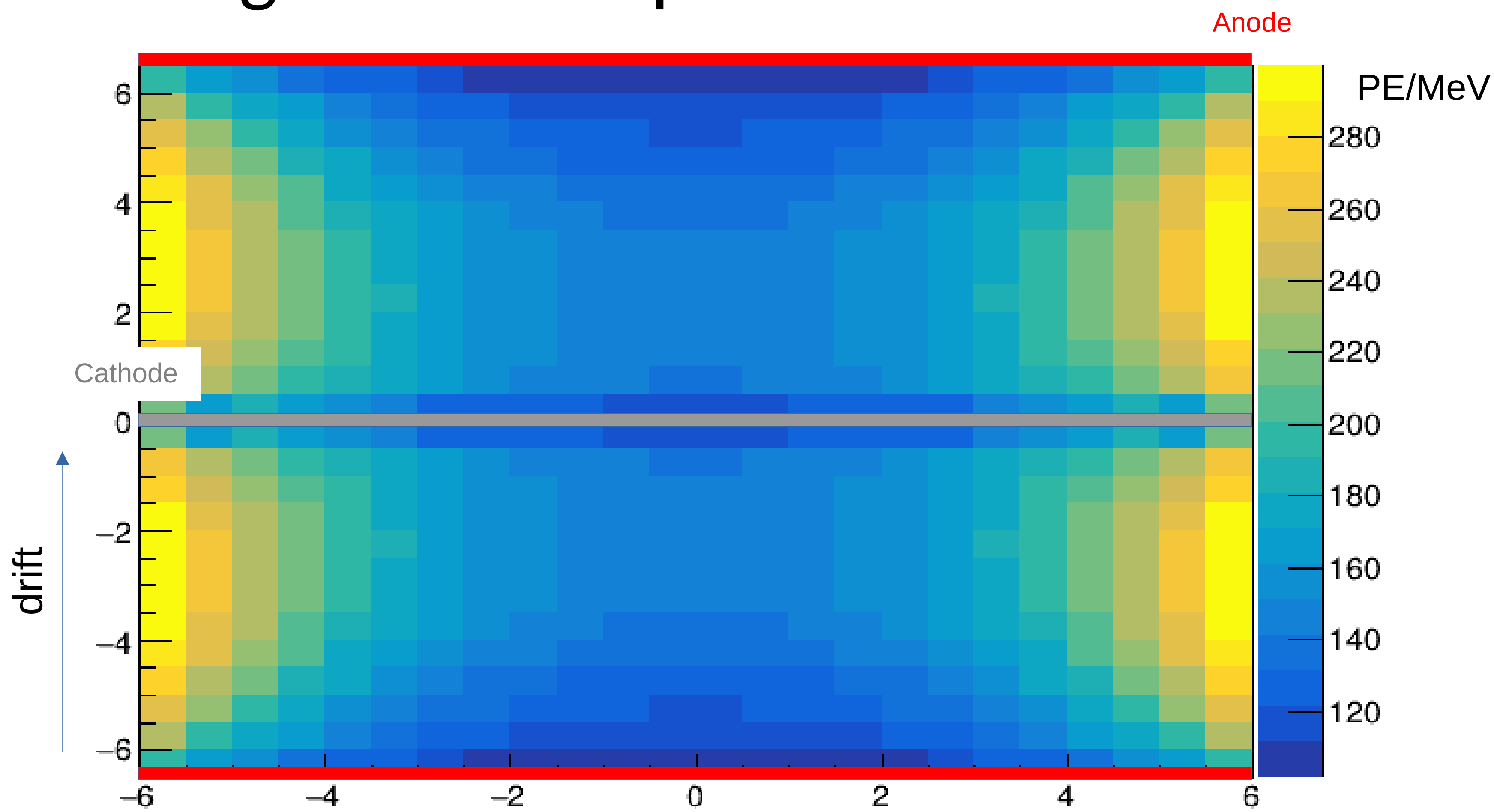
APEX: Simulation setup

- Photons shot from within voxels.
- Isotropic direction and polarization
- Voxel size: 0.5 x 0.5 x 0.5 m^3 *
- Same optical properties as for FD2 DUNE-VD simulations
  - LAr refractive index, Rayleigh scattering, absorption
  - Reflectivity of membrane, anode, field cage, etc
  - pTP emitted photons are also tracked
- All sensors detecting any level of light for evaluation
  - No cut on #pe applied
  - No sensors clustering required

* see A. Paudel's talk tomorrow

Parameter	Value
LAr light yield (mip)	25k ph/MeV
Xenon doping in Ar	10 ppm
Rayleigh scattering	λ_R(@128 nm) = 1 m λ_R(@176 nm) = 8.5 m
Absorption	λ_{abs}(N_2@128 nm) = 20 m λ_{abs}(N_2@176nm) = 80 m
Tile detecting eff.	2%
Reflectivity	
Field cage	70%
Cryostat	R = 30%, 40% @128 nm, 176 nm
Anode	R = 6%, 12% @128 nm, 176 nm

APEX: Light Yield map



Slice at Z_{center}

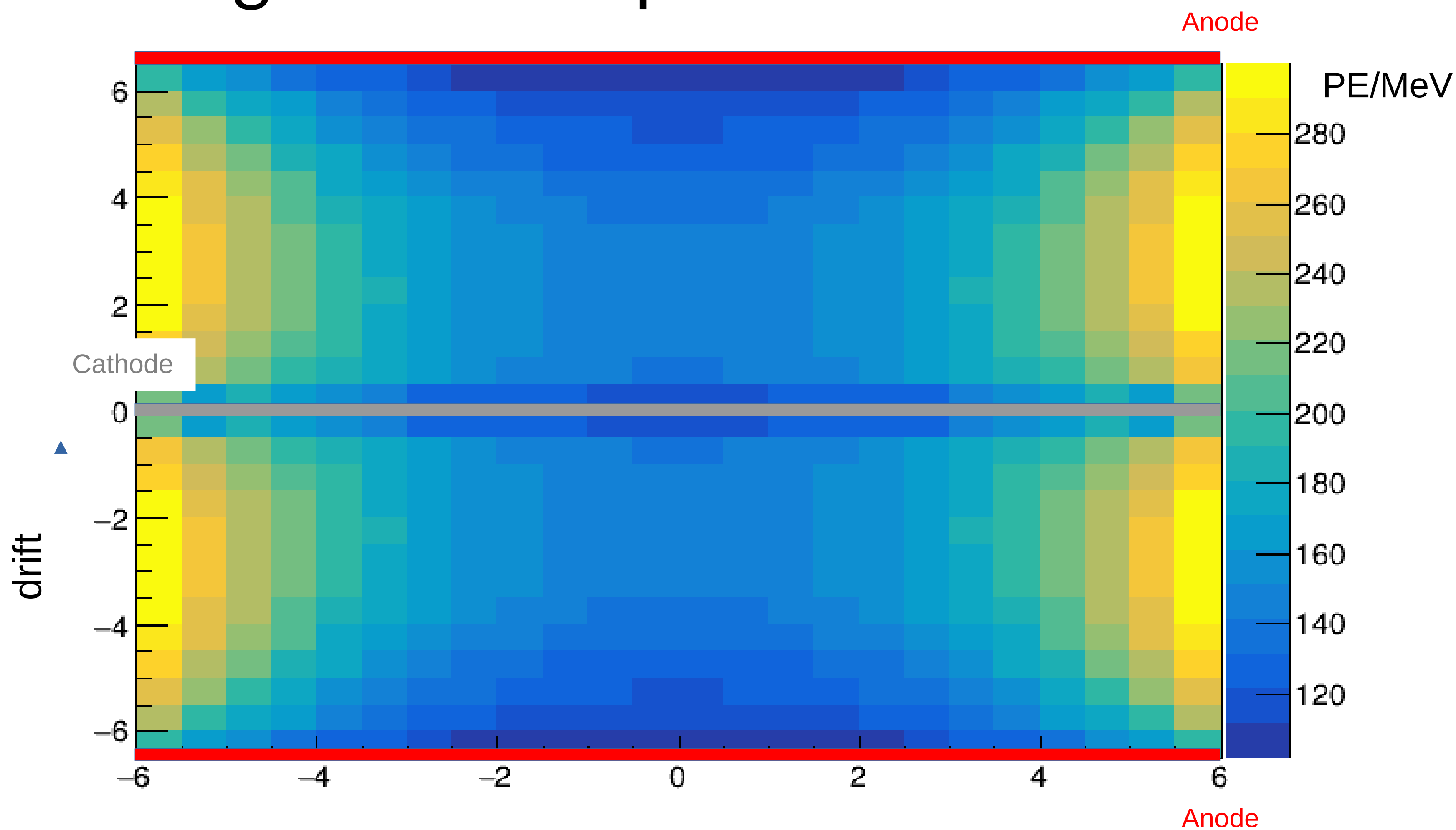
53% of total light emitted @176nm and 35% of light loss @128nm

$LY_{average}$: 180 PE/MeV

$LY_{minimum}$: 109 PE/MeV

arXiv:2312.03130

APEX: Light Yield map



- Xenon light contributes to more uniform LY map
- Total light yield due to backward WLS emissions ~60 %

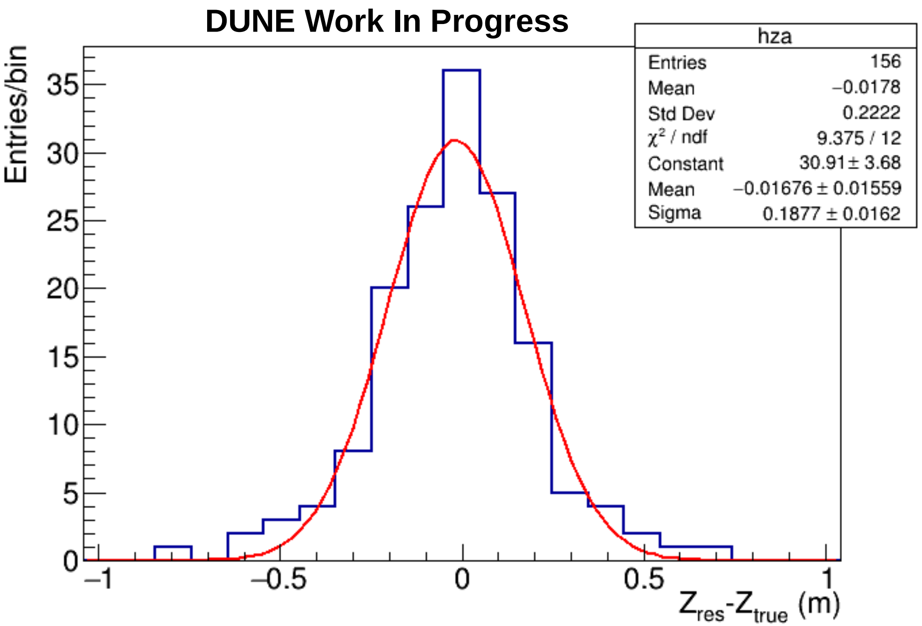
$LY_{ave(min)}$ scaled up wrt FD2 by a factor of 4(6)

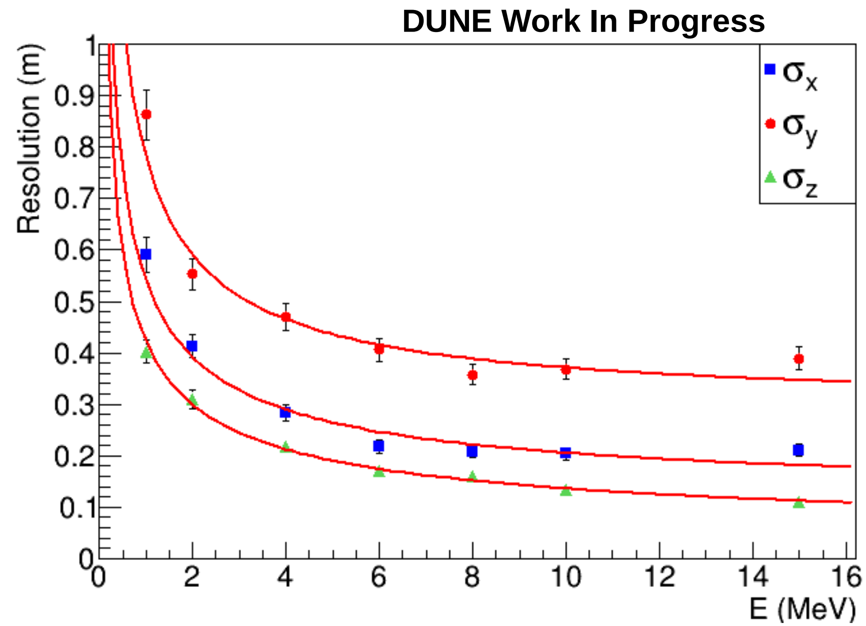
arXiv:2312.03130

A. Abed Abud et al JINST 19 T08004 (2024)

Low energy deposits: coordinates reconstruction

- Point like events as reasonable assumption for ~MeV scale
- Uniform resolution achieved on all coordinates





$$Z_{rec} = Z_{\mathrm{bar}}$$

PE weighted baricenter

$$y_{rec}(r) = L\,r\,(a + b|r|), \quad r = \frac{N_{L+} - N_{L-}}{N_{L+} + N_{L-}}$$

$N_{L\pm}$: Total number of PEs on $x = \pm L$

$$y_{rec} = a(x_{rec}) + b(x_{rec})\, y_{mean}$$

a and *b* linear on x_{rec}

APEX spatial resolution ½ lower than FD2

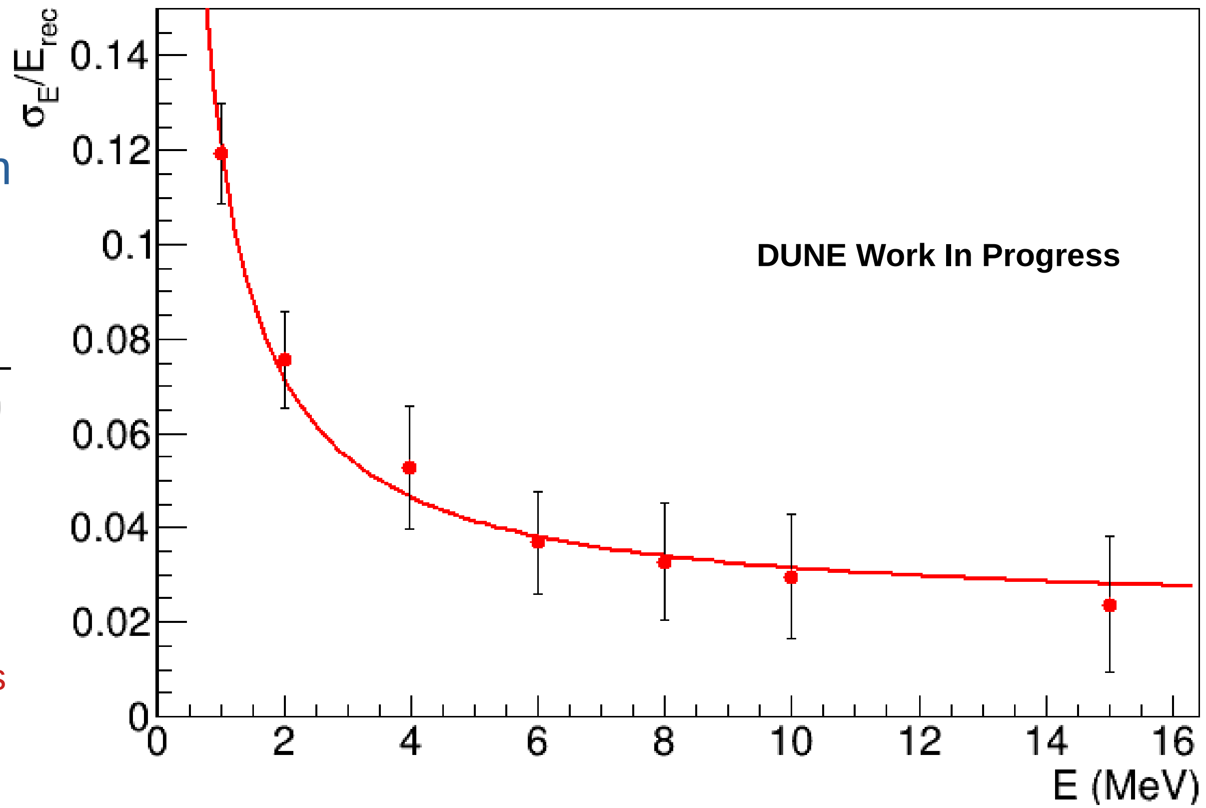
L. Paulucci (DUNE collaboration) 2022 JINST 17 C01067 (2022)

APEX: Energy deposits reconstruction

Light yield and position dependence

$$E_{rec} = \frac{Total\ PE}{LY\left(x_{rec}, y_{rec}, z_{rec}\right)}$$

Erros bars show variation due to scan over coordinates



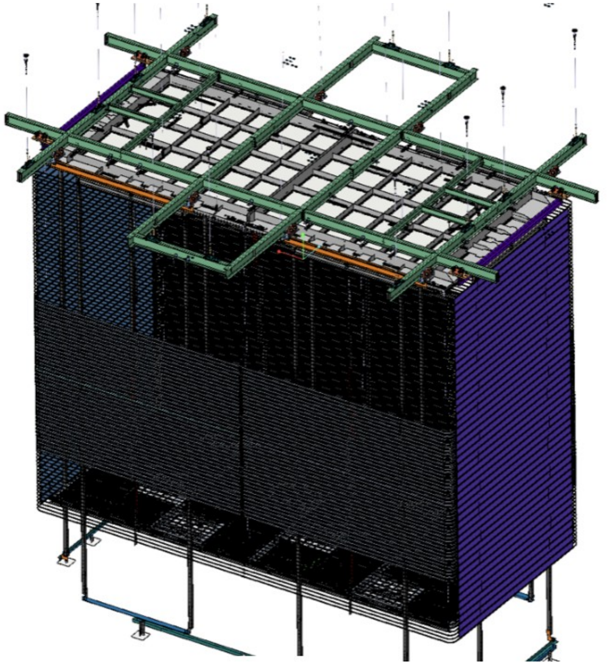
- Statistical fluctuations on PEs due to detection efficiency (binomial)
- Light yield map segmentation: size similar to expected from calibration

Resolution on low energy deposits reduces by factor ~0.4 lower than FD2

L. Paulucci (DUNE collaboration) 2022 JINST 17 C01067 (2022)

Prototypes

- Series of tests to further develop the APEX concept
  - First round @CERN 2024:
    - Impact on drift field uniformity due to insulating material between FC electrodes. number electrodes vs pitch
  - Ton-scale TPC prototype @CERN (2024/25):
    - Up to eight full-size PD modules, for mechanical and cryogenic tests.
    - PD module w/ electronic chain: constructed and fully tested before integration.
  - A larger-sized demonstrator with O(100) P(S)oF in/out fibers (@FNAL 2024/25)
  - Full-sized APEX PD-instrumented field cage to be deployed in VD ProtoDUNE cryostat (@CERN 2025/26)



Conclusions

- We presented the main features of the APEX concept
  - An optimized PD system based on previous DUNE VD R&D
  - Suggested/indicated as reference design option for FD3
- Enhancement of PDS capabilities should impact physics
- Monte Carlo simulations and analyses undergoing
  - Detector performance: High light yield and uniform response
  - Many physics aspects under investigation (MeV-GeV)
- Prototyping stages stablished and advancing (2024-2026)