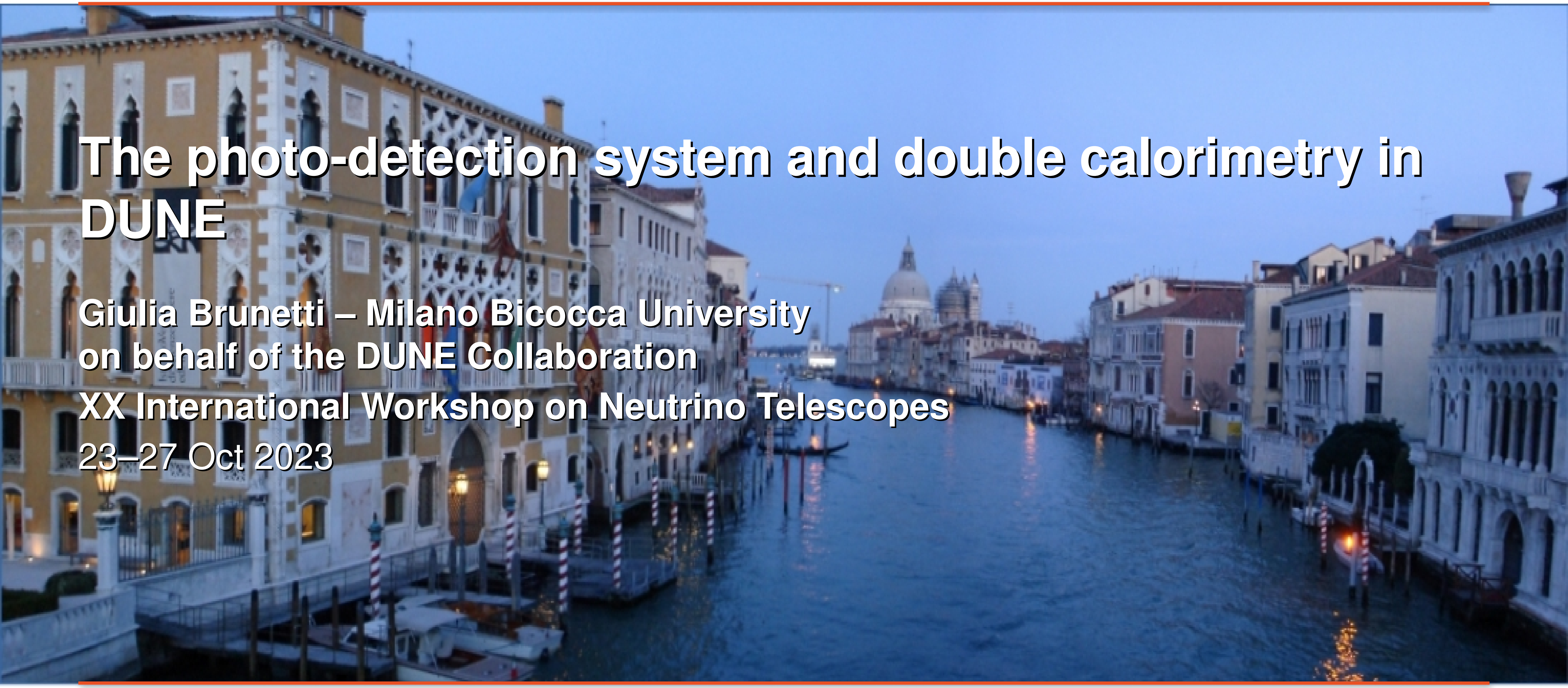


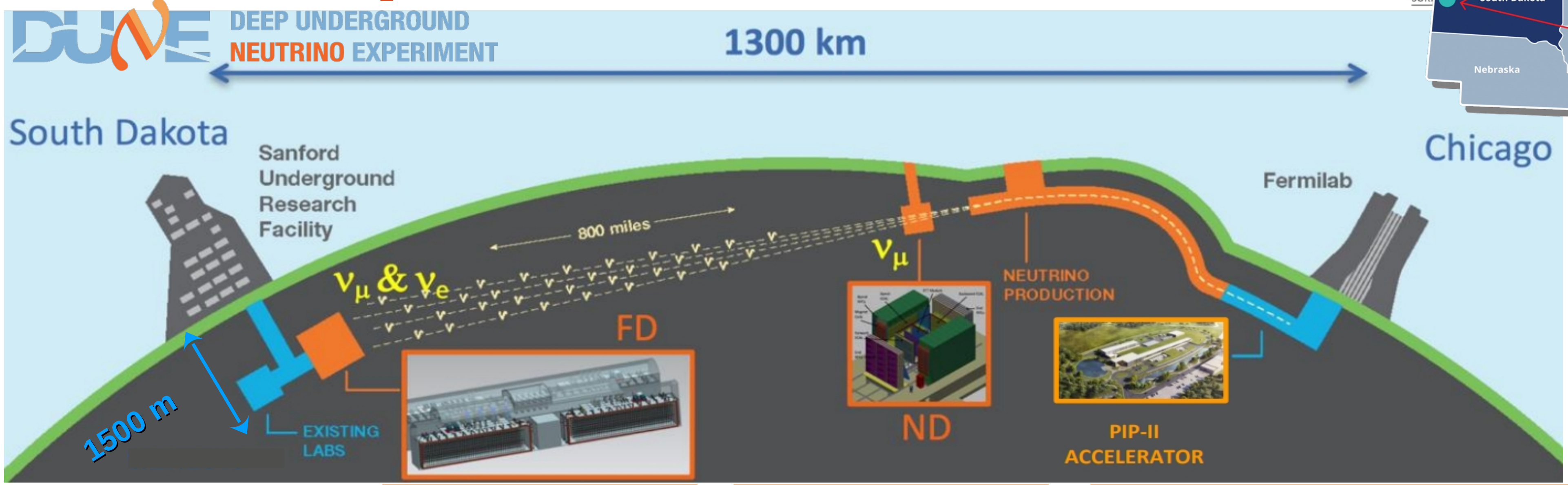
The photo-detection system and double calorimetry in DUNE

Giulia Brunetti – Milano Bicocca University
on behalf of the DUNE Collaboration

XX International Workshop on Neutrino Telescopes
23–27 Oct 2023

INFN Istituto Nazionale di Fisica Nucleare
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
DUNE

The DUNE Experiment



Huge Far Detectors: 4x17kton total mass LAr TPC

Near detector complex for beam characterization

1.2MW proton beam, upgradable to 2.4MW → Powerful LBL wide band beam

A large mass, high precision, Deep-underground accelerator Neutrino Experiment for a wide physics program:

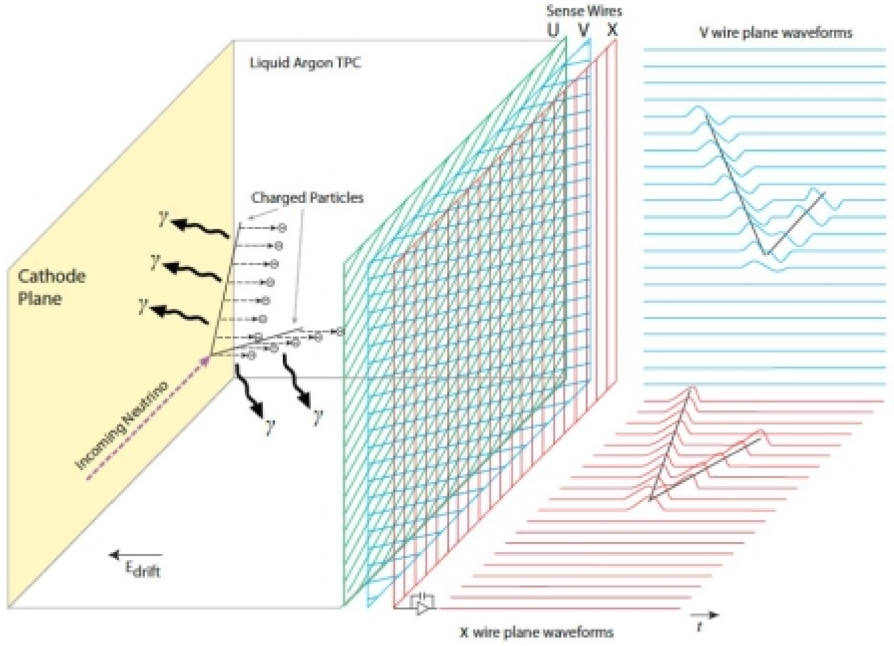
- Discovery of CP-Violating phase δ_{CP}, ν **mass ordering**
- **Measurement of PMNS parameters**: θ_{23} octant, Δm^2_{13}, precision measurement of δ_{CP}
- **Astrophysical ν sources**: SN burst, solar neutrinos
- **BSM physics**: anomalies @ LBNF, dark matter, proton decay

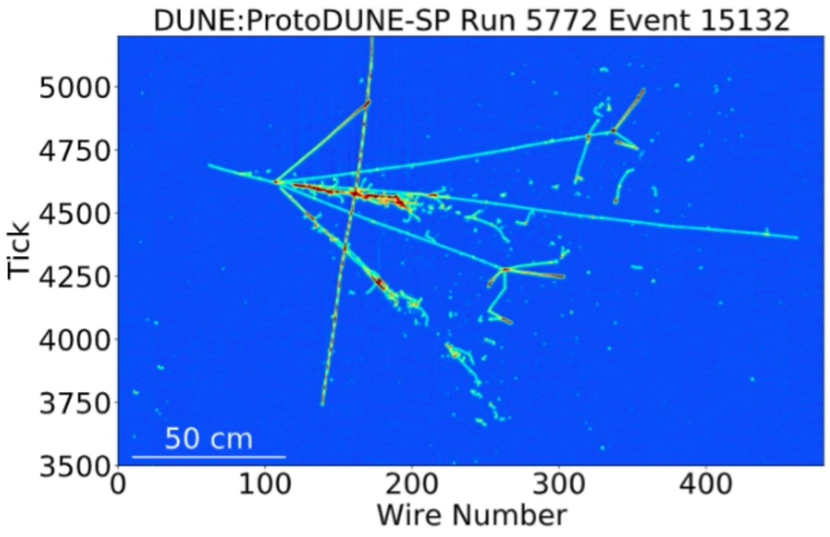
Liquid Argon TPC

Two observables generated from **energy deposition by particles in liquid Argon**:

- **CHARGE** → Ionization electrons, drift to the anode: precise imaging
- **LIGHT** → VUV scintillation photons (λ=128nm): precise event timing

→ Two independent readout systems: **Anodic charge readout** & **Photo Detection System (PDS)**





- Detailed images of final state particles trajectories, clean separation of ν_μ and ν_e
- Good energy reconstruction over broad energy range, low threshold (few MeV)

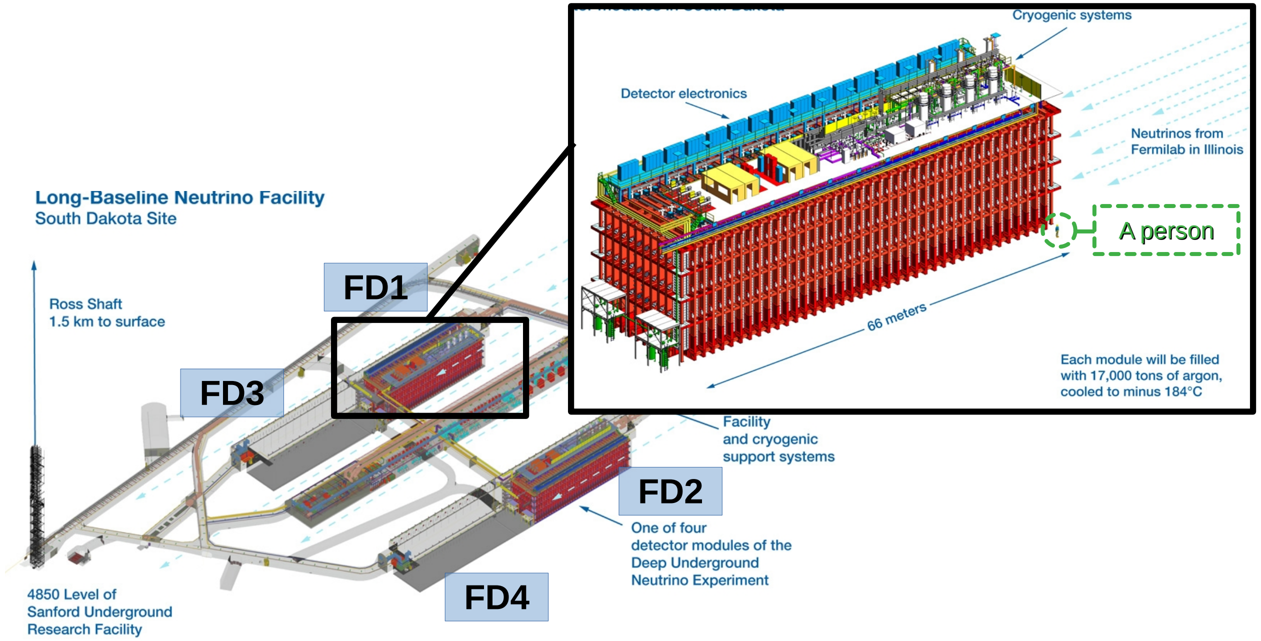
DUNE Detectors

Far Detectors

@ SURF (Sanford Underground Research Facility (South Dakota): **4x17kton modules**:

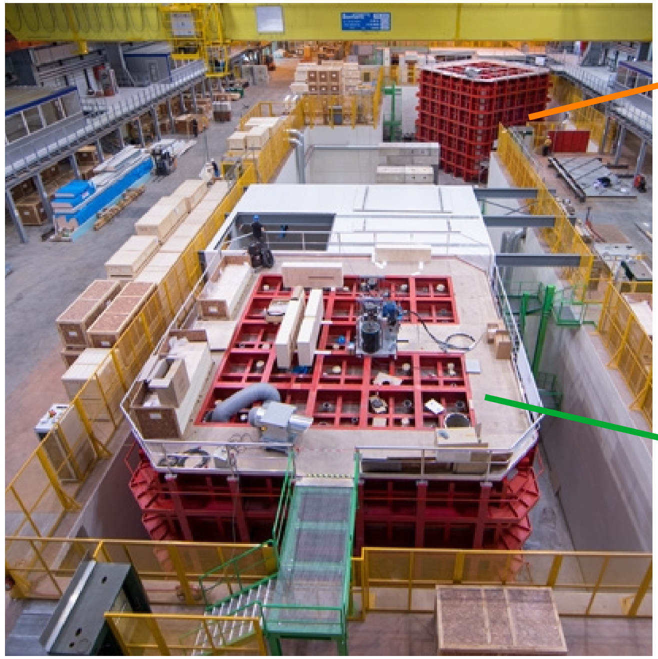
- FD1 – Horizontal Drift (FD-HD)
- FD2 – Vertical Drift (FD-VD)

+ FD3 + FD4="module of opportunity"



ProtoDUNEs

@ CERN: largest LArTPC to date (750 t,~8x8x8 m^3), built to test the technological challenges of DUNE. Next Run: 2024



ProtoDUNE - VD

Will exploit the Vertical Drift Technology

-Drift Length doubled

-Xe doping: better light uniformity and light yield

ProtoDUNE - HD (protoDUNE-SP)

Ran from 2018 to 2020 collecting data from cosmic and test beam data **reaching or exceeding all DUNE specifications**

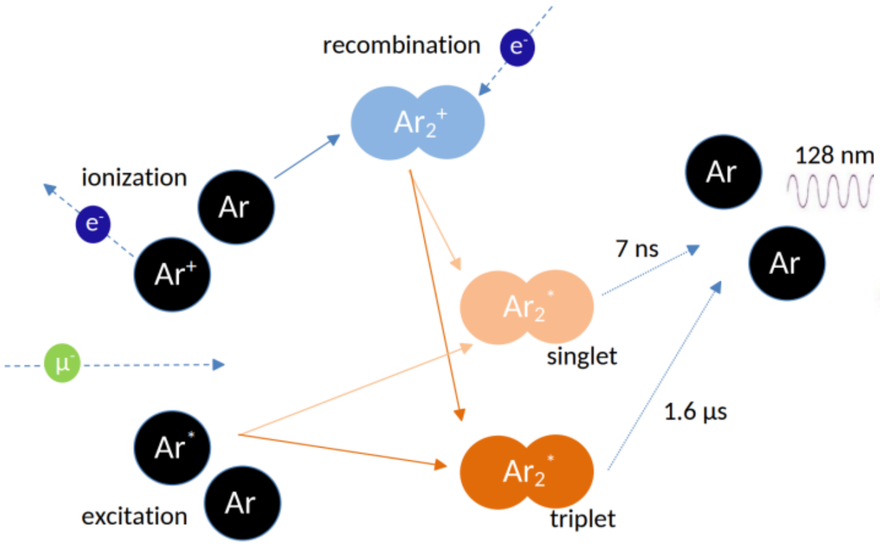
The Photo-detection System
LAr VUV Light detection

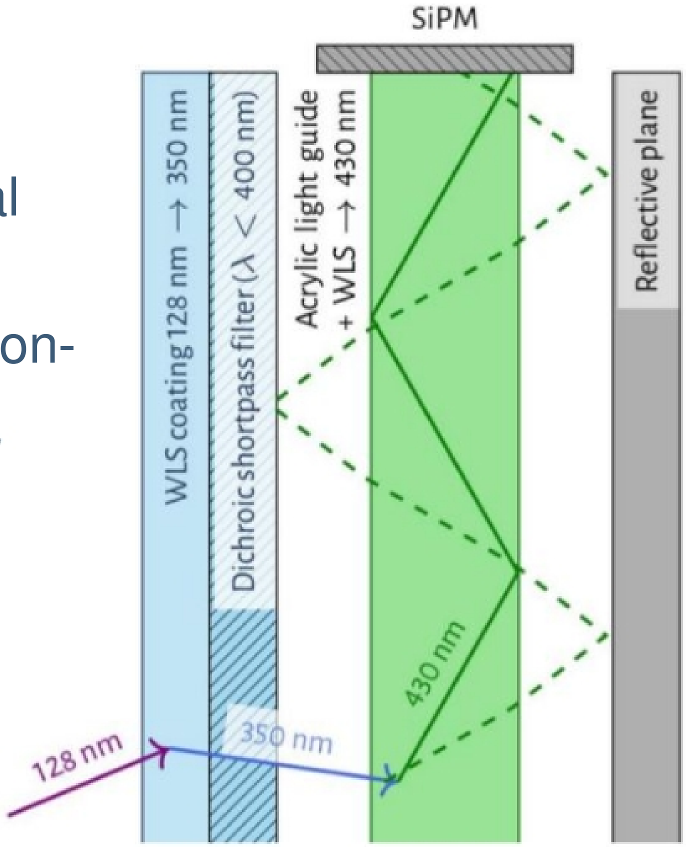
Scintillation light is:

- **Abudant**: 25k photons/MeV @ 500V/cm → combined with charge signal **improves calorimetry**
- **Fast:** fast component τ=7 ns → provides event t_0, crucial for triggering non-beam events

Detection of Light in a DUNE TPC:

- VUV photons converted to longer wavelength (WLS)
- Visible light is trapped inside a module, a fraction is conveyed to Silicon Photomultipliers (SiPM)



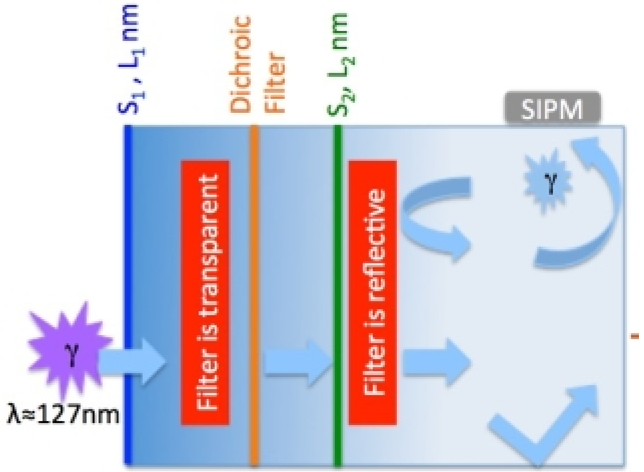


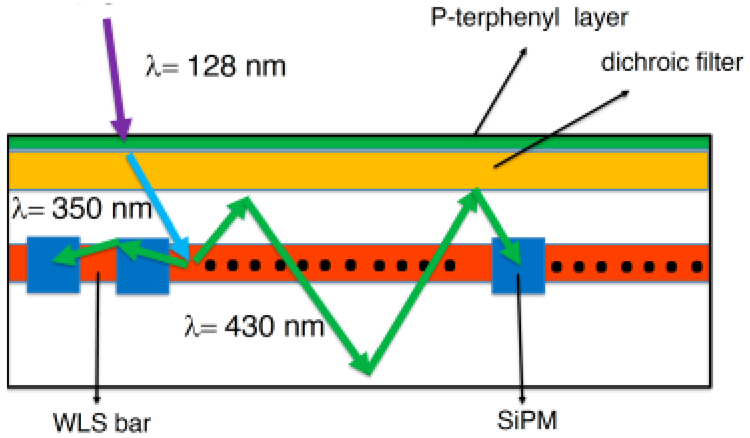
Reflective box equipped with an entrance window, two photon downshifting stages, one dichroic filter and one light guide coupled to SiPM

The Photo-detection System
LAr VUV Light detection: X-Arapuca

X-ARAPUCA Concept: trap photons in a box with highly reflective internal surfaces

- The core of the device is the **dichroic filter**: a multilayer interference film which is highly transparent for wavelength below a cutoff and highly reflective above it
- VUV scintillation light produced in LAr →
  PTP shifter deposited on the dichroic external side converts VUV light to a wavelenght < dichroic cutoff (**light transmitted**)
- The internal WLS bar converts the primary shifted photons to a wavelenght > dichroic cutoff (**light is trapped**)
- After reflections the photons can be detected by SiPM positioned laterally with respect to the WLS plane





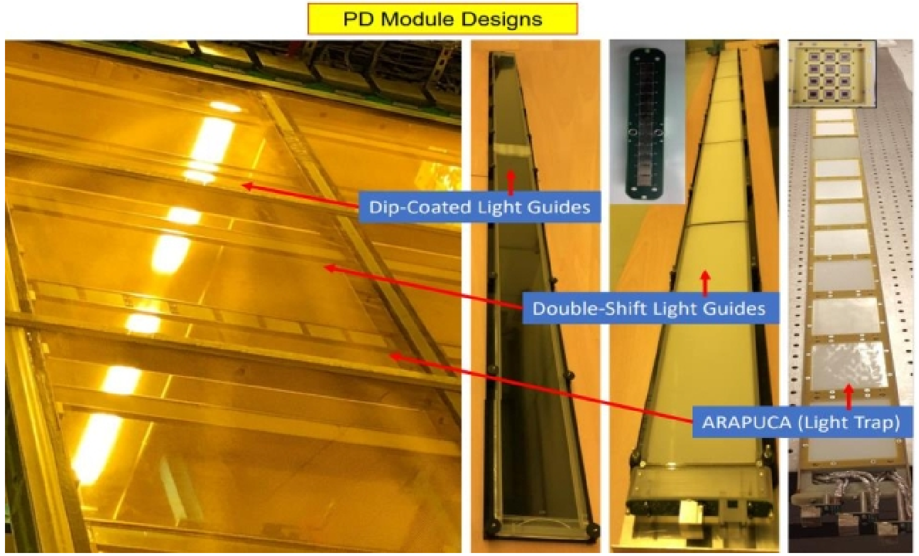
Horizontal Drift: ProtoDUNE-SP PDS

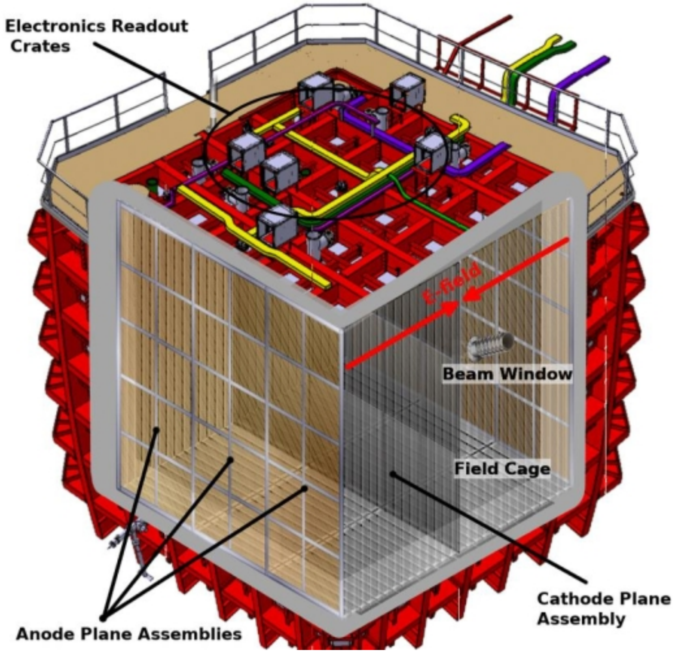
10 bar-shaped photon detectors embedded in the anode planes

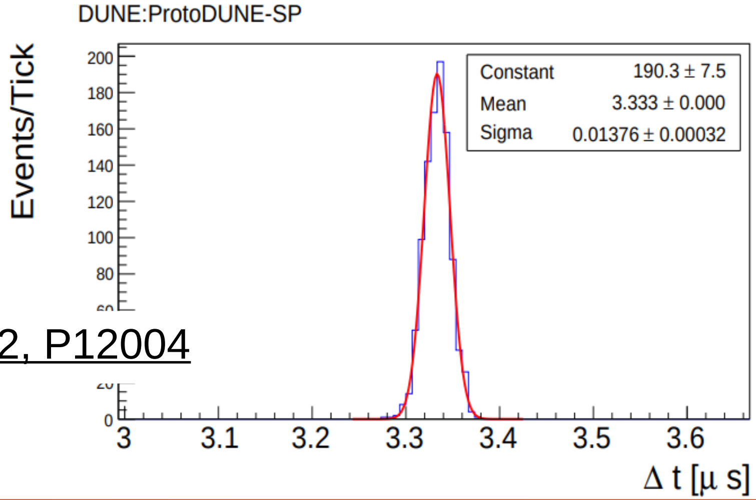
Three designs tested for the 60 PDS modules:

- 29 dip-coated light guides & 29 double-shift light guides
- 2 ARAPUCA light traps

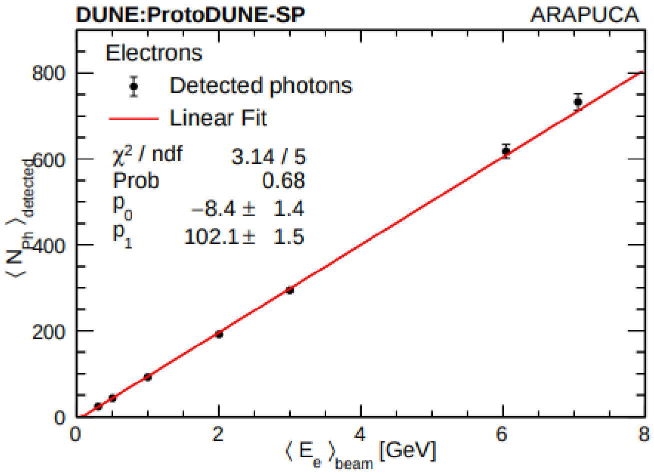
The **PDS performed very well** in terms of both timing (σ_t = 14ns) and calorimetry (1.9 γ/MeV LY)

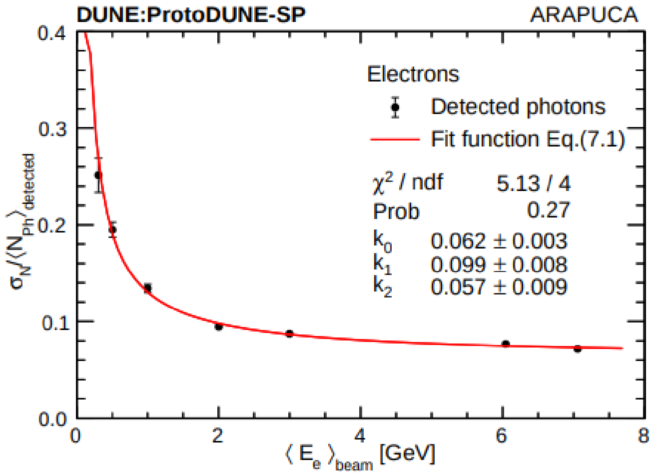






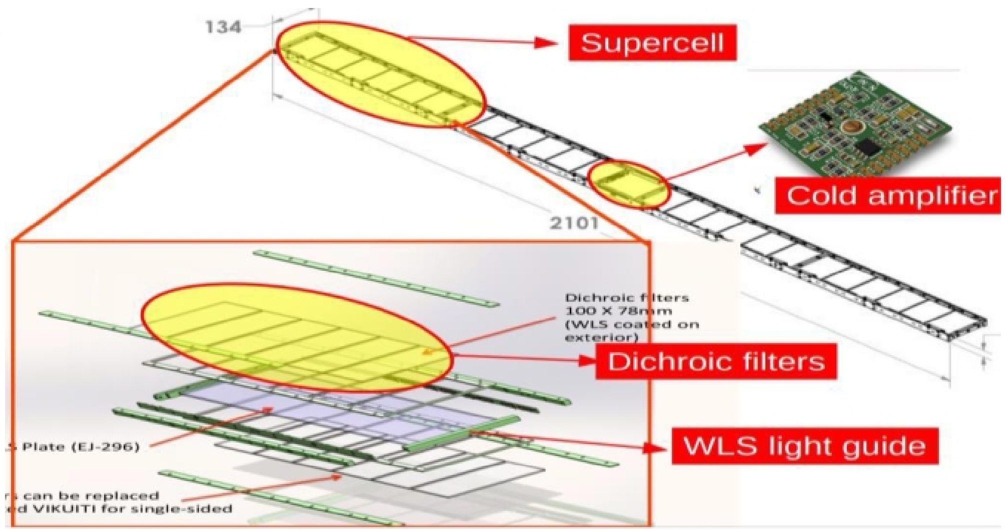
JINST 15 (2020) 12, P12004





Horizontal Drift: ProtoDUNE-HD Phase II

- Second run of ProtoDUNE-HD will validate final DUNE detector components for first two Far Detector modules + new R&D development. Installation completed, cool-down delayed to Spring 2024 due to LAr shortage
- New X-ARAPUCA design: compact, low number of channels, high PDE (2-3%)
  - Major effort to bring the technology to mass production (collaboration w/ vendors, optimization of materials and cryogenic amplification)
  - 48 ganged SiPMs correspond to 1 FD1-XA (8 strips of 6 ganged SiPM = 1 supercell channel readout)
- XA equipped with 1of 4 possible configurations:
  - 2 different WLS guides
  - 2 different SiPMs (Hamamatsu, FBK)

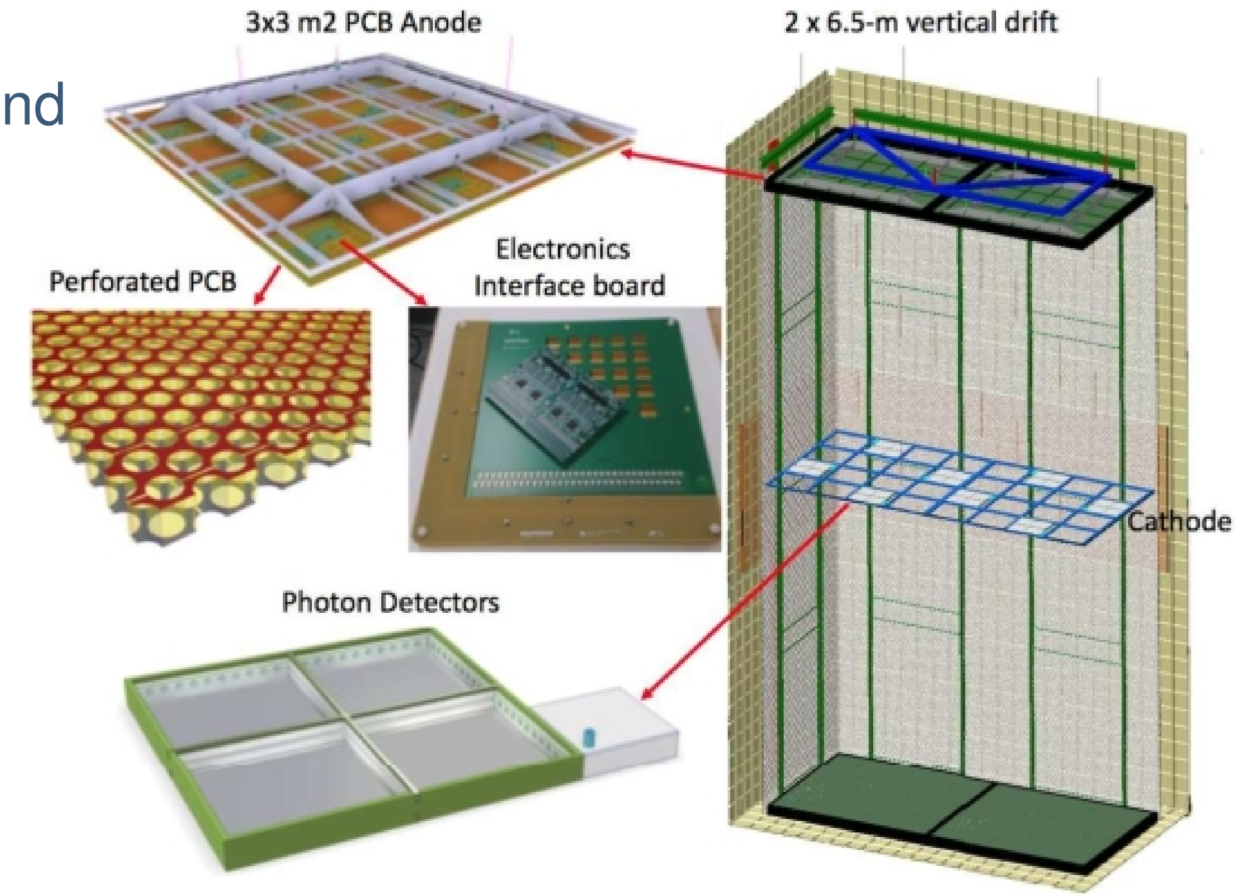


ProtoDUNE Vertical Drift: FD2 Technology

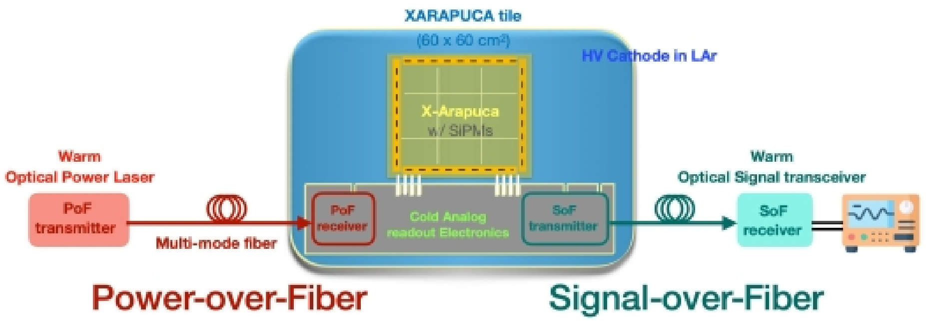
Second ProtoDUNE @ CERN will exploit the FD2 Vertical Drift technology

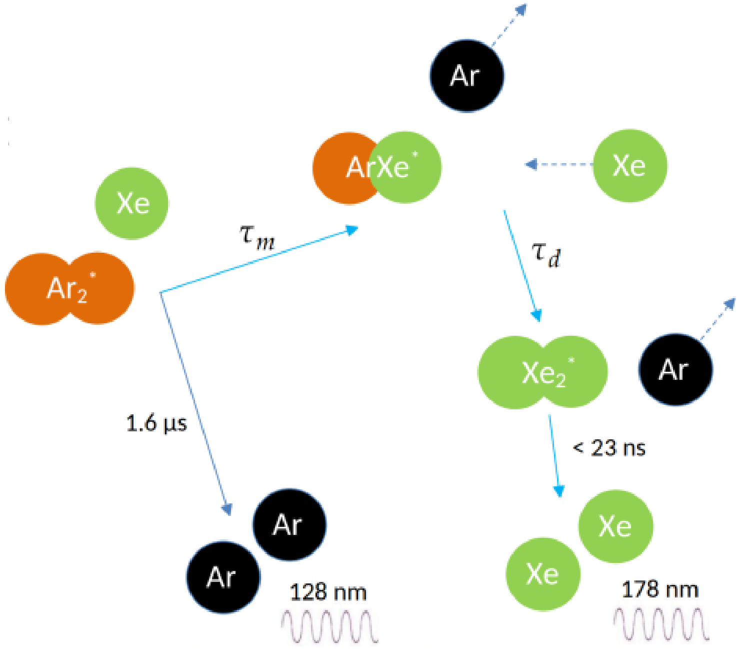
Eur. Phys. J. C 82, 618 (2022)

- Drift Length doubled → ~ 6m, drift vertical w/ cathode in the middle, cold electronics and PCB readouts: similar performance of HD but cheaper, no wires
- PDS:
  - X-ARAPUCA in the Cathode (300 kV!) and outside the field cage
  - Light Uniformity and Light Yield improved with Xenon doping



ProtoDUNE Vertical Drift - PDS





- A new technology to overcome the challenge of powering and reading SiPMs in a 300kV electric field: the **Power over Fibers (PoF)**: Power through optical fibers converted to DC at cold, good performance and durability
- ProtoDUNE-VD now installed @ CERN with novel PoF X-ARAPUCA
  - Major R&D effort (cold-box tests, design optimization,definition of VD PDS baseline towards FD2)
  - PDE of VD PDS membrane modules recently validated w/ a dedicated measurement (~2% preliminary), will be performed also for the PoF modules
- **Xenon Doping:** 178 nm wavelength photons
  - LAr transparent to its own light, but VUV γ scatter Rayleigh on Ar
  - Larger Rayleigh scattering length for 178 nm photons (~9m vs 1m for 128 nm photons) → better light uniformity & LY
  - Xenon doping successfully tested with:
    - ProtoDUNE-DP (GAr+LAr) (5.8 ppm) → Eur. Phys. J. C (2022) 82:618
    - A dedicated run of protoDUNE-SP(18.8 ppm, 13.5 kg): 2 Xe-light sensitive XA (1 Xe-only, 1 Ar+Xe) succesfully tested, 95% of light lost due to N_2 pollution recovered

Double Calorimetry: Charge+Light

The energy deposited in the detector goes into 2 observables: **Charge and Light**

- **Using only the charge** → standard reconstruction of deposited energy in a LArTPC, only the electrons that escape e^--ion recombination and successfully drift to the anode can be used: a correction must be applied to account for the charge lost:

Energy from Charge only:

$$E_Q = Q*R/W_{ion}$$

R=Recombination Factor = electron recombination survival probability.
Depends on the E_{field} and local ionization charge density *dQ/dx* → difficult to determine at all deposition sites, particularly for EM showers → use of an average value
$\mathbf{W_{ion}}$=ionization work function

- **Adding the light**: charge and light are anticorrelated and their sum is directly proportional to the deposited energy:

Energy from Charge+Light:

$$\boldsymbol{E_{QL} = W_{ph}\,(Q+L)}$$

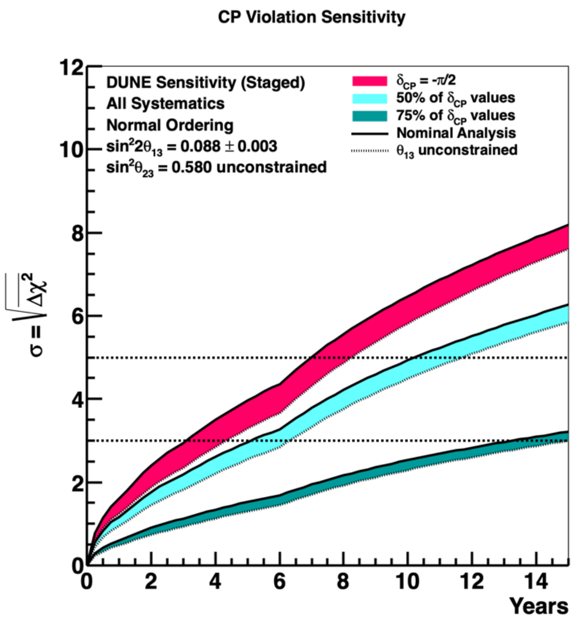
$\mathbf{W_{ph}}$=19.5 eV = average amount of energy deposited by a charged particle to produce an ion or exciton. Related to $\mathbf{W_{ion}}$ through the excitation ratio α: W_{ion}=23.6eV=$(1-\alpha)*W_{ph}$

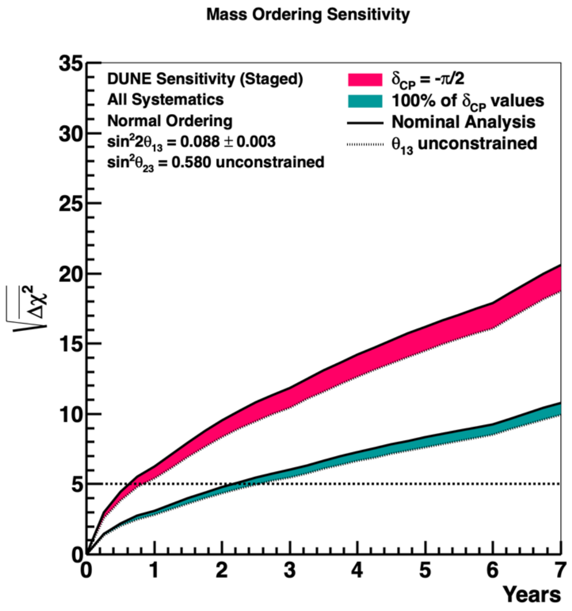
Charge: $\mathbf{Q} = N_i R = \mathbf{N_e}$
Light: $\mathbf{L} = N_{ex} + N_i (1-R) = \mathbf{N_\gamma}$
$\mathbf{Q+L} = N_i+N_{ex} = \mathbf{\Delta E / W_{ph}}$

→ We can perform a calorimetric measurement by-passing the correction for recombination that is no longer necessary and improve energy resolution

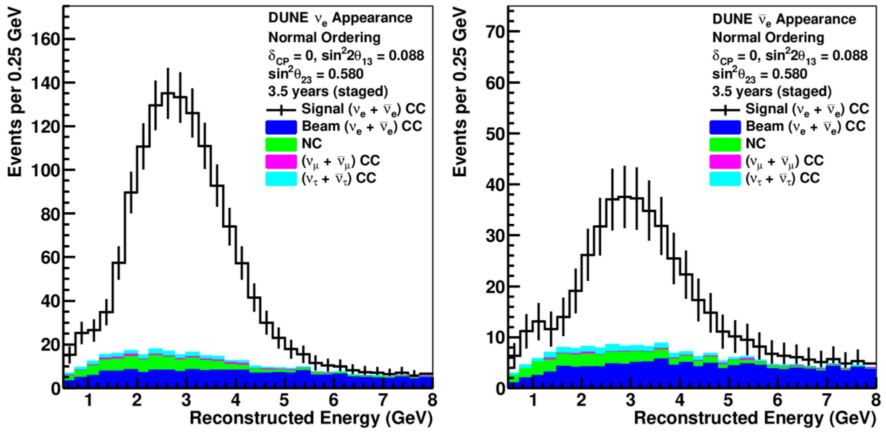
Double Calorimetry: Charge+Light

- The key strength of DUNE is the ability to measure the oscillation patterns of neutrinos over a range of energies spanning the first and second oscillation maxima: <u>coordinated analysis of the reconstructed ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ energy spectra in near and far detectors</u>
- **Improving the energy resolution directly impacts DUNE sensitivity to CPV and Mass Ordering**



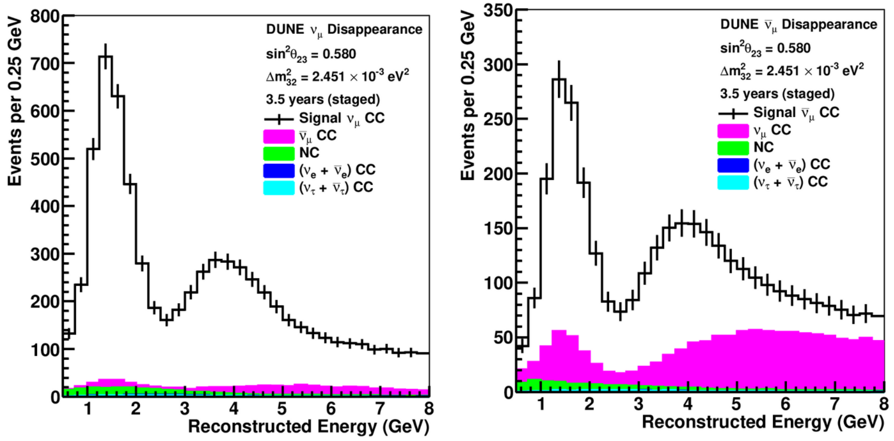


Neutrinos | Antineutrinos



ν_e Appearance

Neutrinos | Antineutrinos



ν_μ Disappearance

Double Calorimetry: Charge+Light

So we need:

Q = N_e = Number of ionization electrons **calculated from reconstructed charge**

L = N_γ = Number of scintillation photons **calculated from reconstructed photo-e⁻ in the optical detectors**

$$Q = C_e^{cal} \sum_i q_i e^{t_i/\tau_e}$$

$q_i e^{t_i/\tau_e}$ = charge corrected by electron lifetime = Sum of all collection plane hits corrected by electron lifetime

C_e^{cal} = ADC to electron calibration constant

$$L = \frac{Total\,PE}{QE \cdot F_{vis}}$$

$Total\,PE$ = reconstructed photo-electrons of the event

QE = photo-detection efficiency, 3% in DUNE-FD1

$$F_{vis} = \frac{\sum_i f_{vis}(p_i) \cdot q_i}{\sum_i q_i}$$

= Charge weighted visibility function of the event, gives the expected photons @ the optical detector w.r.t the photons emitted in position p_i by the passing particle
→ We need a visibility map of the detector!

Light Simulation

1) **Production**: phenomenological model that modifies the Birks' charge recombination model and provides the anticorrelation between light and charge and its dependence with dE/dx and E_{field} :
$Q(dE/dx, E_{field}) + L(dE/dx, E_{field}) = N_i + N_{ex}$ N_i, N_{ex} = model input parameters, with current numerical values extracted from data

2022 JINST 17 C07009

2) **Propagation**: tracking individual photons in Geant4 is prohibitive → **Semi-analytical model** that predicts hits on a PDS module from scintillation photons produced: factorize geometry (Ω), absorption and Reyleigh scattering

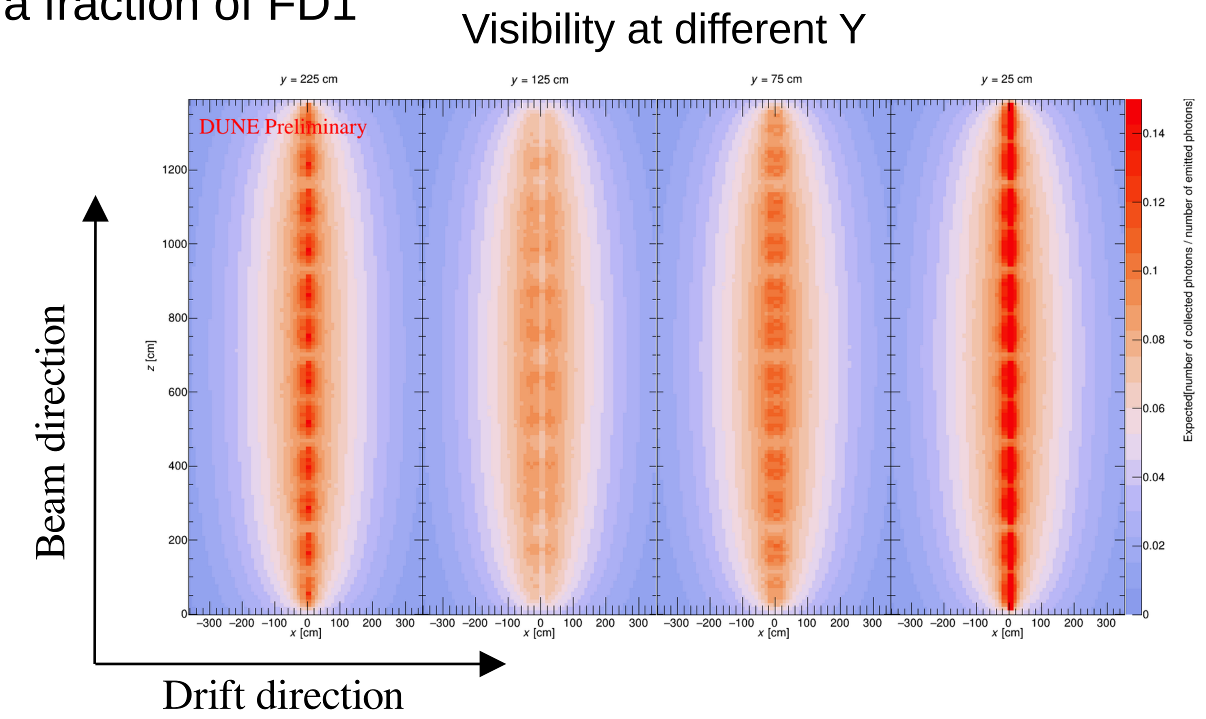
Effective parametrization calibrated on heavy Geant4 simulations

Eur. Phys. J. C 81, 349 (2021)

3) **Digitization**:

- For each p.e., a waveform is created (shape modelled on direct measurements)
- Waveforms filtered to deconvolve detector response and scintillation time profile

Visibility Map from semi-analitycal model corresponding to a fraction of FD1



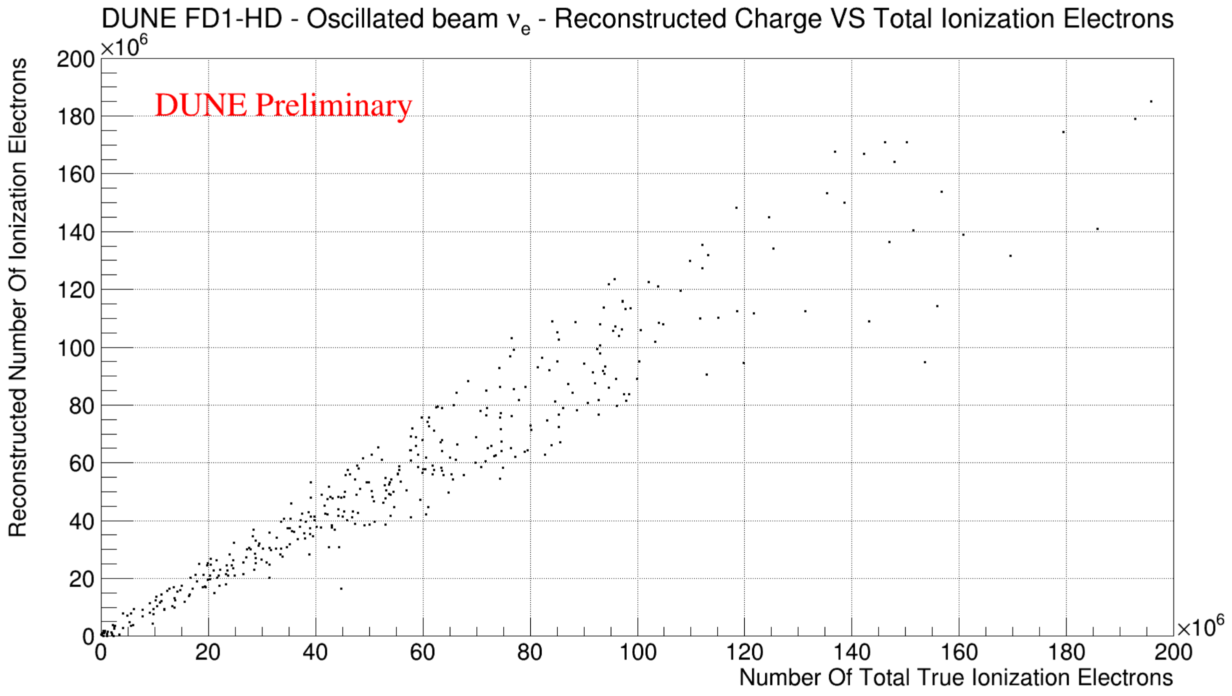
DUNE Far Dector Horizontal Drift – Beam ν_e

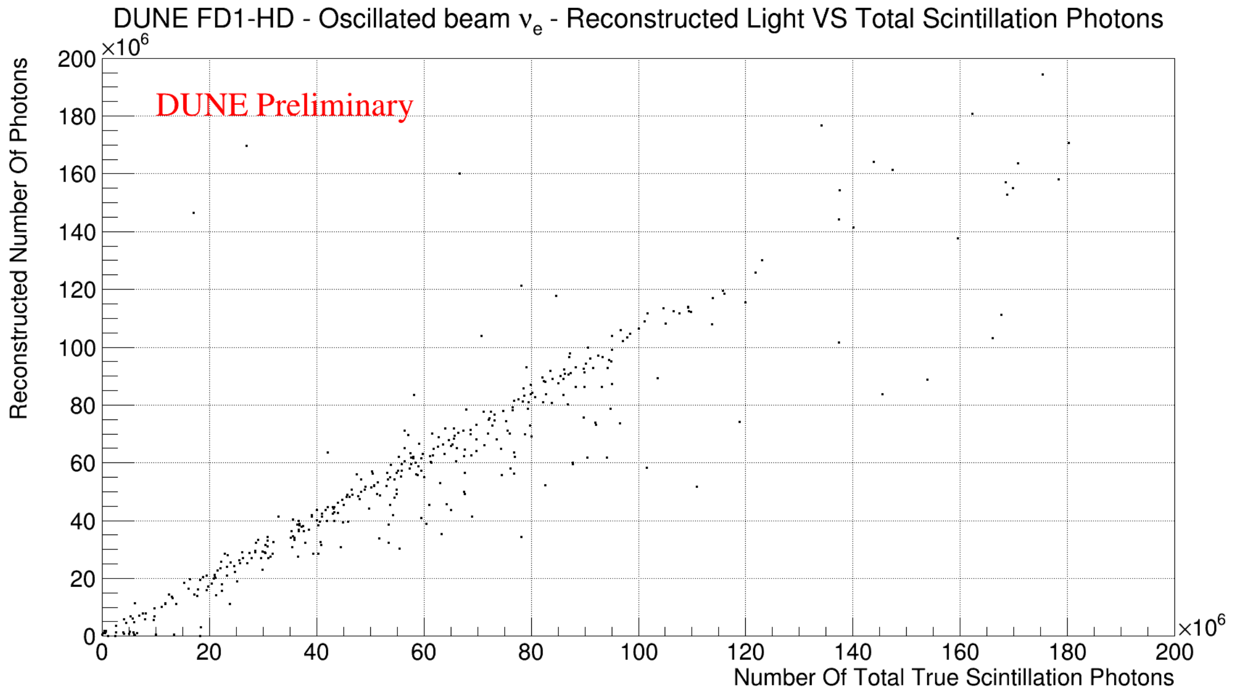
Preliminary studies with beam neutrinos simulated events in the DUNE FD1-HD

Simulation of DUNE-FD1 beam events: 500 beam ν_e

-all collection plane charge hits
-all PE reconstructed

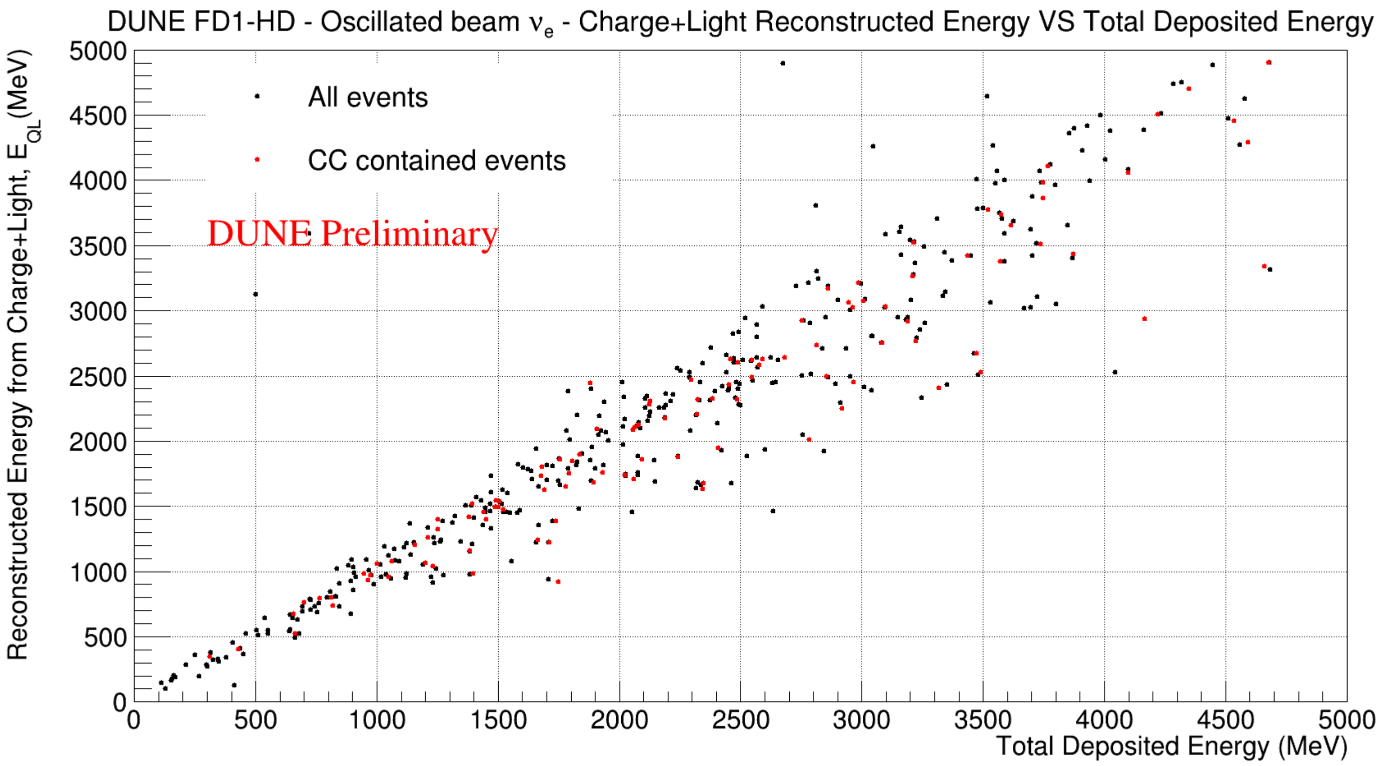
$\Big\}$ Calculation of Q & L → should correspond to Nb of e^- and γ generated in LAr

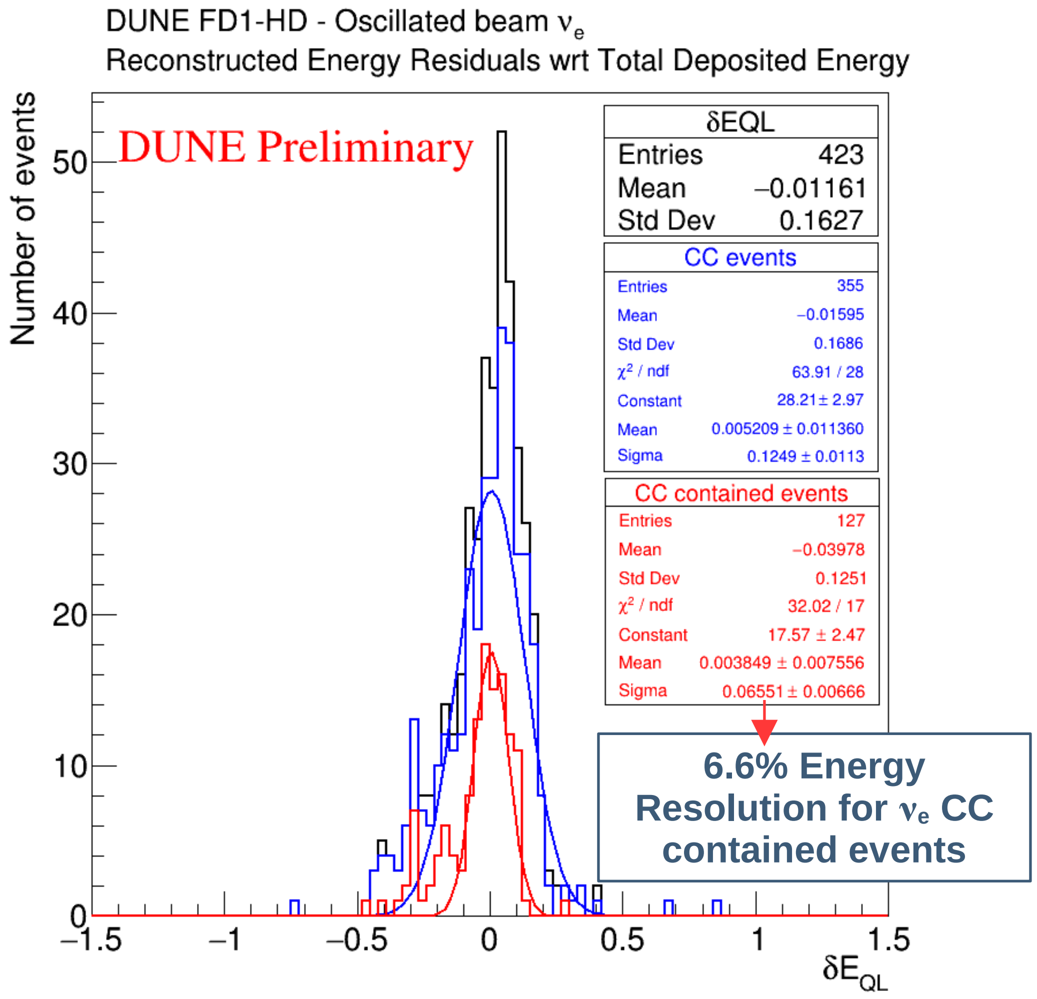




DUNE Far Dector Horizontal Drift – Beam ν_e

Reconstructed event Energy from Charge & Light: $E_{QL} = W_{ph}(Q+L)$ → Comparison to Total Deposited Energy

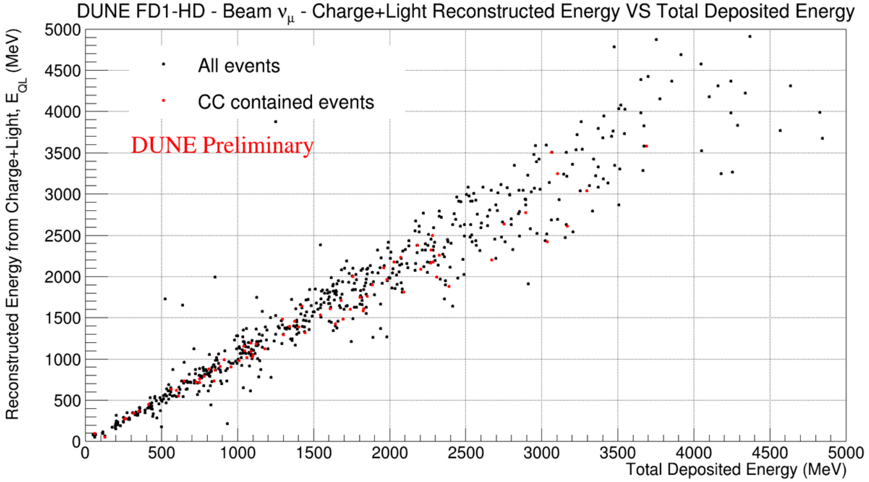


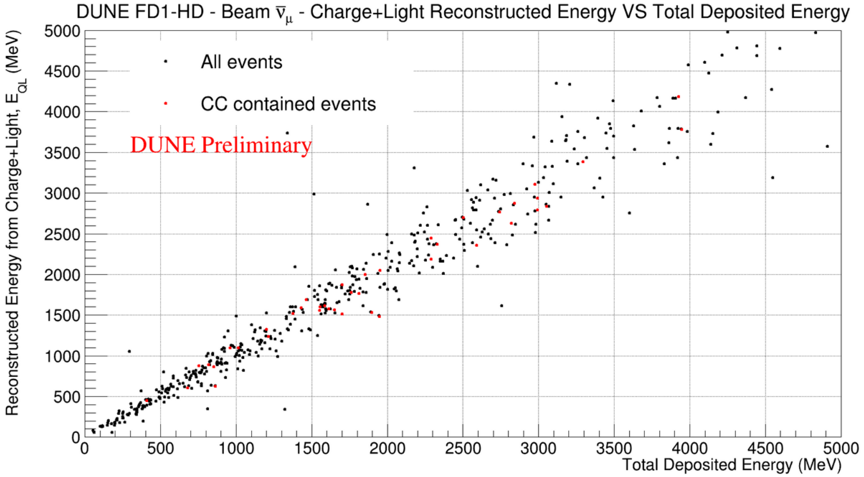


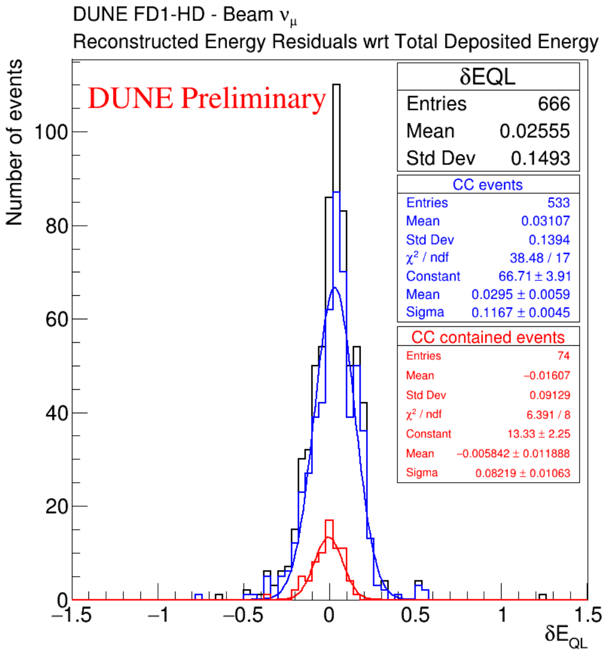
DUNE Far Dector Horizontal Drift – Beam ν_μ & $\overline{\nu}_\mu$

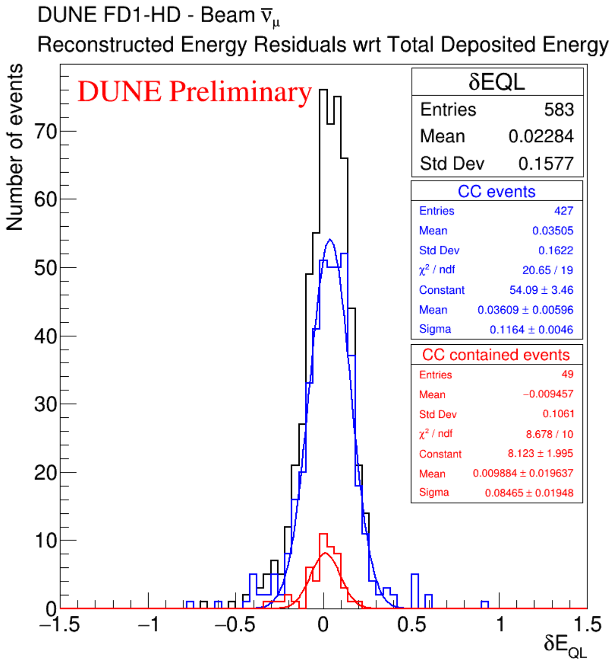
DUNE-FD1 simulated beam events:

- 700 beam ν_μ & beam $\overline{\nu}_\mu$
- Energy from Charge+Light & comparison to Total Deposited Energy
- **Energy Resolution:**
  ν_μ CC contained ~ 8.2%
  $\overline{\nu}_\mu$ CC contained ~ 8.5%









Conclusions

- DUNE detectors are kton **LArTPCs**, collection of VUV LAr scintillation photons is an integral aspect of the technology:
  - An independent **Photo Detection System based on X-ARAPUCA** light collectors
  - **PDS tests performed & on-going @ CERN with protoDUNE-HD & protoDUNE-VD**
    - ProtoDUNE-HD Phase II in Spring 2024
    - Installation of ProtoDUNE-VD in progress

    → DUNE FD1 (HD) & FD2 (VD)
  - **Double Calorimetry**: Combining Charge and Light allows to reconstruct the deposited energy in LAr → by-passing the correction for recombination of ionization electrons → improving the energy resolution!

    Preliminary results on simulated beam events in DUNE FD1:

    σ_E CC contained on Total Deposited Energy:
    6.6 % ν_e, 8.2% ν_μ and 8.5% $\overline{\nu_\mu}$
    Charge-only energy resolution in DUNE in the 0.5–4 GeV range:
    ~15–20%, depending on lepton flavor and reconstruction method
    Eur. Phys. J. C 80, 978 (2020)

    → improve DUNE sensitivity of CPV and Mass Ordering

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

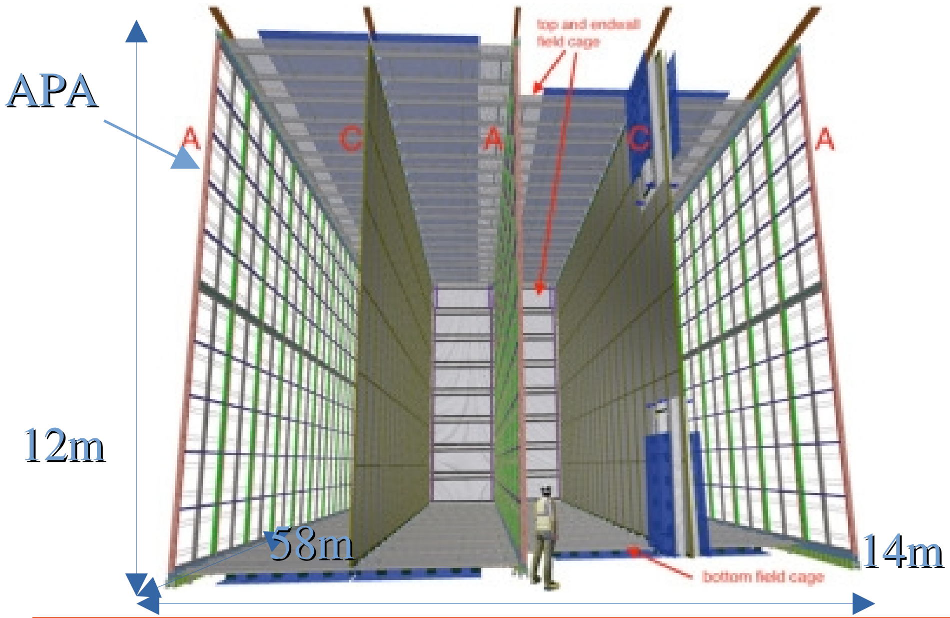
> 1,000 collaborators
over 200 institutions
in over 30 countries + CERN

Thank You!

Back ups

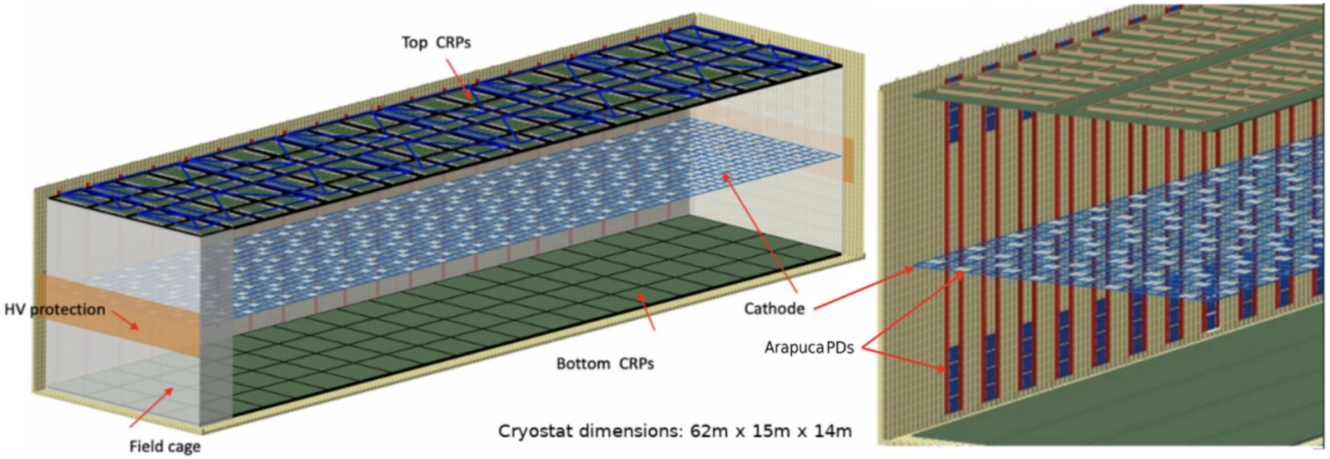
FD1

- **Four 3.2 m Horizontal Drift regions**: alternated Anode and Cathode Plane Assemblies
- **Charge readout with wires** in Anode Planes Assembly (150 APA, 6x2.3m)
- E_{field} = 500 V/cm
- **PDS**: 10 modules for APA = in total 1500 modules in FD-1, 4 channels per module. 1 Module 2092x118x23 mm^3 = 4 supercells 488x100x8 mm^3



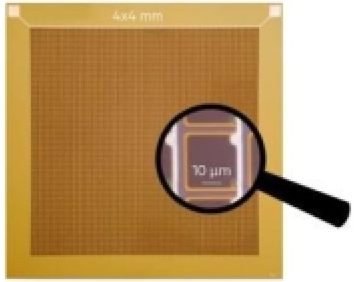
FD2

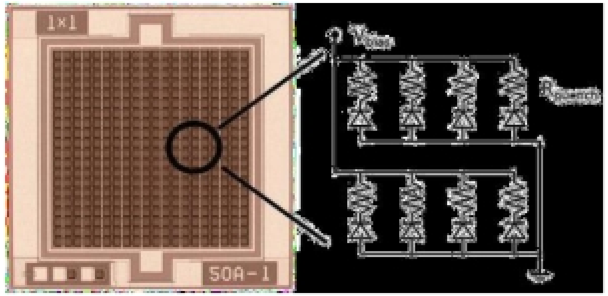
- **Two 6 m Vertical Drift regions**
- **Charge readout with PCB planes** (160 CRPs, 3x3.4m)
- E_{field} = 450 V/cm , 300 kV on Cathode
- **PDS** modules mounted on the cathode and on the cryostat walls:
  - Square geometry: dimension 65x65 cm^2
  - A single large WLS light guide plane
  - Light readout by 160 SiPMs mounted on flexible strips
- **Xenon doped LAr**: Longer Rayleigh scattering length: enhanced light collection in large volumes



SiPMs

- DUNE Photosensors=a matrix of single-photon avalanche photodiodes operating in reverse bias above breakdown voltage Vbd
- Robust, w/ high sensitivity and dynamic range, immune to B field, w/ reduced cost/size
- DUNE specs:
  - Quantum efficiency > 35% for 430 nm light @ 87 K
  - Dimensions compatible w/ ARAPUCA design
  - SiPM + FEE w/ dynamic range 1-2000 photons, even for events far from the ARAPUCA
  - Dark count Rate (DCR) subdominant wrt noise from 39Ar
  - Cross-talk (CT) and after-pulse (AP) < 15%
  - Durability (>10 y) and cryoreliability (resistant to multiple cool-downs)
  - Few µs recovery time
- 6k SiPMs of ProtoDUNE-HD tested in 2022



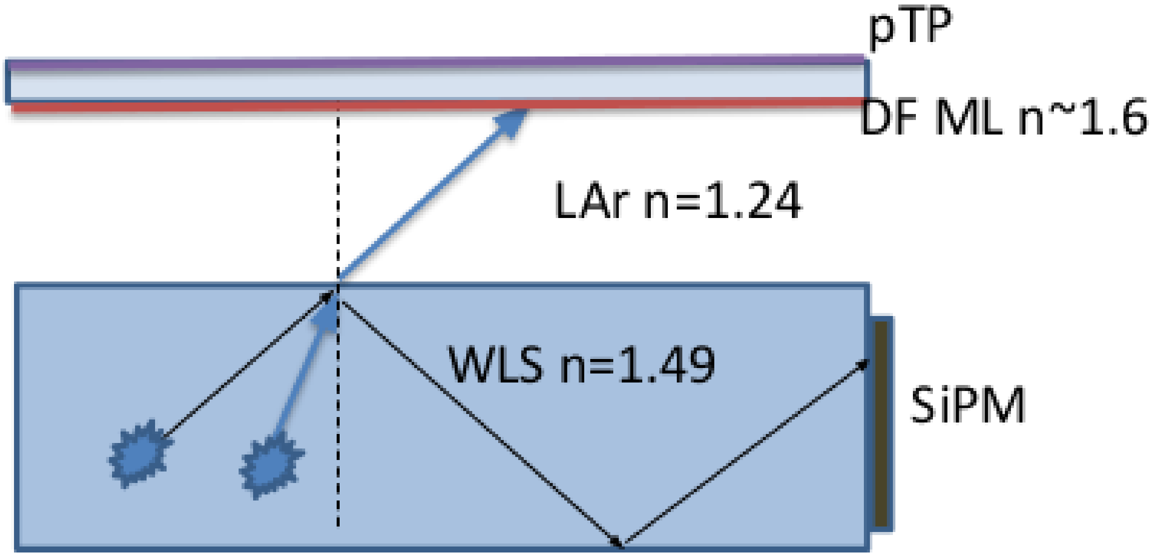


SiPMs & WLS

- **SiPM to WLS coupling**
  - To minimize gap between SiPM and WLS in LAr → SiPMs on flex circuits + spring loaded mount to compensate WLS shrinking (~1% i.e. 6 mm)
  - Also tested SiPM fitting in dimple cuts (flat or cylindrical) machined at the edges of WLS
- **WLS attenuation length (λ_{att})**
  - For PMMA based WLS in LAr, the critical angle for light trapping at the surfaces is $56° = \theta_c$. For $\theta > \theta_c$ light is trapped and guided by TIR to SiPMs
  - Due to multiple reflections the optical path inside large size WLS may reach a couple of meters → dye concentration tailored to FD2 size and optical path → optimization driven by simulations

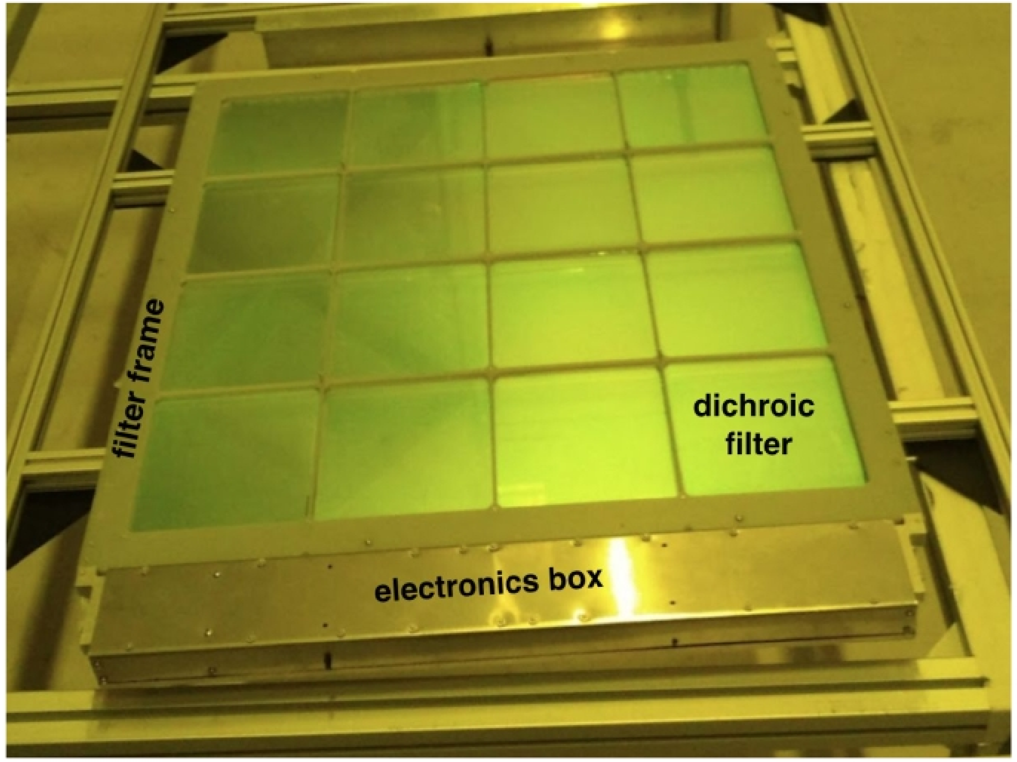
Dichroic Filters

- made of thin film multilayer coatings on a glass/fused silica substrate. They act as Fabry-Perot interferometer to selectively transmit/reflect light.
- For Large volume LAr detectors → Large area DF (minimize optical window dead areas) → challenge: pTP coating uniformity
- The glass window is coated with a primary WLS (pTP) to downshift the 128 nm light to ~350 nm



- Filters have been optimized to operate in LAr (@45°)
- Higher transmittance in the pTP emission range
- Higher reflectivity in the light guide WLS chromophore emission range
- But narrower reflectivity window

FD2 – Vertical Drift X-ARAPUCA



Same technology but different SiPM coverage and dimensions, WLS plate dimensions 60.7x60.7x0.4 cm^3:

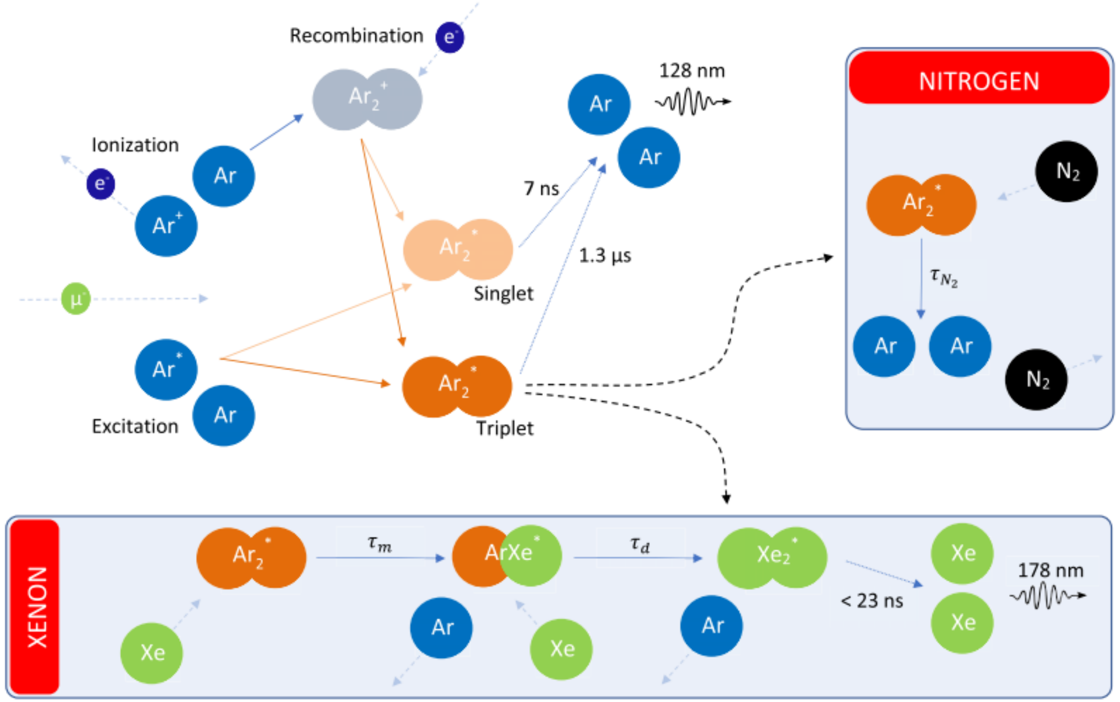
- Maximize photon detection
  - SiPM-WLS coupling
  - optimize Optical Path and plate thickness vs attenuation length i.e. dye concentration
  - new dichroic filters
- Maximize active area
  - larger dichroic filters
- PDE measurements of the large area X-Arapuca are being performed at different sites: INFN Naples, CIEMAT (Madrid)

DUNE FD3 & FD4

- DUNE low energy physics program (Δm^2_{21}, hep, SN busts) takes full advantage of light detection for trigger, PID, and calorimetry (particularly for low-E EM showers)
- Strong drive within DUNE to exploit FD Modules 3 and 4 to extend low-energy physics program
- Improved solar ν and SN physics, SN CEνNS, even $0\nu\beta\beta$ (^{136}Xe doping) and WIMP searches
- All possible in upgraded FD modules w/o losing sensitivity to neutrino mixing parameters
- All these extensions depend on an enhanced PDS → vigorous R&D and design/simulation programs
- Lower threshold wrt baseline DUNE design (10 MeV → O 100 keV)
- Rejection of background (n, Rn, ^{42}Ar, ^{39}Ar), a major challenge, via topology and PSD
- Better E_{res} via charge + light calorimetry (i.e. w/ Arapuca-style module and novel VUV SiPMs that are under study)

Xe Doping

- Xenon added to LAr → Xe atoms can interact with Argon excimers creating an ArXe excited dimer
- Dimer comes across a Xe atom resulting in the creation of Xe^*_2 that decays very fast (<23 ns) emitting 178 nm photons.
  The time constants of these processes are inversely proportional to the rate constant and to the Xe concentration
  (→ increasing the Xe concentration enhances the wavelength shifting efficiency until saturation effects)



- The presence of pollutants like N_2 can reduce the light by quenching. This process is more efficient as the time scale becomes faster, i.e. at larger nitrogen concentrations.
- Xenon becomes a direct concurrent in the process since its reaction rate constant is larger than the one of N_2, the light can be recovered with the wavelength shifting mechanism

Event displays