The photo-detection system and double calorimetry in DUNE

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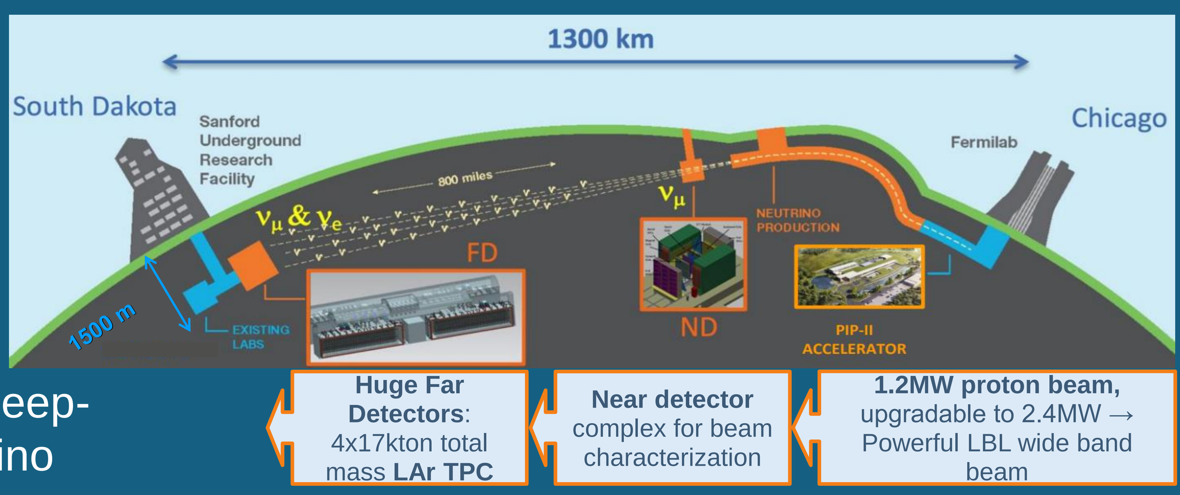
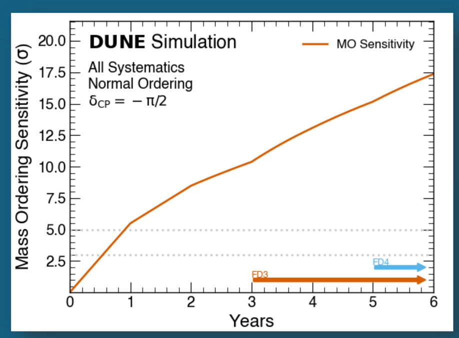
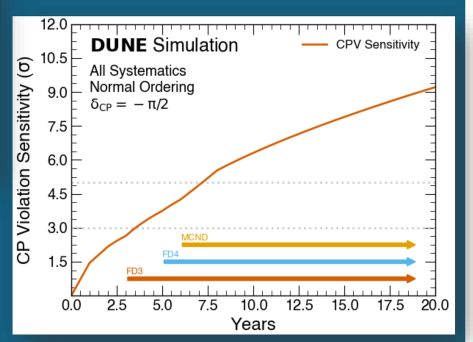
Deep Underground Neutrino Experiment – Liquid Argon TPC Technology



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

- Key strength of DUNE: ability to measure oscillation patterns of neutrinos over a range of energies spanning the first and second oscillation maxima: **coordinated analysis of the reconstructed ν_μ, ν_e and anti- ν_μ, ν_e energy spectra in Near and Far Detectors**
- **Improving the energy resolution directly impacts DUNE sensitivity to CPV and Mass Ordering**

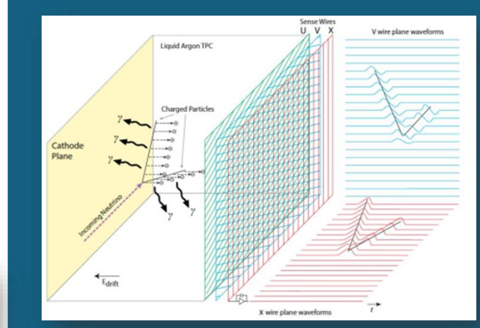


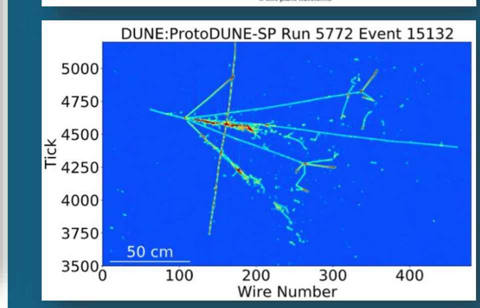


Two observables generated from **energy deposition by particles in liquid Argon:**

- **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)**

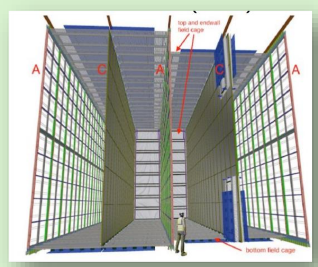




DUNE Far Detectors (17kton modules)

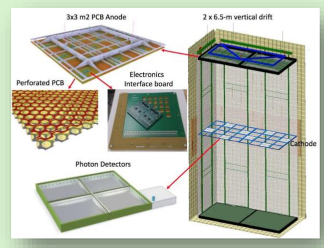
FD1 - Horizontal Drift (FD-HD)

- Wire readout planes
- 4 drift regions



FD2 - Vertical Drift (FD-VD)

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



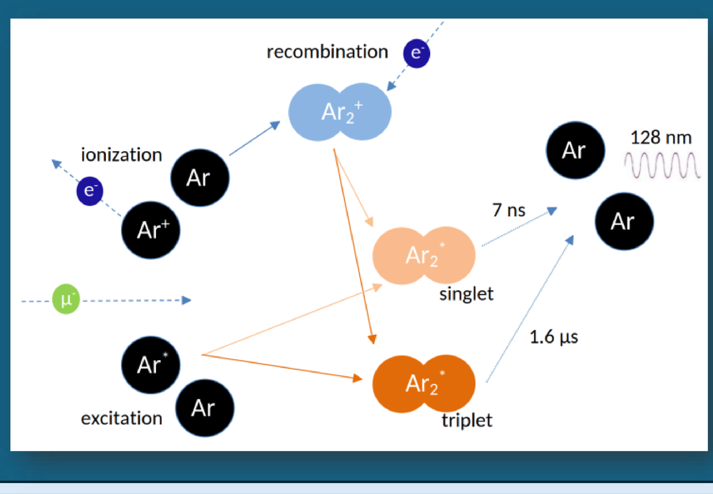
The Photo-detection System LAr VUV Light detection

Scintillation light is:

- **Abundant**: 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

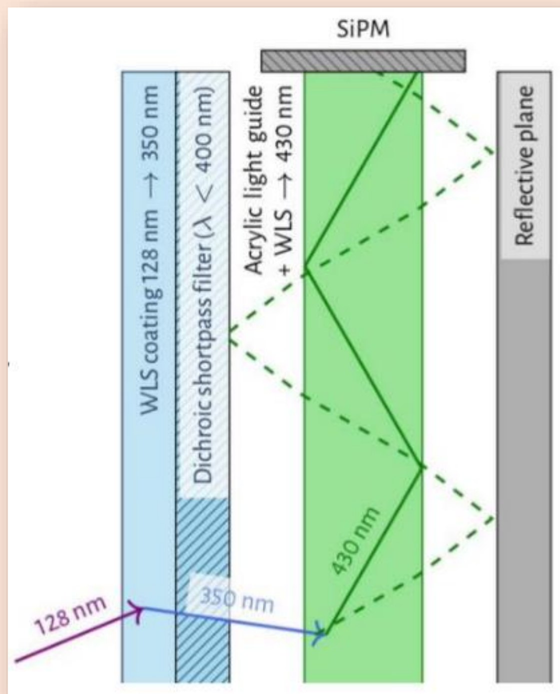
Detection of Light in a DUNE TPC:

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



X-Arapuca

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



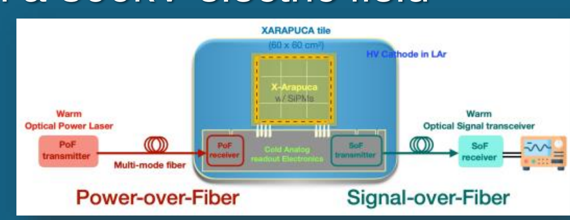
Trap photons in a box with highly reflective internal surfaces

- Core of the device: **Dichroic filter** = multilayer interference film which is highly transparent for wavelength below a cutoff and highly reflective above it
- **Ligth transmitted:** PTP shifter deposited on the dichroic external side converts VUV light to a wavelenght < dichroic cutoff
- **Light Trapped:** internal WLS bar converts the primary shifted photons to a wavelength > dichroic cutoff
- After reflections the photons can be detected by SiPM positioned laterally with respect to the WLS plane

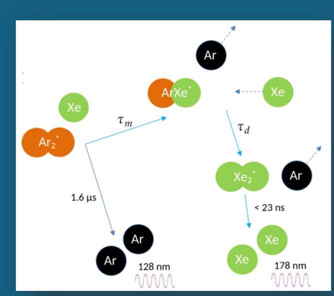
Vertical Drift - PDS

- **PoF (Power over Fibers):** A new technology to overcome the challenge of powering and reading SiPMs in a 300kV electric field

Power through optical fibers converted to DC at cold



- **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



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Double Calorimetry: Charge+Light

- **Charge only** - 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

$$E_Q = Q\,\frac{R}{W_{ion}}$$

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
W_{ion}=ionization work function

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

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

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

Charge: $Q = N_i R = N_e$

Light: $L = N_{ex} + N_i\,(1\text{-}R) = N_\gamma$

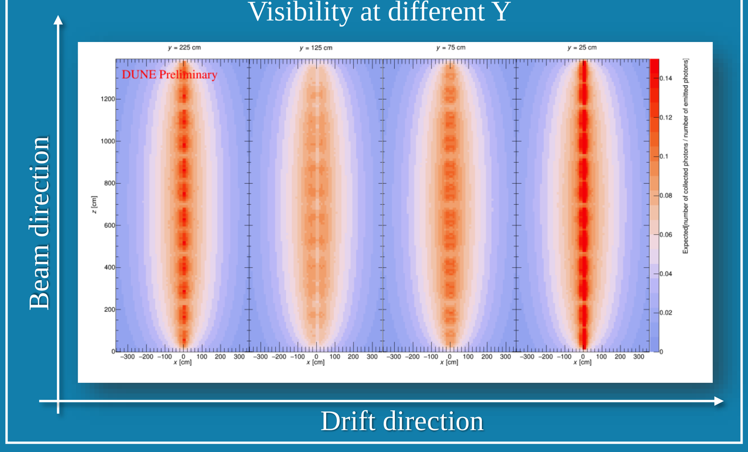
$Q\text{+}L = N_i\text{+}N_{ex} = \Delta E / W_{ph}$

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

Light Simulation

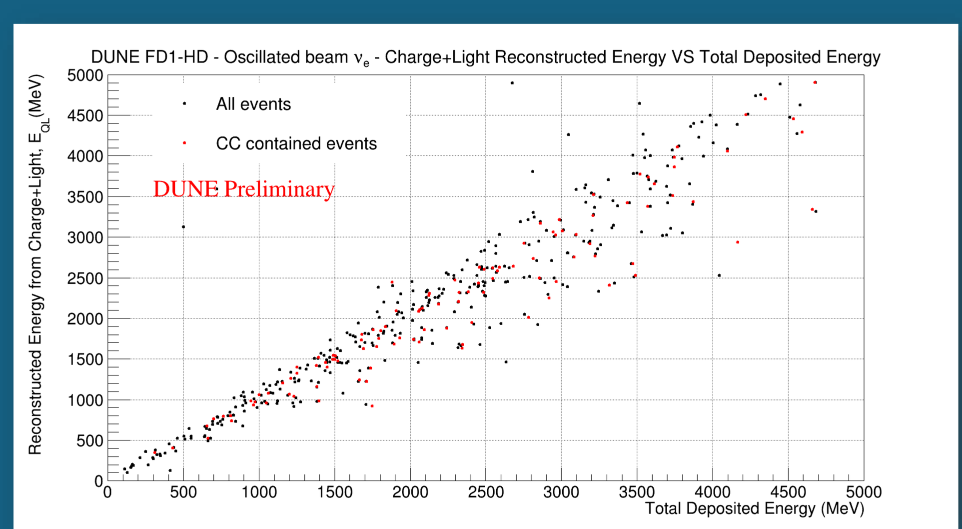
1) **Production**: phenomenological model (modification of the Birks' charge recombination model) that provides the anticorrelation between light and charge and its dependence with dE/dx and E_{field}: $Q(dE/dx, E_{field}) + L(dE/dx, E_{field}) = N_i + N_{ex}$
N_i, N_{ex} = model input parameters, with current numerical values extracted from data (2022 JINST 17 C07009)
2) **Propagation**: **Semi-analytical model** that predicts hits on a PDS module from scintillation photons produced: factorize geometry (Ω), absorption and Reyleigh scattering (Eur. Phys. J. C 81, 349 (2021))
3) **Digitization**:
   - For each p.e., a waveform is created
   - Waveforms filtered to deconvolve detector response and scintillation time profile

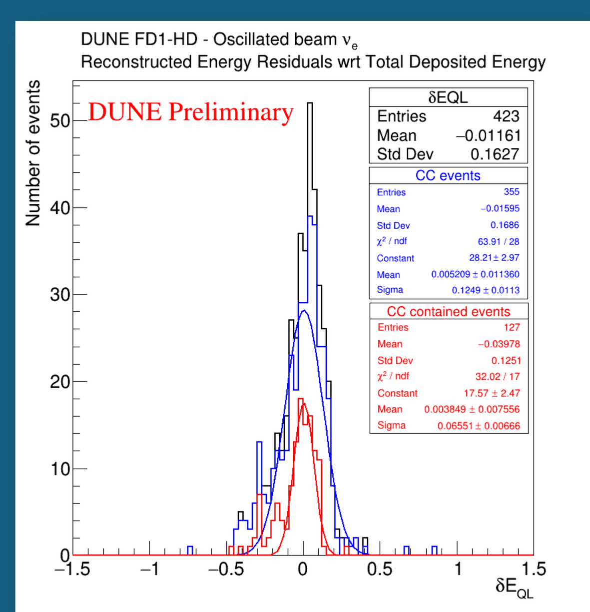
Visibility Map from semi-analitycal model corresponding to a fraction of FD1



Energy Resolution

- Preliminary studies with beam neutrinos simulated events in the DUNE FDs
- Starting from { all collection plane charge hits / all PE reconstructed } of the event → Calculation of Q & L
- Reconstructed event Energy from Charge & Light: $E_{QL} = W_{ph}\,(Q\text{+}L)$ → Comparison to Total Deposited Energy





- Preliminary results on simulated beam events σ_E CC contained on Total Deposited Energy: FD-HD: 6.6% ν_e, 8.2% ν_μ and 8.5% $\overline{\nu}_\mu$

Charge-only energy resolution in DUNE in [0.5-4] GeV range: ~15–20%, depending on lepton flavor and reconstruction method (Eur. Phys. J. C 80, 978 (2020))

→ may improve DUNE sensitivity of CPV and Mass Ordering!

- Next: Double calorimetry for Vertical Drift → Longer drift + Xe doping: Enhanced light collection!

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