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The photo-detection system and double calorimetry in DUNE

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The Deep Underground Neutrino Experiment (DUNE) comprises a suite of Near Detectors and Far Detectors based on the Liquid Argon TPC technology, enhanced by a powerful Photon Detection System (PDS) that records the scintillation light emitted in Argon. Besides providing the timing information for an event, photon detectors can be used for calorimetric energy estimation.
The two observables generated from energy depositions by particles in liquid Argon are charge and light. The visible energy could be estimated using the charge alone. However, only electrons escaping recombination reach the wire planes, so corrections must be applied for this loss. Charge and light are anticorrelated and their sum is directly proportional to the total energy deposited: the advantage of using both is that the correction for recombination is no longer necessary. This proceeding presents an overview of the DUNE PDS and the results obtained for calorimetric analyses in the DUNE detectors by combining charge and light.

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1. Dune detectors - Liquid argon TPC technology

The DUNE experiment is a large mass, high precision, deep underground, accelerator neutrino experiment allowing a wide physics program [1]. The 1.2MW Fermilab accelerator proton beam is used to produce a wide band neutrino beam, that, after being carachterized by a near detector complex, is sent to the underground far detectors (FD) in South Dakota, 1300 km away. In the first phase, DUNE will operate 2 liquid argon (LAr) TPC detectors, 17kton each, 1500 m underground: the FD1, that will drift electrons horizontally (FD-HD), and the FD2, with vertical drift (FD-VD). Neutrino oscillation parameters will be measured with a coordinated analysis of the reconstructed ν_μ, ν_e and anti-ν_μ, ν_e energy spectra in the near and far detectors. Therefore, improving the energy resolution directly impacts DUNE sensitivity to CP violation and mass ordering.

The two observables generated from energy deposition by particles in a LAr TPC are the charge and the light: ionization electrons, that escape recombination and drift to the anode, providing precise imaging of the event, and VUV scintillation photons (λ=128nm), providing precise event timing. DUNE has two independent readout systems, the anodic charge readout and a photo detection system (PDS). The FD-HD uses wire readout planes and has four drift regions, while in the FD-VD the drift length is doubled to ~6m with the cathode in the middle of two drift regions, with cold electronics and PCB for readout (no wires).

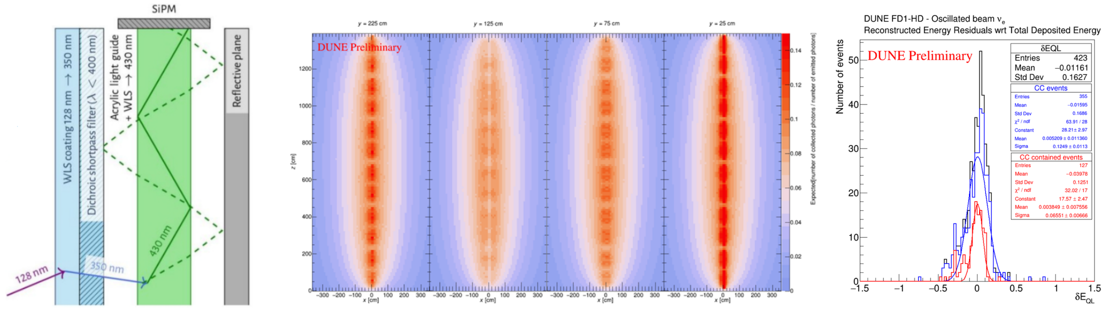
2. The Photo-detection System - LAr VUV Light detection

Scintillation light is abudant (25k photons/MeV at 500V/cm) and fast (τ_{fast}=7 ns). To detect the light signal in a DUNE TPC the VUV photons are converted to a longer wavelength through wavelength shifting (WLS), then they're trapped inside a box with highly reflective internal surfaces (X-ARAPUCA), and a fraction is conveyed to Silicon Photomultipliers (SiPM). The X-ARAPUCA concept is shown in Fig 1a: the core of the device is the dichroic filter, a multilayer interference film which is highly transparent for wavelength below a cutoff (λ=400nm) and highly reflective above it allowing to trap the light inside. X-ARAPUCA modules are used in both FD-HD and FD-VD. Because of the longer drift distance, in the FD-VD light uniformity and light yield will be improved with Xenon doping [2]: liquid Argon is transparent to its own light, however, VUV photons scatter Rayleigh with a scattering length of ~1m, Xenon instead, produces 178 nm wavelength photons with a Rayleigh scattering length of ~9m. The light simulation in DUNE is described in [3, 4].

3. Double Calorimetry

Only the electrons that escape electron-ion recombination and successfully drift to the anode can be used to reconstruct the energy deposited and a correction must be applied to account for the charge lost. Therefore, with charge (Q) information alone, we have: $E_Q = Q(R/W_{ion})$, where $W_{ion} = 23.6 \pm 0.3$ eV is the ionization work function and the recombination factor R represents the electron recombination survival probability, usually an average value is considered because it depends on the E_{field} and on the local ionization charge density dQ/dx and so it's difficult to determine it at all deposition sites, particularly for EM showers. Adding the light (L) information, knowing that it's anticorrelated to the charge, and that their sum is directly proportional to the deposited energy, the reconstructed energy becomes: $E_{QL} = (Q + L)W_{ph}$, where W_{ph}=19.5 eV is the average amount of energy deposited by a charged particle to produce an ion or exciton[1].

[1] W_{ph} is related to W_{ion} through the excitation ratio α: $W_{ion} = (1 - \alpha)W_{ph}$



(a) **(b)** **(c)**

Figure 1: (a) X-Arapuca: reflective box equipped with an entrance window, two photon downshifting stages, one dichroic filter and one light guide coupled to SiPM. (b) Visibility map obtained from the semi-analitycal model corresponding to a fraction of FD-HD, the Y axis corresponds to the beam direction (Z [m]), while the X axis corresponds to the drift direction (X [m]). Different height positions are shown (Y [cm]). (c) Residuals of reconstructed E_{QL} on total deposited energy for oscillated beam ν_e simulated events in the FD-HD. The energy resolution for CC contained events is 6.6%.

This allows to by-pass the recombination correction. Because $Q + L = N_i + N_{ex} = \Delta E/W_{ph}$, with $Q = N_i R = N_{e^-}$, and $L = N_{ex} + N_i(1-R) = N_\gamma$, we calculate Q and L for reconstructed events in the DUNE Far Detectors starting from the collection plane charge hits and the number of reconstructed photo-electrons in the PDS: $Q = C^e_{cal} \sum_i q_i e^{t_i/\tau_e}$, where C^e_{cal} is the ADC to electron calibration constant and $\sum_i q_i e^{t_i/\tau_e}$ is the sum of all collection plane hits corrected by the electron lifetime τ_e in the detector; and $L = Total\ PE/(QE \cdot F_{vis})$, where *Total PE* is the total number of reconstructed photo-electrons of the event, QE is the photo-detection efficiency and $F_{vis} = \frac{\sum f_{vis}(p_i) \cdot q_i}{\sum q_i}$ is the charge-weighted visibility function that gives the expected number of scintillation photons at the optical detectors with respect to the scintillation photons emitted by the passing particle in the reconstructed position $p_i = (x_i, y_i, z_i)$ inside the TPC volume for the associated charge hits q_i, $f_{vis}(p_i)$ is extracted by the visibility map (see Fig 1b) of the detector.

4. Energy Resolution

We have performed preliminary studies with beam neutrinos simulated events in the DUNE far detectors and compared the calculated E_{QL} with the true information of the total deposited energy. An example of the reconstructed E_{QL} compared to the total energy deposited is shown in Fig 1c. Preliminary results show that the energy resolution on total deposited energy, for charge current contained events, is: 6.6% for ν_e, 8.2% for ν_μ and 8.5% for anti-ν_μ in the FD-HD. Previous studies reported for charge-only energy resolution in DUNE in [0.5-4] GeV range, $\sigma(E) \sim 15-20\%$, depending on lepton flavor and reconstruction method [5]. The next steps of this study will include simulated events for the FD-VD in order to exploit even more the light information given the enhanced light collection due to Xe doping.

References

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