Study of Charge and Light Correlation in Electron Beam Energy Response of DUNE prototype ProtoDUNE-SP LArTPC

Zelimir Djurcic, David Antón Martin, Aleena Rafique
for the DUNE collaboration
Argonne National Laboratory
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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Argonne NATIONAL LABORATORY

1. Abstract

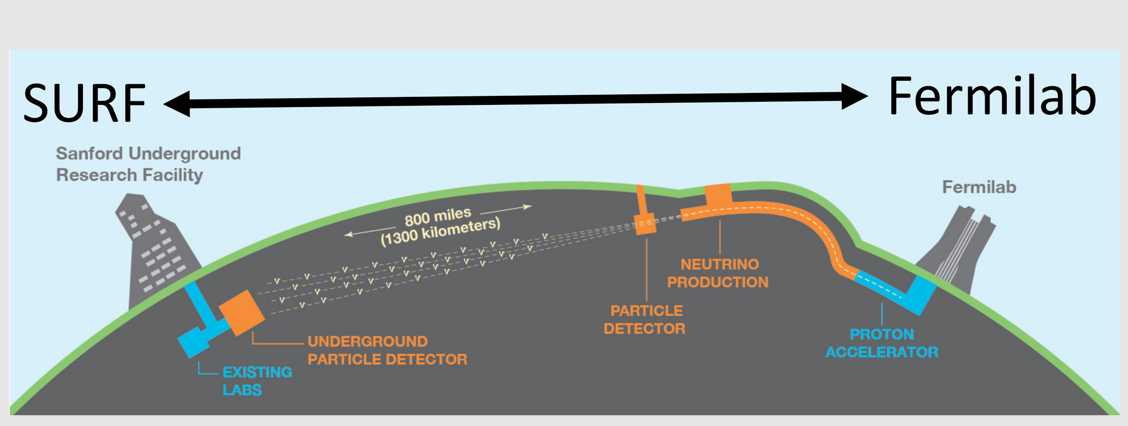
The Deep Underground Neutrino Experiment (DUNE) is a cutting-edge experiment for neutrino science and proton decay studies. The single-phase liquid argon prototype detector at CERN (ProtoDUNE-SP) is a crucial milestone for DUNE that will inform the construction and operation of the first, and possibly subsequent 17-kt DUNE far detector modules. We have studied the response of DUNE LArTPC prototype detector ProtoDUNE-SP to test beam positrons via both ionization and scintillation signals. We searched for (anti) correlation between fluctuations of both scintillation and ionization in liquid argon, on event-by-event basis. Preliminary results, to be presented at the conference, reveal anti-correlated statistical fluctuation between scintillation and ionization in liquid argon.

2. Motivation

- Detection and reconstruction of neutrino interaction in DUNE LArTPCs
- Detect final state particles by both ionization charge and light flashes
- Goal is to improve the event reconstruction and resolution in DUNE
- Focus here on electron reconstruction at GeV energy scale.

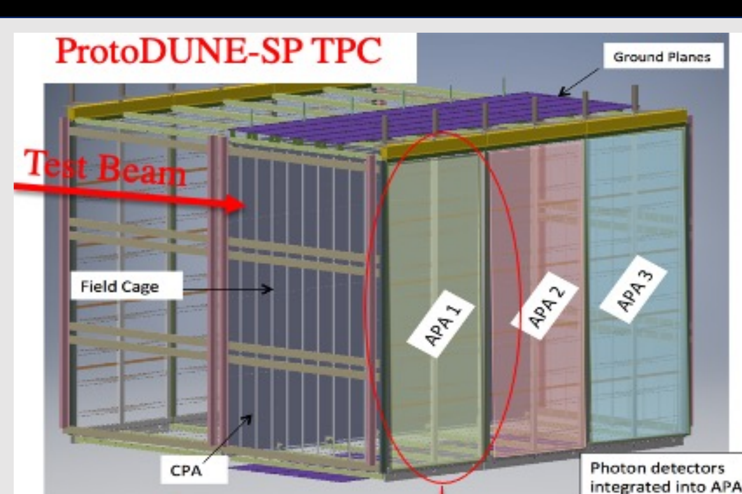
3. DUNE Experiment

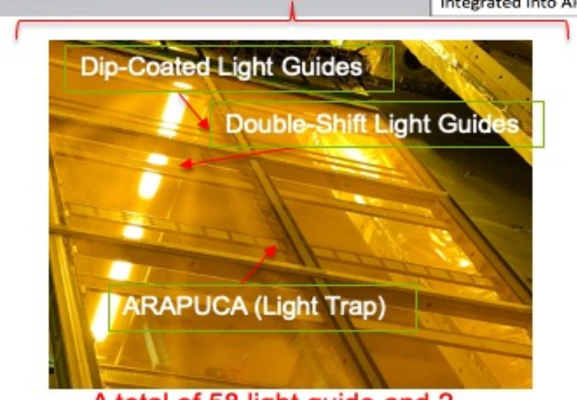
- LBNF neutrino beam
- Large far 70kt LArTPC and capable near detectors
- Search for neutrino CP violation, mass ordering, low-energy neutrinos, BSM-physics.



4. ProtoDUNE-SP LArTPC

- **LArTPC located in EHN1 Hall@CERN**
  - -760 tons of liquid argon
  - -Provides a full drift length of future DUNE SP Far Detector
- **Main Detector Elements include:**
  - -Time Projection Chamber (TPC)
  - -Front-end cold electronics
  - -Photon Detector System (bottom right)
  - -Comic-Ray Tagger.
- **ProtoDUNE-SP Goals:**
  - -Prototype the production and installation for SP DUNE Far Detector.
  - -Validate performance with cosmic- rays
  - -Calibrate with different test-beam particles
  - -Demonstrate photon-detector concept.

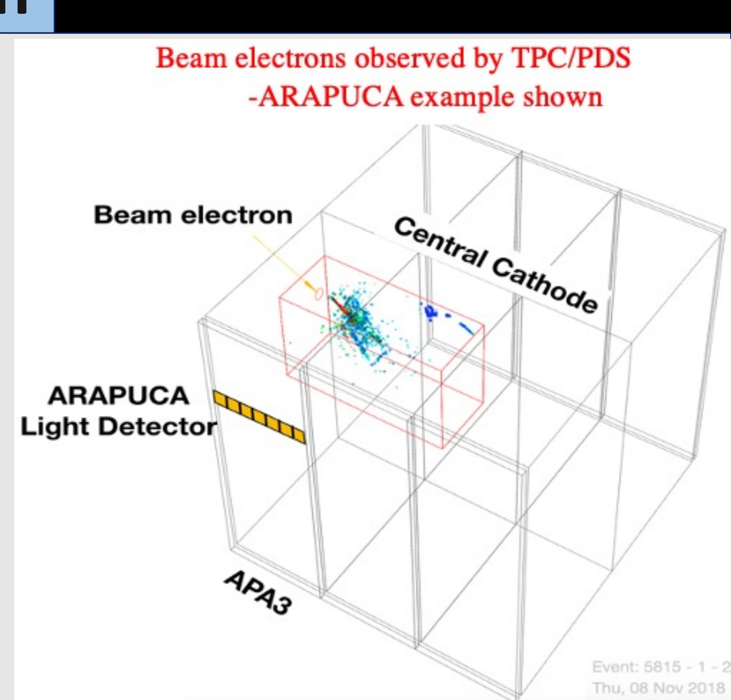




A total of 58 light guide and 2 ARAPUCA photon collectors

5. Beam Electron Study and Event Selection

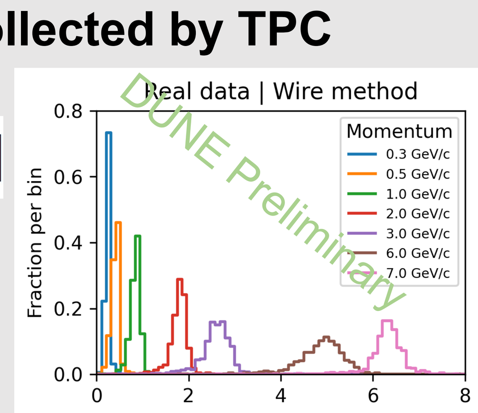
- **Study beam electrons by combining light and charge information on event-by-event basis:**
  - -Reconstruction of energy through charge showers (by TPC)
  - -Reconstruction of energy via the photon-detector light yield measurement (by PDS)
  - -Energy resolution and correlation between light and charge for each event.
- **Select beam electron events based on:**
  - -Number of hits in charge-collecting wires
  - -Number of light flashes observed by PDS elements
  - -Shower direction consistent with beam direction.



6. Charge Collection

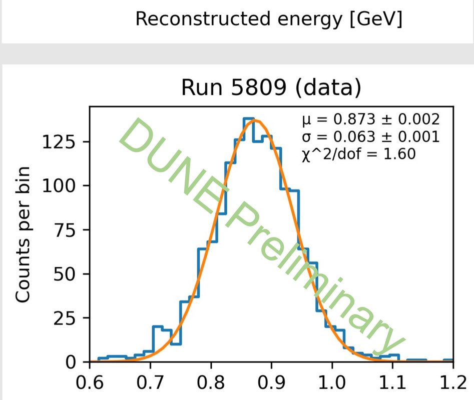
- **Electron shower energy estimated from the charge collected by TPC**

$$E = \frac{C_{norm} * W_{ion}}{C_{rec} * C_{cal}} * \sum_{i=1}^{N} \left[\epsilon(X_i) * \epsilon(Y_i, Z_i) * dQ_i \right]$$

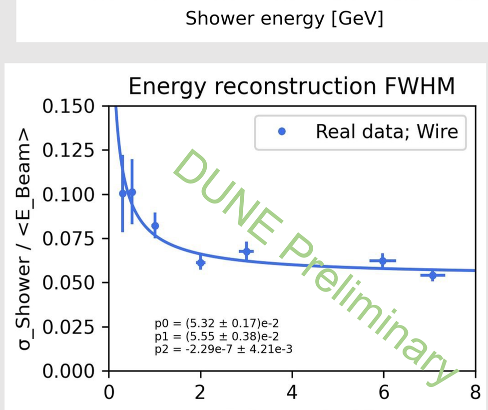


- Energy resolution
  - -ProtoDUNE modeled as a homogeneous calorimeter

$$\frac{\sigma_{Shower}}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$

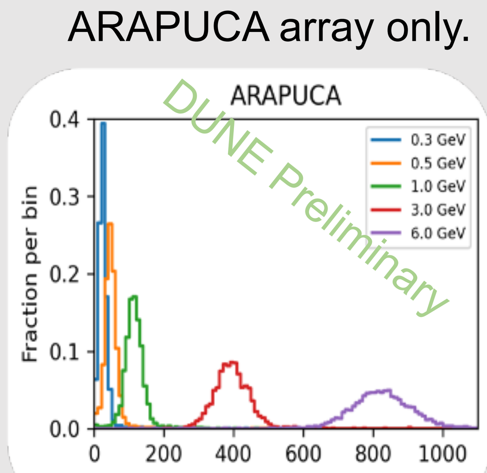


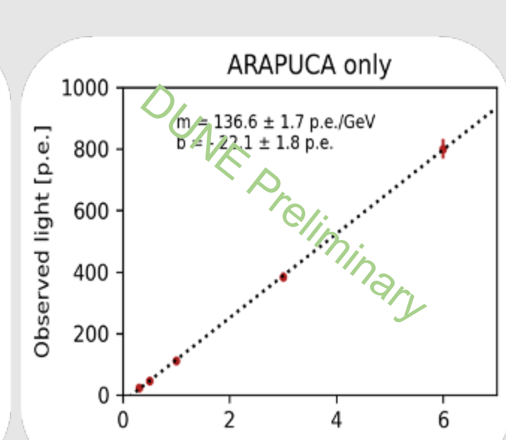
- -Constant (p0) and stochastic term (p1) dominant
- -Noise term (p2) is negligible.



7. Light Collection

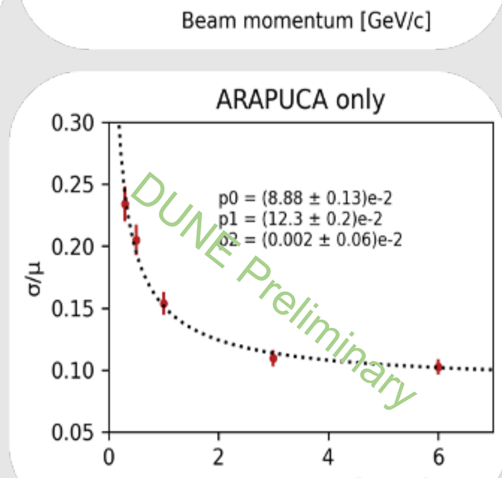
- **The light signal is extracted in terms of so-called optical flash for each event**
  - -Represents reconstructed light yield as number of detected photo-electrons
  - -Performed for all optical channel or for ARAPUCA array only.





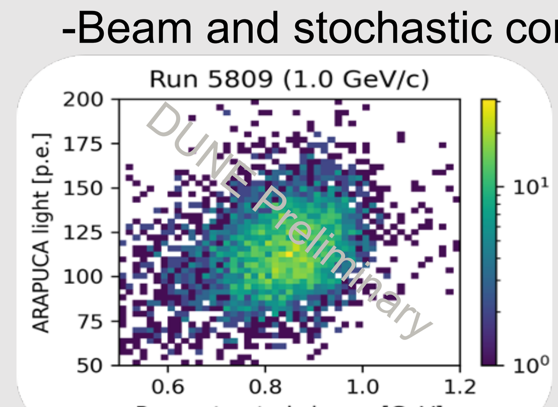
- PDS energy resolution modeled in analogy to TPC charge i.e.

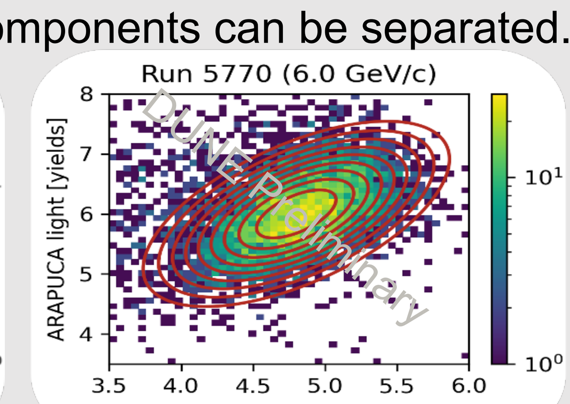
$$\frac{\sigma_{Shower}}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$



8. Light and Charge Correlation

- **There are two significant effects**
  - -Beam variations (∝E) will result in positive correlation; Stochastic quanta production (∝ √E) expected to result in a negative correlation due to conservation of energy
  - **Thus, we naively expect the overall correlation index to increase with the electron beam energy**
- **We pair each event's charge and light response in 2D distributions:**
  - -Overall correlation is positive indicating that beam effects are dominant
  - -Beam and stochastic components can be separated.





$$G(N_e, N_p) = He^{\left(\frac{-1}{2(1-\rho_{ep}^2)}\left[\frac{\Delta N_e^2}{\sigma_e'^2} + \frac{\Delta N_p^2}{\sigma_p^2} - \frac{2\rho_{ep}\Delta N_e \Delta N_p}{\sigma_e' \sigma_p}\right]\right)}$$

$$\rho_{ep} = V_{ep}/V_{ep} = \langle (N_e - \bar{N}_e)(N_p - \bar{N}_p) \rangle$$

- **Perform 2D Gaussian fits on charge-light histograms and extract the overall correlation coefficient between charge and light ρ_{ep} for each run.**
- **The light-charge correlation may be described by the formula:**

$$\rho_{ep}\sigma_e\sigma_p = \rho_{ep}^b \sigma_{eb}\sigma_{pb} + \rho_{ep}^f \sigma_{ef}\sigma_{pf} + \rho_{ep}^n \sigma_{en}\sigma_{pn}$$

- Assuming $\rho_{ep}^b = 1$ and $\rho_{ep}^n = 0$, we obtain negative light-charge stochastic correlations

$$\rho_{ep}^f = \frac{\rho_{ep}\sigma_e\sigma_p - \sigma_{eb}\sigma_{pb}}{\sigma_{ef}\sigma_{pf}}$$

Energy [GeV]	ρ_{ep}	ρ_{ep}^f
0.3	0.157 ± 0.036	-0.027 ± 0.255
0.5	0.221 ± 0.029	-0.032 ± 0.264
1.0	0.291 ± 0.023	-0.115 ± 0.290
3.0	0.412 ± 0.032	-0.628 ± 0.336
6.0	0.395 ± 0.022	-1.00 ± 0.12

DUNE Preliminary

9. Summary and Next Steps

- **Preliminary results presented in this initial study reveal anti-correlated statistical fluctuation between scintillation and ionization in liquid argon**
  - -Our calculation indicates the negative light-charge stochastic correlations, as expected from conservation of energy.
- **We expect indicated charge and light anti-correlation to allow for improvements in calorimetric energy resolution when charge and light signals are combined.**
- **Future studies may include the following:**
  - -With additional data and Monte Carlo statistics optimize TPC/PDS event selection
  - -Simulation/modeling of correlated light and charge effects in beam events
  - -Examine opportunity to enhance the PID and energy reconstruction.

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