Study Of Charge and Light Correlation in Electron Beam Energy Response in ProtoDUNE-SP

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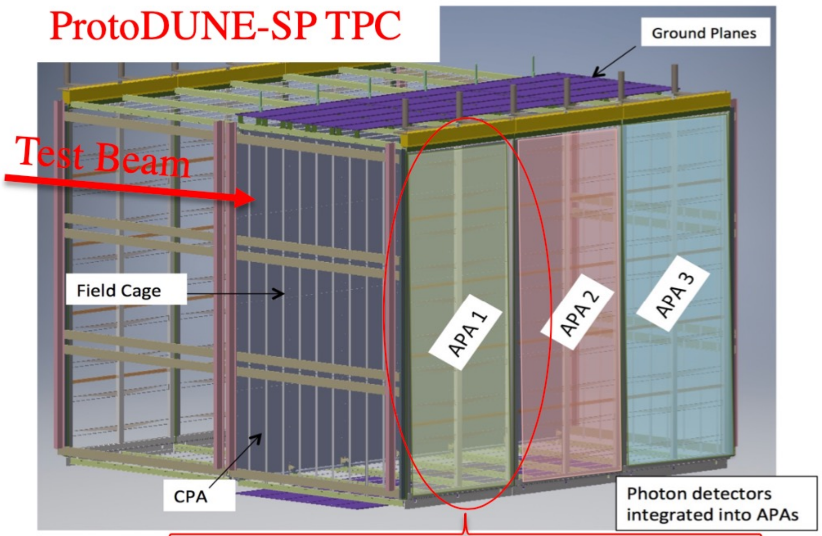
DUNE

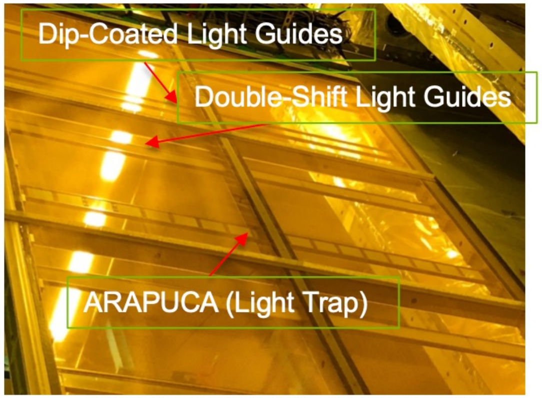
Goal of the Study

- A primary focus of the DUNE experiment is to measure CP violation with neutrino and anti-neutrino beams.
- The CP violation phase δCP measurement depends on both the rate of measured electron neutrino appearance events and on accuracy of neutrino energy scale.
- The measurement requires an accurate reconstruction of the neutrino energy scale based on measurements of leptonic and hadronic components of the neutrino interaction.
- In future DUNE oscillation analyses we will be looking for selection and reconstruction of electron showers from an electron neutrino appearance in DUNE Far Detector.
- It is critical for DUNE experiment to understand the far detector LArTPC response to electromagnetic showers.
- Our initial goal will be to start understanding detector response to test-beam electrons (positrons) collected with ProtoDUNE-SP.

ProtoDUNE-SP LArTPC Overview

- **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
  - -Comic-Ray Tagger.
- **ProtoDUNE-SP Goals:**
  - -Prototype the production and installation for SP DUNE Far Detector.
  - -Validate detector performance with cosmic-rays
  - -Calibrate with different test-beam particles
  - -Demonstrate photon-detector concept.
- **Operated 2018-20**
  - -First Results published: JINST 15 (2020) 12, P12004.

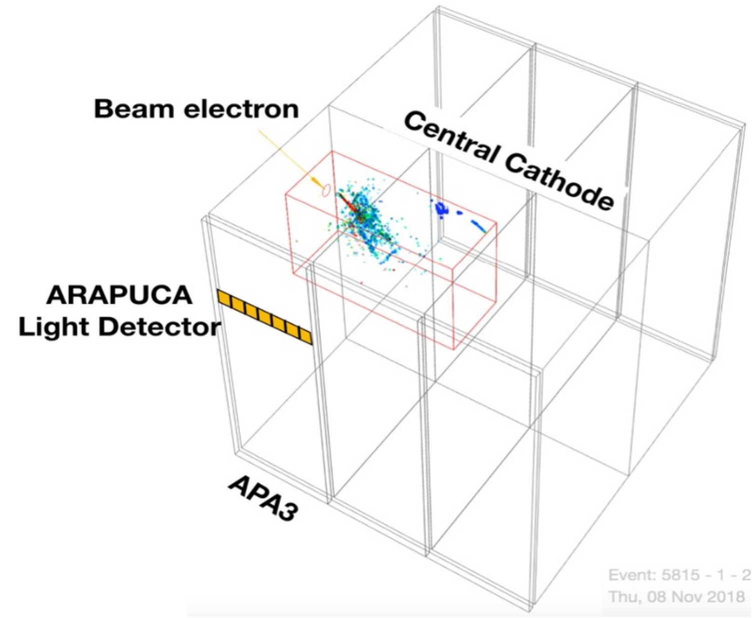




A total of 58 light guide and 2 ARAPUCA photon collectors

Beam Electron Study and Event Selection

Beam electrons observed by TPC/PDS
-ARAPUCA example shown



- **We 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.

- Studied beam electron data sets E(GeV): 0.3, 0.5, 1.0, 3.0, 6.0.

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Beam Electron Study and Event Selection

- **We select beam electron events (from real data) through a series of cuts:**
  - Number of hits in charge-collecting wires

Momentum [GeV/c]	Minimum TPC charge hits	Maximum TPC charge hits
0.3	250	600
0.5	300	1000
1.0	950	1500
2.0	1900	3000
3.0	2800	5000
6.0	5000	8000
7.0	6000	10000

Table 2: Cuts applied on the number of TPC charge hits as a function of energy.

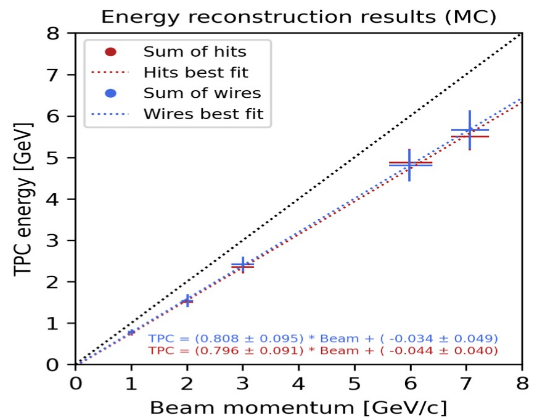
  - Cosine θ > 0.9: Charge shower direction consistent with beam direction
  - Cherenkov counter detection, low/high pressure based on beam momentum
  - Time of flight selection.

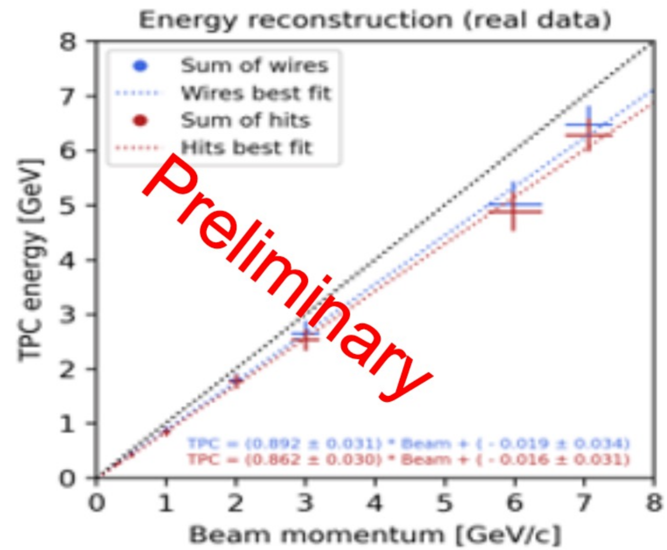
ProtoDUNE-SP Charge Detection

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

  -Calibration and Recombination constants applied.

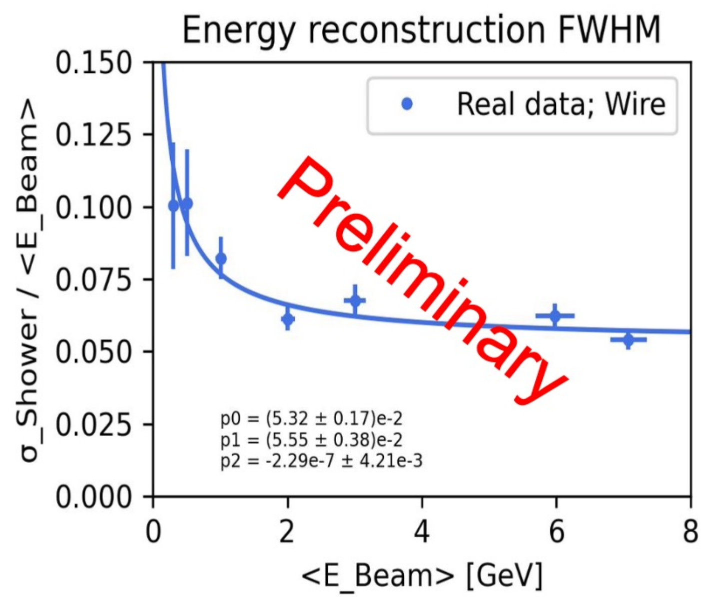
$$E = \frac{C_{norm} * W_{ion}}{C_{rec} * C_{cal}} \sum_{i=1}^{N} \left[\epsilon(X_i) * \epsilon(Y_i, Z_i) * dQ_i \right]$$





- ProtoDUNE-SP modeled as a homogeneous calorimeter

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

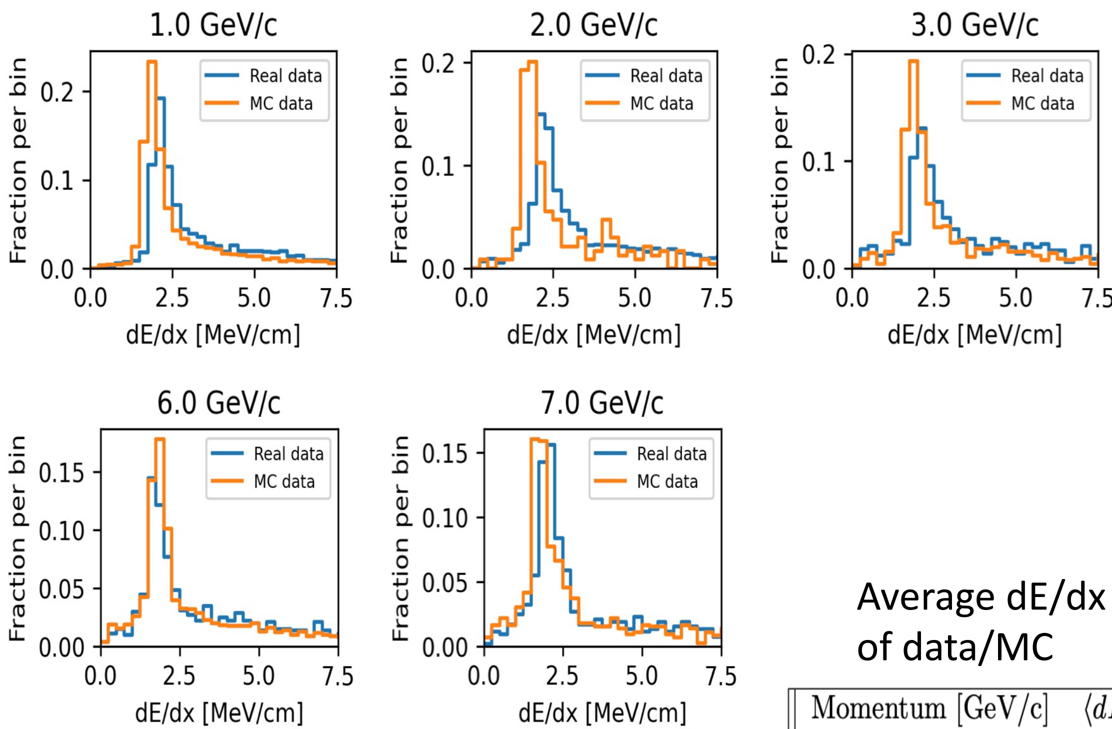


-Constant (p0) and stochastic term (p1) dominant

-Noise term (p2) is negligible.

Comparison of dE/dx values

Reconstructed dE/dx distribution for different energies and data types.

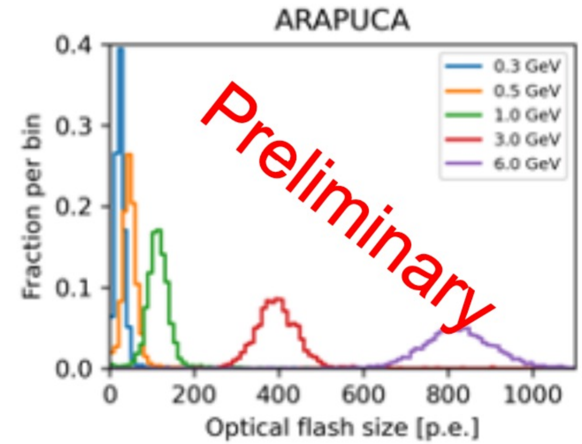


Average dE/dx values and corresponding dE/dx ratios of data/MC

Momentum [GeV/c]	$\langle dE/dx \rangle_{Data}$ [MeV/c]	$\langle dE/dx \rangle_{MC}$ [MeV/c]	Correction
1.0	3.472	2.963	1.171
2.0	3.688	2.946	1.251
3.0	3.653	3.158	1.156
6.0	3.515	3.114	1.128
7.0	3.490	3.122	1.117

ProtoDUNE-SP Light Detection

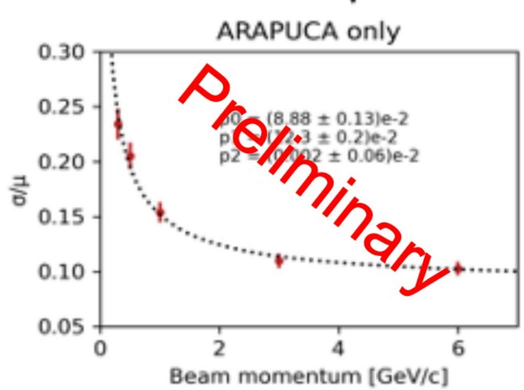
- **The light signal is extracted in terms of so-called optical flash for each event**
  - -Represents reconstructed light yield as number of detected photo-electrons
  - -Performed for all optical channel or for ARAPUCA array only.

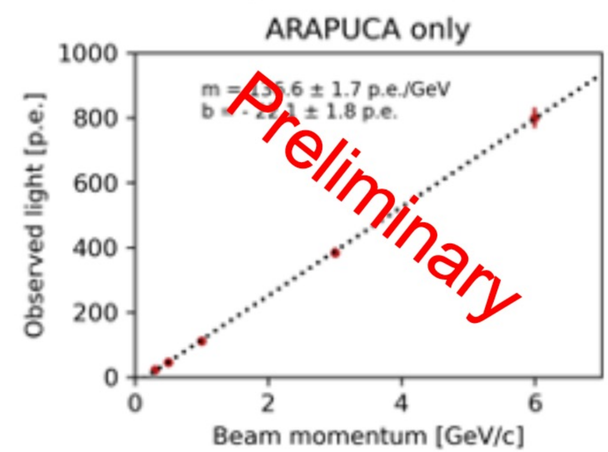


- Electron shower energy reconstructed from the light yield measured by photon detector system (PDS)

- PDS energy resolution modeled in analogy to TPC charge component ie

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





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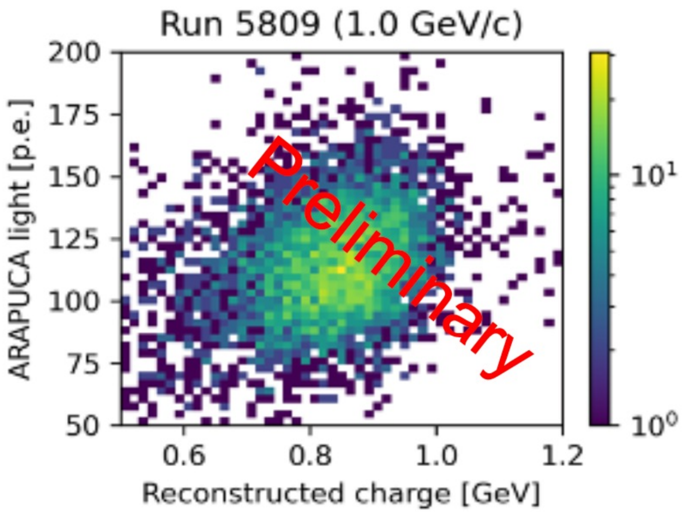
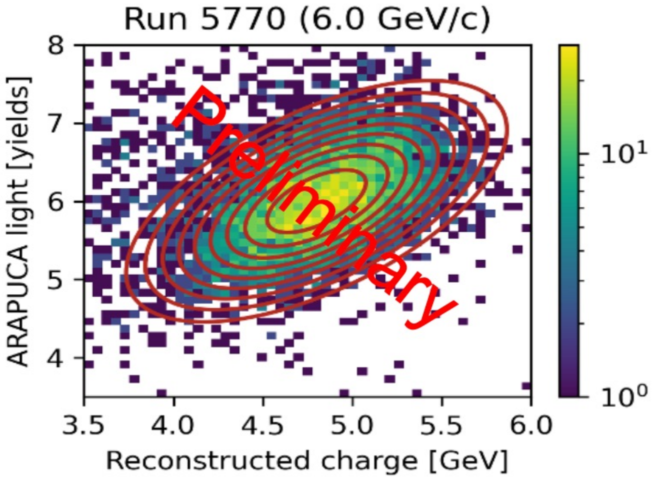
Light and Charge Correlation

- **For each event we pair charge and light response and plot them on 2D histograms**
  -Two-dimensional fit is performed to extract correlation coefficient.

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

$$H = 1/2\pi\sigma_e'\sigma_p\sqrt{1-\rho_{ep}^2}$$





-2D fit results:

Energy [GeV]	Correlation coefficient
6.0	0.395 ± 0.022
3.0	0.412 ± 0.032
1.0	0.291 ± 0.023
0.5	0.221 ± 0.029
0.3	0.157 ± 0.036

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Light and Charge Correlation

- **There are two significant effects to consider**
  -Beam variations (∝E) will result in positive correlation as these would affect energy released via both charge and light in identical way
  -Stochastic quanta production (∝ √E) expected to result in a negative correlation of light vs charge due to conservation of energy.

- **Therefore, we naively expect the overall correlation index to increase with the electron beam energy** (see previous slide).

- **The overall light-charge correlation observed with beam electrons may be described by three correlation terms** i.e., with the formula:

$$\rho_{e,p}\sigma_e\sigma_p = \rho^b_{e,p}\sigma_{eb}\sigma_{pb} + \rho^f_{e,p}\sigma_{ef}\sigma_{pf} + \rho^n_{e,p}\sigma_{en}\sigma_{pn}$$

b = beam (constant) term
f = statistical fluctuation
n = noise term

- We assume $\rho^n_{e,p} = 0, \rho^b_{e,p} = 1$, and look for statistical (anti) correlation $\rho^f_{e,p}$

  ➢ **Our preliminary findings:**
  We obtain the negative light-charge stochastic correlations, as expected from conservation of energy.

E[GeV]	$\rho_{e,p}$	$\rho^f_{e,p}$
6	0.395 ± 0.022	- 1 (±0.12)
3	0.412 ± 0.032	- 0.628 (± 0.336)
1	0.291 ± 0.023	- 0.115 (± 0.290)
0.5	0.221 ± 0.029	- 0.032 (± 0.264)
0.3	0.157 ± 0.036	- 0.027 (± 0.255)

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Summary

- **We have studied the response of DUNE's prototype detector ProtoDUNE-SP (aka ProtoDUNE-HD) to test beam electrons 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 presented in this initial study reveal anti-correlated statistical fluctuation between scintillation and ionization in liquid argon.**

- **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 should include the following:**

  -With additional data and Monte Carlo statistics optimize event selection of TPC and PDS signatures
  -Simulation/modeling of correlated light and charge effects in energy scale of beam events
  -In a longer term apply ML methods to combine image information from TPC charge readout (slow response) with time-series information from photon-detector (fast response)
  -Examine opportunity to enhance the PID and energy reconstruction.

Thanks!

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