Characterization and Understanding of Novel 8-inch Microchannel Plate Photomultiplier Tubes

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in cooperation with
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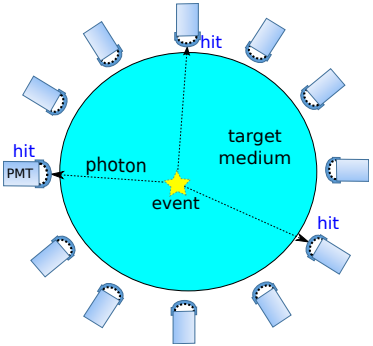
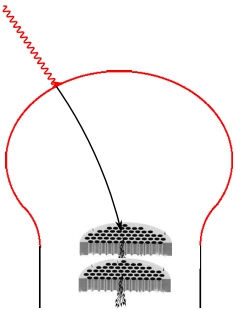
Photons Are Precious at Neutrino[1] Scintillation Calorimetry





- Photons are precious information carriers in rare event searches.
- Uncertainties of photon counting determines energy resolution.
- Needs high photon detection efficiency.

[1] or dark matter

Channel Open-Area Ratio of an MCP

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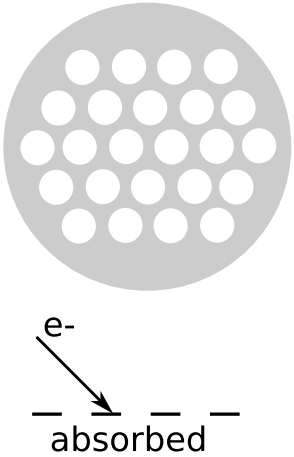

- ✗collection efficiency $< 70\%$.

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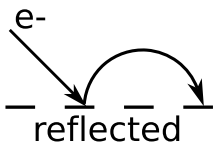

- ✗collection efficiency $\rightarrow 100\%$, but noticeable delay.

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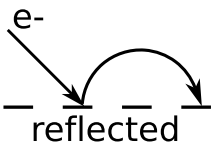

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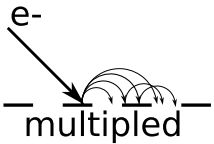
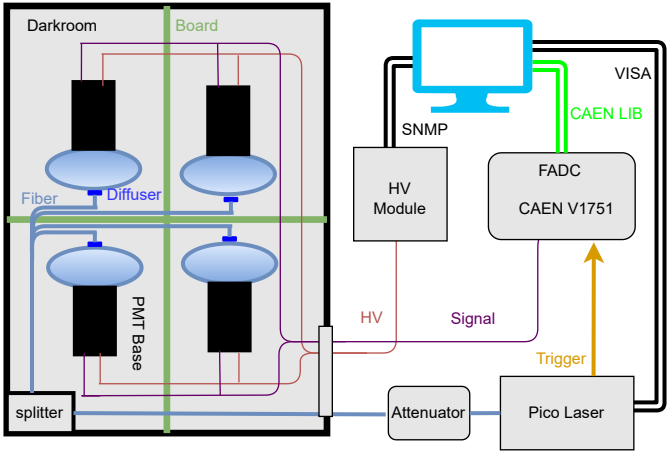


- ✓collection efficiency $\rightarrow 100\%$ and fast.

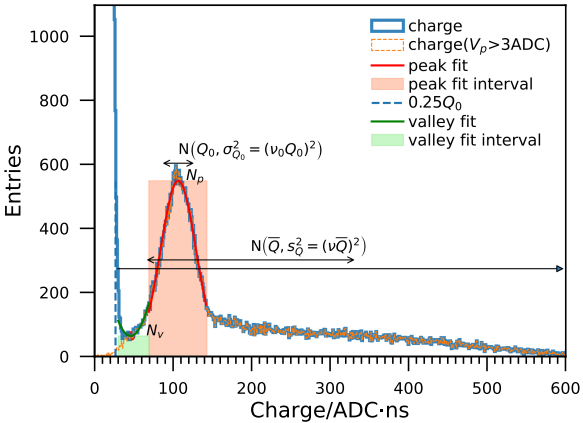
Testbench Setup: Illumination with Laser



- Measure the photon detection efficiency relative to a reference dynode PMT.

Zhang et al. Performance evaluation of the 8-inch MCP-PMT for Jinping Neutrino Experiment, 2023, NIM A

The Jumbo Charge from a Single Photo-Electron



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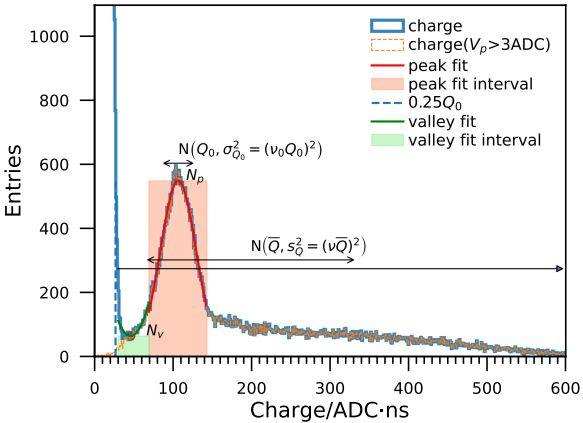

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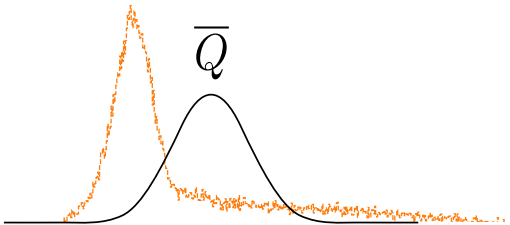


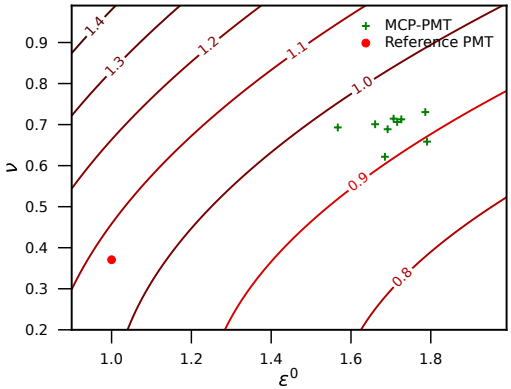
- Jumbo charges worsens the energy resolution, if photon counts is estimated from total charge: $\sum Q/\overline{Q}$.

Energy Resolution Boost

- $\nu = \dfrac{\sqrt{\mathrm{Var}[Q]}}{\mathrm{E}[Q]}$ is the width of charge distribution.

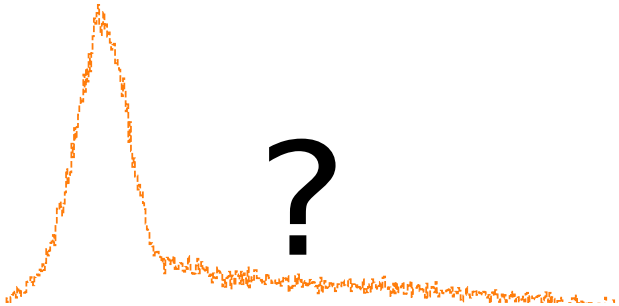
$$\frac{\sqrt{\mathrm{Var}[\hat{E}]}}{\mathrm{E}[\hat{E}]} \propto \frac{\sqrt{1+\nu^2}}{\sqrt{\epsilon^0}} \frac{1}{\sqrt{E}}$$

- The improvement of photo detection efficiency dominates.
- Overall, the energy resolution is boosted.



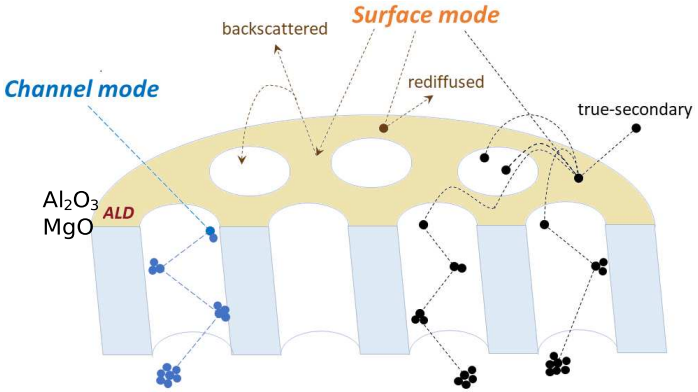
Zhang et al. Performance evaluation of the 8-inch MCP-PMT for Jinping Neutrino Experiment, 2023, NIM A

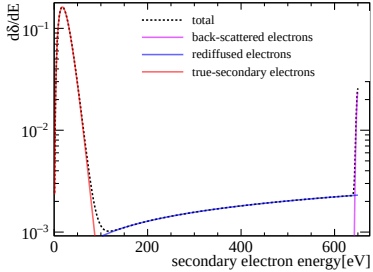
Can We Do Better?

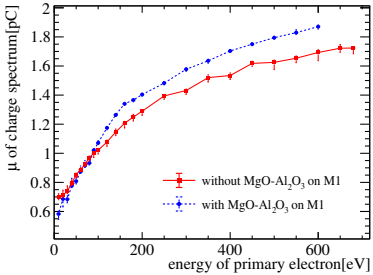


- What determines the shape of the charge spectrum?
- What is the physics behind?

The Physics of a Photo-Electron

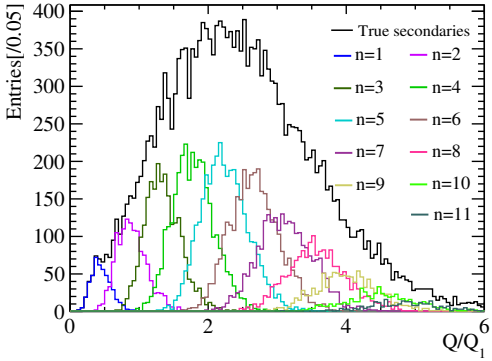


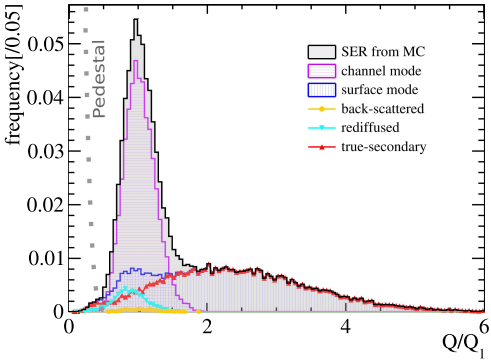




- Multiplication at the MCP end-face.
- True secondary electrons have low kinetic energy and thus gain.

Shape Prediction of the Jumbo Charge

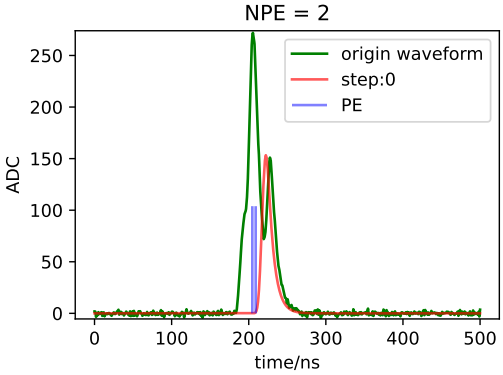


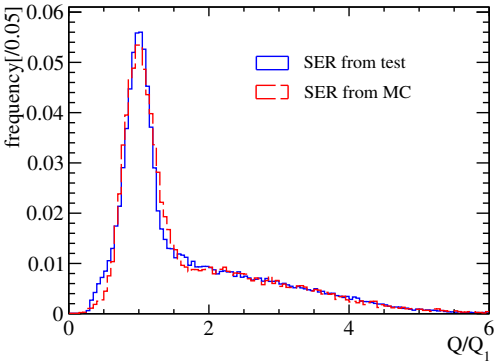


- Should have small-charged contributions at the same time.
  - It overlaps with pedestal, tricky to see.

Weng et al. Single electron charge spectra of 8-inch high-collection-efficiency MCP-PMTs, arXiv:2402.13266

Fast Stochastic Matching Pursuit

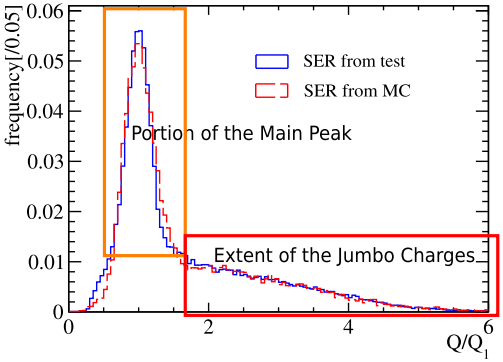


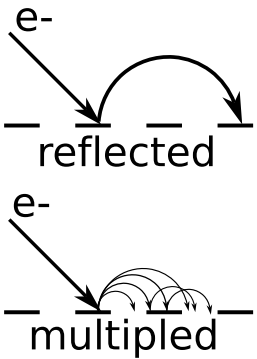


- Single-electron templates to fit the charge.
- Separates small pulses from while noise.
- The small charge is visible!

Poster 210 Wang et al., The Fast Stochastic Matching Pursuit, arXiv:2403.03156

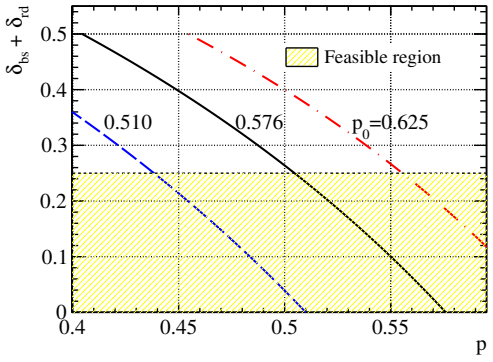
Are the Mode Parameters Experimentally Interpretable?

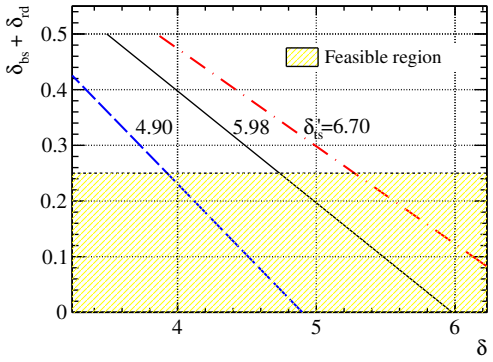




- Portion of the main peak p_0 is affected by open-area ratio.
- Extent of the jumbo charges is determined by the true secondary yield δ'_{ts}.
- They are both affected by the probability of multiplication (true secondary process).

The Fitted Parameters Are Realistic



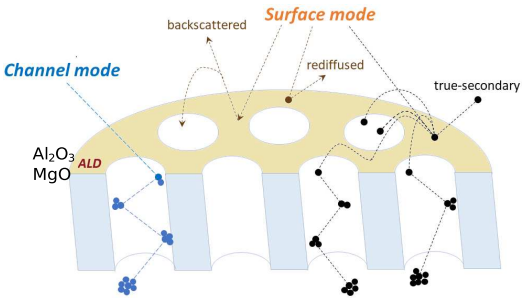


$$\delta = \delta_{\mathsf{bs+rd}} + (1 - \delta_{\mathsf{bs+rd}})\delta'_{\mathsf{ts}}$$

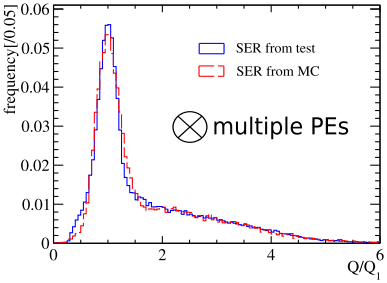
$$p_0 = \frac{p}{1 - (1 - p)\delta_{\mathsf{bs+rd}}}$$

- From literature: $\delta \approx 5, p \approx 0.55, \delta_{\mathsf{bs+rd}} < 0.25$,
- From our measurement: $p_0 = 0.54, \delta'_{\mathsf{ts}} = 6$,
- Consistent.

Can We Do Better Still?



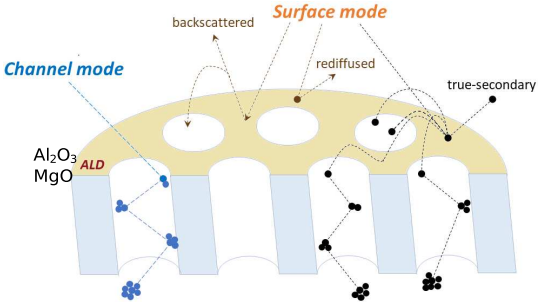
- Look for delays from the round trips.
- Should be more manifested with 20-inch MCP-PMTs.

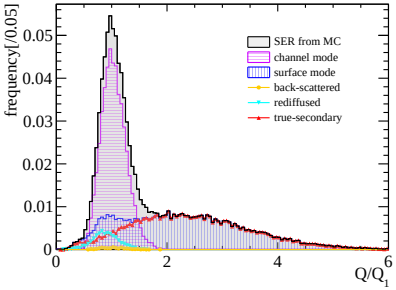


- Batch calibration with moderate light intensities.
- Mixture and compound Poisson for PMT calibration.

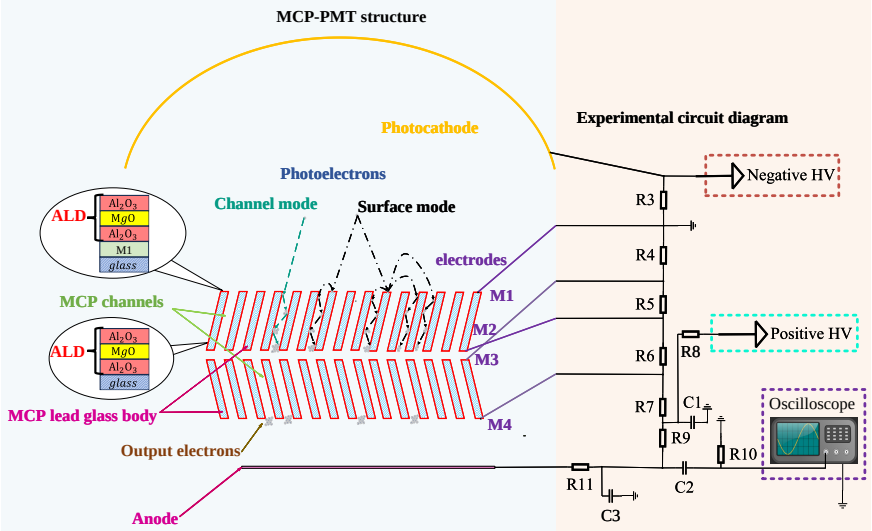
Summary

- We observed jumbo charges in single electron response from the 8-inch high-collection-efficiency MCP-PMT.
- We constructed an experimentally verifiable model to explain it.
- Our study sets the stage for counting photons more precisely at neutrino detectors.





Experiment of Tune the Acceleration Voltage



Calibration with Light Intensity

SER charge probability density function as $S(Q)$, total charge of k PE(s) is:

$$
\begin{aligned}
S_k(Q = \sum_{i=1}^{k} q_i) &= \underbrace{\int_{-\infty}^{+\infty} \mathrm{d}q_1 \cdot S(q_1) \cdots \int_{-\infty}^{+\infty} \mathrm{d}q_k \cdot S(q_k)}_{k}, \\
&= \underbrace{S(q) \otimes \cdots \otimes S(q)}_{k} \text{ with probability } \pi(k;\mu).
\end{aligned}
\tag{1}
$$

Here μ is the mean of PEs. By applying Fourier transform (FT), total charge becomes:

$$
\tilde{S}_{\text{total}}(p) = \sum_{k=0}^{\infty} \pi(k;\mu)\tilde{S}^k(p) = e^{\mu(\tilde{S}(p)-1)}. \tag{2}
$$

$S_{\text{total}}(Q)$ could be obtained losslessly by Discrete FT (DFT) and Inverse DFT (IDFT).

Consistency

- p_0 includes electron reflections
- δ is the Manifestation of 3 Distinct Processes