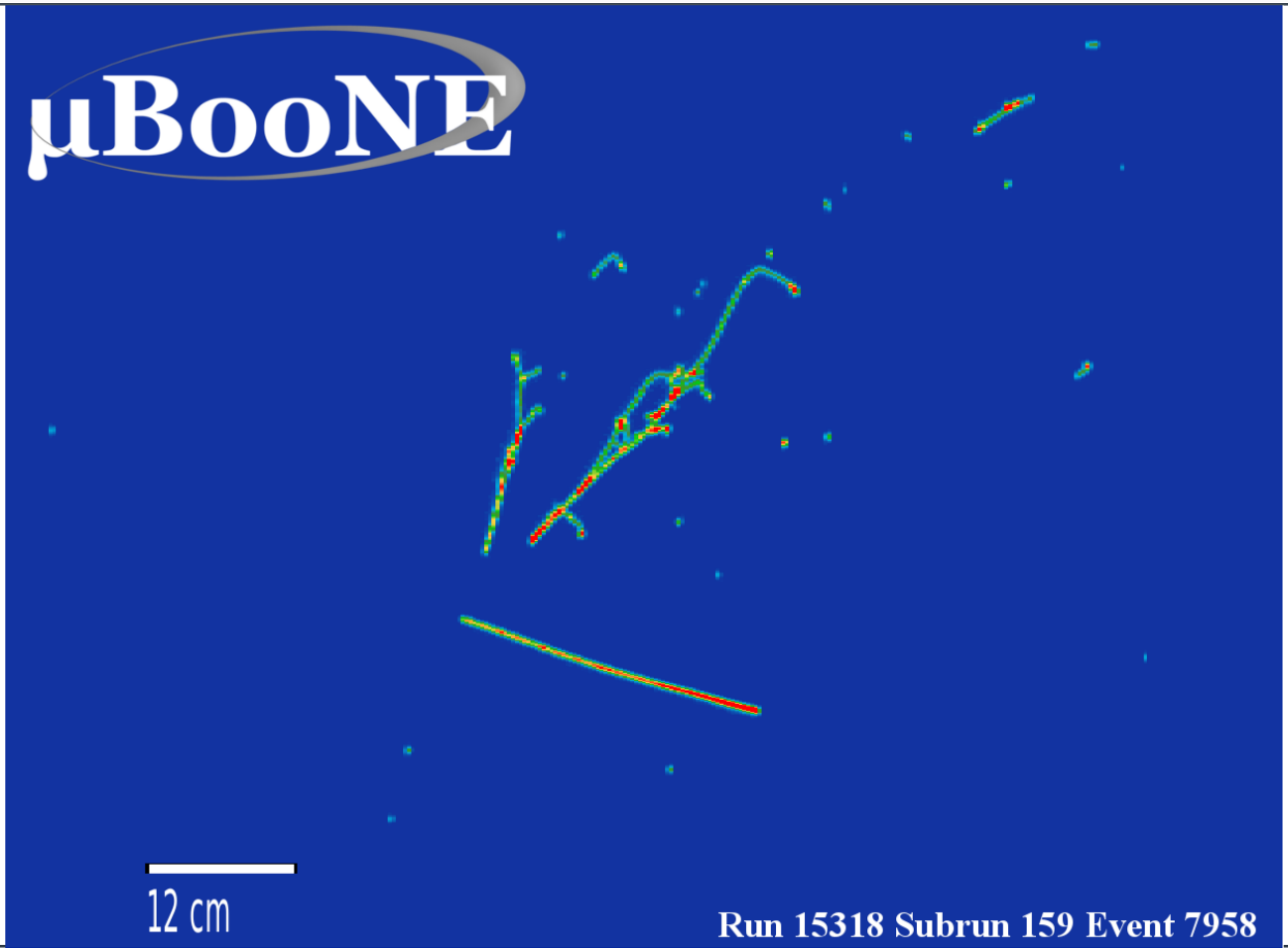
Using Light to Constrain Neutrino-Induced Single Photons in MicroBooNE

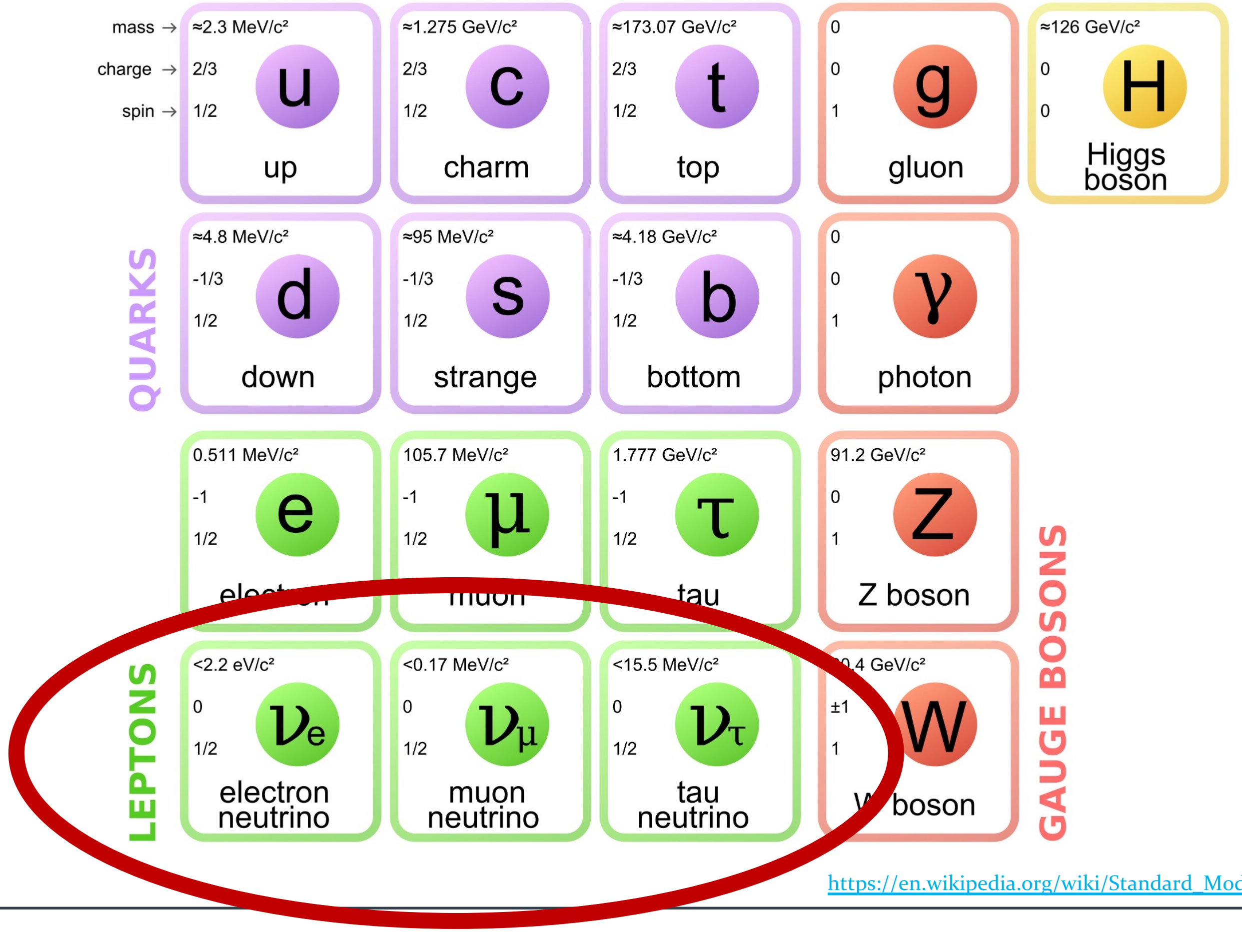
Katherine Pulido

Amherst College



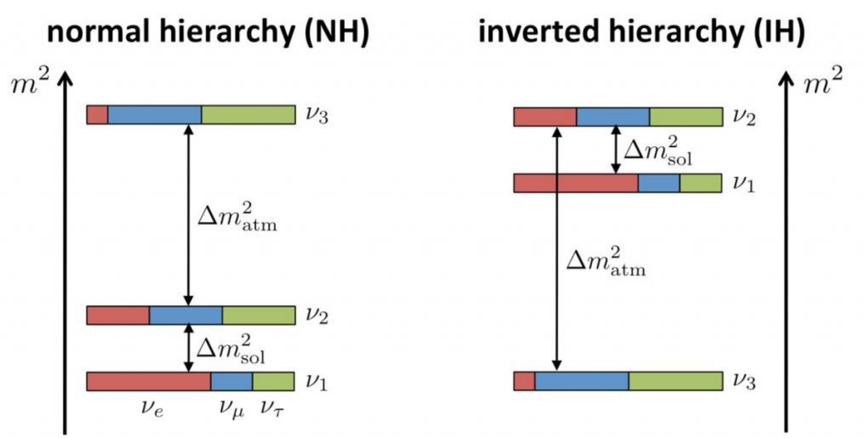
Neutrinos in the Standard Model

- ‘Little Neutral Ones’
- 3 flavors - electron, muon, and tau
- Very weakly interacting
- Very small mass
- Very hard to detect!

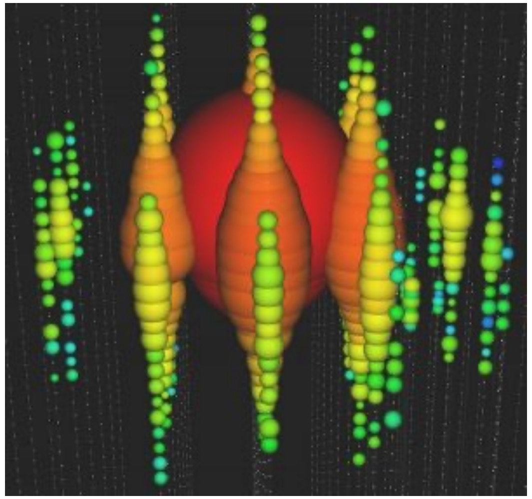


https://en.wikipedia.org/wiki/Standard_Model

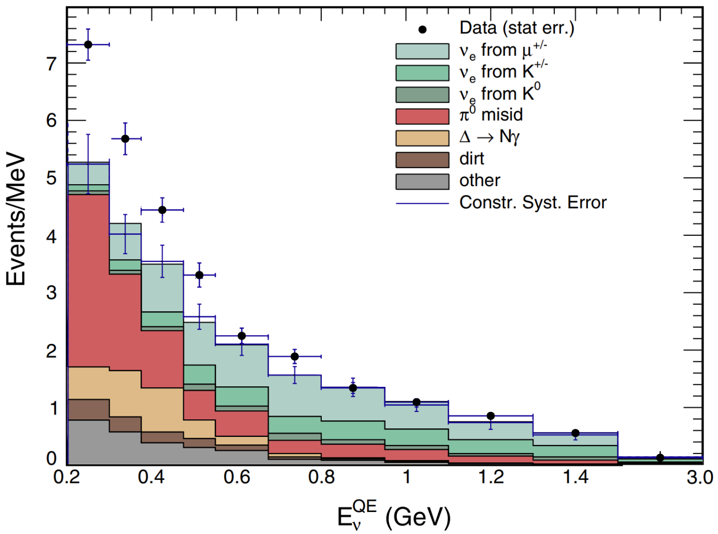
Lots of Mysteries in Neutrino Physics!



What are the neutrino masses? What order?



What can neutrinos tell us about the earliest and most energetic processes in the universe?



Anomalies from previous experiments

https://arxiv.org/pdf/2006.16883
https://neutrinos.fnal.gov/

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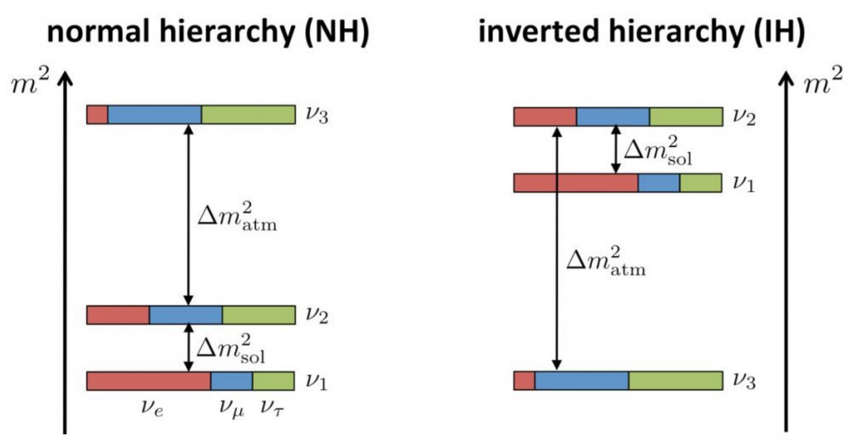

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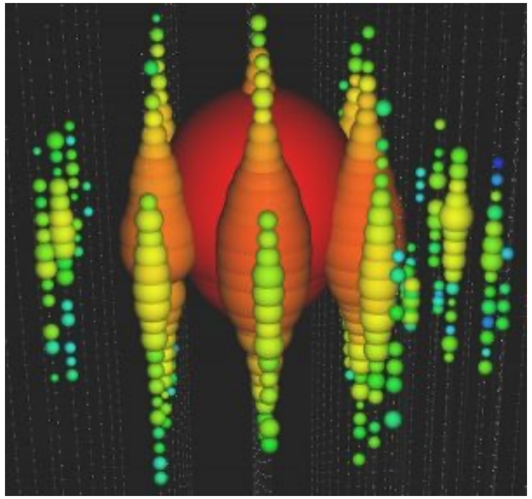

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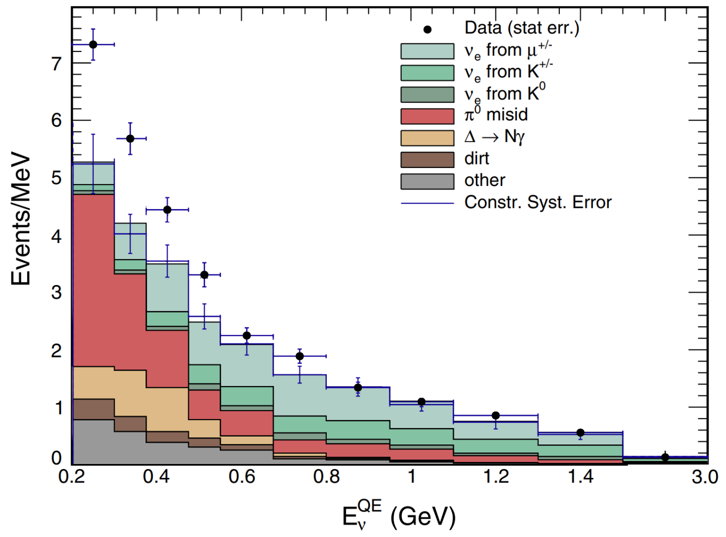

Anomalies from previous experiments

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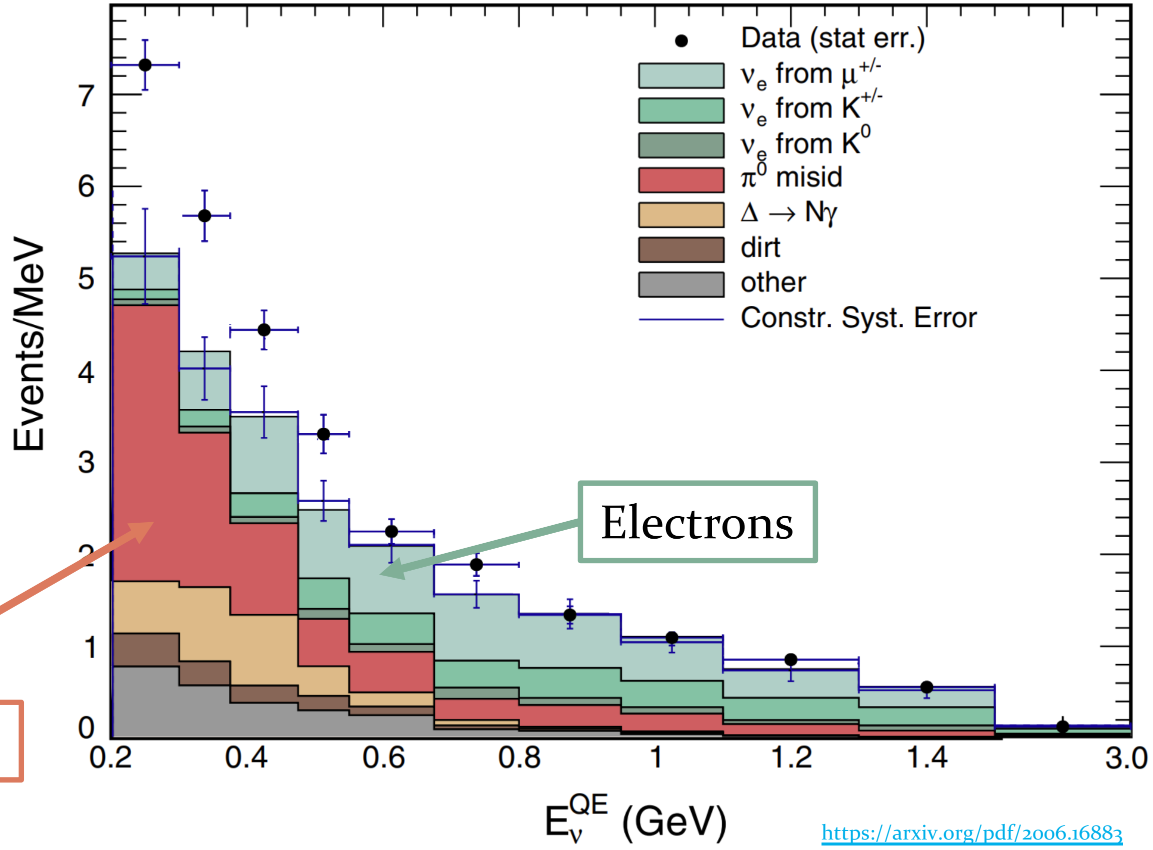
The MiniBooNE Low Energy Excess (LEE)

- Observed a 4.8σ events excess caused by single electromagnetic showers at low energies
- Cherenkov detector could not distinguish between showers caused by photons or those caused by electrons
- Standard Model Explanations and other more exotic explanations involving new physics Beyond the Standard Model (BSM)
- Needs to be explained!

MiniBooNE Data and Simulation



Mostly photons

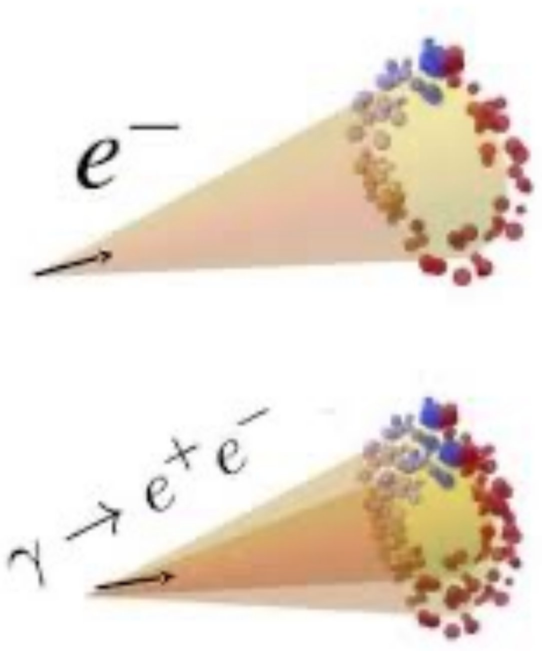
https://arxiv.org/pdf/2006.16883

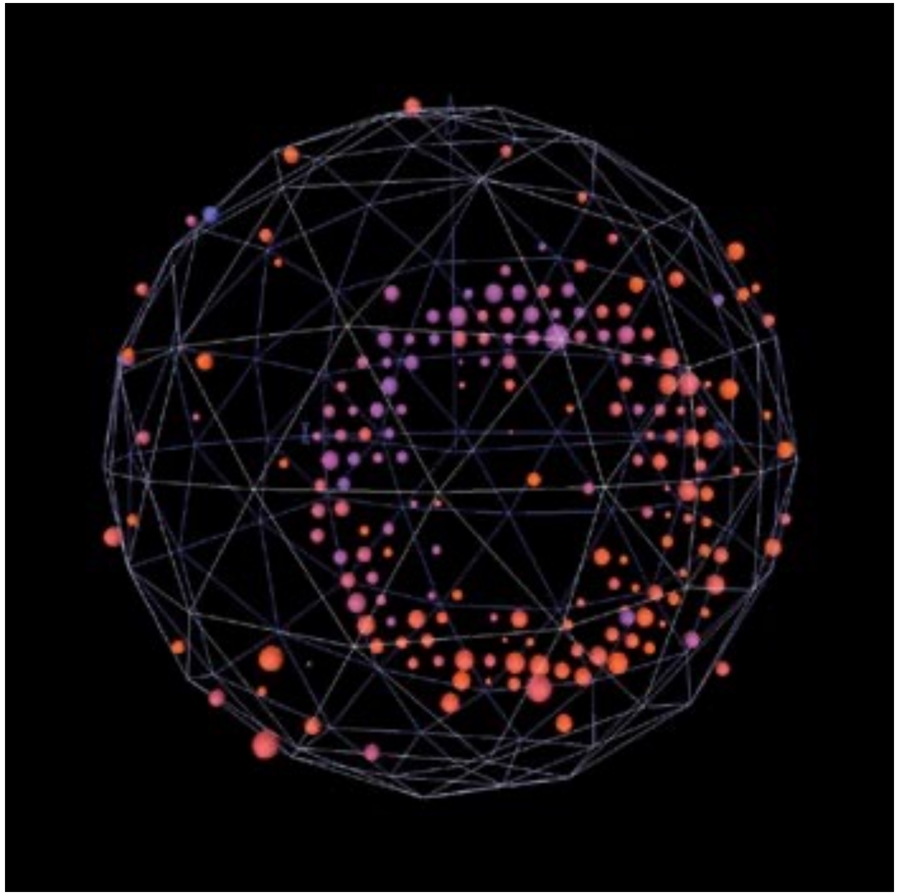
Neutrino Events with an EM Shower in a Cherenkov Detector

- Neutrino interacts with an atom, creates high energy particles

- Electrons and photons that pair produce to an e+/e- pair create signature rings of Cherenkov light as they move through the detector

- Photons and electrons look almost identical in MiniBooNE – we need to separate these to understand the anomaly!

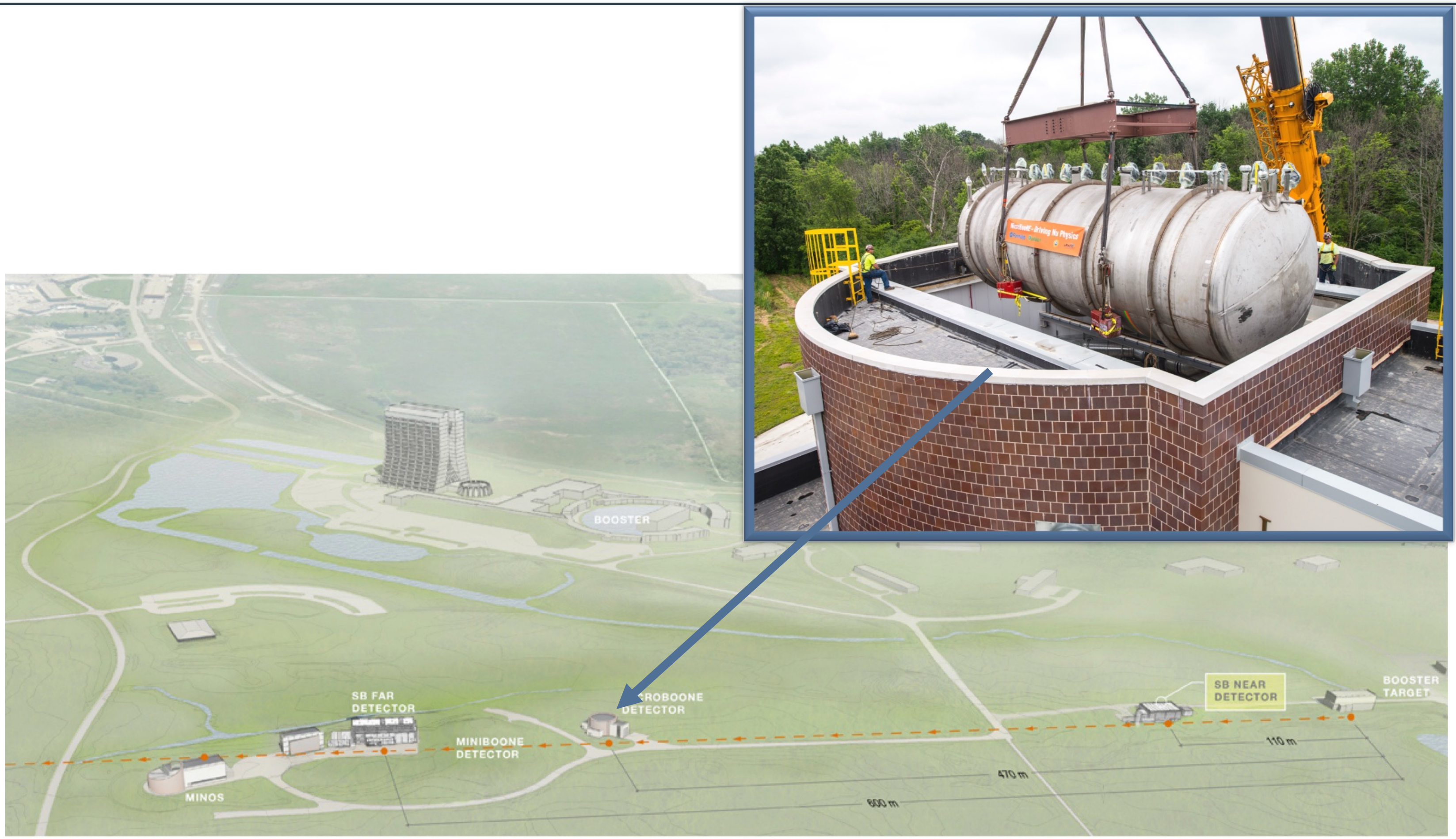




https://www.nytimes.com/2007/04/12/science/12neutrino.html

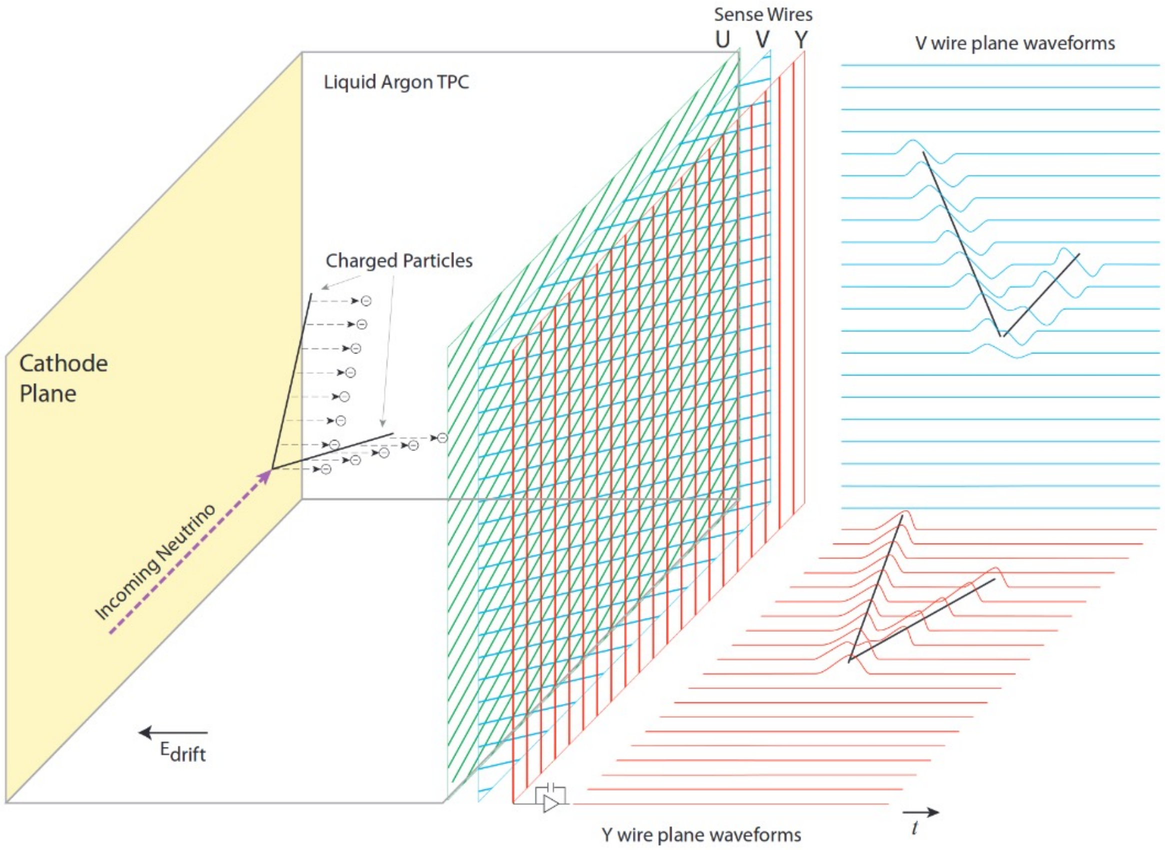
Enter MicroBooNE!

- ‘Micro Booster Neutrino Experiment’
- New detector technology in the same beam line
- Explicit goal of addressing the MiniBooNE LEE



MicroBooNE Liquid Argon Time Projection Chamber

- After a neutrino interacts, the released charged particles ionize Argon atoms
- Because of the strong electric field, charged ionized particles immediately drift toward planes of wires where they are detected as voltage spikes
- Traces the 3D path of charged particles proportional to their energy



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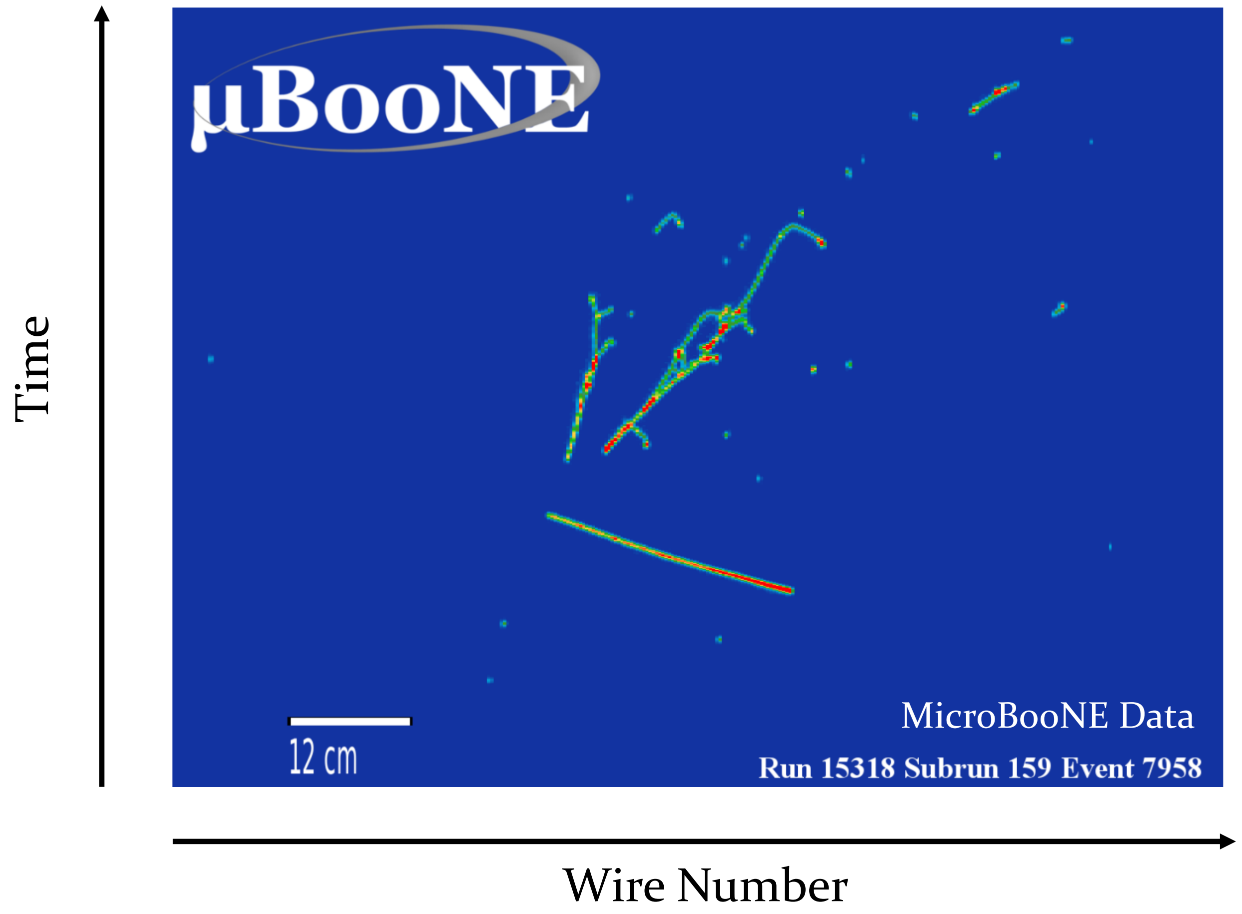
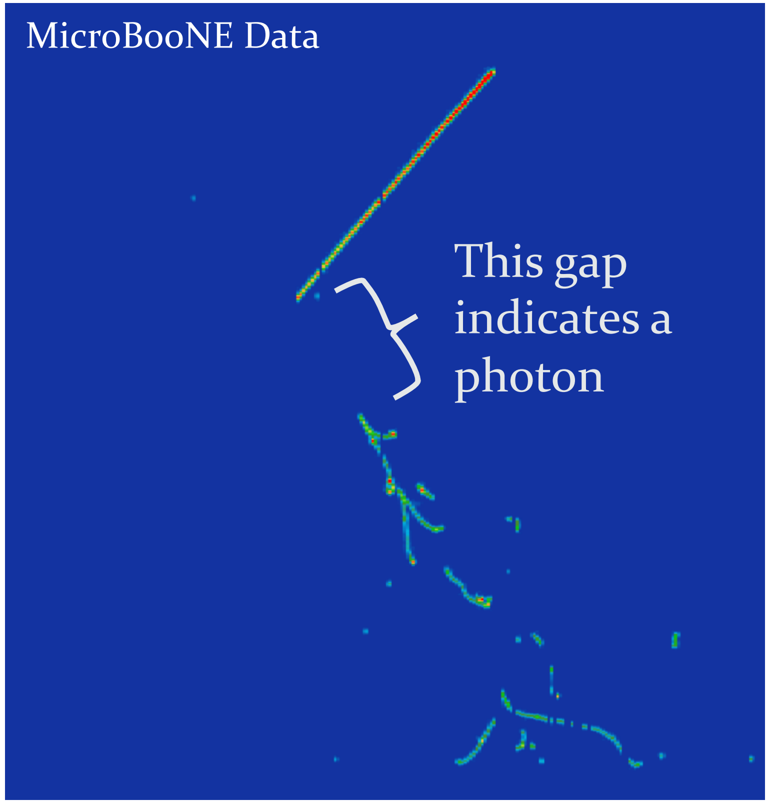
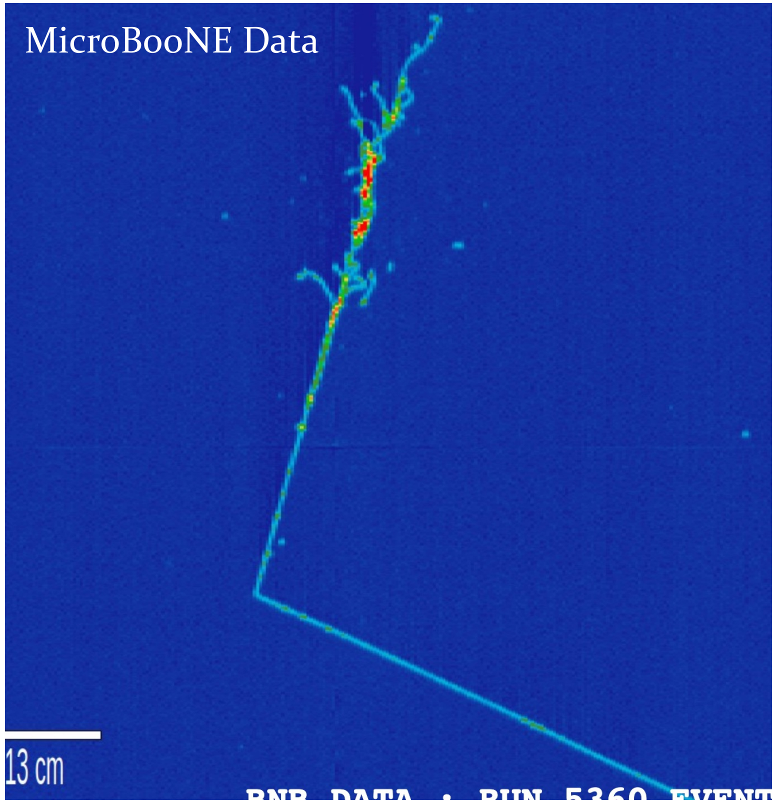
- After a neutrino interacts, the released charged particles ionize Argon atoms
- Because of the strong electric field, charged ionized particles immediately drift toward planes of wires where they are detected as voltage spikes
- Traces the 3D path of charged particles proportional to their energy
  - Can create these beautiful event displays!
- Argon is also a scintillator – more on this later!



MicroBooNE Can Distinguish Between Photons and Electrons!



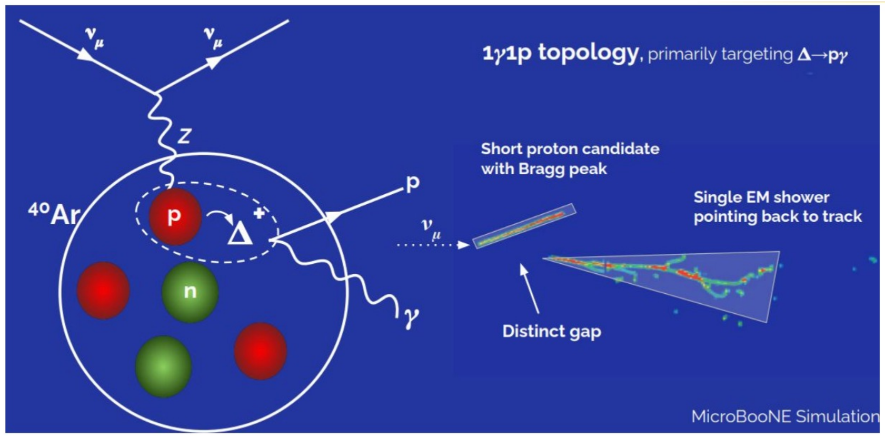
Event with a single photon

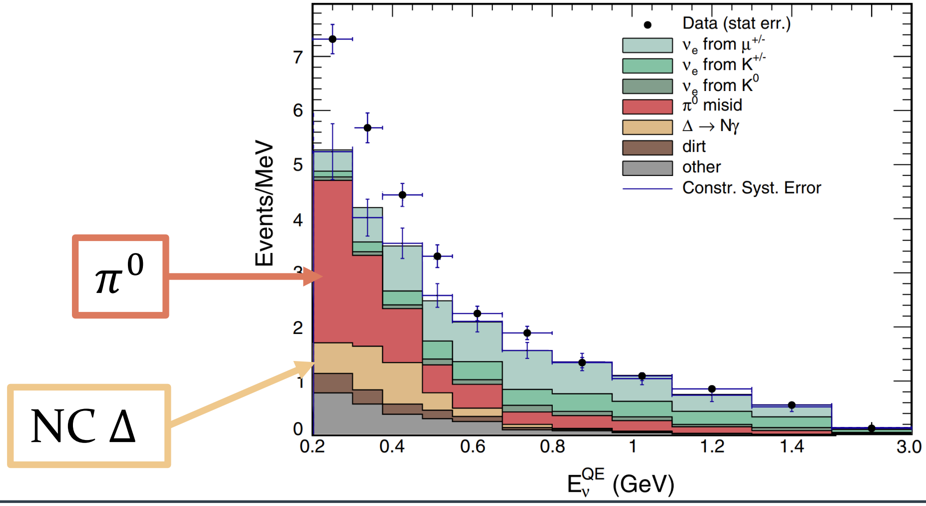


Event with a single electron

Single-Photon Interpretation of the LEE

- Standard model explanations
  - An increase in known processes fits the anomalous data very well
- Beyond the Standard Model?
- All single photon searches share one difficult background: NC π^0 production resulting in two photons





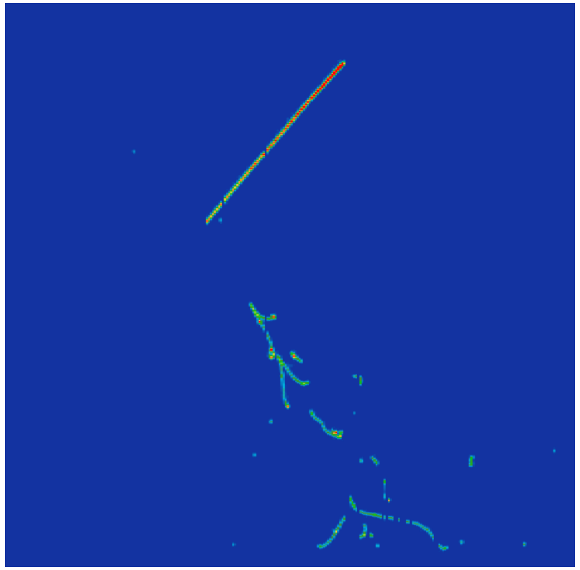
More than 3 neutrinos?

'Photon-like'?

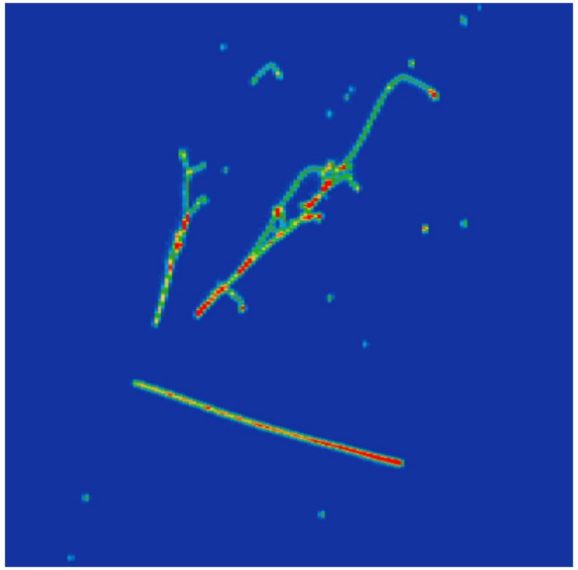
Dark matter portals?

π^0 Background in a Single-Photon Search

Single Photon



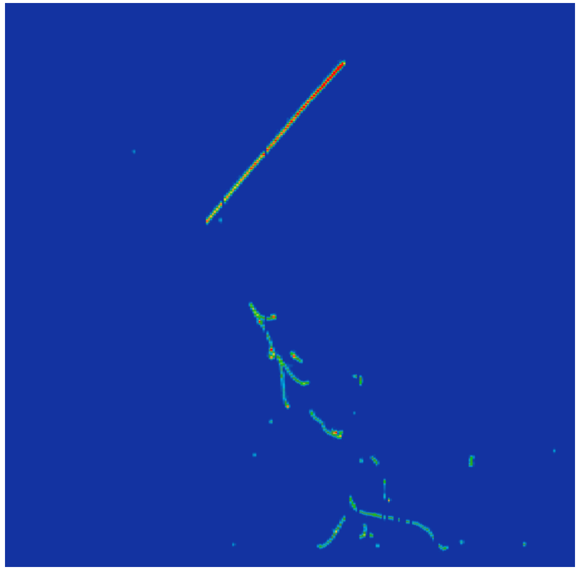
NC π^0 ($\sim\mathcal{O}(250)$x as common)



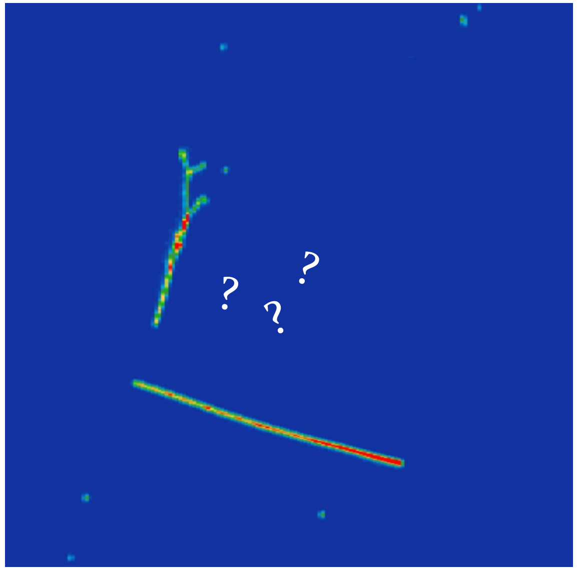
MicroBooNE Data

π^0 Background in a Single-Photon Search

Single Photon



NC π^0 (~$\mathcal{O}(250)$x as common)



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π^0 Background in a Single-Photon Search

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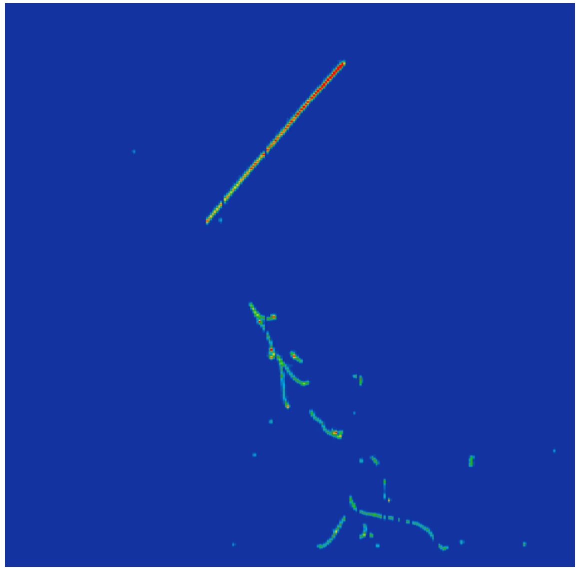

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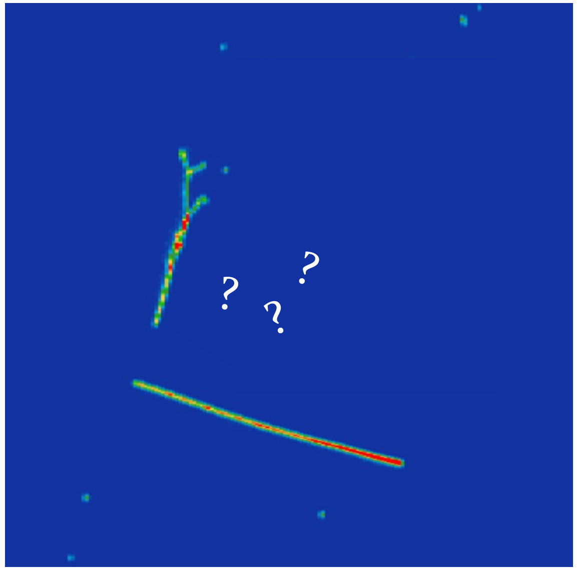

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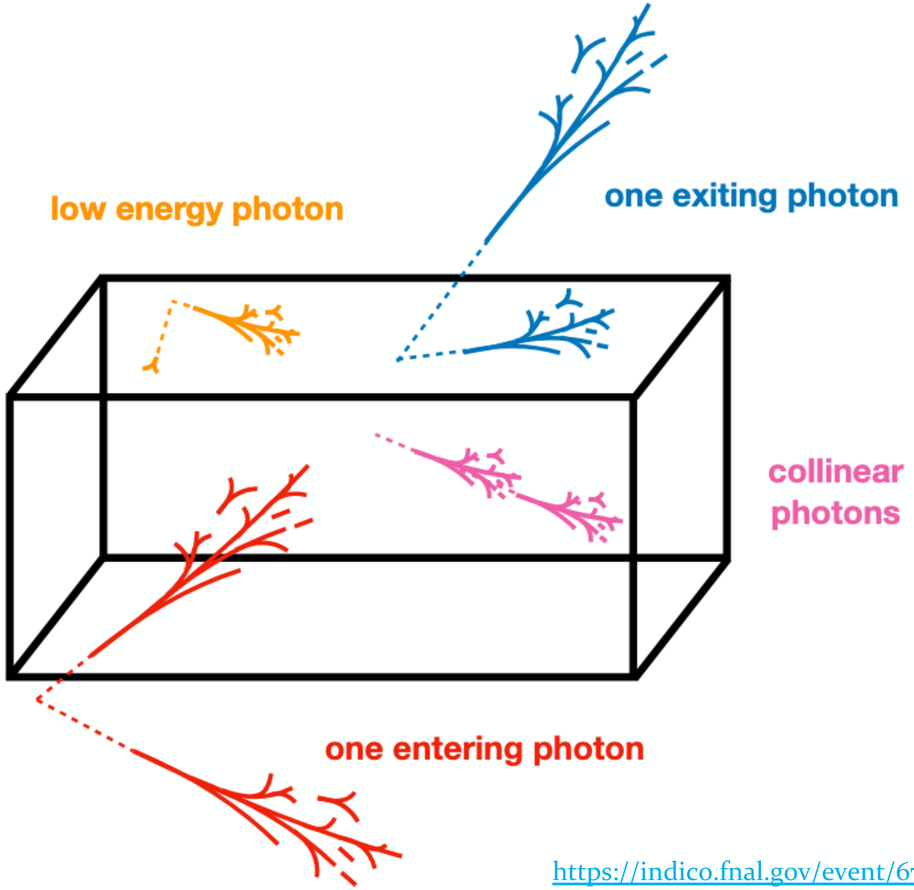
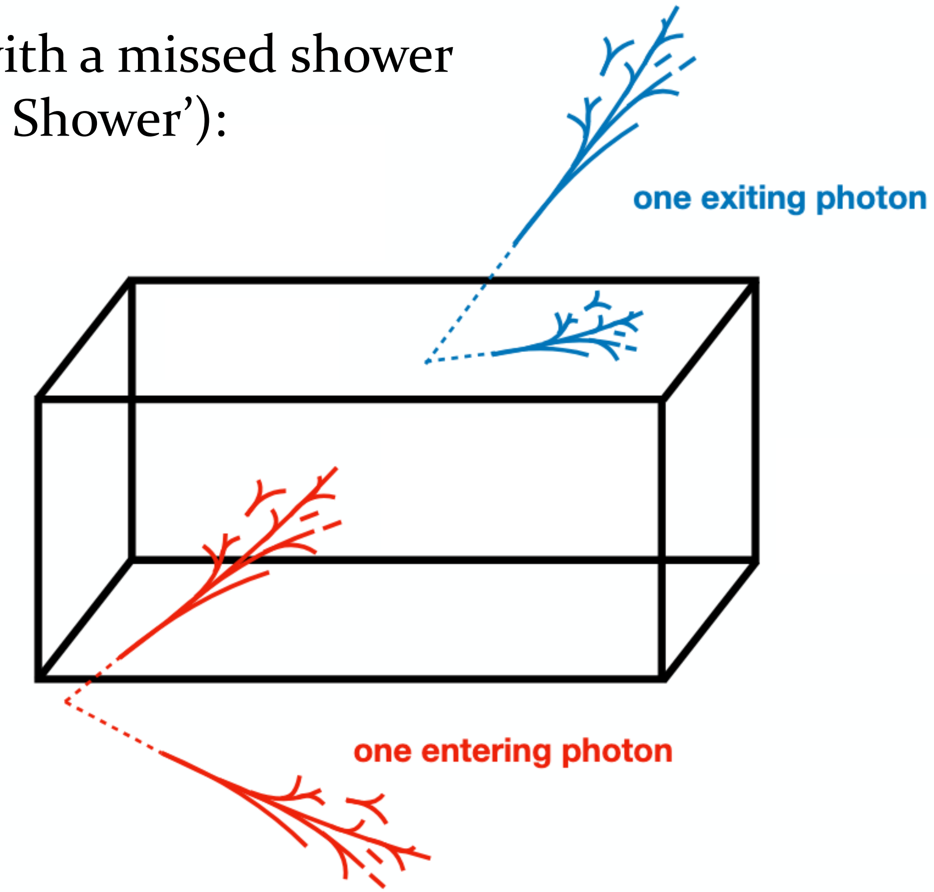


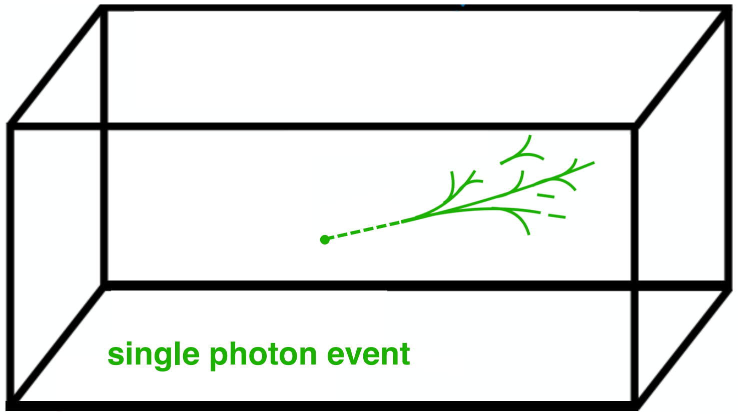
https://indico.fnal.gov/event/67154/

My Project Goal (Ideally): Reject NC π^0 Events with One Out-of-TPC (OTPC) Shower

NC π^0 with a missed shower ('Missed Shower'):



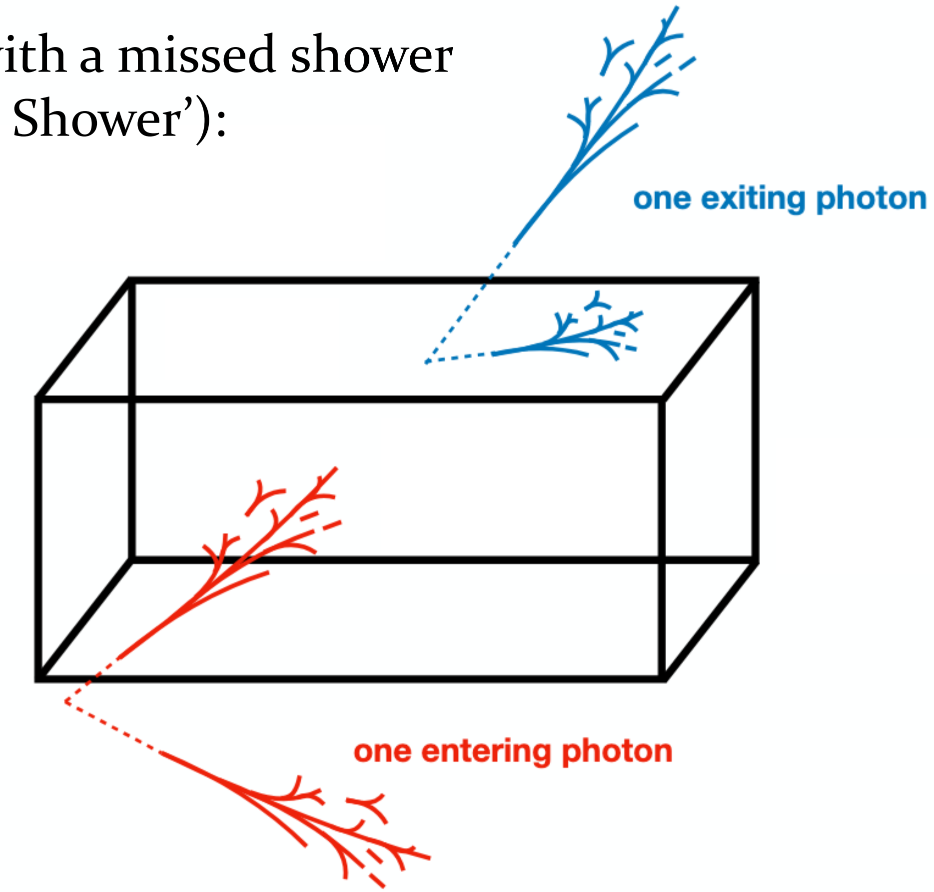
True Single Photons:



Images adapted from https://indico.fnal.gov/event/67154/

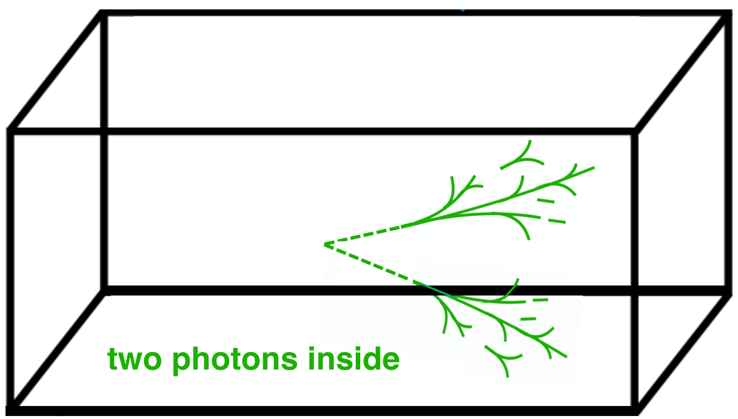
My Project Goal (Actually): Reject NC π^0 Events with One Out-of-TPC (OTPC) Shower

NC π^0 with a missed shower ('Missed Shower'):



~~True Single Photons:~~

NC π^0 with no missed shower ('Contained Shower'):



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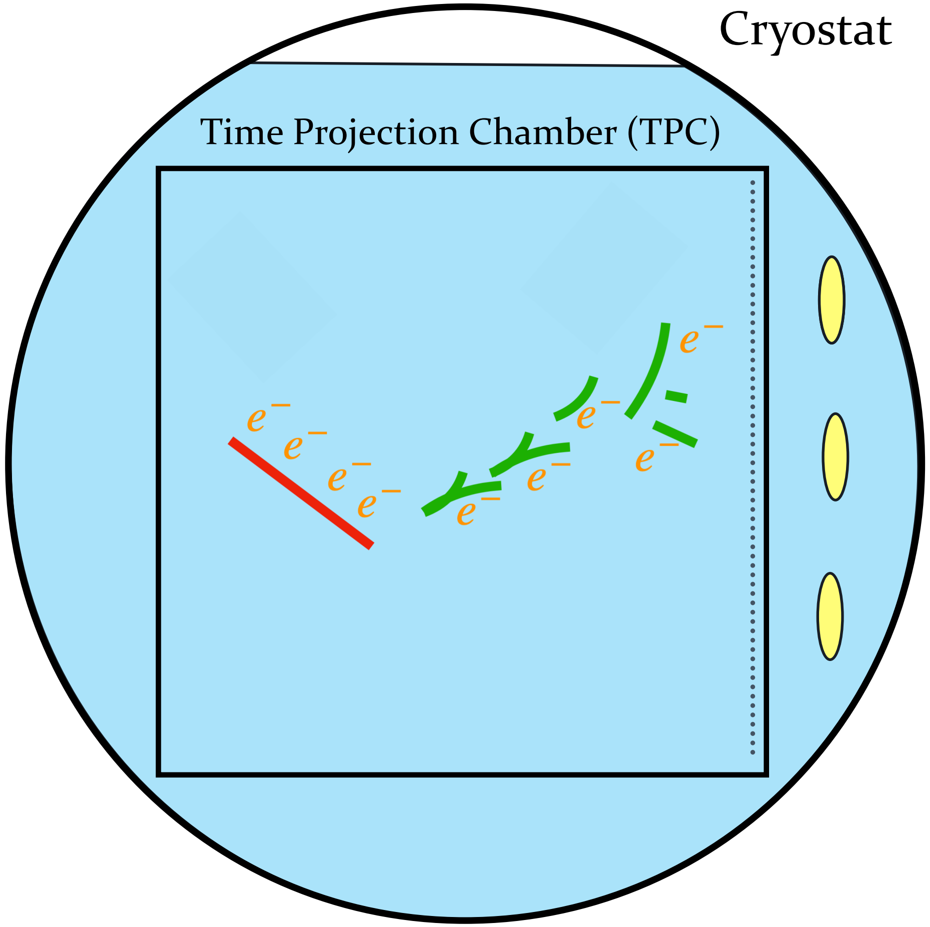
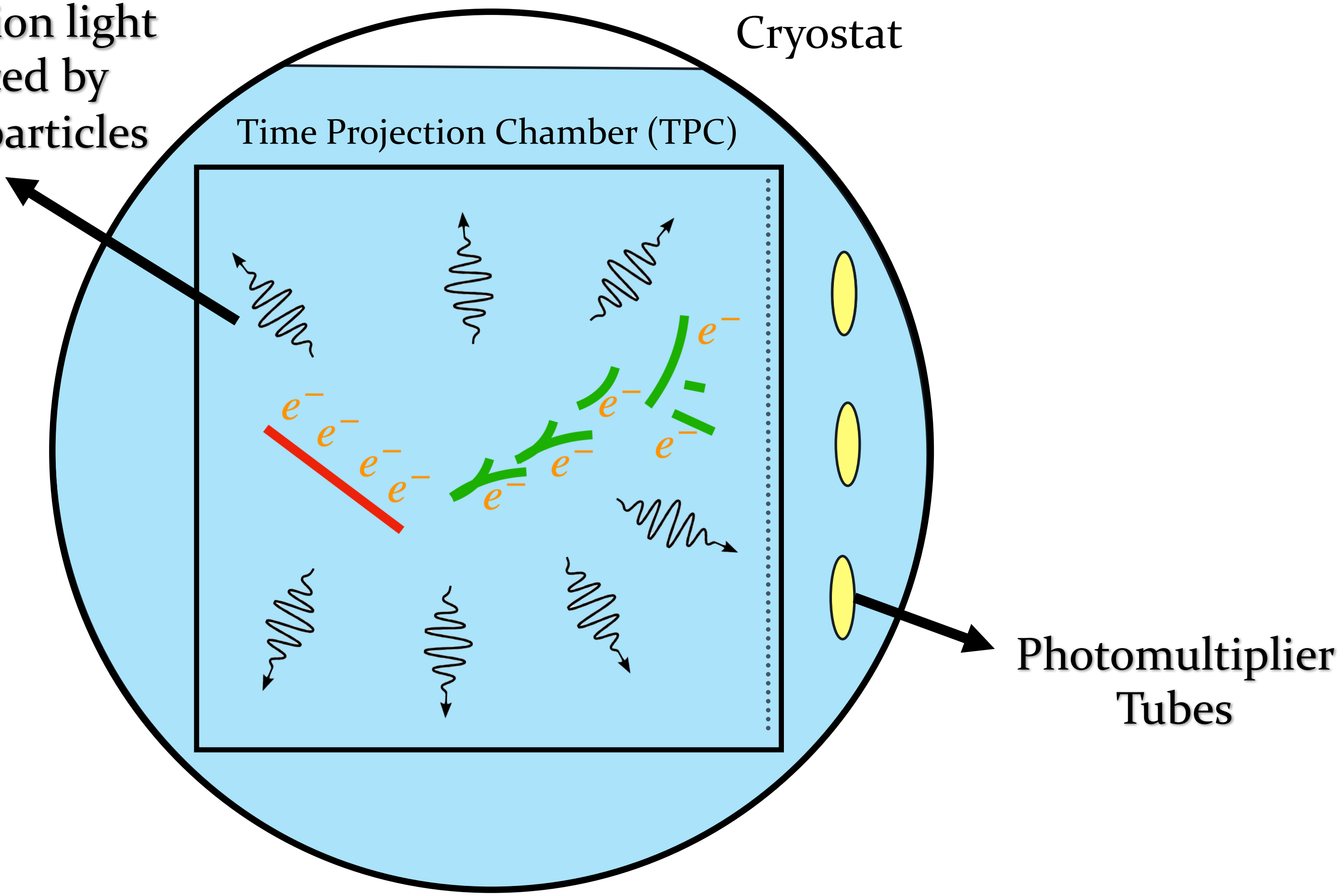
Light in a LArTPC



Light in a LArTPC

Scintillation light produced by ionized particles



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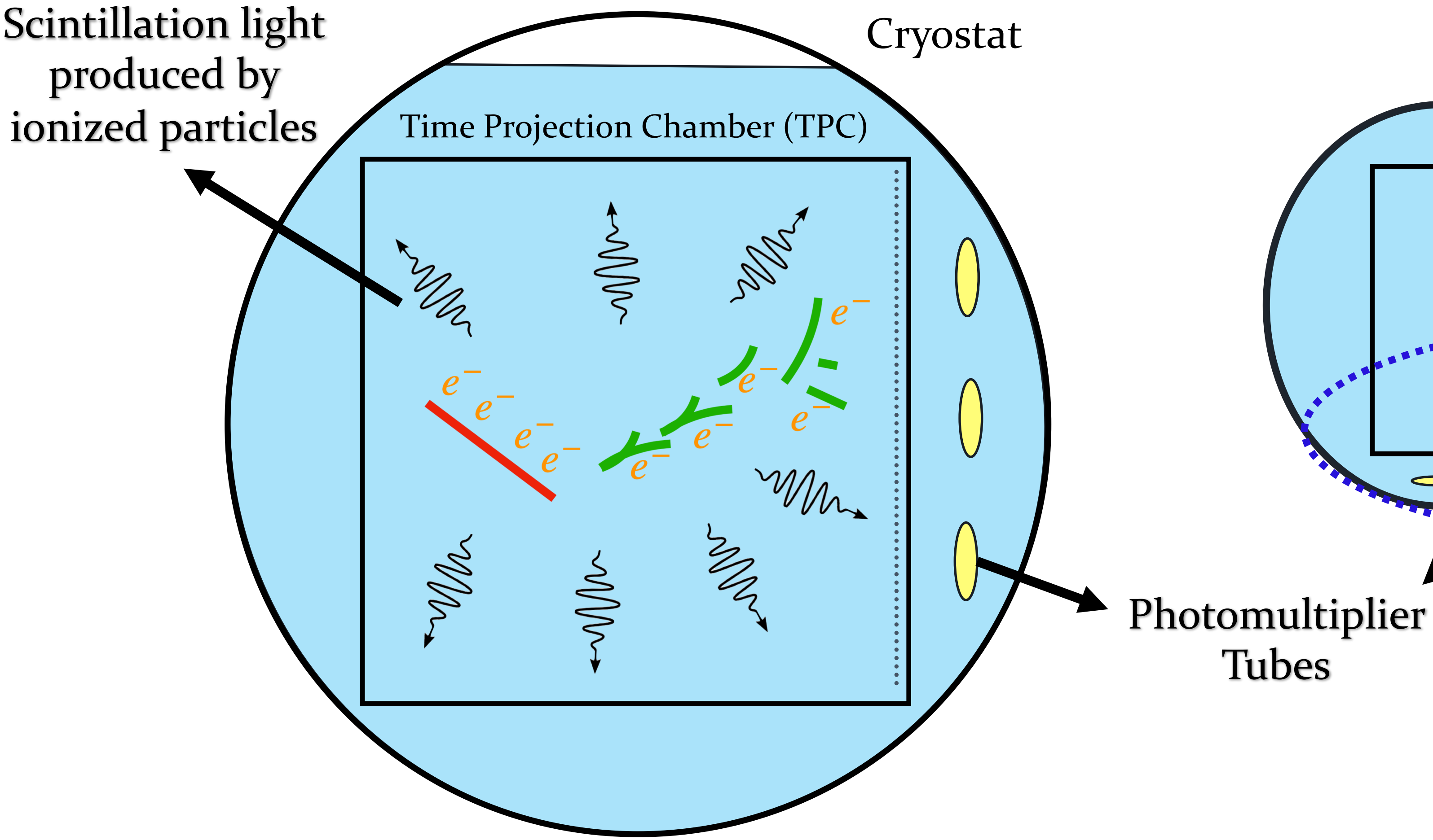
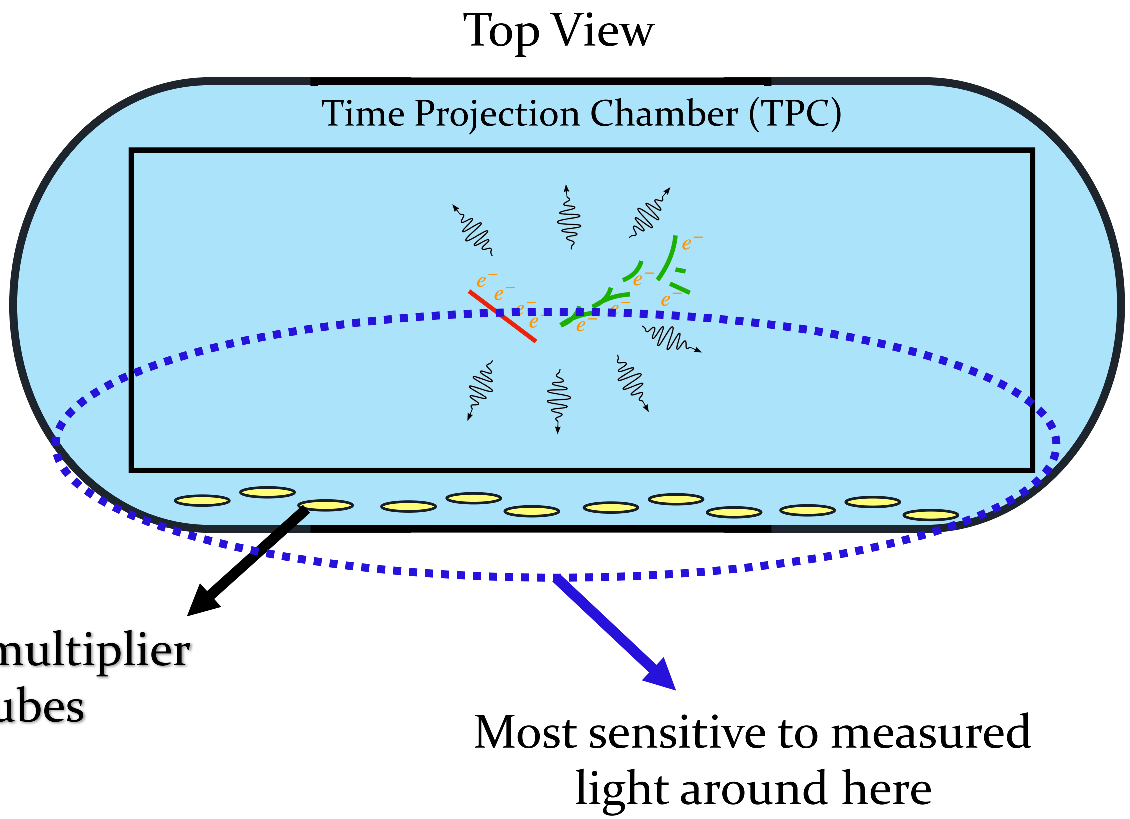
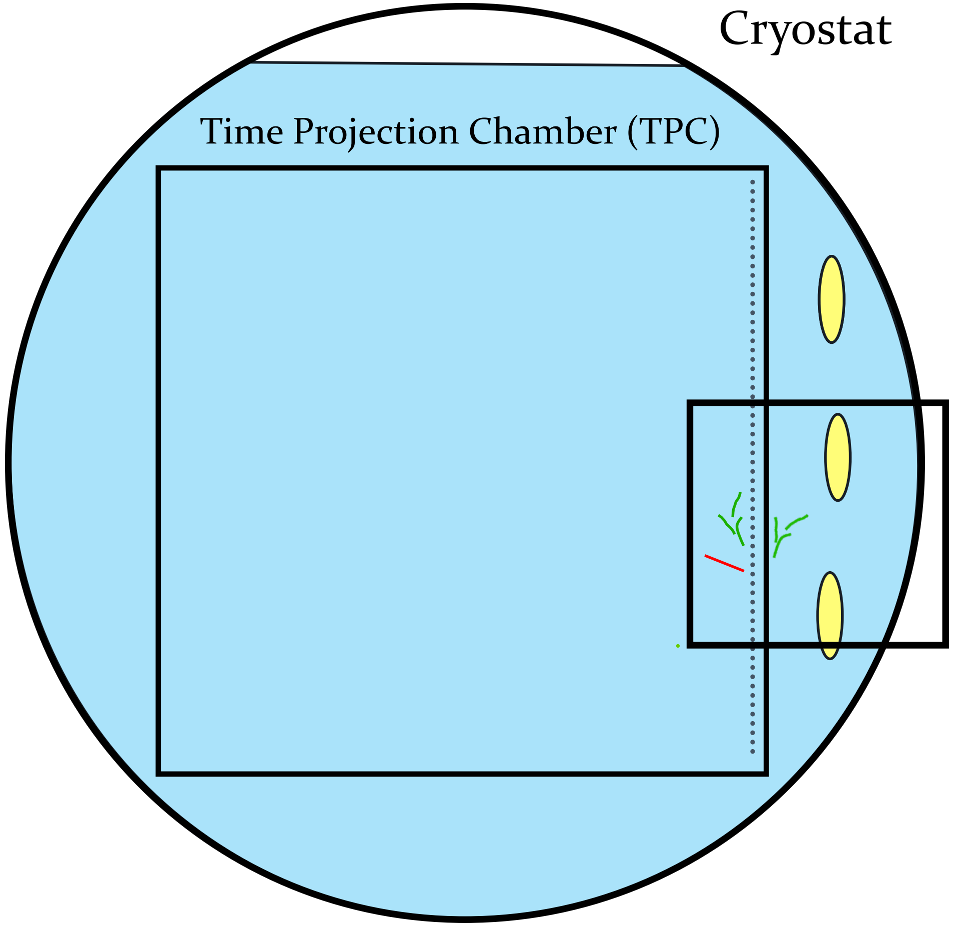
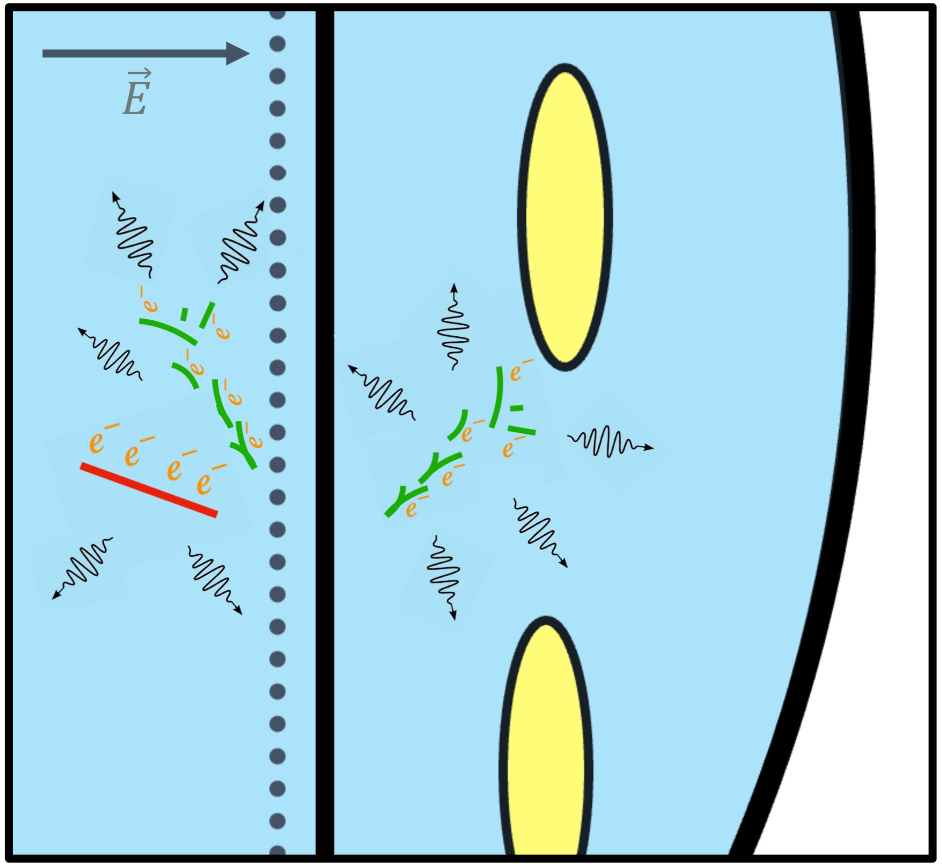




Light Predictions Rely on Charge Inside TPC





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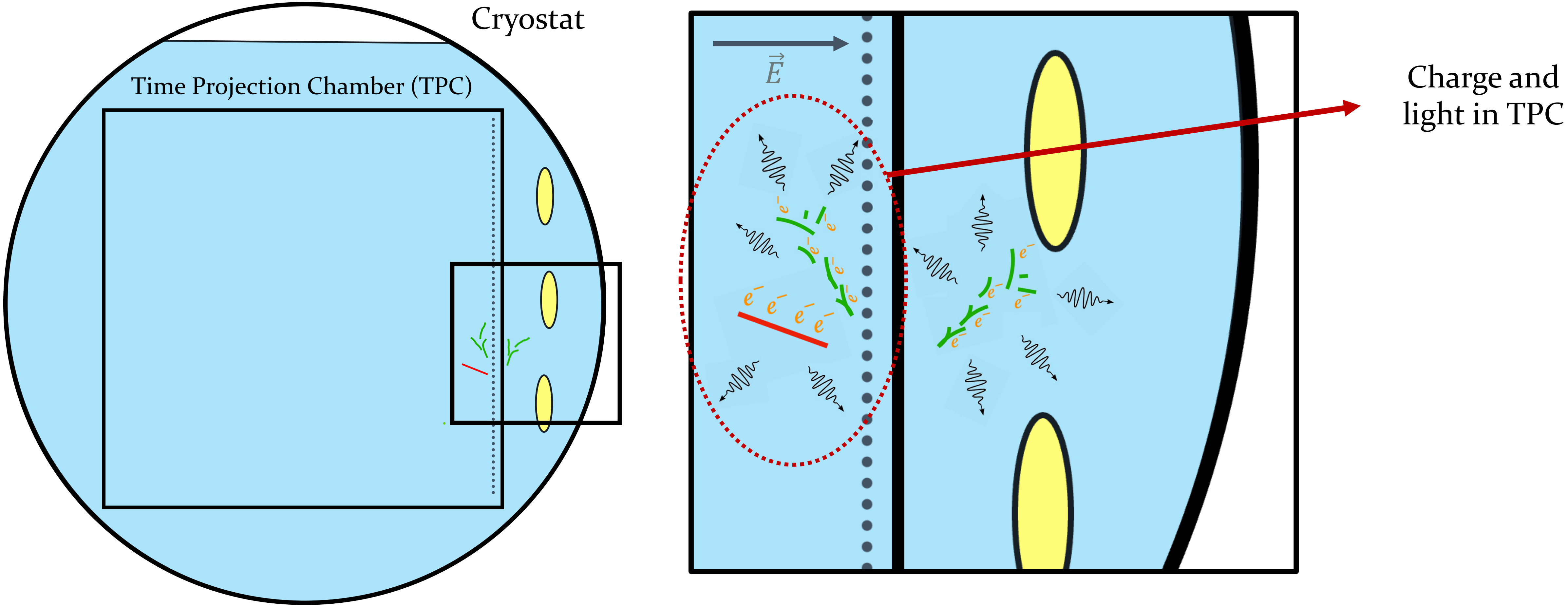

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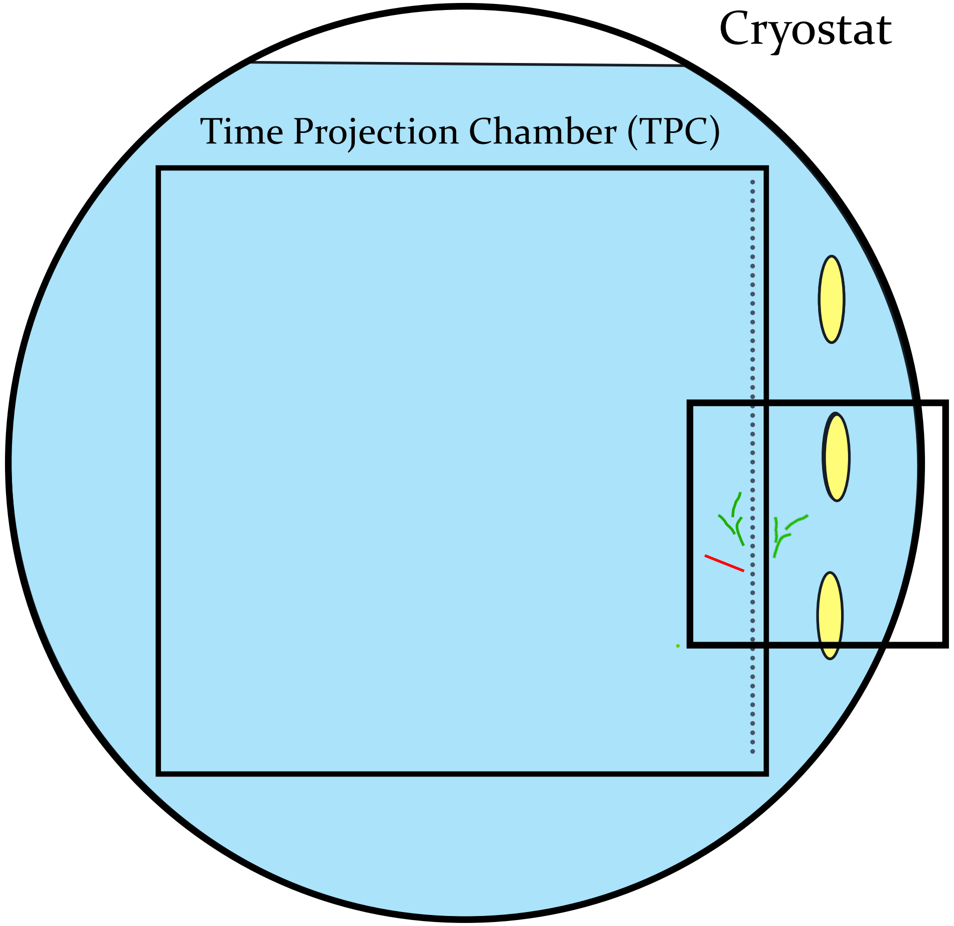
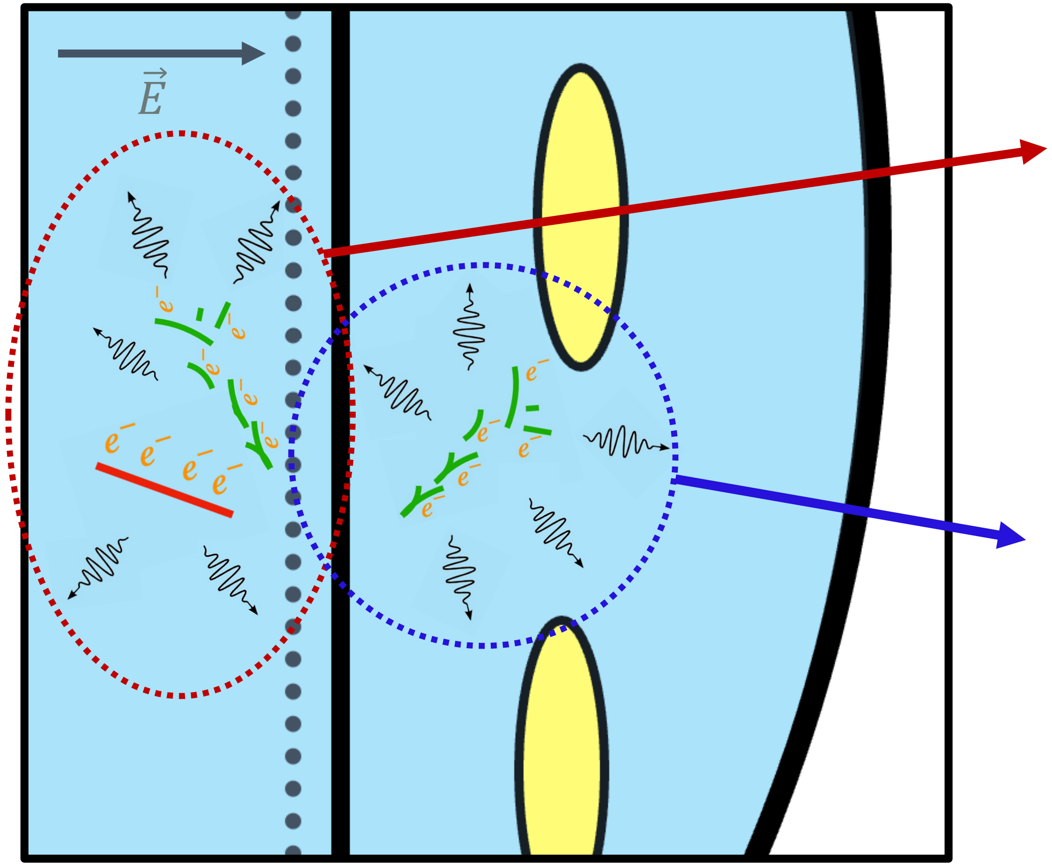
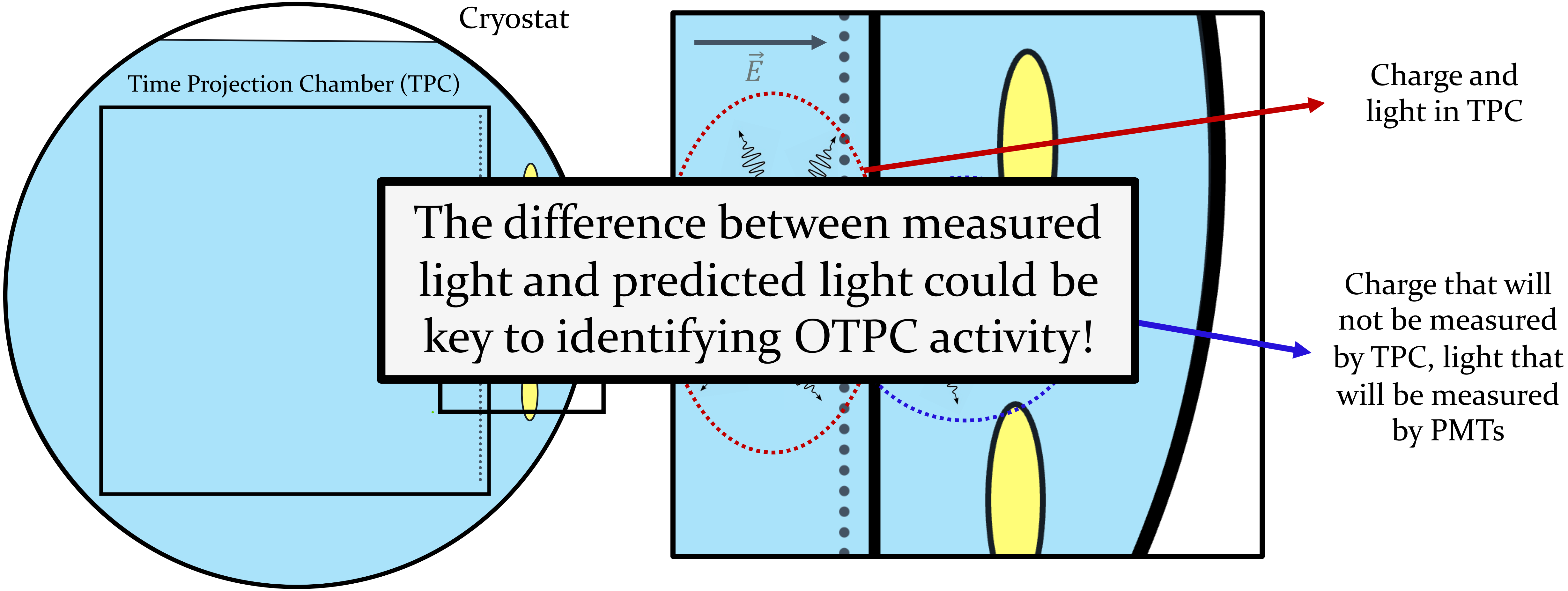




Charge and light in TPC

Charge that will not be measured by TPC, light that will be measured by PMTs

Light Predictions Rely on Charge Inside TPC

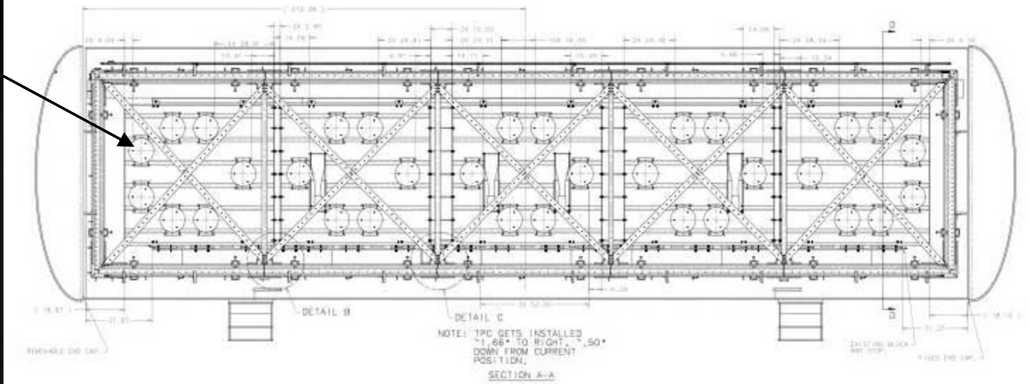


The difference between measured light and predicted light could be key to identifying OTPC activity!

Array of Photomultiplier Tubes (PMTs)

- 32 extremely sensitive light detectors
- Used to trigger data collection when a neutrino is detected and to get accurate timing information
- Also used in analyses to match deposited charge to the light flash
- Allows us to use the entire cryostat as a detector!

https://mod.fnal.gov/mod/w1/Lectures/WC/presentations/211001Ross-Lonergan.pdf



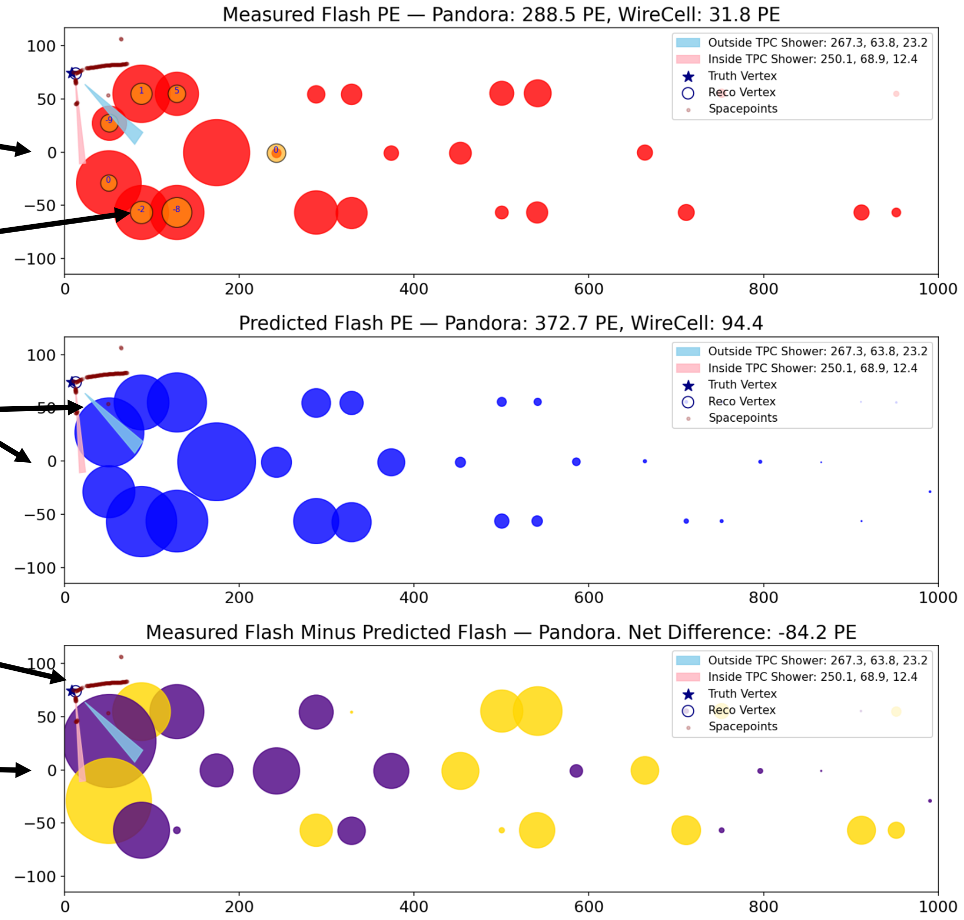
https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1064-TECH.pdf

Turn Simulated Data into Something Recognizable

- Measured PMT-by-PMT light
- Predicted PMT-by-PMT light
- Nanosecond timing
- Truth shower location + direction
- Truth + Reco Vertex
- Spacepoints
- Some metric to see difference between measured and predicted

Turn Simulated Data into Something Recognizable: 'Flash Viewer'

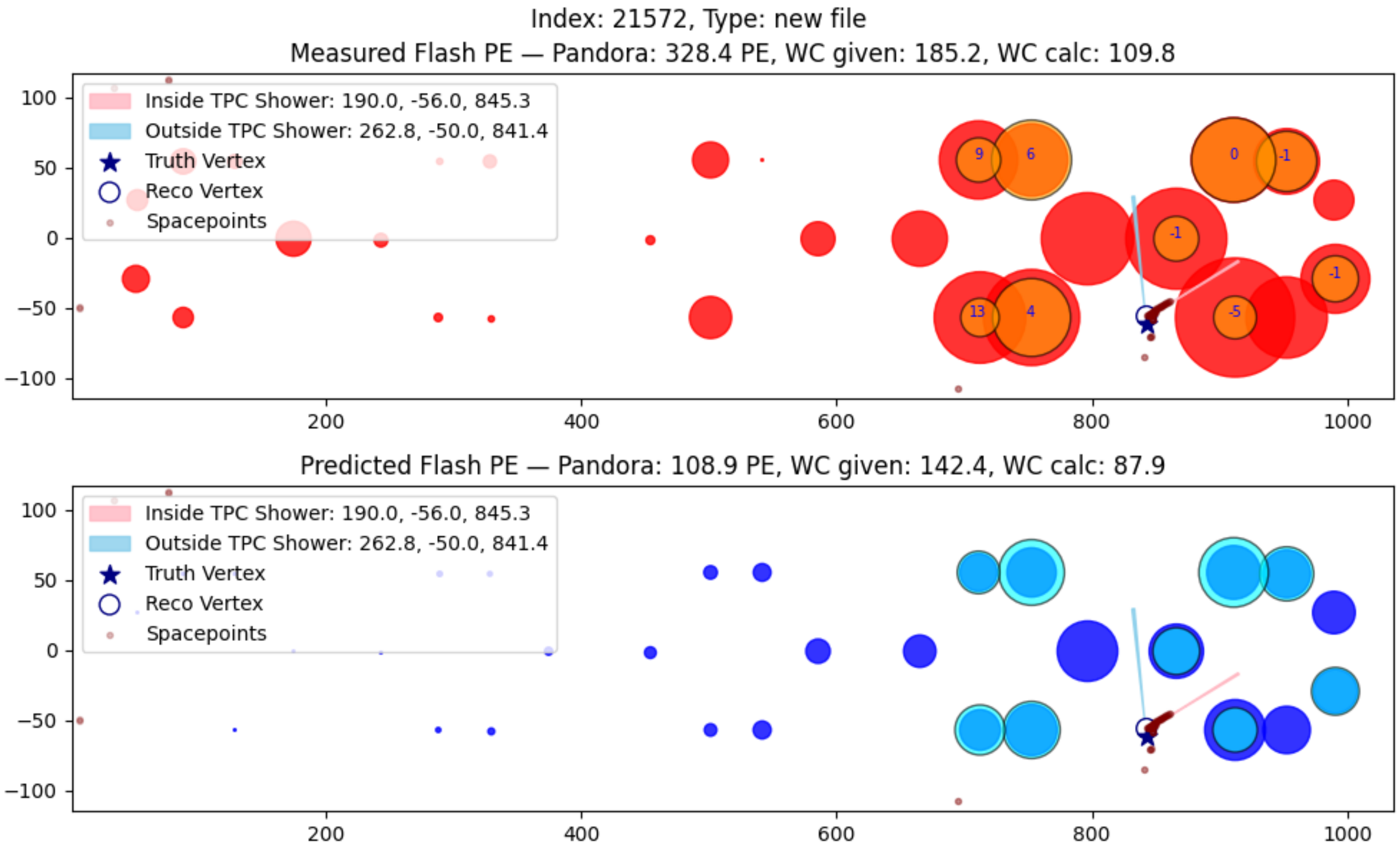
- Measured PMT-by-PMT light
- Predicted PMT-by-PMT light
- Nanosecond timing
- Truth shower location + direction
- Truth + Reco Vertex
- Spacepoints
- Some metric to see difference between measured and predicted



MicroBooNE Simulation

Lots of Interesting Things to Look At – Measured and Predicted light

- Simulated, reconstructed neutrino events
- Look at PMT behavior by hand to identify patterns associated with missed photon showers
- Measured light and predicted light, 2 separate ways
  - Some disagreement between the two

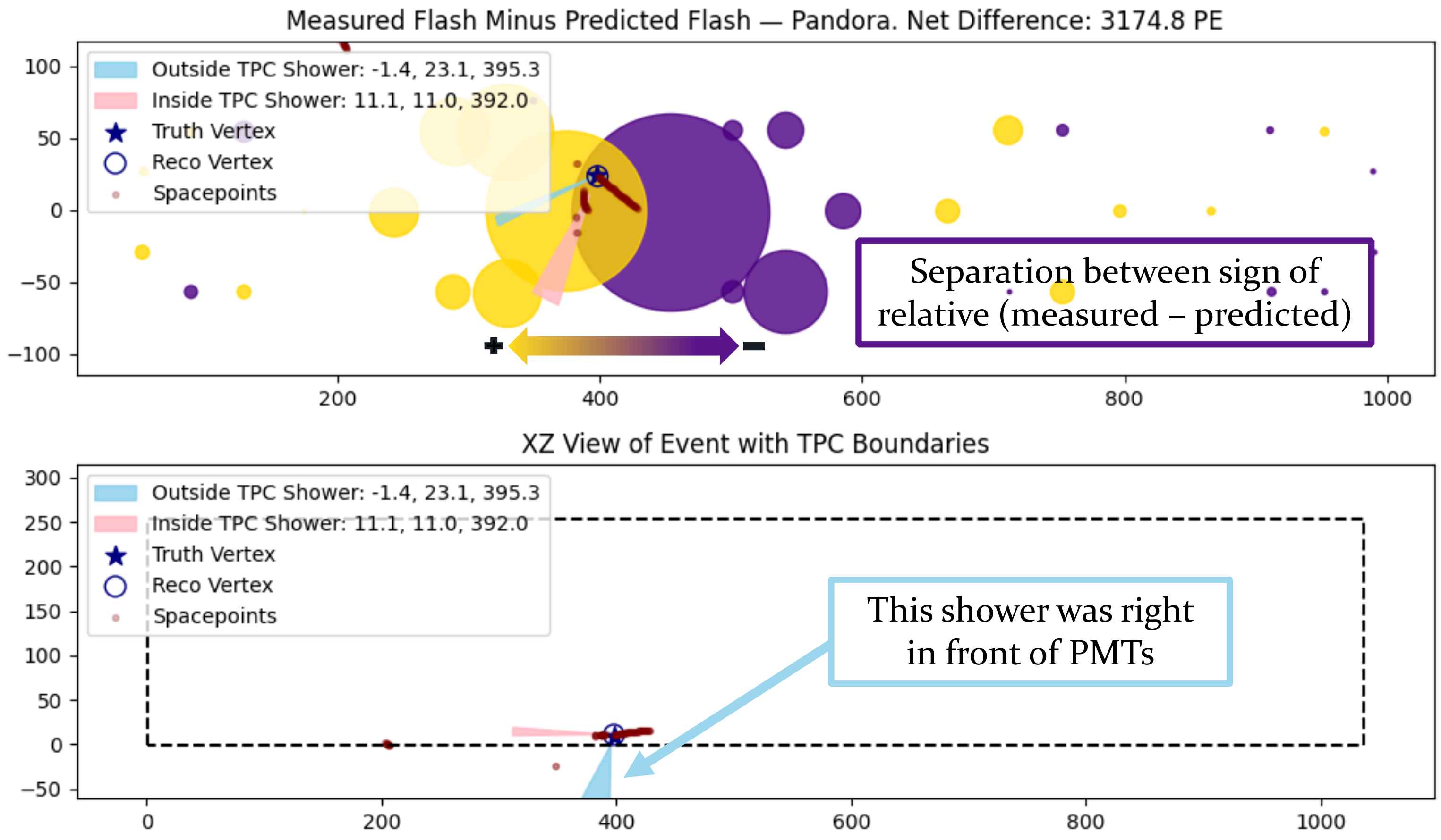


MicroBooNE Simulation

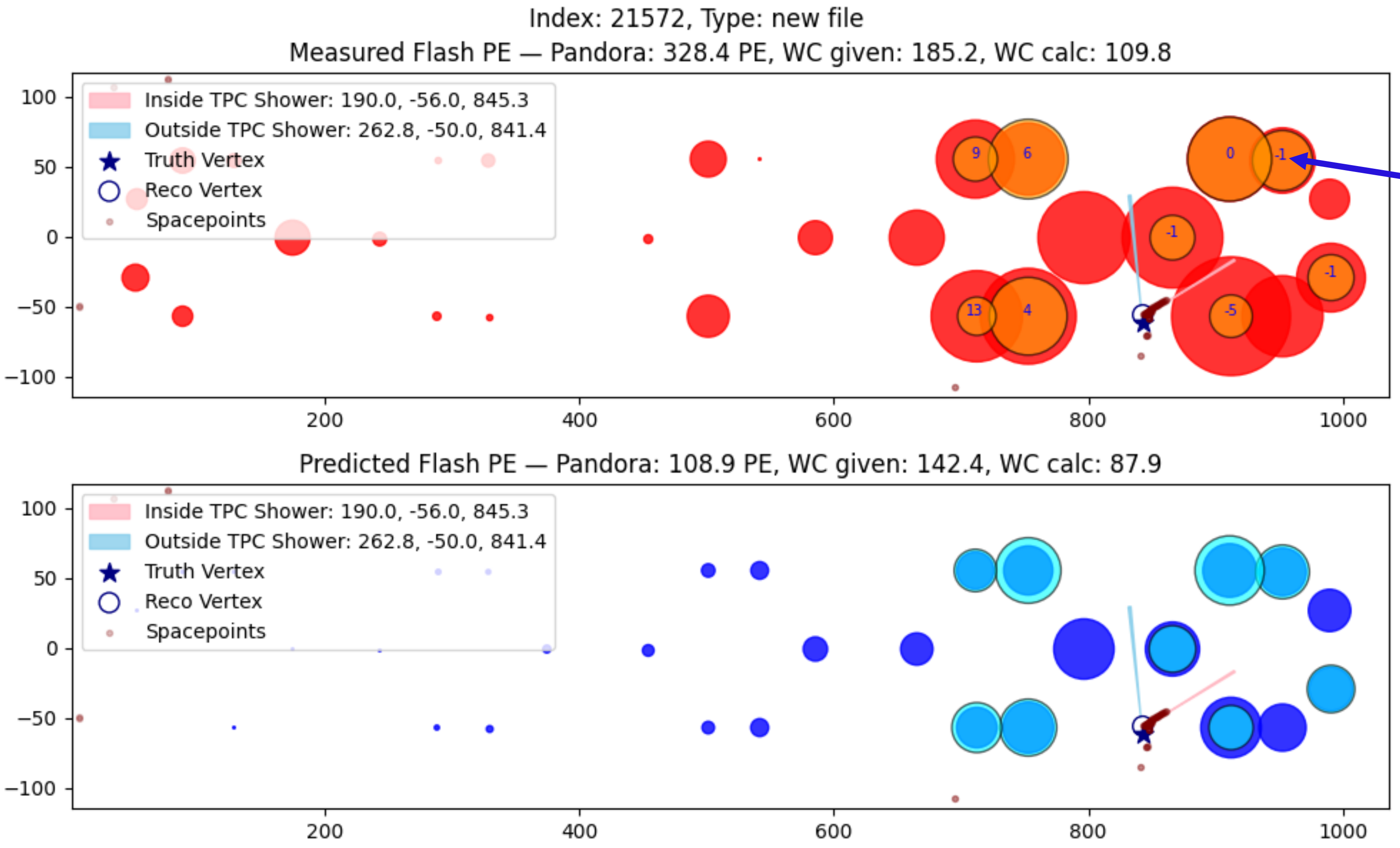
Difference between Measured and Predicted Light

MicroBooNE Simulation

- Predicted light depends on deposited charge
- The difference between measured and predicted light might help identify missed charge
- Can look at this on a total event basis or PMT-by-PMT basis



Nanosecond Flash Timing



Time in ns away from the median

- Light travels 1 foot / ns
- OTPC activity may have some characteristic timing pattern

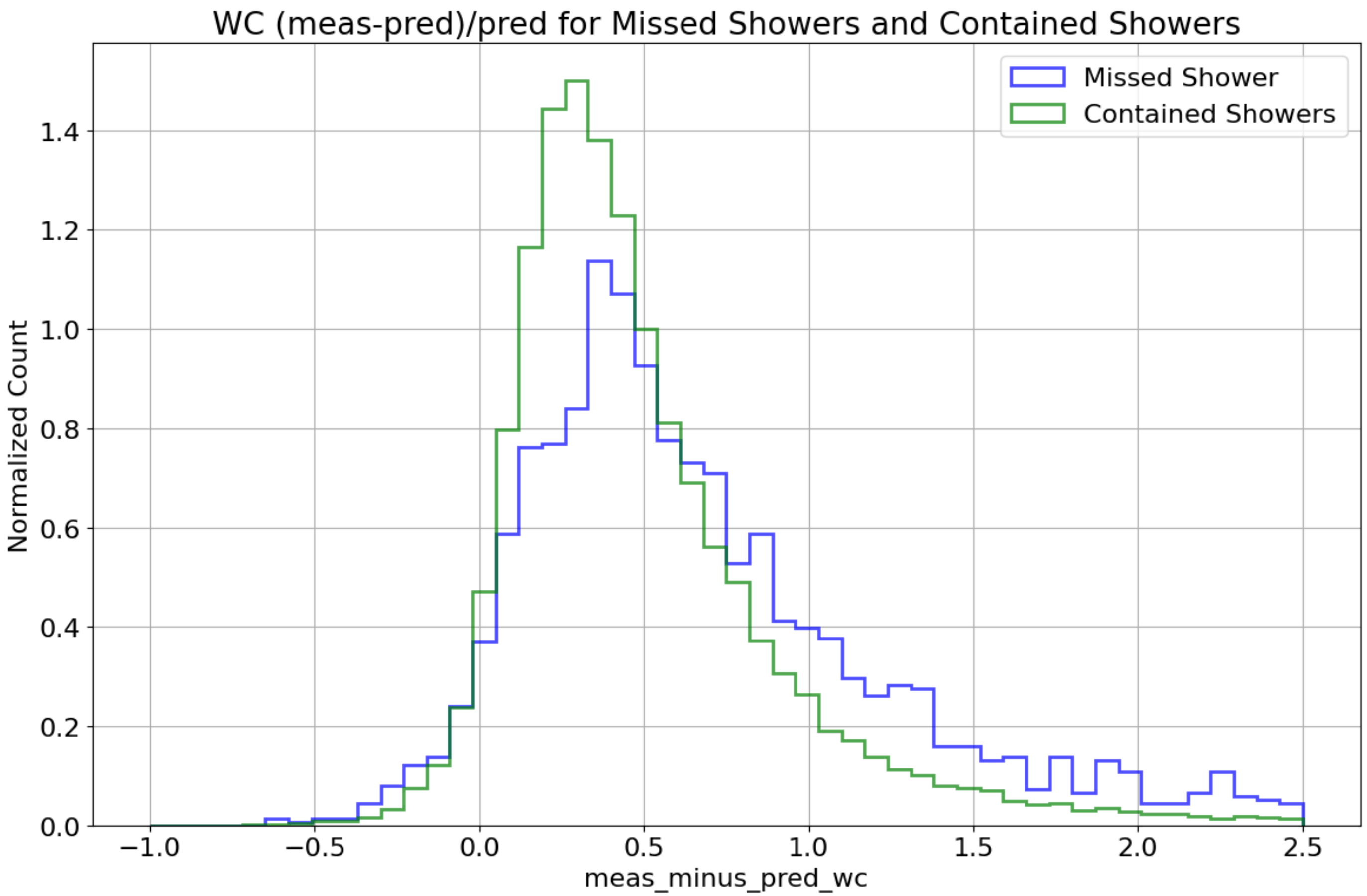
Example - Difference Between Measured and Predicted

Based on
Simulated Data

- Histogram based on truth level information

- No clear place to make a cut

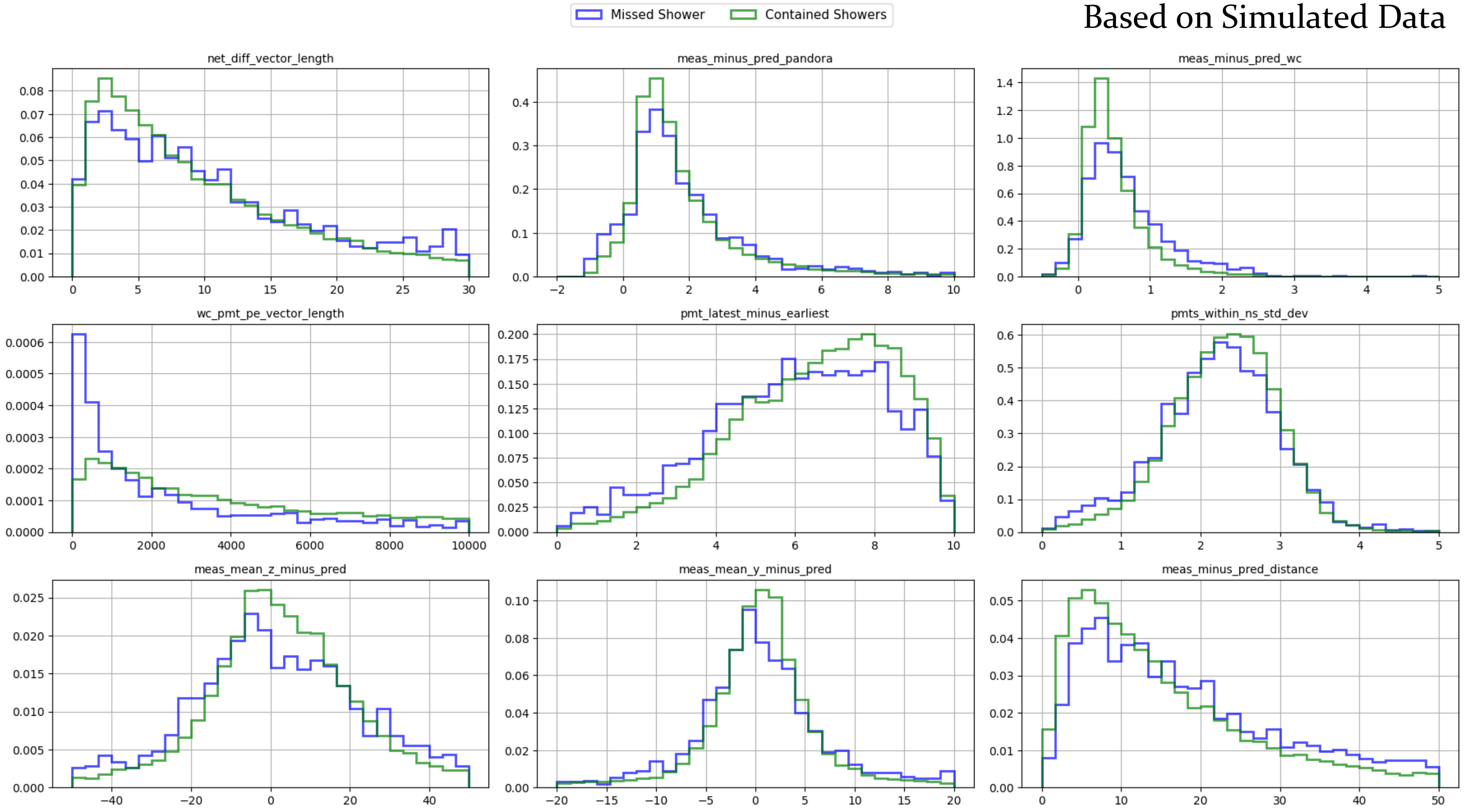
- Slightly different distribution



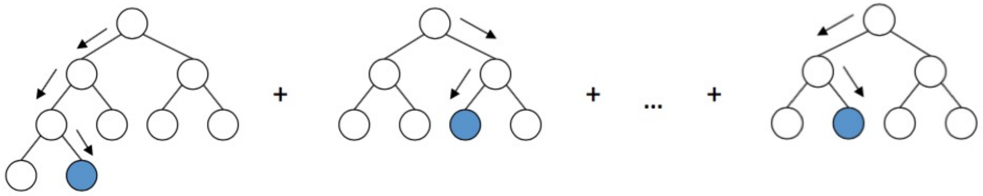
Clear Separation Between Missed Showers and Contained Showers?

This is just a subset of the light-based variables looked at, but none of them can singlehandedly separate signal from background

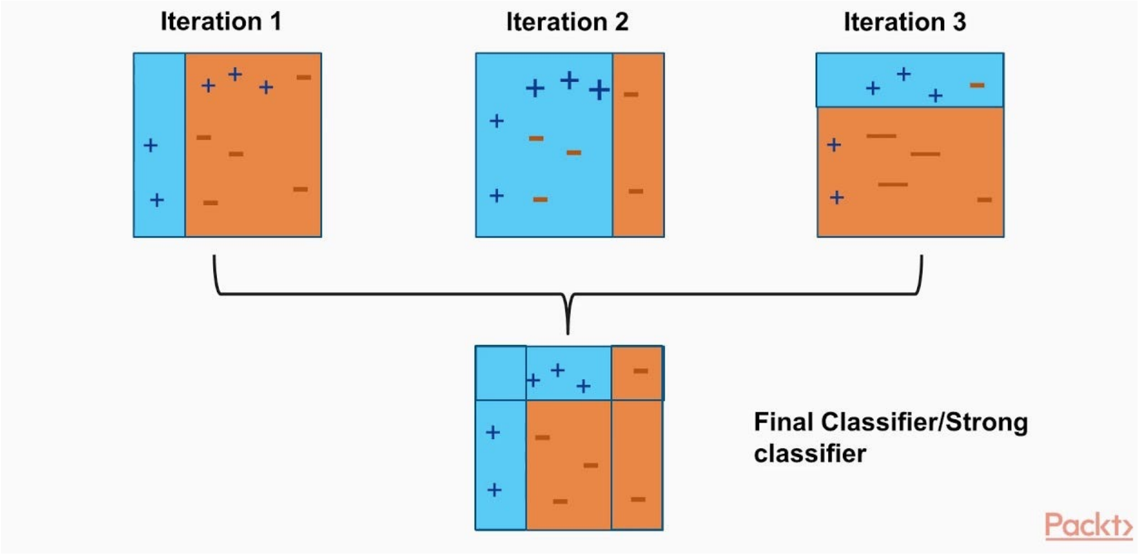
Based on Simulated Data



Boosted Decision Trees (BDTs)



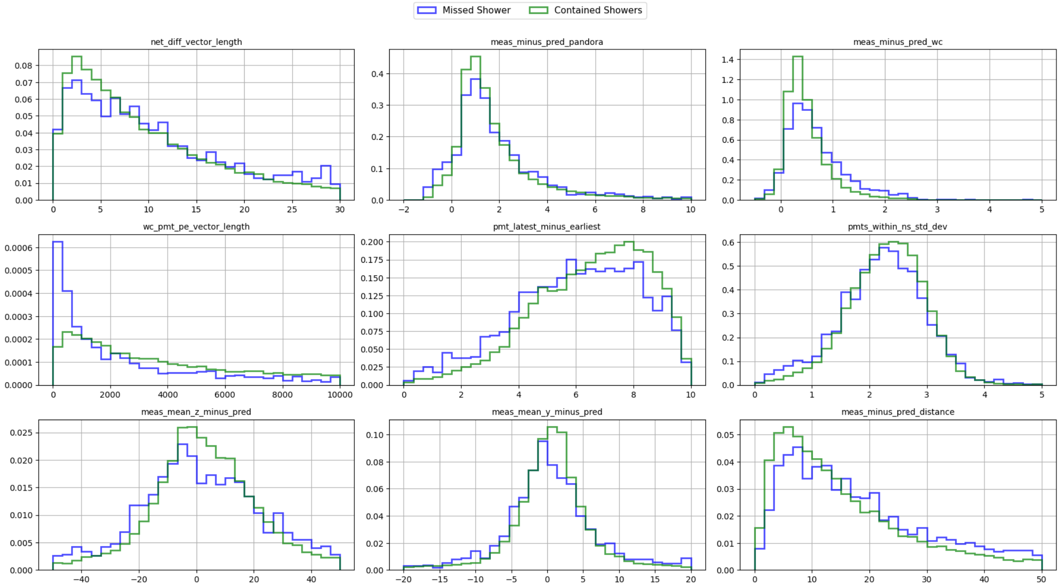
https://medium.com/@ruchi.awasthi63/gradient-boosted-decision-tree-clearly-explained-bd1d8c7d9923

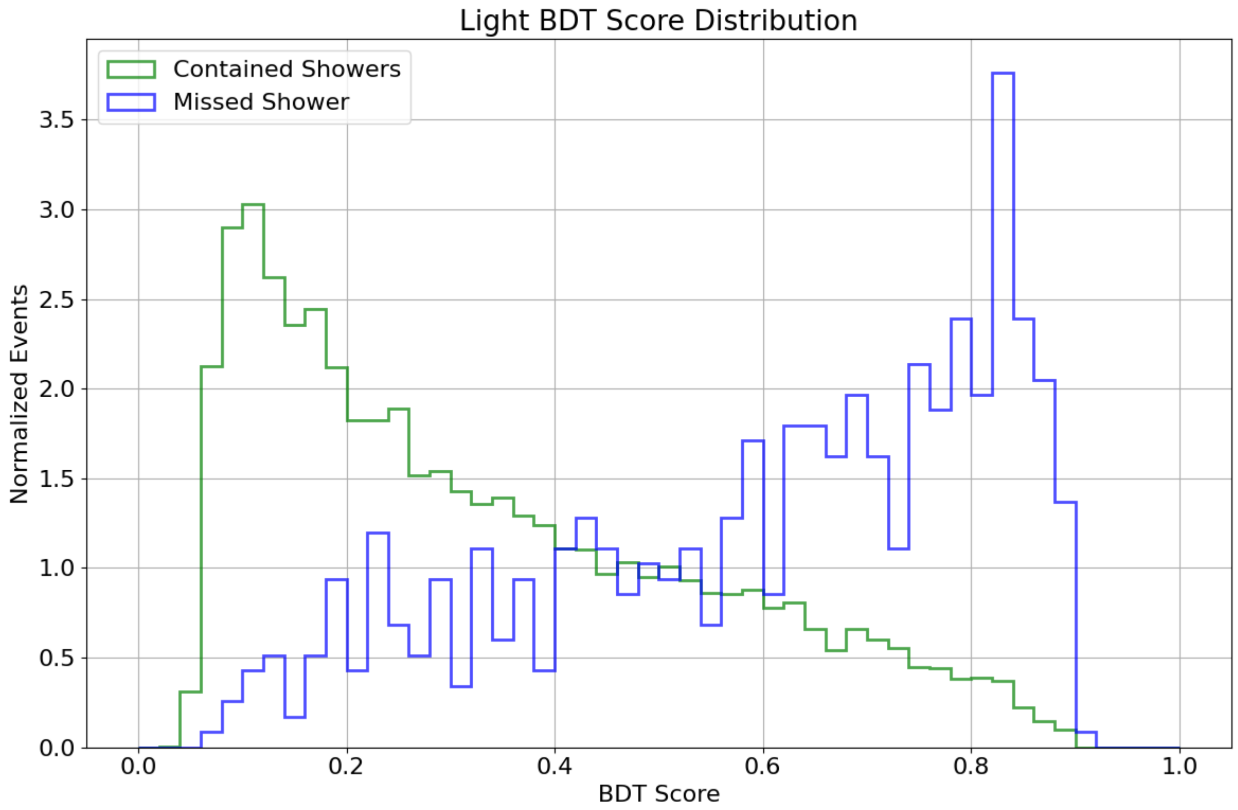


https://www.packtpub.com/en-us/learning/how-to-tutorials/iterative-machine-learning-step-towards-model-accuracy/

- Simple and robust machine learning algorithm that classify events into signal/background based on known parameters
- Assigns a score to each event that is analogous to a probability that it is 'signal'
- Decision trees
  - Uses a series of cuts to find patterns in many numerical parameters
- Boosting
  - Puts extra weight on previously failed classification attempts
- Hyperparameter tuning and reweighting

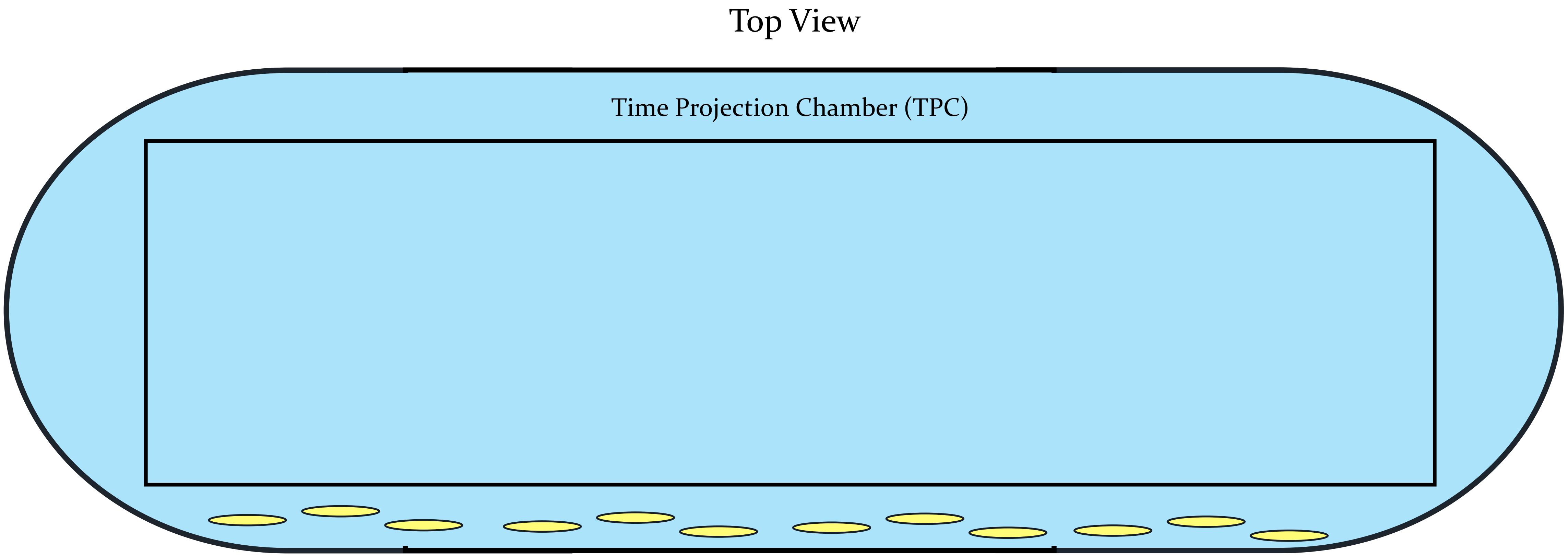
Results – BDT separates much better than individual variables





Based on Simulated Data

How do we know BDT is effective?



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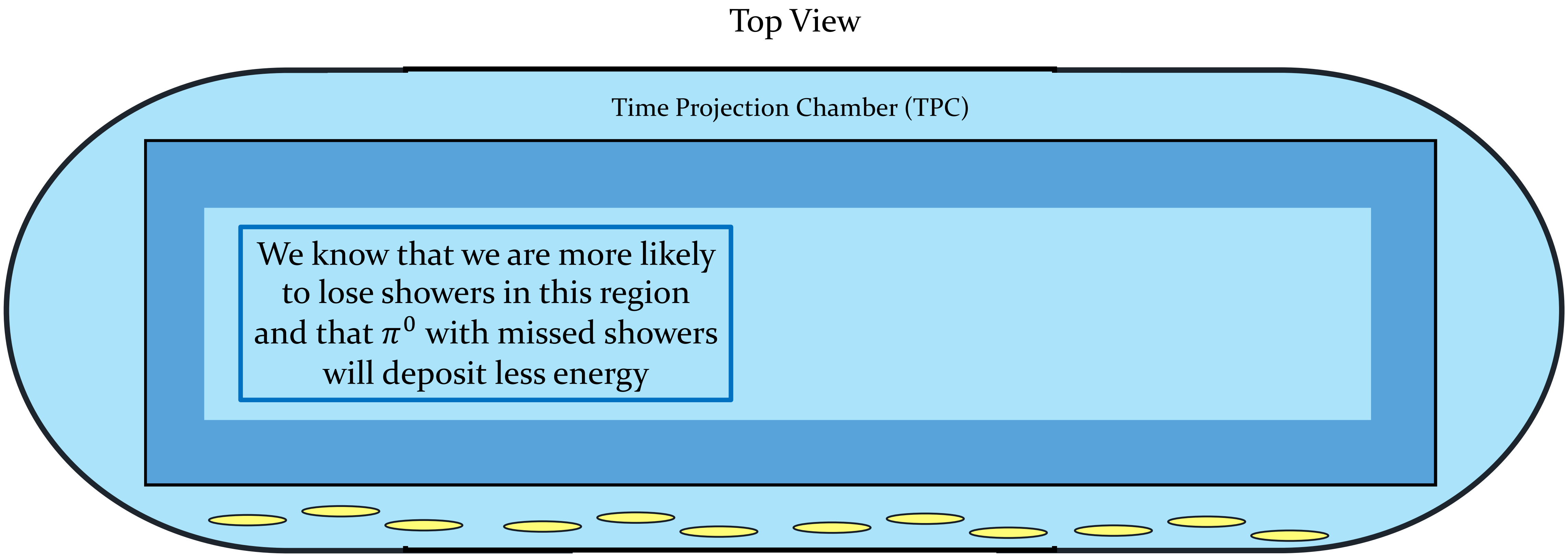

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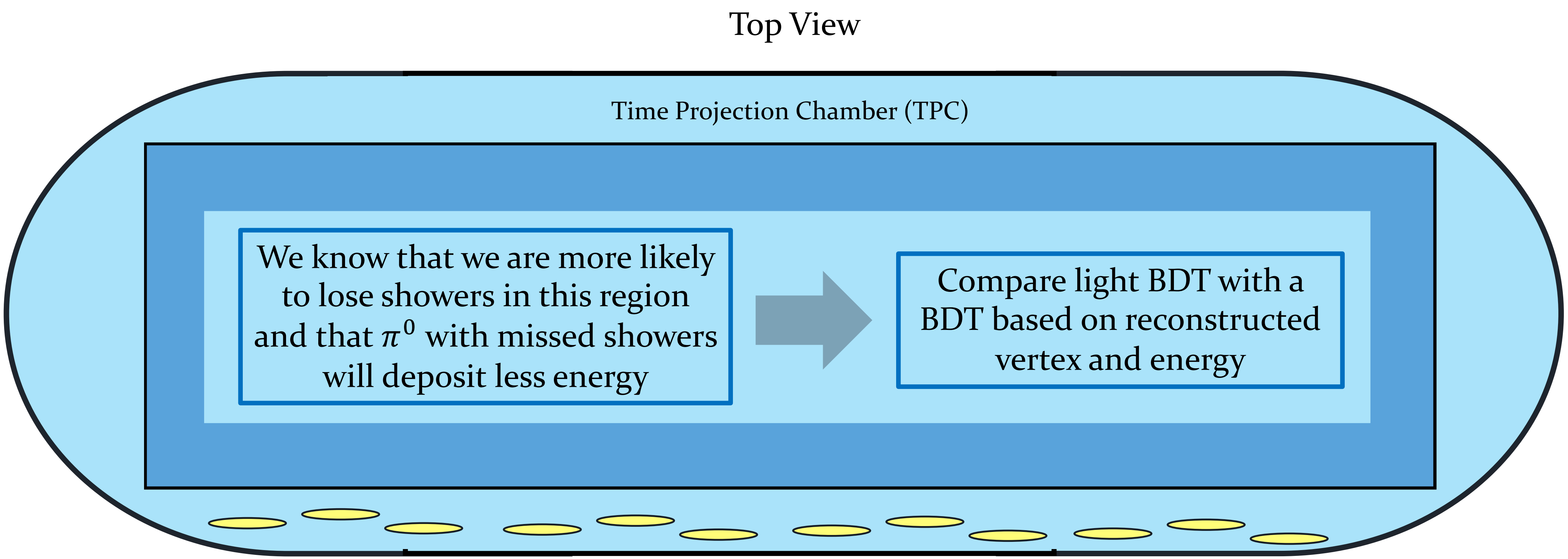


Results – light variables assist in selecting missed shower events

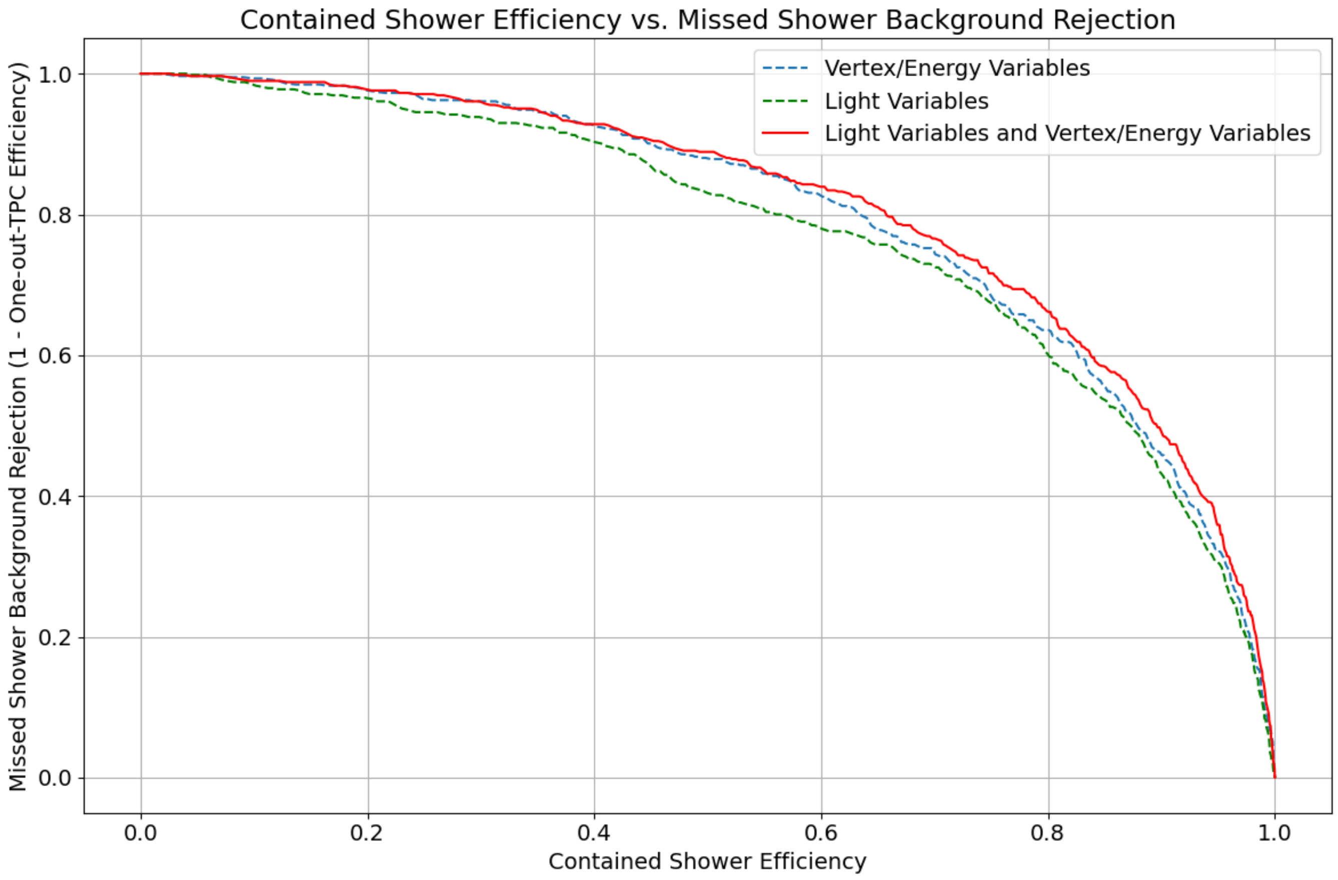
- Comparing light variables with BDT trained on reconstructed vertex and energy
- Efficiency:

$$\frac{\text{Correctly Labelled Contained Showers}}{\text{All True Contained Showers}}$$

- Background Rejection:

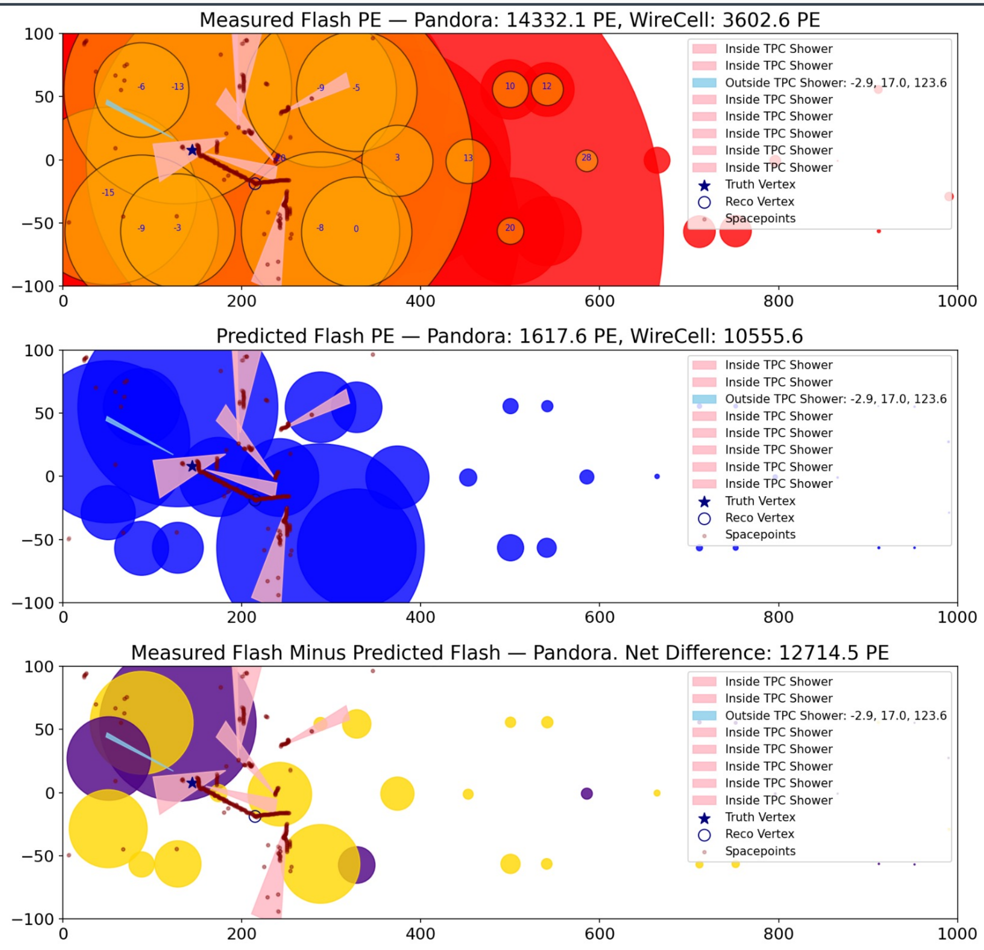
$$\frac{\text{Correctly Rejected Missed Showers}}{\text{All True Missed Showers}}$$

- Higher efficiency and higher background rejection with light!



Summary + Next Steps

- Created pipeline to view, evaluate, and analyze PMT data from new SURPRISE files
- Trained a BDT to separate NC π^0 events with a missed shower from those without missed showers
- Light variables within a BDT can help identify out-of-TPC activity
- Eventual goal is to separate NC π^0 events with a missed second shower from true single photon events



Acknowledgements

I'd like to thank my mentors, Professor Mark Ross-Lonergan and Dr. Lee Hagaman, as well as everyone else at Nevis who made this REU so enjoyable and rewarding!

This material is based upon work supported by the National Science Foundation under Grant No. PHY-2349438.

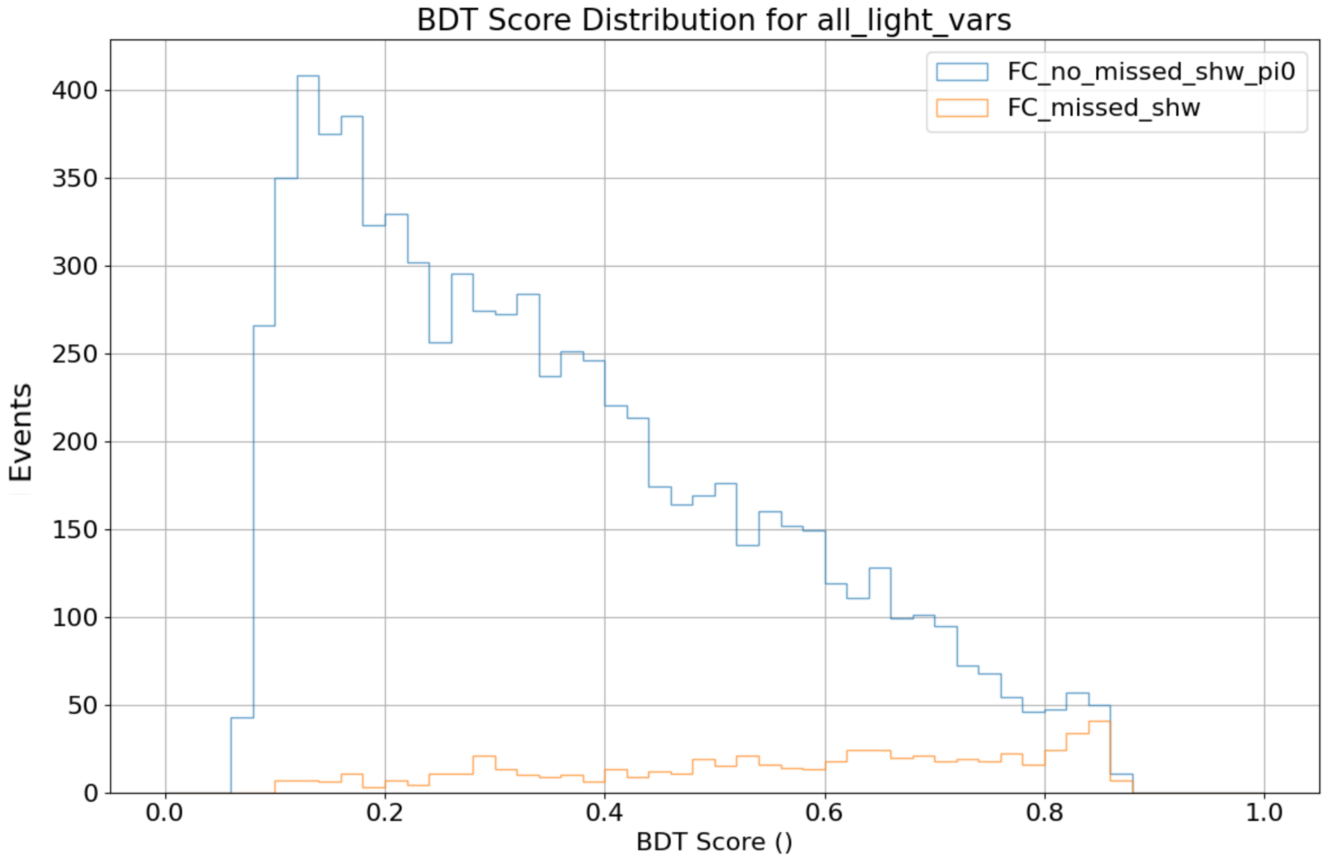
Mark Ross-Lonergan

Lee Hagaman

Questions?

Non-Normalized BDT Score

- There were 2072 missed shower events and 25451 contained shower events
- Needed to tune hyperparameters, train BDT, and test with so few events



Sensitivity to Light in MicroBooNE

8 inch Hamamatsu 5912-02MOD PMTs

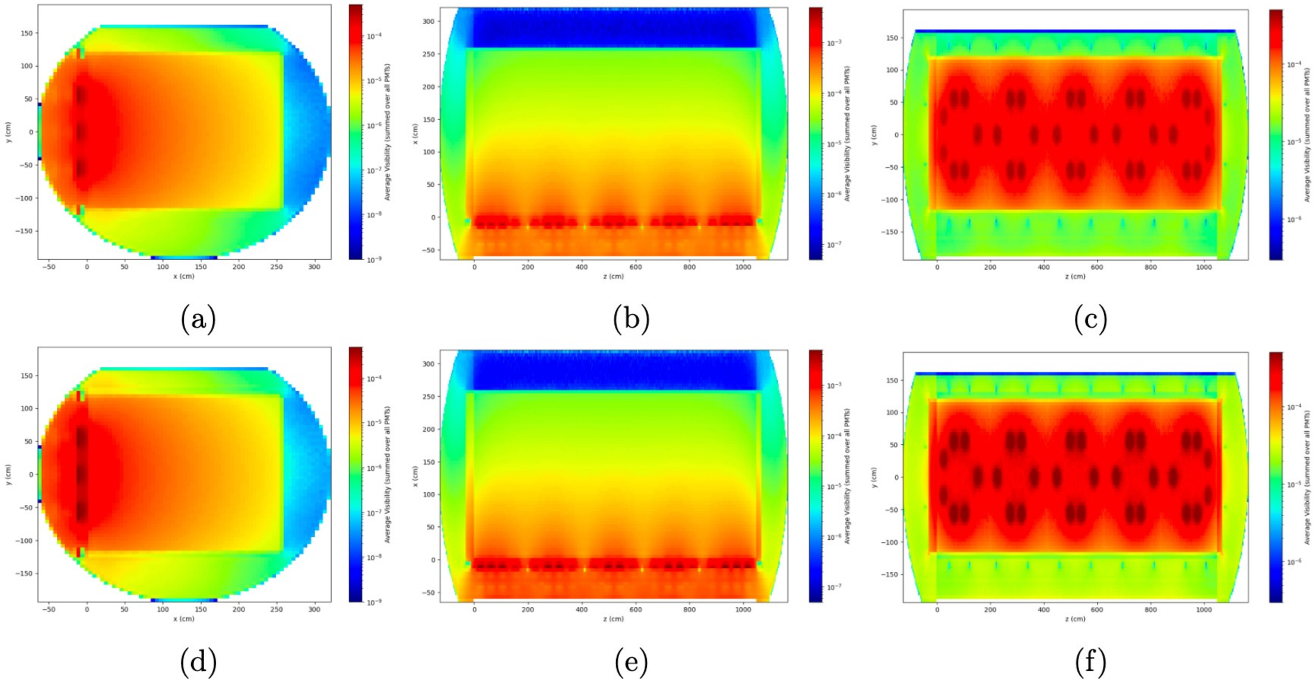
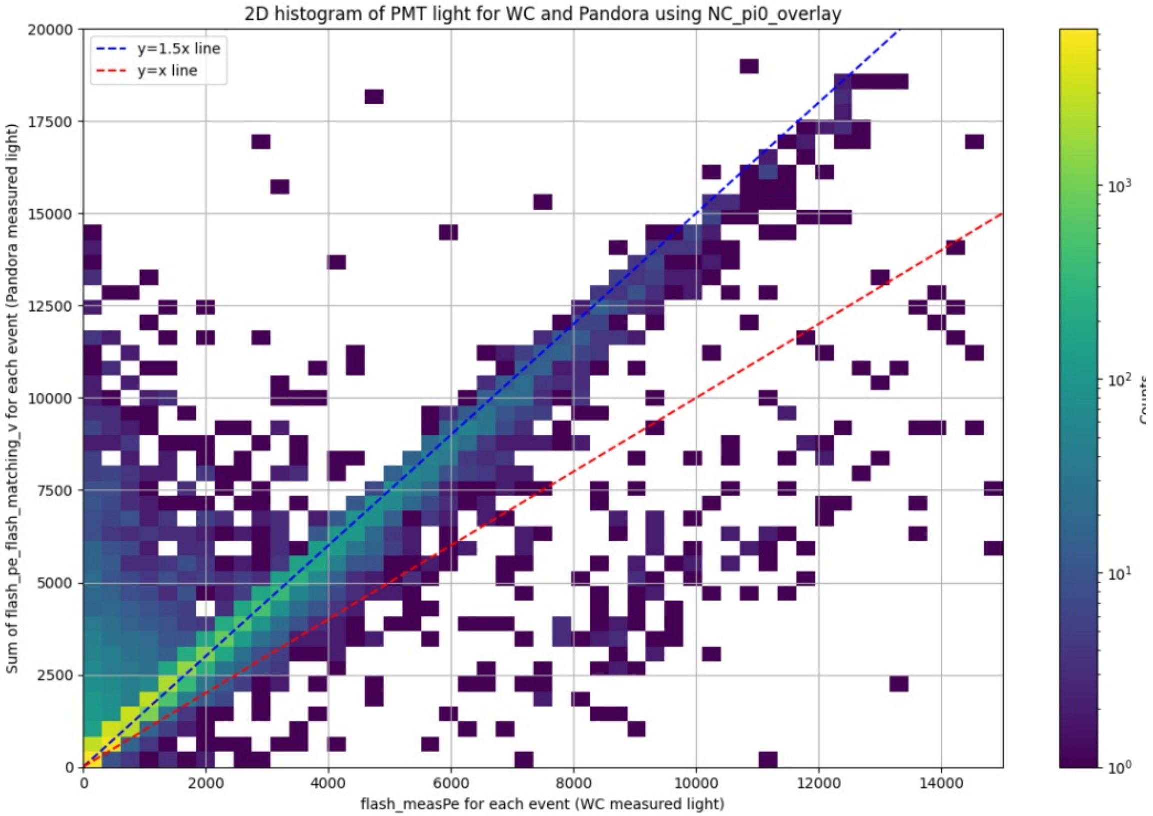


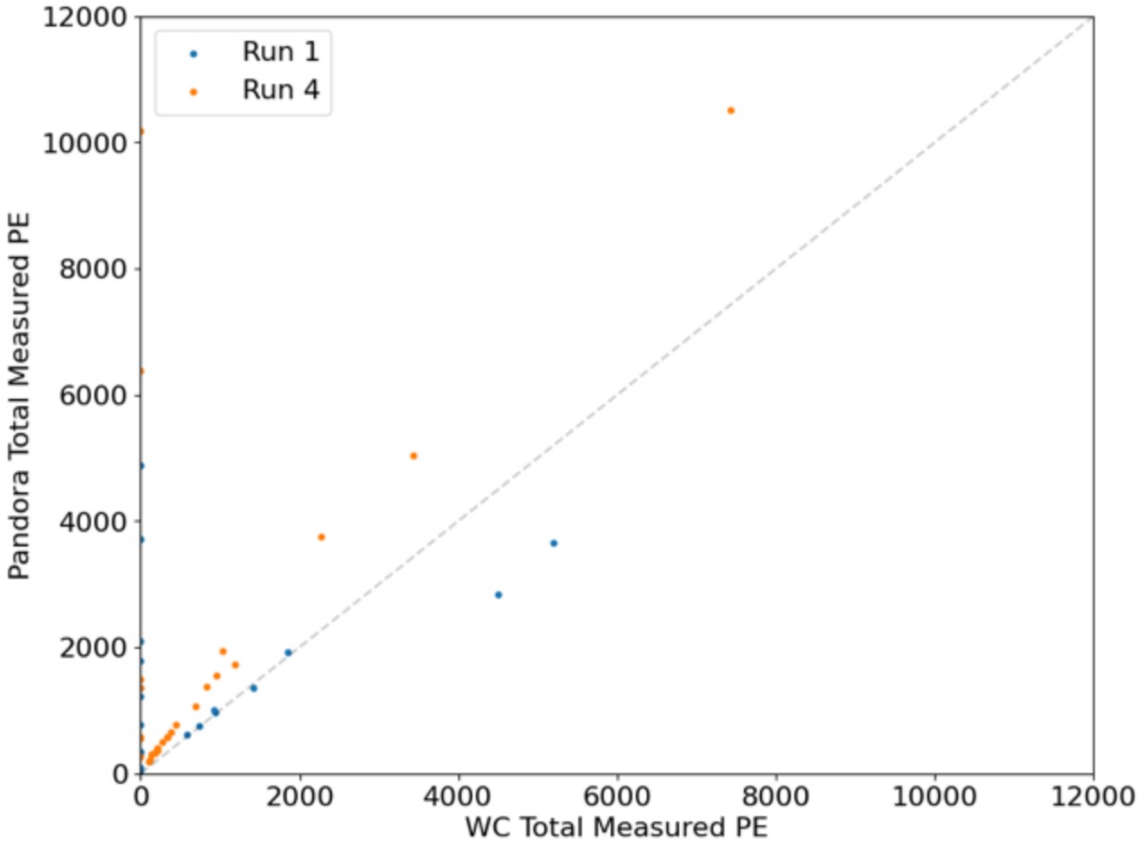
Figure 5.11: PMT photon libraries. Panels (a), (b), and (c) show the nominal light maps, integrated across all PMTs. Panels (e), (e), and (f) show the modified light maps, with 50% increased light yield outside of the TPC. In these maps, we can clearly see the positions of the PMTs and the transparency of the field cage. Small differences are visible between these two light maps in certain locations.

Lee Hagaman Thesis:
https://arxiv.org/pdf/2506.18956

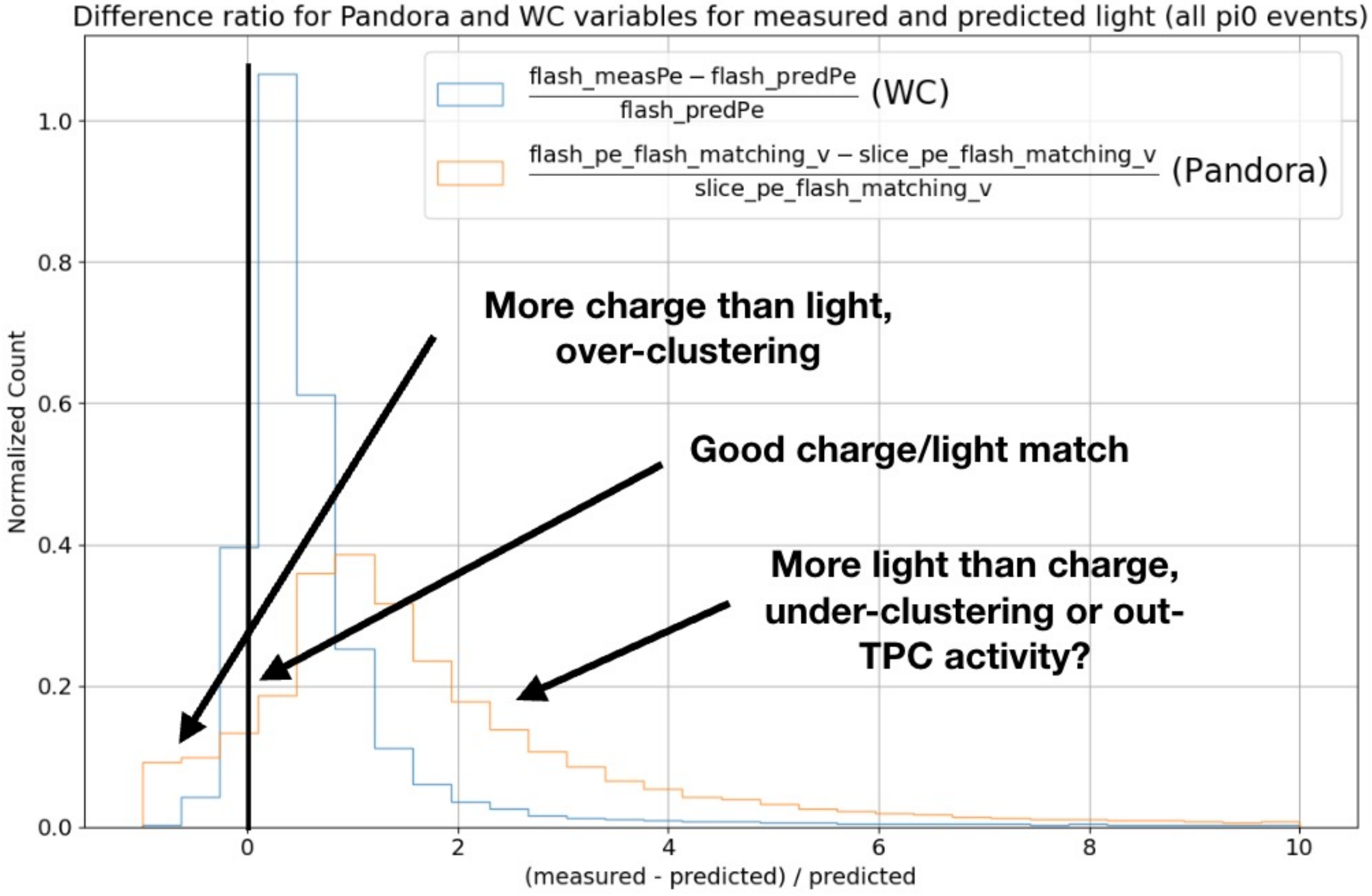
Difference Between WireCell and Pandora Measured



4



Difference Between WireCell and Pandora Measured



PMTs Used for Flash-Matching

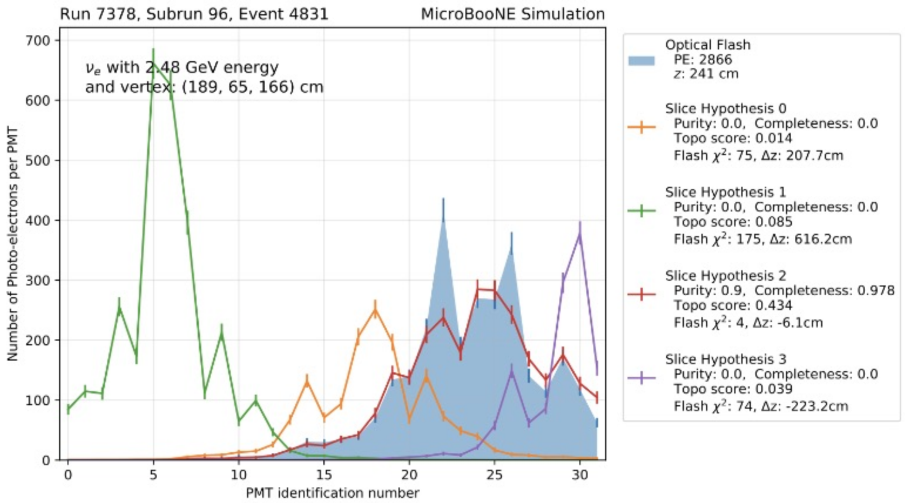


Figure 6.17: Flash-matching example for a simulated ν_e CC event with a true neutrino energy of 2.5 GeV. The reconstructed optical flash (blue) is compared to the flash hypothesis of four neutrino candidates (coloured lines). Δz is Charge z - Flash z. Slice 2 (red) has the lowest χ^2-value and is selected. Note that the selected slice also is the closest to the flash – smallest $|\Delta z|$ and has the highest topological score. The purity and completeness serve as a truth-level based indication of the reconstruction quality as introduced in Section 6.2.2. The horizontal axis shows the PMT number.

Wouter Van De Pontseele thesis:
https://ora.ox.ac.uk/objects/uuid:3a626a2c-fe7a-4a13-9f80-0fc090d6913a