EM Showers

Ed Tyley, Dom Brailsford, David Caratelli, Andrzej Szelc

Introduction

1. A short intro to LArTPCs - how they work, and which ones we're talking about
2. Particle Interactions with matter - what do we expect when photons and electrons interact in argon?
3. Electron Photon/separation - methods of telling one from the other
4. Validation with other samples: Pi-naughts/Michels?
5. Thoughts on what reconstruction can or cannot do.
6. Thoughts on future.

LArTPCs
(we're interested in)

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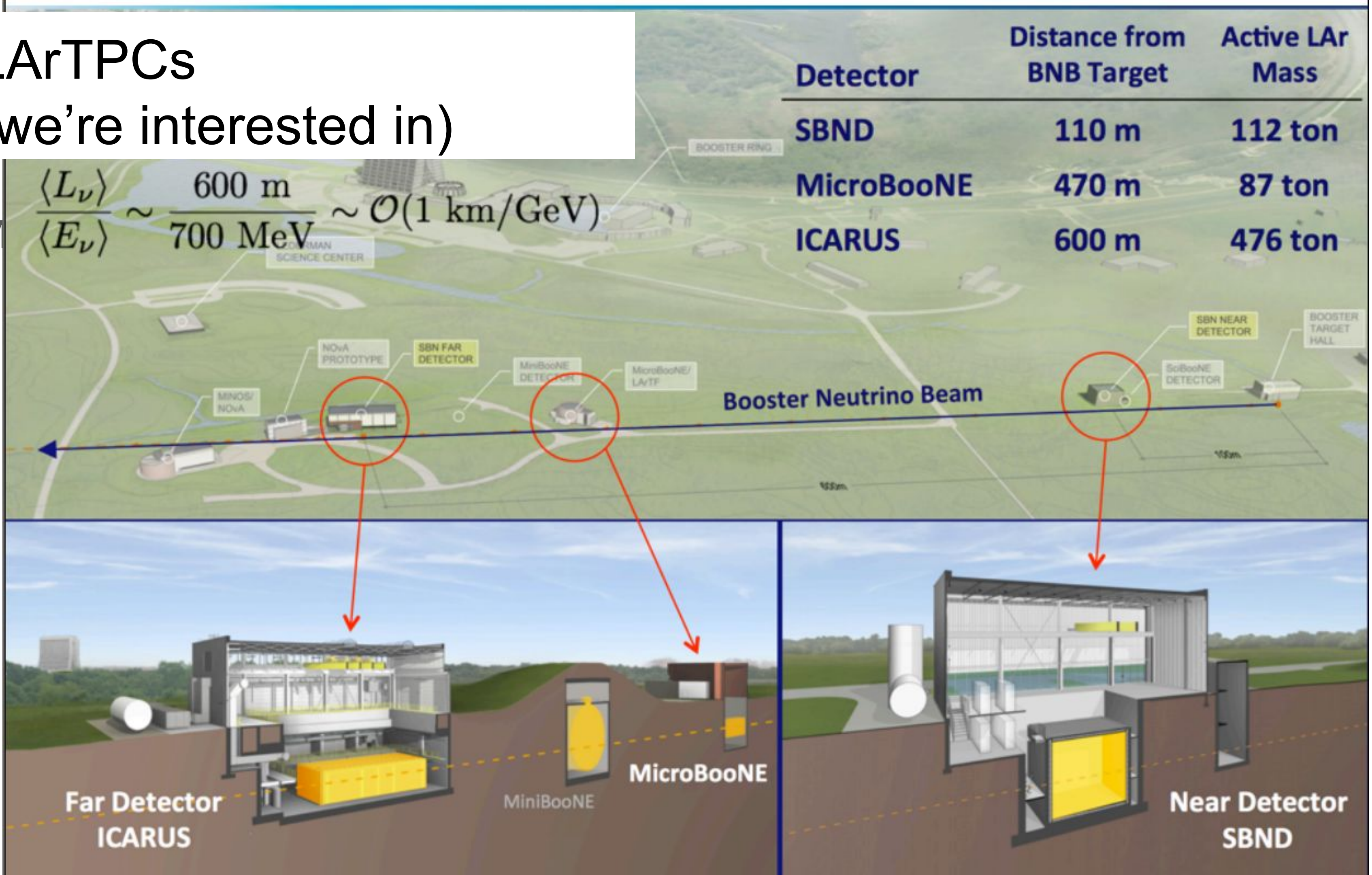

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

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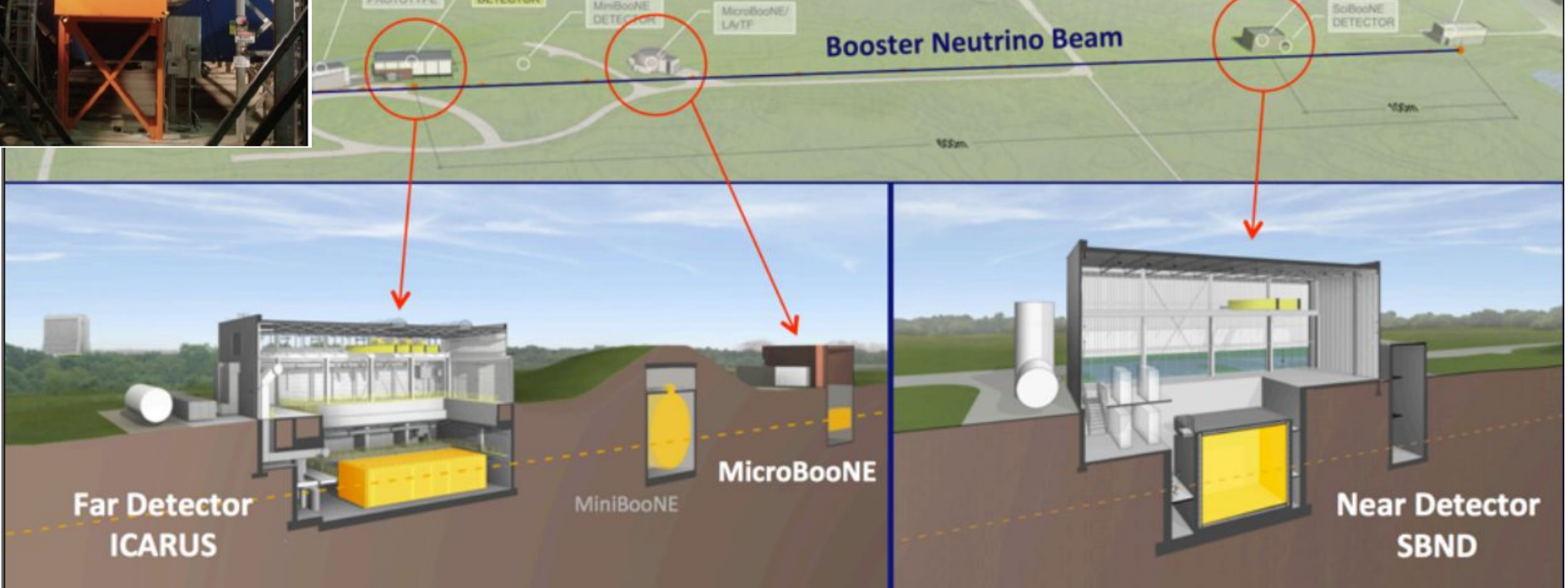
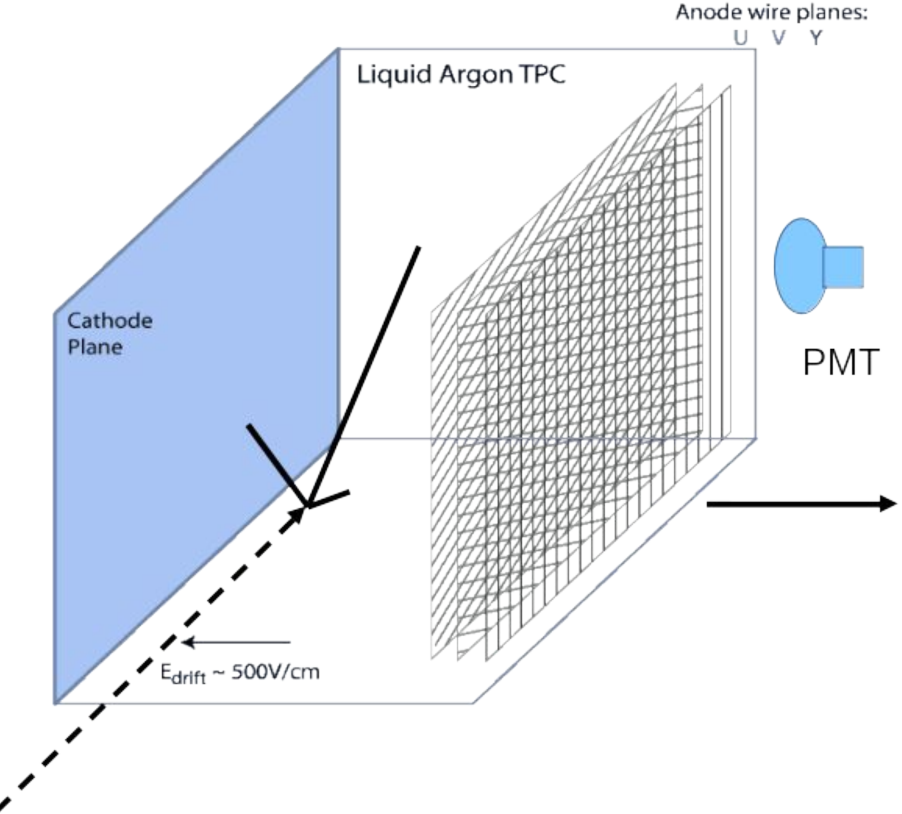
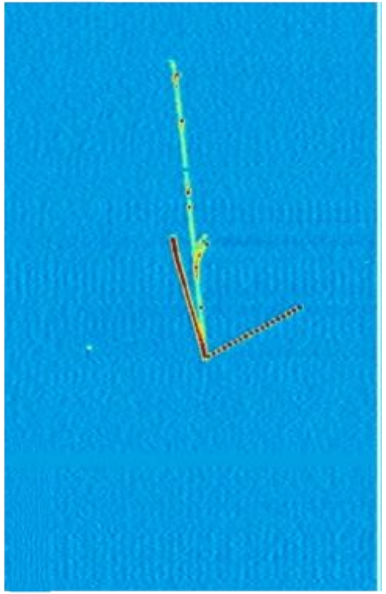
$\sim \mathcal{O}(1\ \mathrm{km/GeV})$



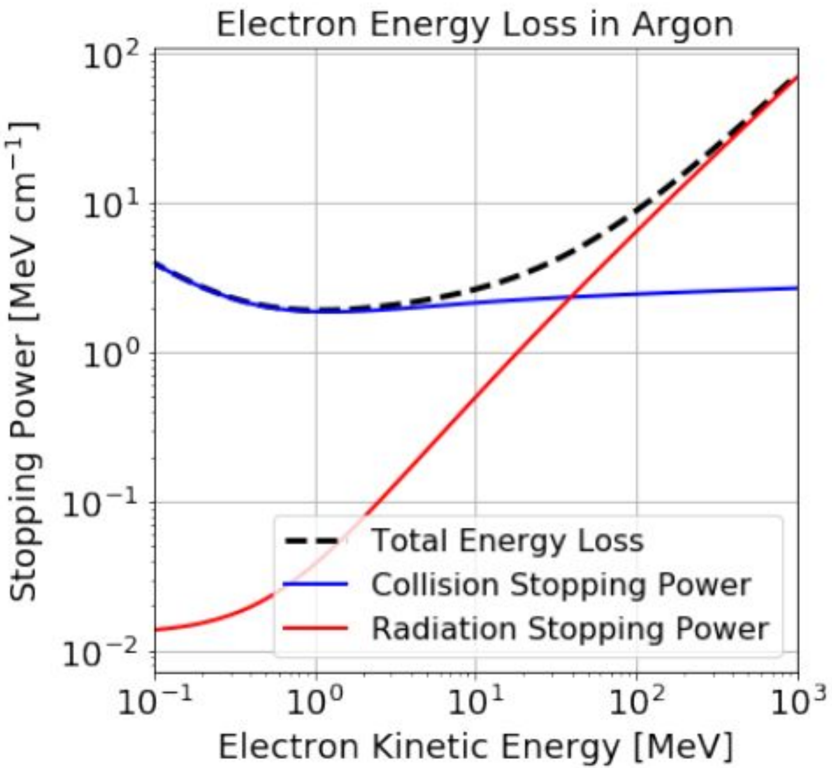
LArTPC operation

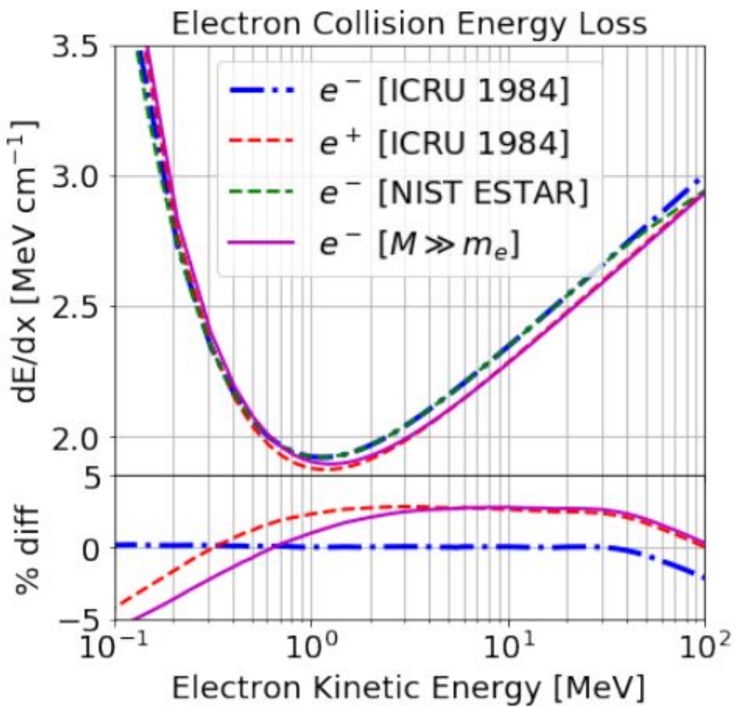




- Charged particles ionise LAr
- Ionised electrons drift to instrumented anode
- Signal from electrons induced/collected on wires at anode

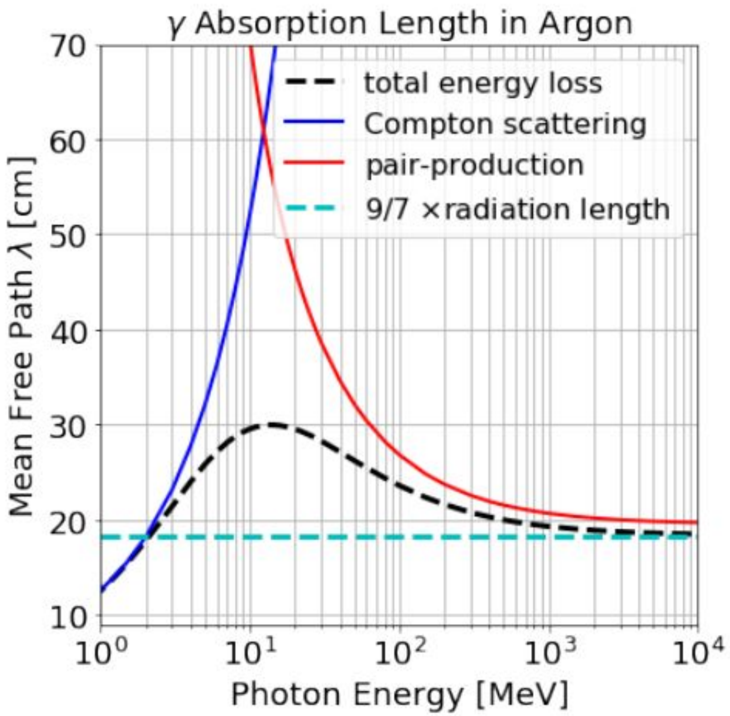
Particle Interactions with Matter (electrons)

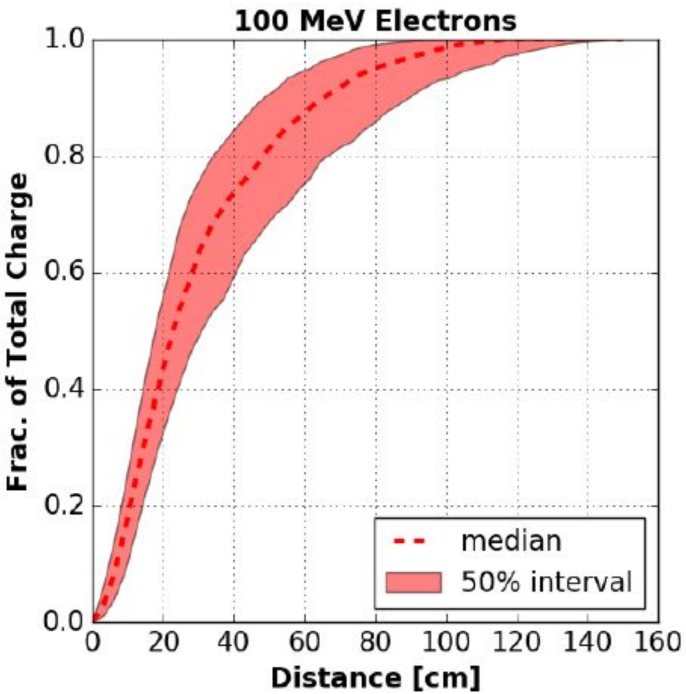




plots from *JINST* 15 (2020) 02, P02007 1910.02166 hep-ex]

Particle Interactions with Matter (photons)

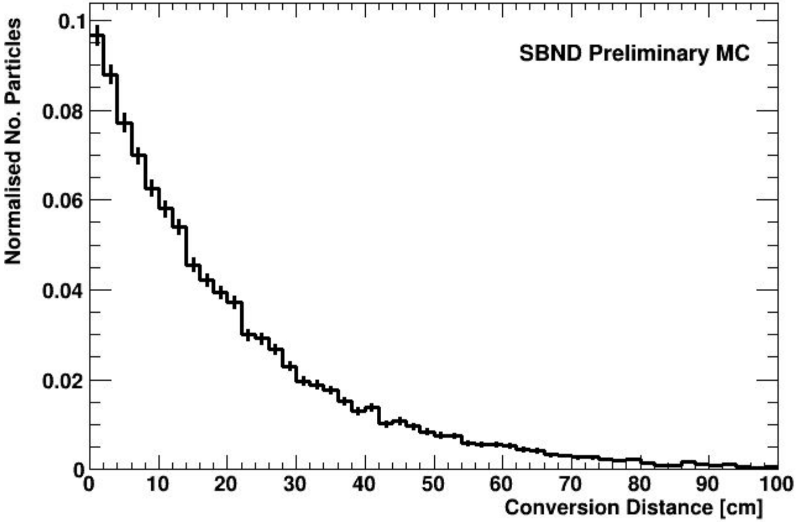


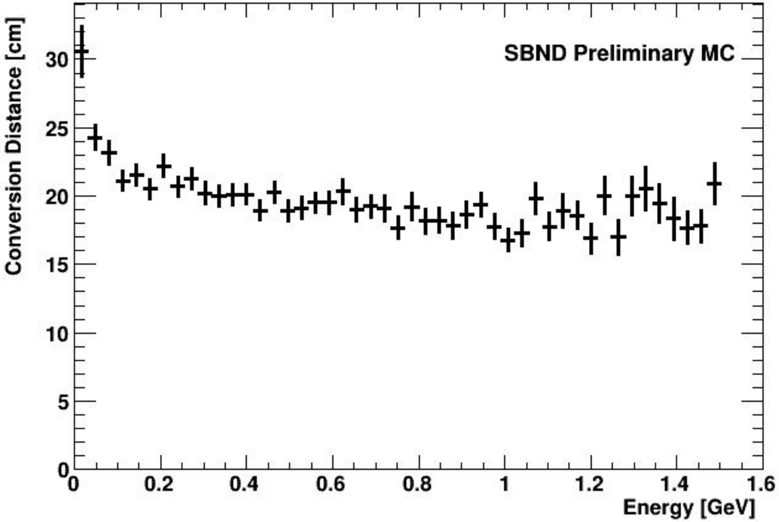


plots from *JINST* 15 (2020) 02, P02007 1910.02166 hep-ex]

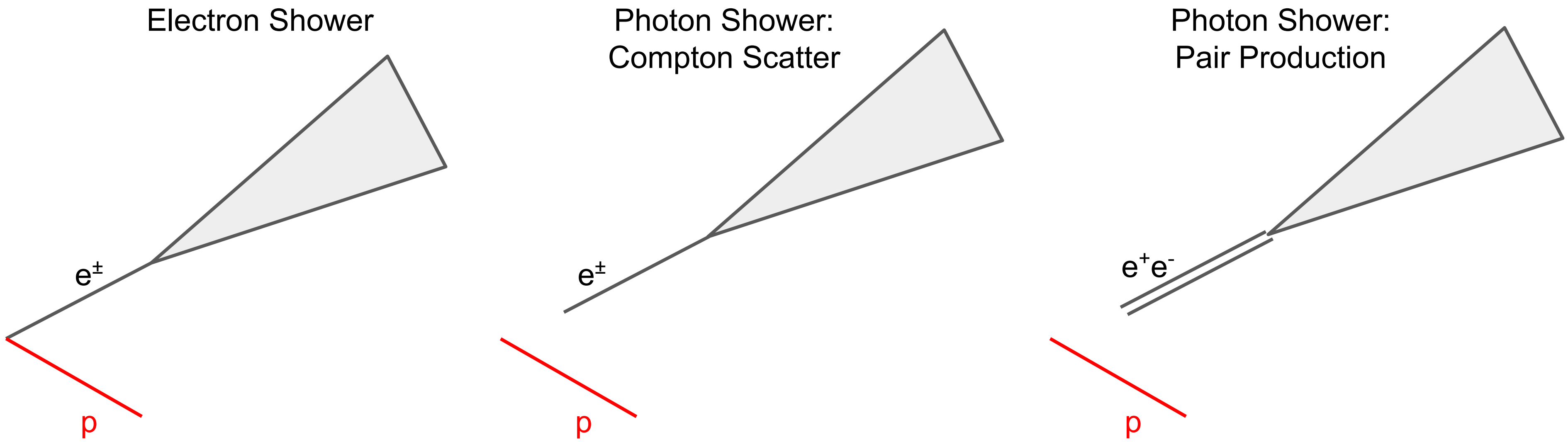
Electron-Photon Separation in Truth: Conversion Gaps

Gap between photon creation and showering follows expected exponential distribution (Radiation length 14.1 cm) which can be used to differentiate them from electrons





What that means in our EM Shower searches



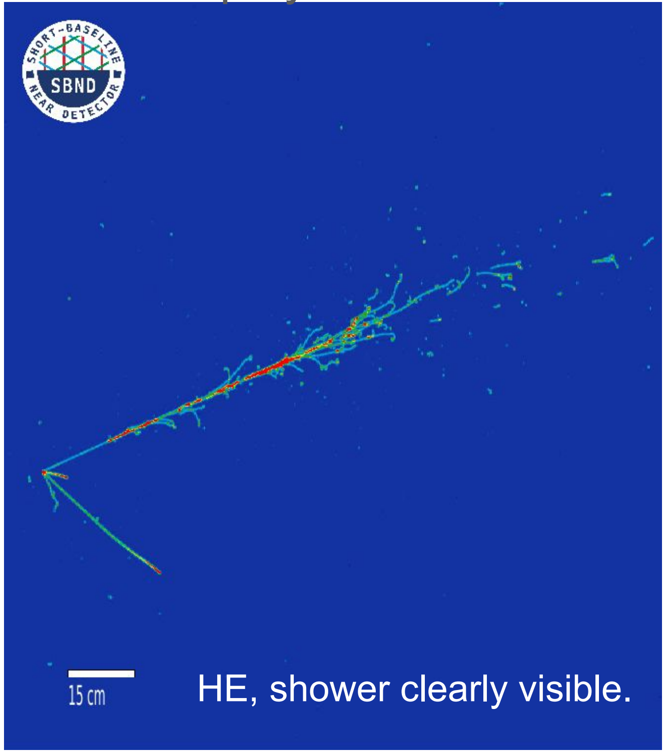
Charged particle track (proton or pion) - not always there

Track
(not always there)

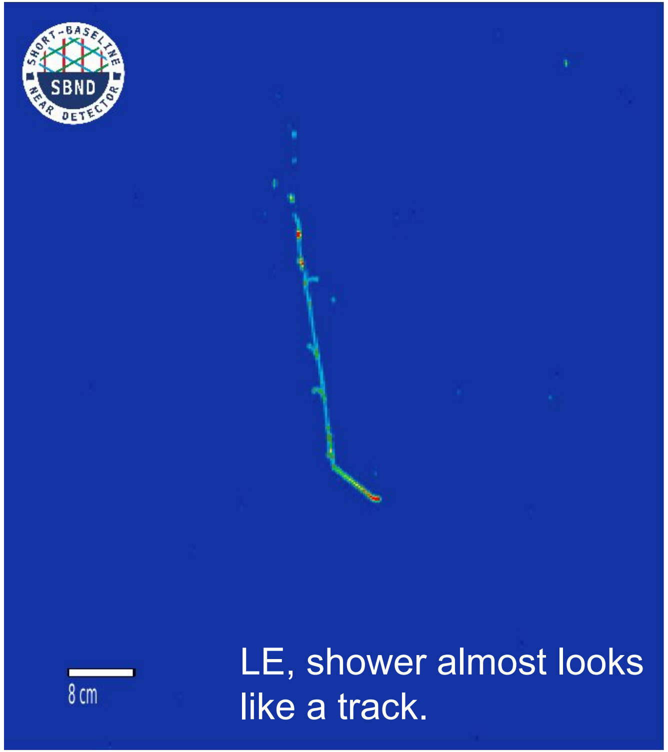
Track
(not always there)

Reality of low energy showers

Event displays of HE and LE showers



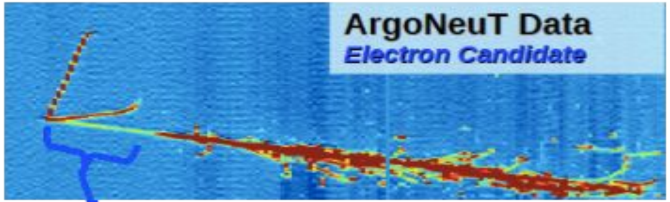
HE, shower clearly visible.

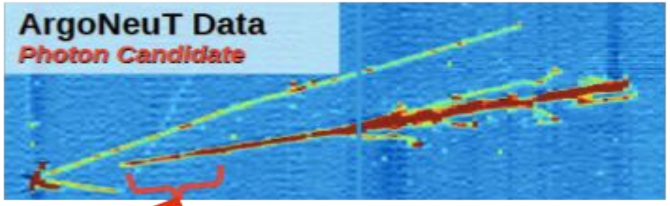


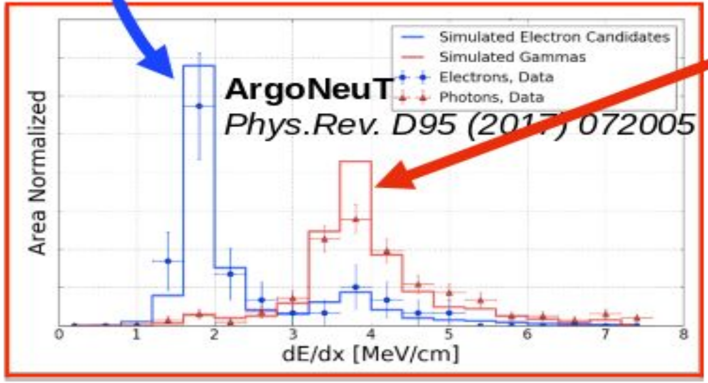
LE, shower almost looks like a track.

dE/dx and gap as shower discrimination

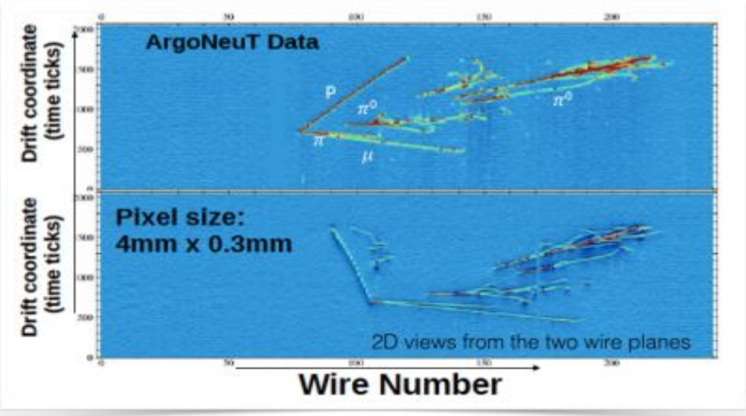
Electron / photon separation







Double handle:
topology and dE/dx



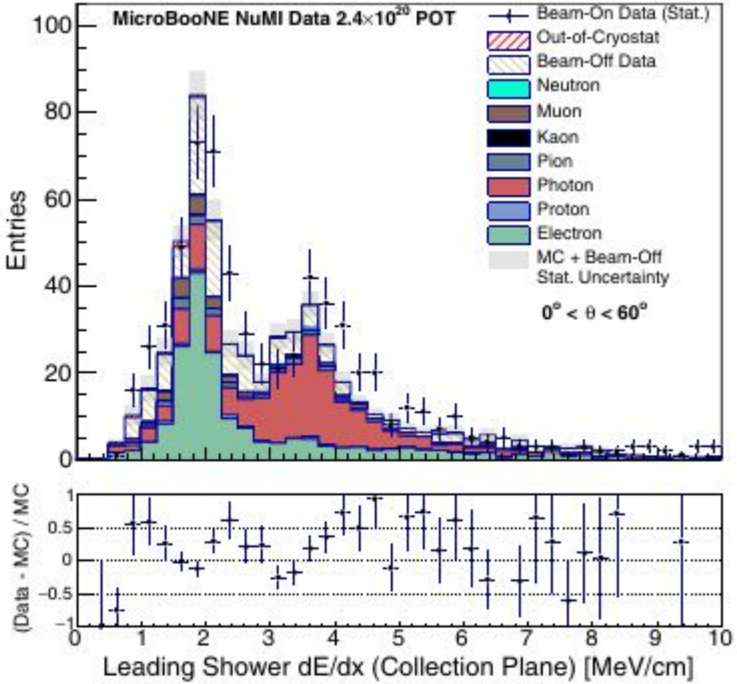
The LArTPC is an excellent tool for electron/photon separation

dE/dx + gap continued

Fully automated reconstruction

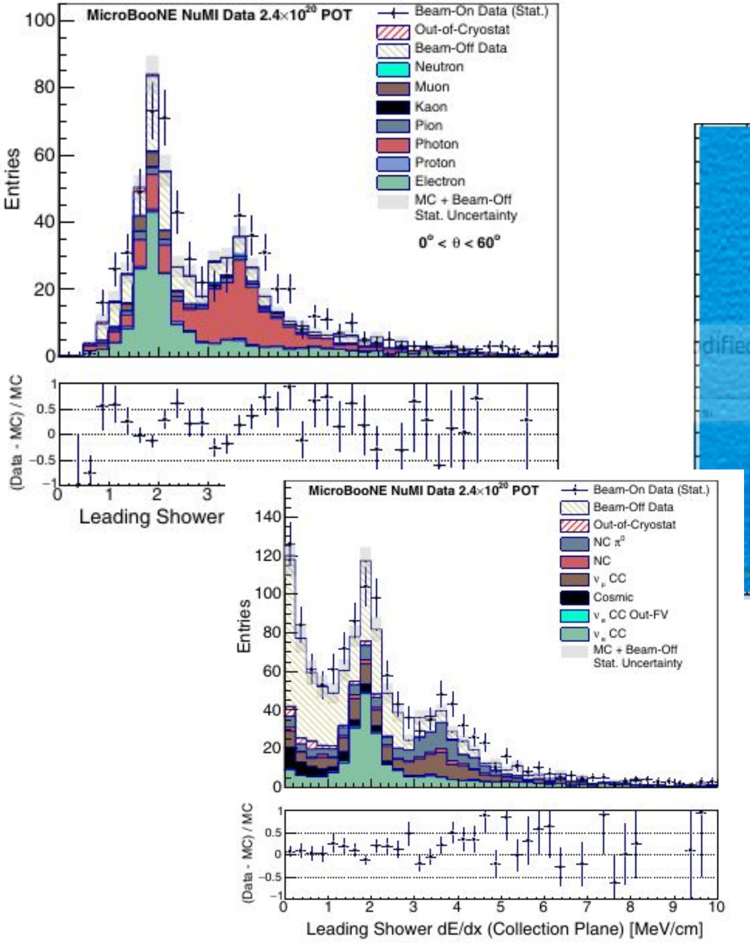
dE/dx seems more powerful than gap

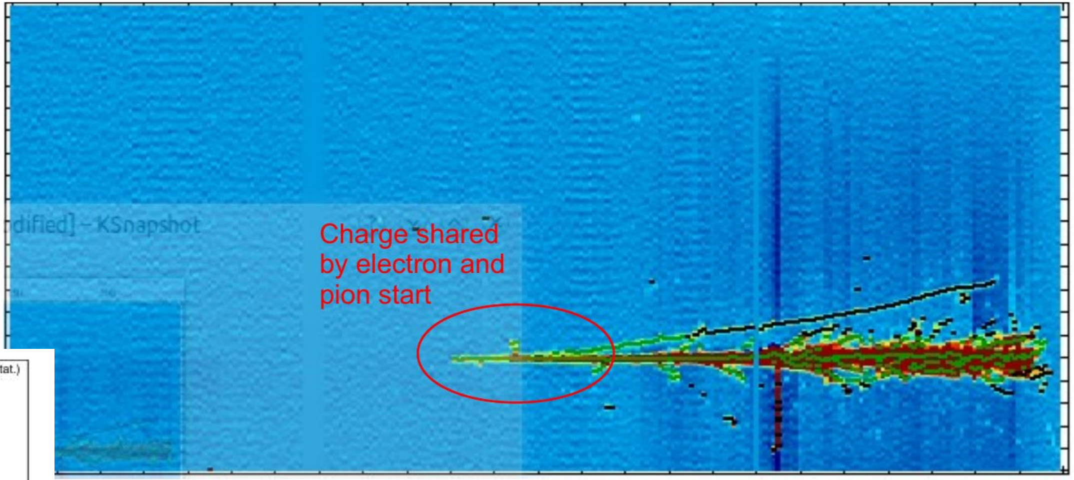
New reconstruction available.



Selection stage	Electrons	Photons	Other
EM shower selection	951	771	273
dE/dx (only)	65%	27%	52%
Shower-vertex distance (only)	89%	72%	73%
Combined	59%	19%	39%
Shower-vertex distance (Only, ≥1 track)	89%	53%	64%

How things can go wrong (vertex activity, DIC)

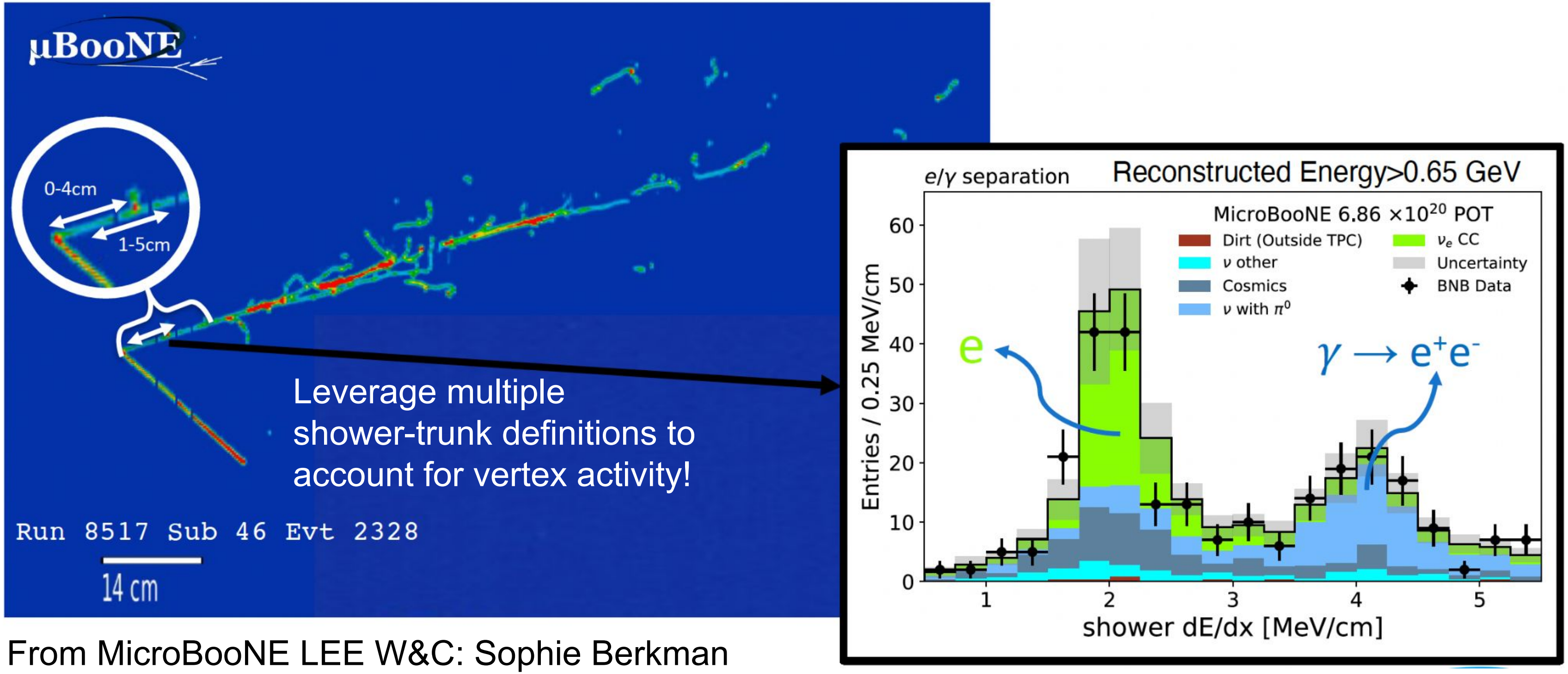




ArgoNeuT event reconstructed as double MIP.

dE/dx: Recent MicroBooNE LEE Results

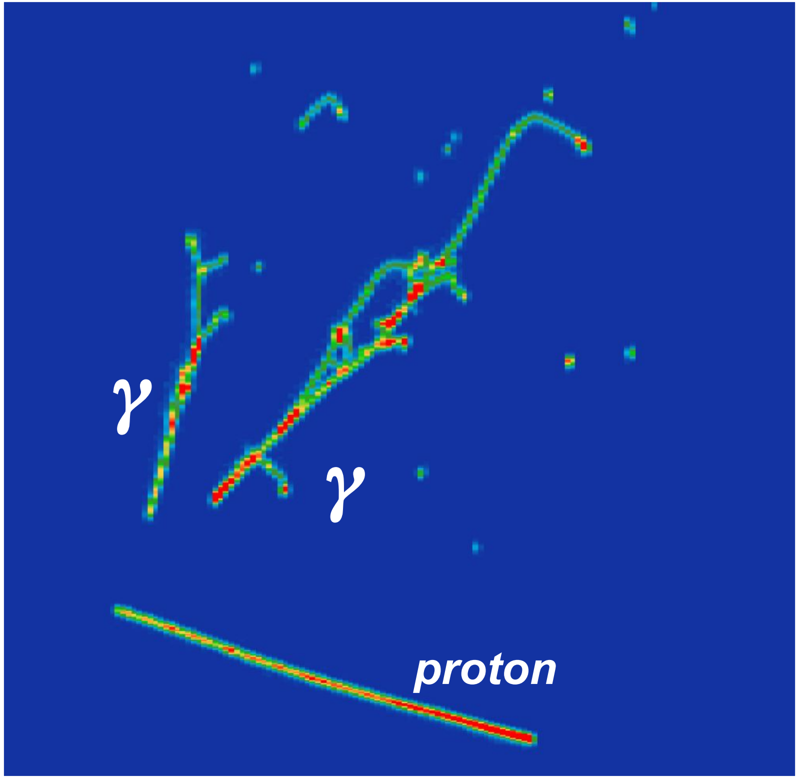
Energy deposited per length (dE/dx) at start of shower



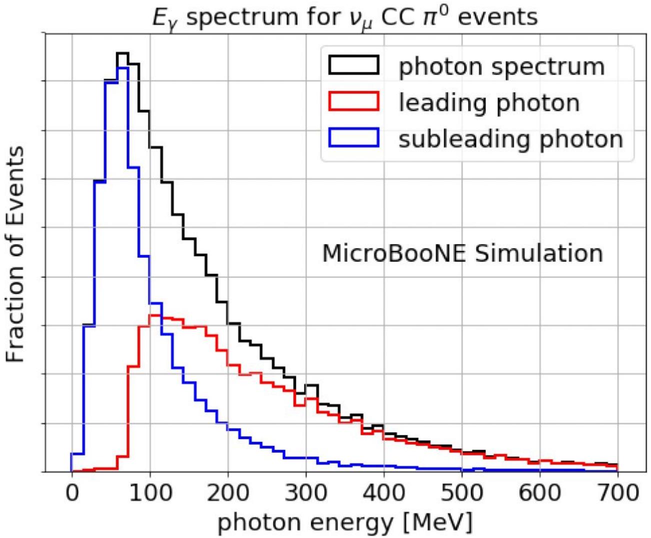
From MicroBooNE LEE W&C: Sophie Berkman

Pi^0 and Photon reconstruction examples

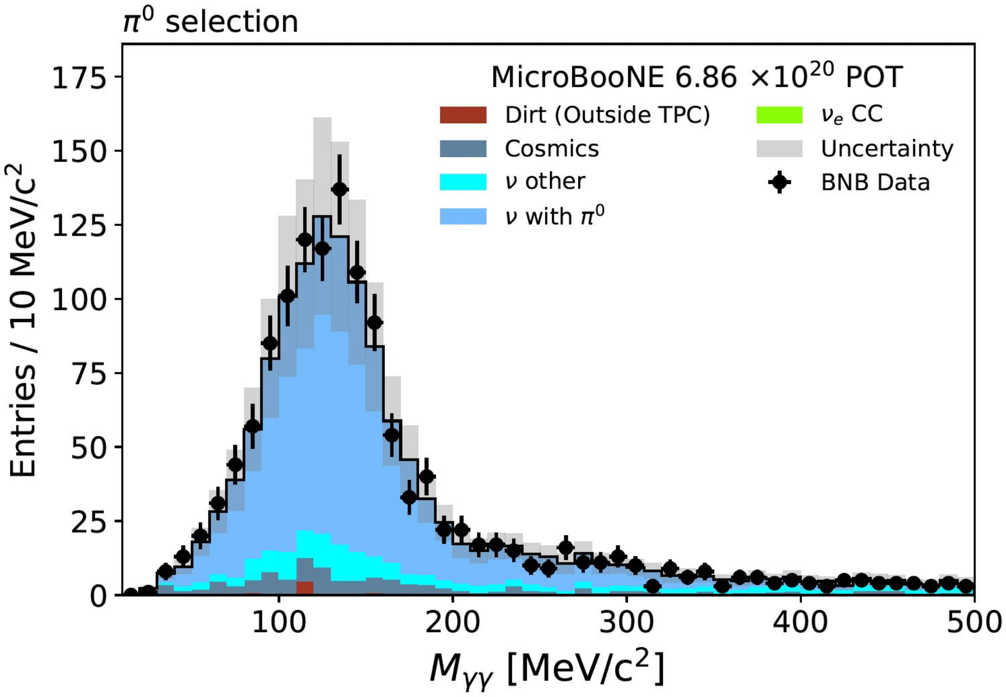
π^0s: What They Look Like



- Two photons, though sometimes not both easy to find.
- Detached from neutrino interaction point
- In BNB O(50-300) MeV photons.



π^0 Reconstruction - Status



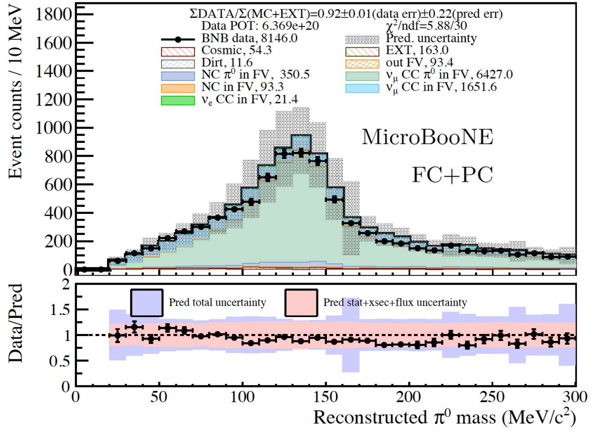
Search for an anomalous excess of charged-current ve\nu_eve interactions without pions in the final state with the MicroBooNE experiment [2110.14065 hep-ex]

Come a long way in automated EM shower reconstruction…

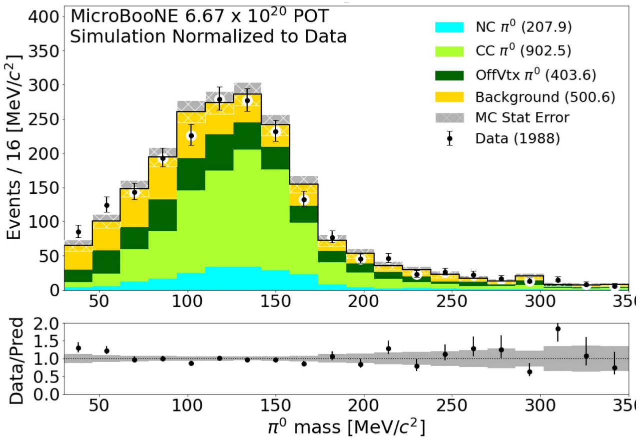
- Few degree angular resolution
- 10-20% energy resolution.

Energy reconstruction in particular still largely driven by reconstruction inefficiencies.

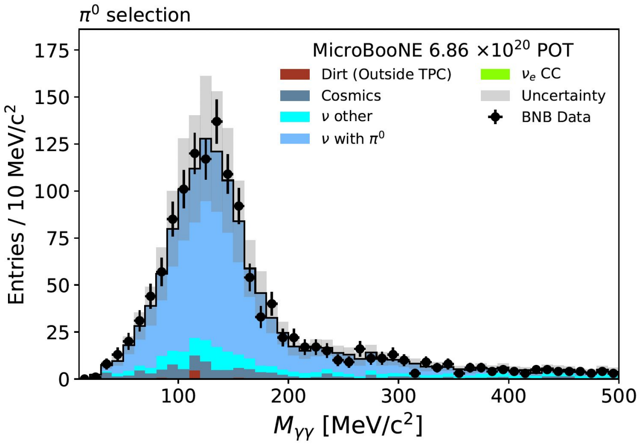
π^0 Reconstruction - Status



MicroBooNE, Wire-Cell 2110.13978 [hep-ex]



MicroBooNE, Deep Learning [2110.11874 hep-ex]



MicroBooNE, Pandora 2110.14080 [hep-ex]

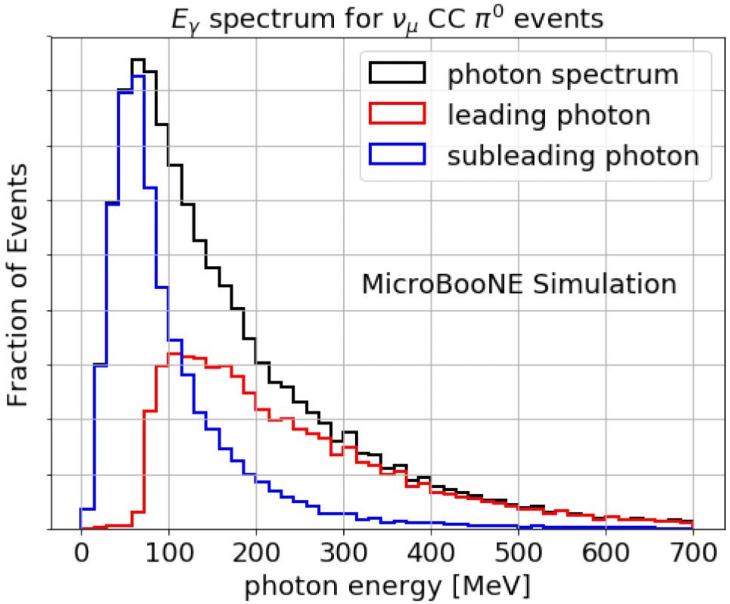
Multiple reconstruction paradigms leveraging different techniques and tools.

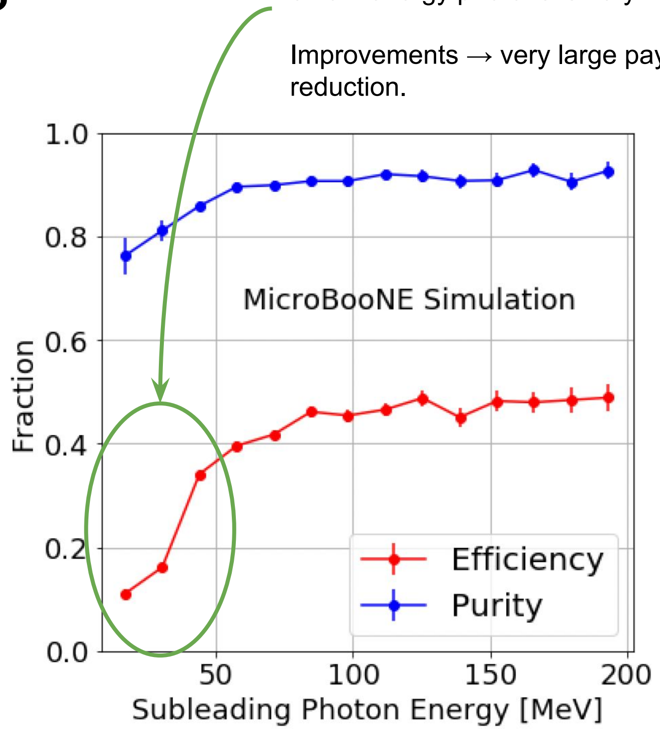
Examples here are from MicroBooNE LEE analyses, building on EM shower (and π^0 in particular) reconstruction development in ICARUS & ArgoNeuT

π^0 Reconstruction - Limitations

Qualitatively same picture for all reconstruction paradigms: upturn in efficiency where still BNB flux of low-energy photons is very high!

Improvements → very large payoff in BSM mis-ID reduction.





Reconstruction and Measurement of O(100) MeV Energy Electromagnetic Activity from $\pi^0 \to \gamma\gamma$ Decays in the MicroBooNE LArTPC [*JINST* 15 (2020) 02, P02007 1910.02166 hep-ex]

Things that can affect our reconstruction

- Recombination
- Lifetime/impurities while drifting
- Diffusion while drifting
- Dynamically Induced Charge
- Vertexing
- Collecting all of the charge

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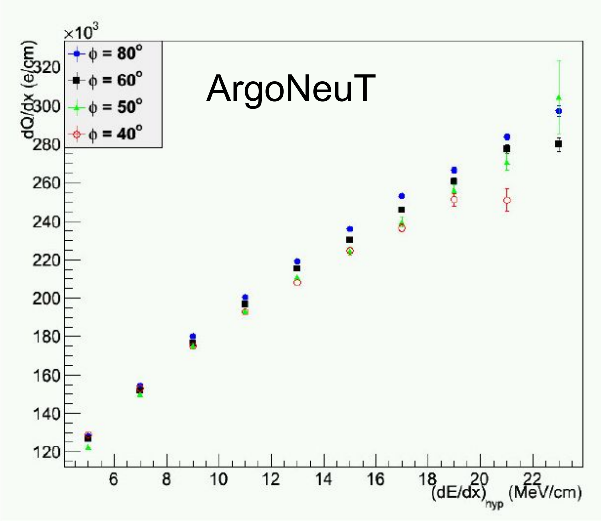

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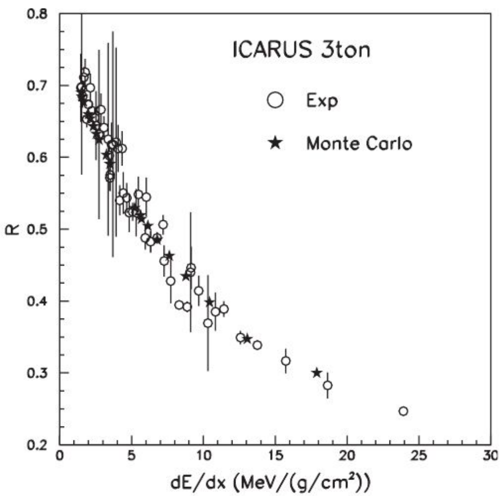
Ion recombination drives energy → charge conversion. dE/dx and E-field dependent.

While dE/dx for showers does not vary too much (unlike e.g. protons), E-field corrections can become important.

Typically accounted for with “effective” correction based on simulation.



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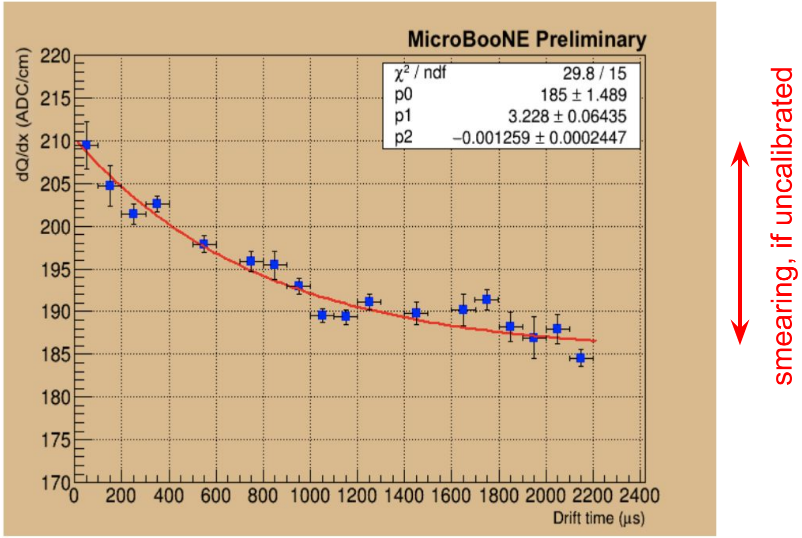

MICROBOONE-NOTE-1026-PUB

- Uncalibrated, leads to a position-dependent variation in energy response.
- Large impurity concentration → higher effective thresholds further away from TPC wires.
- Similar story for Space-Charge effects.

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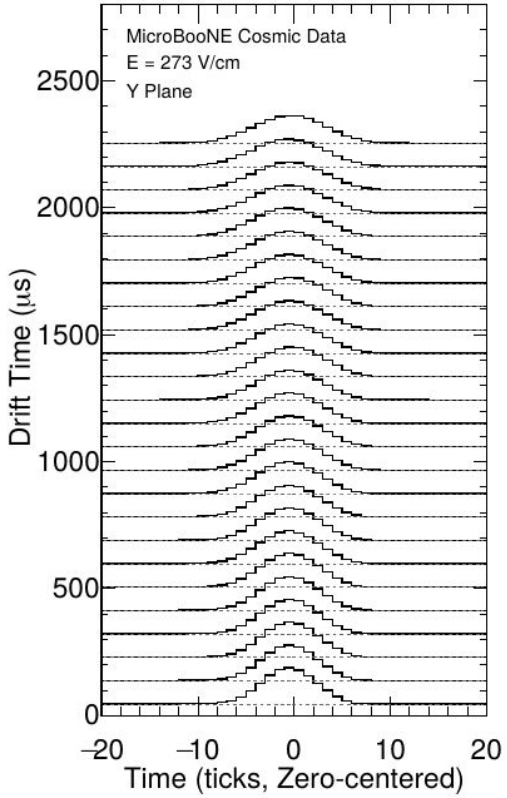
Diffusion changes the shape of pulses on wires.

More diffusion → wider, less peaked pulses.

Impacts pattern-recognition, hit-threshold, and consequently EM-shower identification and energy reconstruction.



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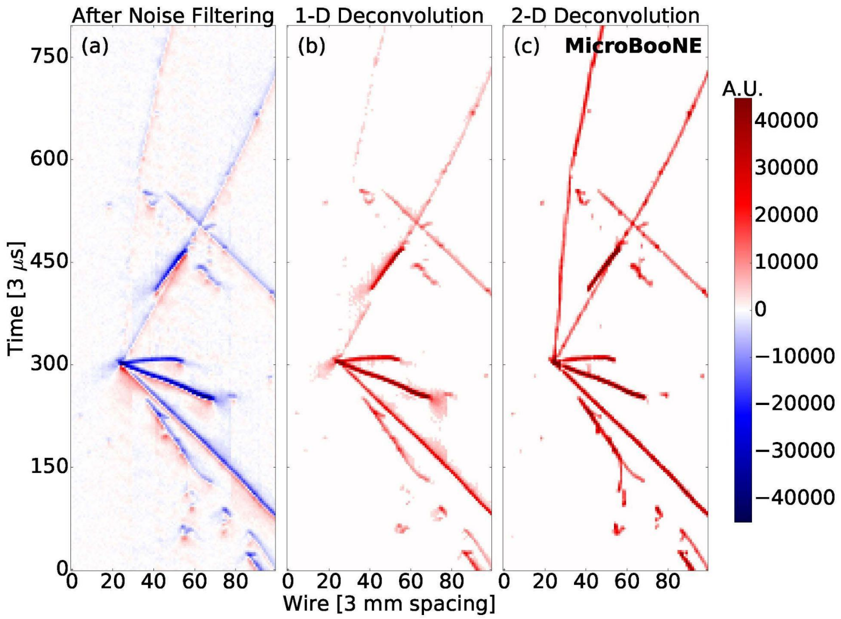
Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34

Impact of detector systematics (dominated by DIC in MicroBooNE's first ν_e xsec on NuMI
MicroBooNE, *Phys.Rev.D* 104 (2021) 5, 052002 2101.04228 [hep-ex]



MicroBooNE, *JINST* 13 (2018) 07, P07006 1802.08709 [physics.ins-det]

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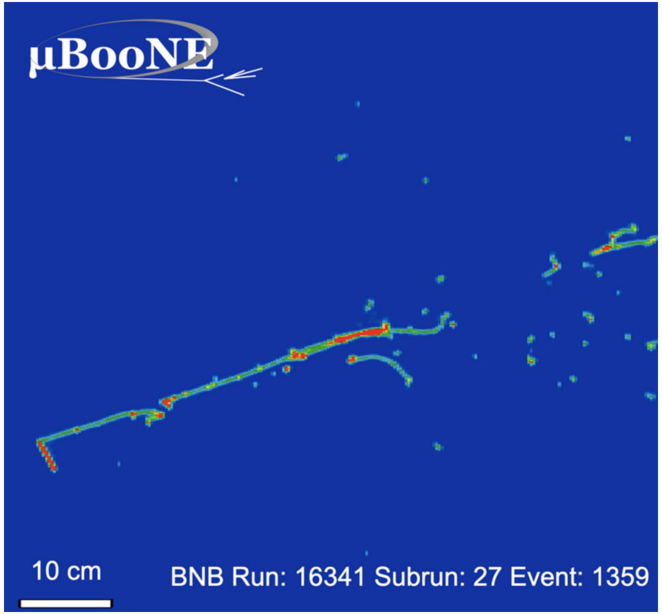
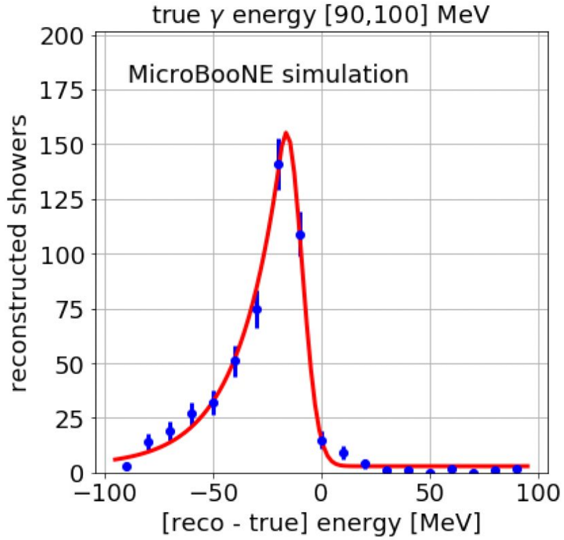


Correctly reconstructed interaction vertex and EM shower start-point are key to the primary deliverables hoped for:

- e/γ separation
- Characterization of hadronic activity
- Accurate energy reconstruction

Things that can affect our reconstruction



JINST 15 (2020) 02, P02007 1910.02166 hep-ex]

- Recombination
- Lifetime/impurities while drifting
- Diffusion while drifting
- Dynamically Induced Charge

- Collecting all of the charge
  - Multi-Gaussian fitting can perform poorly when multiple energy deposits overlap
  - Some charge is below threshold and not picked up by the hit finding
  - Some, primarily low energy, photons can travel a long distance before interacting and leave isolated energy deposits far from the main shower

Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT

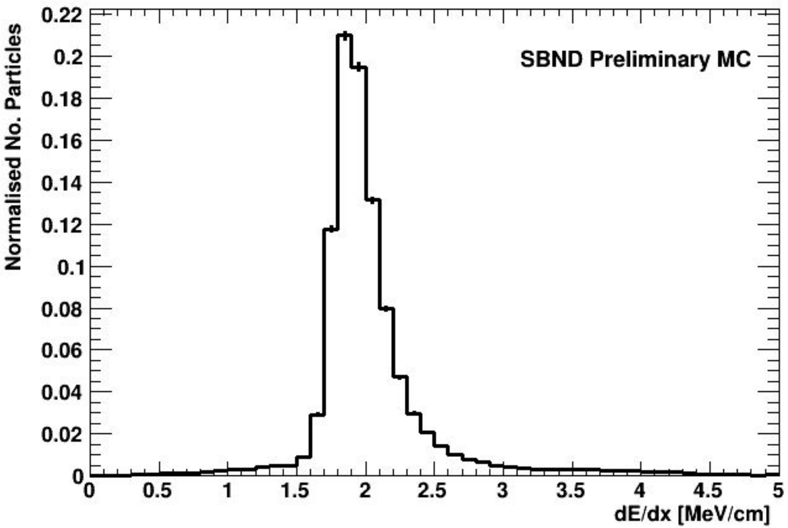
Phys. Rev. D 99, 012002 (2019), arXiv:1810.06502v1

Reconstruction in Development

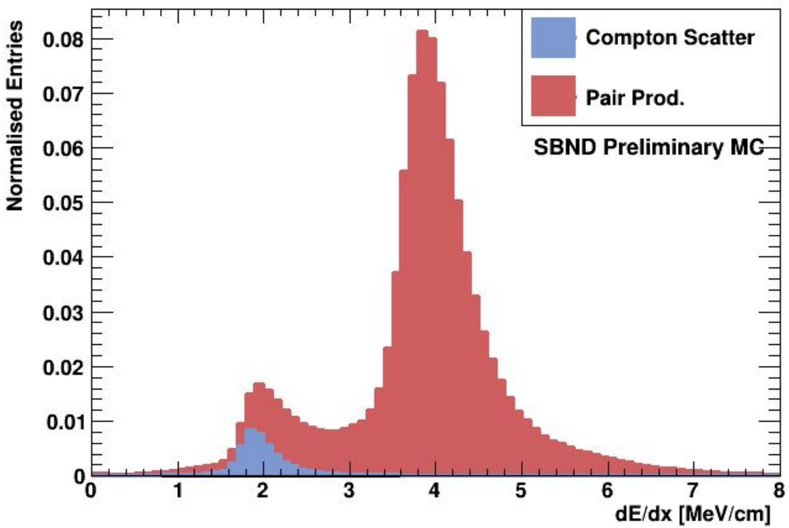
- Using truth studies to tell us where reconstruction will be limited by physics and detector construction.

Electron-Photon Separation in Truth: dE/dx

Look at the dE/dx for electrons (left) and photons (right) by calculating the median dE/dx over the wires within 3 cm of the shower start



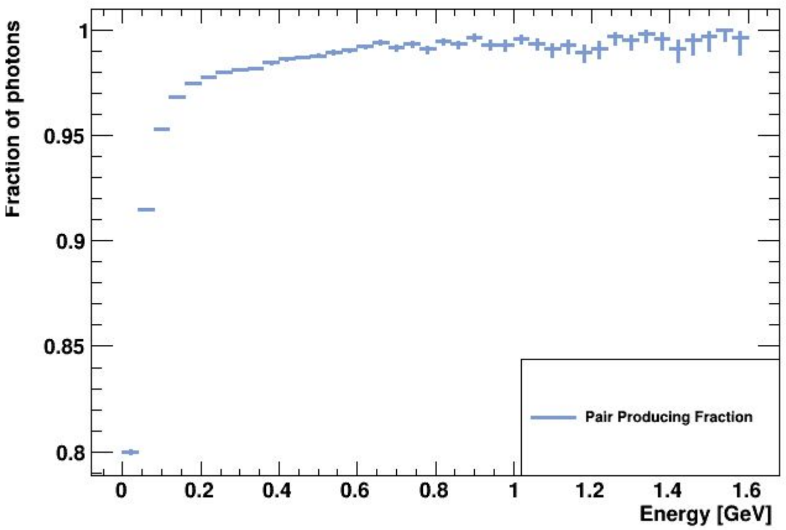
Electrons

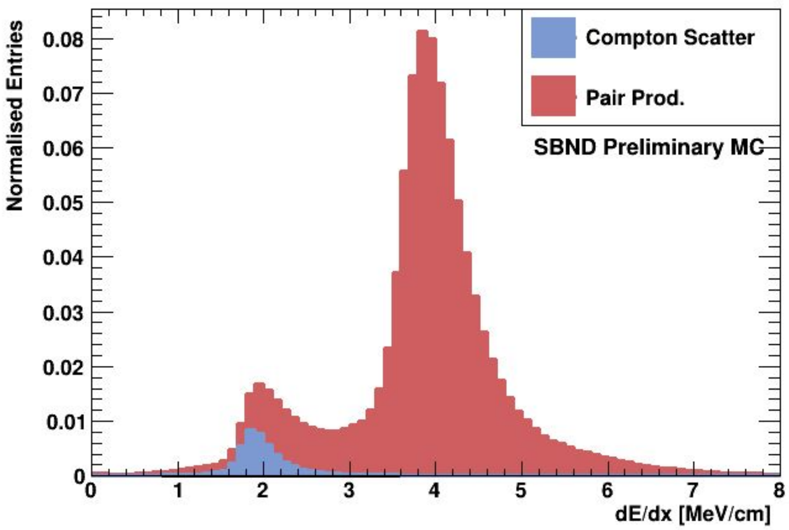


Photons

Electron-Photon Separation in Truth: dE/dx

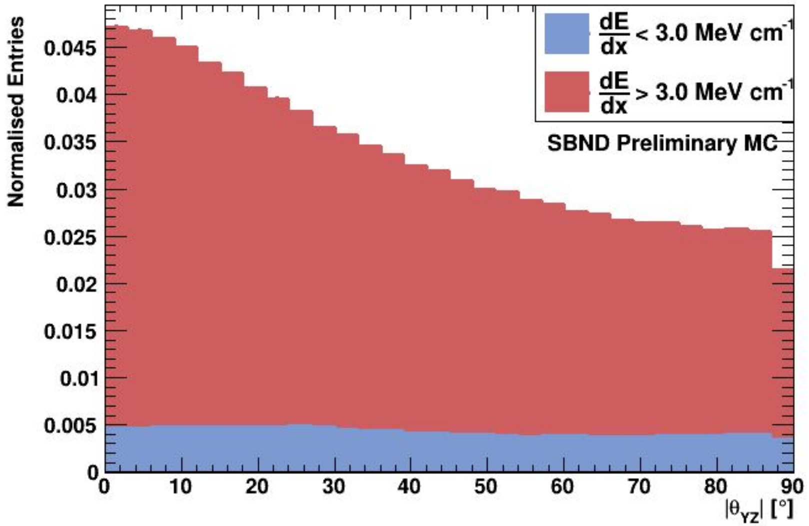
Compton scatters dominate at low energies



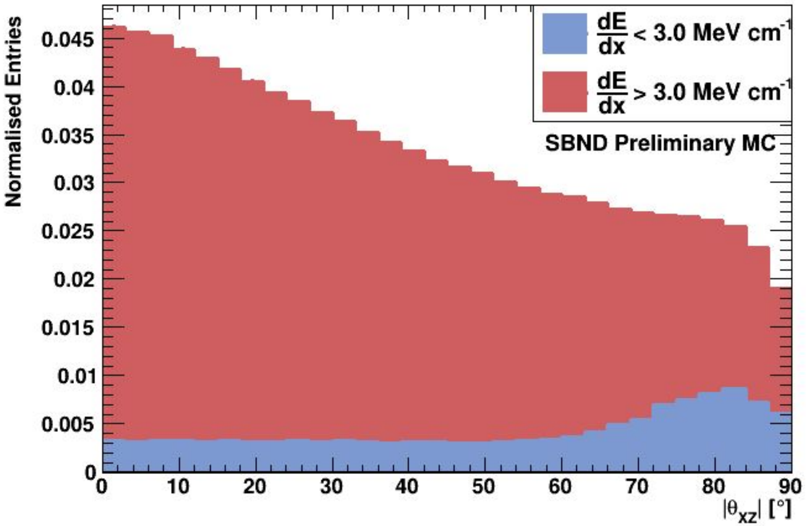


Electron-Photon Separation in Truth: Angular Dependence

Explore the fraction of single MIP pair-producing photons across detector angles:
Poor performance when particles are (almost) parallel to drift field (θ_{XZ} = 90°)



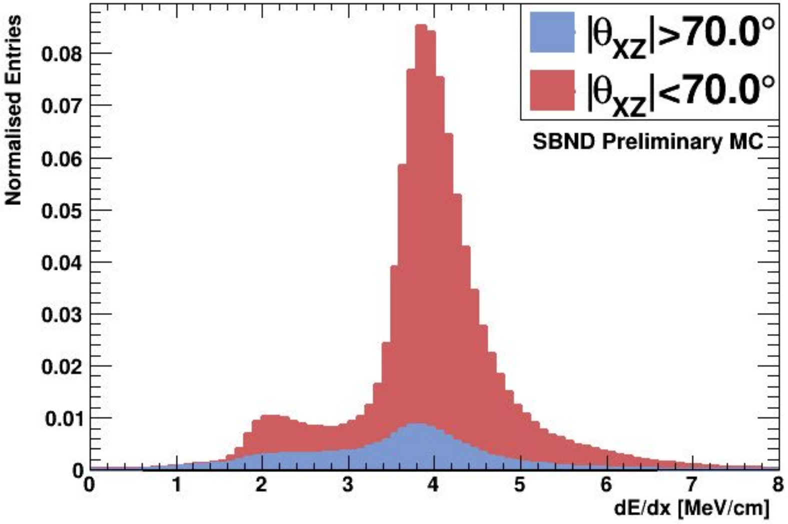
Angle WRT beam within the wire plane

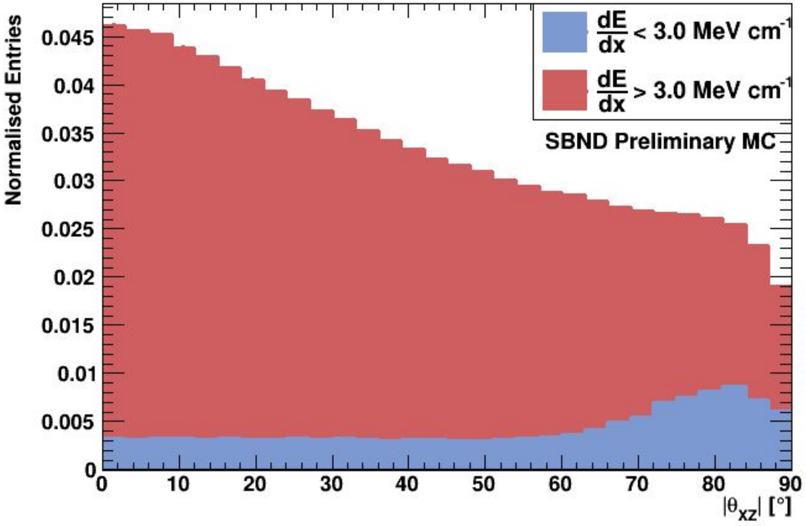


Angle WRT beam in compared to drift field

Electron-Photon Separation in Truth: Angular Dependence

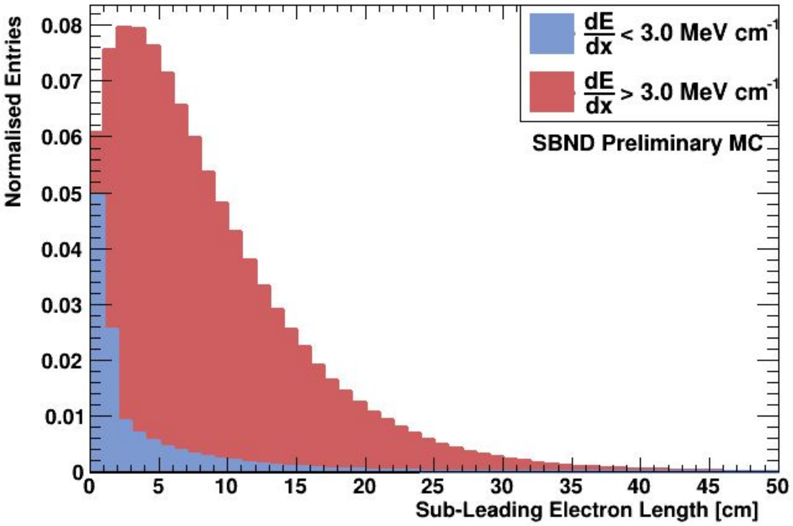
Particles (almost) parallel to drift field smear out the dE/dx distribution

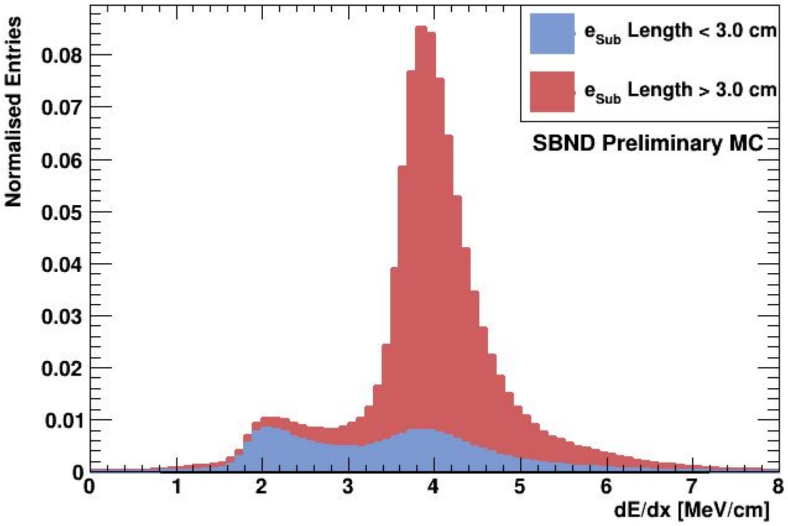




Electron-Photon Separation in Truth: Energy Dependance

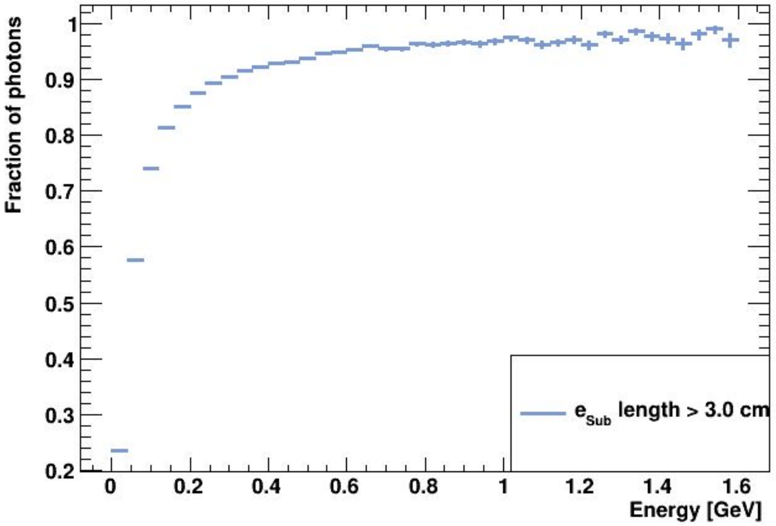
When the sub-leading election of the pair-produced is low energy it can travel < 3 cm and create a single MIP peak

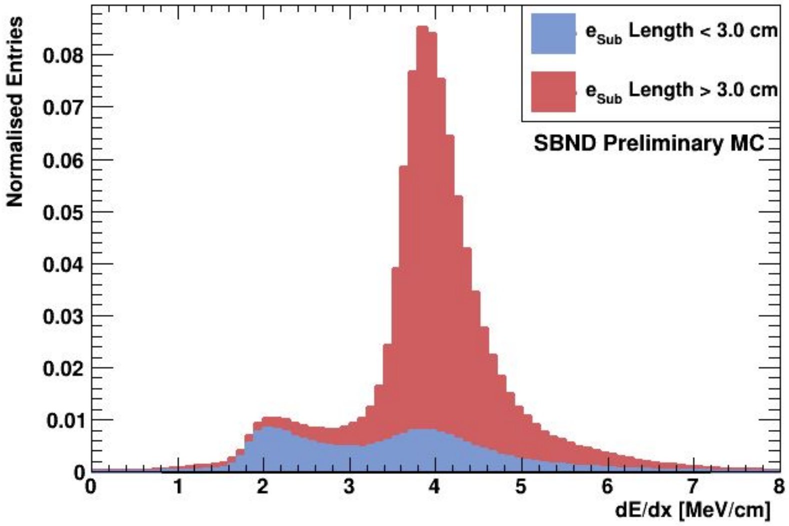




Electron-Photon Separation in Truth: Energy Dependance

This effect strongly correlates with the initial photon energy, degrading performance at low energy

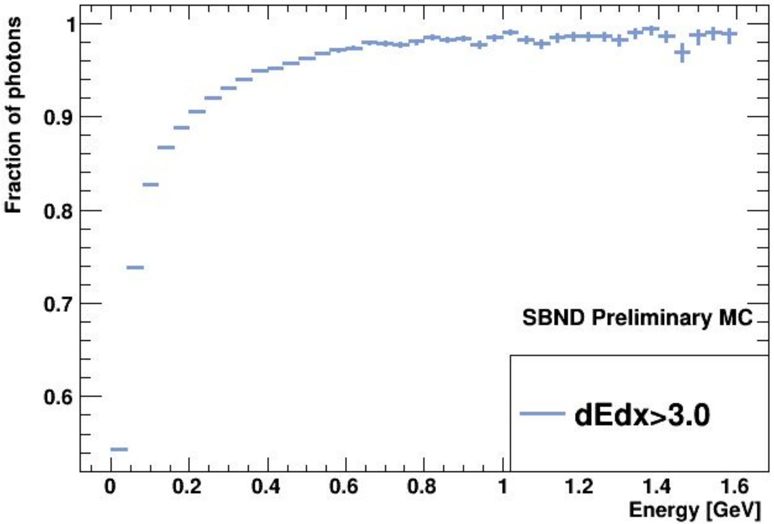


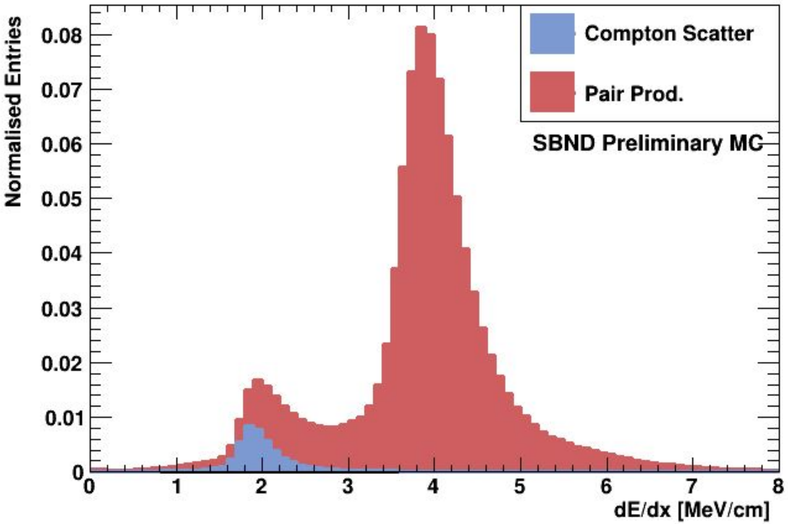


Electron-Photon Separation in Truth: Energy Dependance

The overall background rejection for photons is very dependant on energy:

Integrated over BNB energies yields 83% rejection with 95% electron acceptance



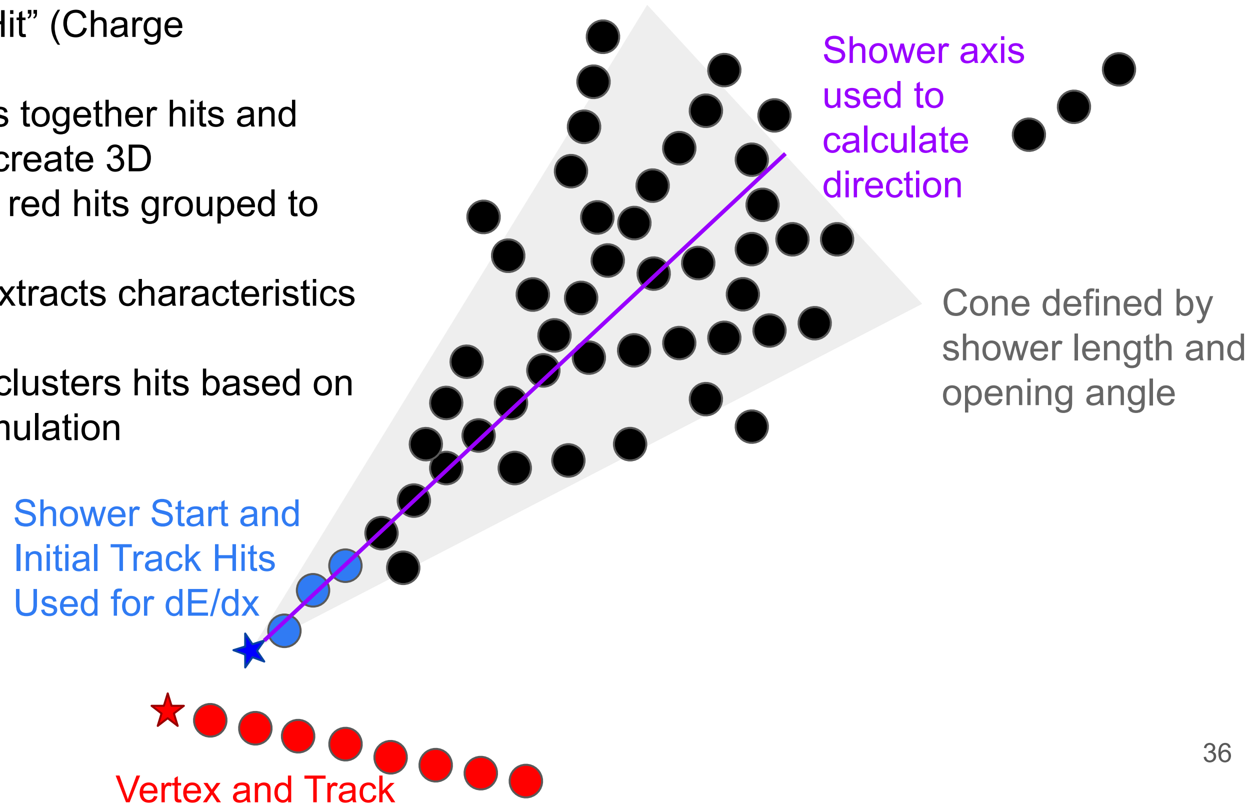


Reconstruction in Development

- Current status of SBN reconstruction

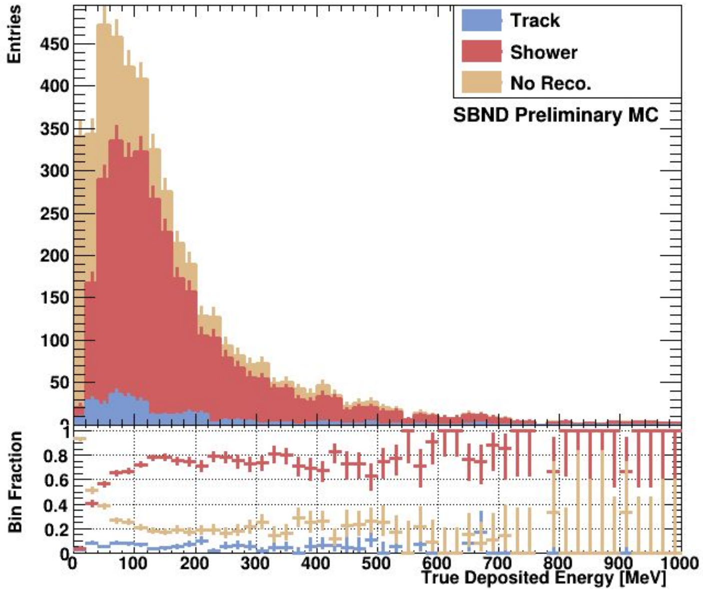
Reconstructed Shower Diagram

- Each circle represents a “Hit” (Charge deposition on a wire)
- Pattern recognition clusters together hits and matches across planes to create 3D reconstructed objects (e.g. red hits grouped to make a track)
- High level reconstruction extracts characteristics from these 3D objects
- “Cheated” Reconstruction clusters hits based on underlying Monte Carlo simulation

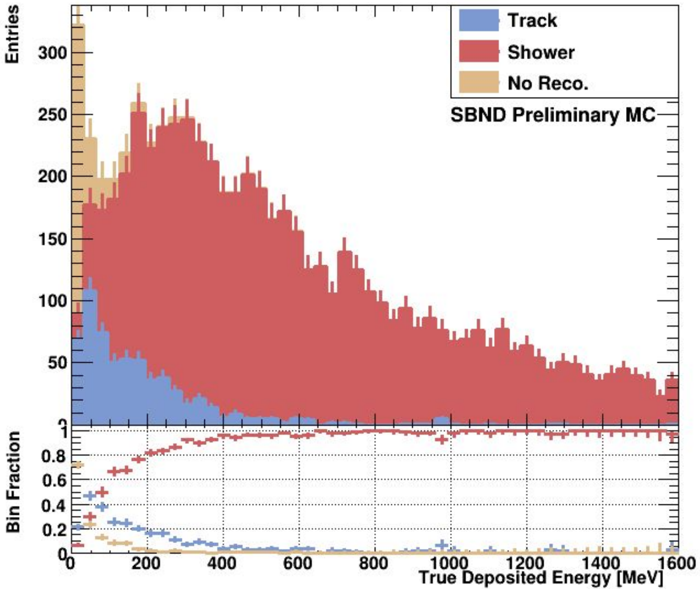


Classification Metrics

Each 3D object is classified as either a track or a shower



BNB Photons

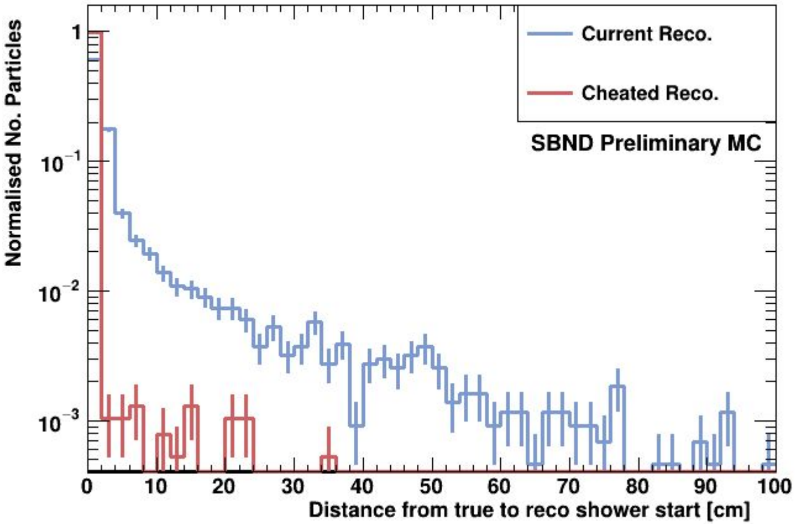


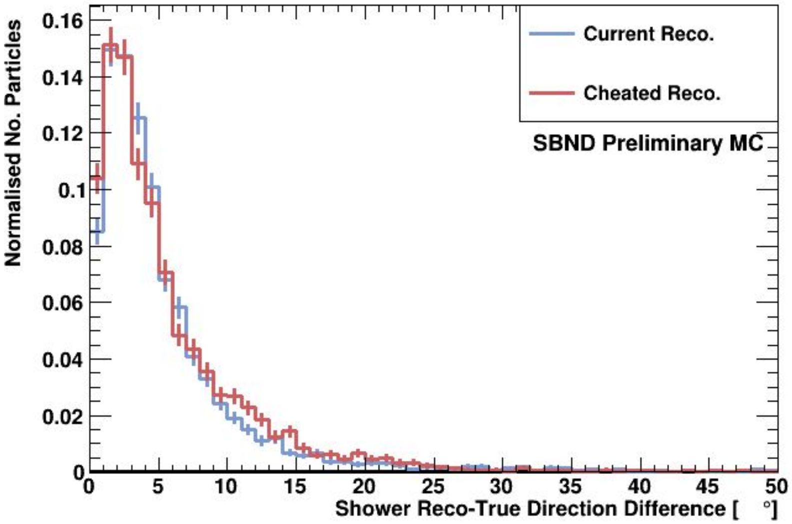
BNB Electrons

“Cheated” Reconstruction clusters hits based on underlying Monte Carlo simulation

Shower Reconstruction Topological Metrics

Compare the performance between the Current reconstruction and the cheated pattern recognition (Running the same high level reconstruction algorithms)

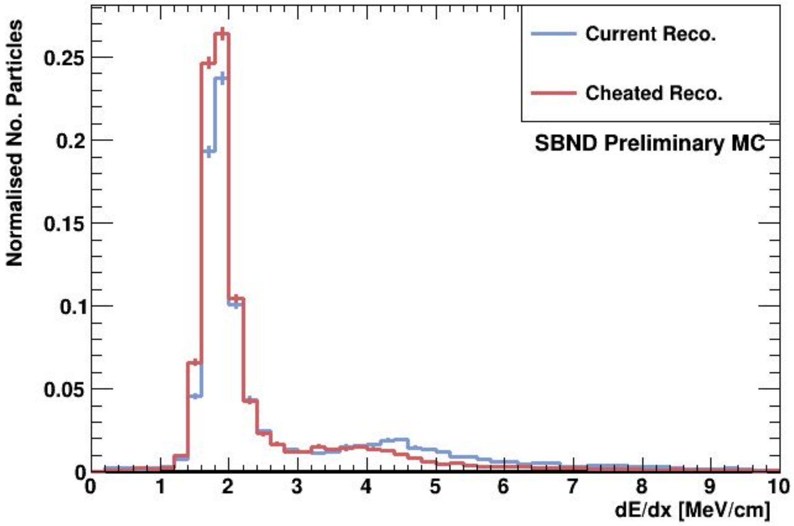




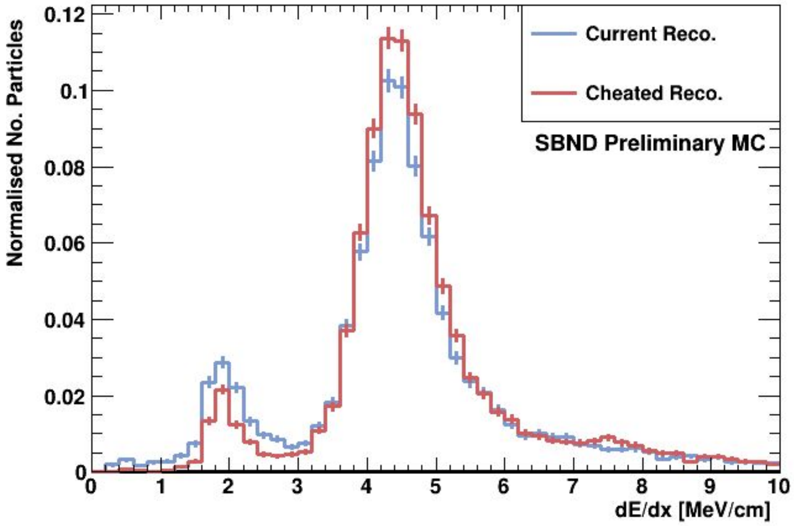
“Cheated” Reconstruction clusters hits based on underlying Monte Carlo simulation

Shower Reconstruction dE/dx

Compare the performance between the Current reconstruction and the cheated pattern recognition (Running the same high level reconstruction algorithms)



Electrons

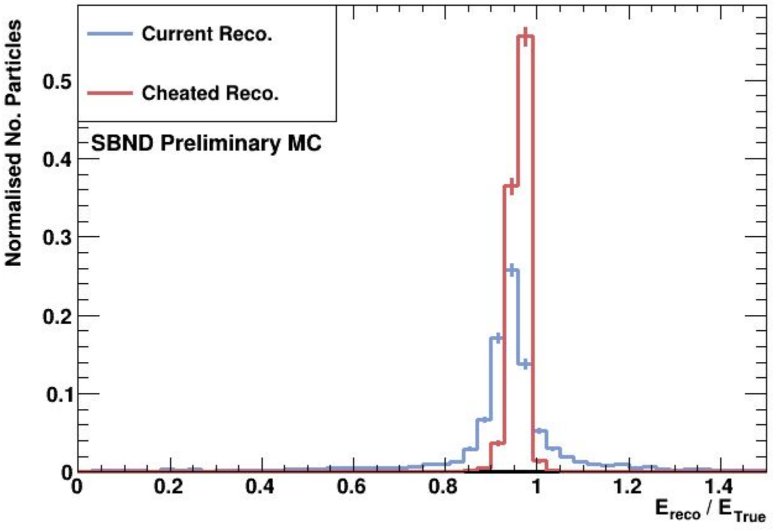


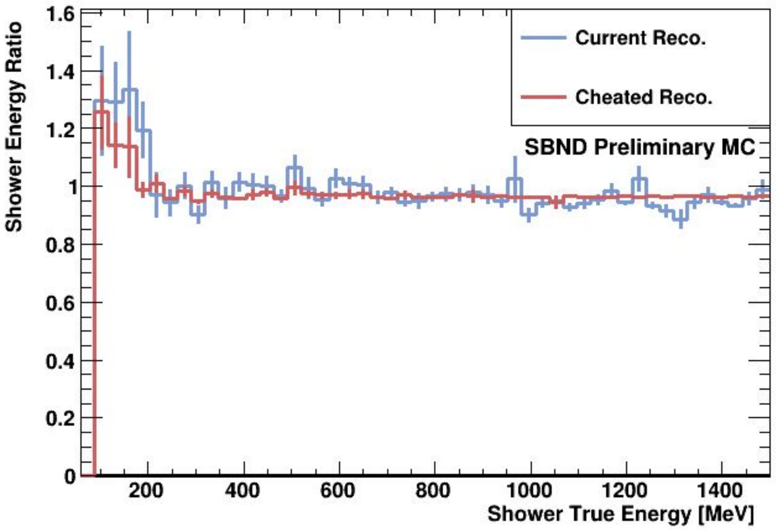
Photons

“Cheated” Reconstruction clusters hits based on underlying Monte Carlo simulation

Shower Reconstruction Energy Resolution

Compare the performance between the Current reconstruction and the cheated pattern recognition (Running the same high level reconstruction algorithms)

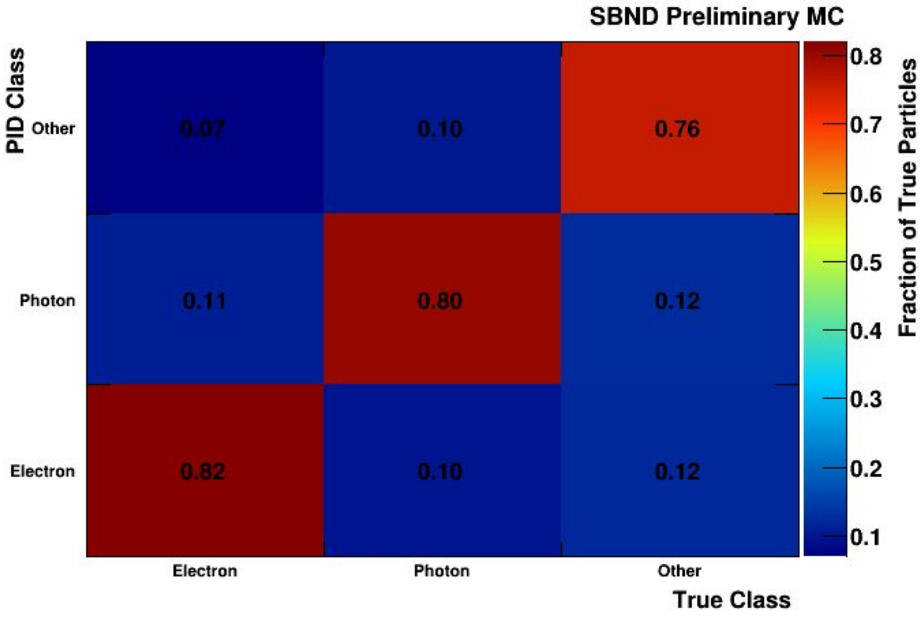




(Peak offset from 1 can be calibrated out using standard candles (e.g. Pi0))

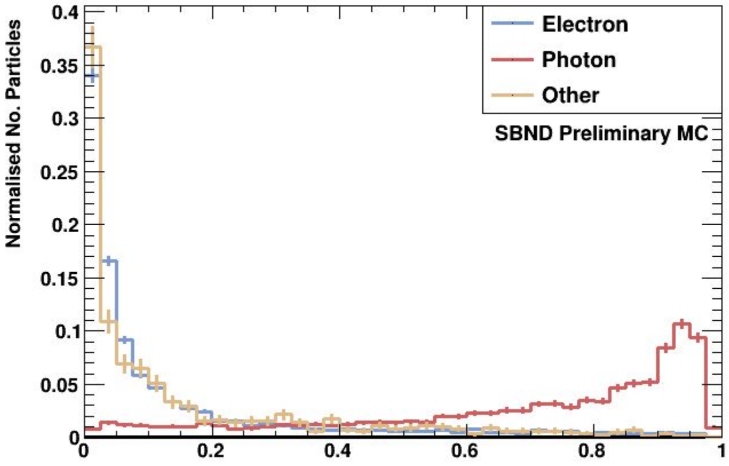
Razzle PID

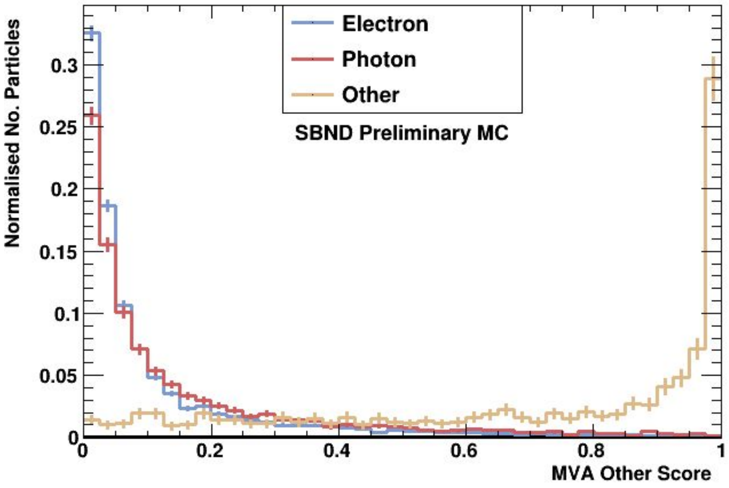
- SBND has developed a Multi-Class BDT(G) to perform shower PID
- This combines the dE/dx, conversion gap, opening angle and density of a shower
- Calculates a score for every shower for three hypotheses:
  - Electron
  - Photon
  - Other (dominated by misclassified tracks)
- Confusion matrix shows performance when taking hypothesis with largest score
- Accompanying track BDT: Dazzle

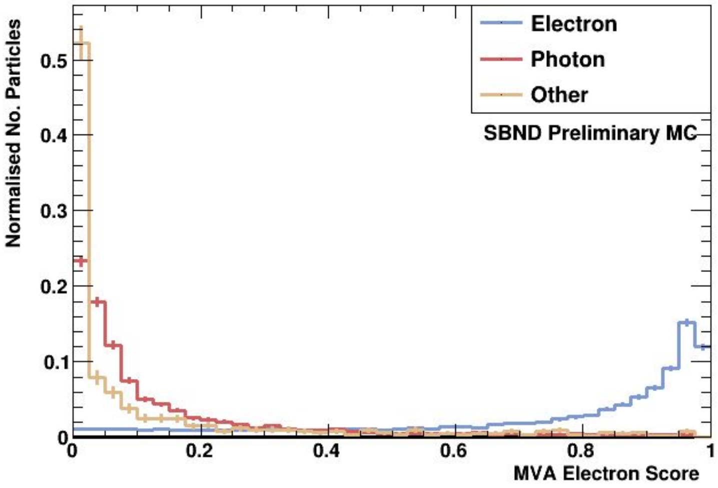


Razzle PID

- Can also cut on scores of individual BDTs for tuned efficiency or purity
- BDTs are co-normalised so sum of scores across all hypotheses sums to unity



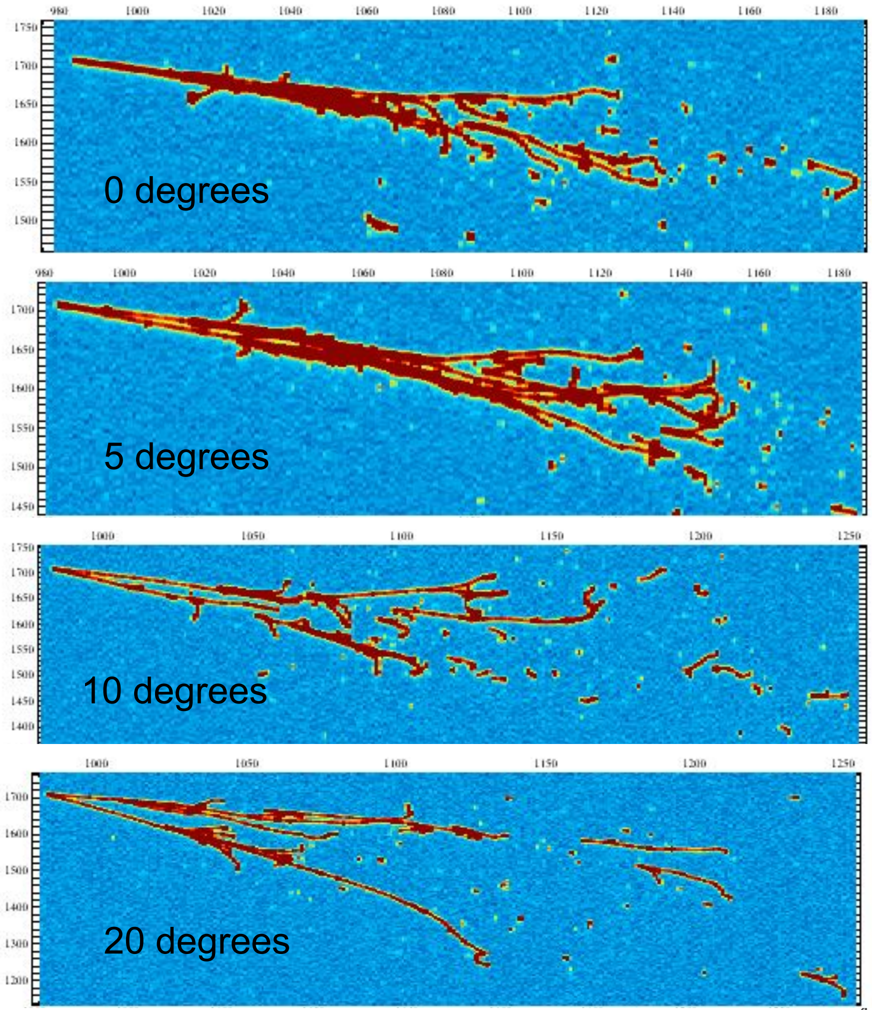




First look at e+/e- pairs

First look at e+/e- pairs

- Simulated e+e- pairs in the SBND detector
- Fixed 600 MeV and 400 MeV initial momenta
- Fixed, shared starting position
- Varied the opening angle between the e+/e- pair
- Initial track-like sections of the shower separate at higher angles, but the shower cascade can still easily overlap



Future Developments in Shower Reconstruction

Future Developments in (SBND) Shower Reconstruction

- Dedicated studies to look at performance of isolated showers
    - Pandora heavily relies on hadronic activity for to identify the vertex
    - Isolated showers are interesting for both ν-e scattering and BSM studies
- Studies on overlapping showers (as shown in the event displays) to study the separation at which the showers become individually resolvable
- Improvements to the pattern recognition:
    - Ongoing work to improve the vertex finding used to “grow the event”
    - Exploration of targeted deep learning to augment existing pattern recognition algorithms
        - E.g. Semantic segmentation tags hits as track-like or shower-like allowing more aggressive shower merging whilst protecting track reconstruction quality

Conclusions

We've gone a long way in EM shower reconstruction.

It is a difficult problem, so we still have a way to go, but situation is promising.

Multiple ideas in reconstruction are progressing:

- we presented primarily Pandora here, but WireCell and Deep Learning efforts are going on in parallels (some paper links on the next slide).

Articles Relevant to EM Shower Reconstruction

- First Measurement of Inclusive Electron-Neutrino and Antineutrino Charged Current Differential Cross Sections in Charged Lepton Energy on Argon in MicroBooNE [2109.06832 hep-ex]
- Measurement of the flux-averaged inclusive charged-current electron neutrino and antineutrino cross section on argon using the NuMI beam and the MicroBooNE detector [*Phys.Rev.D* 104 (2021) 5, 052002, 2101.04228 hep-ex]
- First measurement of electron neutrino scattering cross section on argon [*Phys.Rev.D* 102 (2020) 1, 011101 2004.01956 hep-ex]
- First Observation of Low Energy Electron Neutrinos in a Liquid Argon Time Projection Chamber [*Phys.Rev.D* 95 (2017) 7, 072005 1610.04102 hep-ex]
- Electromagnetic Shower Reconstruction and Energy Validation with Michel Electrons and π^0 Samples for the Deep-Learning-Based Analyses in MicroBooNE [2110.11874 hep-ex]
- Wire-Cell 3D Pattern Recognition Techniques for Neutrino Event Reconstruction in Large LArTPCs: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation [2110.13961 physics.ins-det]
- Semantic segmentation with a sparse convolutional neural network for event reconstruction in MicroBooNE [*Phys.Rev.D* 103 (2021) 5, 052012 2012.08513 physics.ins-det]
- Electromagnetic Shower Reconstruction and Energy Validation with Michel Electrons and π^0 Samples for the Deep-Learning-Based Analyses in MicroBooNE [2110.11874 hep-ex]
- Reconstruction and Measurement of O(100) MeV Energy Electromagnetic Activity from $\pi^0 \rightarrow \gamma\gamma$ Decays in the MicroBooNE LArTPC [*JINST* 15 (2020) 02, P02007 1910.02166 hep-ex]
- The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector [*Eur.Phys.J.C* 78 (2018) 1, 82 1708.03135 hep-ex]