MicroBooNE as a Laboratory for Studying ν + Ar Interactions

Joel Mousseau

University of Michigan

State of the Nu-tion workshop

Toronto, ON

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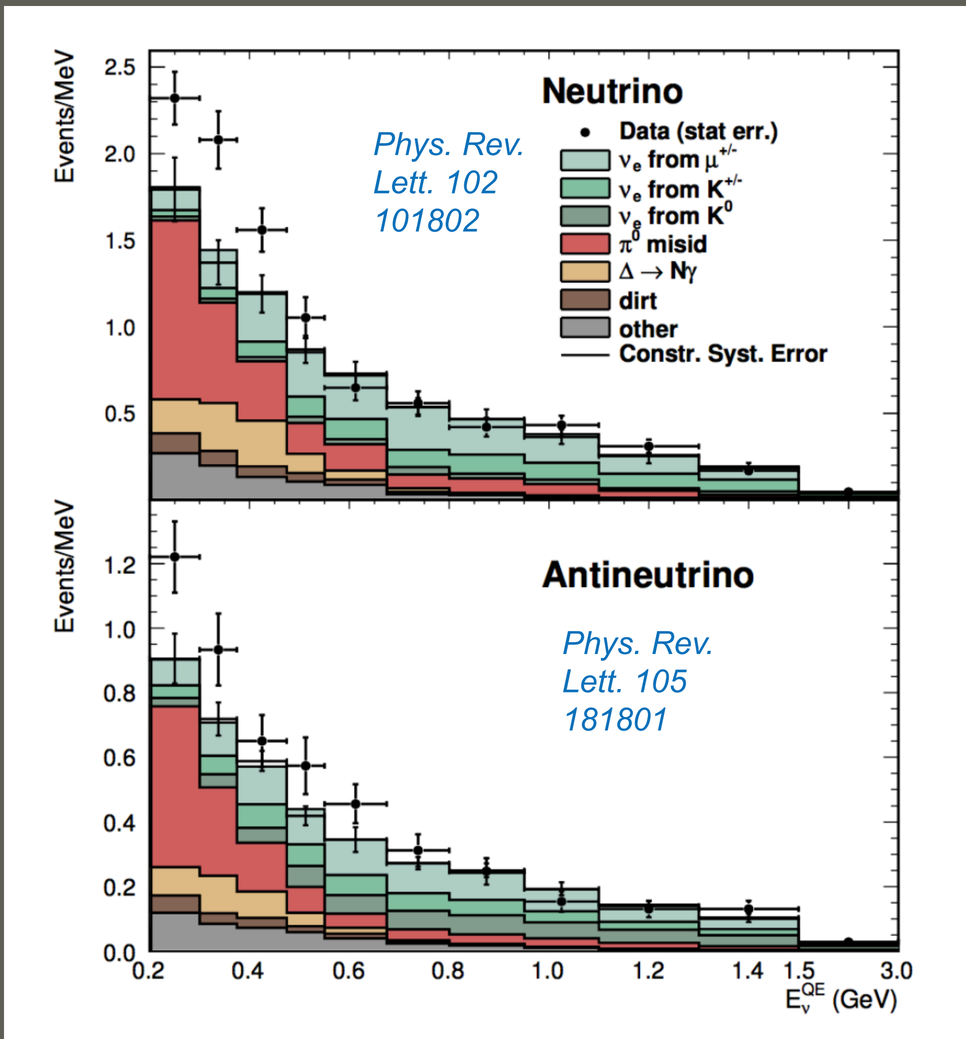
MicroBooNE: Hunting an Excess and More

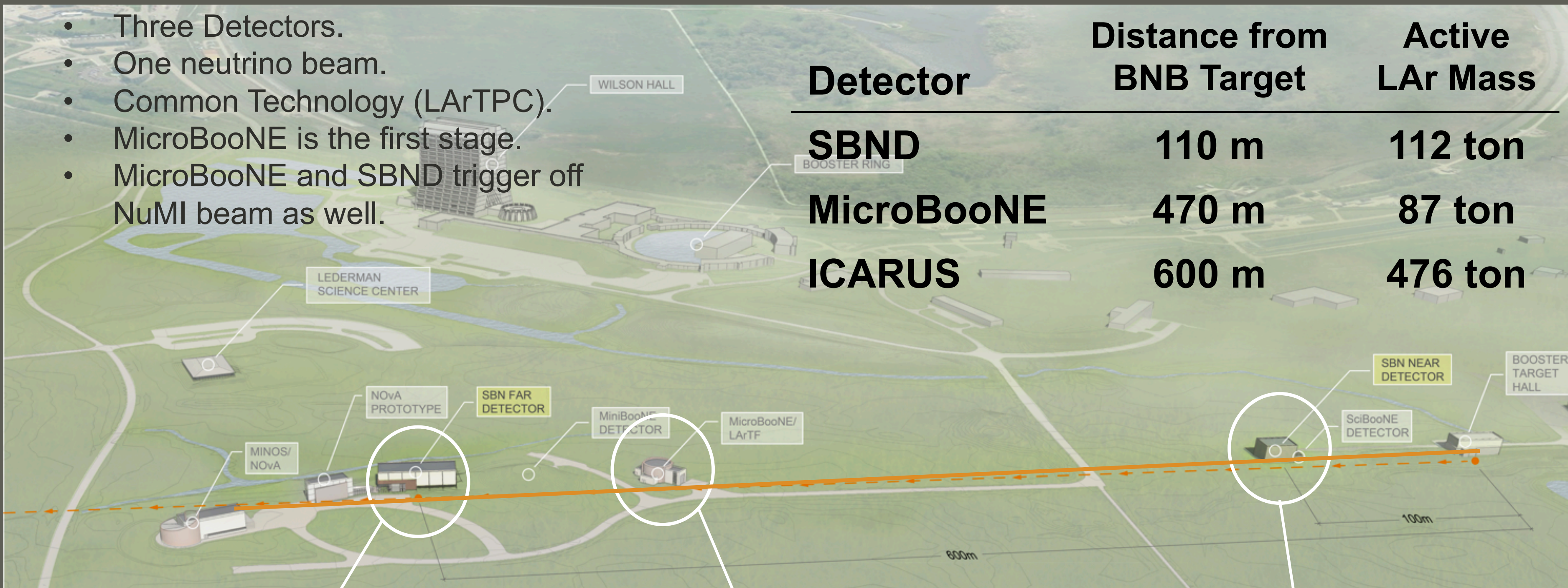


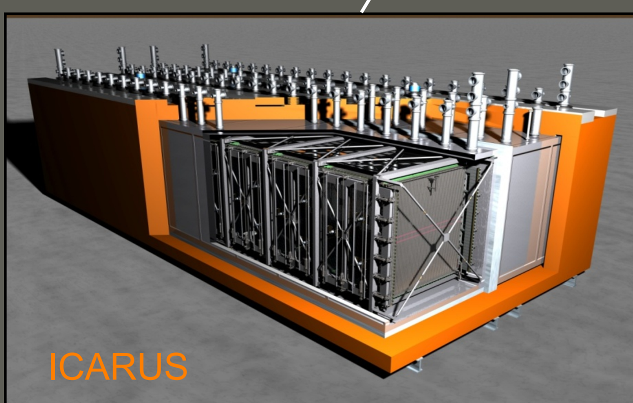
- MicroBooNE: primarily designed to confirm / refute the MiniBooNE excess of neutrino events at low energy (200 – 475 MeV).
- e^- / ɣ separation drives choice of detector technology, leads to liquid argon time projection chamber (LAr TPC).
- MicroBooNE is excited to contribute to the field of cross-sections:
  - Provide vital studies of interaction physics for future, larger LAr experiments (DUNE).
  - Contribute to the development of analysis tools for the Fermilab Short Baseline Program, which also uses LAr TPCs.

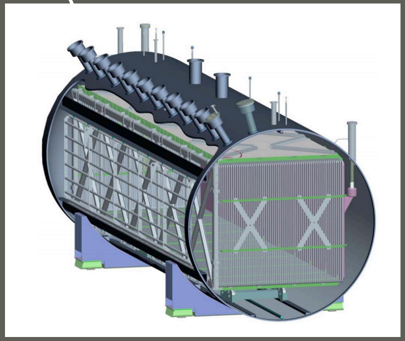
MicroBooNE's Place in the SBN Program

- Three Detectors.
- One neutrino beam.
- Common Technology (LArTPC).
- MicroBooNE is the first stage.
- MicroBooNE and SBND trigger off NuMI beam as well.

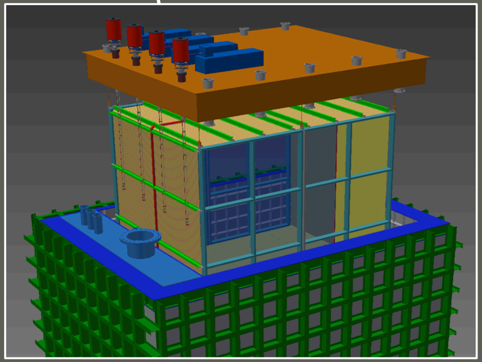
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton







MicroBooNE

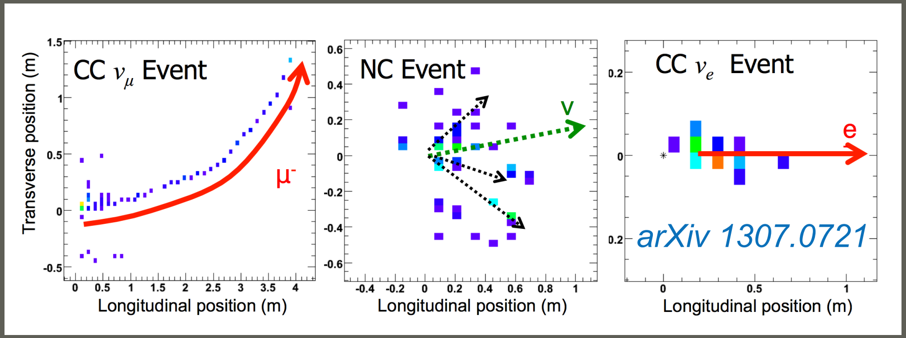


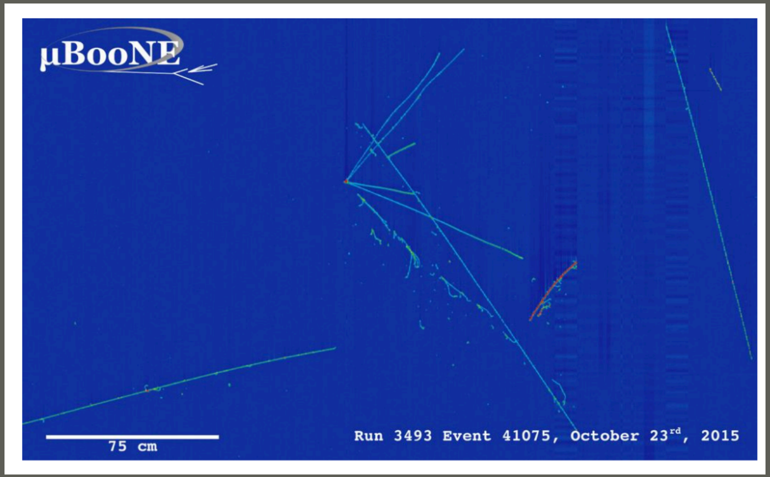
SBND

Argon is Interesting in it's Own Right!

- Independent of any future or current running projects, argon is an interesting nucleus to study in its own right!
- Argon is heavy, (A = 40). Compare that to Iron (A = 56) and Carbon (A = 12).
- As a result, Argon is a great nucleus for studying all the A dependent nuclear effects we like to talk about (MEC, TEM, FSI).

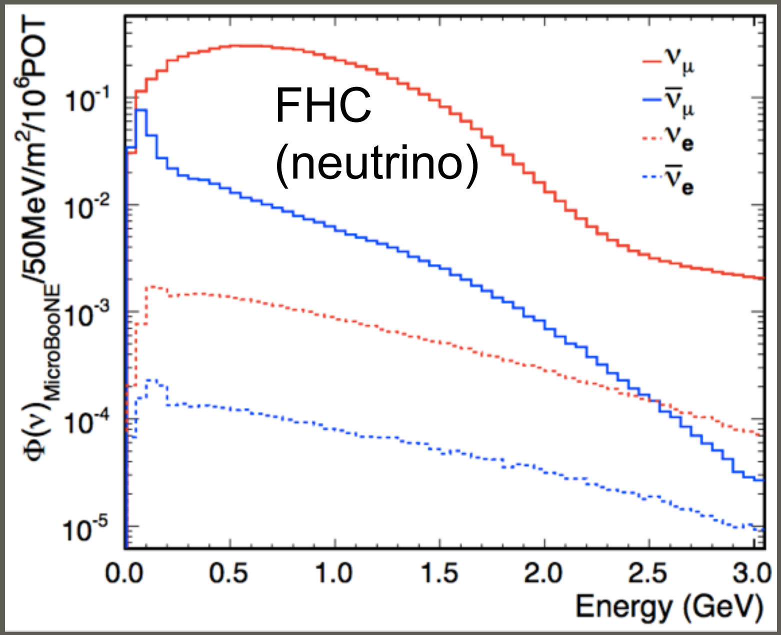
We tend to think of large A detectors as sampling calorimeters, such as MINOS on the right…

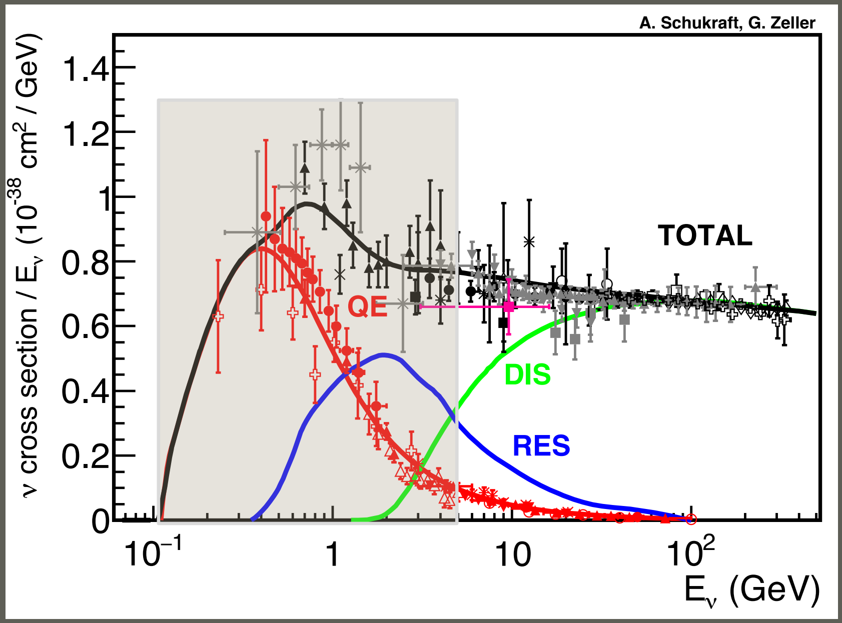




…TPCs give us the ability to study these interactions in a tracking-like detector (albeit one with many cosmic tracks).

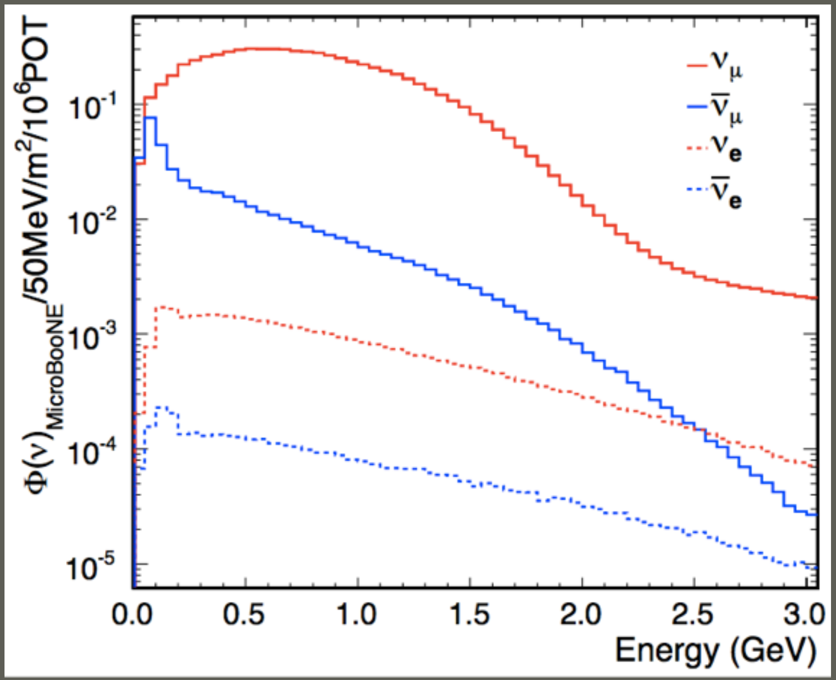
BNB Flux





- MicroBooNE see approximately the same flux as MiniBooNE (same beamline, similar location).
- Primarily ν_μ with some contribution of intrinsic ν_e. Anti-neutrino mode has a significant wrong-sign contribution.
- MicroBooNE does not plan to take anti-neutrino data pre-SBN era.
- 0-3 GeV energy range gives us good coverage of QE, MEC and RES events.

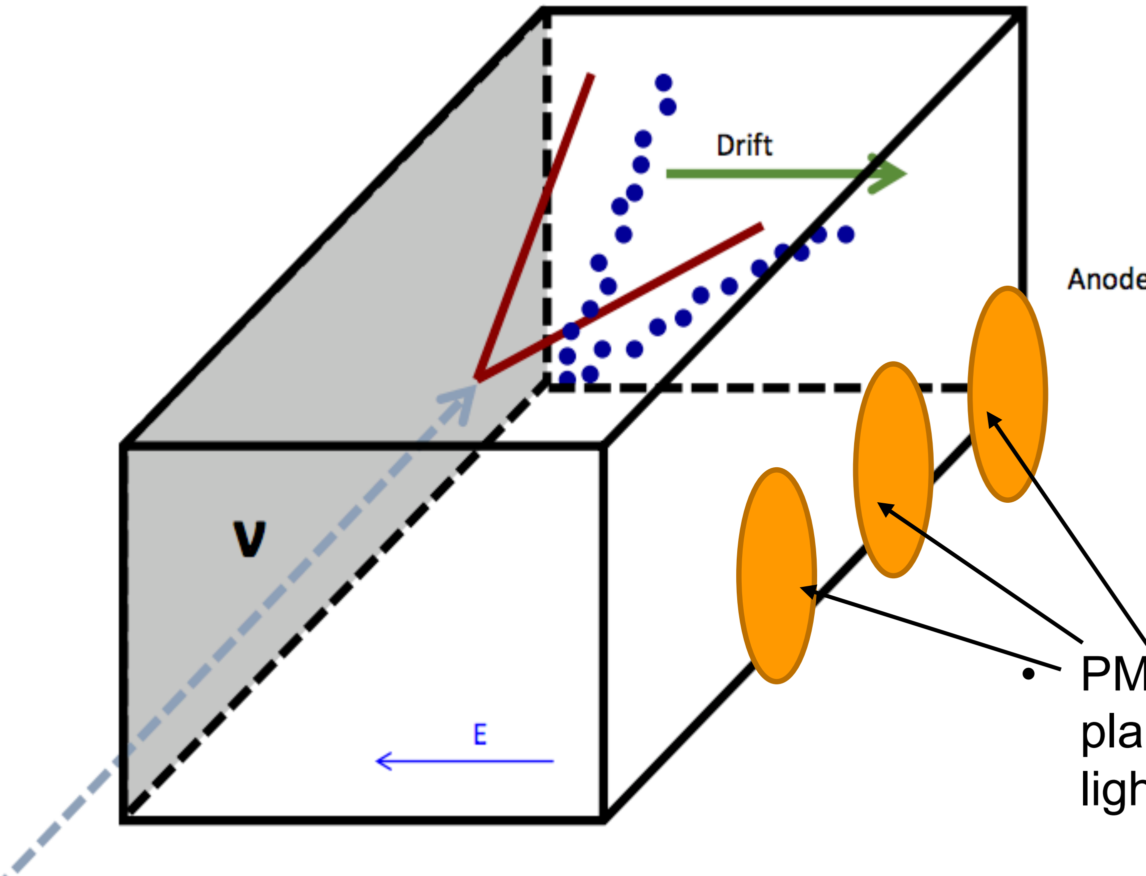
BNB Flux Uncertainties



Channel	Flux Uncertainty	Ref
ν_μ CCQE	8.66% (norm.)	PRD81 2010
CC π^+	9.2% (norm. + shape)	PRD83 2011
CC π^0	10.5% (norm + shape)	PRD83 2011

- MicroBooNE is currently using MiniBooNE's latest flux calculation / uncertainties.
- It is a priority of the experiment to re-evaluate the flux and improve these uncertainties, new flux calculation is on the way.

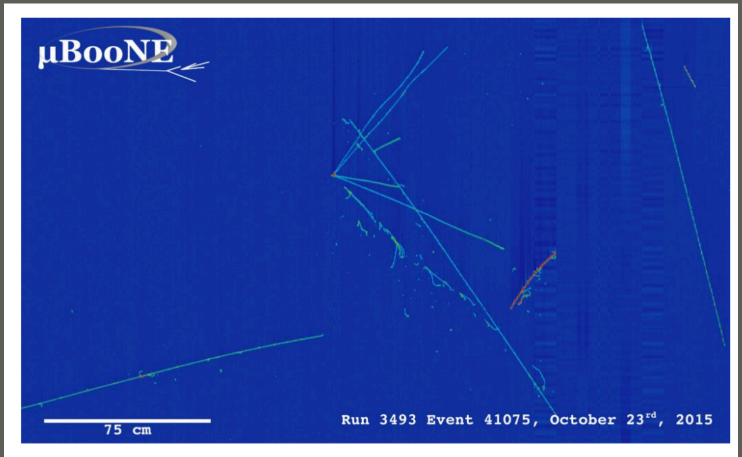
Operation of a LAr TPC

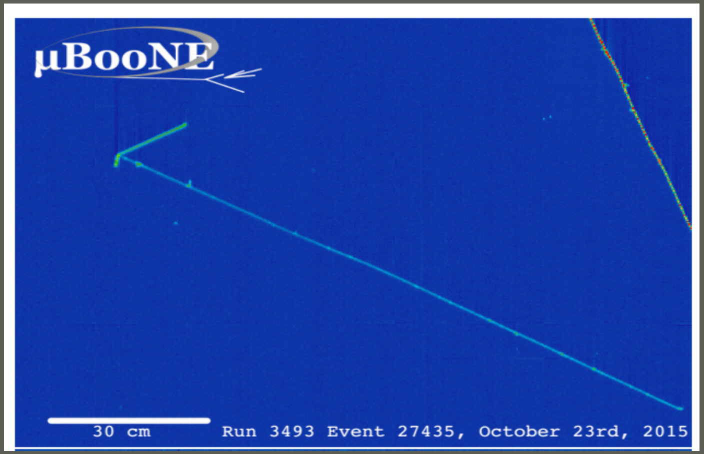


- Charged particles ionize Argon molecules, electrons drift toward Anode where they deposit charge on wires.
- Drift time is long: ~2.0 ms.
- PMTs sit behind anode plane, detect scintillation light from Ar.

For more details, see our detector paper: 2017 JINST 12 P02017

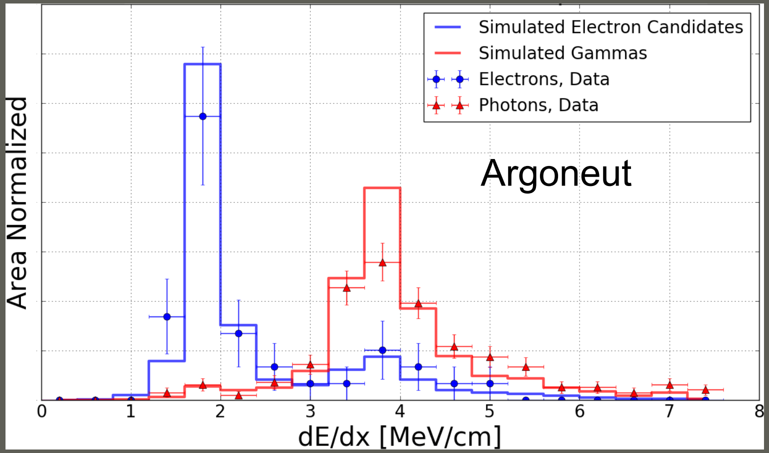
What we Gain From TPCs





Beautiful Events!

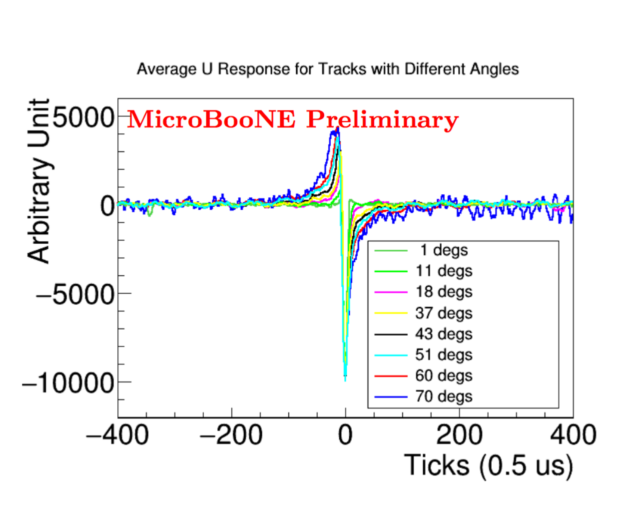
Particle ID based on dE/dx!



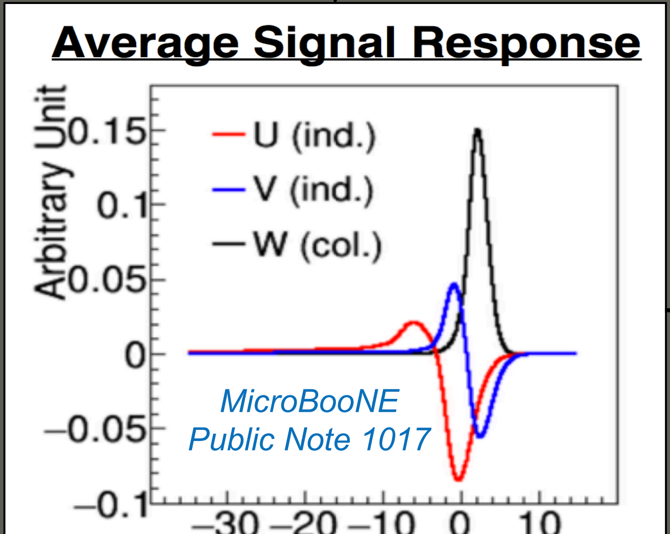
Phys.Rev. D95 (2017) no.7, 072005

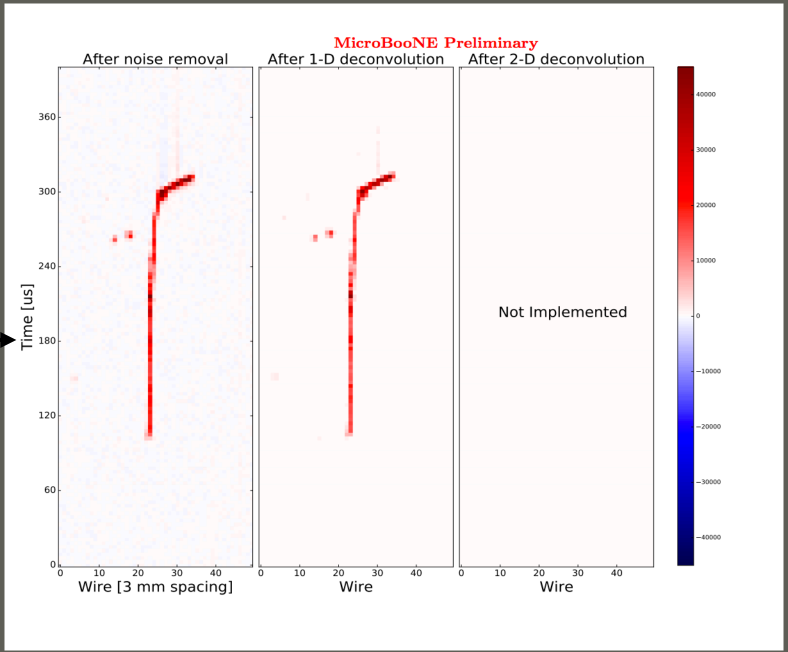
- LAr TPCs are very good at and tracking and particle identification based on charge deposited.
- BUT:
  - You have a complicated signal (charge on a wire.
  - You have a complicated detector.
  - You have a heavy nucleus (Ar) which is not modeled well.
- *Taken together, it implies we should be reporting results in detector variables (track length, muon momentum, etc.)*

LAr TPC Reconstruction: Deconvolution



- What you get from your wires is a waveform in *t* space, and remember you have the entire 5 ms waveform…
- This is in stark contrast to tracking style detectors, where you have a digitized charge in some small ns sized time bin.
- Or a Cherenkov detector which give a spatial distribution of charge on PMTs.

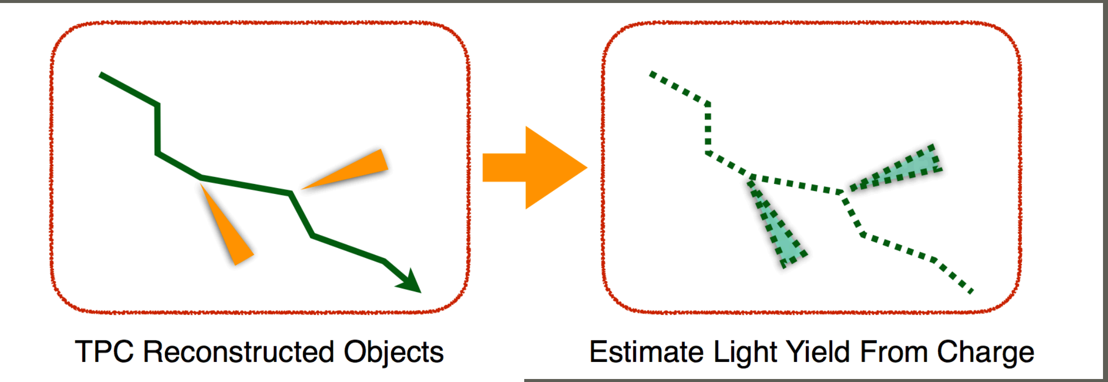


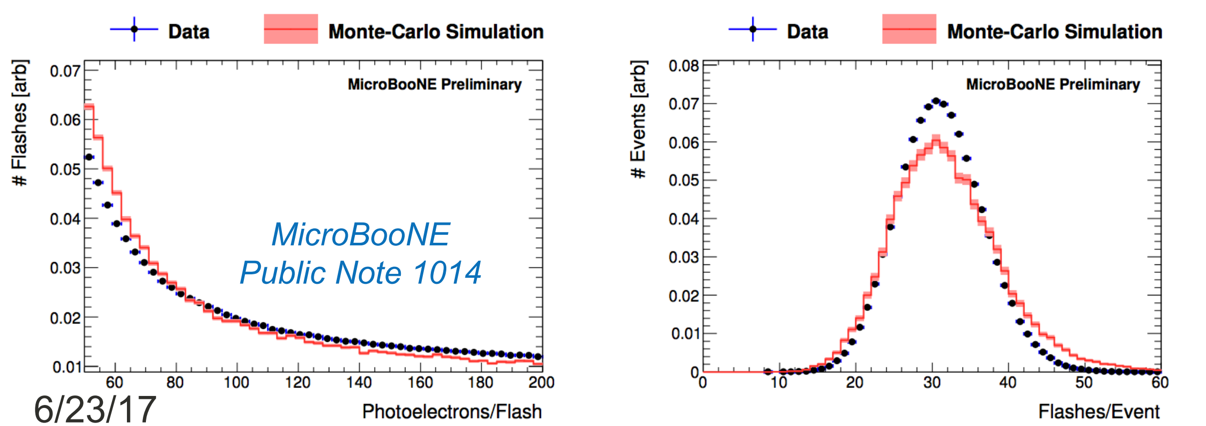


LAr TPC Reconstruction: Flash Matching

- To beat back cosmic ray backgrounds, attempt to match TPC tracks to “flashes” in the PMTs.
- Estimate light yields of hits in the TPC, and match that to deposits within the PMTs.
- Interesting events (events with a long muon) typically deposit above 50 PE (bottom).

- Mitigating cosmic rays in time within the long drift window is challenging, flash-matching is our best (but not sole) technique.





- Working to improve the MC optical model, should improve cosmic mitigation

Cosmic Backgrounds

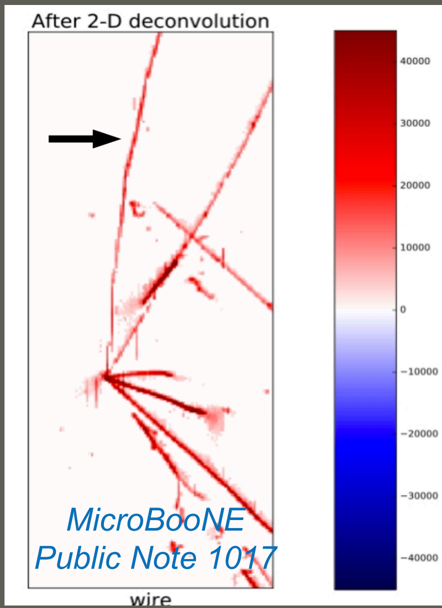
Abridged Cut Table of
CC 1 μ + X (inclusive)

Cut	Survival Fraction (Overall / Relative)
> 1 Flash with > 50 PE	25%/25%
Candidate vertex in FV	55%/14%
Flash matched to longest track	29%/4.0%
Track Containment	49%/1.9%

"The healthiest thing we can do is ignore this and pretend it doesn't exist."

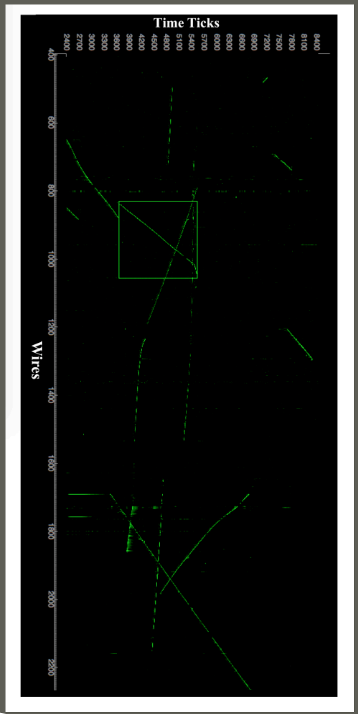
- Backgrounds from cosmic rays are a serious concern for surface TPCs.
- Mitigated by cosmic detectors, and PMT flash matching. However MicroBooNE has found some cutting on reconstruction level quantities is necessary.
- This leads to some model dependence on your signal definition, as well as a complicated acceptance map and low detector efficiency.

Hierarchical Reconstruction Path



Wire Signal Processing

PMT Reconstruction



Pandora

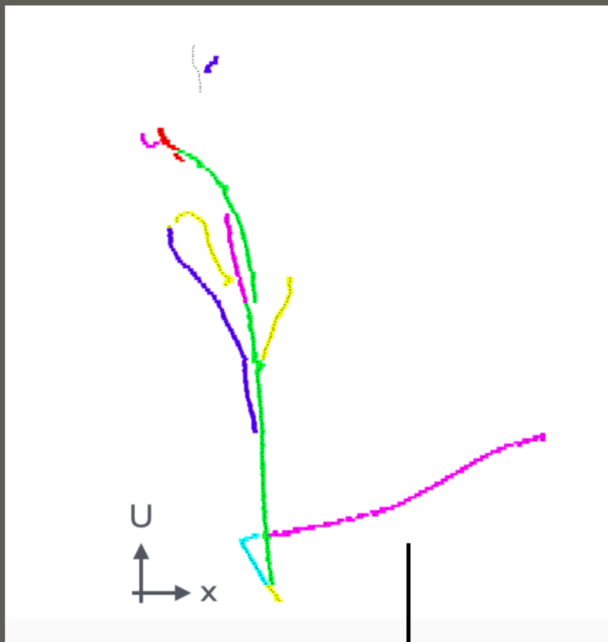
WireCell

Deep Learning / CNN

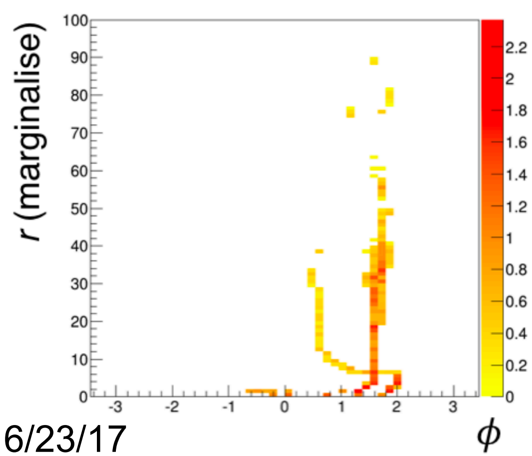
Pixelated / tracking

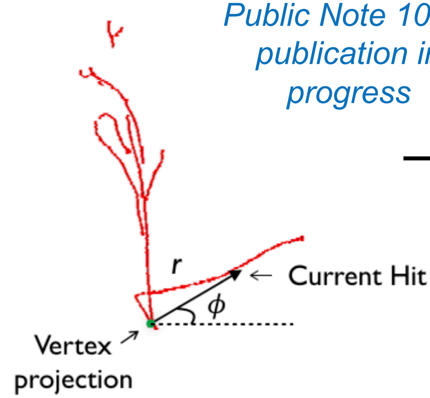
Image Processing, LEM

Pandora Reconstruction

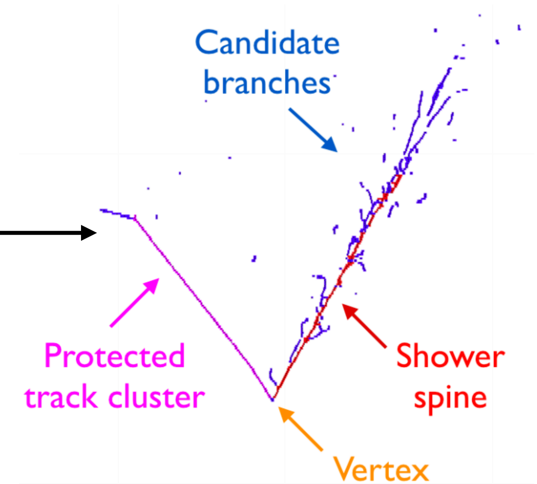


- Done in two passes, including a cosmic tuned reconstruction and a neutrino tuned reco. pass.
- Pandora spatially groups hits into clusters, tracks and showers.
- Neutrino pass includes vertex finding, track/shower discrimination and PID.
- Track containment and direction is used to determine if a track is cosmogenic in nature.

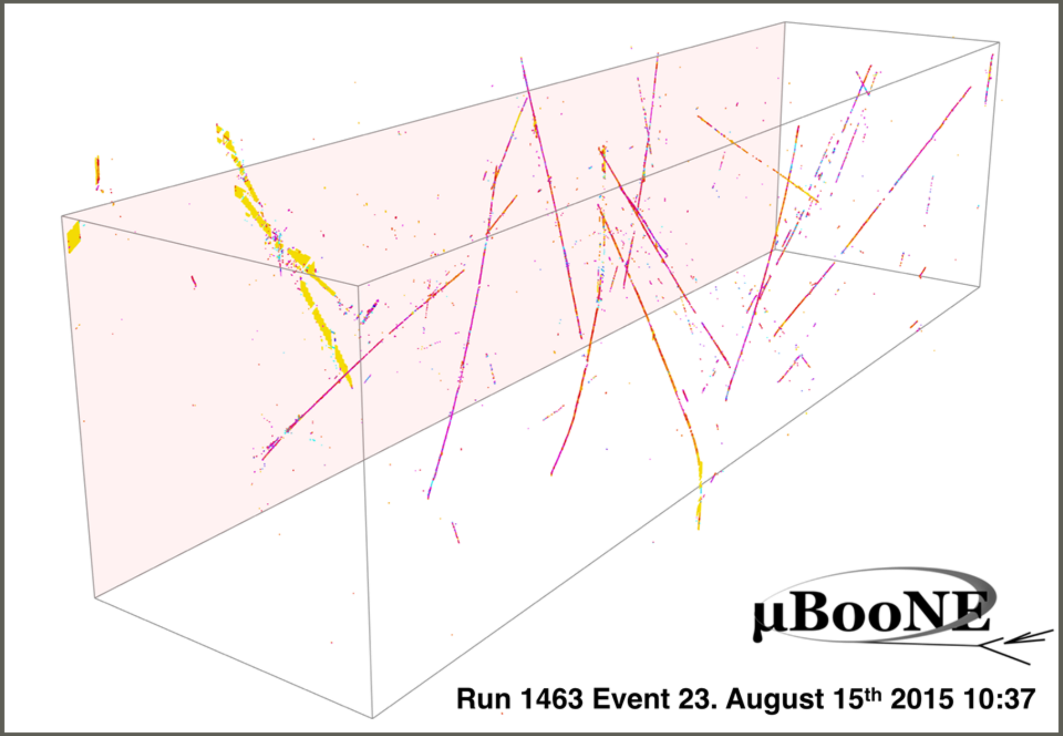




MicroBooNE Public Note 1015, publication in progress



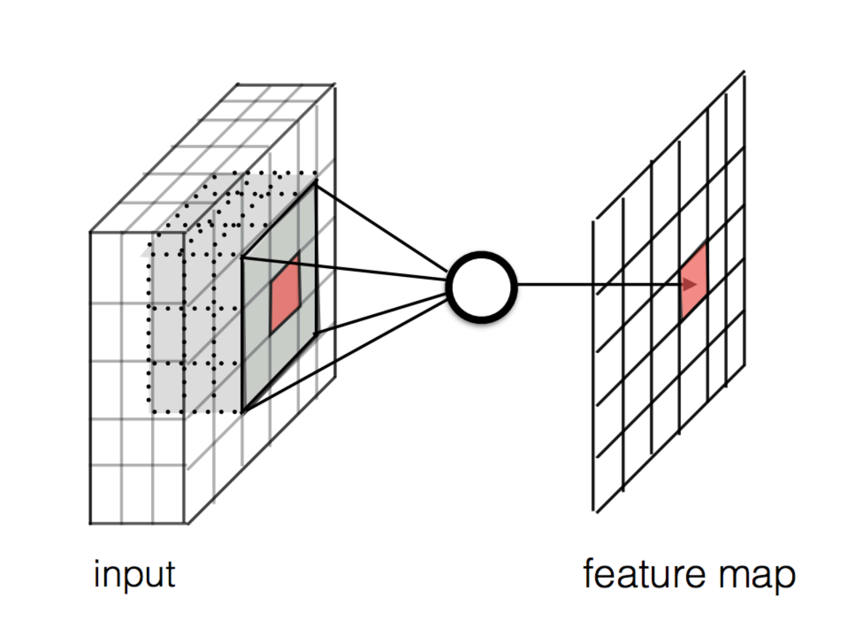
Wire Cell



- Fully 3D reconstruction; uses linear algebra (tomography) to solve for intersections of wires.
- Wirecell incorporates its' own deconvolution, one needs to deconvolve multiple signals within a given cell.
- Much of the PID and kinematic reconstruction would follow from the Pandora chain, however the base tracks and showers are manifestly 3D objects.
- Actively being explored by MicroBooNE.

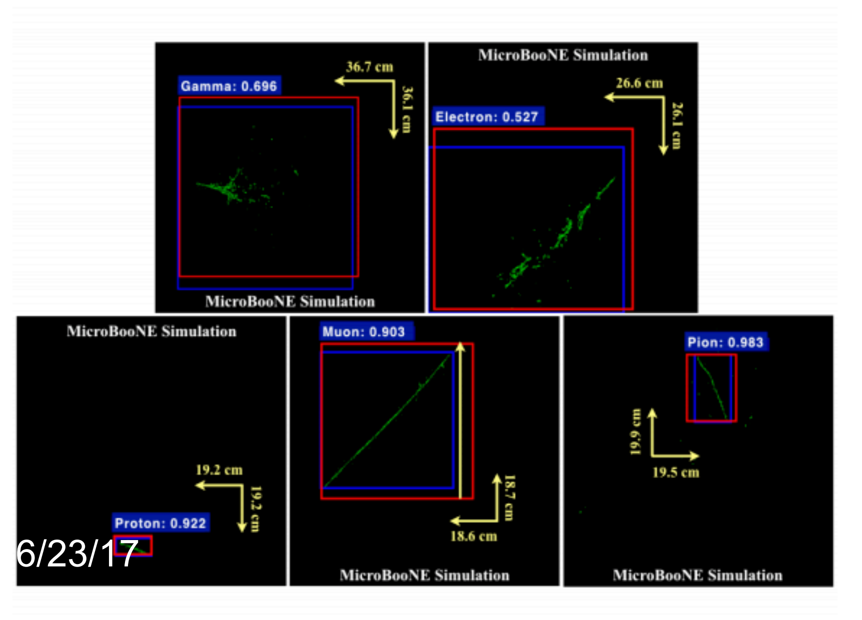
Convolutional Neural Networks

- Unlike Pandora, where one considers discrete hits correlated in different views, CNN/Deep Learning considers the entire TPC image.
- Consists of “training” a set of nodes (neurons) to known images; the network picks up on image features which one can use to build classifiers.



uBoone DL Publication: JINST 12, P03011 (2017)

- Train your network to recognize regions of interest, beats down cosmic backgrounds.
- Almost by design, CNN is very good at dividing events by particle type and multiplicity (1 proton + 1 lepton, 1 proton + 2 gammas).

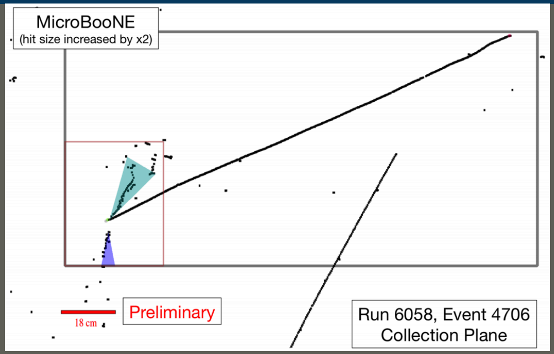


Reconstruction to Analysis

Pandora / Track Based:

- Ammenable to topological variables (track length, angle, etc). PID is possible, but needs to be based on these underlying topologies.

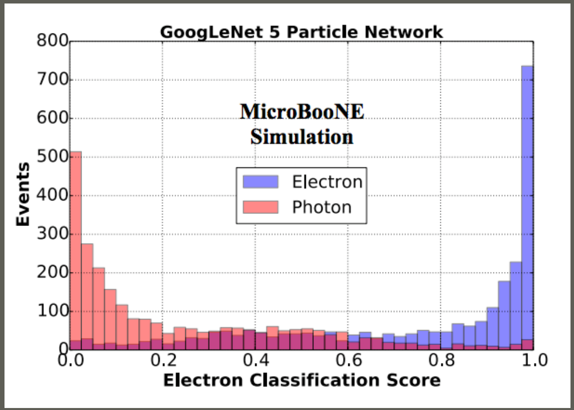
MicroBooNE Pubilc Note 1006



Deep Learning Based:

- Very good at classifying broad event types; (1 μ + 1 p, 1 e + 1 p). There is a trade-off in that you lose some information as to what goes into these classifiers.

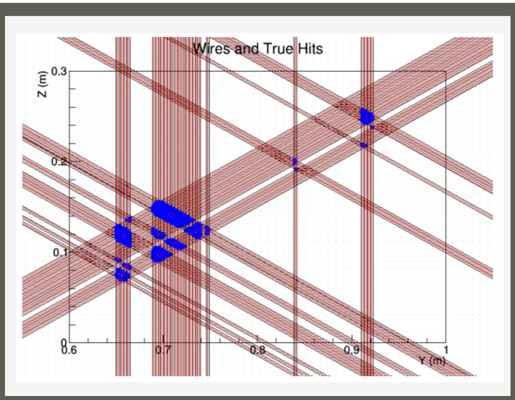
JINST 12, P03011 (2017)



Wirecell / Tomography Based:

- Hybrid where you consider the TPC image in all three dimensions, but still retain the underlying pixel information.

http://lar.bnl.gov/wire-cell/

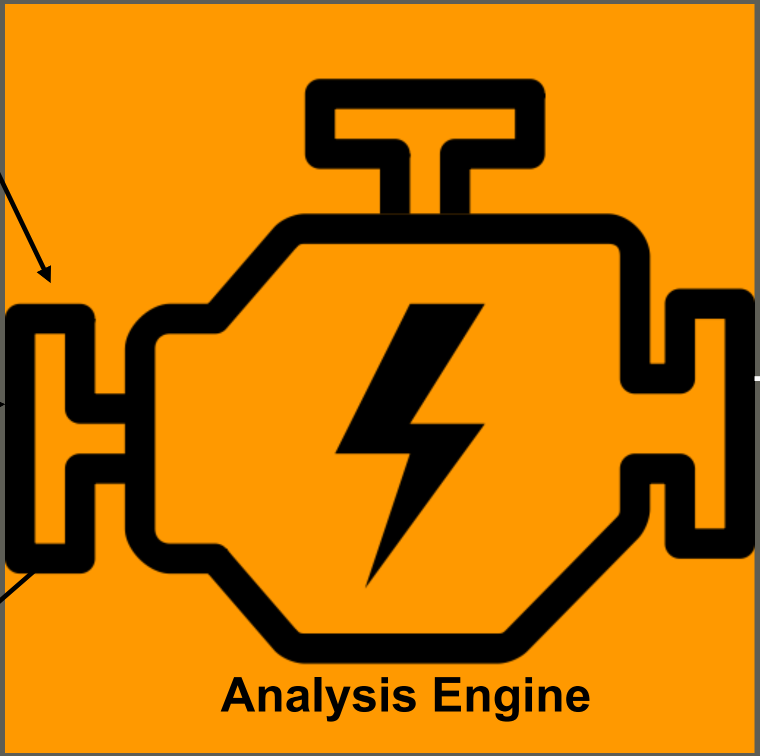


Reconstruction to Analysis

Pandora

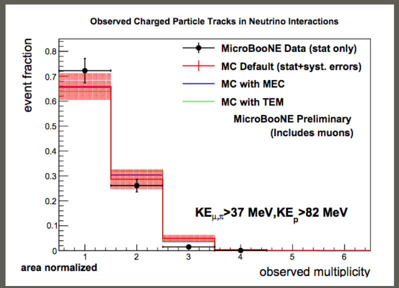
WireCell

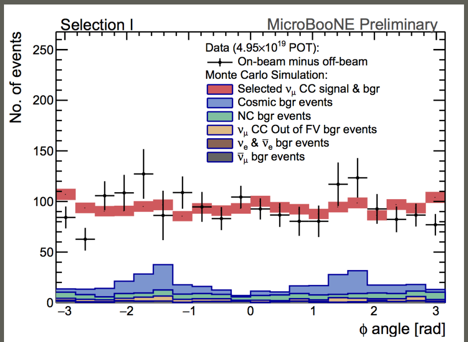
Deep Learning / CNN



Each strategy involves introducing different model dependencies!

How do we report results?
Do we unfold?
Efficiency Correction?
What do we normalize to?





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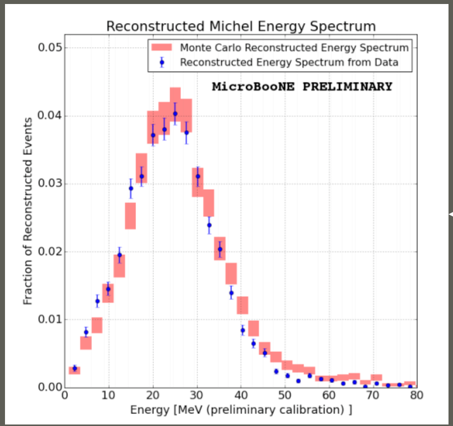
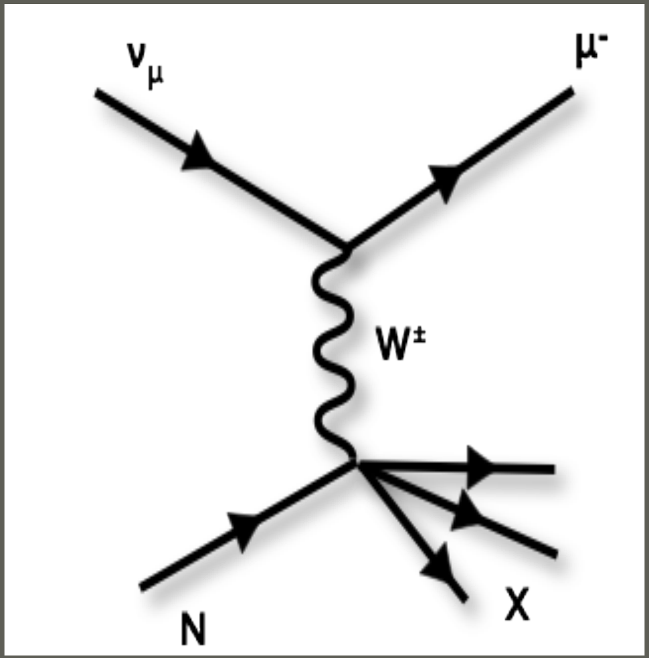


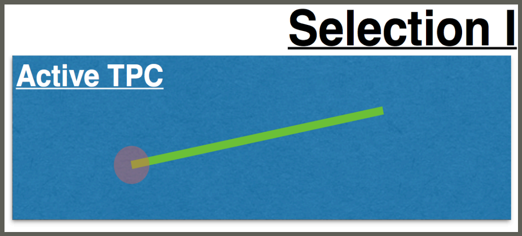
MicroBooNE Public Note 1008

Example: CC Inclusive

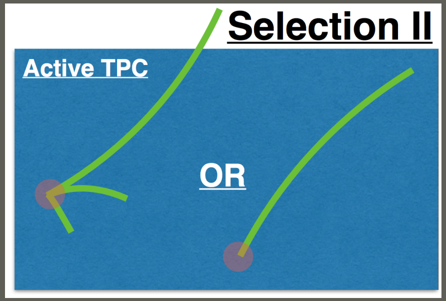
- CC Inclusive is a pandora based analysis where we search for at least one muon.
- Due to significant cosmic contamination, number of other cuts are imposed to improve purity.
- Boils down to a “contained” and ”uncontained” sample.



- Strict requirements on containment (longest track must be contained)

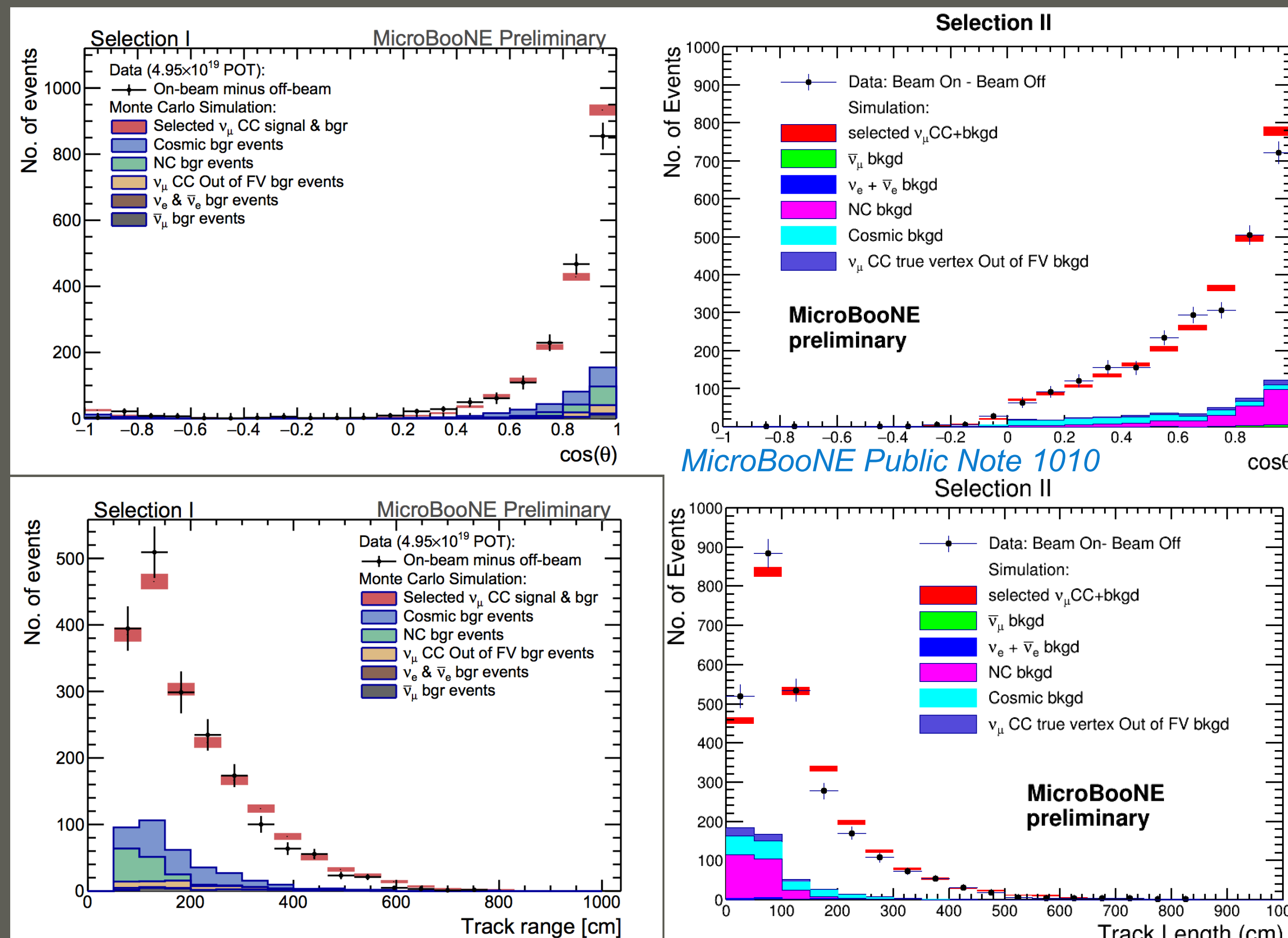


- Looser requirements on containment (for multitrack events).
- Cuts events with a Michel tag, likely a stopping cosmic ray.



Example: CC Inclusive

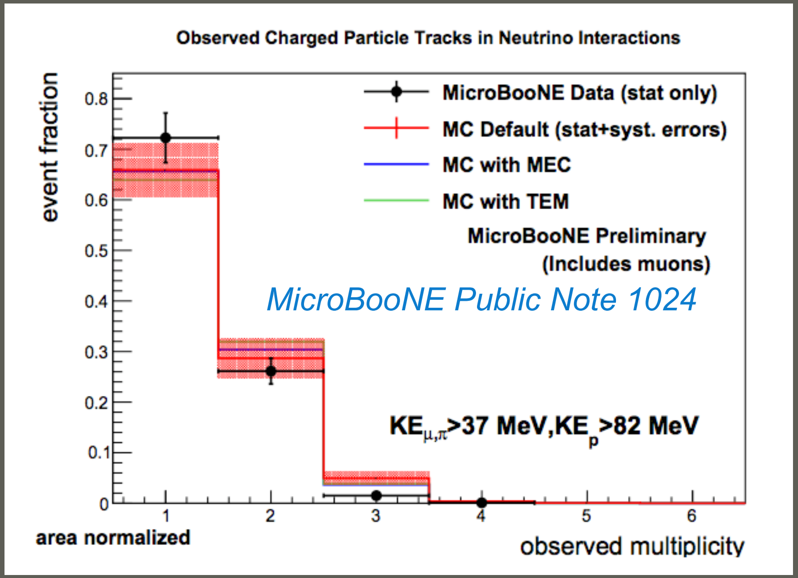
- Look into *tracking* type variables: track length, cos(θ).
- How useful are these distributions relative to “higher level” quantities like E_ν or Q^2, which contain significant model dependence?
- Advantage to these tracking variables is it is natively how our complicated efficiency and acceptance is calculated.

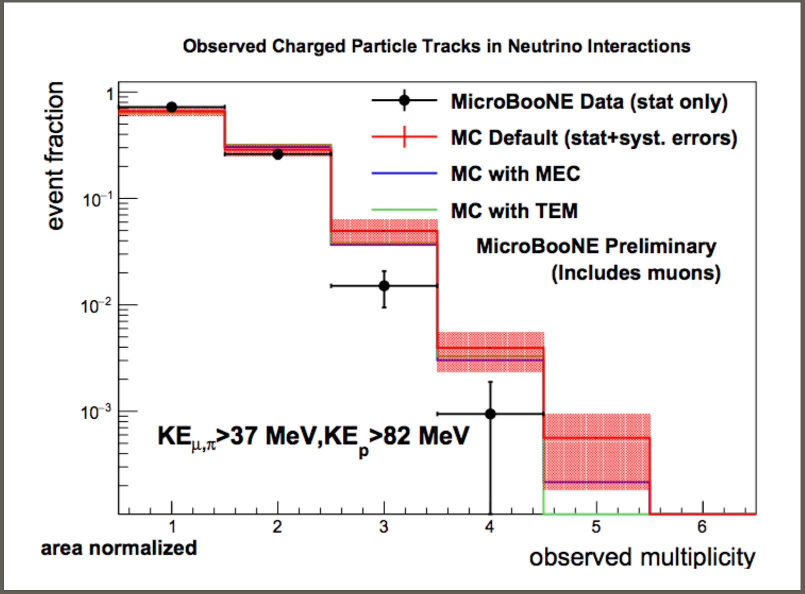


MicroBooNE Public Note 1010

Example: CC Multiplicity

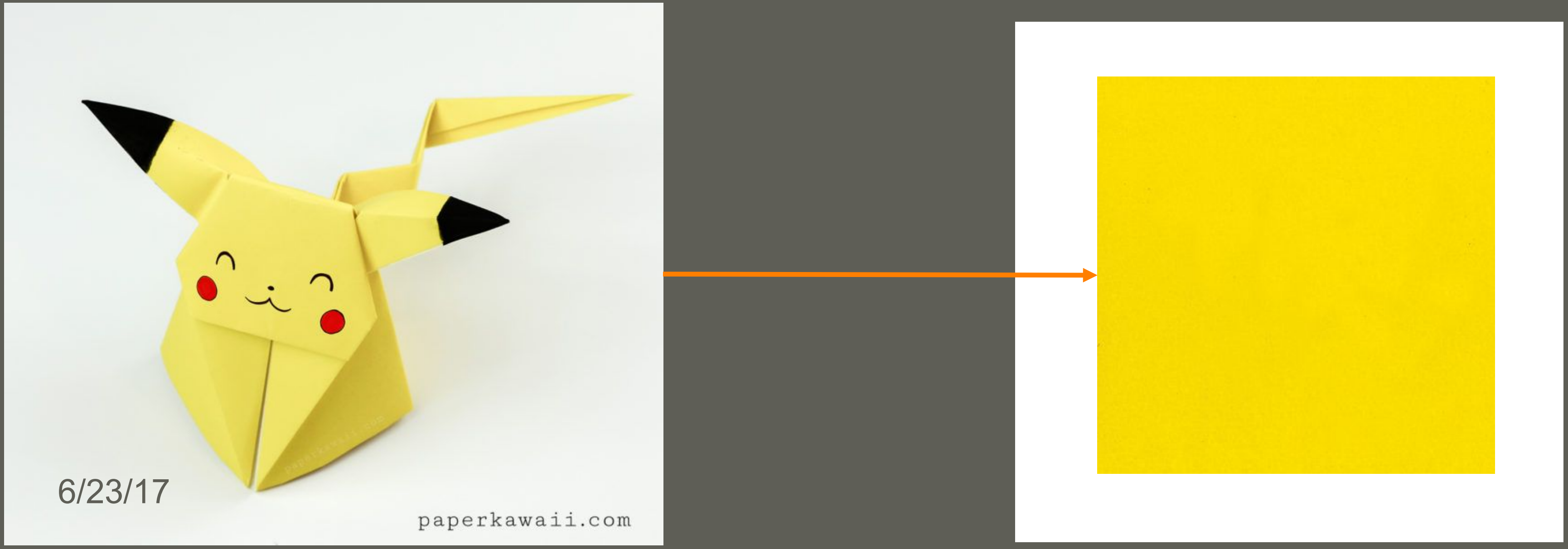
- E_ν or Q^2, these are hard. What if we measured something nice and easy like track multiplicity?
- Model builders can predict multiplicity, it's something we natively measure and something which we (generally) agree on a definition.
- Of course, real life is always more complicated:
  - How do we deal with neutral particles?
  - What about charged particles below our detection threshold?
  - What about how our acceptance changes as a function of multiplicity?
- In principal this is all solvable, *but it affects how you do your measurement.*





Unfolding

- Unsmearing detector effects is a painful process one would like to avoid.
- Should MicroBooNE move to a model where we unfold only when we think an unfolded distribution adds value to the work being presented?
  - Otherwise, publishing the smearing matrix.
- Moving toward unfolding our charged current multiplicity distributions.
- … But an E_μ distribution from the inclusive sample does not seem to add much value.



Conclusions

- Studying neutrino interactions in liquid Argon is an important, and quite frankly interesting endeavor.
  - Try thinking of it as liquid iron. Really cold, non-conductive liquid iron.
- MicroBooNE is leading the charge on this effort, and has already made important contributions:
  - Developing advanced cosmic ray mitigation techniques.
  - Pushing forward with traditional pixel and tracking reconstruction.
  - CNN and tomography approach to reconstructing entire detector images.
- The nature of our detector, and reconstruction leads us toward releasing results in detector variables, with suitable smearing matrices and efficiency corrections.
- This is already underway, our cross-section analyses will prove to be very interesting once finalized.
- There is a lot to learn (and be learned) from LAr TPCs.

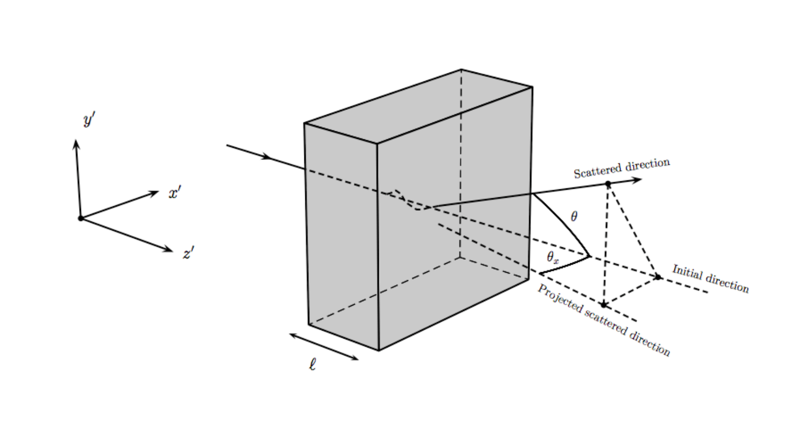
Thank you for Listening!

Backup

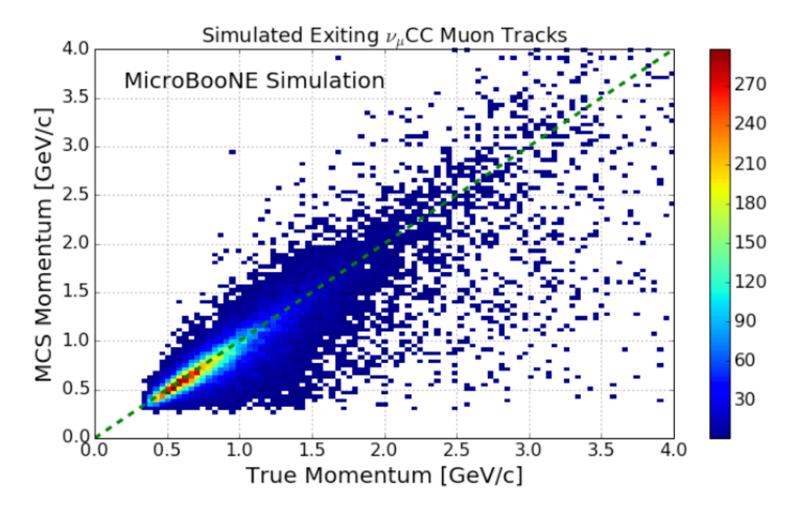
Multiple Coulomb Scattering

- Method for measuring the momentum of exiting muons based on the muons scattering.
- RMS of scattering defined by Highland formula:

$$\sigma_o^{HL} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0}\right)\right],$$



- Validated against MC and has been re-tuned for liquid Argon.
- Powerful way for MicroBooNE to measure muon momentum, a very fundamental quantity.



MicroBooNE Public Notes

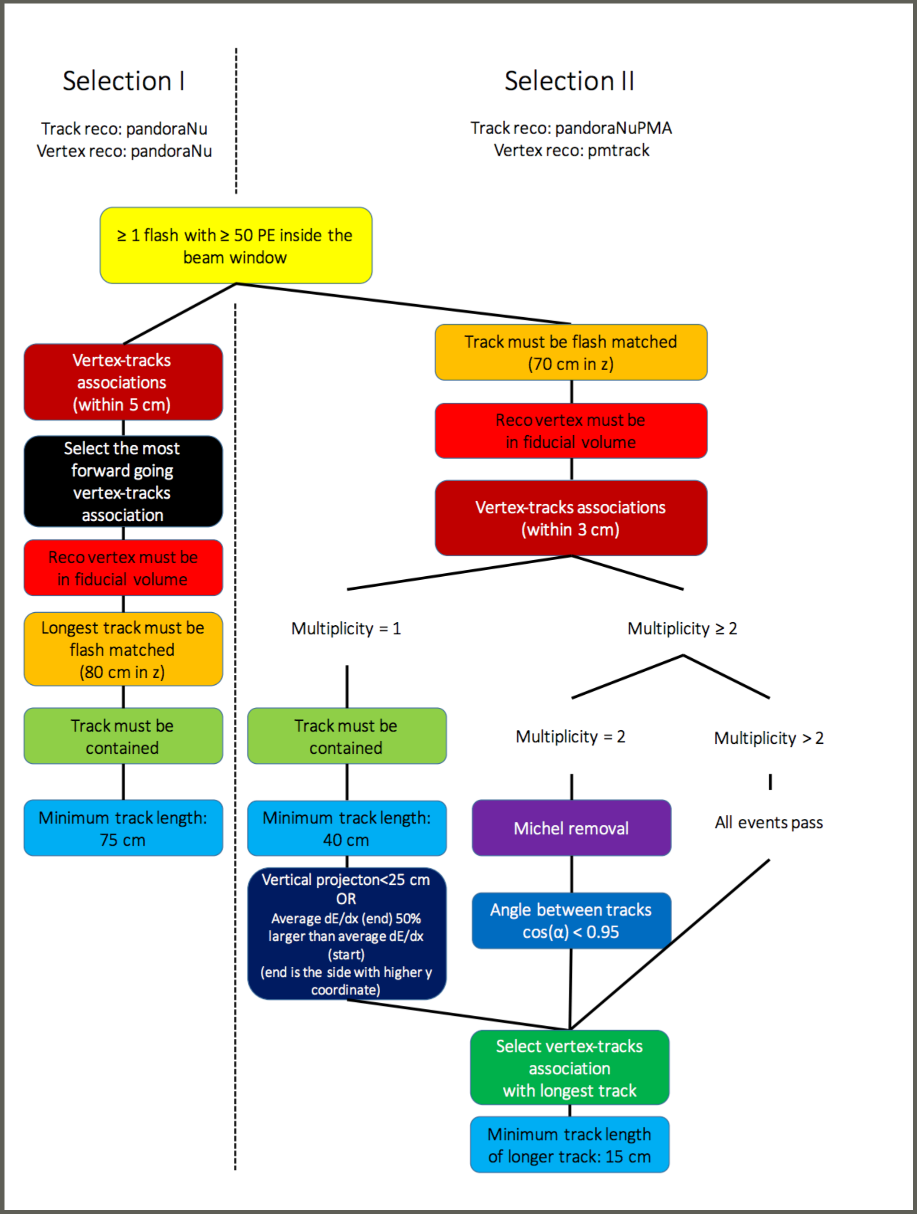
May be found at this URL:

http://wwwmicroboone.fnal.gov/publications/publicnotes/

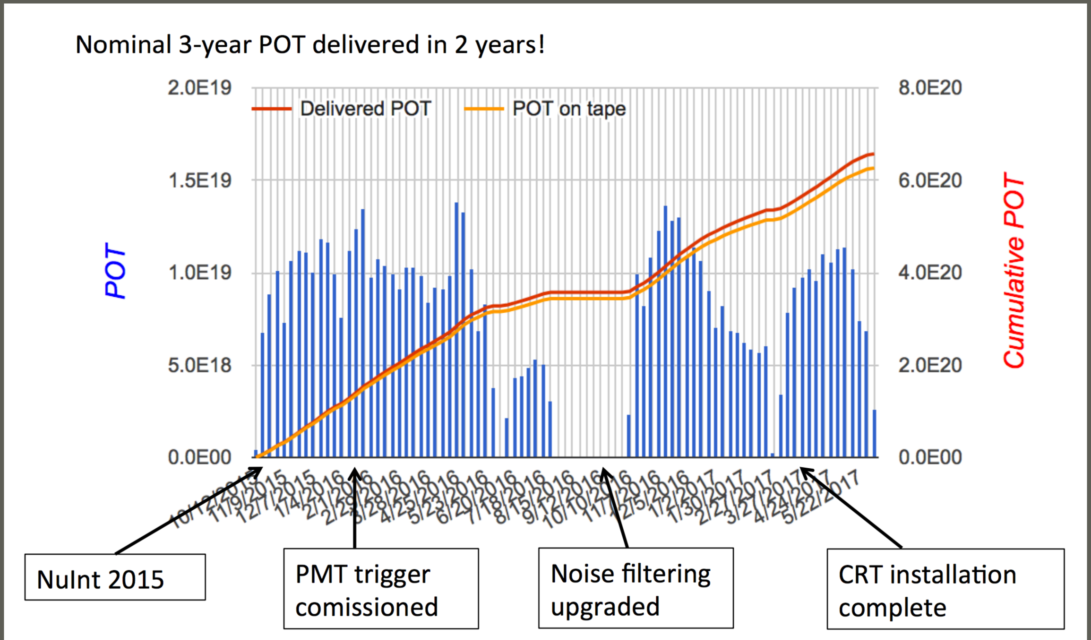
Selection I Full Cut Table

Cut	Events	Survival Fraction
All Events	547000	100%
> 1 Flash with > 50 PE	136000	25%/25%
> 1 Track within 5 cm of vertex	135000	99%/25%
Candidate vertex in FV	75000	55%/14%
Flash matched to longest track	22000	29%/4.0%
Track Containment	10000	49%/1.9%
Tack length > 75 cm	3000	30%/0.6%

CCInclusive Cuts



MicroBooNE Run Plan



- MicroBooNE approved for 6.6e20 POT in pre-SBN era.
- Collected 6.3e20 so far, will likely acquire our full approved data set by the 2017 Fermilab summer shutdown.
- Plan to continue running in neutrino mode after the shutdown.