Calibration and Detector Systematics for DUNE

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DUNE Physics Week

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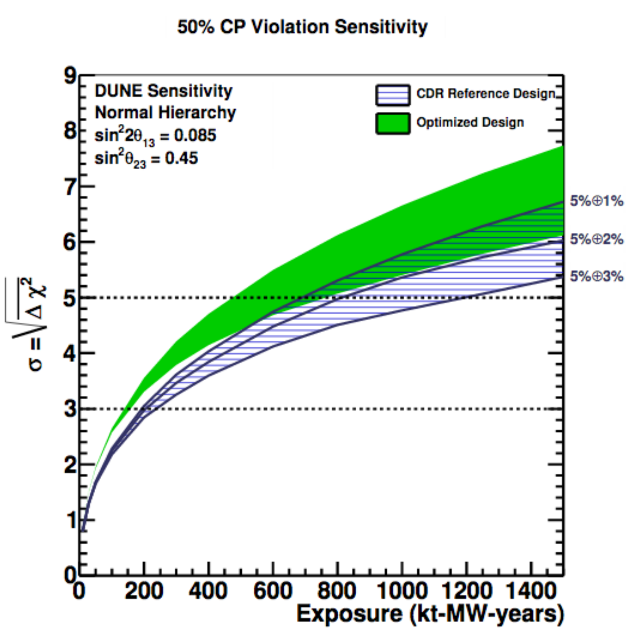
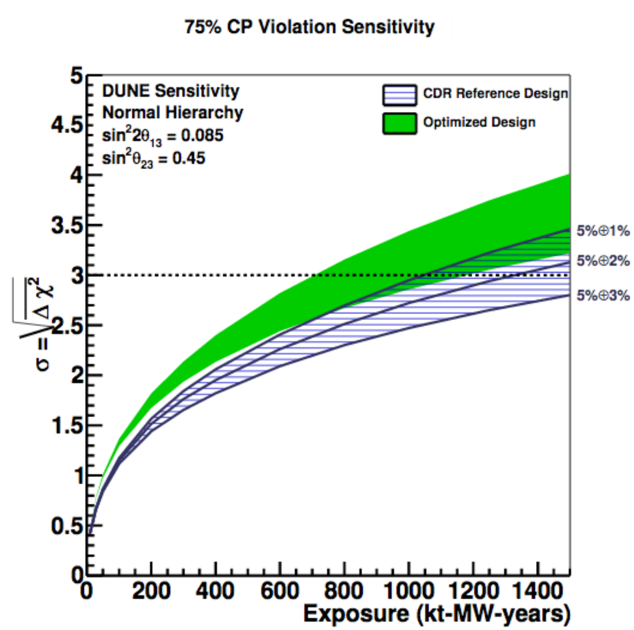
Introduction

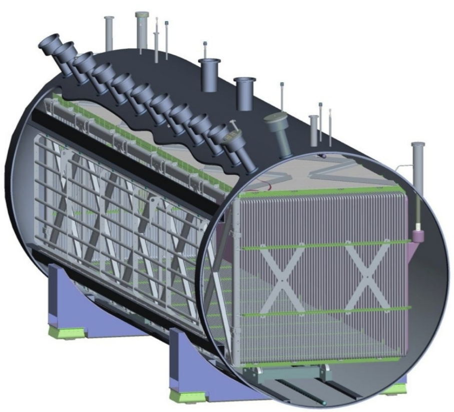
- DUNE is a hard experiment!
  - Our energy scale uncertainty budget is **2%** – this is in total… so each detector effect must be pinned down more precisely than that
- Careful percent-level calibration of DUNE FD will be **critical** to achieving CP violation result within lifetime of experiment
  - How well we can calibrate will set our **detector systematics**

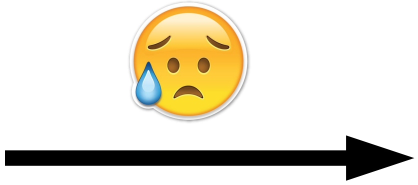


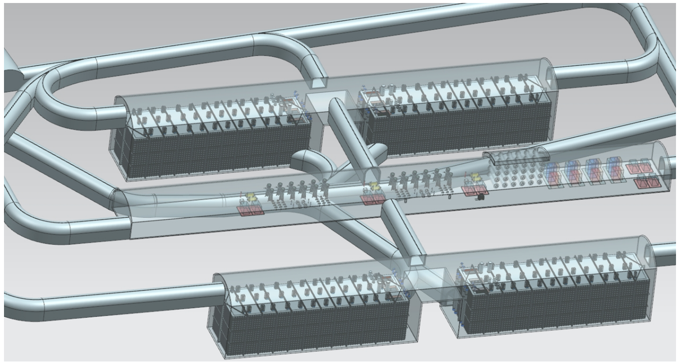


Different Paradigms

- Experience w/ MicroBooNE calibrations very helpful
- However, not a rinse-and-repeat!
  - Jump in calibration precision needs: **O(10%)** → **O(1%)**
  - Different calibration tools (e.g. few cosmics at DUNE FD)
- Correspondingly, some additional thought necessary



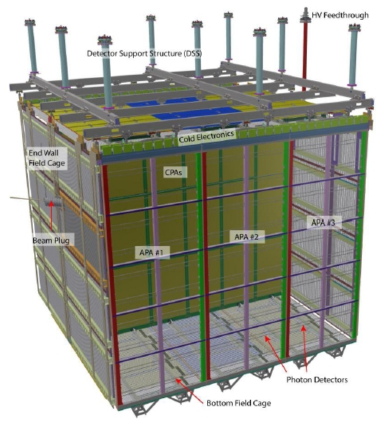




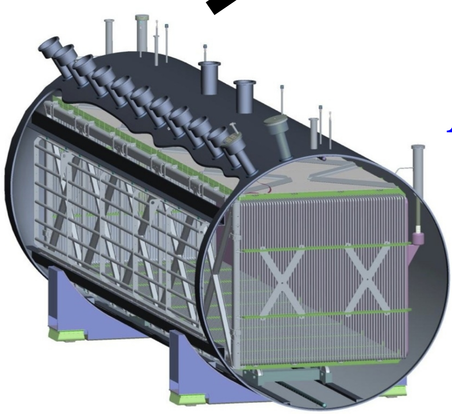
MicroBooNE:
A O(10%) Experiment

DUNE:
A O(1%) Experiment

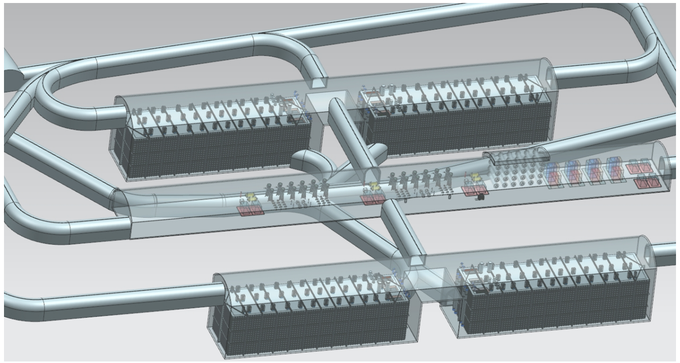
- Bridging the uncertainty gap with ProtoDUNE will be useful



ProtoDUNE:
An Intermediate Step



MicroBooNE:
A O(10%) Experiment



DUNE:
A O(1%) Experiment

TPC Calibration Items

- Break calibrations items into three categories: ex-situ, in-situ w/ pulser, in-situ w/ ionization signals
- Ex-situ (can also be performed in-situ, at least in principle):
  - Diffusion (longitudinal and transverse)
  - Recombination (angular/energy dependence, fluctuations)
  - Wire field response (modulo potential wire-to-wire variations)
- In-situ w/ pulser:
  - Electronics response (gain, shaping time, pole-zero effects, etc.)
  - ADC ASIC calibrations (linearity, other "features" like stuck codes)
- In-situ w/ ionization signals:
  - Electron lifetime (including spatial/temporal variations)
  - Space charge effects and other field effects (e.g. field cage resistor failure)
  - Wire field response wire-to-wire variations (negligible? should check)
- Nail these, then study "standard candles" in data (e.g. Michels)

TPC Calibration Items

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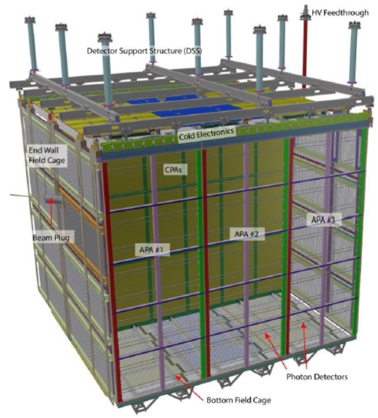
- Ex-situ (can also be performed in-situ, at least in principle):
  - Diffusion (longitudinal and transverse)
  - Recombination (angular/energy dependence, fluctuations)
  - Wire field response (module potential wire-to-wire variations)
- In-situ
  -
  - ADC AS… …ck codes)

This list neglects the photon detector system!
This deserves thought as well.

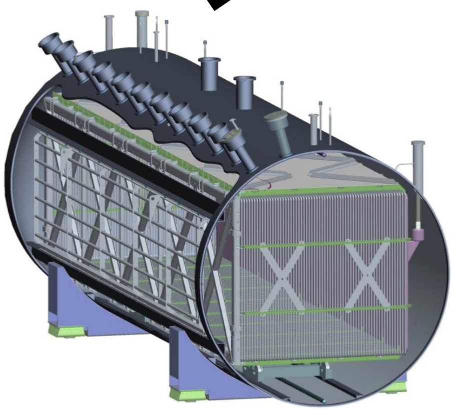
- In-situ w/ ionization signals:
  - Electron lifetime (including spatial/temporal variations)
  - Space charge effects and other field effects (e.g. field cage resistor failure)
  - Wire field response wire-to-wire variations (negligible? should check)
- Nail these, then study "standard candles" in data (e.g. Michels)

Differing Concerns

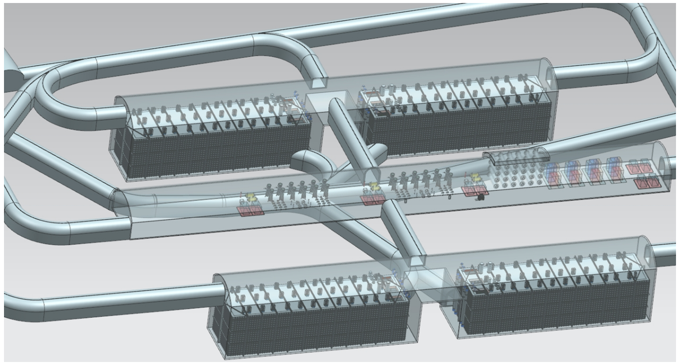
- Different experiments face somewhat different issues



All Items:
SCE Worse,
ADC Issues



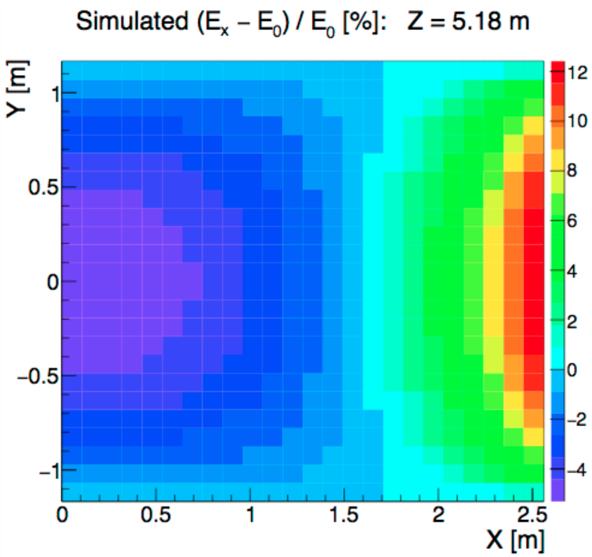
All Items Except ADC Issues
(And Less Requirements)



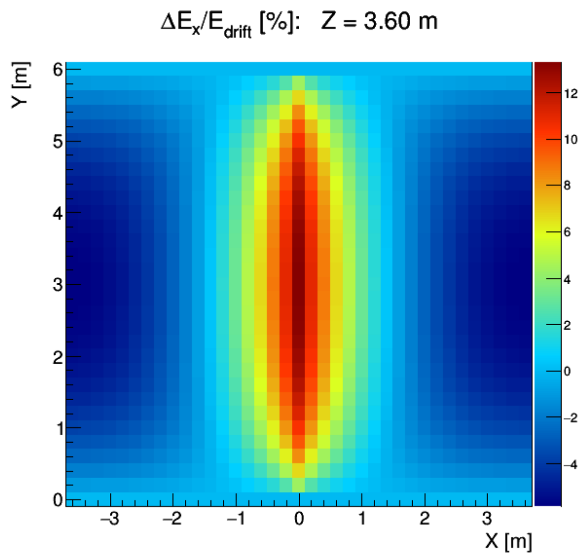
All Items Except
SCE, ADC Issues

Example: Space Charge Effects

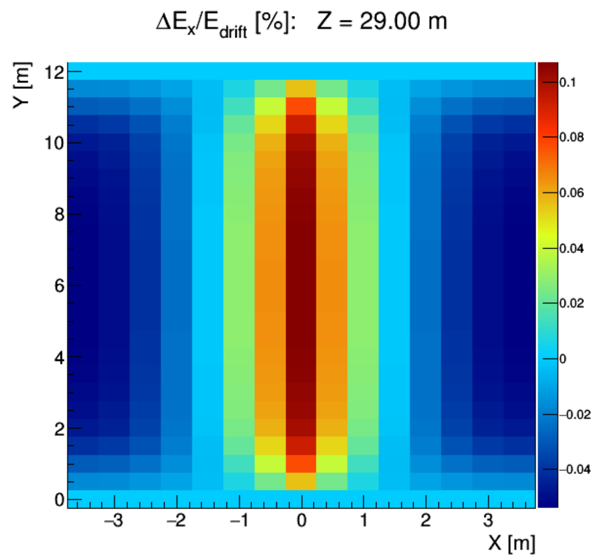
- Case study: space charge effects worse for detectors on surface
  - MicroBooNE and ProtoDUNE-SP see significant distortions
  - DUNE SP FD sees negligible impact (unless space charge piles up due to liquid argon flow pattern – not observed at MicroBooNE)



MicroBooNE:
O(15%) E Field Distortions
5-7% dQ/dx Bias



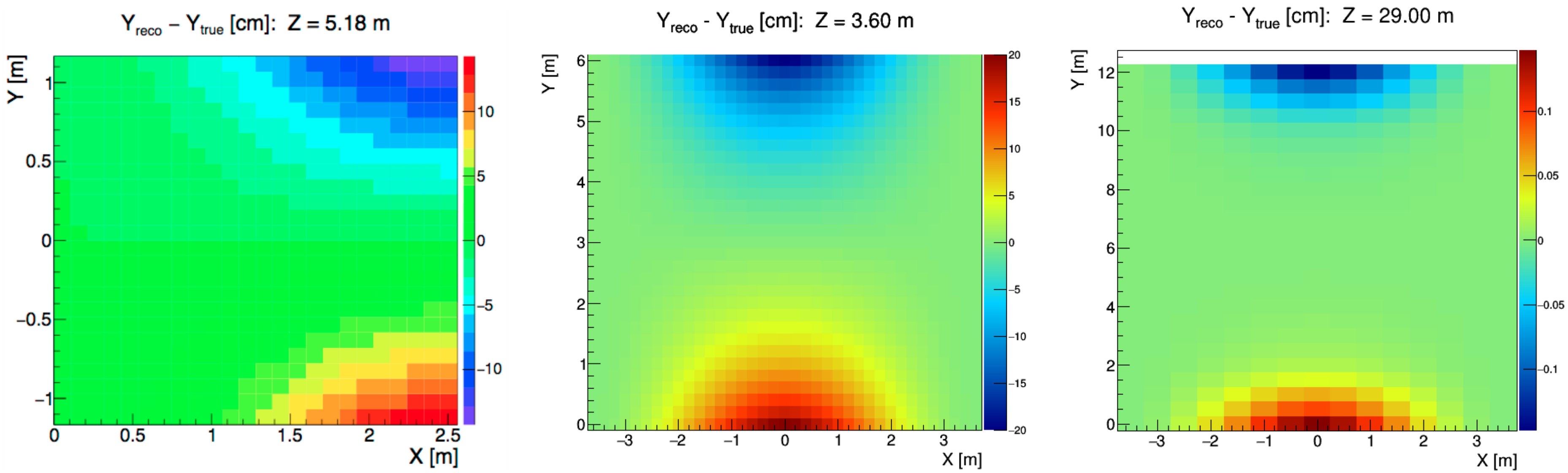
ProtoDUNE-SP:
O(15%) E Field Distortions
6-8% dQ/dx Bias



DUNE SP FD:
O(0.1%) E Field Distortions
< 0.1% dQ/dx Bias

Example: Space Charge Effects

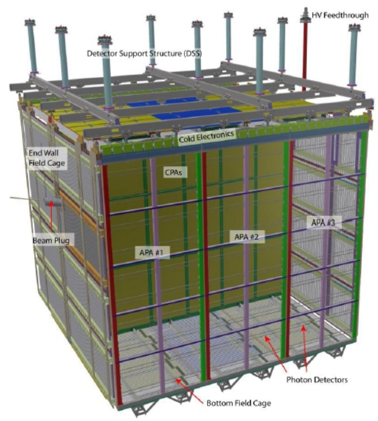
- ♦ <u>Case study</u>: space charge effects worse for detectors on surface
  - MicroBooNE and ProtoDUNE-SP see significant distortions
  - DUNE SP FD sees negligible impact (unless space charge piles up due to liquid argon flow pattern – not observed at MicroBooNE)



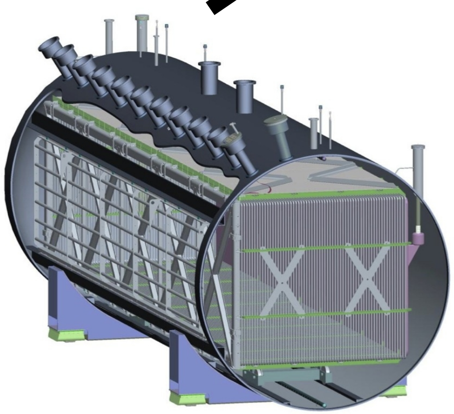
<u>MicroBooNE</u>:	**<u>ProtoDUNE-SP</u>:**	**<u>DUNE SP FD</u>:**
O(15 cm) Spatial Distortions	**O(20 cm) Spatial Distortions**	**O(0.1 cm) Spatial Distortions**
5-7% dQ/dx Bias	**6-8% dQ/dx Bias**	**< 0.1% dQ/dx Bias**

Differing Tools

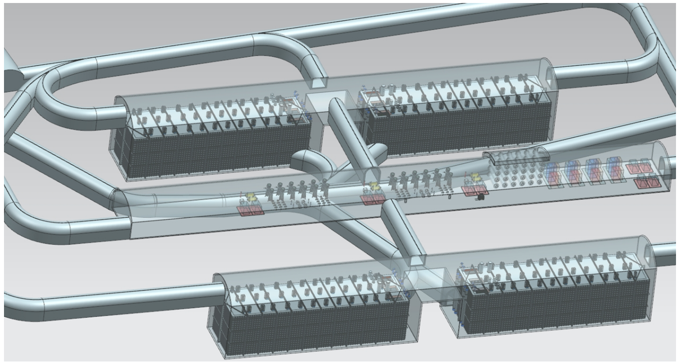
- Each experiment has different calibration tools to utilize



Partial CRT, Plenty of Cosmics/Michels, Ar-39



UV Laser System, Full CRT, Plenty of Cosmics/Michels, Ar-39

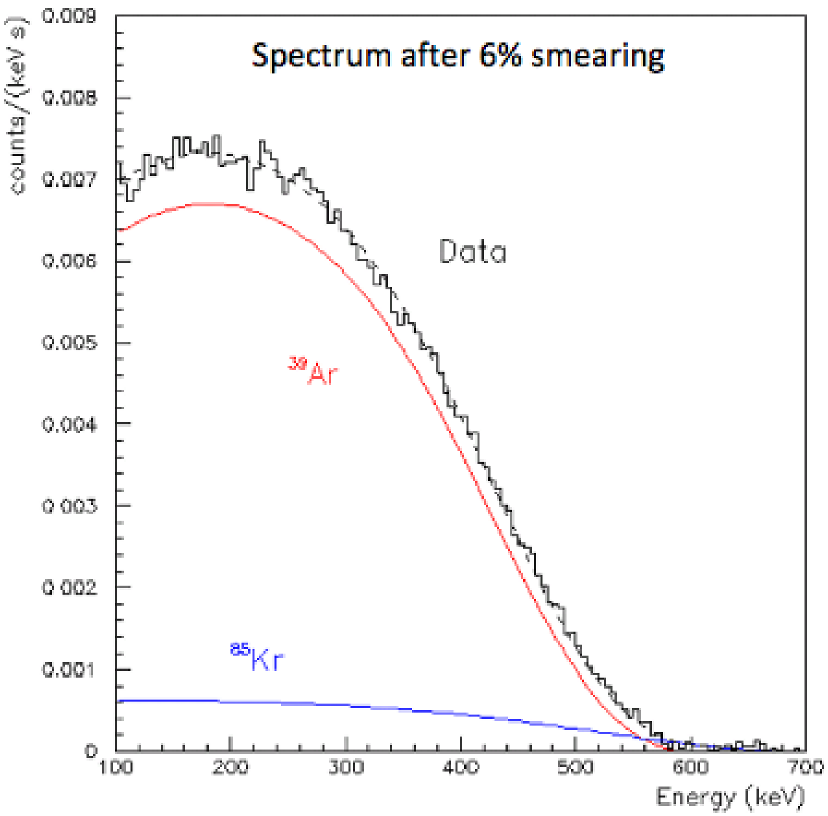


UV Laser System (?), Radioactive Sources (?), Few Cosmics/Michels, Ar-39

Reality Check for DUNE FD

- Many calibrations done at MicroBooNE utilize cosmic rays
  - MicroBooNE on surface → **4000 cosmics/second**
- Not a reliable option at DUNE FD due to being almost a mile underground
  - DUNE FD: **4000 cosmics/day** (and **20 Michels/day**)
  - … and this is for an entire 10 kt module!
  - Corresponds to 5 cosmics/day/m^3
- Cosmics can still help, but need alternative charge sources
- Plenty of Ar-39 beta decays at DUNE FD (O(50000) per readout) – good option that should be explored for DUNE
  - Can first **study use at MicroBooNE**
  - Some brief discussion is warranted here

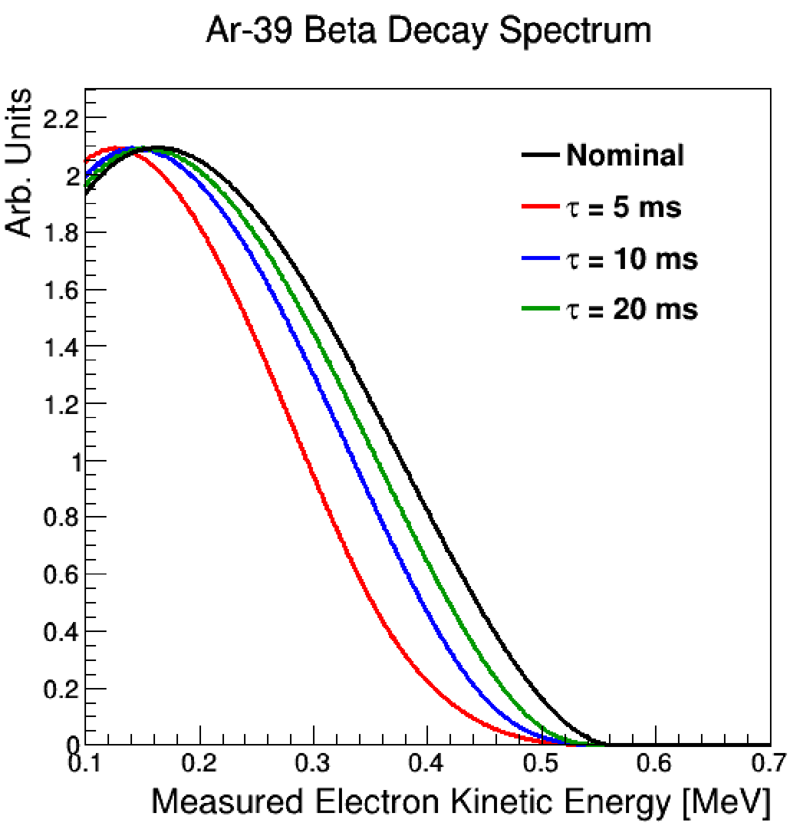
Ar-39 Beta Decays



Benetti et al., "Measurement of the specific activity of Ar-39 in natural argon" (2006).

- Ar-39 beta decay cut-off energy is 565 keV
  - This is **close** to the energy deposited on a single wire by a MIP at MicroBooNE
- Several things smear observed **charge spectrum**, e.g.:
  - Noise
  - Recombination fluctuations
  - Unknown location of Ar-39 decay in TPC
- <u>For last point</u>: we know decays are **uniform in x**

Ar-39 Beta Decays

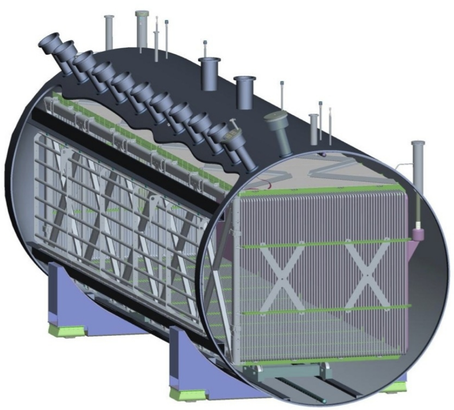


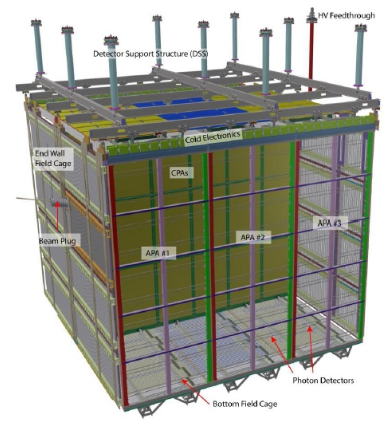
Example Use Case: Fine-Grained Electron Lifetime Measurement

- Ar-39 beta decay cut-off energy is 565 keV
  - This is **close** to the energy deposited on a single wire by a MIP at MicroBooNE
- Several things smear observed **charge spectrum**, e.g.:
  - Noise
  - Recombination fluctuations
  - Unknown location of Ar-39 decay in TPC
- For last point: we know decays are **uniform in x**

MicroBooNE Calibrations

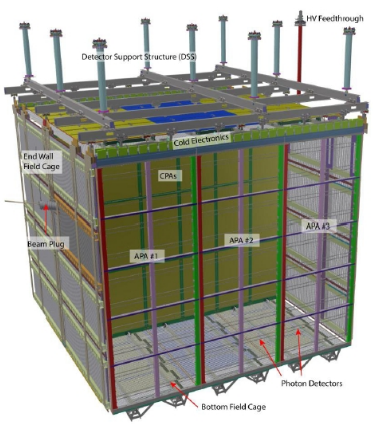
- Several calibrations still in progress at MicroBooNE
  - Brief overview of some preliminary results in backup slides
  - Will inform calibration efforts at both ProtoDUNE and DUNE FD

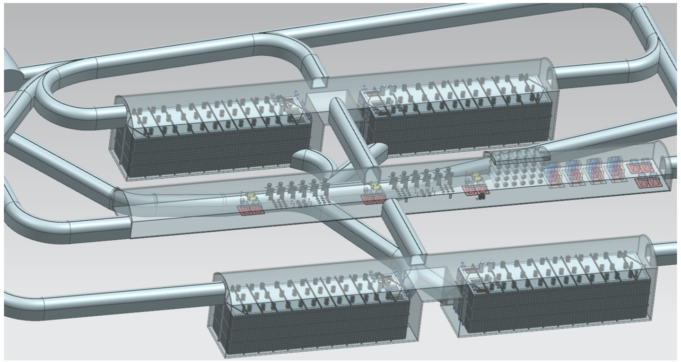




ProtoDUNE Calibrations

- No data yet of course, but already planning out calibrations at ProtoDUNE
  - Goal: calibrate ProtoDUNE, learn as much as we can about DUNE FD
    - Keep in mind: negligible SCE and no ADC issues at DUNE FD
  - A lot of discussion in DUNE "DRA" meetings (Thursdays, 8 am CT)
    - ProtoDUNE-SP calibrations convener: Mike M.





DUNE Physics Week Goals

- Main goal for the DUNE physics week is very basic: get the discussion going regarding calibrations and detector systematics at DUNE (including utilizing ProtoDUNE data)
  - Detector systematics for **LBL physics** is a good motivator
- Beyond that:
  - Create a priority list for things most important to tackle in calibrations (based upon what we think will impact us the most)
    - Preliminary list (TPC only) earlier in talk, but should “rank”
  - Study impact of **individual systematics** on LBL sensitivity
    - Requires some tool development, interface to simulations/reco.
    - Maybe start with a “simple” case study, like electron lifetime?
- Please let me know if you're interested in contributing!
- Questions?

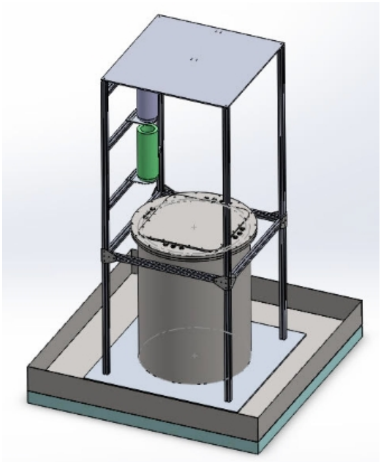
BACKUP SLIDES

Calibrations with Ar-39

- Can use Ar-39 beta decays for two types of calibrations: **normalization** and **shape**
- Normalization (reconstructed energy):
  - Electron lifetime (spatial/temporal variations)
  - Recombination (at low energies)
- Shape (shape of signal on wires):
  - Field response (variations across wires)
  - Diffusion (longitudinal and transverse)
- Also measure Ar-39 rate, study low-energy charge detection/reconstruction (e.g. for SN neutrino studies), use methods to study other radiological sources in TPC, etc.
- Can't t_0 tag, but **uniform in x**, enabling calibrations use

Recombination and Ar-39

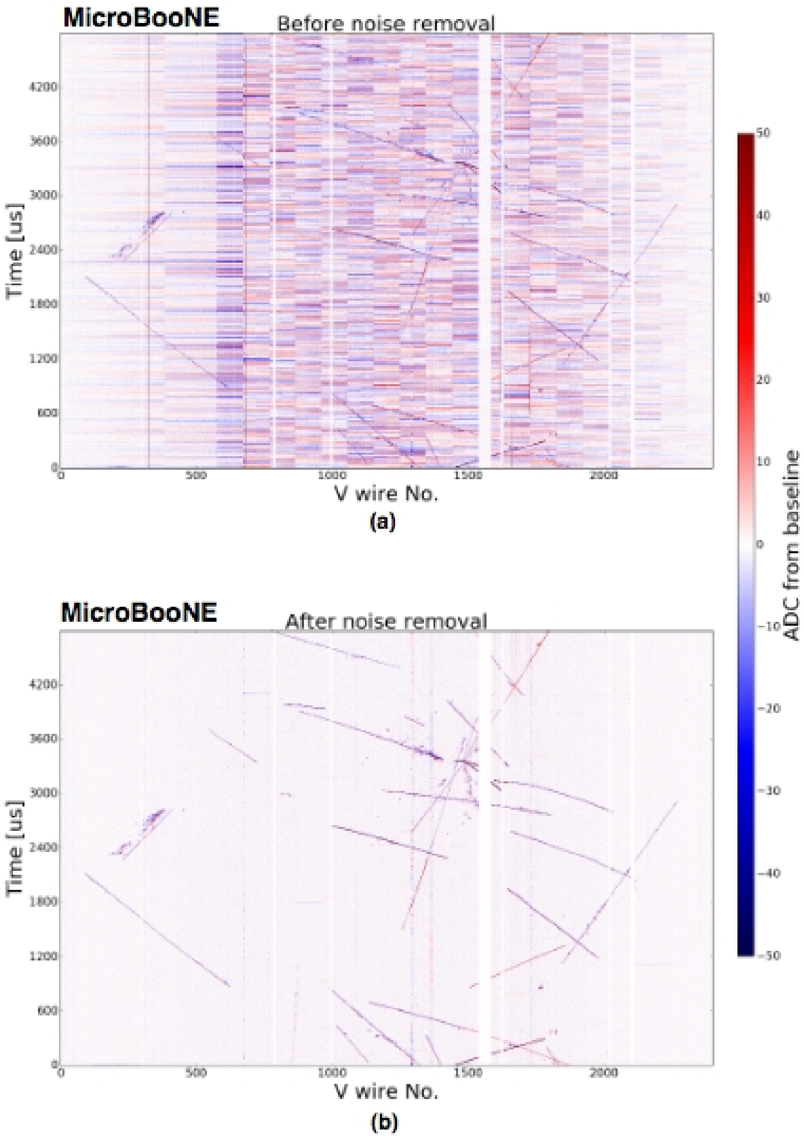
- Lack of knowledge of recombination will complicate use of spectrum for nailing down electron lifetime
  - Need to know both mean recombination and fluctuations in recombination at this energy scale
  - Chatting with experts, conclusion is that we don't know this very well for argon, needs study for precision calibration
- Ahead of DUNE, **measure Ar-39 charge spectrum**
  - Being studied by CSU group at MicroBooNE (ongoing)
  - In separate TPC setup for precision measurement
    - Underground
    - Short drift
    - t_0 tag from light

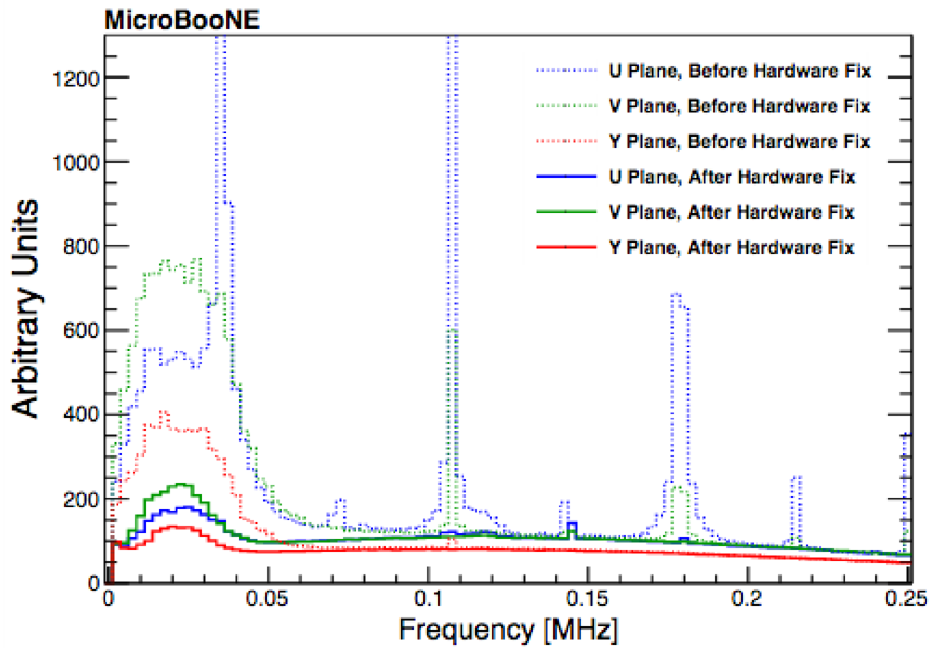


M. Mooney, D. Warner

Conceptual design for portable cryostat

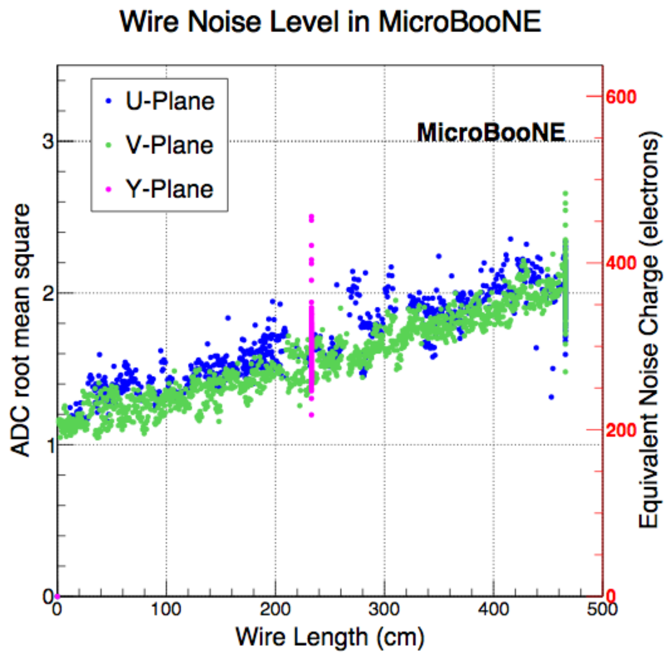
Filtering Out Excess Noise

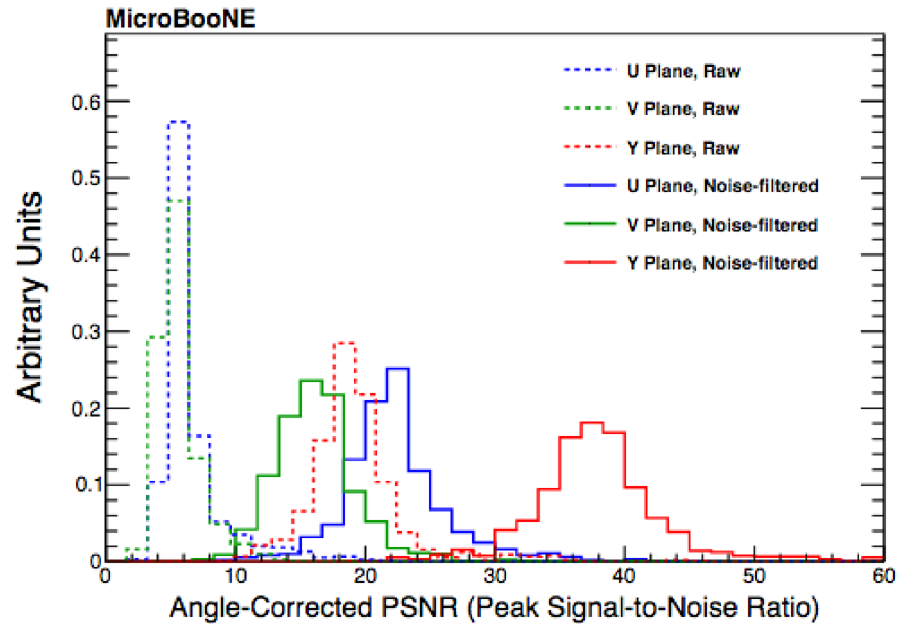




- MicroBooNE originally had excess noise "out of the box"
- Developed software noise filtering scheme – virtually gone
- Also addressed in hardware

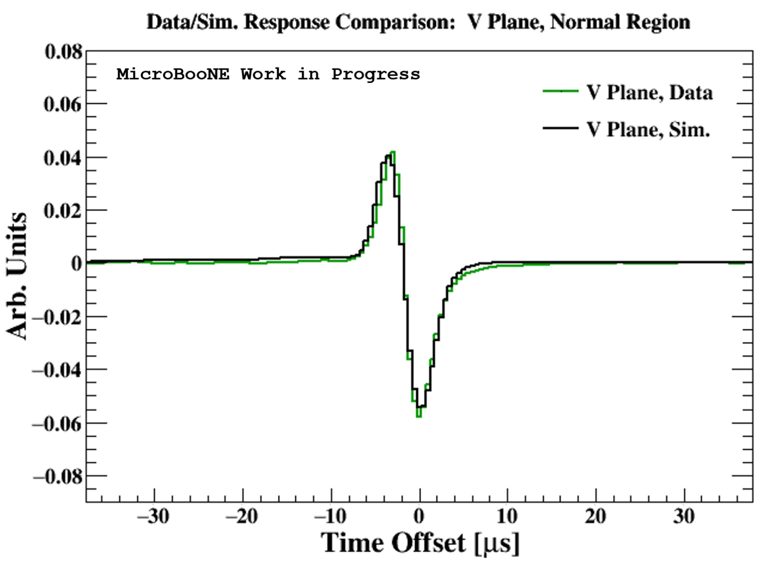
Noise Filtering Performance

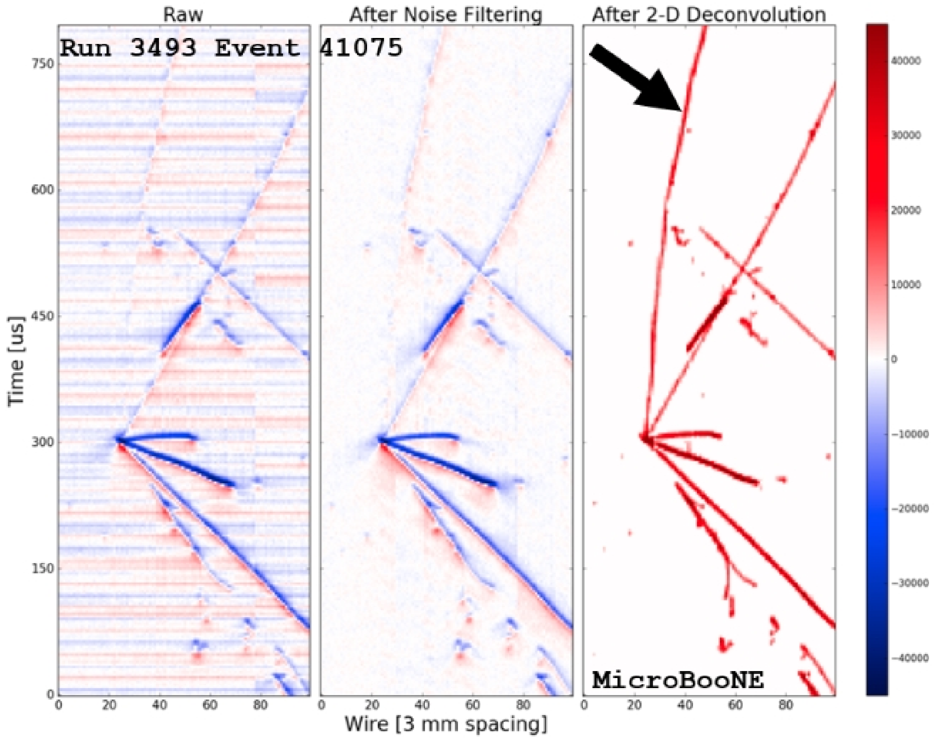




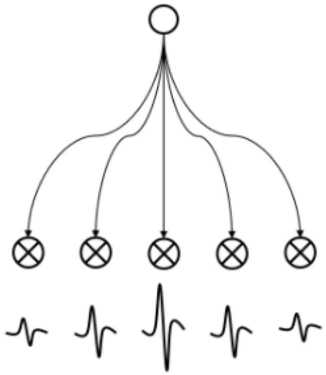
- Noise level rises linearly with capacitive load (wire length) after noise filtering, **matches test stand expectations**
- After noise filtering, Peak Signal-to-Noise Ratio (PSNR) increases from **20** (**6**) to **38** (**19**) for **collection** (**induction**) plane(s)
- See **MicroBooNE noise paper**

Signal Processing



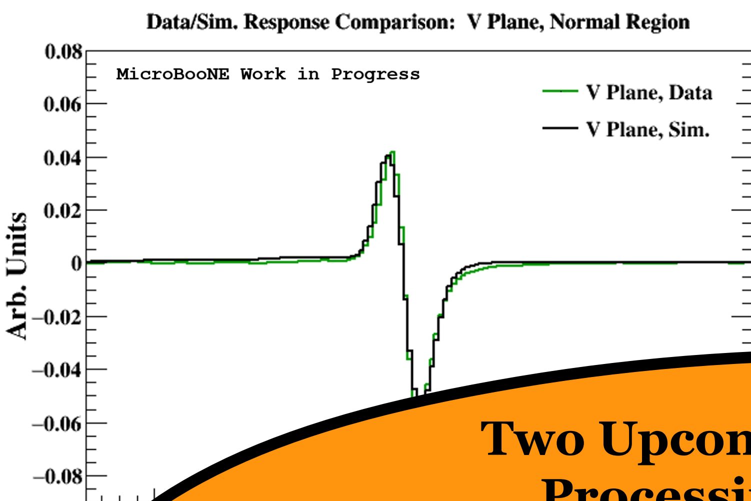


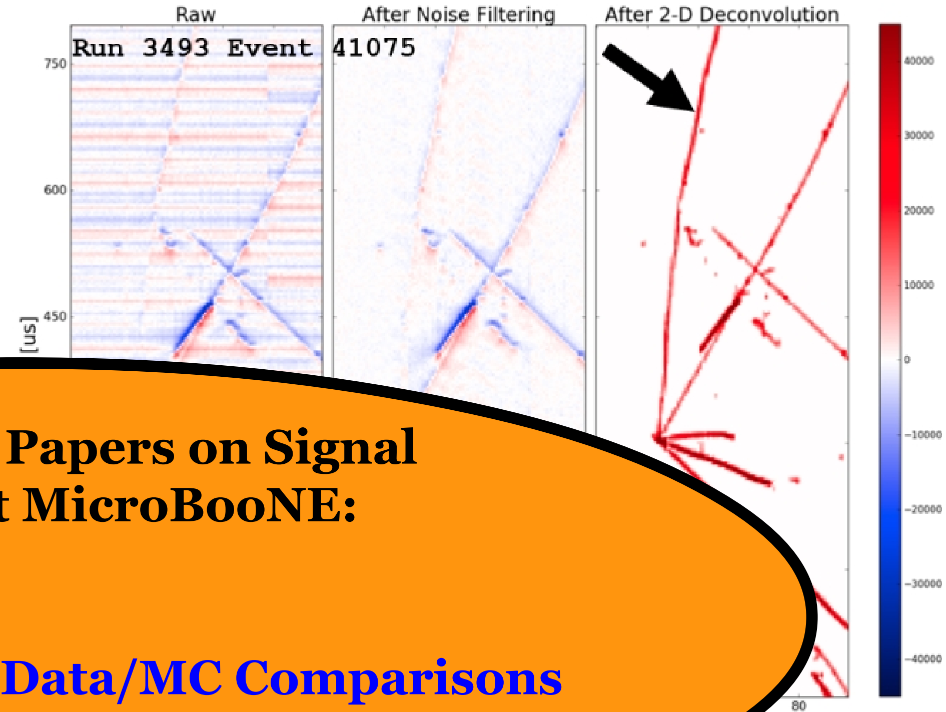
APS Four Corners Parallel Talk by Ivan Caro Terrazas (CSU Student)



- Tuned wire field response simulation to data
- Account for induced charge on neighboring wires
  - Leads to recovery of tracks at high angle w.r.t. anode
- Redo simulation for DUNE (~5 mm pitch vs. 3 mm)

Signal Processing





Two Upcoming Papers on Signal Processing at MicroBooNE:

1) **Methodology**
2) **Performance, Data/MC Comparisons**

Stay Tuned!

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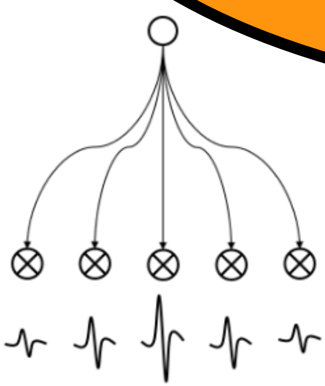
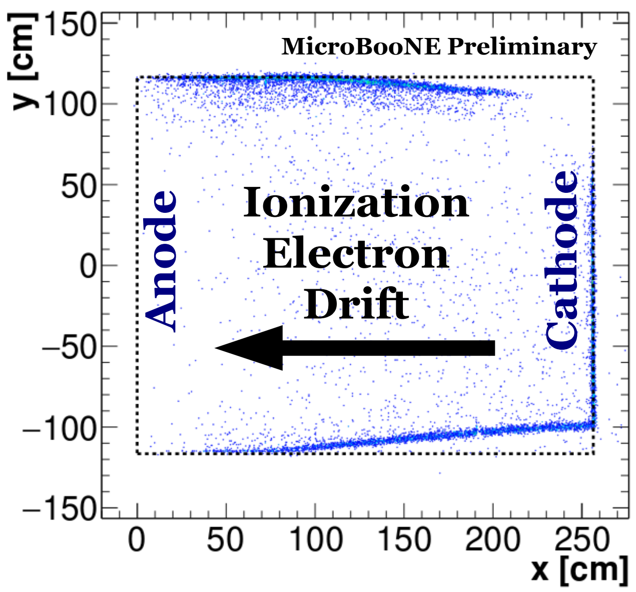


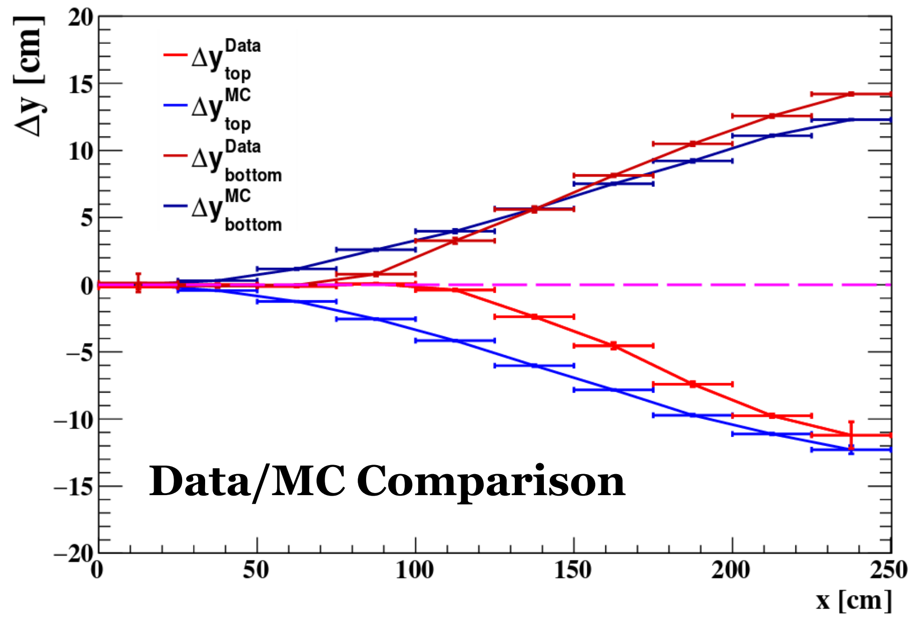
♦ T… …tion to data

♦ Account for induced charge on neighboring wires
  - Leads to recovery of tracks at high angle w.r.t. anode

♦ Redo simulation for DUNE (~5 mm pitch vs. 3 mm)

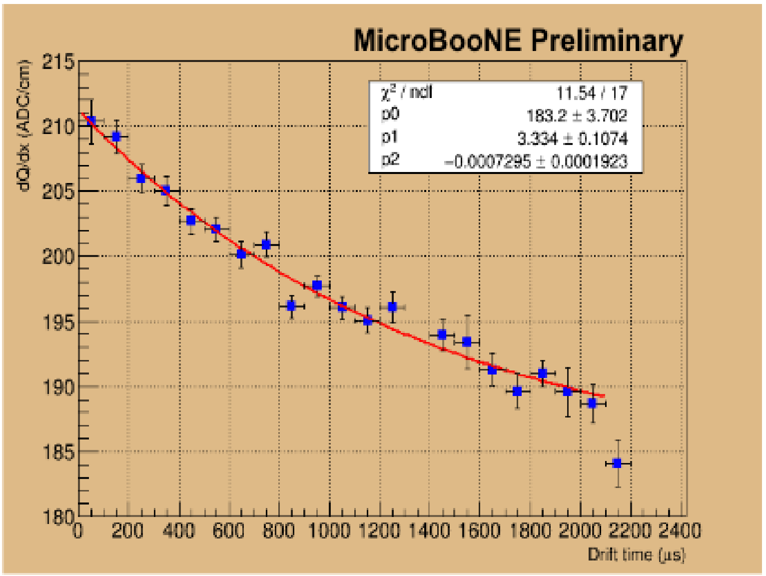
Space Charge Effects

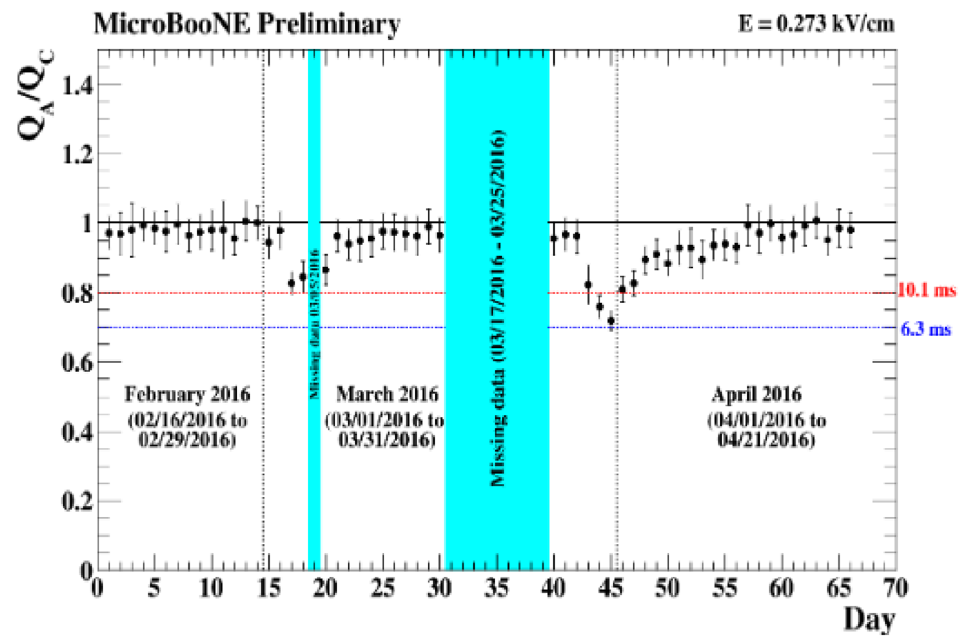




- Studied SCE spatial distortions using muon counter system
- SCE simulation qualitatively reproduces effect
  - Agreement in normalization, basic shape features, but offset near anode in data… impact from **liquid argon flow?**
  - Calibration in progress using UV laser system, cosmic muons
- See **MicroBooNE public note on SCE studies**

Electron Lifetime Measurement

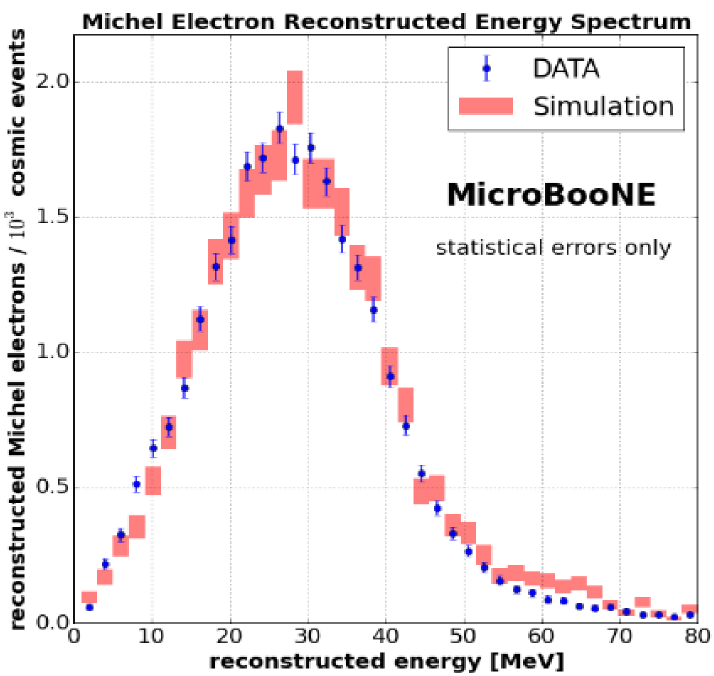


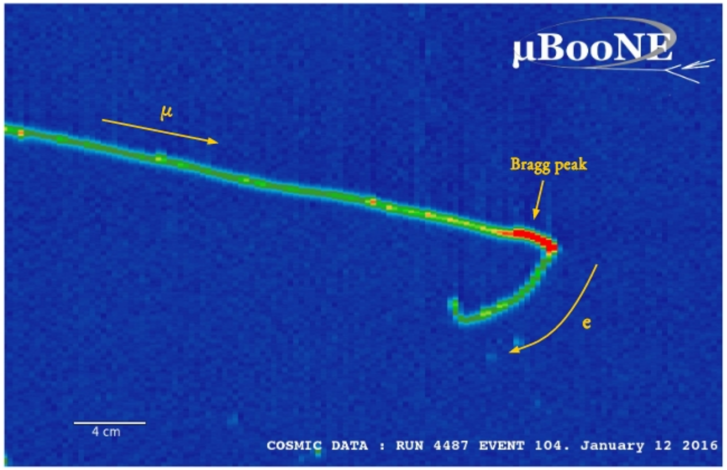


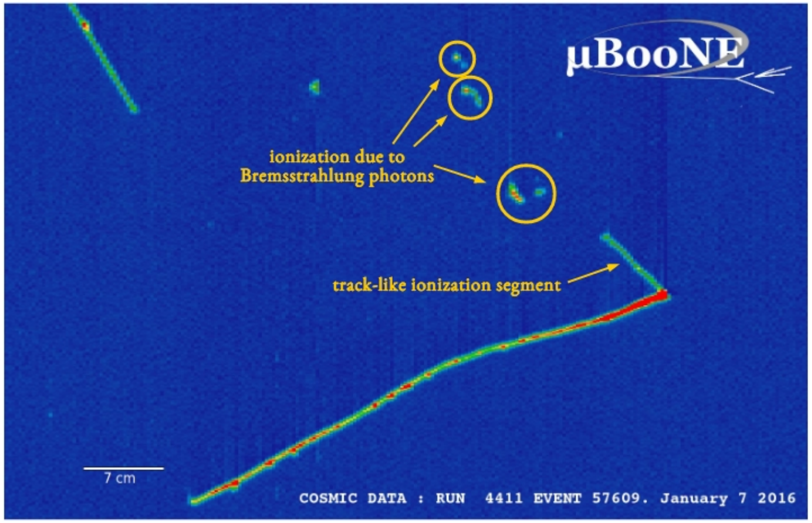
- Measured electron lifetime daily by fitting to distribution of cosmic muon track dQ/dx vs. ionization electron drift time
  - Complications from space charge effects (systematic for first pass)
- Lifetime consistently **above 10 ms**, often much higher
- See **MicroBooNE public note on electron lifetime**

Michel Electron Spectrum

- Tag Michel electrons from cosmic muon decay using “kink” topology and muon Bragg peak
  - Callibration sample for **energy scale**, tuning **e⁻, γ reco.**
  - Tells us how well we **cluster charge**
  - See **MicroBooNE Michel paper**



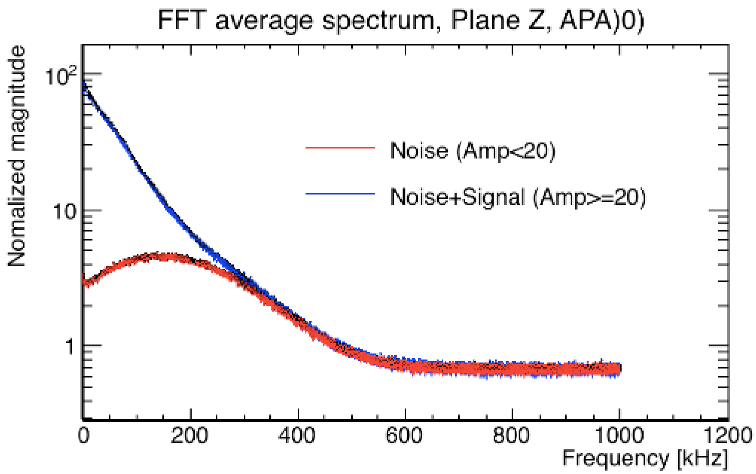


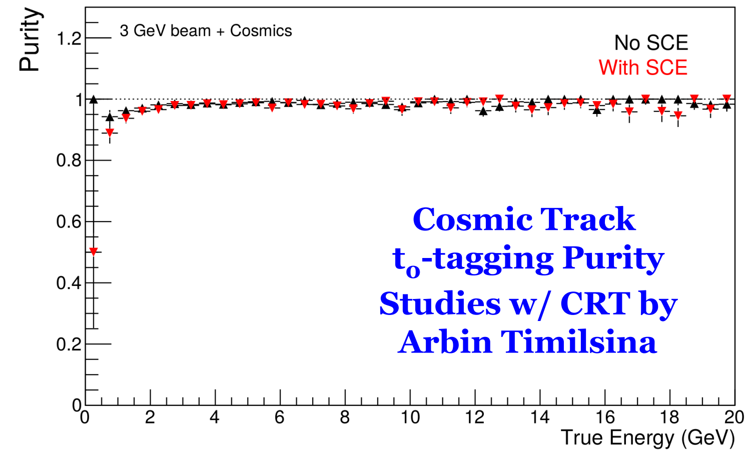


ProtoDUNE Developments

Data-Driven Noise Model Implemented by Jingbo/Mike

Based on work by Adam Lister, Jyoti Joshi and others at BNL



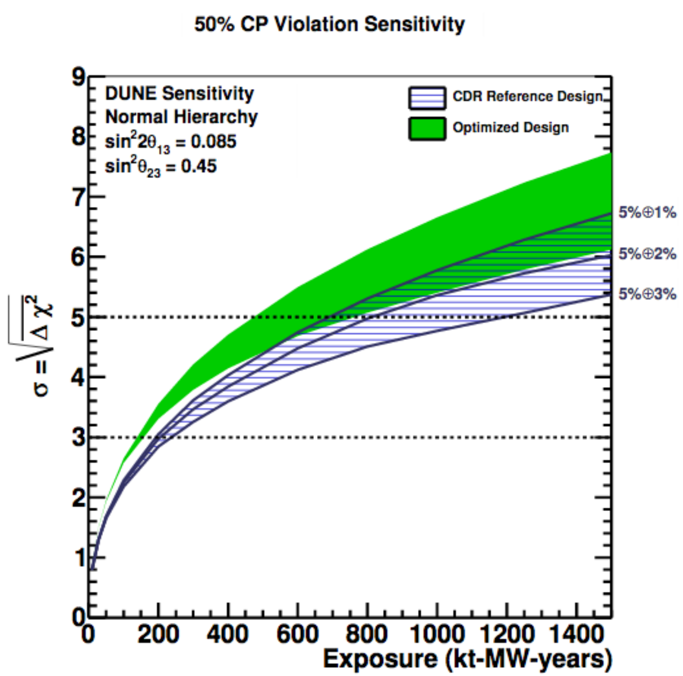


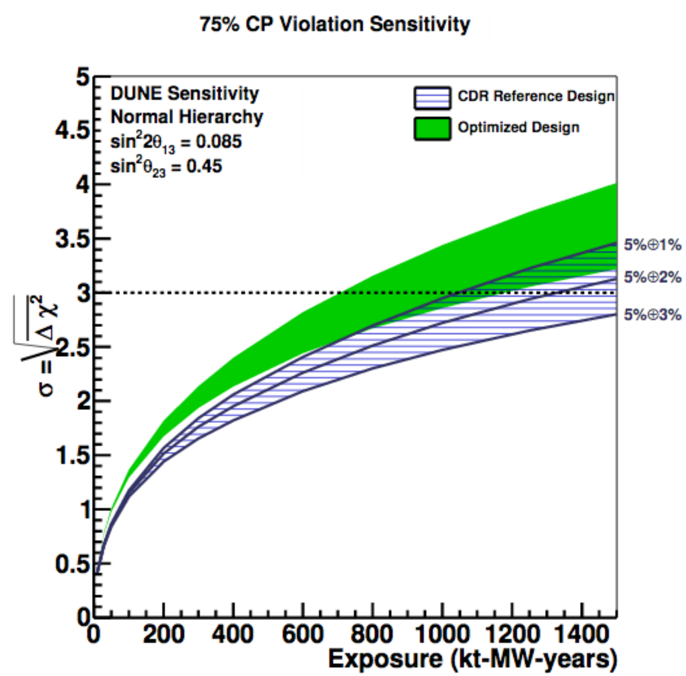
Cosmic Track t_o-tagging Purity Studies w/ CRT by Arbin Timilsina

- Many ongoing ProtoDUNE calibration studies
  - New noise model (based on MicroBooNE)
  - Signal processing updates
  - Track-based calibrations (e.g. t_o-tagging with CRT)
  - Study/calibration of ADC “features” (Ryan LaZur, CSU student)
  - Studying impact of SCE in numerous ways
  - … and many other topics!

Summary

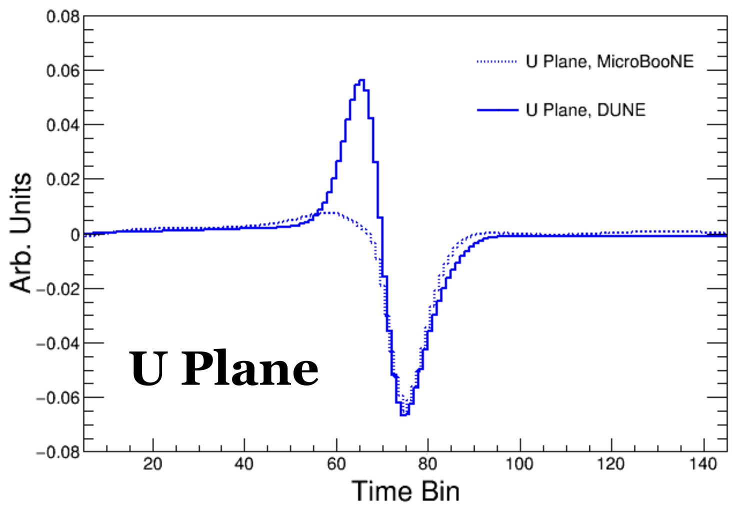
- Again… DUNE is a hard experiment!
  - <u>Remember</u>: our **total** energy scale uncertainty budget is **2%**
- Precision calibrations are essential for DUNE physics program
  - Learn from experiences at MicroBooNE
  - Extrapolate to DUNE FD via studies at ProtoDUNE

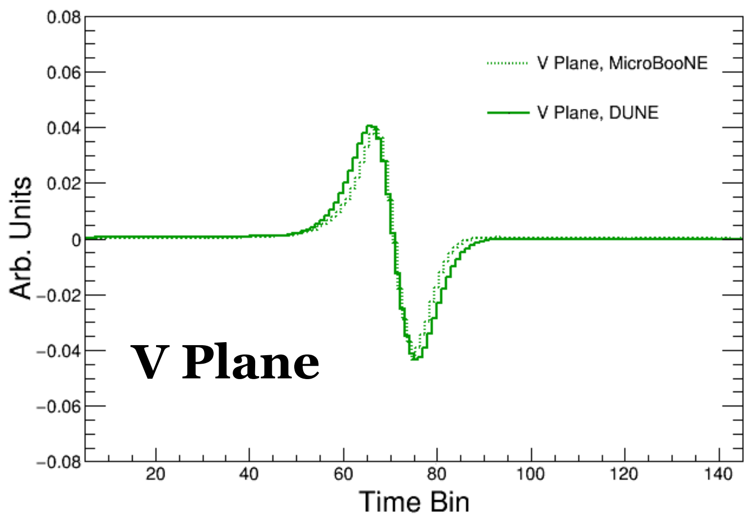


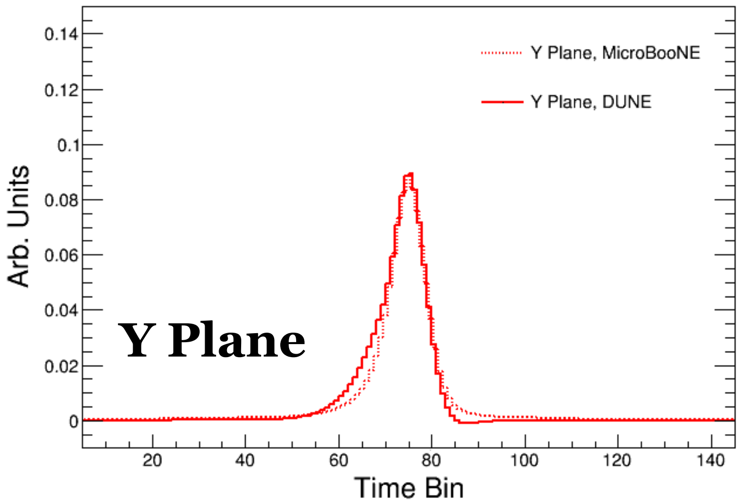


Field Response Comp.

- Compare DUNE and MicroBooNE, full responses (field and electronics)
- Fix max signal amplitude in comparison
- Very similar shape, despite MicroBooNE at 273 V/cm due to larger inter-plane distance

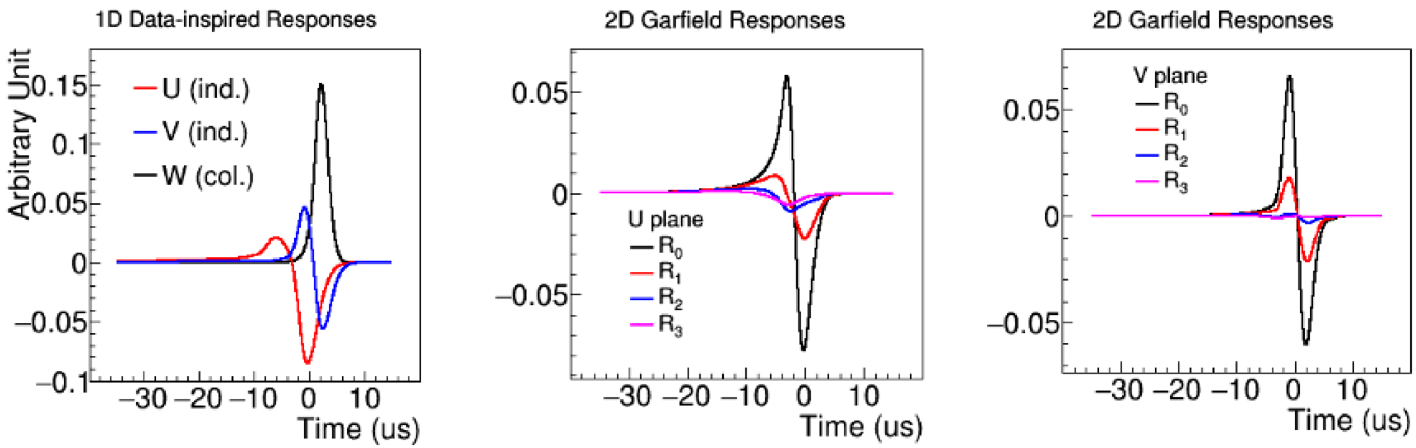






MicroBooNE SP Public Note

- MicroBooNE has released public note documenting signal processing techniques useful for LArTPC experiments
  - See public note here: **MICROBOONE-NOTE-1017-PUB**
- This note describes 2D deconvolution technique
  - Technique improved since public note – paper forthcoming
  - Nature of detector response different than current assumption that only closest wire matters (see below figure)
  - Worst for MicroBooNE (3 mm spacing), still important for PD-SP



Signal Processing Concepts

- Also detailed in the note is the importance of a deconvolution filter – prevents noise blow-up when dividing out response

Deconvolution → $$S(\omega) = \frac{M(\omega)}{R(\omega)} \cdot F(\omega)$$

$$F(\omega) = \frac{S^2(\omega)}{S^2(\omega) + N^2(\omega)}$$ ← **Wiener Filter**

- Wiener filter gives optimal peak-to-peak separation, but if fitting to Gaussians (GaussHitFinder) ⟶ better to use Gaussians!