MINERvA calibrations for 2x2

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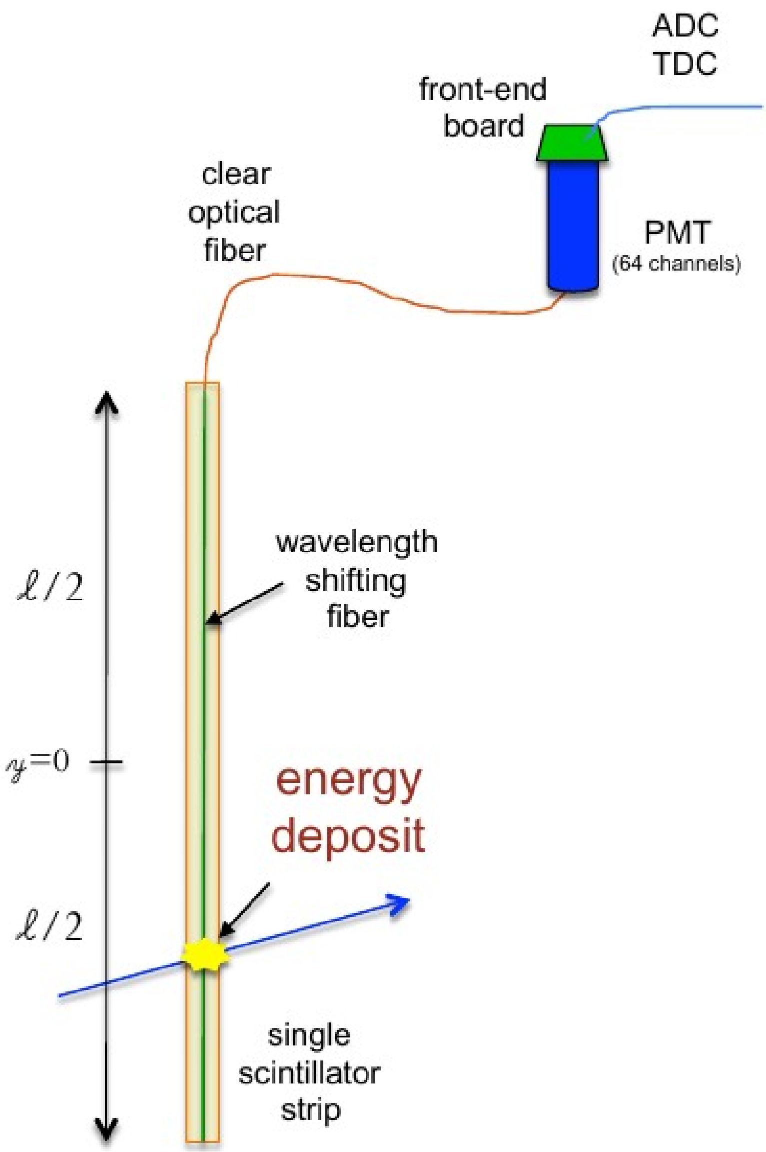
19 January, 2023

Why I am giving this talk

- I was a Ph.D. student on MINERvA 2010-2016
- Analysis was K^+ production, which used timing information in a unique way within MINERvA
- Primary service contribution was calibrations work:
  - Made substantial algorithmic improvements to relative energy calibration ("strip to strip" or S2S), plane alignment calibration, and timing calibration, and maintained those calibrations for ~5 years
  - Developed algorithmic way to determine plex
  - Maintained calibrations postgres database
  - Developed and maintained a quasi-automated calibrations production procedure
- Main reference for all of this is arXiv:1305.5199

Basic overview of muon to DAQ



- Ionization energy produces scintillation light in plastic strip
- Light is absorbed and re-emitted by WLS fiber
- Light propagates down WLS fiber in strip, then through clear fiber to PMT box, with some loss due to attenuation
- Photoelectrons are amplified by PMT
- PMT signal is digitized by FEB, giving pulse height in ADC counts and timestamp in clock ticks

Calibration high-level overview

$$E_i = \left[C(t) \cdot S_i(t) \cdot \eta_i^{att} \cdot e^{\ell_i/\lambda_{clear}} \cdot G_i(t) \cdot Q_i(\mathrm{ADC})\right] \times \mathrm{ADC}_i$$

- E_i = energy in strip i
- ADC_i = ADC counts in channel i
- Q_i(ADC) = FEB calibration ADC → Q
- G_i(t) = PMT gain Q → PE
- l_i, λ_{clear} = fiber length outside of strip and attenuation length
- S_i(t) = relative energy correction (strip to strip)
- C(t) = global energy scale factor PE → MeV
- Missing from this formula: plex, pedestals, alignment, cross-talk

Rest of this talk outline

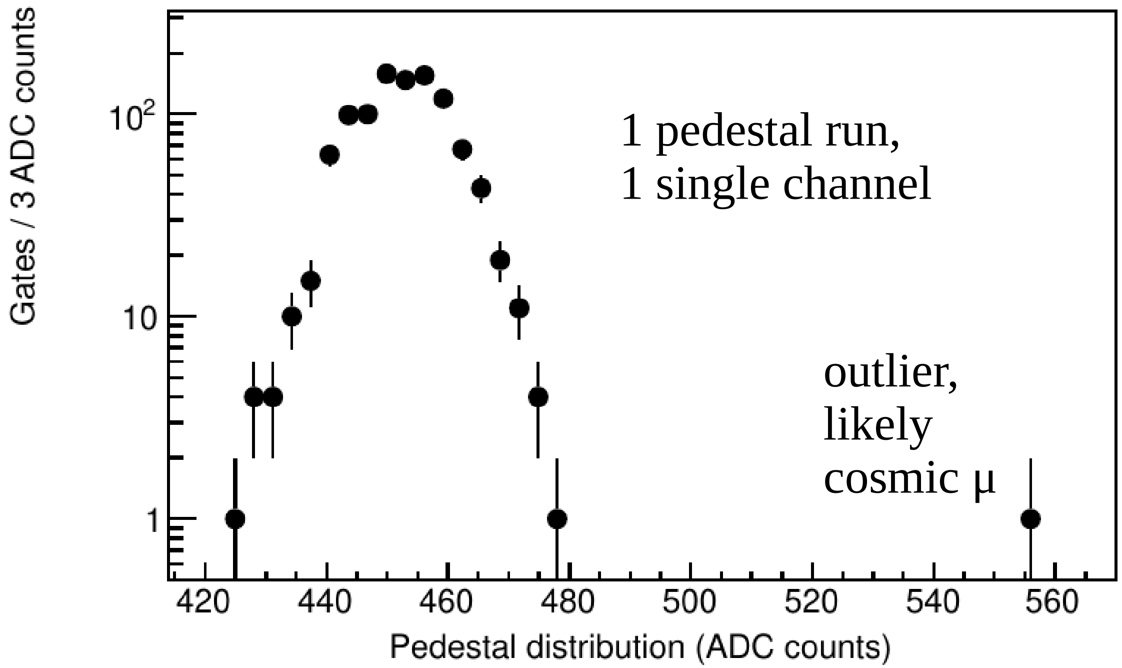
- Step through each calibration, address:
  - What does it do?
  - How is the calibration stored and accessed?
  - How is the calibration determined, and with what frequency?
  - Is it actually needed for 2x2?
  - Can we re-use anything from original MINERvA?
  - Who are the experts?

Plex

- Map of electronics address (crate-croc-chain-board-channel) to physical strip (module-plane-strip)
- Stored in xml files (one for each plane), code reads xml into a C++ map from a ChannelID to StripID and vice versa
- xml files are mostly created from knowledge of the fiber weave, O(50) “errors” were determined from looking at correlations between muon path length in one strip and energy in another
- Absolutely required for 2x2 for any tracking in MINERvA
- Existing plex files must be mapped to the new plane locations, and otherwise the existing calibration can just be used
- In principle, plex can change when PMTs are swapped, but not when FEBs are swapped, because there are two fiber weaves
- Experts: CM, Rob Fine

Pedestal calibration

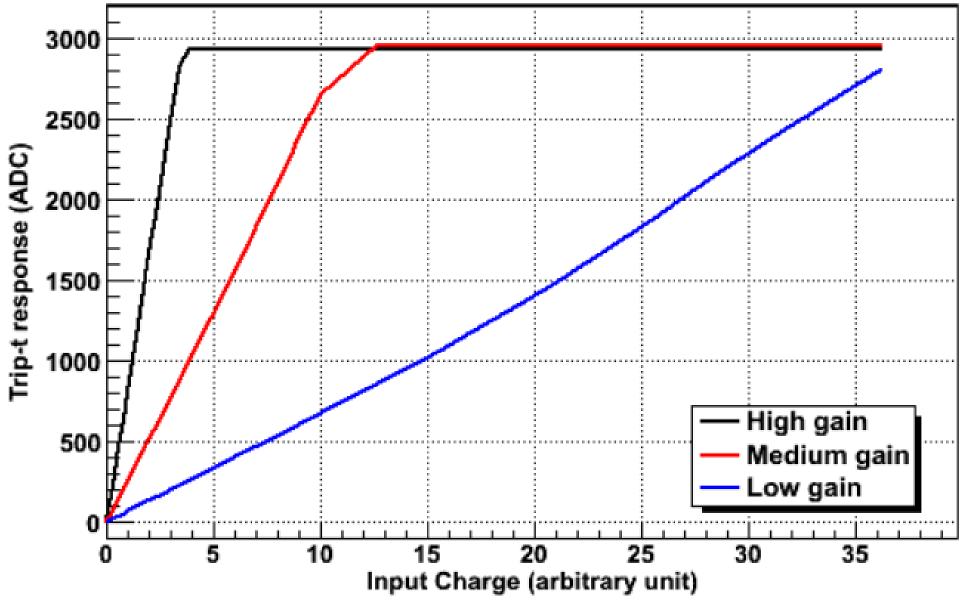
- Measures baseline ADC counts when no energy deposits are present, observed variations of ~7% across channels
- Stored and accessed via postgres database
- Determined from dedicated pedestal triggers taken in between beam triggers, about 1000/day during dedicated pedestal subrun



- Critical for 2x2 for any tracking
- Algorithm can be reused from MINERvA, but new pedestal data will need to be continuously taken
- Expert is Aaron McGowan (teaching faculty at RIT, and willing to help but would need some support, and is not a good candidate to continuously maintain the calibration)

FEB calibration

- Measures ADC response to charge
- Stored in text files that give tri-linear fit parameters to each gain channel (18 numbers total, high gain is by far most important)
- Not time dependent – one file for each FEB for all time

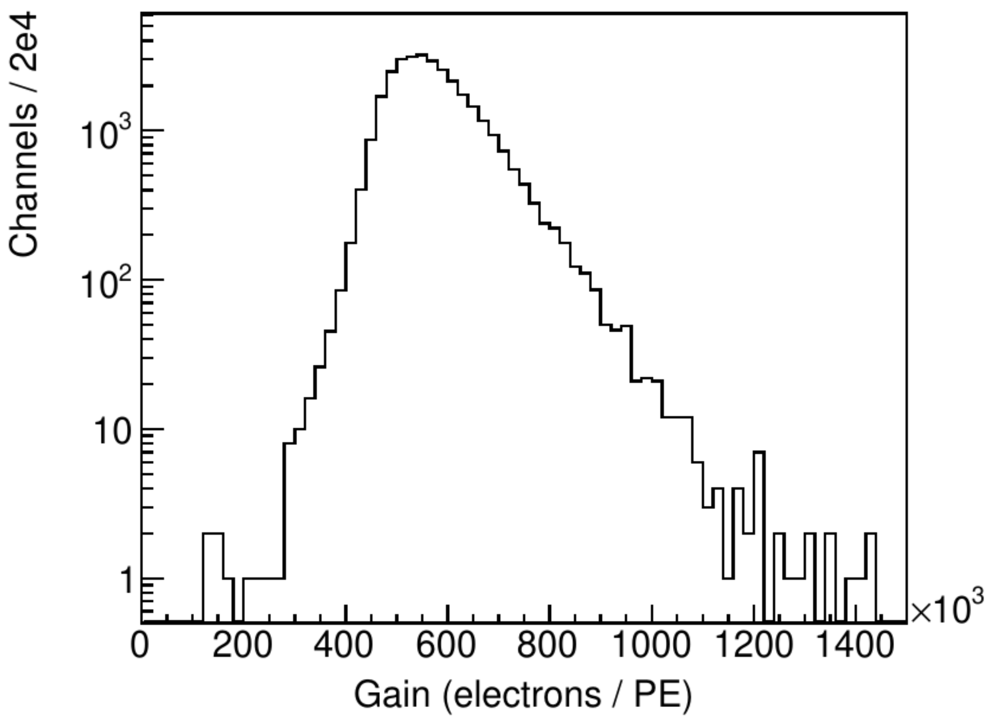


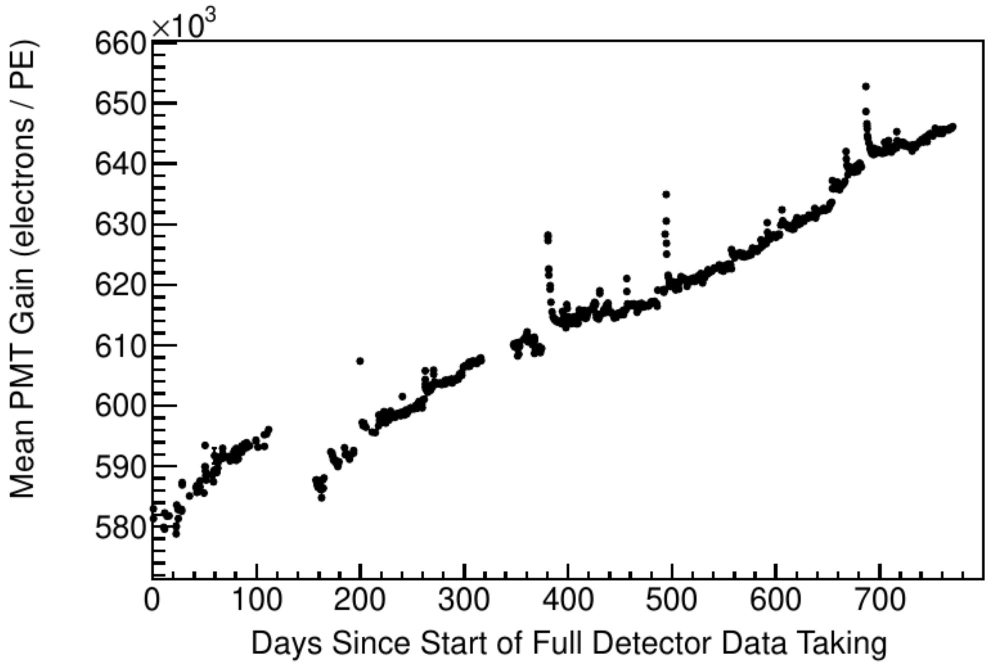
- Measured on bench, data exists for every FEB that there is, can be reused, but need to map FEB serial numbers to board addresses
- Not sure what variations are, it might be possible to just use a typical file for all boards for 2x2 at cost of some loss of uniformity, but probably it is easy enough that we should just do it
- Fairly sure all students who worked on this have left field

PMT gain calibration

- Measures PMT charge (in electrons) per photoelectron, used to determine the number of PE
- Gain of every channel is stored in postgres database
- Measured using dedicated light injection data runs, about once every ~few days; light level decreases vs. time due to aging
- Algorithms could be reused, but LI data would need to be continuously taken; automated LI production would need to likely be re-written, and code probably will not “just work”
- I believe this is one of the more time consuming calibrations for 2x2, so I will devote several slides to the consequences of not doing it
- Original expert is Brandon Eberly, Cheryl Patrick maintained this calibration for several years and is a DUNE member who might be persuaded to work on it

PMT gain calibration: variations





- Significant variation from channel to channel at any one time (~30%), general upward slope vs. time due to aging effects
- Significant changes whenever target voltages are modified, and also whenever any hardware is swapped → likely requires regular maintenance

PMT gain calibration: what if we just didn't do it

$$E_i = \left[C(t) \cdot S_i(t) \cdot \eta_i^{att} \cdot e^{\ell_i/\lambda_{clear}} \cdot G_i(t) \cdot Q_i(\mathrm{ADC})\right] \times \mathrm{ADC}_i$$

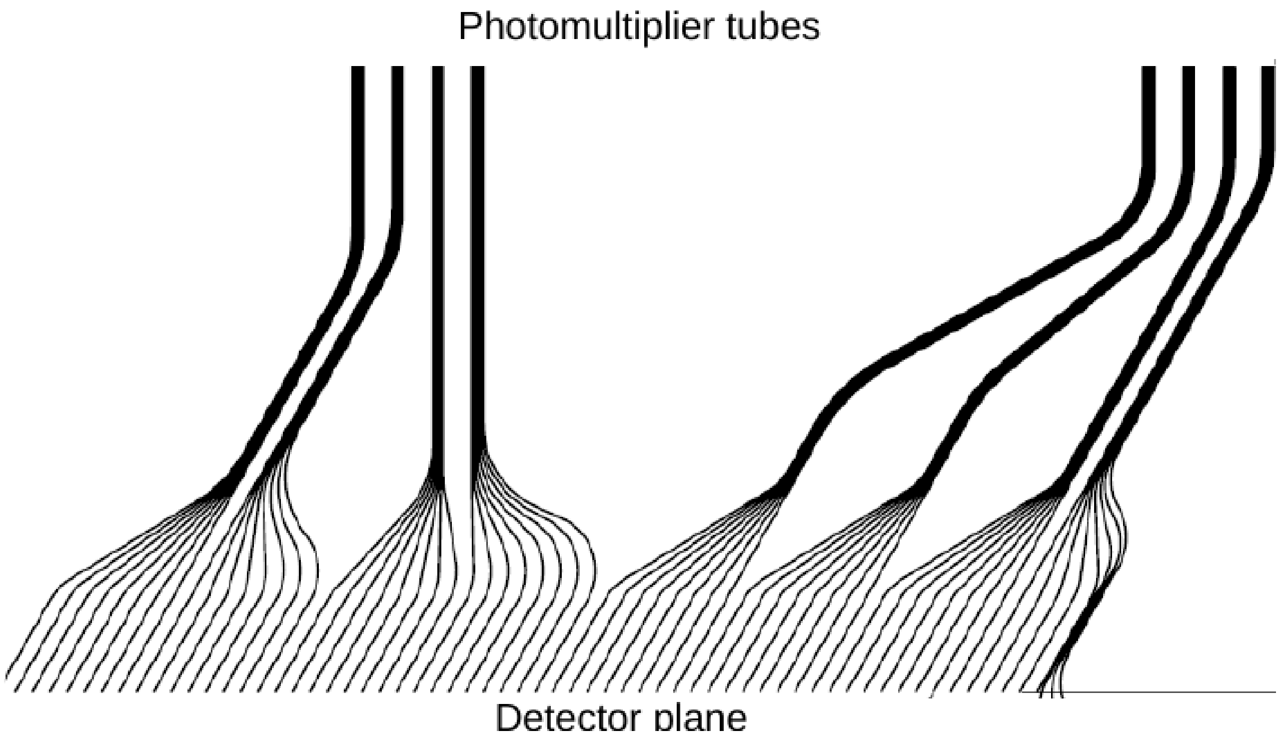
- Energy is a product of C (MeV/PE)
- C is determined with rock muons extracted from regular beam running, and would not require additional calibration data
- In principle, you could redefine a new C that is just MeV/Q, and skip the step of converting to PE, and use a default number to guess at the light level
- This would give significant non-uniformity, which could be corrected by folding it into S2S, or just taken if we decide that we don't care about response uniformity
- The downside is the PE will not be exactly correct, which affects the photostaticstics and timing (will come back to this)

Attenuation corrections

- Actually three attenuation sources: strip, baggie, clear
- Strip attenuation is along the WLS fiber inside the strip, which is up to 2m
- WLS fiber goes into light-tight "baggie" where the fibers are brought together; baggie length can be very short for some strips and up to ~2m for strips on the other end
- Clear fiber has measured attenuation length of 7.38 meters; depending on plane view and where the strips are there are four possible lengths: 1.08, 1.38, 3.13, 6.00 m

Attenuation drawing

- Fibers are ~1.7 cm apart inside strip
- Brought together inside baggie (length depends on strip number in a known way)
- Clear fibers go to PMTs (lengths are known)



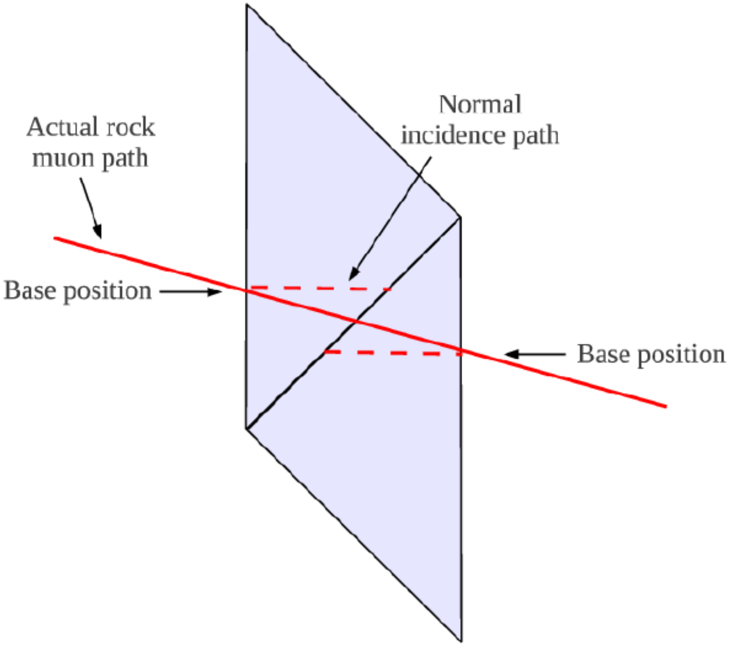
Do we need attenuation for 2x2?

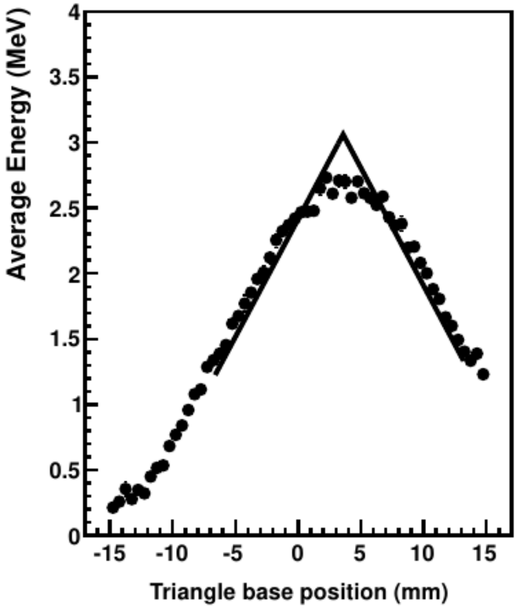
- We could apply an average attenuation factor, which will give large non-uniformity but probably won't affect muon tracks
- Baggie and clear lengths are known, and strip attenuation function is measured from mapper data taken before original installation
- Those files can be re-used, we just need to do some archaeology to hook them to the correct planes in the new geometry
- Typical attenuation varies by ~2x, so this is probably worth doing
- Technical detail: strip attenuation is initially corrected to strip center, and then for hits that are part of tracks, the attenuation correction is updated after all other calibrations are applied to the actual hit position along strip

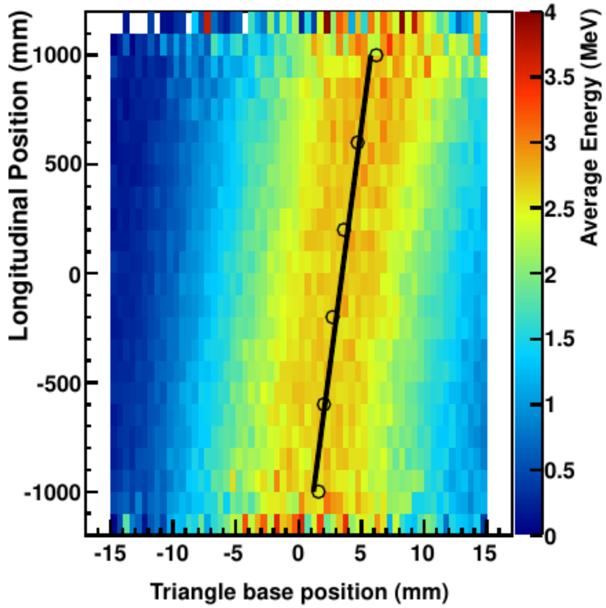
Scintillator plane alignment

- In original installation, we observed O(few mm) and O(few mrad) missalignments between scintillator planes, which are corrected with a calibration
- Alignment shift and rotation for each plane is stored in xml files, only need to do this once
- Corrections are determined using through-going rock muon sample; energy deposit in a strip is linear with position due to triangular strips
- This affects tracking, and would only need to be done once, so I think we should do this
- Expert is me

Alignment with rock muons





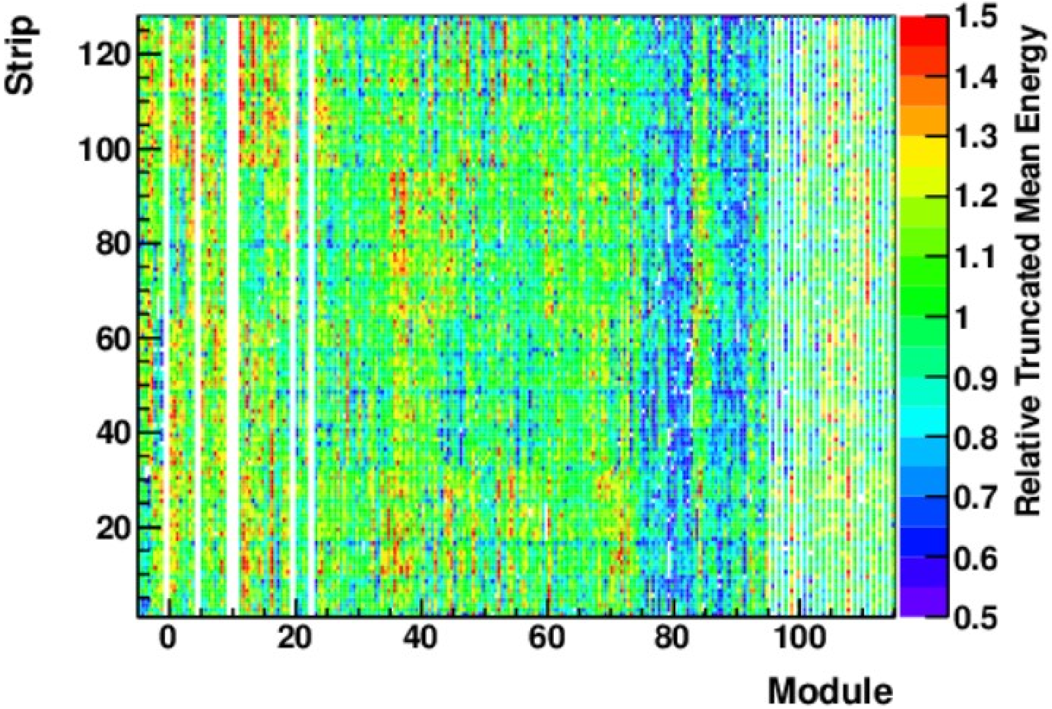


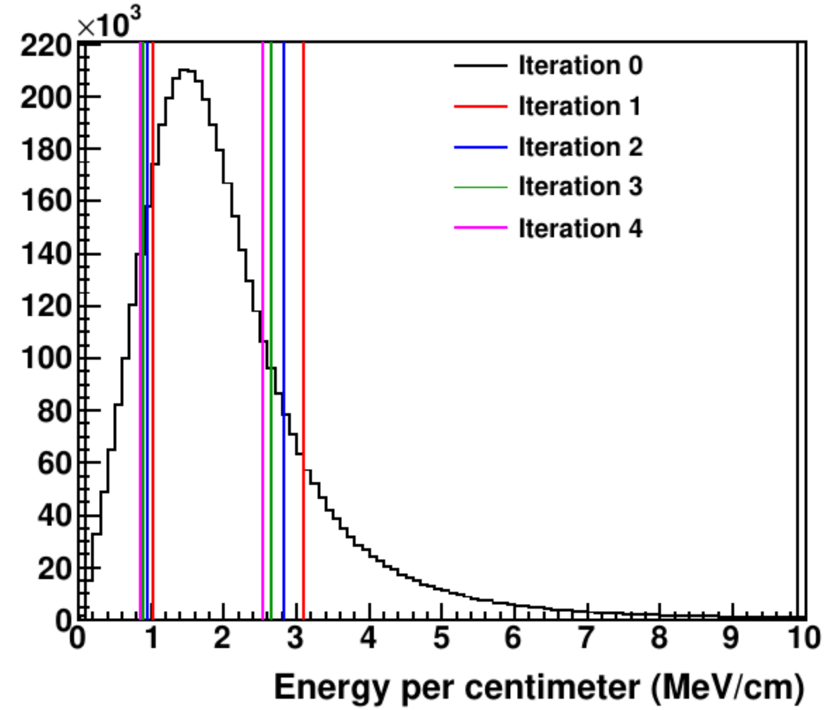
- Correct path length to “normal incidence path” based on track angle
- Perform “triangle fit” in slices of longitudinal position to determine transverse shift and rotation; especially misaligned example shown

Relative energy (strip to strip) calibration

- Corrects for O(15%) variation in energy response between strips, due to differences in scintillator production there is an observed spread in light yield
- Also used to identify and suppress bad channels
- Very slowly time varying due to non-uniformity in aging effects; this was important over 10-year MINERvA run but probably isn't important over 2x2 run, so we could just do this once
- Stored and accessed from postgres database
- Evaluated with through-going rock muons

How S2S constants are determined



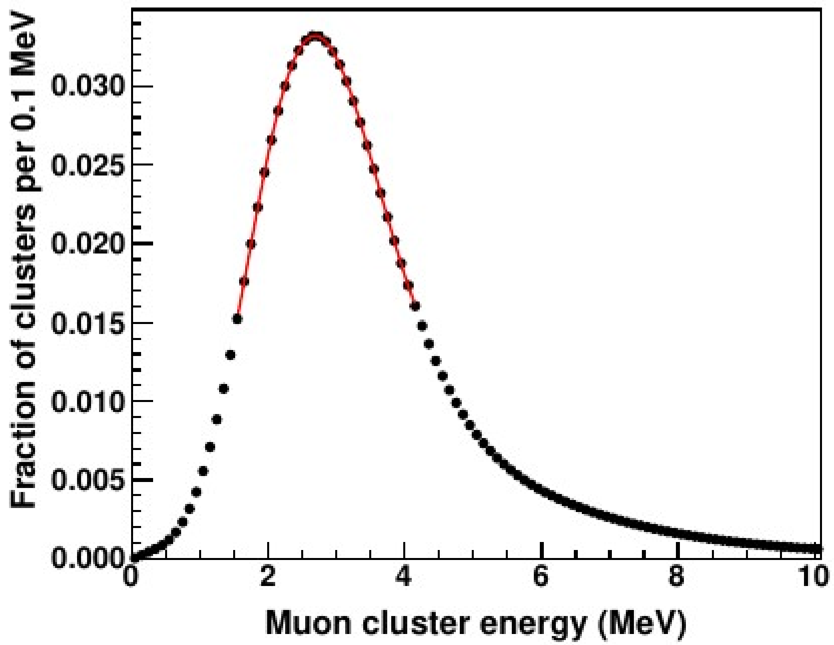


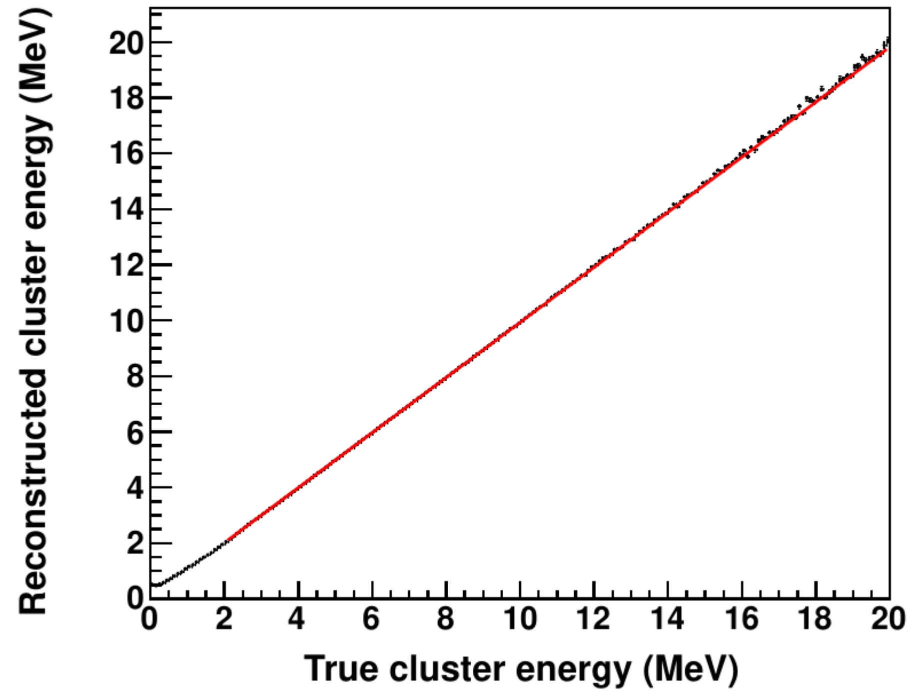
- Iterative truncated mean is used instead of Landau-Gauss fit due to poor statistics in edge strips (demonstrated to track the peak very well from strip to strip, and is far more robust with low statistics), with a subsequent plane-by-plane correction that is the ratio of the L-G MPV to the truncated mean

Absolute energy calibration

- Sets overall energy scale of detector by measuring PE/MeV from through-going rock muons; also sets the overall light level in simulation
- Performed every ~2 days due to light level decreasing from scintillator aging; depending on required energy response for 2x2 this could be done once, or less frequently, or just estimated if we don’t care about the detector energy scale at the few percent level
- In MINERvA this used momentum-analyzed rock muons to ensure we were in the MIP region, and simulated an identical sample based on reconstructed four-vectors; this will not be possible in 2x2 so there will be some loss of precision
- Stored and accessed from postgres database
- Expert is Jeffrey Kleykamp, who is on DUNE

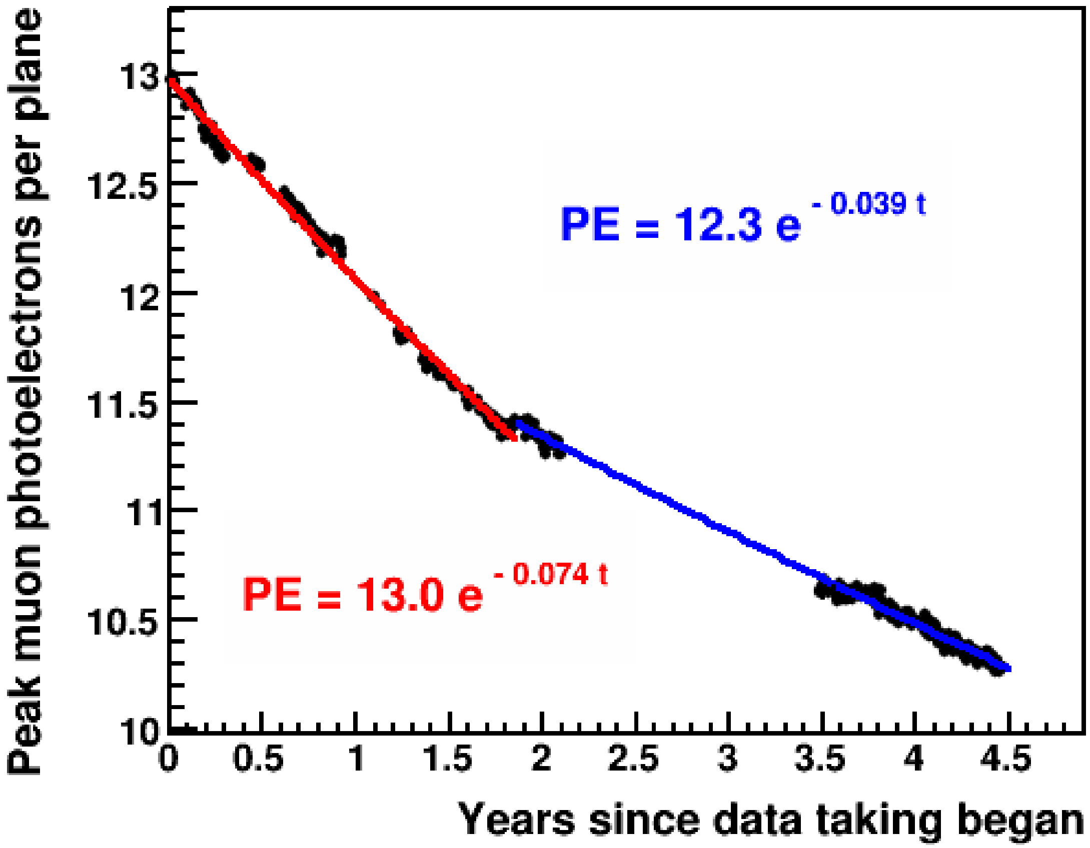
Some details: MEU





- Start by guessing an “MEU” factor, in practice this is just the measured factor from the previous period
- Use a fit to determine the peak reconstructed muon cluster energy in data and MC
- Use a linear fit of reco vs. true in MC to tie it to true energy, and update the MEU guess based on (MCreco / DATAreco) * (MCtrue / MCreco)

Scintillator aging: light vs. time



- Fit PE per plane for through-going muon to exponential to determine aging lifetime
- Two regions due to an observed slope change when cooling system was installed underground
- Gap is due to long shutdown, data after 3.5 years is NOvA beam
- This is old, and recent data shows this flattening considerably, so this effect might not be important to do in a time-dependent way as it was during the LE era

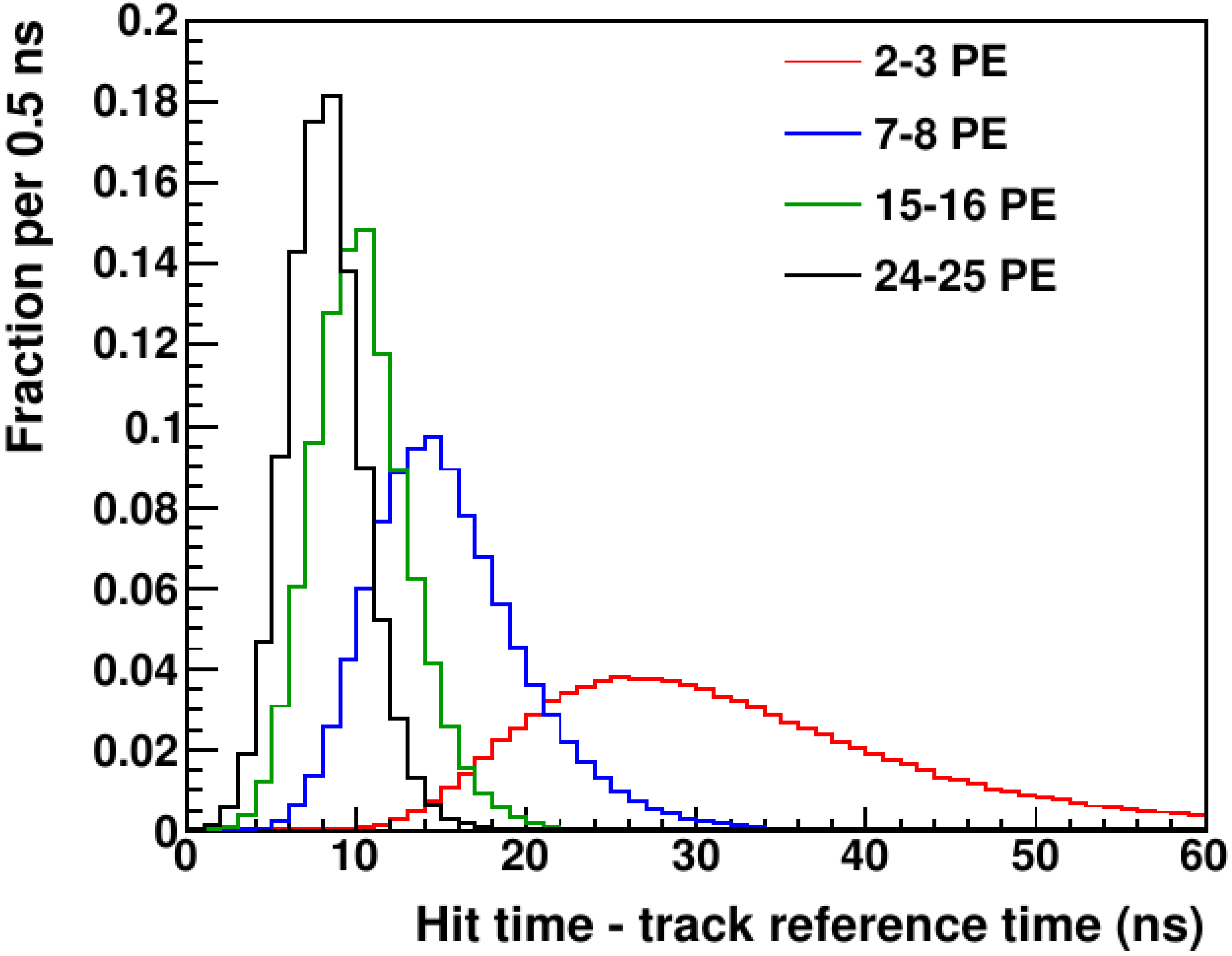
Timing calibration

- Corrects for timing offsets on each FEB, and average PE-dependent “slewing” effect due to scintillator and fiber decay times
- Offsets stored in database, slewing correction is a histogram that is loaded in
- Calibration is determined using through-going rock muons, which travel at ~speed of light, and therefore true *relative* time between pairs of hits are known
- Complication is that there are two unknowns, and the solution is to use an iterative procedure
- Slewing effect is measured once; board offsets change any time the FEBs are power cycled, so calibration has to be repeated when there are hardware swaps
- This calibration is critical for 2x2 in order to do timing-based track matching between MINERvA and LAr

Basic procedure for timing

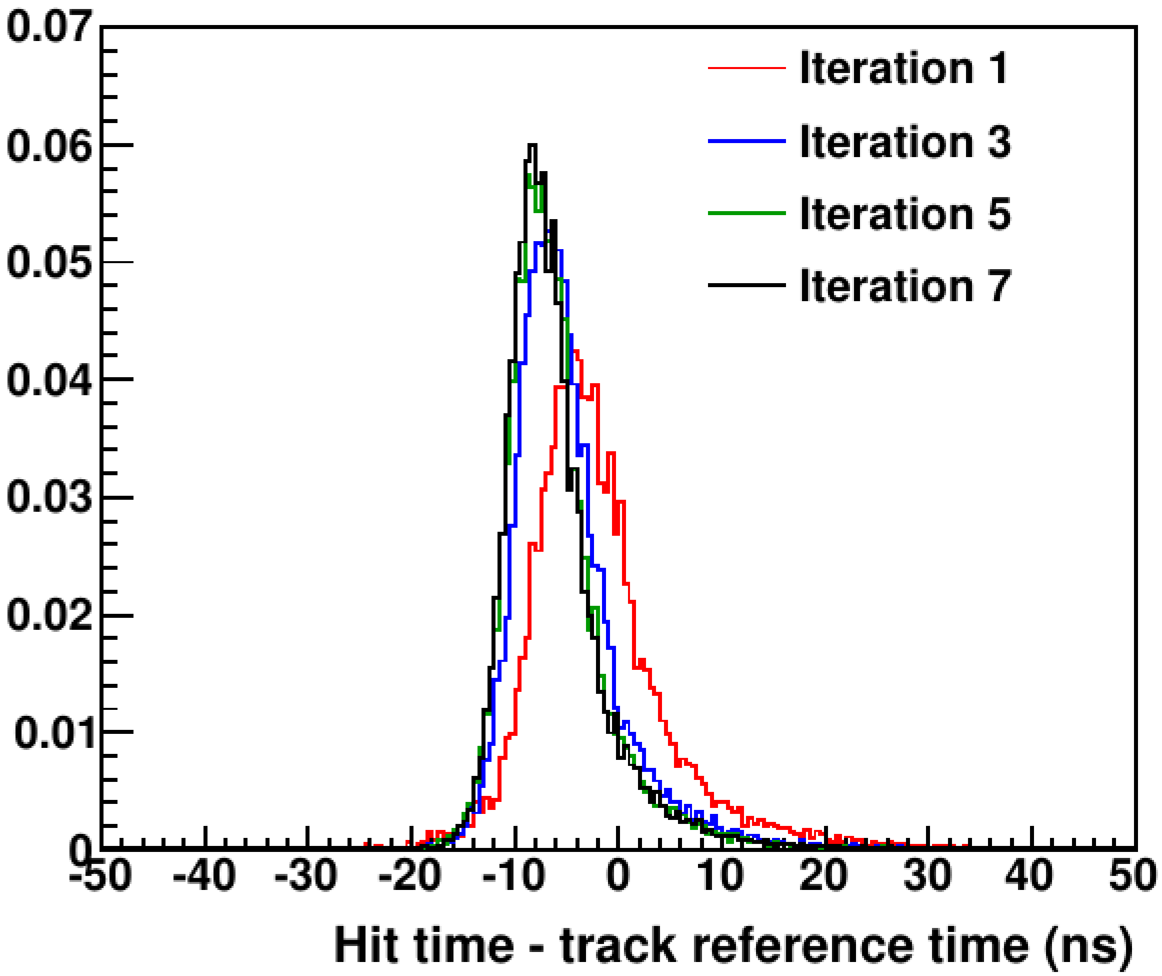
- Select through-going rock muons
- Iteratively:
  - Measure the track time at O(1 ns) precision by averaging over hundreds of hits
  - Apply board offset corrections from previous iteration, and determine peak slewing effect vs. PE
  - Apply peak slewing effect vs. PE from previous iteration, and determine board offsets
- Do this 8 times so that it converges

Slewing effect



- At high PE, the earliest PE always direct light, and scintillator+fiber decay time = ~0
- At low PE, there is some probability that the first PE was actually reflected
- The scintillator+fiber decay time may be long

Board offsets



- Now we are integrating over all PE > 3, so there is some width to the distribution
- In first iteration, slewing effect is not corrected, and it is very smeared
- Subsequent iterations converge to -9.8 ns → this board is one clock tick earlier than the average of all boards
- There is a “floating zero” that doesn’t matter, only the relative times of all hits in the 16 μs gate matters

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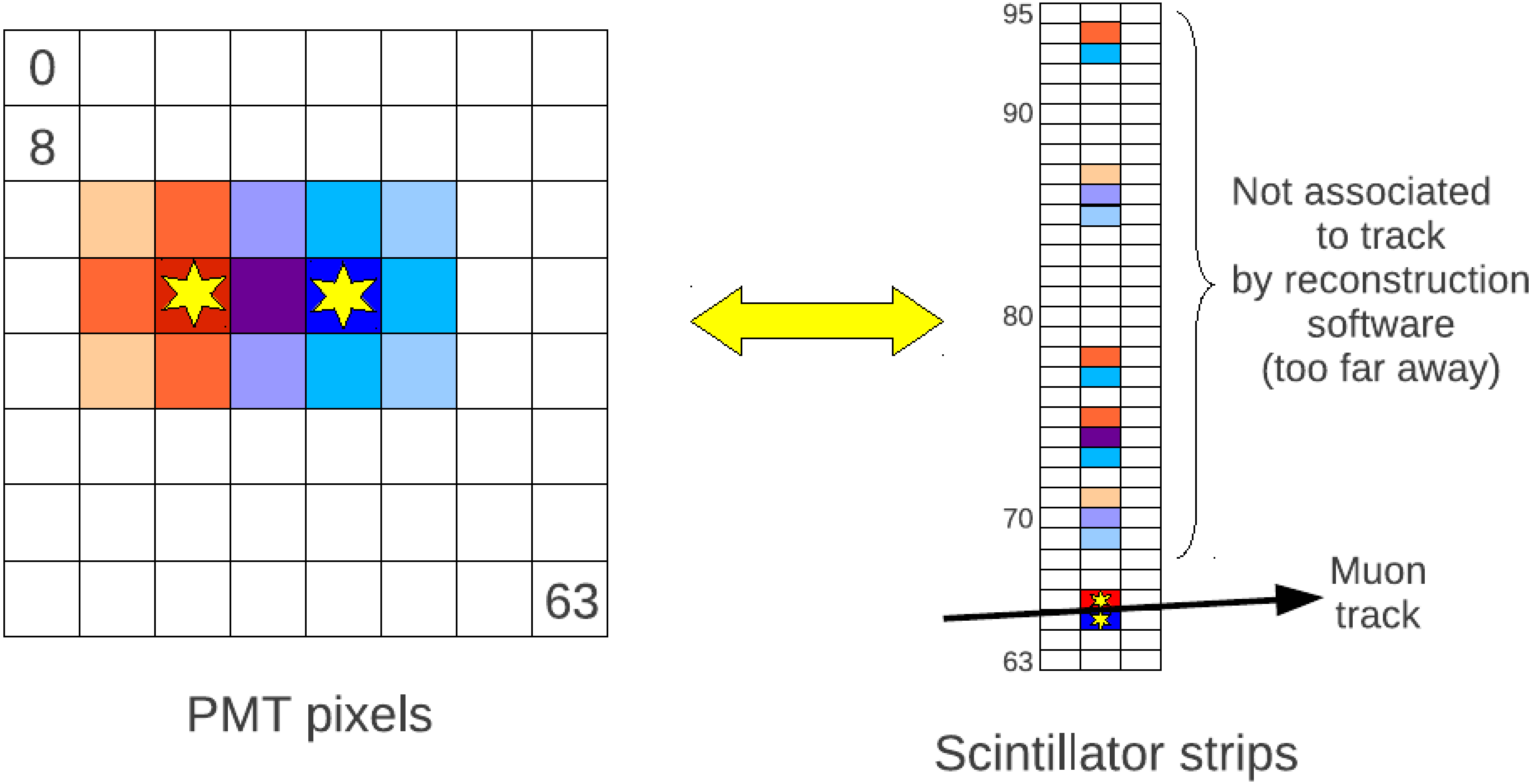
Back to the gain calibration issue

- If we don't take and analyze regular LI data, the PE distribution in data will be wrong
- The statistical fluctuations in the number of PE will not be simulated correctly
- The PE-dependence of the slewing effect will be wrong compared to the energy of the hits
- There are two main consequences:
  - Possible that the position resolution will be different in data and simulation, because fluctuations of low-PE hits affects charge sharing between adjacent triangle strips
  - Timing distributions might not agree exactly in data and MC due to having the wrong slewing effect

Finally, cross talk



- PMT weave maps adjacent pixels to far away strips so that cross talk hits are not confused with wide hits

Cross talk calibration

- Typical PMT has ~4% total optical cross talk, but some PMTs have somewhat higher, up to ~15%
- This is measured in situ by correlating muon energy deposits with smaller energy deposits in adjacent *pixels*
- The correlation matrix is used in clustering algorithm to determine a cross-talk probability for a given cluster, which helps to suppress these clusters from tracking
- This might not be critical for 2x2, but it’s probably straightforward to re-use the matrix from original MINERvA, and it shouldn’t be time dependent
- The expert is Jeremy Wolcott

Proposal

- For 2x2, I suggest that we aim to implement:
  - Plex (existing, maybe minor updates)
  - Pedestals (new data, continuous)
  - FEB correction (existing)
  - Attenuation (existing)
  - Alignment (redo once, rock muons)
  - Strip to strip (redo once? occasionally? rock muons)
  - Absolute energy (redo once? occasionally? rock muons)
  - Timing (redo whenever power cycles, rock muons)
  - Cross talk (existing)

Type of work required

- What sort of work is required
  - Plex (matching old files to new geometry)
  - Pedestals (rewriting production code, implementing existing calibration code, uploading regularly to DB)
  - FEB correction (matching old files to new geometry)
  - Attenuation (matching old files to new geometry)
  - Alignment (rewriting rock muon production, implementing existing calibration code)
  - Strip to strip (implementing existing calibration code, uploading to DB)
  - Absolute energy (implementing existing calibration code or writing something simpler, uploading to DB)
  - Timing (implementing existing calibration code, uploading to DB)
  - Cross talk (matching old files to new geometry)

What sort of people are needed

- Matching old files to new geometry: someone familiar with new geometry, someone familiar with old MINERvA files
- Rewriting production code: someone familiar with modern FNAL production infrastructure, someone familiar with MINERvA calibration files
- Database updating: MINERvA DB expert helps new person(?) learn how to load DB
- Implementing existing calibration codes: 1-2 new people to spend significant time for ~1-2 months learning how it works from MINERvA experts, then <1 FTE for maintaining during run
  - Pedestals, S2S, timing, energy scale

Corner cutting options

- Ignore energy nonuniformity (save implementing S2S)
- Determine approximate energy scale correction via simple procedure (save implementing MEU)
- Ignore attenuation (save some archaeology work)
- Ignore cross talk, and hope it doesn't affect tracking (save some archaeology work)
- In my opinion, these are not worth it because:
  - Most work toward S2S+MEU overlaps with what is needed for timing
  - Archaeology might not be that hard and we should at least try