NOvA Calibration

Calorimetric Energy Scale in the NOvA Detectors

- ✦ **The NOvA Detectors**
- ✦ **What impacts the energy of a hit**
- ✦ **Calibrate Relative Effects**
- ✦ **Calculate Energy Scale**

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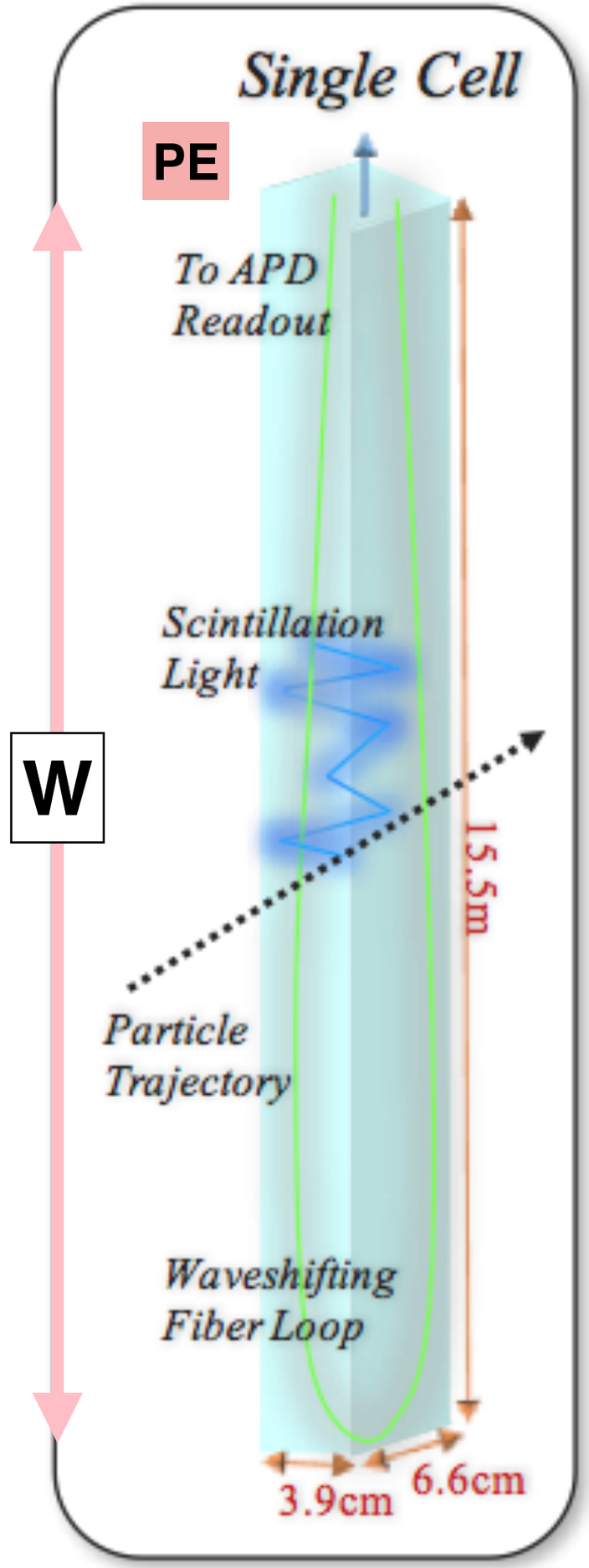
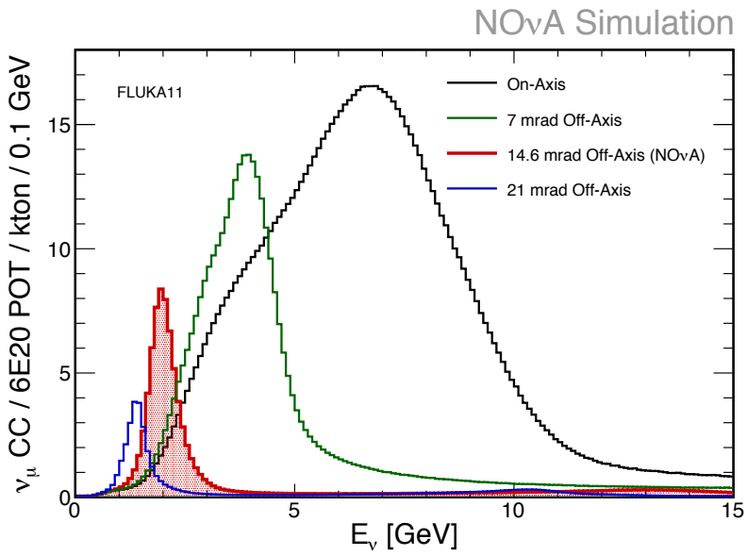
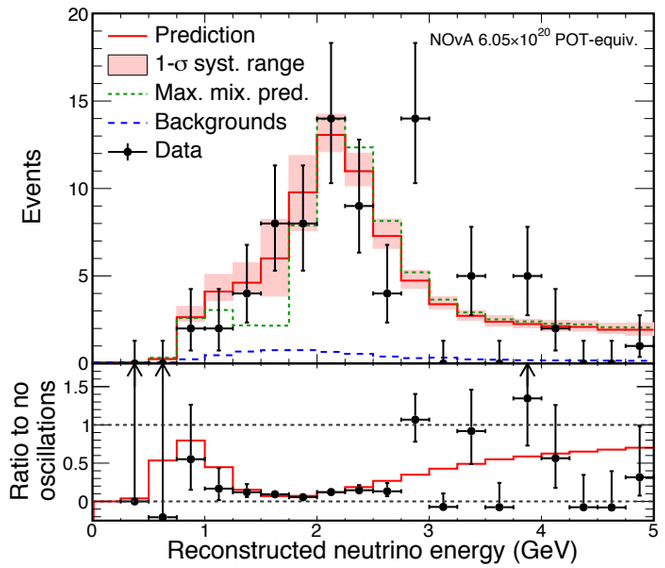
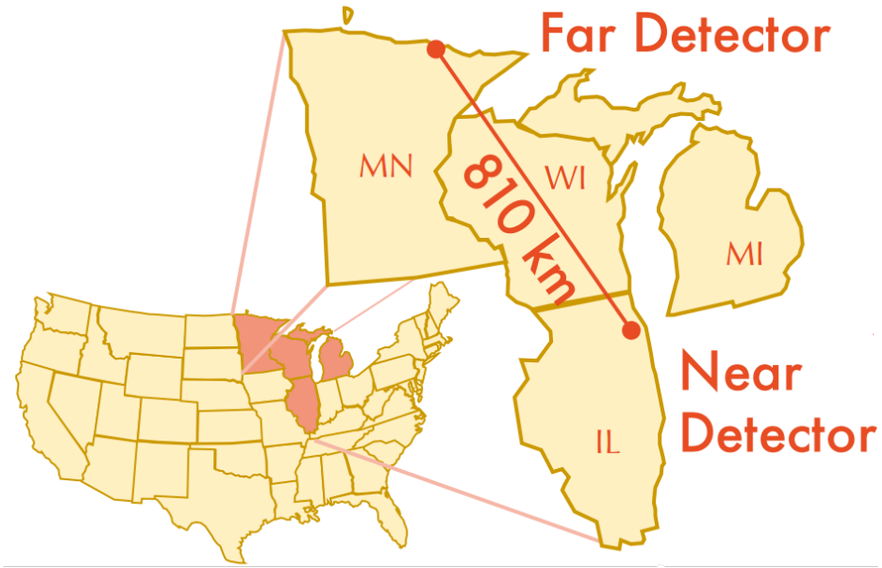
26 March 2018

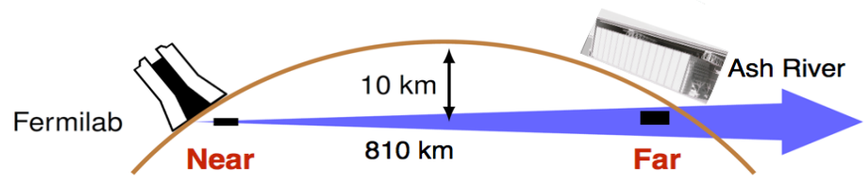


NuMI Off-Axis ν_e-Appearance Experiment









Neutrino Beam: NuMI (Neutrinos at the Main Injector)
120 GeV Protons on a target produce kaons and pions decaying into muons and neutrinos

Beamline: 810 km between functionally similar Near and Far Detectors, both 14mrad off-axis from beam

Physics Program:

- Three-Flavour Oscillation
  - Search for Sterile Neutrinos
  - Inclusive ν_μ-Charged-Current Cross Section
  - Other ND physics
  - Supernova Neutrinos

ν_e Appearance

ν_μ Disappearance

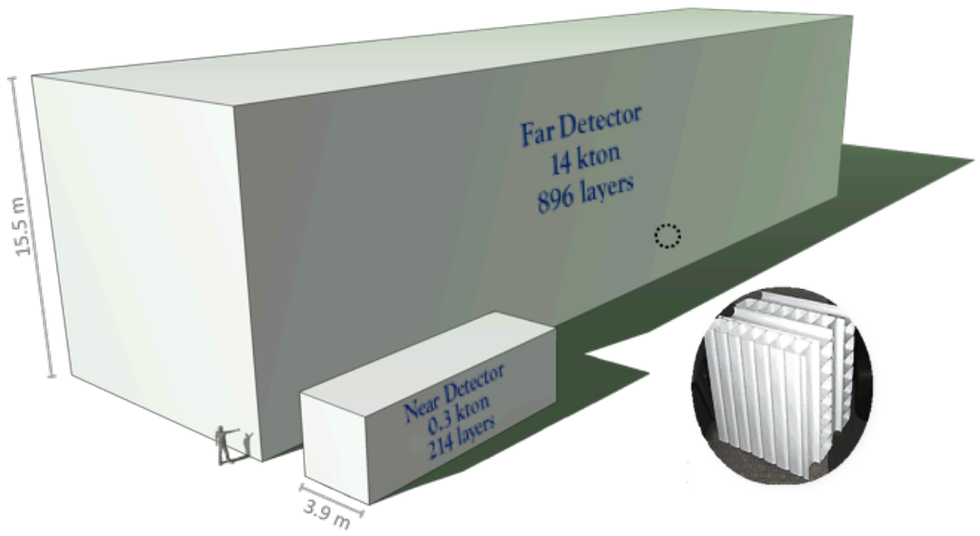
— θ_{23} Octant?
Maximal?

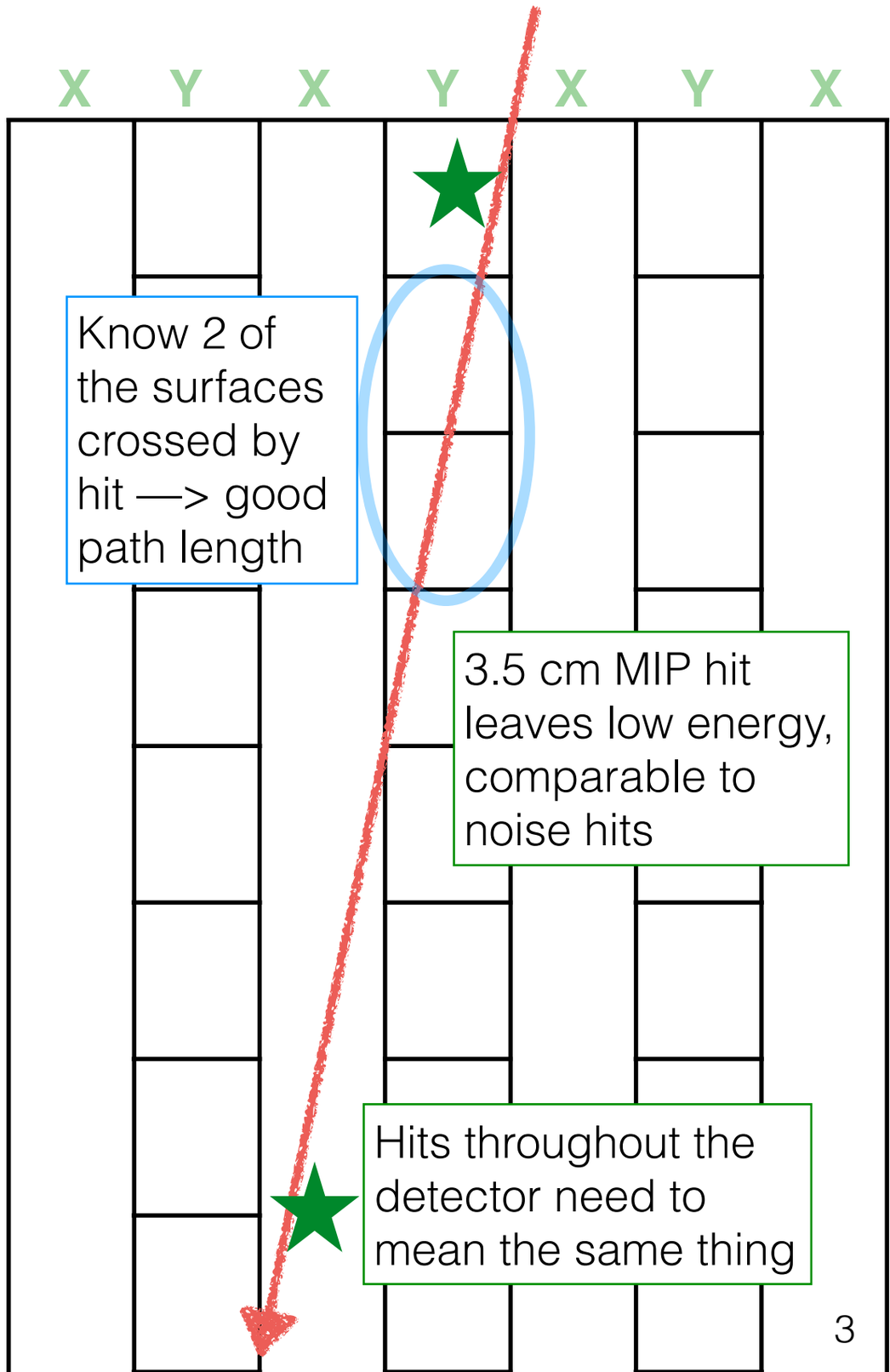
— Mass Hierarchy?

— CP Violation?

The NOvA Detectors

- **Tracking scintillators**
  - Orthogonal views X & Y
  - Light collection calorimetry
- Light collected exclusively through WLS fibers
- FD about 4x the size of ND in each dimension
- “Slice” up continuous readout into events less than a few 100 ns long





Energy Calibration

With our large sample of Cosmic Muon Data

PE

Photoelectrons

Rescaling of ADC to approximate photoelectrons

PECorr

Corrected

Effective PE with all relative effects calibrated out

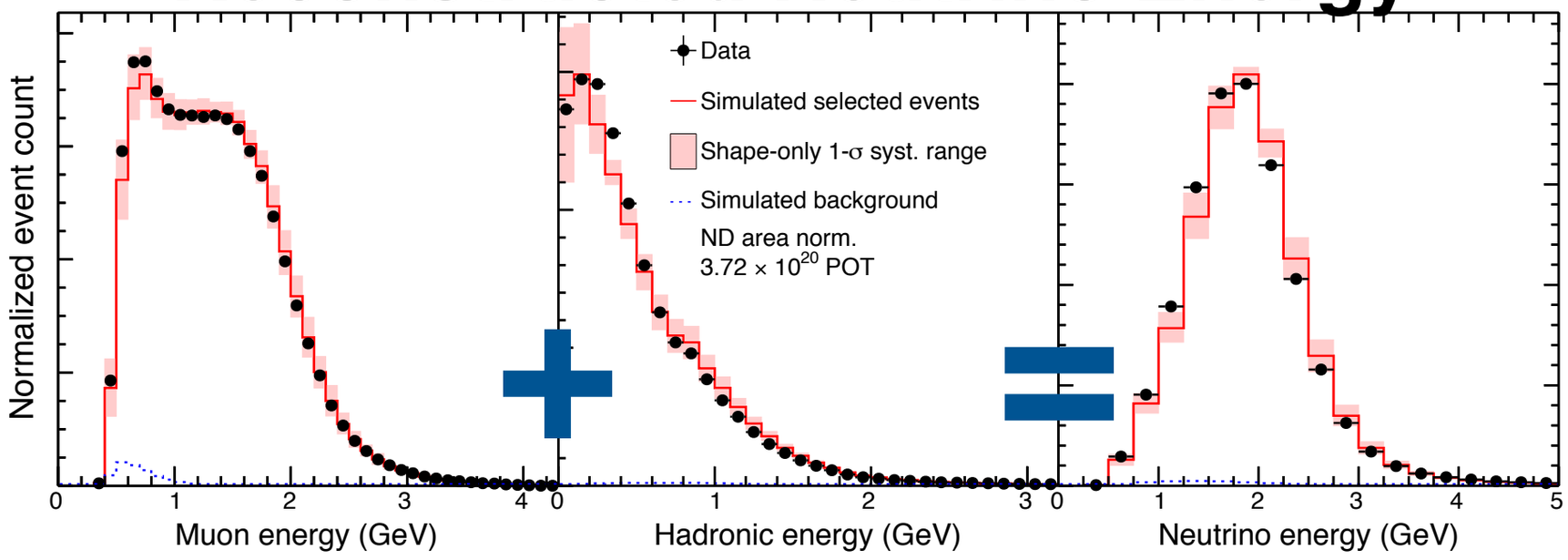
GeV

Energy Deposited

Energy deposited by each hit

Muon Energy from Track Length

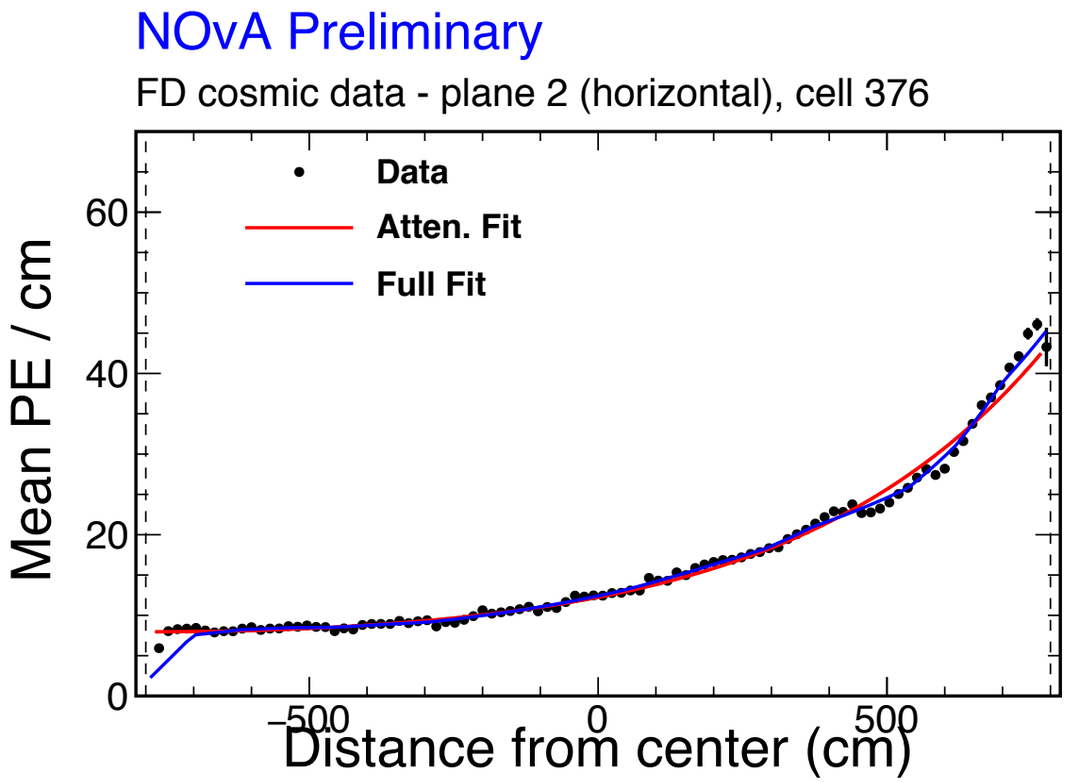
Reconstructed Neutrino Energy

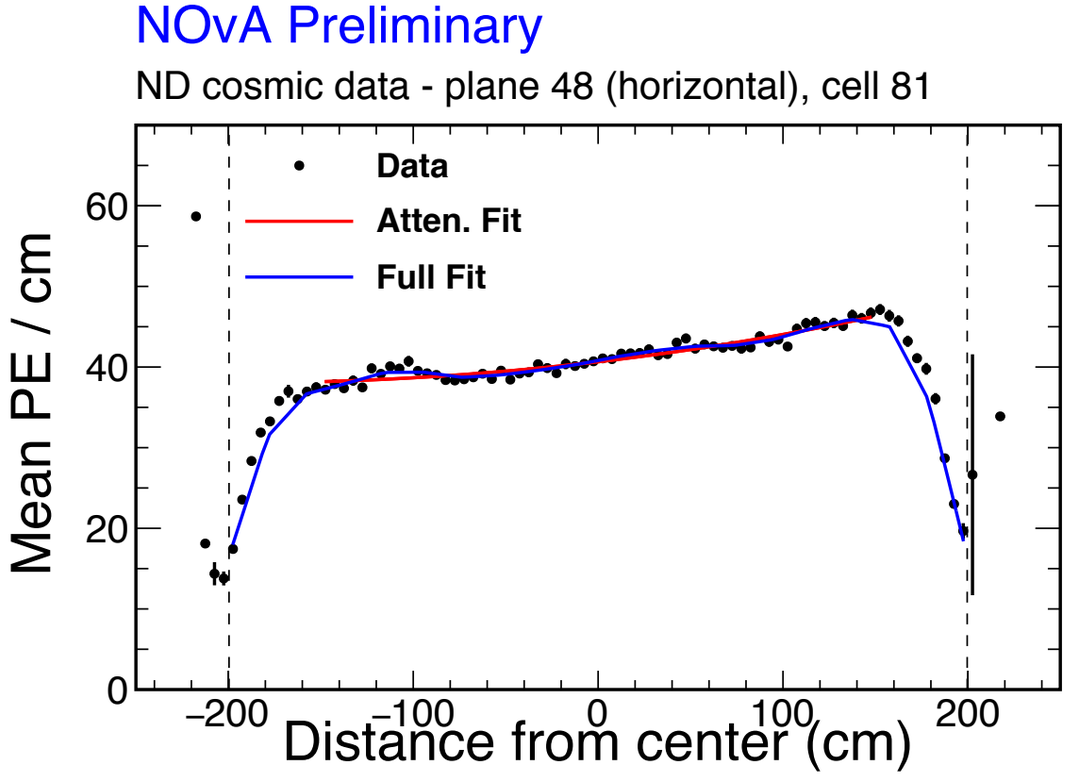


Energy Calibration directly impacts Reconstructed Hadronic Energy

Bias of Deposited Energy

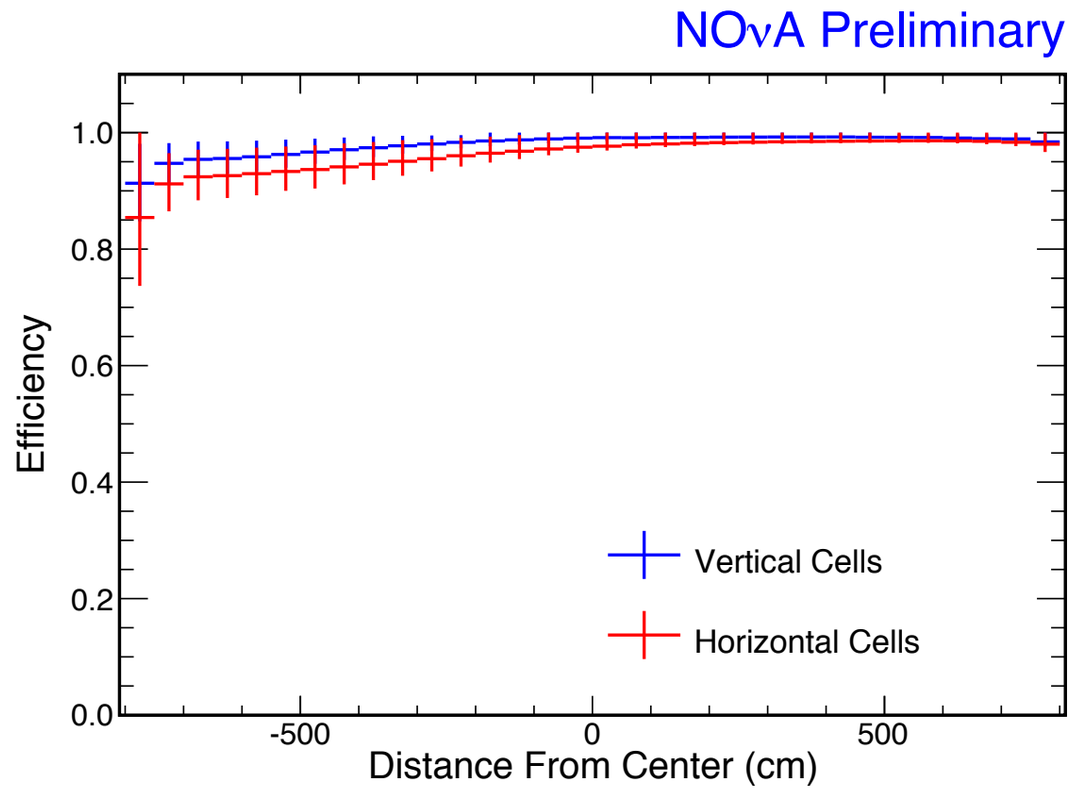
- **Light Attenuation**
  - More light absorbed further away from the readout, FD > ND
- Threshold Bias
- Detector Shadowing
- Non-Uniform Reflectivity
- Twisted Fiber Loops
- Air bubbles (Y)
- Fiber sag (Y)

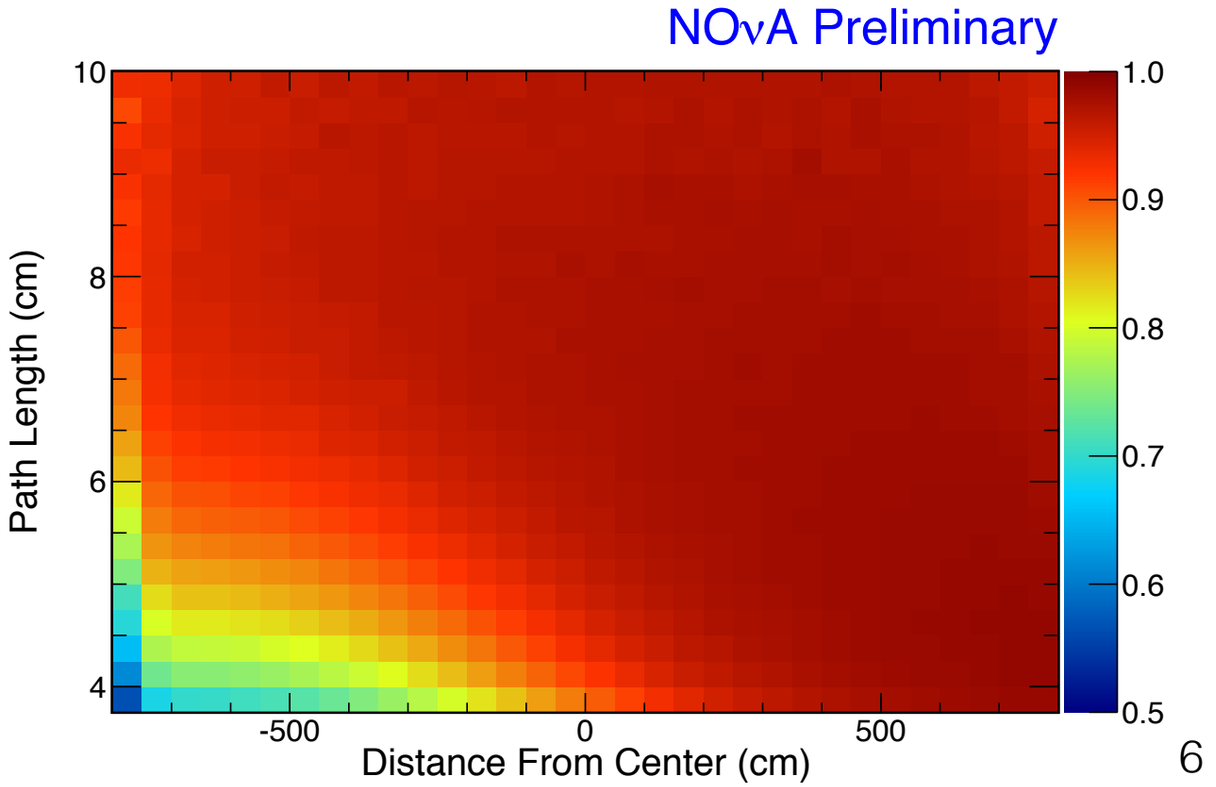




Bias of Deposited Energy

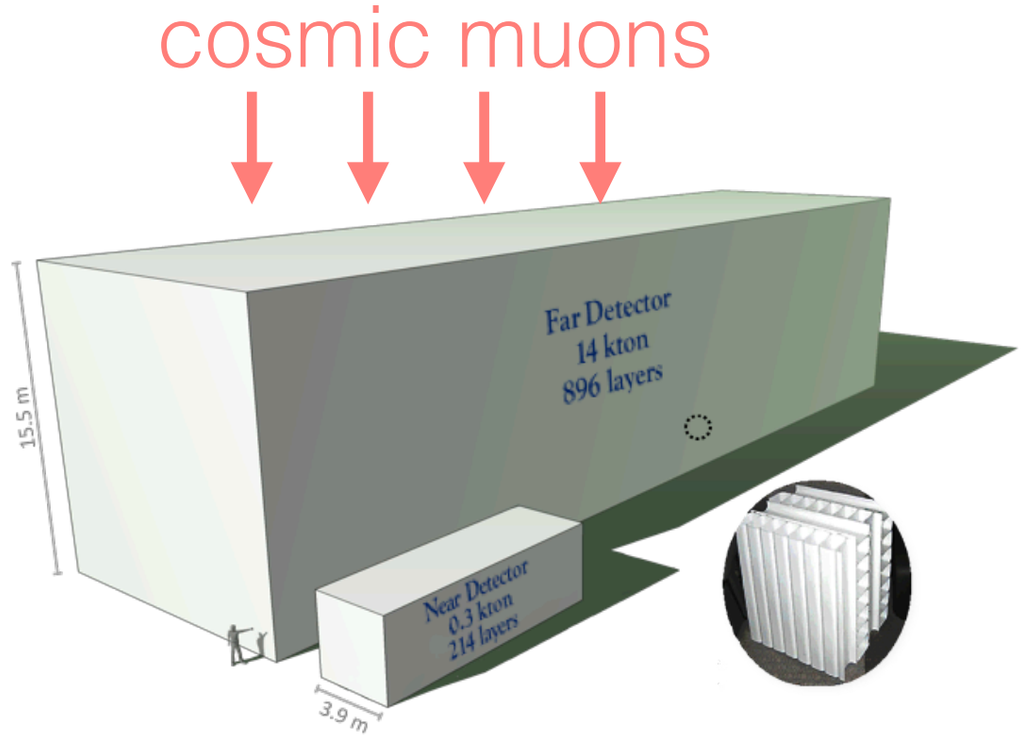
- Light Attenuation
- **Threshold Bias**
  - Readout threshold filters noise
  - Short hits far from readout can fluctuate below
  - Hit not seen —> Energy bias
- Detector Shadowing
- Non-Uniform Reflectivity
- Twisted Fiber Loops
- Air bubbles (Y)
- Fiber sag (Y)





Bias of Deposited Energy

- ✦ Light Attenuation
- ✦ Threshold Bias
- ✦ **Detector Shadowing**
  - ✳ Few-percent effect with big impact
  - ✳ Entangled with threshold bias
- ✦ Non-Uniform Reflectivity
- ✦ Twisted Fiber Loops
- ✦ Air bubbles (Y)
- ✦ Fiber sag (Y)

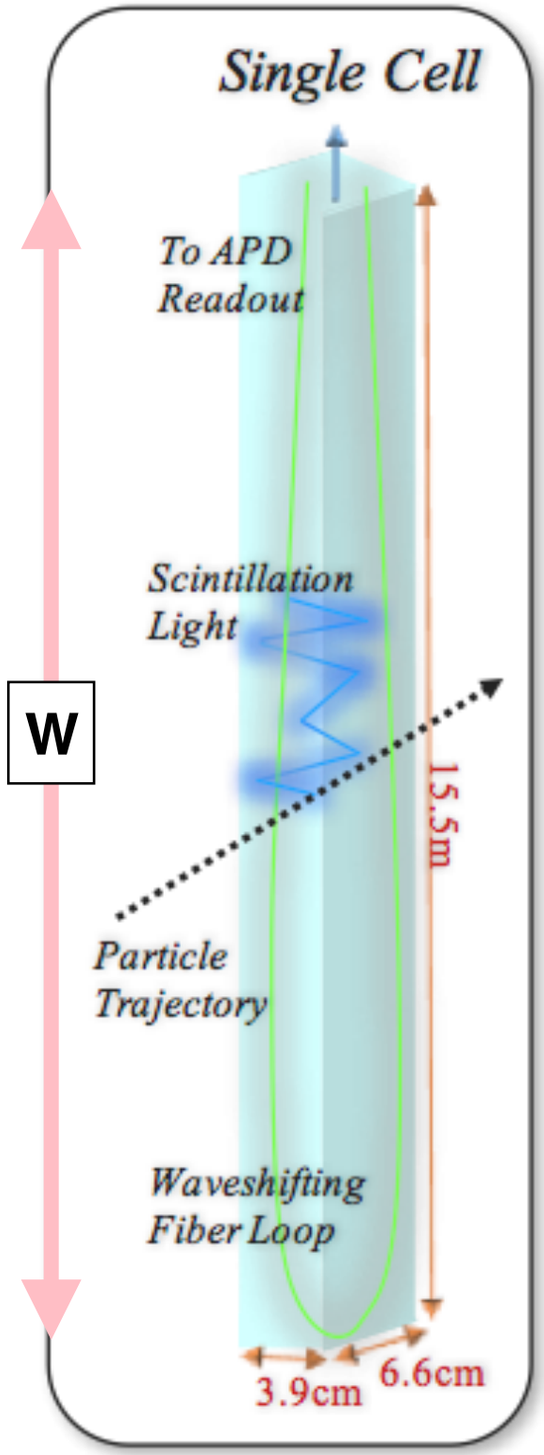


Muons tend to be higher energy at the bottom, slightly higher dE/dx

Bias of Deposited Energy

- ✦ Light Attenuation
- ✦ Threshold Bias
- ✦ Detector Shadowing

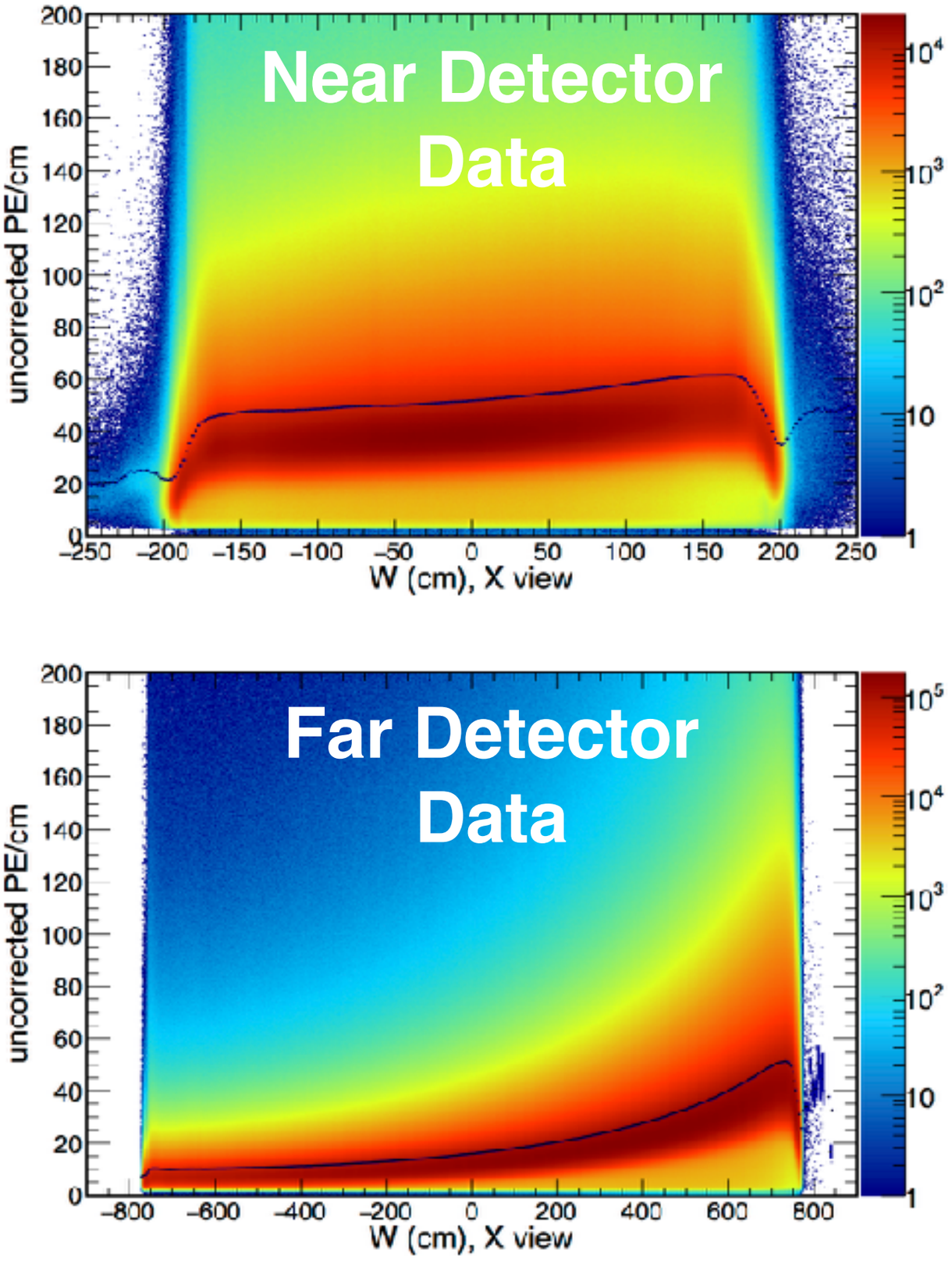
- ✦ **Non-Uniform Reflectivity**
  - ✳ Brightness of fibers significantly impacts attenuation
- ✦ **Twisted Fiber Loops**
- ✦ **Air bubbles (Y)**
- ✦ **Fiber sag (Y)**
  - ✳ Horizontal bars

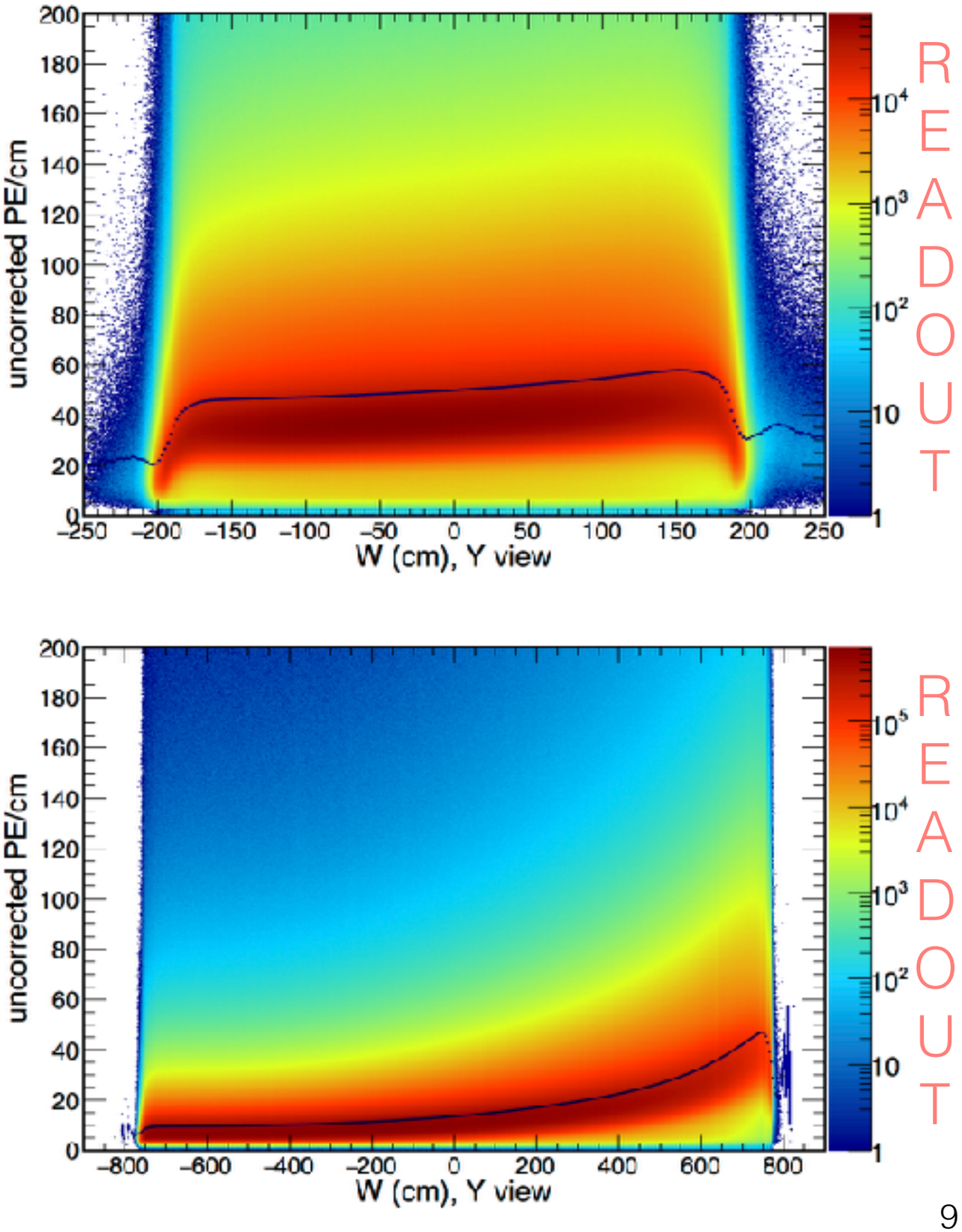


$$e^{-W/\lambda}$$

Attenuation length is different in every cell, due in part to different fiber brightness

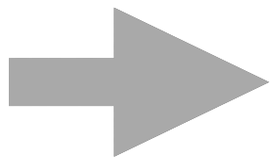
Attenuation of Scintillation Light





Calibration Strategy

PE
Photoelectron



PECorr
Corrected

Attenuated Response

$$= C + A\left(\exp\left(\frac{W}{X}\right) + \exp\left(-\frac{L+W}{X}\right)\right)$$

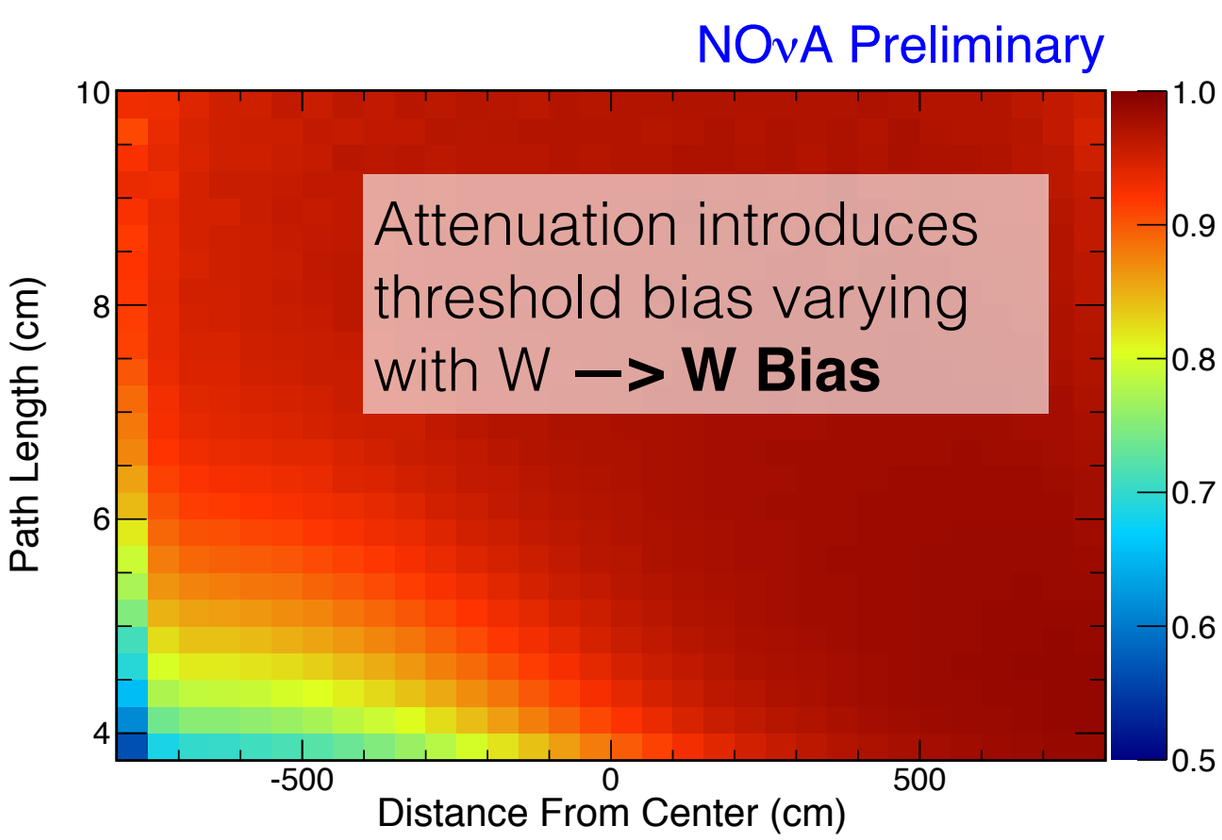
L: cell length
W: cell pos.
X: Att. Length

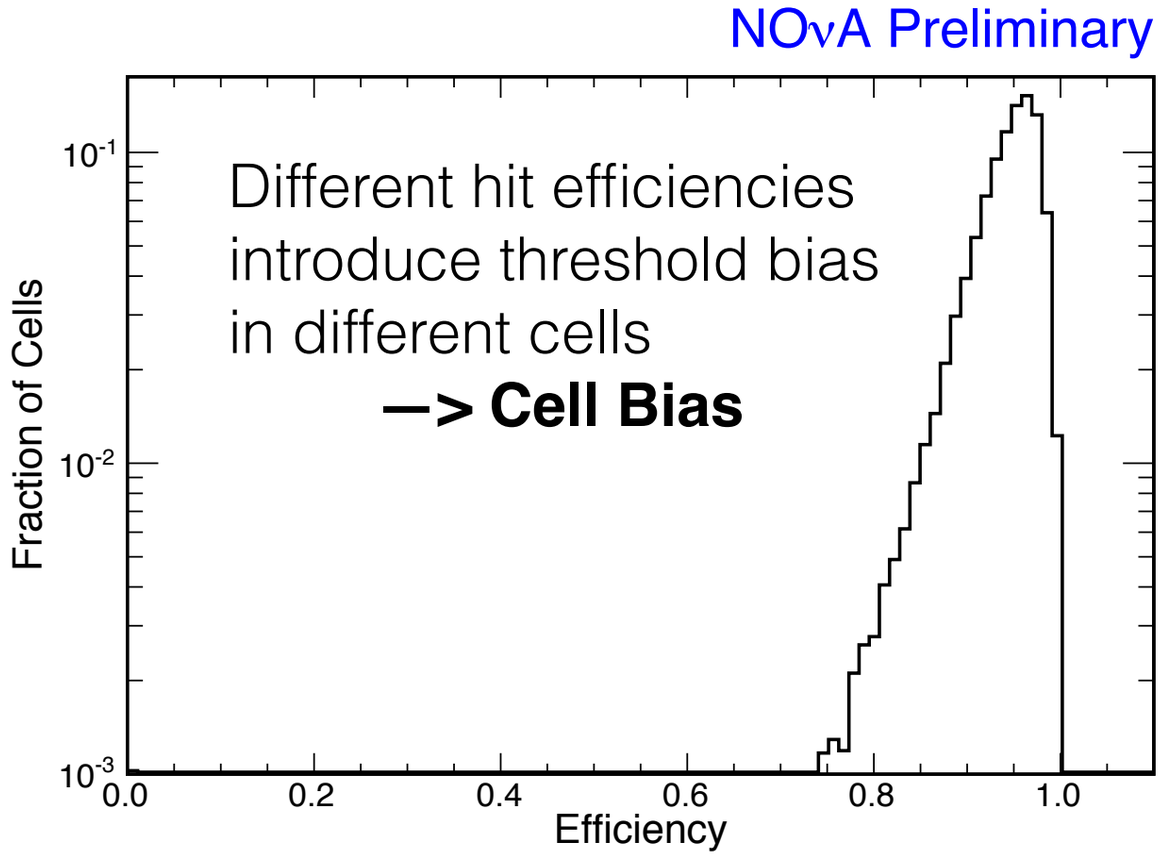
- **Fit Attenuation Profiles** (PE/cm vs Position)
  - Separately for every cell
  - Using Mean Response (Eventually use Median)
  - Free Parameters
    - **A, C** adjust for cell-To-cell Scale/Efficiency differences
    - Attenuation Length **X** different for each cell

- But first, need to remove bias from cosmic muon sample
  - Threshold & Shadowing Correction *from MC*

Hit Threshold

For a hit to be seen above threshold, the energy deposited may need to be an upwards fluctuation within the underlying Landau distribution





- Short MIP hits are impacted the most — Horizontal Y View
  - ✳ Especially hits which have attenuated
- Different cells throughout the detector affected to a different degree

Combined Threshold & Shielding Correction

$$T = \frac{PE}{\lambda} * \frac{E_{\text{true}}}{E_{\text{MIP}}}$$

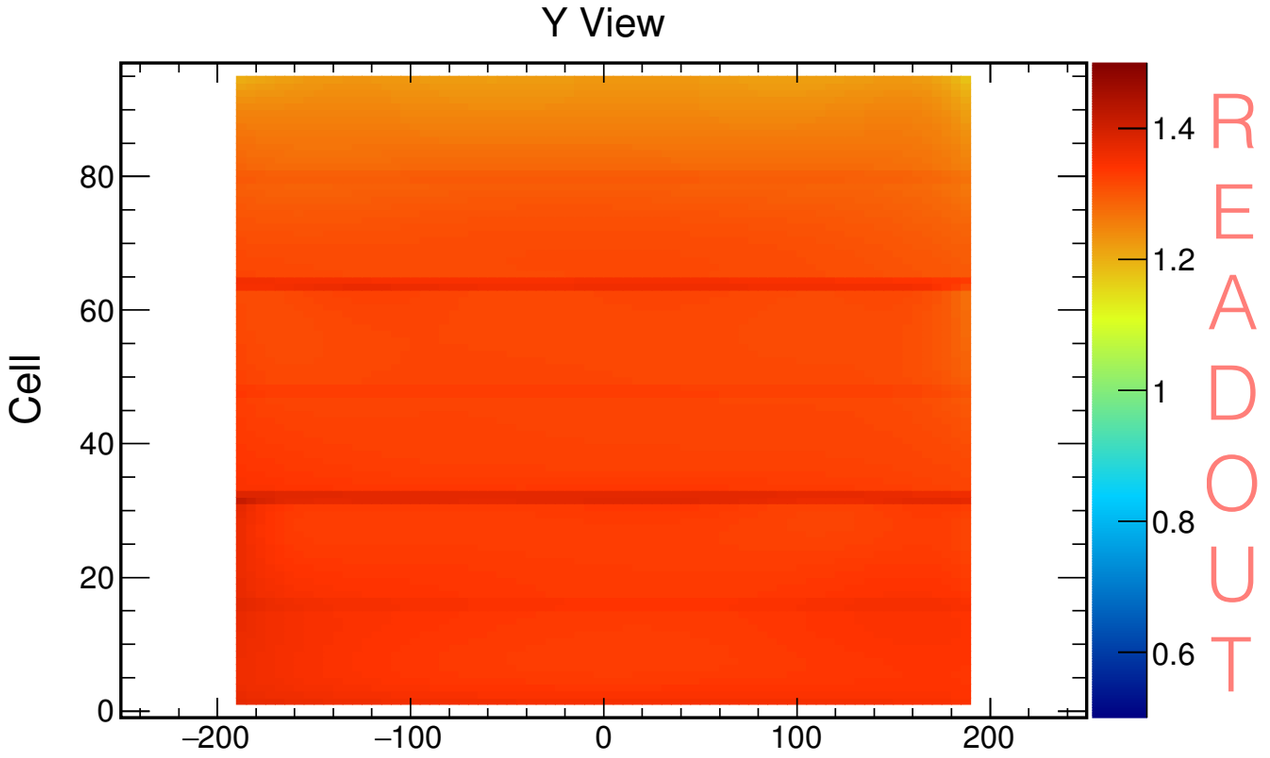
Threshold — — Shileding

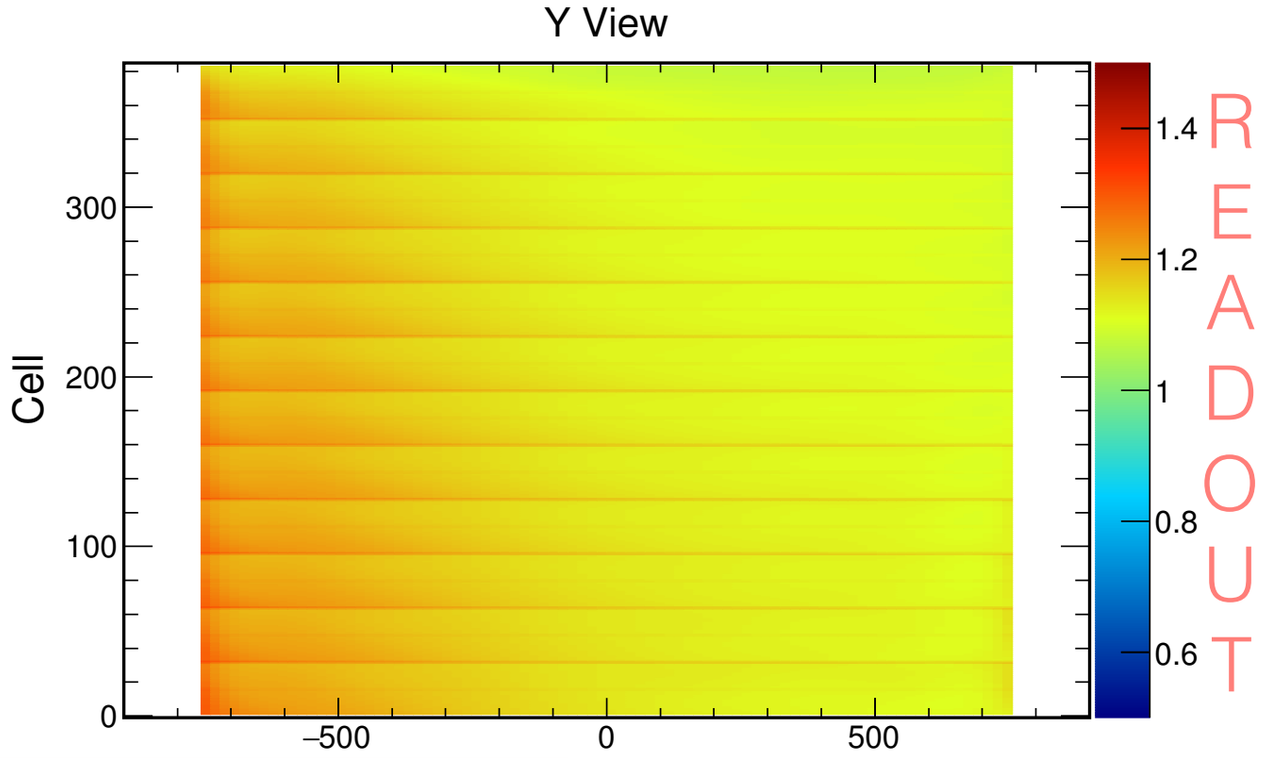
- PE: Simulated photoelectrons at the readout
- **λ**: number of simulated photons expected at readout in the absence of fluctuations (PE is Poisson distributed)
- E_{true}: True energy deposited in cell
- E_{MIP}: Path length * dE/dx of minimum ionising particle

- Use MC Sample to to construct ***T***, depending on cell and position within,

Applied to both MC and Data

Relative Correction Factors



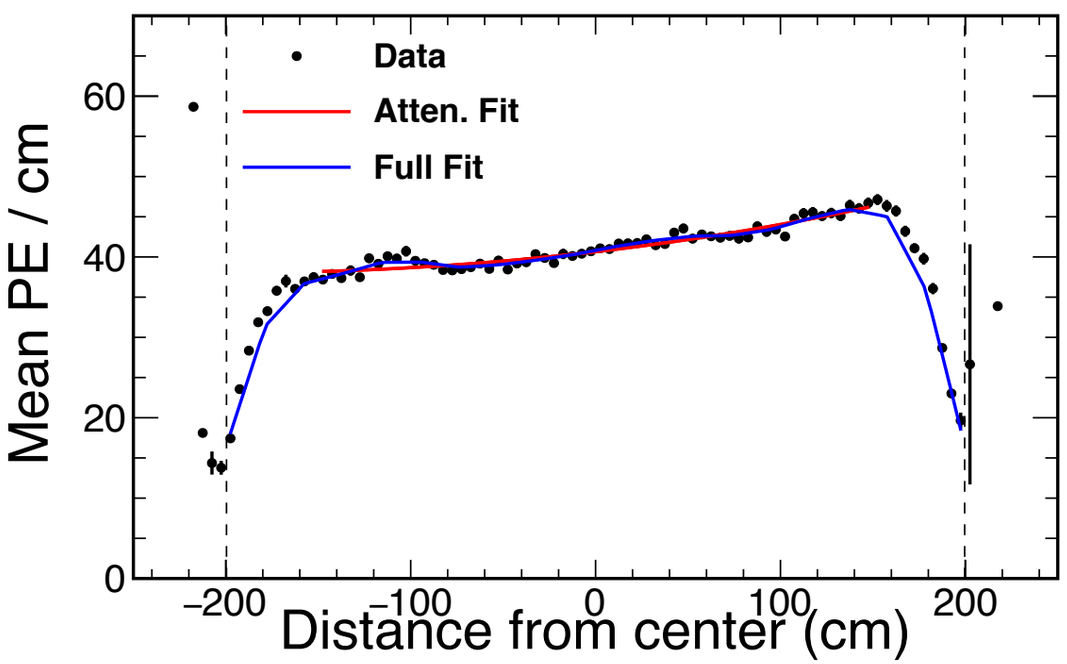


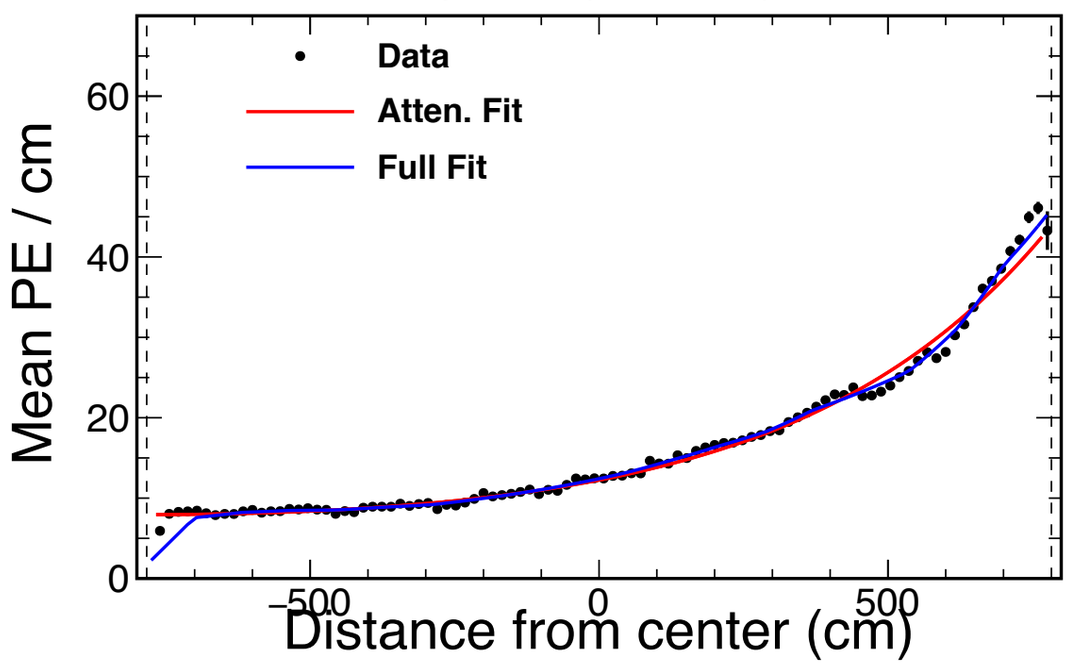
Near Detector

Far Detector

Threshold & Shadowing Correction Factor

Attenuation Fit, each cell



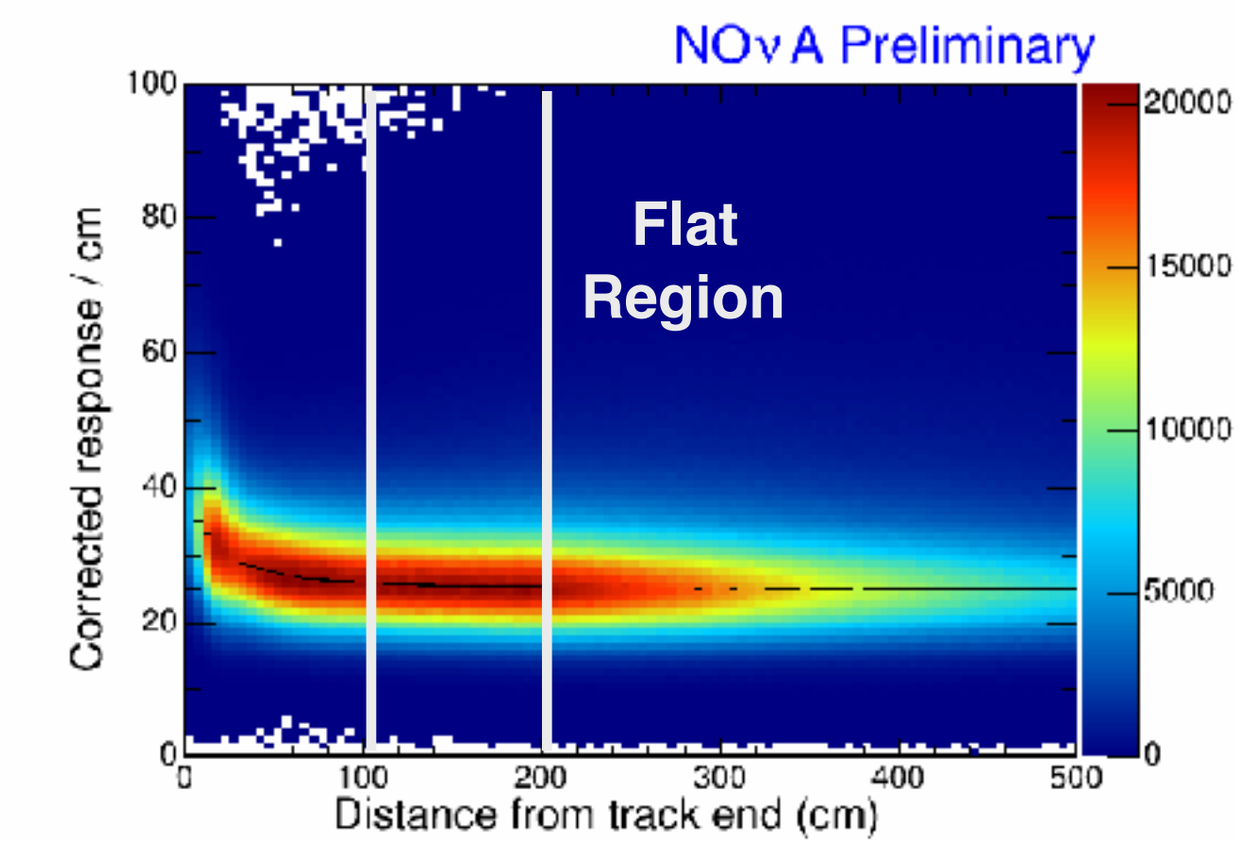


Absolute Calibration

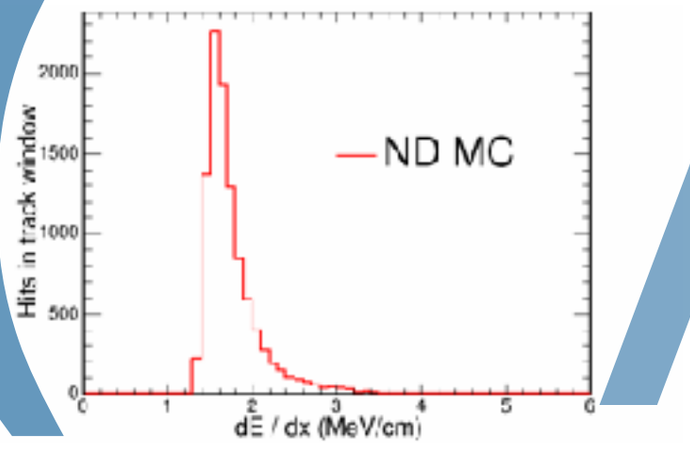
Energy Scale

$$PECorr_{\text{hit}} * \left(\frac{MeV/cm}{PECorr/cm} \right) = MeV_{\text{hit}}$$

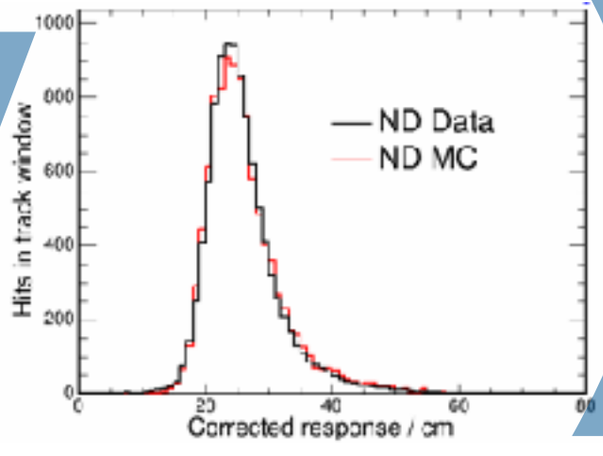
- Select **Stopping Muons**
- Tighten dE/dx peaks by selecting hits in the Bethe-Bloch flat region
- MC: True dE/dx and Response
- Data: Response (PECorr/cm)



MeV/cm

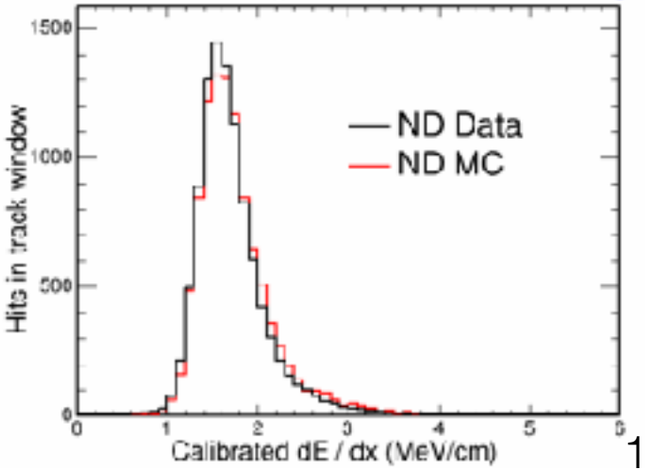


PECorr/cm

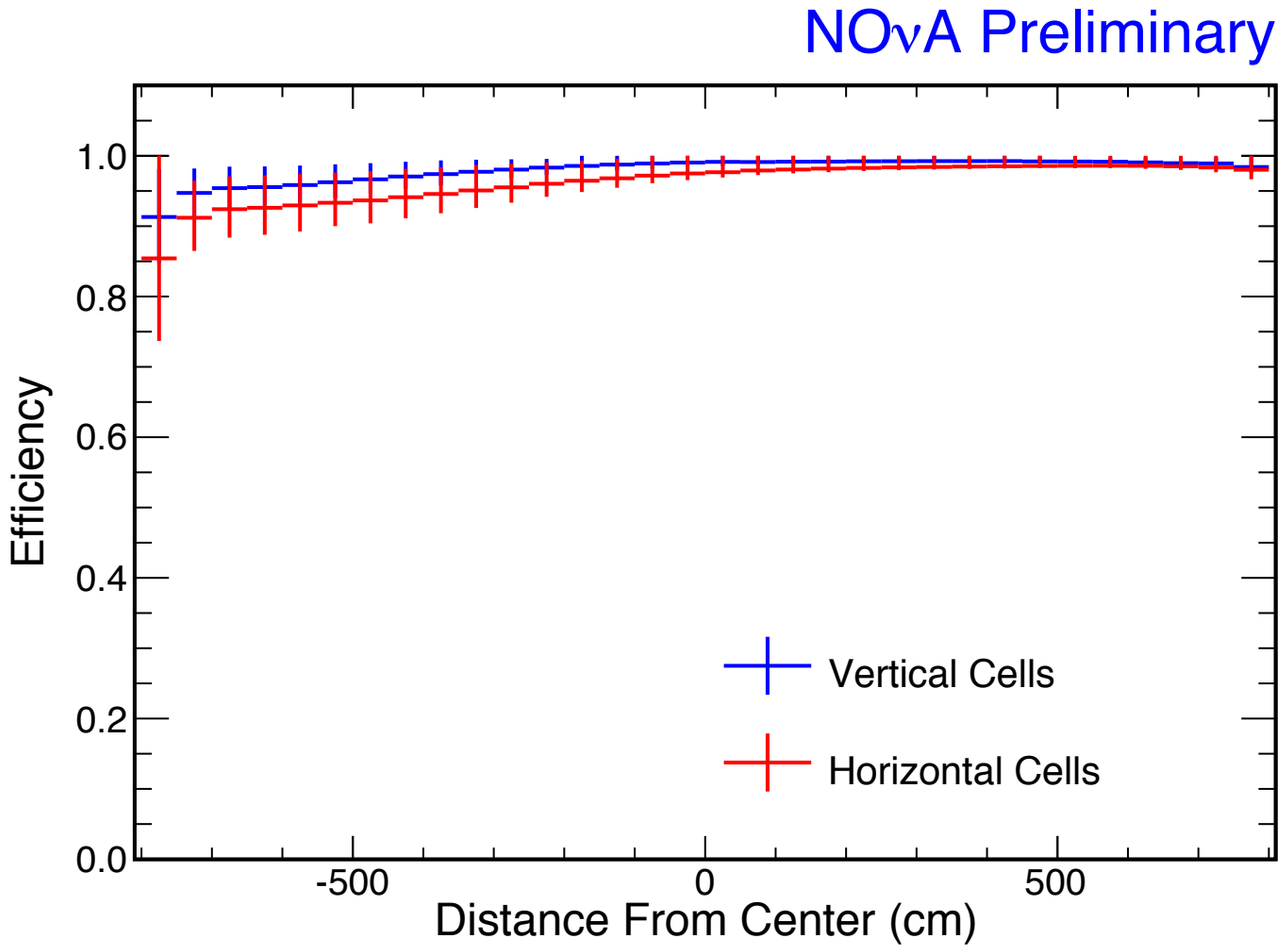


***PECorr**

MeV/cm



Absolute Calibration



Far Detector Hit Efficiency

- Threshold means selected hits were more likely to be up-fluctuations in *true* energy deposition
  - Select only flat region of W so Energy scale is not biased
- Horizontal Y View has many more hits, calibrate separately and average

Energy Calibration

Cosmic Muon Data and MC

PE
Photoelectrons

Rescaling of ADC to approximate photoelectrons

PECorr
Corrected

Effective PE with all relative effects calibrated out

GeV
Energy Deposited

Energy deposited by each hit

Relative Calibration

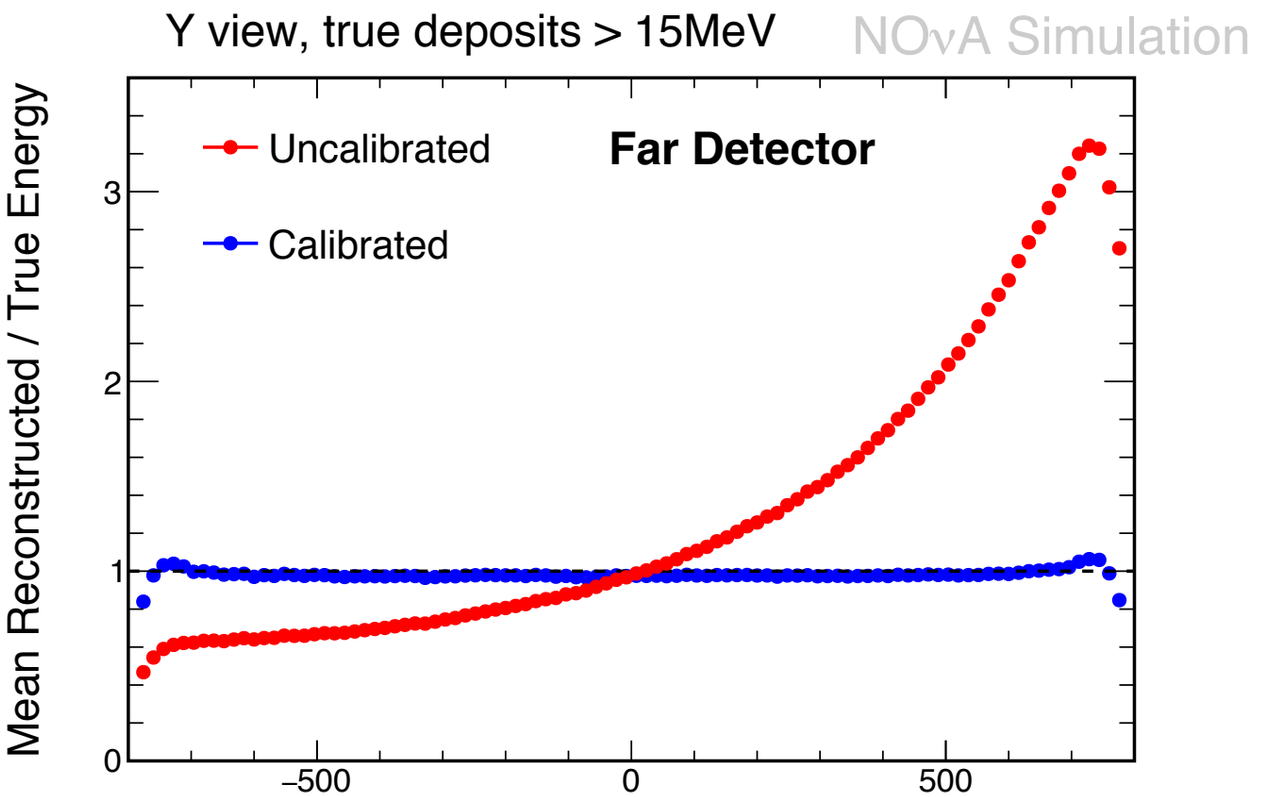
- **Attenuation** along length of a given **cell**
- Cosmic Muon Sample

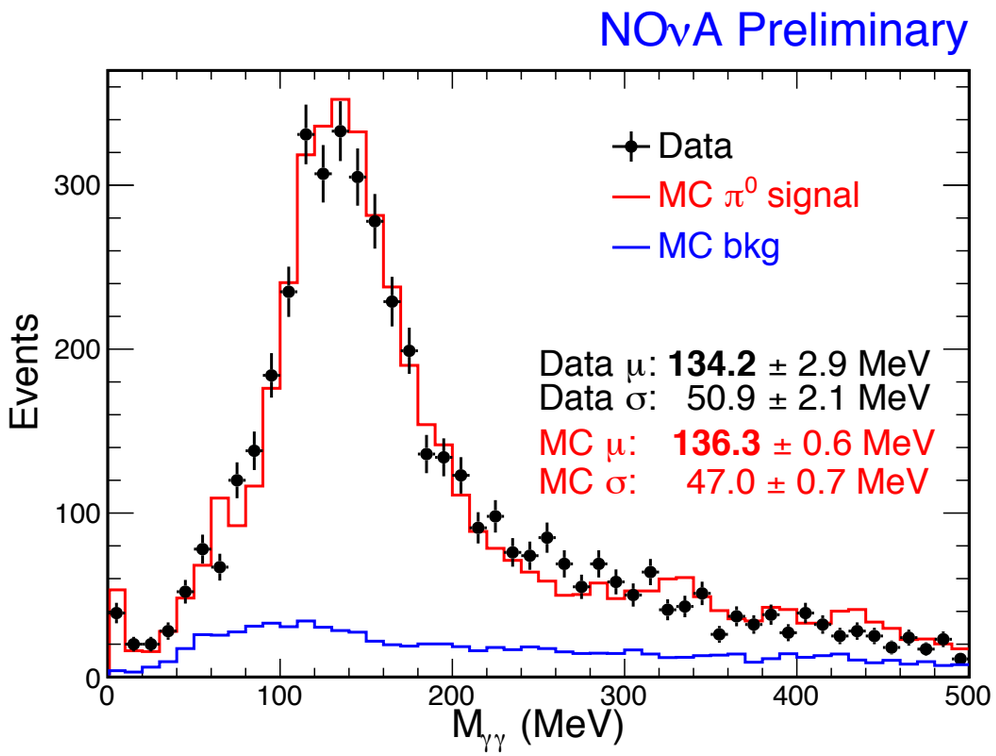
Absolute Calibration

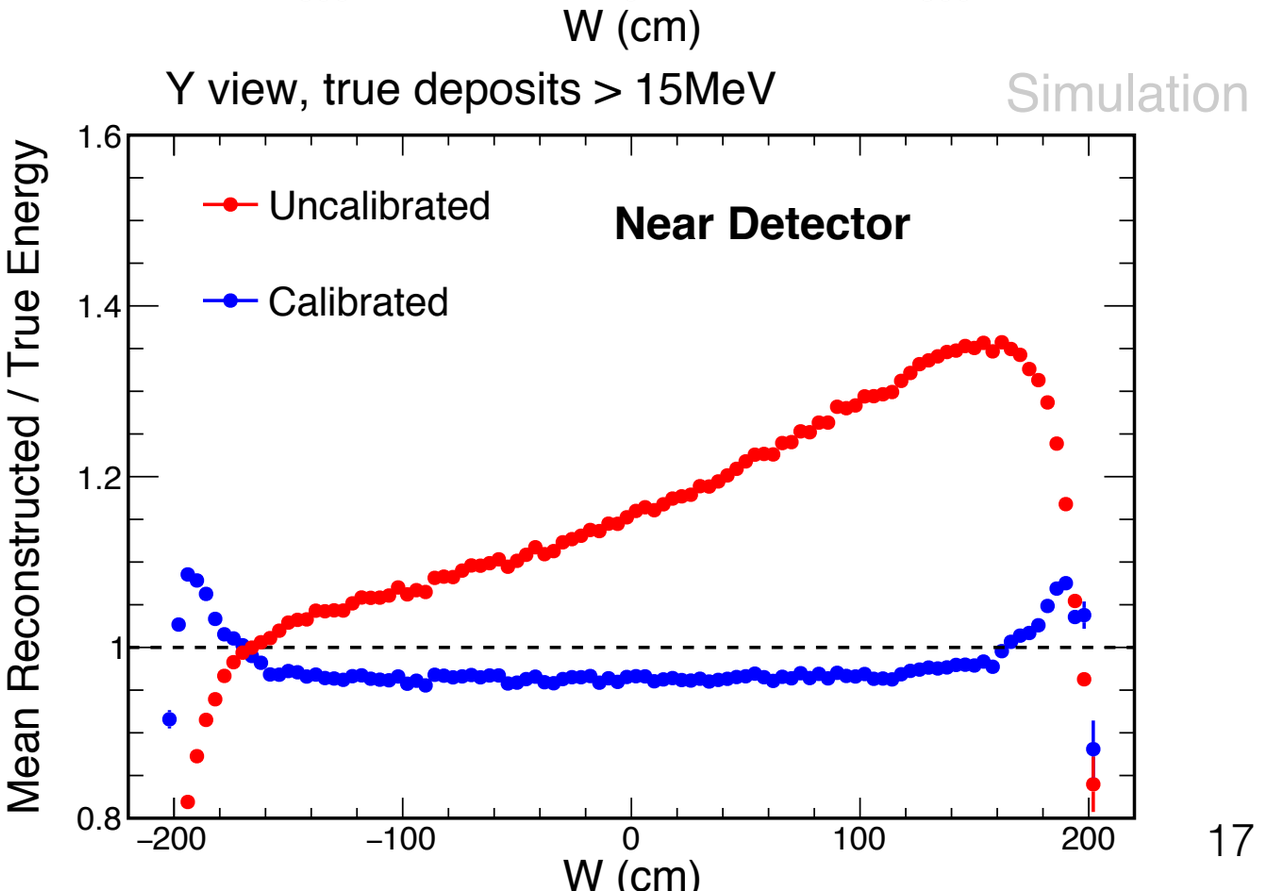
- Energy Scale Factor **(GeV/PECorr)**
- Stopping Cosmic Muon Sample

Verification with MC

- Profile Ratio of Reconstructed over True Energy
  - ✳ **Energy Scale**: average vertical deviation from 1
  - ✳ **Relative Calibration**: shape along W, cell, plane
- Pi-Zero Mass Peak
- Muon/Proton dE/dx
- Michel Electron Spectrum







Takeaway Points

- **Full chain of correction factors** to take measured PE to a best estimate of energy deposited, GeV

- **Scintillation Light attenuates** to different degrees in each cell
  - ✳ Fit a double-exponential form to PE/cm response for each cell: attenuation correction factor

- **Remove bias from the cosmic muon sample** before calibrating
  - ✳ Threshold and Shielding Effects

- Do not let **threshold effects bias the absolute energy scale**
  - ✳ <MeV / cm> / <PECorr / cm>

- Ongoing Work
  - ✳ Threshold & Correction Factor with data instead of MC
  - ✳ Fit to Response (PE/cm) Median
  - ✳ Rigorous understanding of systematic uncertainty