# ART (Algebraic Reconstruction Technique) for Electron Shower Reconstruction

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# Overview

- Electron Final States
- MINERvA Detector
- EM Calorimetry
- What is ART?
- Simple ART Demos with X-Y and Hex Image Array
- Angular resolution using ART

# Electron Final States

$$\nu_e n \rightarrow e^- p$$
$$\bar{\nu}_e p \rightarrow e^+ n$$

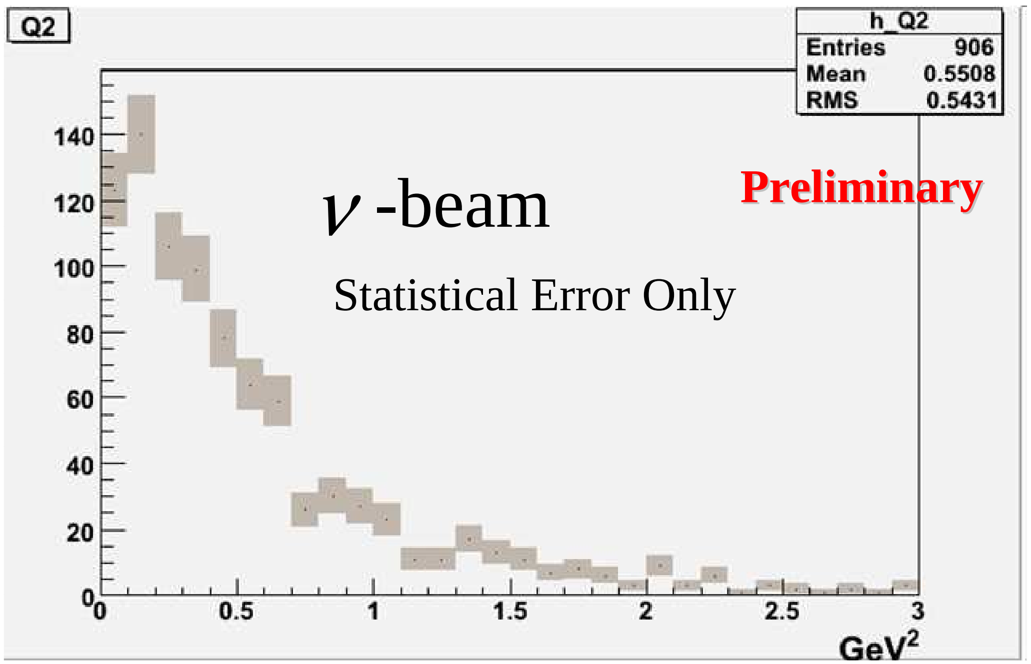
- Fraction of electron neutrino in the neutrino beam is small (~1%)
- Proton and neutrino may not be visible when it has too low energy
- $Q^2$ (4-momentum square) distribution has not been measured

$$\nu_\mu + e \rightarrow \nu_\mu + e$$
$$\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$$

- Well-known cross section
- Very small cross section
- Very forward electron
- Measurement can give loose constrain to flux

- Background has not been studied yet

# $\nu_e, \overline{\nu}_e$ CCQE $Q^2$ Distribution




$$E_\nu = \frac{m_n E_e - m_e{}^2/2}{m_n - E_e + p_e \cos\theta}$$

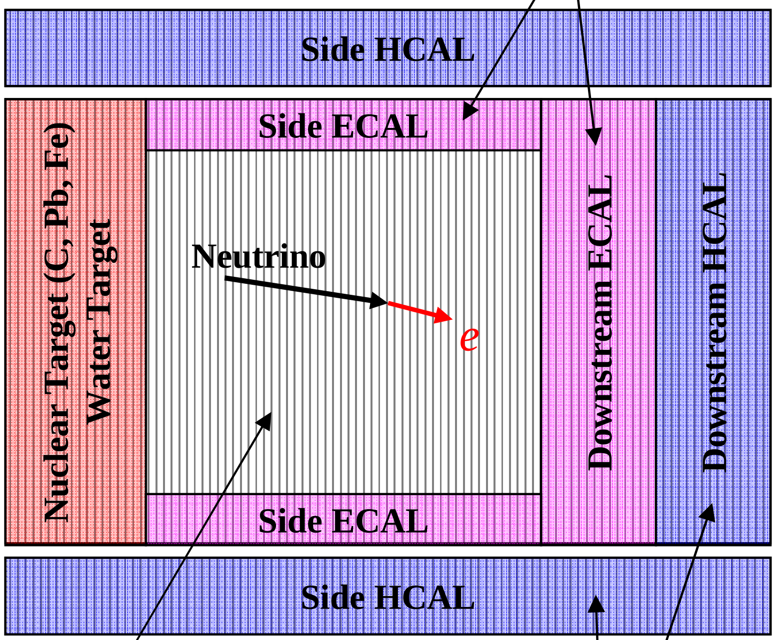
$$Q^2 = 2M_n(E_\nu - E_e)$$

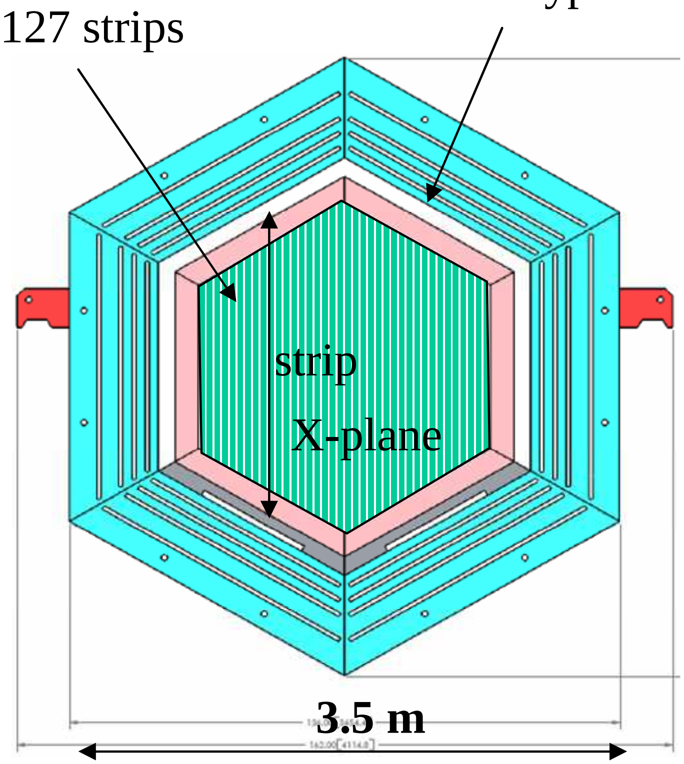
- This is GENIE MC prediction

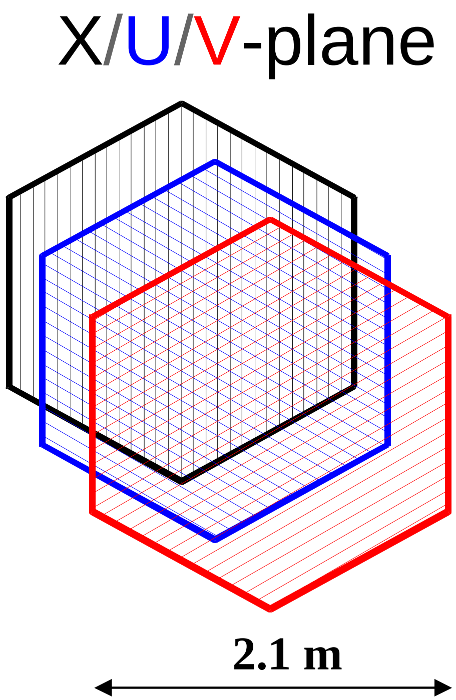
# Minerva Detector

**ECAL**: Scintillator + lead sampling calorimeter

One module has two scintillator planes.
Module Type: XU module, XV module



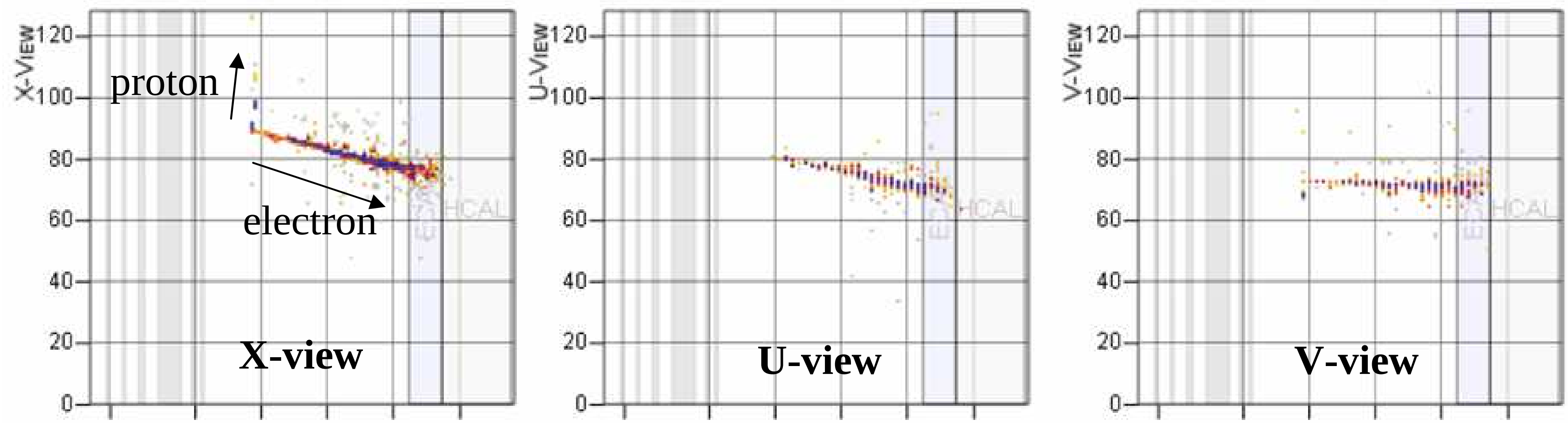




**Tracker** serves as target (CH)

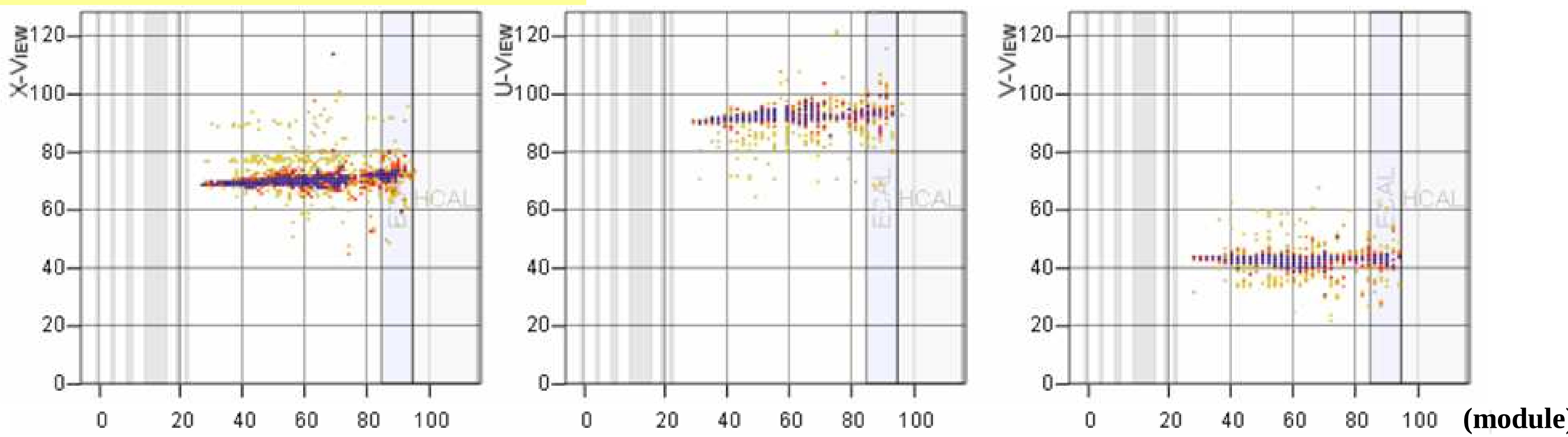
**HCAL**: Scintillator + steel sampling calorimeter

# Event Display
## (Real Data)

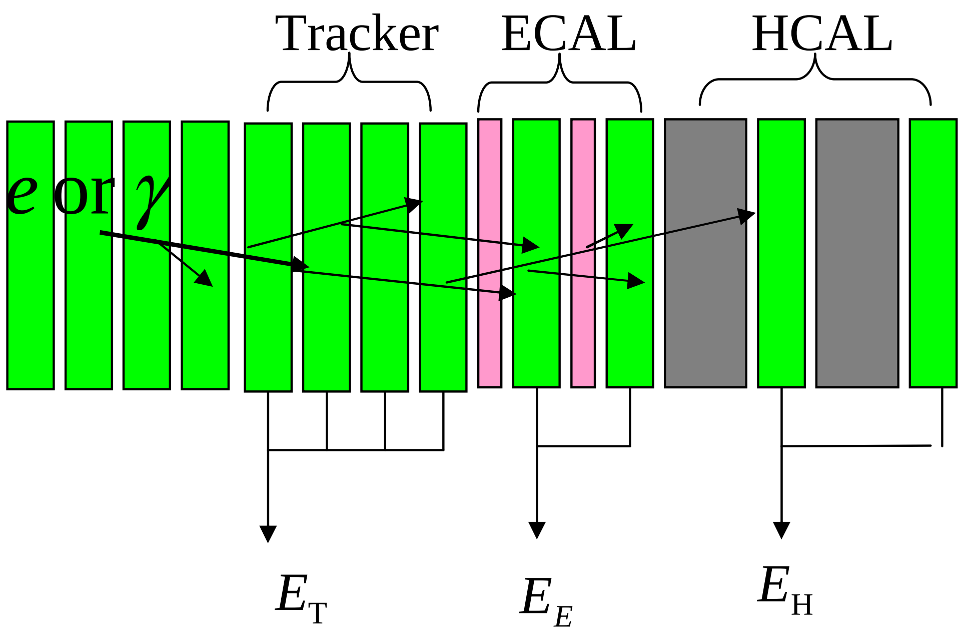
$\nu_e n \rightarrow e^- p$ candidate event

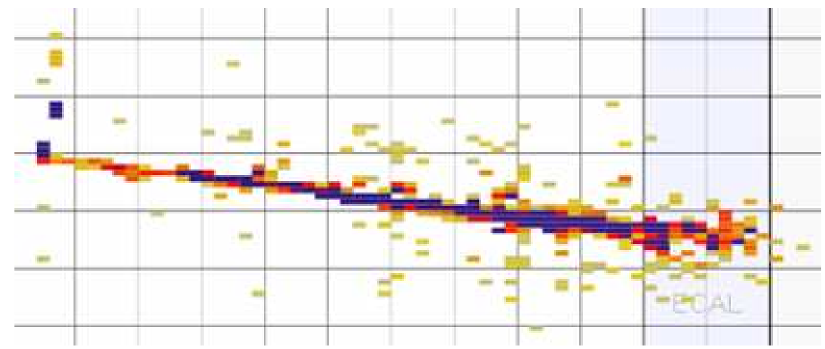


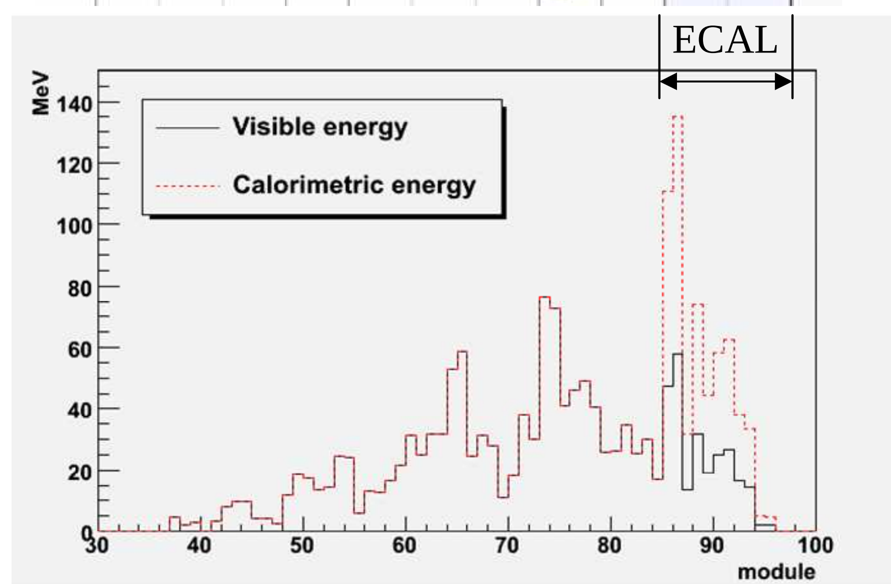

$\nu_\mu e^- \rightarrow \nu_\mu e^-$ candidate event



# Calorimetric Energy



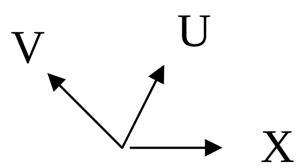


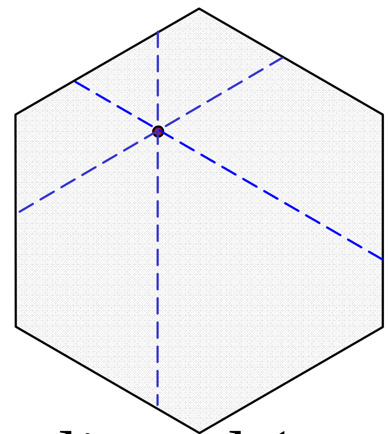

$$E = \alpha(E_T + k_E E_E + k_H E_H)$$

- Typical sampling calorimeter has structure of alternating absorbers (lead or steel) and active mediums (scintillator).
- In calorimetric energy calculation, we need to compensate energy loss in absorber.

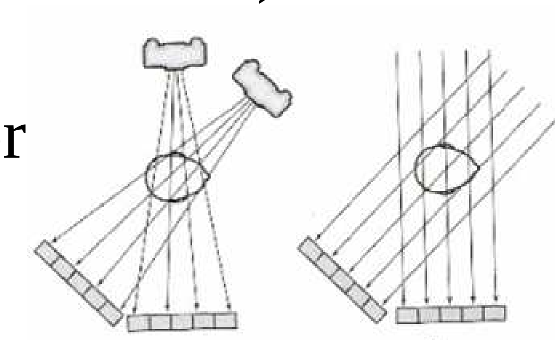
# ART

- Current tracking algorithm reconstructs thin track well.
  - It uses X=U+V matching condition.



- It's not easy for shower event or complicated ( multi-track) event.
- Finding 3D coordinates from 3 different views (or projections) is very similar to problem solving in Computed Tomography (CT).
- Among several methods, algebraic reconstruction technique (ART*) is adopted.

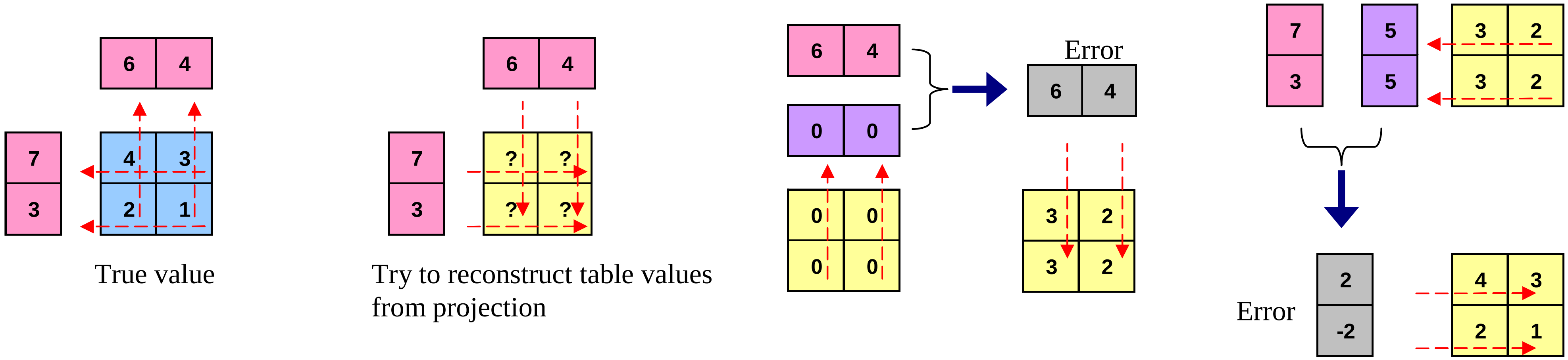


**CT Scan**

*** Stefaan Vandenberghe et al, Phys. Med. Biol. 51 (2006) 3105 http://iopscience.iop.org/0031-9155/51/12/008**

# Algebraic Reconstruction Technique (ART) Example

- Example of reconstructing 2D position from x and y projections



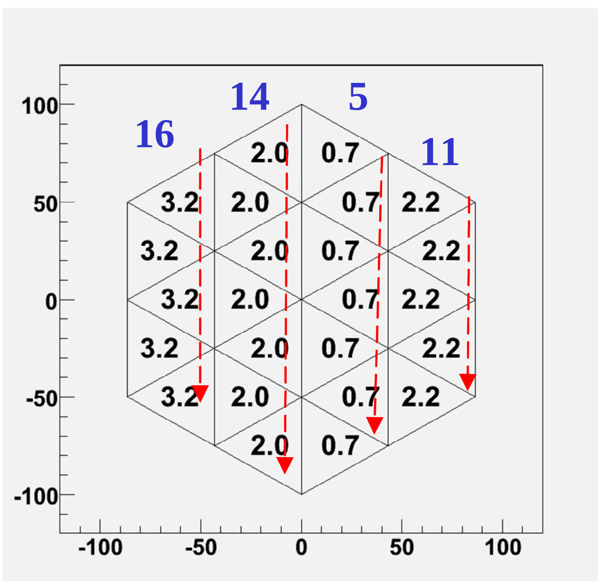

(a) (b) (c) (d)

- This is an iterative algorithm

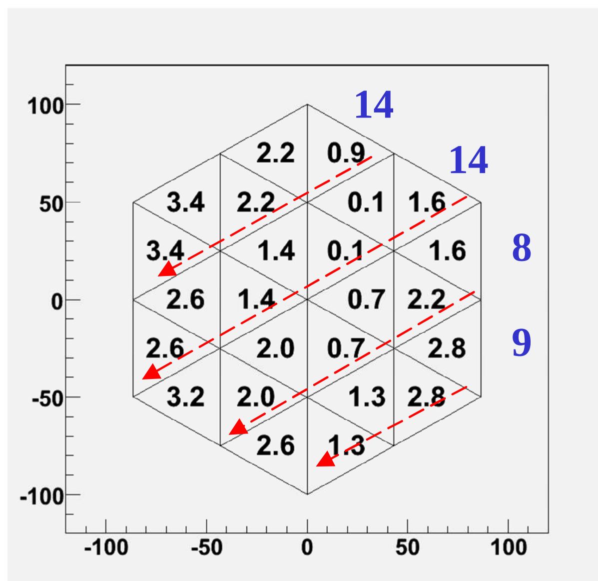
# 2D image from XUV projection

- MINERvA has hexagonal planes and three views.
- Triangular image grid is used for easy applying three views' projection.
  - X-Y grid to XUV grid.

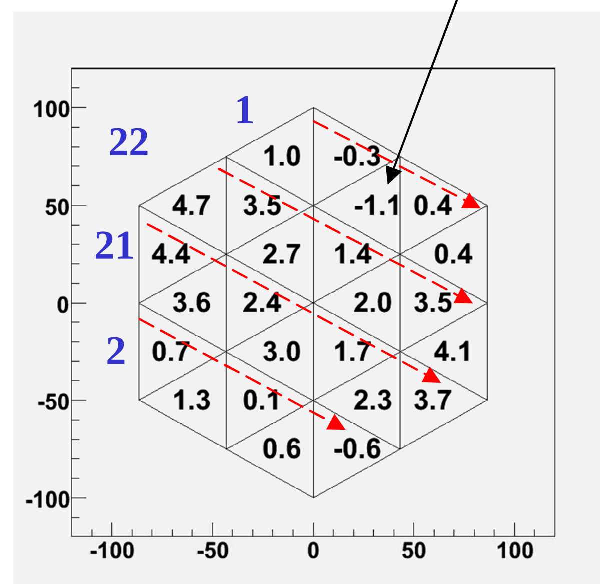
**Negative number is unphysical (Use constraint to be positive)**



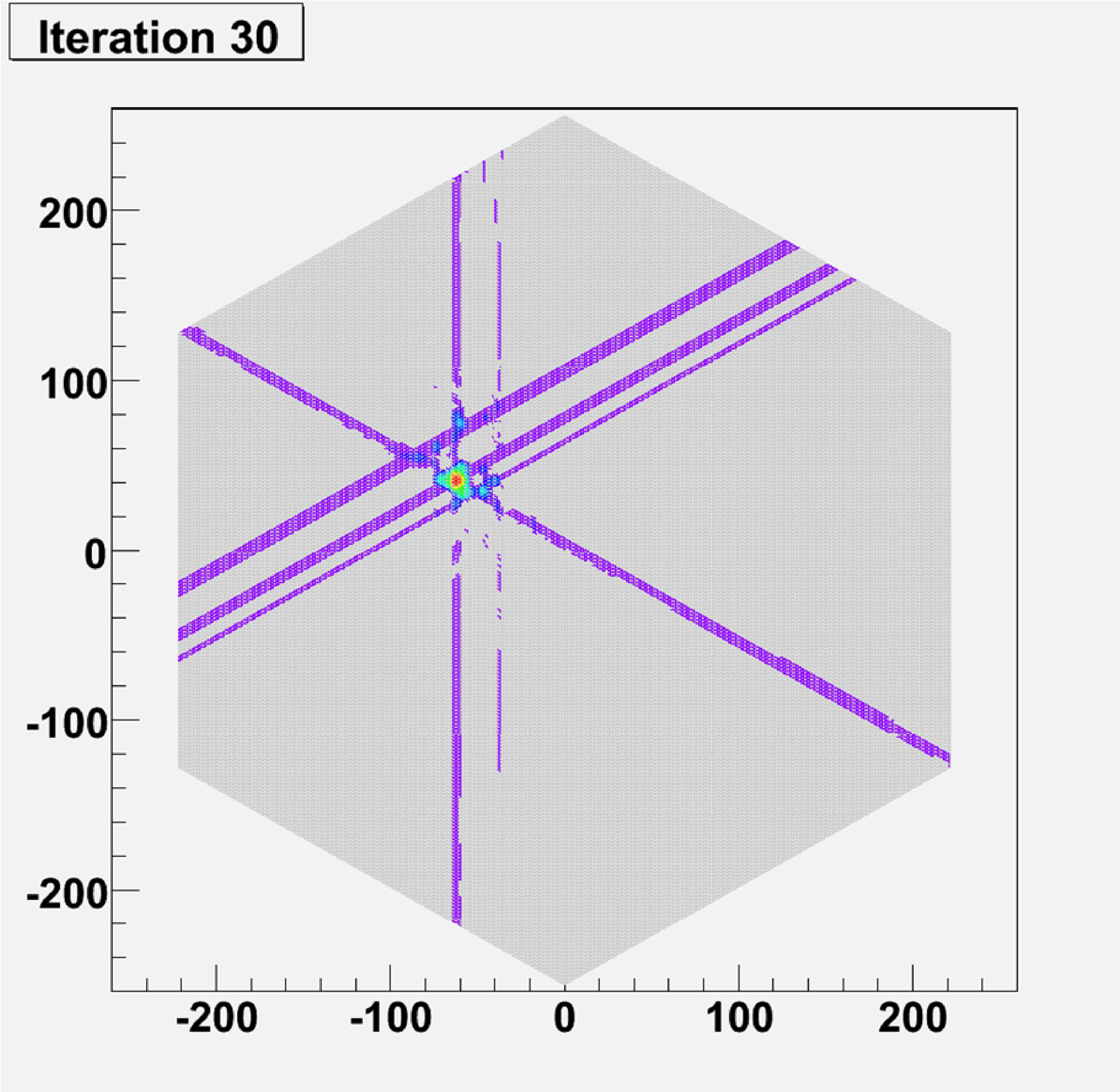

**Iteration for X**



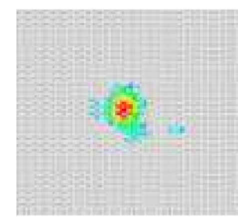

**Iteration for V**



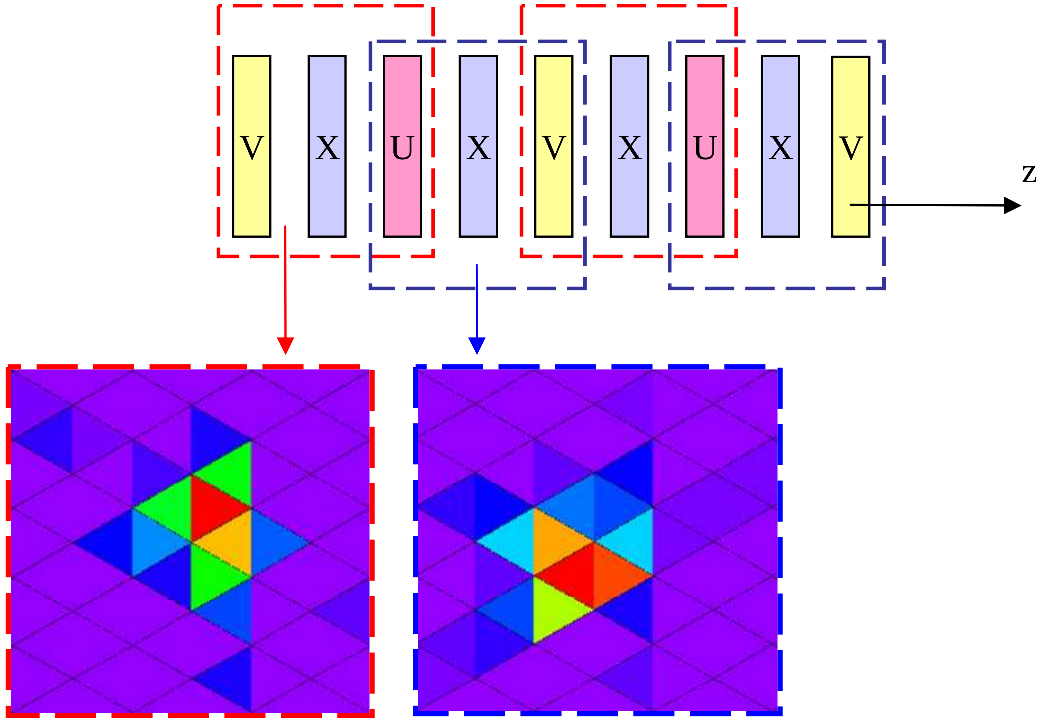

**Iteration for U**

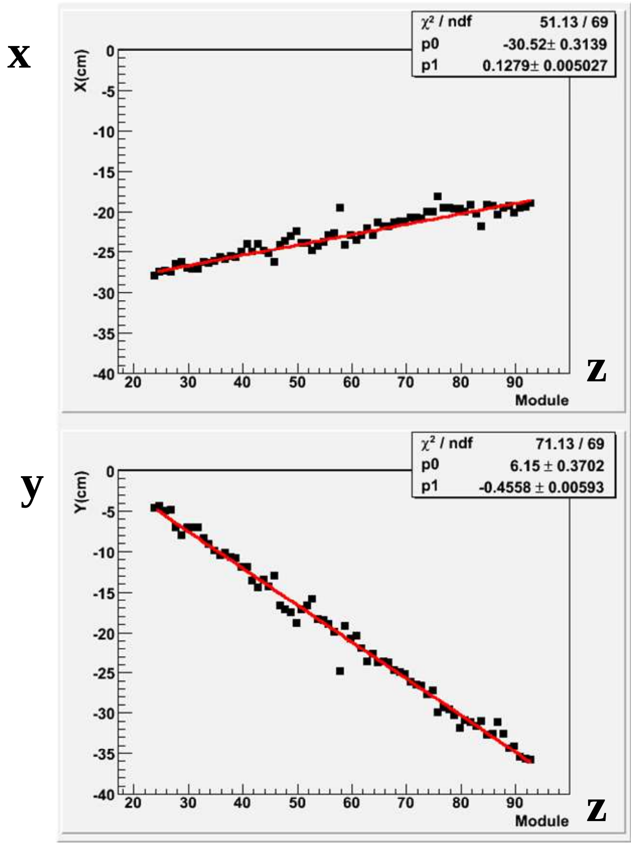



**Actual reco uses minimum energy cut**



# 2D coordinates → 3D track




- Can take VXU or UXV module set to apply ART from VXUX module pattern.
- x, y positions are based on energy weighted mean position of cells.

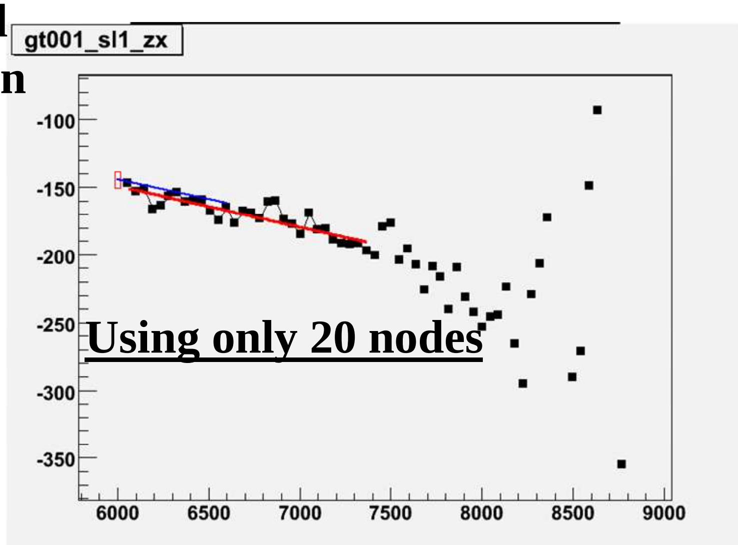
$$x = \frac{1}{\text{Total Cell Energy}} \sum_k (\text{Cell position x})_k \cdot (\text{Cell energy})_k$$

$$y = \frac{1}{\text{Total Cell Energy}} \sum_k (\text{Cell position y})_k \cdot (\text{Cell energy})_k$$

# Electron Direction Fit using MC sample

**Fitting only beginning of shower gives better angle resolultion**

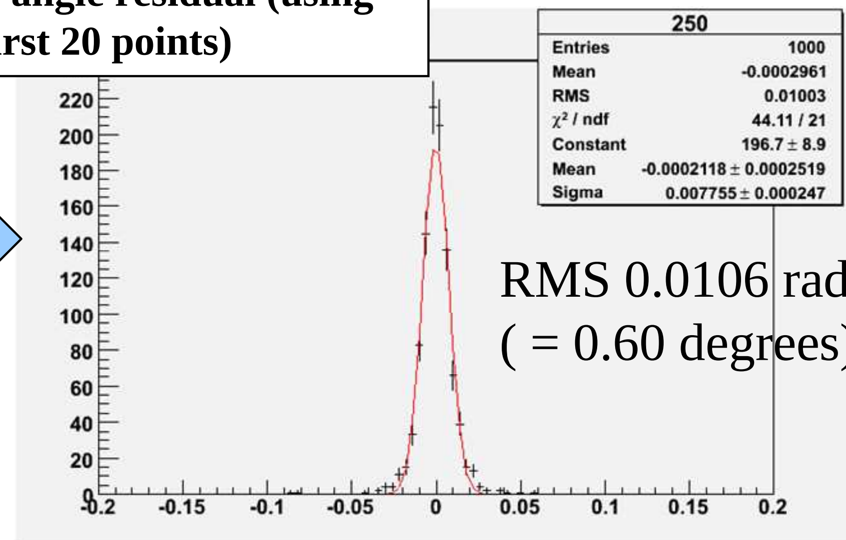
**Centroid x-position (mm)**




**Using only 20 nodes**

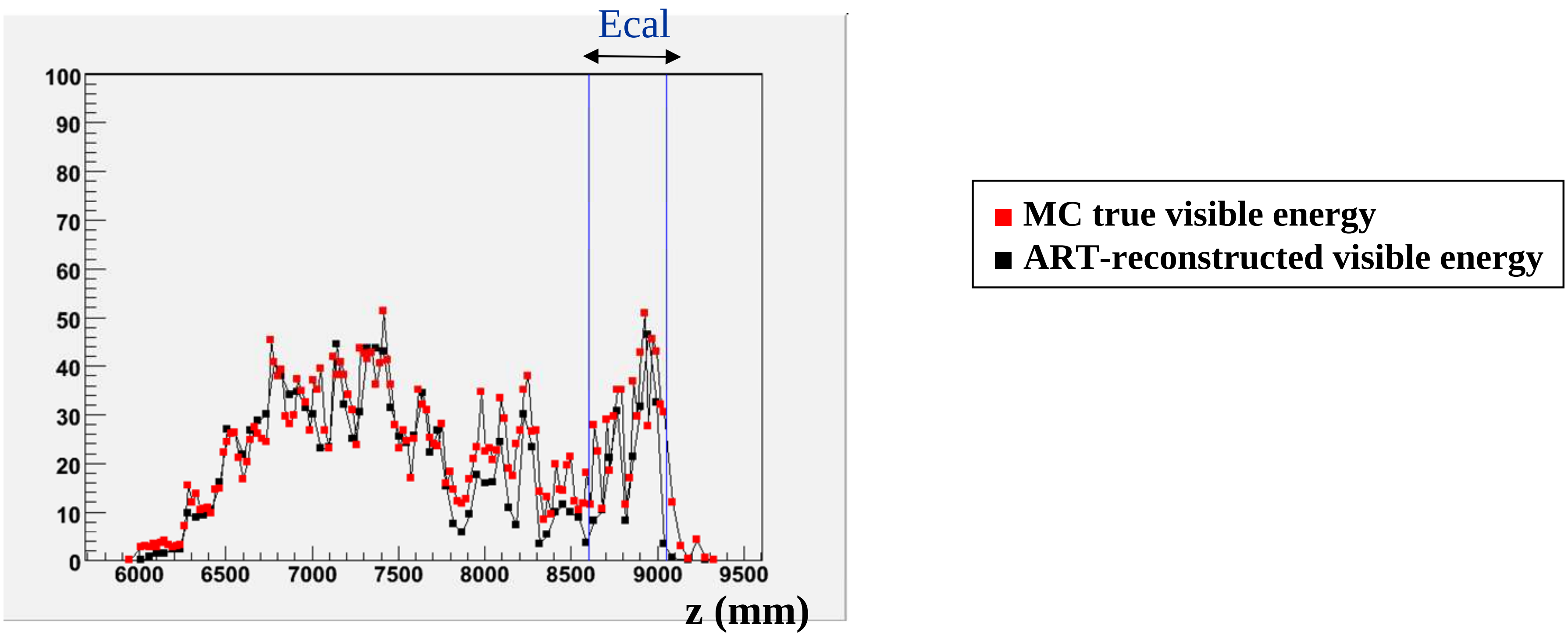
**z (mm)**

**x-angle residual (using first 20 points)**




RMS 0.0106 radian
( = 0.60 degrees)

# Longitudinal Energy Profile




- ART reconstructs longitudinal energy profile reasonably well

# Conclusion

- ART gives good angular resolution for electron shower
- ART reconstructs longitudinal energy profile pretty well
- ART is currently slow ~19 seconds/event but
  - Current code is not optimized on performance yet
  - ART can be used with pre-filter
- ART is a very powerful reconstruction technique for electron shower

# (Backup Slides)

# Data Sample and Event Sample Size

- Data sample to be used
  - Frozen detector, $\bar{\nu}$-beam, $8\times10^{19}$ POT
  - Minerva detector, $\nu$-beam, $1.28\times10^{20}$ POT
  - Minerva detector, $\bar{\nu}$-beam, $1.5\times10^{20}$ POT
- Event Sample size (After fiducial cut, $E_e$>0.8GeV)

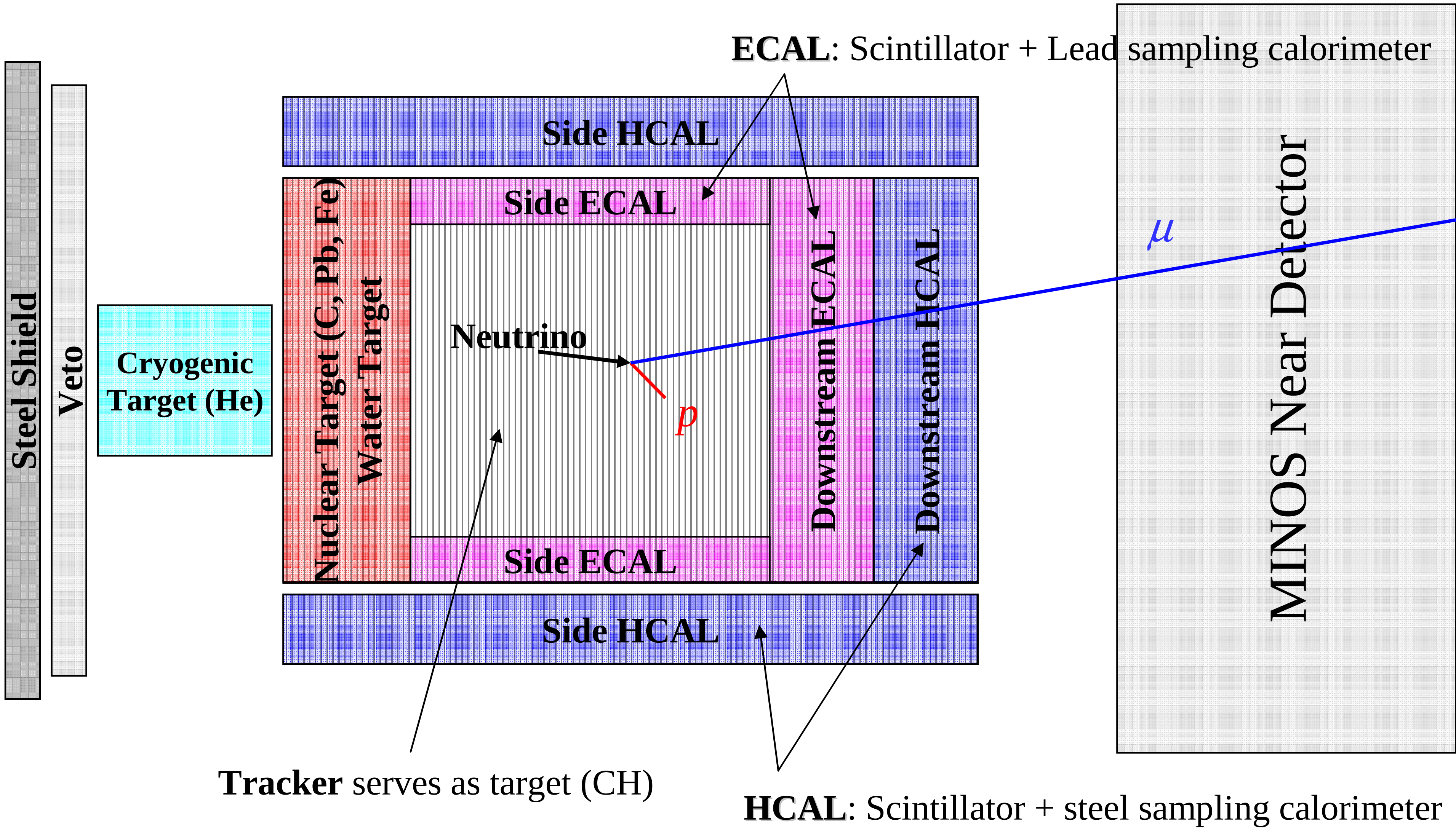
$\nu$-beam

| | |
|---|---|
| $\nu_e$ CCQE | 816 |
| $\bar{\nu}_e$ CCQE | 90 |
| $\nu_\mu e$ , $\bar{\nu}_\mu e$ | 46 |

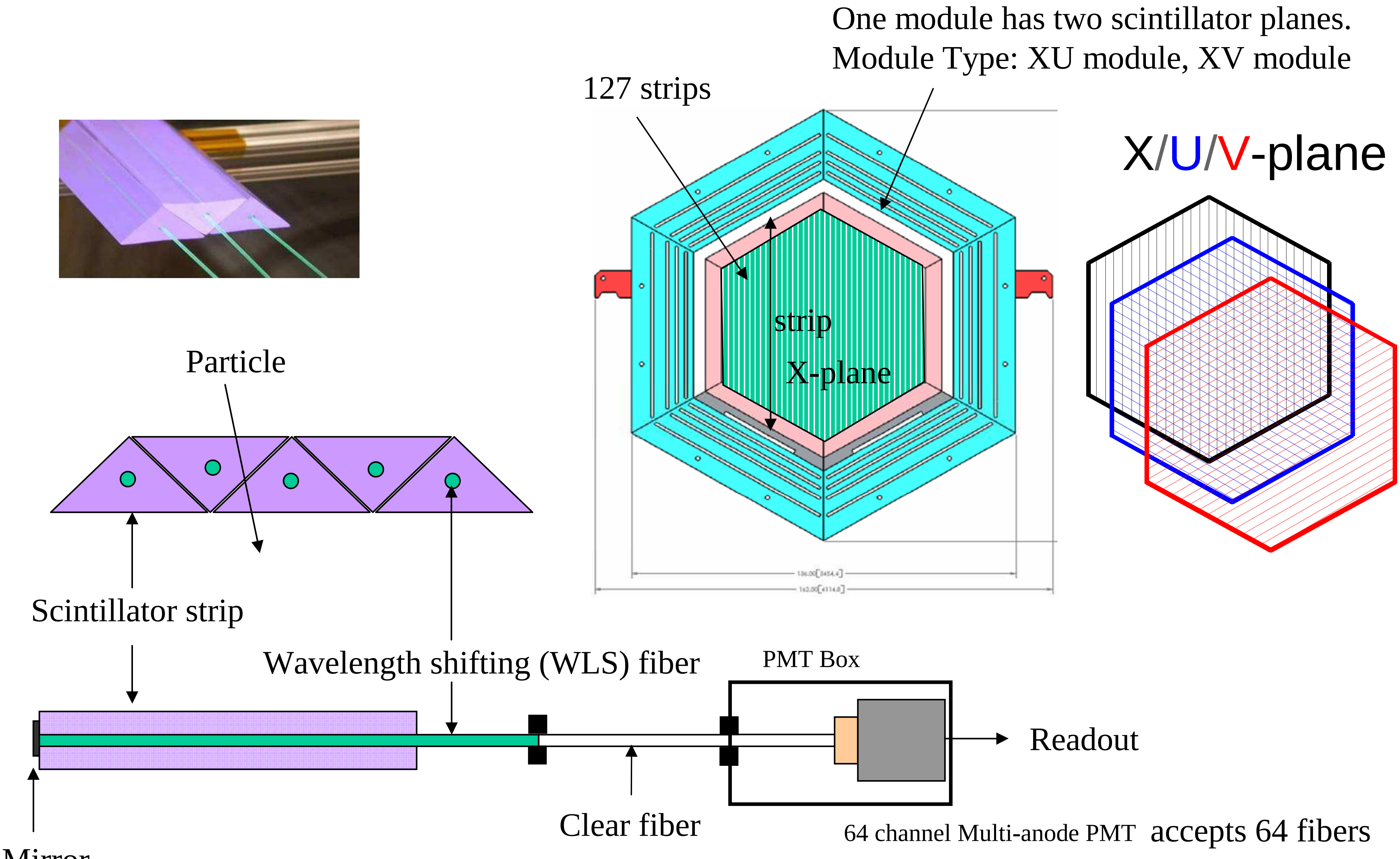
$\bar{\nu}$-beam

| | |
|---|---|
| $\nu_e$ CCQE | 231 |
| $\bar{\nu}_e$ CCQE | 597 |
| $\nu_\mu e$ , $\bar{\nu}_\mu e$ | 52 |

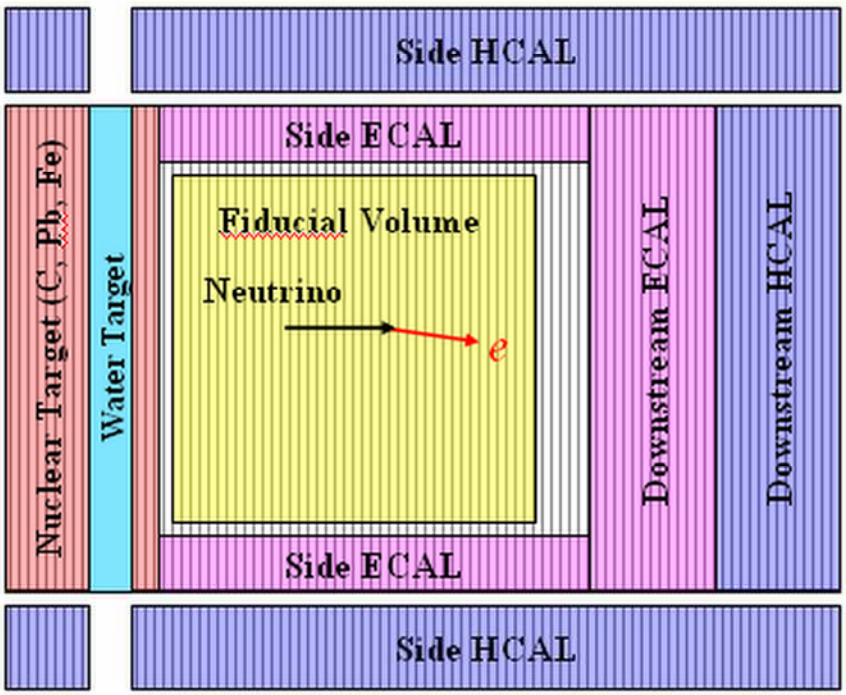
# Minerva Detector

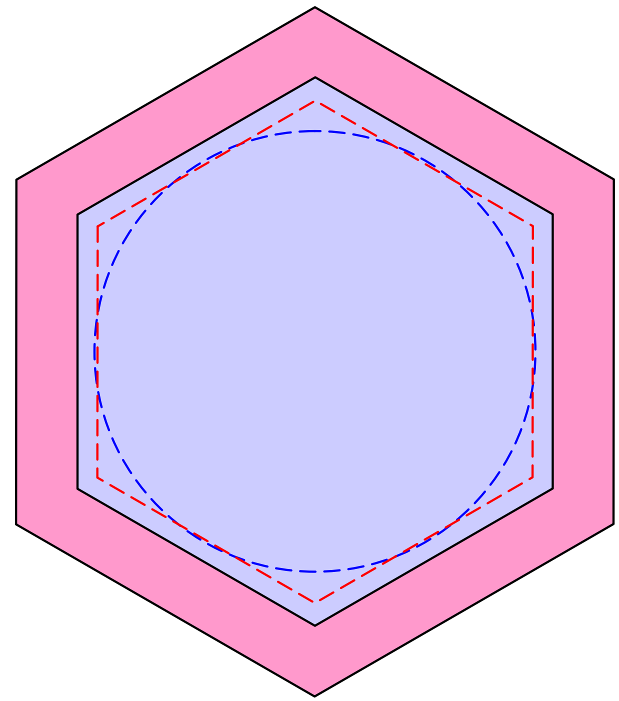


# Detector Technology



# Fiducial Volume



- First module is not used to veto nuclear target events
- The last four modules are not used to get electron direction
- Hexagonal fiducial volume to maximize fiducial volume

# X=U+V

$$U = X\cos 60^\circ - Y\sin 60^\circ$$

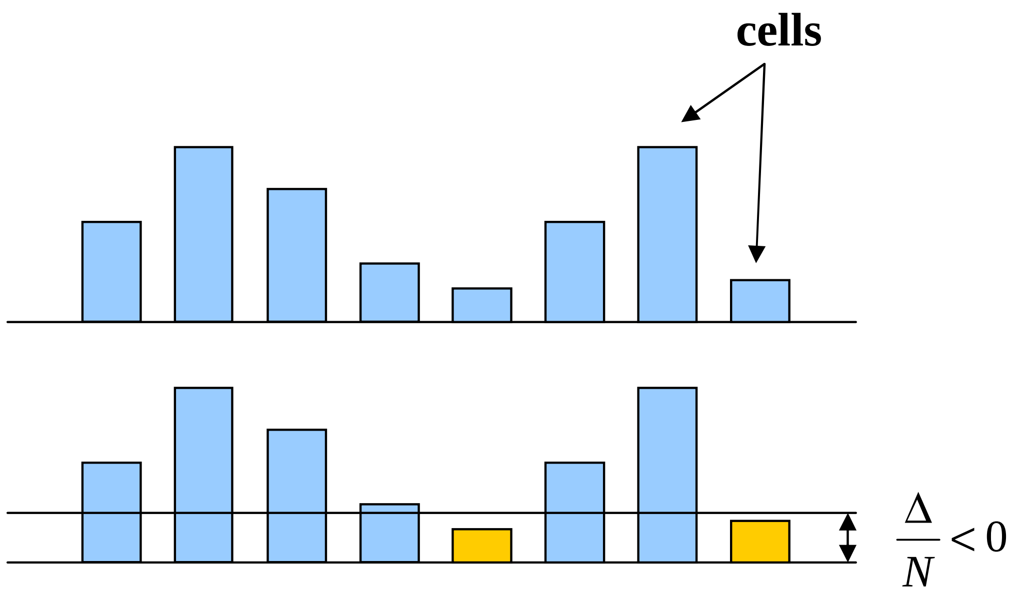
$$V = X\cos 60^\circ + Y\sin 60^\circ$$

$$U + V = 2X\cos 60^\circ = X$$

$$V - U = 2Y\sin 60^\circ = \sqrt{3}Y$$

# Preventing Negative Cell Value

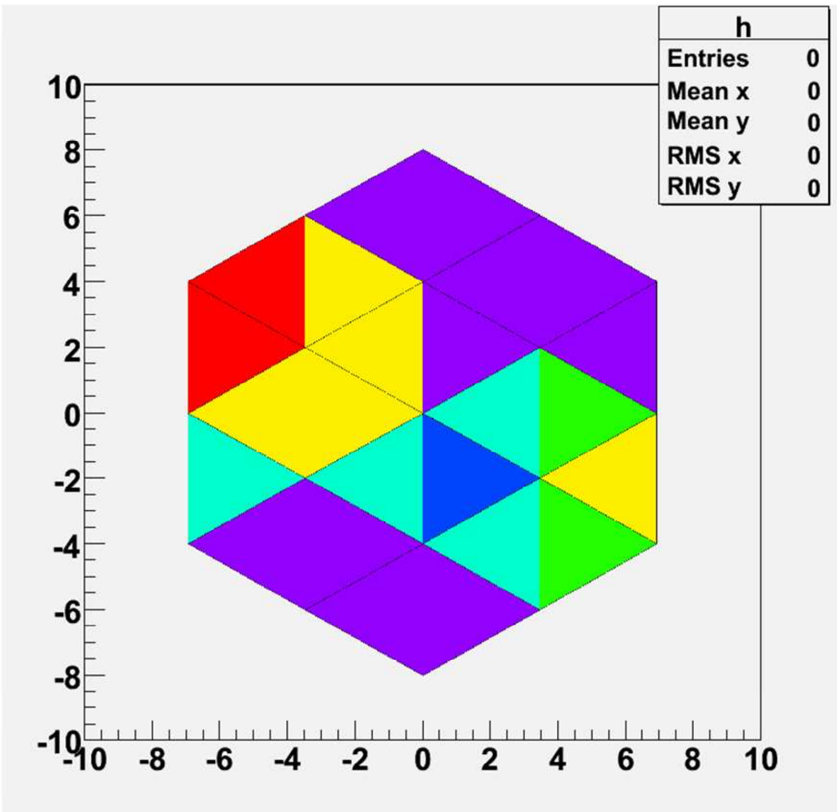
$$x_i' = x_i + \frac{\Delta}{N}$$



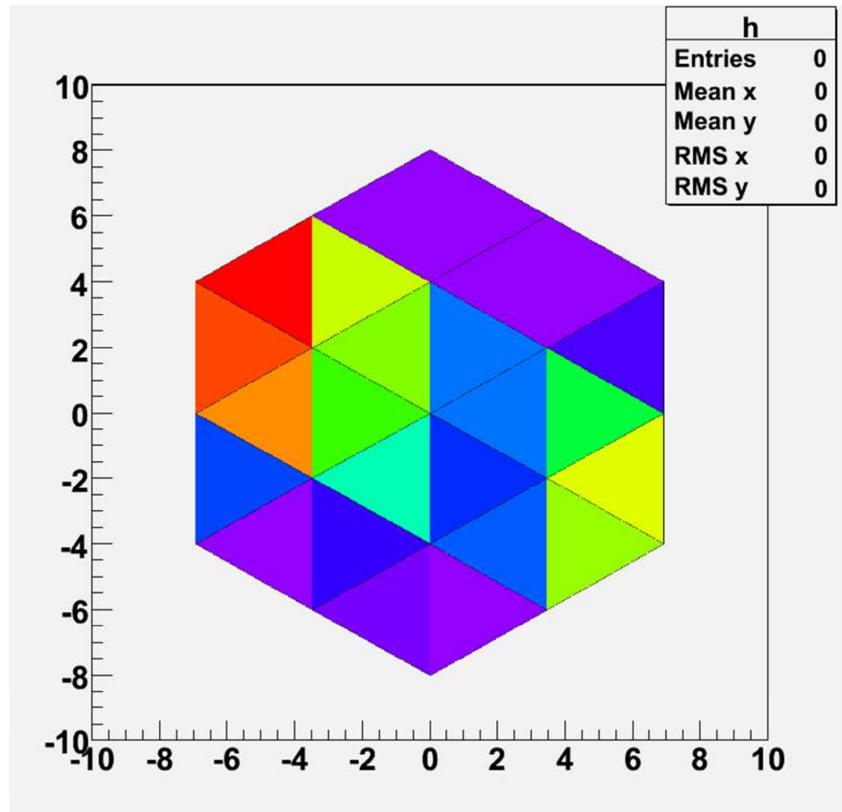

- Negative cell values are unphysical
- The iteration skips correction on some cells if corrected cell becomes negative.
- If we don't do this, iteration sometimes diverges.
  - Amplitude of the negative cell becomes bigger and bigger for each iteration

# ART demo with Small Hex

True value

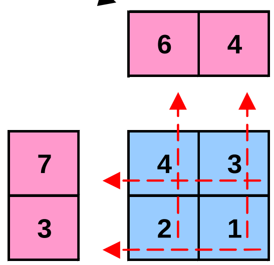



Reconstructed



# Energy Scale in ART

**These x and y-projections are in same z position**

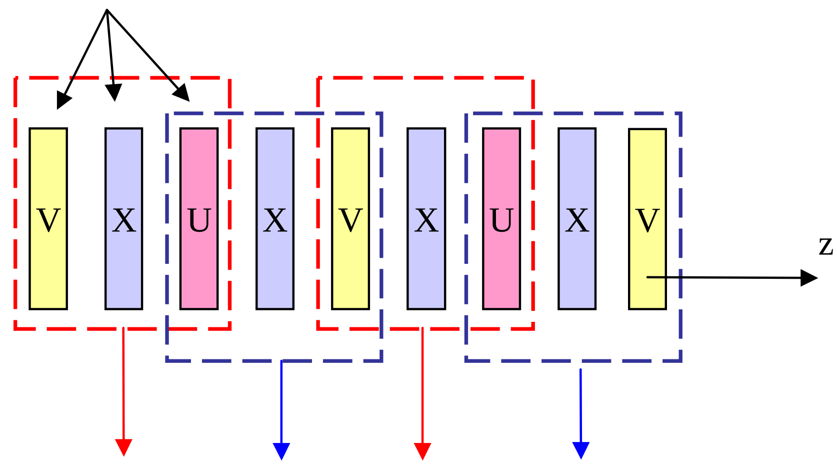



True value

E sum in ART: 10=1+2+3+4

E sum in projection: 20=7+3+6+4

**These x, u and v-projections are in different z positions**




$$\frac{1}{3}X+\frac{2}{3}V(\mathrm{or}\,U)=\frac{1}{3}\frac{1}{2}+\frac{2}{3}\frac{1}{2}=\frac{1}{2}$$

**1/3 = three views are used for one z-node**

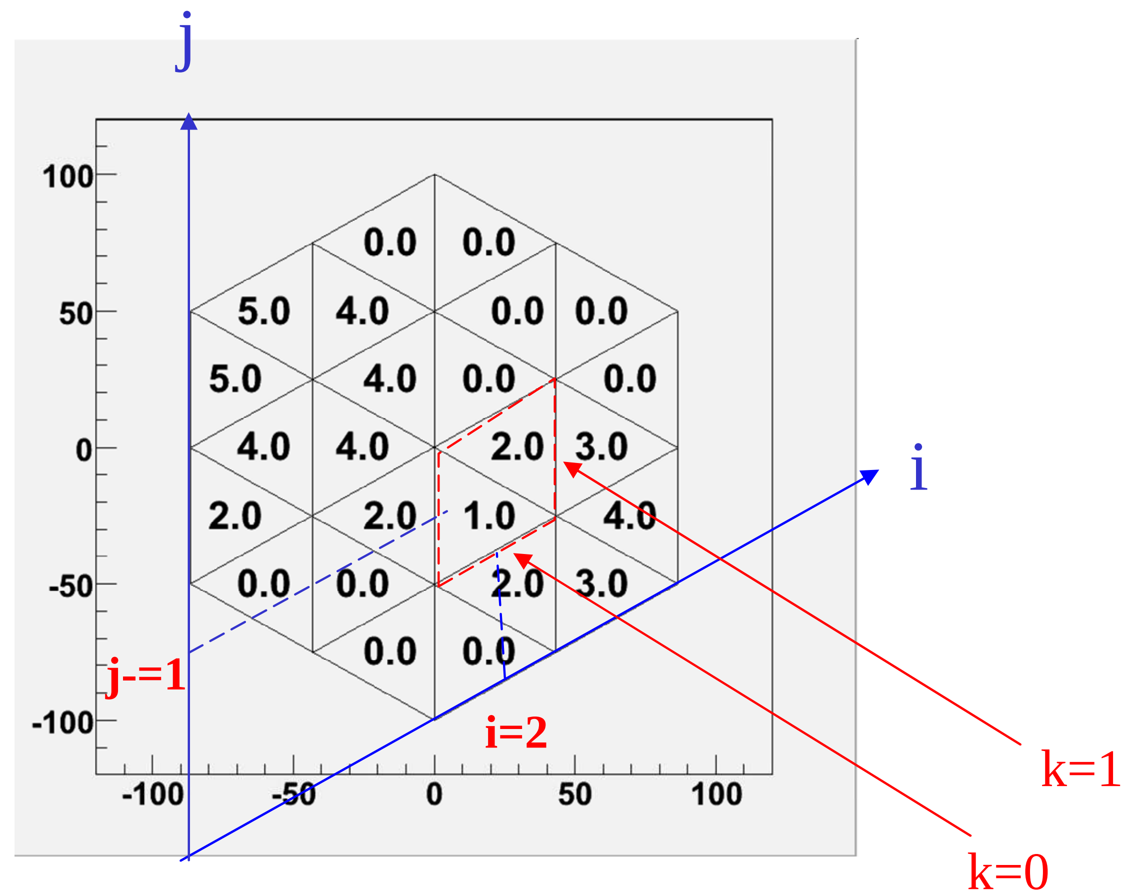
**Factor 2 is added because V (or U) is used twice**

**Factor ½: z-node is per two planes**

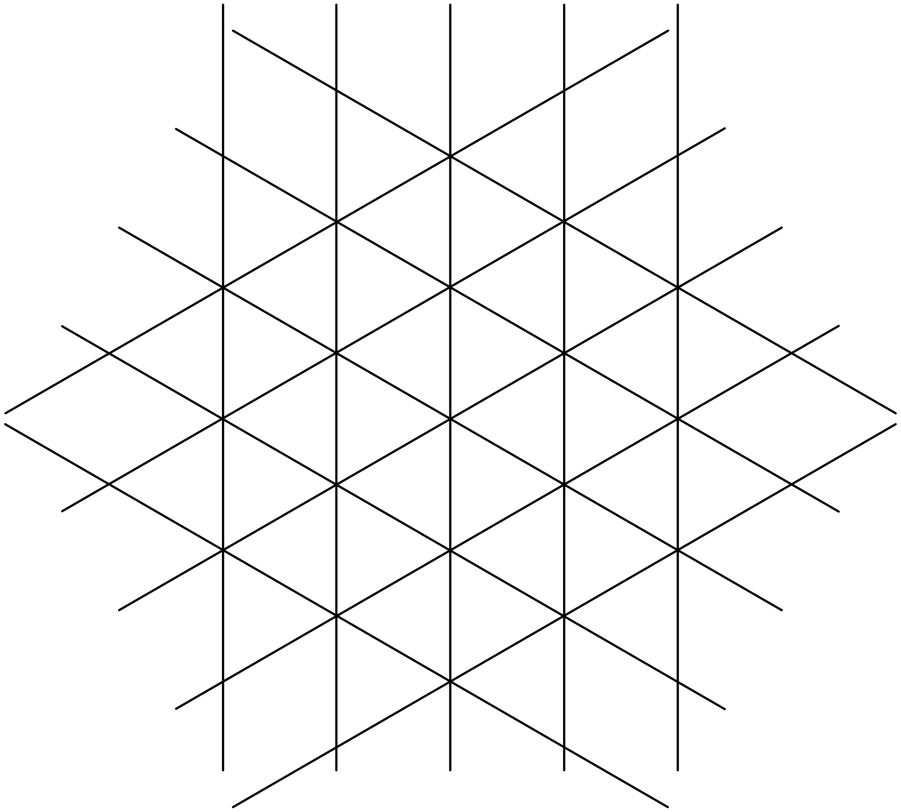
- Energy sum of ART energy cell ~ ½*(simple energy sum)
- ART energy is scaled up by factor 2

# Data Structure

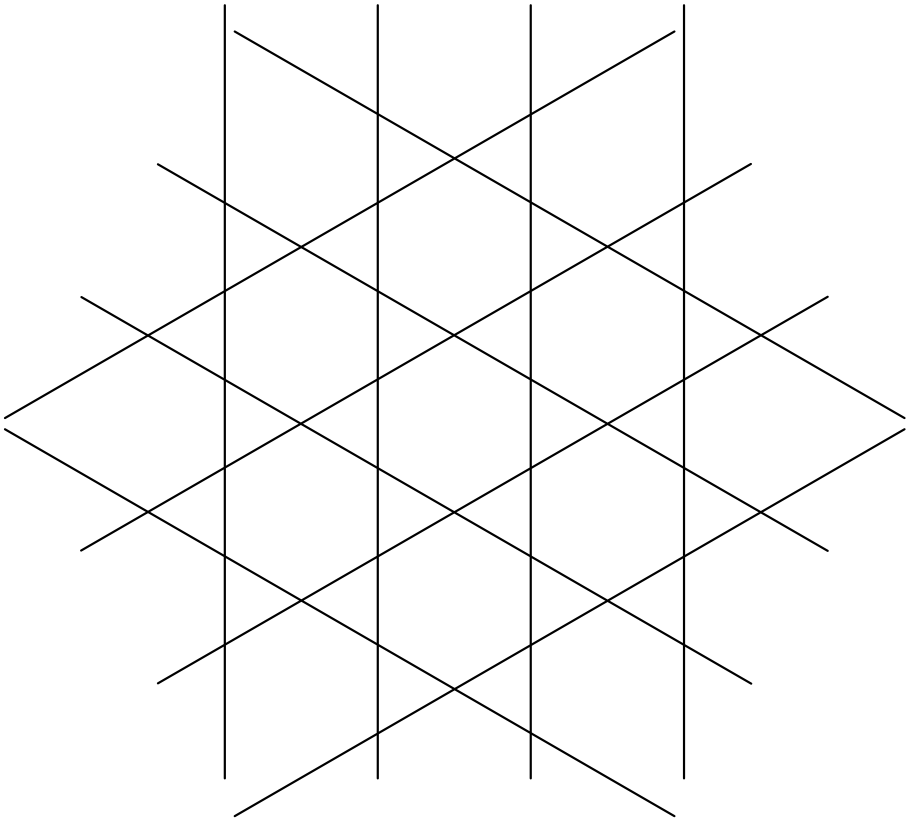
- M[i][j][k]
  - i=0, nstrips-1
  - j=0, nstrips-1
  - k=0 or 1



# Event Number of Strip Vs. Odd Number of Strips



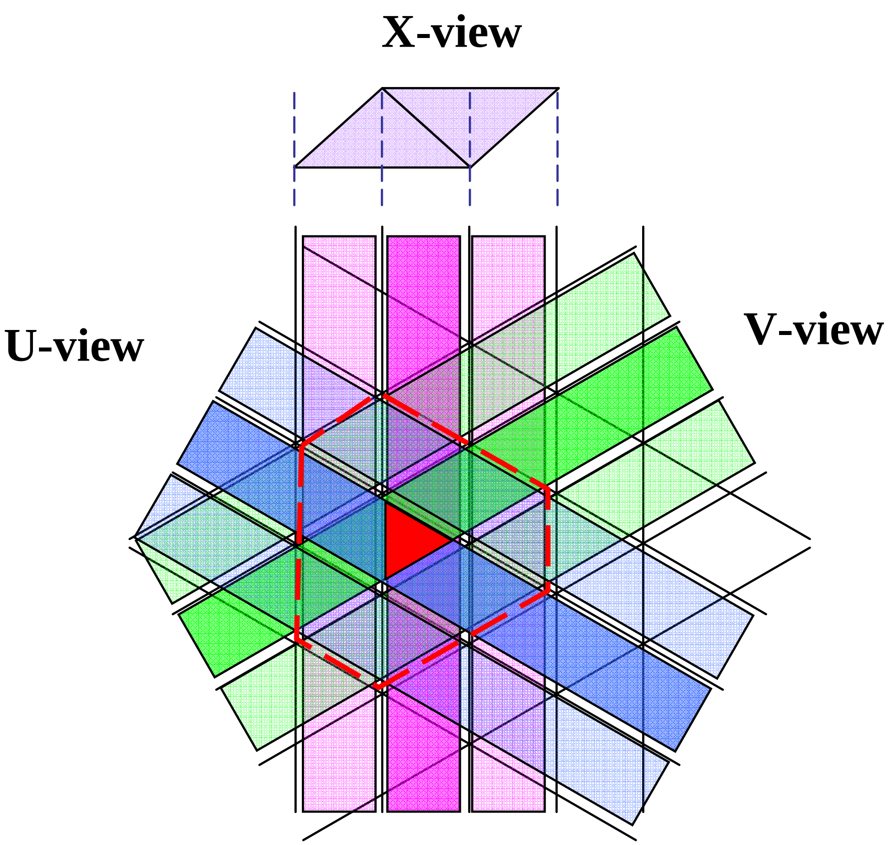
Event number of strips



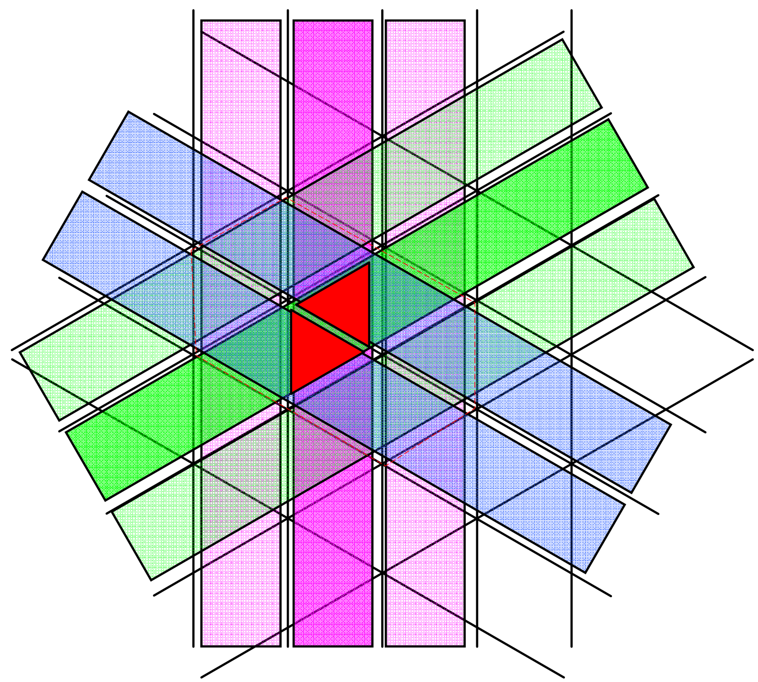
Odd number of strips

# Shapes of XUV Intersection

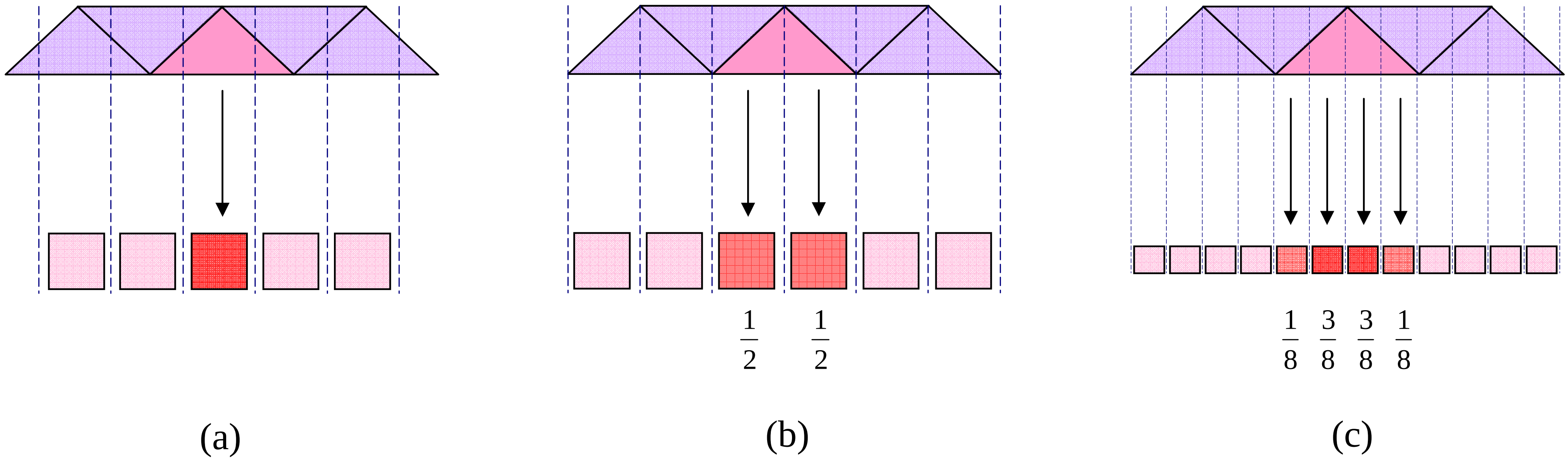
**Doublet in three views**




**Doublet in two views and Singlet in one view**



# Smaller Cell




- Initially 128 columns are used.
  - Symmetry of cell is only available in even number of columns.
  - Actual number of strips are 127.
- ART implies X=U+V matching condition implicitly.
  - Slight mis-matching XUV hits are suppressed.
- To loosen XUV matching condition, one strip is projected to two columns.
  - It also solves odd number of column problem.
- Further smaller cell mimics charge sharing between adjacent strips